P-35: Characterizing Laser Speckle and Its Effect on Target Detection

James P. Gaska, Chi-Feng Tai, and George A. Geri
AFRL Visual Research Lab, Link Simulation and Training, 6030 S. Kent St., Mesa, AZ, USA

Abstract

In this study we examine a power spectral density metric for characterizing laser speckle and predicting its effect on target detection. To evaluate the metric, we measured contrast energy thresholds on both a laser speckle background and backgrounds consisting of randomly modulated pixel luminance (i.e., pixel noise). We found that, at the same power spectral density levels, energy thresholds obtained for gratings superimposed on pixel noise were slightly higher than analogous thresholds obtained with laser-speckle noise. In the discussion section, we outline necessary improvements to the laser speckle power spectral density metric.

1. Introduction

Simulation of the out-the-window view of pilots requires a high-resolution, wide field-of-view display, which in turn requires a high pixel count. One approach to this problem has been the development of laser projectors capable of displaying up to 20 megapixels. One major disadvantage of laser projectors, however, is the laser speckle that is generated whenever coherent radiation is scattered from a surface whose roughness is comparable to or greater than the wavelength of the radiation. Laser speckle appears as a grainy pattern superimposed on the displayed image, which can potentially limit target detection.

The goal of this research is to develop a metric that characterizes laser speckle and quantifies its effect on target detection. One metric often used to characterize speckle is RMS contrast, or speckle contrast. This metric has the benefit of being easy to compute from the speckle image in that it is equal to the standard deviation of the image pixel luminance values divided by the mean luminance. However, speckle contrast is an incomplete description in that it does not account for the spatial scale of the noise elements (or spatial frequency bandwidth) of the speckle noise. A more appropriate metric is power spectral density (i.e. noise power per unit bandwidth).

Many studies have shown that the threshold contrast-energy (E) of a target is linearly related to the power spectral density (N) of superimposed broadband noise [1]. This linear relationship is found for a variety of targets (e.g., letters and gratings), although the slope of threshold energy verses power spectral density function (or E-N function), varies with the type of target used.

In this study, we measured energy thresholds on both a speckle background and backgrounds consisting of randomly modulated pixel luminance (pixel noise). The pixel noise data were then used to generate E-N plots for two targets. Further, the power spectral density of the laser speckle pattern imaged on the retina was estimated using measured speckle contrast and the optical parameters of the human eye. We found that, at the same power spectral density levels, energy thresholds obtained for gratings superimposed on pixel noise were slightly higher than those obtained for gratings superimposed on speckle noise. That is, speckle noise was less effective than pixel noise in raising energy thresholds.

2. Methods

2.1 Observers

Two observers, 23 and 28 years old, participated in the study. Both observers had normal or corrected to normal acuity.

2.2 Stimuli and Apparatus

There were three stimulus conditions referred to here as speckle, uniform-luminance, and pixel-noise. In the speckle condition, a grating test-target was superimposed on a background speckle pattern. In the uniform-luminance condition, a grating test-target was superimposed on a uniform, background field. In the pixel-noise condition, the test-target was embedded in pixel-noise. This image was then superimposed on a uniform field. In all cases the grating test-target had a sinewave luminance pattern multiplied by a unit-height Gaussian aperture, whose standard deviation was about 0.48°. The width of the target was defined as +/- 3 standard deviation units or 2.88 degrees. The spatial frequencies of the sinewaves were 2.2, 4.4, 8.7, and 17.4 cycles/deg. The mean luminance of the test-targets was about 2.0 cd/m^2. The grating test-targets were generated in Matlab using the Psychophysics Toolbox extensions [2, 3], and were displayed using a DLP projector.

The speckle background was obtained from a pre-production, scanning laser projector (Evans & Sutherland), and the uniform-luminance background was obtained using an LCD projector. The size of the relevant backgrounds were adjusted so that they subtended about 34° horizontal by 16° vertical for both the 0.965 and 1.93 m viewing distances. The mean luminance of the backgrounds was 4.8 cd/m^2. All test and background stimuli were displayed on a rear-projection screen with a gain of 1.0 and a high-contrast tint (ProScreen Inc.).

