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(6) # STATISTICS OF OPTICAL RADIATION SCATTERED FROM ROUGH SURFACES

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When coherent illumination is scattered from a rough surface, the resulting pattern of light (speckle pattern) has stochastic variations in irradiance which relate to the scattering surface itself. A computer simulation for a particular scattering geometry has been made in which four statistical parameters of speckle patterns have been related to various pairwise combinations of surface height and correlation interval for a gaussian scattering surface. The corresponding optical analogue of this simulation has potential application to studies of gun erosion.

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I. INTRODUCTION

When a laser beam is used to illuminate a rough surface, the resulting scatter pattern takes on a random, mottled character. This pattern is usually referred to as a speckle pattern, and its statistics relate not only to the particular radiance pattern on the surface of the scatterer but to the surface roughness as well. For another investigation[1], a computer program was written to evaluate numerically the far-field scatter pattern due to coherent illumination from a one-dimensional surface characterized by gaussian statistics. For that particular study, the statistics of the speckle pattern were examined with respect to the form of the radiance distribution over the scattering surface.

This present investigation was prompted by a problem related to gun erosion. Central to the estimation of gun tube wear is the assessment of surface roughness from one firing to the next. With a view toward developing an experimental technique useful in the analysis of surface structure, we utilized our one-dimensional analytical model to examine the relationship between roughness at a scattering surface and certain statistics of the scattered radiation.

II. PROBLEM FORMULATION

An attempt was made to model a scattering geometry which might be used in an actual measurement. With this in mind, an object 1 mm in length was chosen with radiation at 0.6-micron wavelength. The geometry is shown in Figure 1. The line source formed the input to a 15-cm focal length lens. At the output focal line, the speckle field was evaluated using the Huygens-Fresnel equation. The integral form of this equation describes the output field as an integral over the input aperture, where

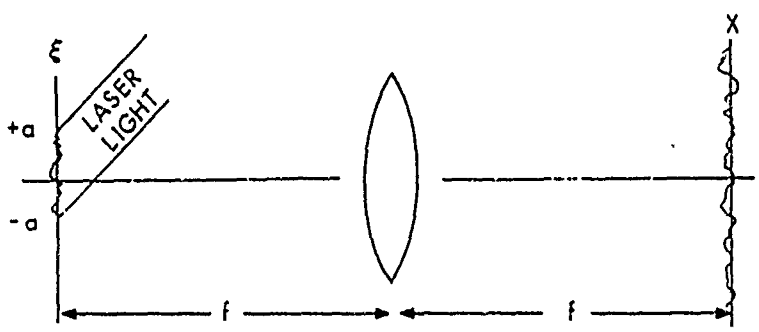

Figure 1. Setup for generation of optical scattering pattern. Laser light impinges on surface at ξ plane. Radiation is transformed by lens to plane X. The problem is to relate the statistics of the optical radiation at plane X to the surface characteristics in plane ξ.

1. R. Barakat, P.H. Deitz and T.E. Buder, "A New Class of Communications Systems: II. Theory", BRL Memorandum Report to be published.

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$$V(x) \propto \int_{-a}^{a} V(\xi)\exp\left[-i\ \frac{2\pi}{\lambda f}\ x\ \xi\right] d\xi, \qquad (1)$$

Here, V(x) is the output field, the limits of integration are from -a to a where a is ½ mm, V(ξ) is the complex scattered field at the rough surface, λ is the wavelength of the radiation, and f is the focal length of the lens.

In our evaluation, a special subroutine was used which generates stochastic functions which are gaussian in nature and conform to chosen parameters of standard deviation (vertical surface structure) and correlation interval (average scale size along the surface). Since the illuminated spot is small, a constant amplitude was assumed within the scattering aperture so that the statistics of the scattered radiation were a function of phase only. Figure 2 shows one computer realization of the phase of the optical beam immediately after scatter at the rough surface for one set of parameters. The standard deviation is one-tenth of a wavelength and the correlation interval is 5 microns.

