Surface-Roughness-Induced Laser Speckle Intensity Distributions

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Introduction and Background

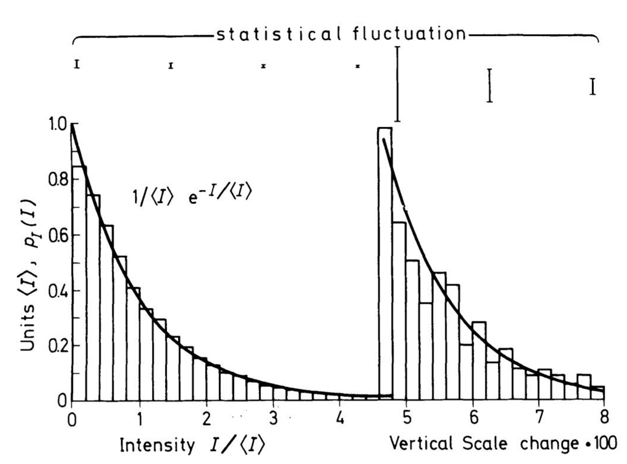
Research Question

How does the surface roughness of transparent materials affect the intensity distribution of laser-speckle patterns formed by shining laser light through the material?

Background

By considering rough surfaces (either transmitted or reflected) as a field of isotropic point radiators, it can be found that light intensity follows a negative exponential whereas phase is uniformly random, both of which are statistically independent [1]. Given the complexity of measuring phase, intensity was the sole focus of our experiment.

This theory was tested in a series of experiments with an increasing number of data-points, culminating in McKechnie's 23,000 data-point experiment [2]. The histogram below shows McKechnie's findings and its excellent agreement with the negative exponential intensity distribution.



Experimental Setup

The experimental setup consisted of a laser pointer shining through the sample, projecting a speckle pattern onto a screen photographed by a camera.

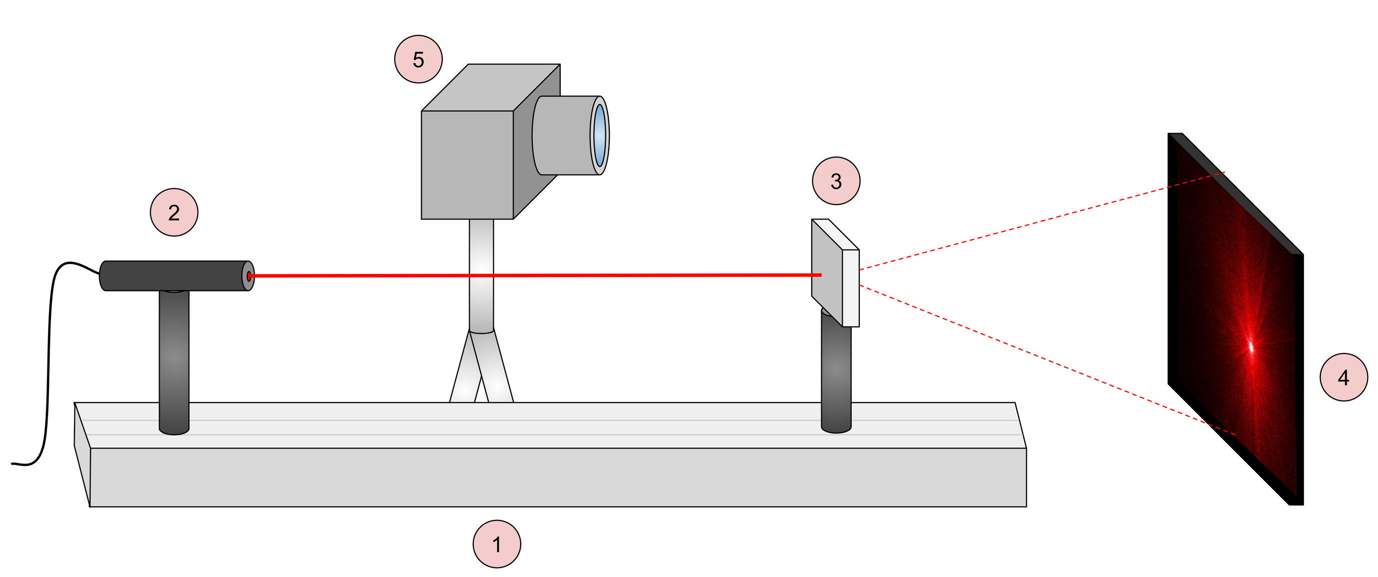
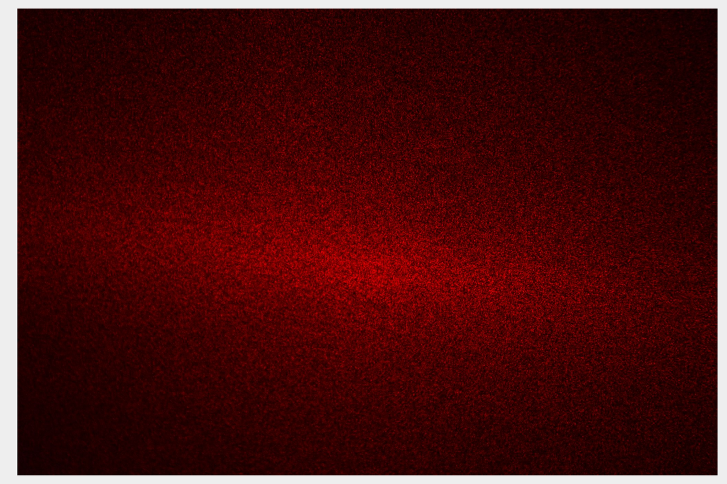