The RMS contrasts of the targets and backgrounds were estimated from images captured by an imaging photometer (Lumetrix model 500c). The contrast of each image pixel was calculated by dividing its deviation from the mean image luminance by the mean image luminance. The RMS contrast was computed by taking the square root of the mean squared contrast.

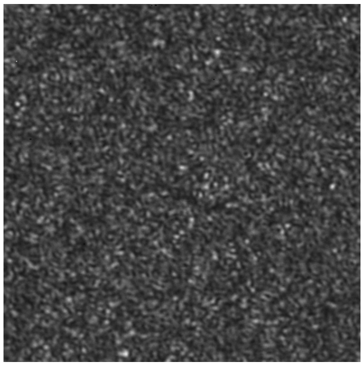

Figure 1. A photograph of the laser-speckle background stimulus.

ISSN/007-0966X/07/3801-0318-$1.00 © 2007 SID

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAY 2007**	2. REPORT TYPE **Journal Article**	3. DATES COVERED **01-01-2005 to 30-06-2006**

4. TITLE AND SUBTITLE **P-35: Characterizing Laser Speckle and Its Effect on Target Detection**	5a. CONTRACT NUMBER **FA8650-05-D-6502**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER **62202F**
6. AUTHOR(S) **James Gaska; Chi-Feng Tai; George Geri**	5d. PROJECT NUMBER **1123**
	5e. TASK NUMBER **AE**
	5f. WORK UNIT NUMBER **07**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Link Simulation and Training,AFRL Visual Research Laboratory,6030 South Kent Street,Mesa,AZ,85212-6061**	8. PERFORMING ORGANIZATION REPORT NUMBER **AFRL; AFRL/RHA**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **Air Force Research Laboratory/RHA, Warfighter Readiness Research Division, 6030 South Kent Street, Mesa, AZ, 85212-6061**	10. SPONSOR/MONITOR’S ACRONYM(S) **AFRL; AFRL/RHA**
	11. SPONSOR/MONITOR’S REPORT NUMBER(S) **AFRL-RH-AZ-JA-2007-0005**

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

Published in the SID Symposium Digest of Technical Papers, 38(1), 318-321. Presented at the 44th SID International Symposium, Jun 4-6, 2006, San Francisco CA

14. ABSTRACT

In this study we examine a power spectral density metric for characterizing laser speckle and predicting its effect on target detection. To evaluate the metric, we measured contrast energy thresholds on both a laser speckle background and backgrounds consisting of randomly modulated pixel luminance (i.e., pixel noise). We found that, at the same power spectral density levels, energy thresholds obtained for gratings superimposed on pixel noise were slightly higher than analogous thresholds obtained with laser-speckle noise. In the discussion section, we outline necessary improvements to the laser speckle power spectral density metric.

15. SUBJECT TERMS

Spectral density; Laser speckle; Target detection; Pixel luminance; Pixel noise; Laser projectors; Laser projection; Energy thresholds;

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Public Release**	**4**	

Figure 2. A photograph of the pixel-noise pattern that was added to the test-stimulus and thus effectively acted as a background image.

2.3 Procedure

Observers first adapted for 8-10 min to the ambient illumination of the experimental room. Each experimental trial consisted of two temporal intervals demarcated by tones. Only one interval contained the target, and the observer was instructed to push a button corresponding to that interval. The 81%-correct threshold was estimated using the Quest procedure [4], which terminated after 30 trials. The four target spatial frequencies were tested in a random order for each observer, and each observer produced 3-7 threshold estimates for each target/noise condition. The mean and standard error of the mean for a given stimulus condition were computed using the combined data of both observers. Thus, the contribution of each observer's data to the mean was weighted by the number of measurements produced by that observer.

3. Results

Figure 3 shows RMS contrast thresholds as a function of target spatial frequency. The individual curves represent different noise conditions. Speckle increases contrast thresholds relative to the uniform (no noise) condition at all spatial frequencies, consistent with the wide spatial frequency bandwidth (small speckle size) of speckle noise.