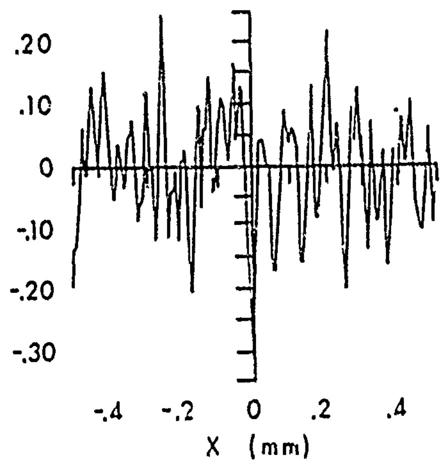

Figure 2. Computer-generated guassian phase surface having standard deviation (sigma) of 0.1 lambda (where lambda (L) is 0.6 microns) and a correlation interval (alpha) of five microns.

Equation (1) was utilized in discrete form for 400 equally spaced points across the 1-mm object and evaluated at 400 locations in the detection plane over a distance of 40 cm. After the 400 complex field calculations were made in the detection plane, the results were squared to give the measurable quantity, the intensity pattern.

For the gun erosion application, a range of height-roughness variations from 0 to 0.9 λ (in standard deviation), where λ is the wavelength, were examined together with correlation interval variations from 5 to 105 microns. Six particular values of standard deviation were used with five values for the correlation interval in every possible pairwise combination. For each of these 30 pairs of parameters, 15 realizations of the radiation pattern in the detection plane were generated. Various statistical parameters were extracted from these speckle patterns and are discussed in the next section.

III. RESULTS OF CALCULATIONS

Using the 15 realizations of speckle pattern for each of 30 pairs of surface height (sigma) correlation interval (alpha), four specific statistical variables were examined: mean irradiance, standard deviation, ratio of RMS/average, and the correlation interval.

For each of the four statistical parameters examined, the procedure was similar. The parameter under evaluation was computed for each speckle pattern and then averaged over the 15 realizations computed for each of the 30 pairs of sigma/alpha variables. Standard deviations about these means were also computed to give an indication of the statistical uncertainty. Figure 3 gives the expected value of the speckle

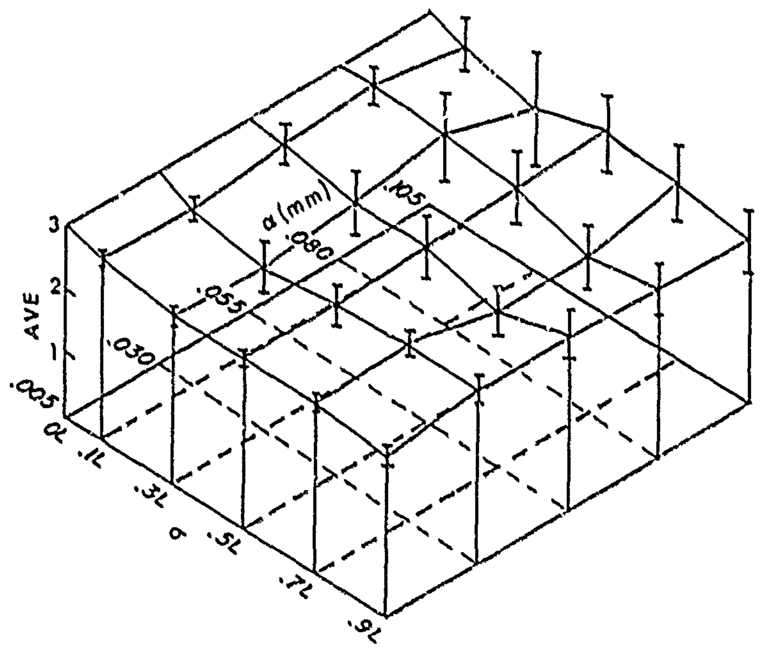

Figure 3. Three-dimensional perspective plot showing expected value of average irradiance of scattering pattern vs. pairwise combinations of surface height (sigma) and correlation interval (alpha) of illuminated surface. L is the wavelength of the optical illumination (0.6 microns). Each point represents the expected value of 15 realizations of a speckle pattern for which the average value has been computed. Error bars indicate the one-sigma variations about the expected value. Absence of error bars indicates a nonstochastic calculation.