*Diagram of experimental setup. **1)** Laser rail **2)** Laser (Thorlabs 635 nm USB laser) **3)** Sample (sanded ¼" acrylic) **4)** Projection screen **5)** Camera (Canon EOS Rebel T7 DSLR)*

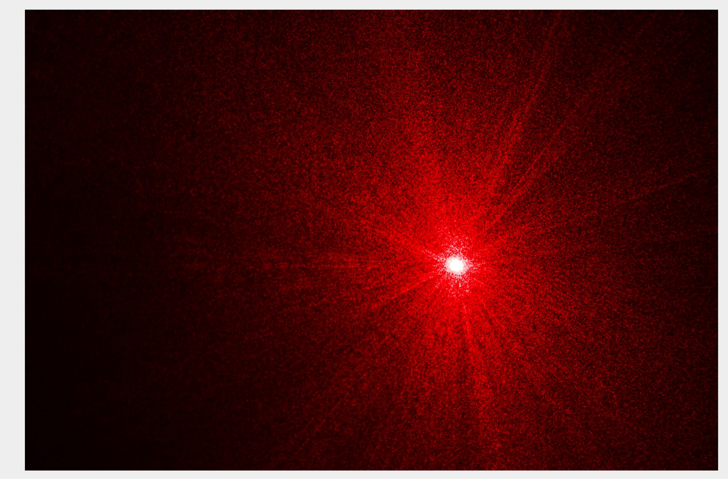
- A total of 11 samples were prepared by sanding eleven 1.5" x 1.5" x 0.25" acrylic squares, each with one of the following sandpaper grits: **150, 180, 240, 320, 400, 600, 800, 1000, 1500, 2500, or 3000**. All samples were wet sanded in a circular pattern until their speckle patterns ceased to change. A control sample (no sanding) was also imaged. A clamp-mount on the optical rail allowed for easy interchange of different samples.
- For a given grit, 10 photographs were taken, each with the laser shining through a different region of the acrylic square. For each grit, a photograph was also taken while the laser was off, providing a background noise reference which was subtracted from the 10 sample photographs during the processing.
- The camera was mounted on a fixed tripod, and was triggered with a remote shutter button. All photos were taken with the following camera settings: **⅛ second exposure time, f/5.6, at 55 mm focal length**. No autofocus or any other "smart" camera settings were enabled to ensure consistency across images. Photos were saved in the lossless .CR2 raw format at a resolution of 6000 x 4000 pixels at 16 bit depth.
- A total of 132 photographs were taken [11 grits x (10 samples per grit + 1 background) + 1 control grit x (10 samples + 1 background)], resulting in 11.8 GB of raw photographic data (~3.2 billion pixels).

Data Processing

Level 0: Raw Images (110 speckle photos)