The RMS contrast of the speckle noise was more than four times that of the pixel noise—0.29 and 0.07, respectively. However, Figure 3 shows that speckle noise increased thresholds less than the pixel noise. In the next section we show how the small angular size of the speckle elements reduces its effectiveness in increasing target thresholds.

3.1 Estimation of the Power Spectral Density of Pixel noise

If independent samples of zero-mean Gaussian luminance noise are added to each square region (check) on a display, the power spectral density is defined [5] to be the square of RMS contrast divided by the two-sided bandwidth of the noise. That is,

$$N = C_{RMS}^{2} / \omega \ , \qquad (1)$$

where the two-sided noise bandwidth is given by:

$$\omega = \frac{1}{\Delta x \Delta y}, \qquad (2)$$

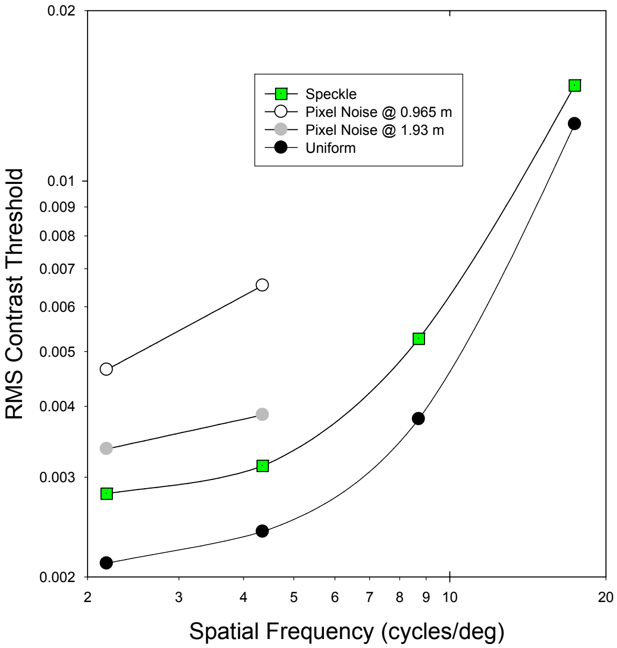

Figure 3. Contrast threshold as a function of spatial frequency.

where Δx and Δy are the width and length, respectively, of the noise elements in degrees of visual angle.

The product $\Delta x \Delta y$ is the area, A, of the noise elements, and it is customary to compute N as follows [2]:

$$N = C_{RMS}^{2} \cdot A \quad (\mathrm{deg}^{2}) \ , \qquad (3)$$

where C is the RMS contrast. In the present study, the RMS contrast of the pixel noise, measured using the imaging photometer, was 0.07. At the 1.93 m viewing distance, the angular length and width of a pixel noise element was $57.40 \cdot 10^{-3}$ degrees and so the pixel area was $826.56 \cdot 10^{-6}$ degrees^{2}. Using these values with Equation (3) yields a power spectral density of $4.05 \cdot 10^{-6}$ degrees.

For the 0.965 m viewing distance, the angular width and length of the noise element double which increases the angular area and power spectral density by a factor of four. The contrast and area values used to compute power spectral density are shown in Table 1.

Table1 1. Values used to compute PSD.

	Pixel Noise 1930 mm Viewing distance	Pixel Noise 965 mm Viewing Distance	Speckle 4.31 mm Pupil diameter
Contrast	0.07	0.07	0.29
Noise element area (10^{-6}deg^{2})	826.56	3306	56.74
PSD (10^{-6}deg^{2})	4.05	16.2	4.77

3.2 Estimation of the Power Spectral Density of Speckle

The width of a speckle element on the retina is proportional to the pupil diameter of the observer. Pupil diameter was computed using a formula developed by Barten [6]

$$p = 5 - 3\ \tanh\left\{ 0.4 \log\left(L\,\mathrm{A}/40^2 \right) \right\} \qquad (4)$$

which, for the mean luminance L (6.8 cd/m^2) and display area A (891 degrees^2) used in this study, results in a pupil diameter of 4.31 mm.