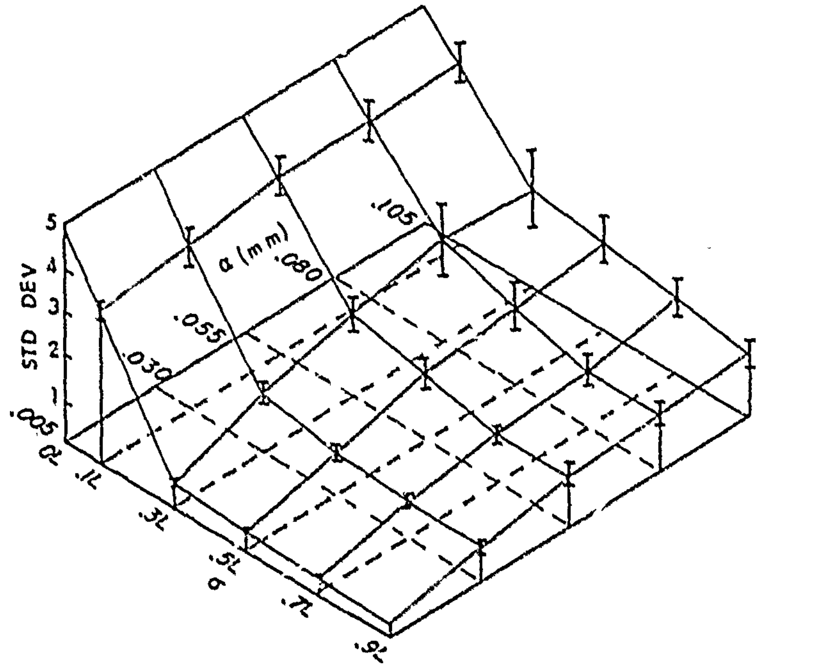

Figure 4. Perspective plot showing expected value of standard deviation vs. pairwise combinations of surface height (sigma) and correlation interval (alpha) of scattering surface.

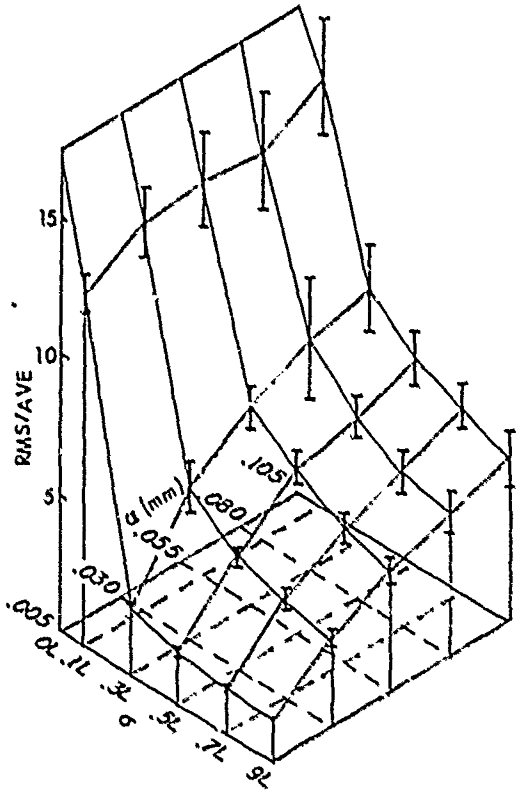

Figure 5. Perspective plot showing expected value of RMS/AVE ratio vs. pairwise combinations of surface height (sigma) and correlation interval (alpha) of scattering surface.