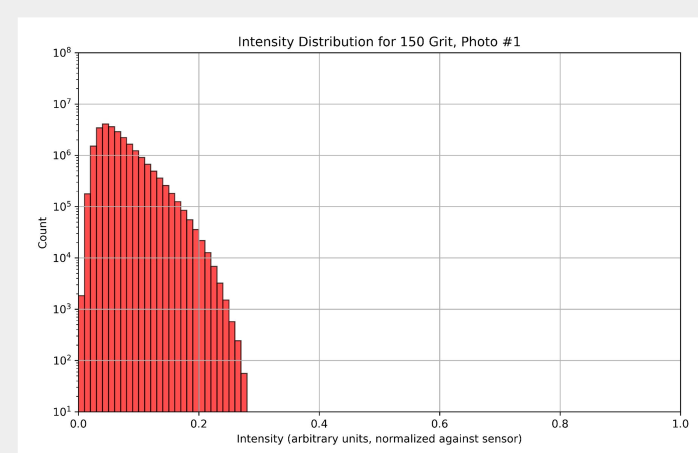
Unmodified photo of 150 grit, sample #1



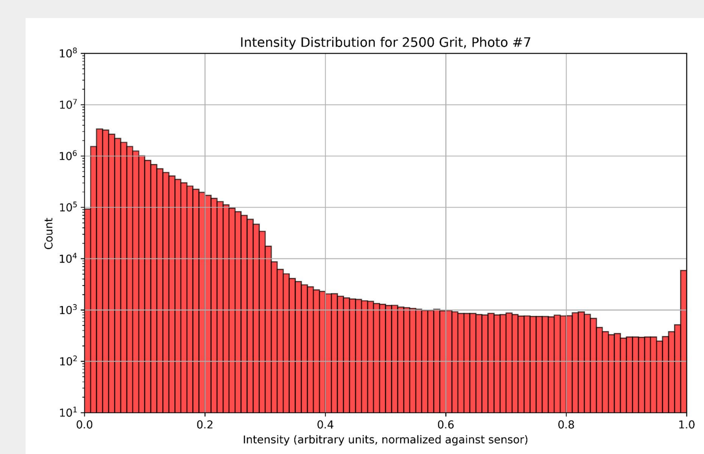
Unmodified photo of 2500 grit, sample #7

Two examples of unmodified photos captured with the camera. These photos represent the extrema of observed speckle patterns; the left photo was the most spatially-diffuse speckle we observed, whereas the right photo was the most spatially-concentrated photo we observed.

Level 1: Individual histograms (110 histograms)



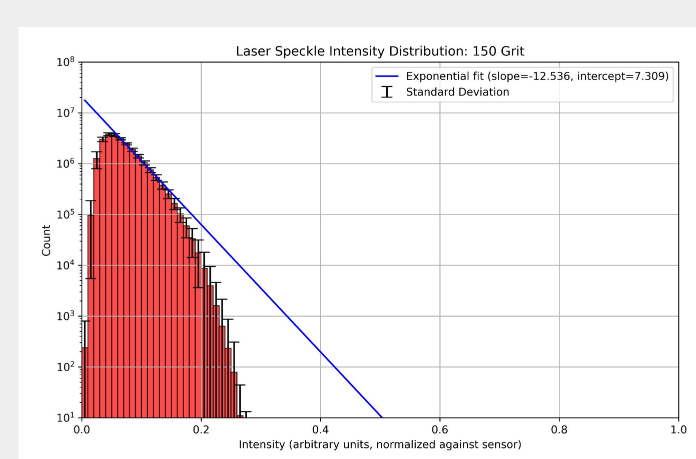
Individual histogram of same 150 grit sample above



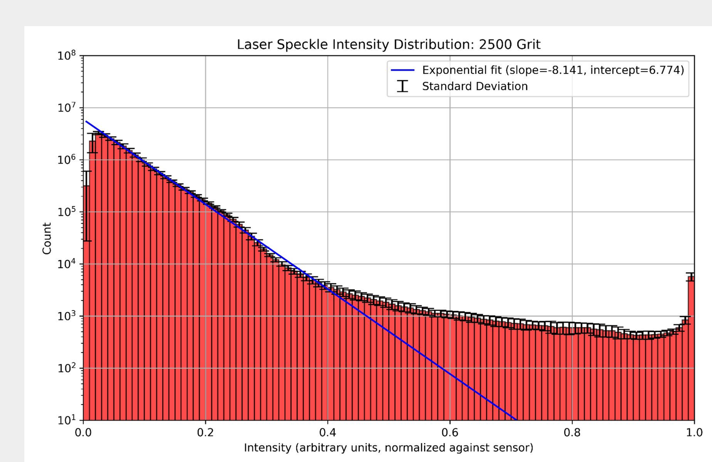
Individual histogram of same 2500 grit sample above

For each image, we extracted a histogram of pixel intensities. All histograms use the same bucket boundaries. Horizontal axes are shared across histograms, with 1.0 representing sensor saturation. Background noise was subtracted from all buckets.

Level 2: Grit-Averaged Exponential Fits (11 average histograms)