The average width of a speckle element on the retina was computed using the Airy disk formula:

$$w = 1.22\lambda \frac{f}{p}\ , \qquad (5)$$

where λ is wavelength, f is the distance from the nodal point of the eye to the back of the retina, and p is pupil diameter in mm. Using Equation (5) with a 4.31 mm pupil diameter, a laser wavelength of 0.532 µm (the green channel of our display), and an f of 16.5 mm yields a speckle width of $8.50 \cdot 10^{-3}$ µm. Because a speckle element is circular, the speckle area is $\pi(w/2)^2$ or 4.91 µm^2. Finally, the angular speckle area is produced by multiplying the speckle area in µm^2 by $1.16 \cdot 10^3$ degrees/µm. [7]

The power spectral density of the speckle pattern was estimated using Equation (3). The contrast and area values used to compute this power spectral density are shown in Table 1.

3.3 E-N Plots

The data of Figure 3 are presented in Figure 4 as threshold energy verses power spectral density (E-N) plots. Energy is equal to the product of squared RMS contrast and stimulus area (6.15 degrees^2). The solid lines represent linear fits to the two pixel-noise and one uniform-luminance thresholds (circles). The speckle thresholds are shown by the square symbols.

The speckle thresholds were lower than thresholds on pixel noise of the same power spectral density. For the 2.18 cycles/deg grating the difference was marginally significant [$t(10) = 1.72$, $p < 0.058$]. For the 4.36 cycle/degree grating the difference was highly significant [$t\ (10) = 4.96$, $p < 0.0003$].

The dashed horizontal lines in Figure 4 connect the speckle-threshold data points to the function fitted to the pixel-noise and uniform-luminance threshold data. A lines dropped from this intersection to the power spectral density axis provide an estimate of the equivalent pixel noise. The equivalent pixel noise represents the power spectral density of pixel noise that produces the same threshold as speckle. The average equivalent pixel noise was $1.97 \cdot 10^{-6}$ degrees^2 which is less than half of our estimate of the power spectral density of speckle.

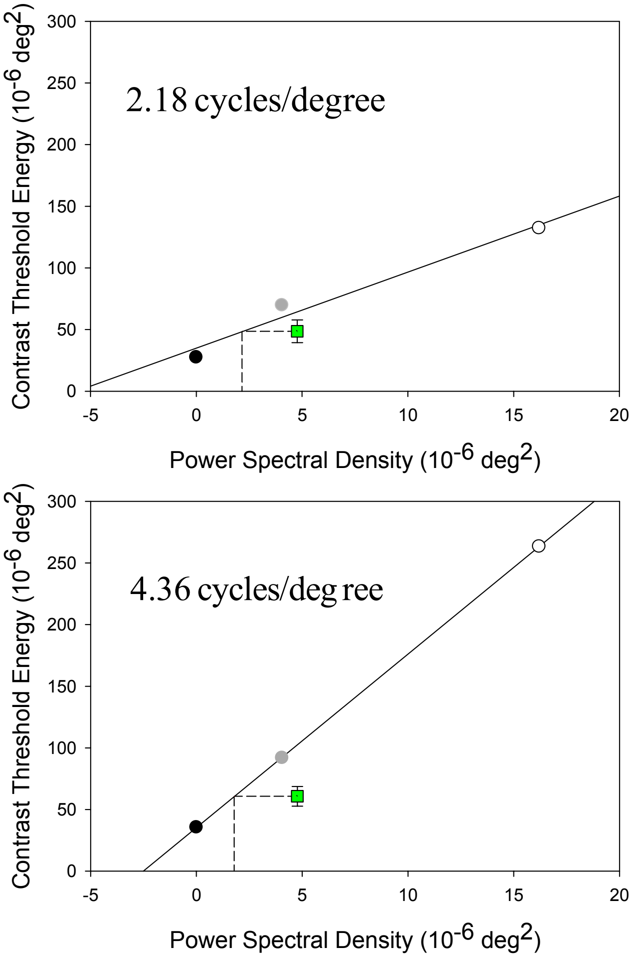

Figure 4. E-N plots.