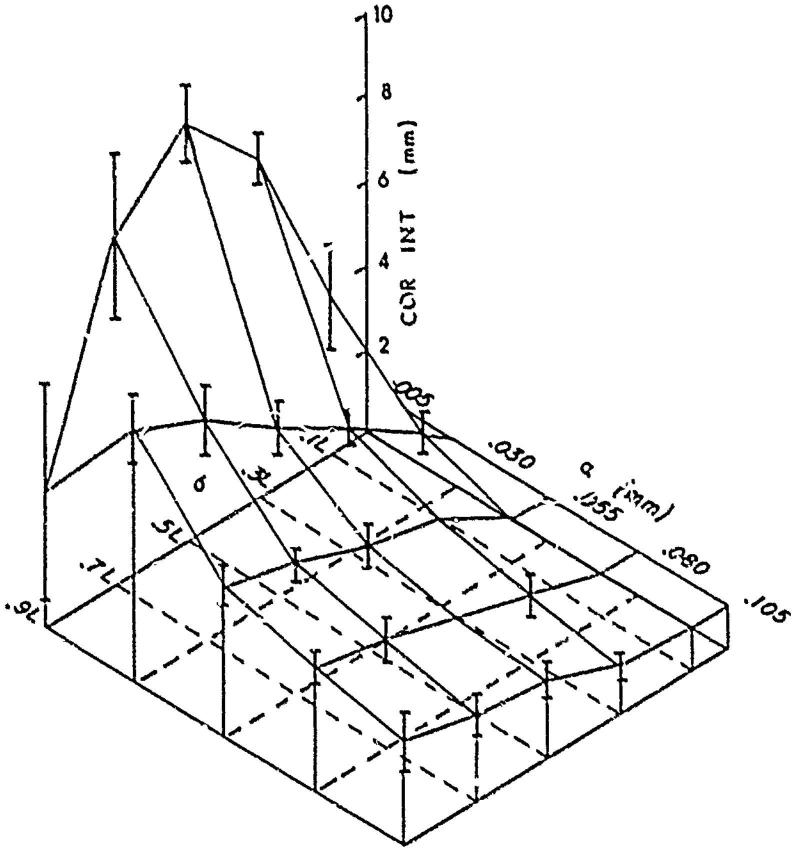

Figure 6. Perspective plot showing expected value of correlation interval (in mm) vs. pairwise combinations of surface height (sigma) and correlation interval (alpha) of scattering surface.

irradiance (in relative units) versus various sigma/alphas. As might be expected, the mean is essentially independent of surface structure. Bars above and below the mean values indicate the one-sigma values based on 15 realizations. An increase in the correlation interval gives a greater uncertainty in the value of the expected irradiance. Absence of error bars indicates a nonstochastic calculation.

Figure 4 gives the results for the standard deviation of speckle statistics versus the pair-wise independent parameters. Standard deviations are generally higher for low surface standard deviation and/or large correlation interval. Figure 5 shows the ratio of RMS surface roughness to average. This ratio follows the same trend as the standard deviation given in Figure 4. This result is to be expected since the standard deviation and RMS are essentially identical computations for a large sample size, and the mean here is relatively constant.

Finally, Figure 6 gives the expected correlation interval (in mm) as a function of the sigma-alphas. This function goes through a noticeable peak for a small correlation interval of surface roughness and the midrange of surface standard deviation.

IV. CONCLUSIONS

The surface shapes suggested by Figures 4-6 indicate that it may be possible to associate specific scatter statistics with particular surface parameters. The central problem is to associate a unique set of surface conditions with a particular statistic in the measured speckle pattern. From these results, it can be seen that specification of, for example, a particular ratio of RMS/AVE value does not relate to just one, but a restricted set of alpha-sigma pairs. However, the combined use of both the RMS/AVE results (Figure 5) together with the correlation interval calculations (Figure 6) would help reduce the number of sigma/alpha pairs which can result in the same scattering statistics. Further, if it can be argued on physical grounds that the correlation interval and the surface height of the scattering surface must be correlated in some way, then the ambiguity in the interpretation of the scattering data might further be reduced.

From such optical scattering experiments as those described here, it might then be possible to relate a series of speckle measurements to a specific set of surface roughness characteristics.

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