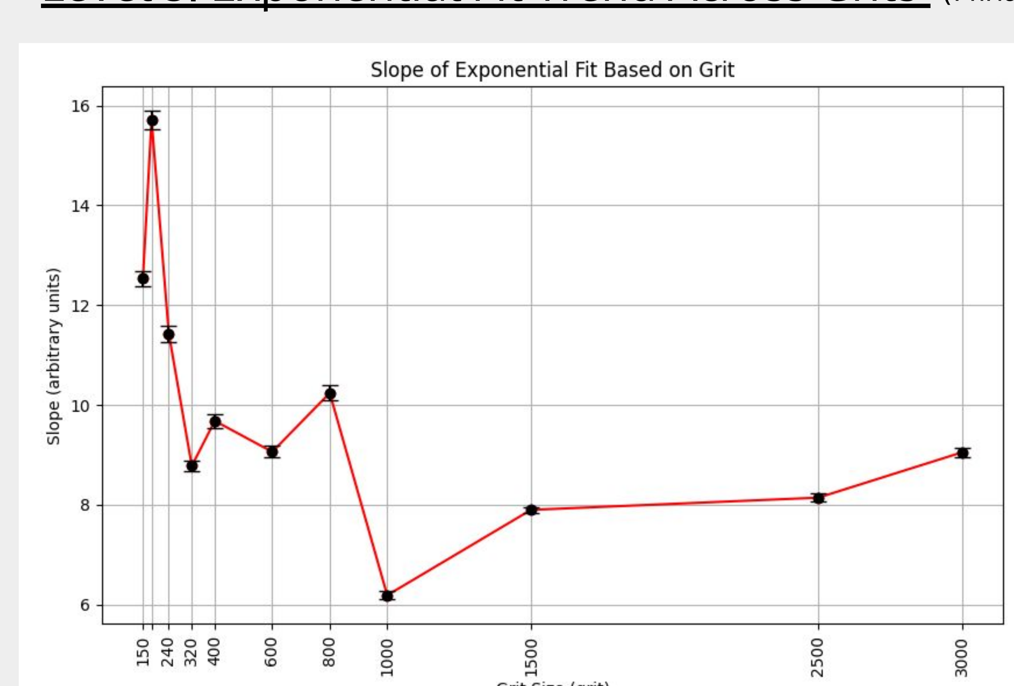
Average histogram for all ten 150 grit samples



Average histogram for all ten 2500 grit samples

The average and standard deviation of each bucket was calculated from all ten samples of a given grit. An exponential curve was then fitted over buckets in the linear regime of the camera (blue line in graphs above). *Further discussion of this fit explained in "Justification."*

Level 3: Exponential Fit Trend Across Grits (1 final graph)



The slope of each exponential fit (as plotted on a semi-log graph) was plotted against the grit value for all 11 grits. Uncertainties of slopes were propagated from the covariance matrices of level 2 exponential fits. Control sample (no sanding) excluded from the above graph.

Findings

Confirmation of Negative Exponential Relationship Across Surface Roughnesses

The data confirms that speckle intensity distributions follow a negative exponential. Furthermore, it demonstrates the robustness of this phenomenon across a wide range of surface roughnesses.

Negative Relationship Between Surface Roughness and Fitted Slope

The inverse relationship between grit number and slope revealed in the final (Level 3) plot confirms that the increased number of bright spots in high-grit samples continue to follow negative exponential distributions. More specifically, as grit increases (and resulting surface roughness becomes finer) the speckle pattern approaches the unadulterated laser beam pattern, whose beam energy is predominantly reflected in high intensity spots. This negative relationship shows that, even as the speckle spatial distributions get narrower, the exponential fit remains valid.

Discussion

Justification

Several decisions were made during the data collection and analysis which require further justification

- **Sanding pattern** Three sanding patterns (mono-directional, 90° bi-directional, and circular) were tested to see how sanding impacted the resulting speckle pattern. The mono-directional and 90° bi-directional produced highly-striated speckle patterns which were unusable. Circular sanding produced consistent results, though occasional striations occurred at high grits. Sanding pressure and time spent sanding had no effect on speckle pattern after ~30 strokes.
- **Buckets selected for exponential fit** The nine buckets immediately higher in intensity than the peak bucket were used to perform the exponential fit. This specific arrangement was chosen for two reasons
  - There is an unavoidable "cropping" that occurs when photographing only a limited region of the speckle; low intensity speckle pattern outside the camera's field of view is not captured, leading to inaccurate low-intensity bucket values. The bucket with peak intensity represents where the captured speckle "meets" with the actual speckle distribution, thus lower-intensity buckets must be omitted.
  - The camera sensor features a small, but nontrivial, nonlinearity at ~0.25 intensity (as seen across all histograms as a downward knee). Nine is the maximum number of buckets that remains within the linear region across all grits.

Further Exploration

- A more objective, consistent, and repeatable technique for introducing surface roughness (such as media blasting or chemical etching) would reduce striations at higher grits and allow for quantitative statements about surface roughness (as opposed to the far less general "grit")
- A comprehensive exploration of effects of convolution, blurring, and other image pre-processing would ensure findings are not inadvertently influenced by the data processing

References

[1] J. W. Goodman, Stanford Electronic Laboratories Report TR 2303–1 (SEL-63-140) (1963).

[2] T.S. McKechnie: Optik 39, 258 (1974) and thesis, University of London (1975)