4. Discussion

The results of this study suggest that, at the same power spectral density, speckle may be slightly less efficient than pixel noise in increasing target thresholds. One possible explanation of this finding is that scattering by the ocular media may differentially affect laser and non-coherent radiation. However, before we can conclude that speckle is less efficient than pixel noise in increasing target contrast, improvements to the method used to estimate speckle power spectral density are required

Equation (3), which was used to estimate power spectral density, is only accurate for a Gaussian luminance distribution. Shown in Figure 5 are the luminance distribution of the pixel-noise image (red line) and a Gaussian distribution, demonstrating that this condition was satisfied for the pixel noise.

Shown in Figure 6 are the luminance distribution of the speckle image (red line) and a Gaussian distribution. The speckle luminance distribution is clearly not Gaussian. We are currently attempting to modify the equation used to estimate the power spectral density of speckle in order to account for the non-Gaussian luminance distribution. We are also investigating using discrete Fourier transform techniques to estimate the power spectral density of the noise patterns.

It is clear from the present data that speckle contrast is an incomplete metric for characterizing the effect of speckle on target detection, in that pupil diameter must also be considered.

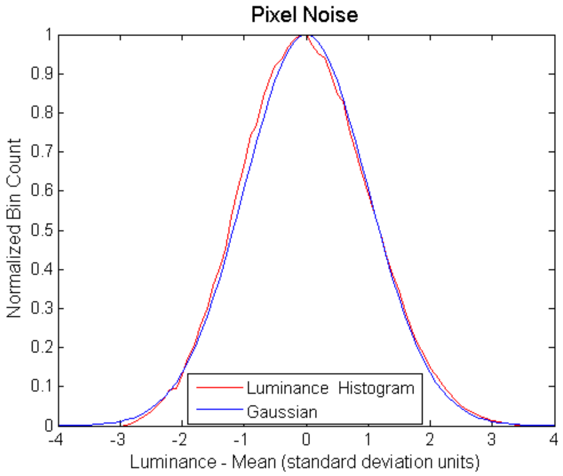

Figure 5. Normalized histograms of standardized luminance calculated as: (Pixel Luminance – Mean Luminance)/Standard Deviation of the Luminance Values.

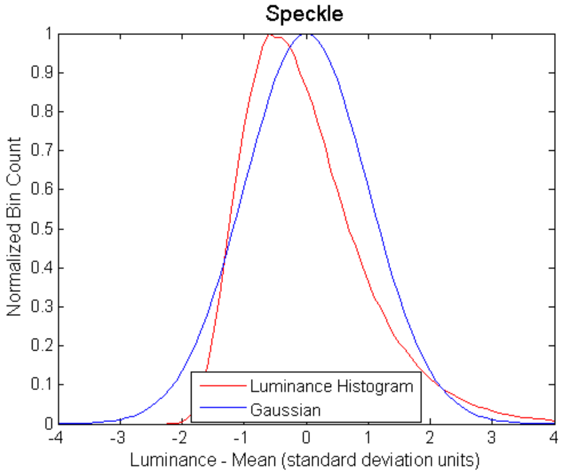

Figure 6. Normalized histograms of standardized luminance calculated as: (Speckle-Element Luminance – Mean Luminance)/Standard Deviation of the Luminance Values.

Artigas *et al.* [8] used artificial pupils and also found that decreasing the diameter of the pupil increased speckle-contrast thresholds.

This finding that pupil diameter must be considered when assessing target detection on laser speckle has practical implications for the design of laser displays. As the luminance of a laser display increases, the pupil diameter of observers viewing the display will decrease. This will increase the power spectral density of the speckle, making targets more difficult to detect. Therefore, methods designed to reduce the speckle contrast [9] will become more important as the luminance of laser displays is increased.

5. Acknowledgements

This work was supported by U.S. Air Force contract FA8650-05-D-6502. In addition, the following agencies provided financial and/or technical support for this research: Air Combat Command (ACC/A8AT), Secretary of the Air Force International Affairs (SAF/IA), and Defence Research and Development Canada – Toronto. We thank Leonard Best and Ben Surber for assistance in calibrating the laser display and Byron Pierce for providing direction for the research.

6. References

[1] D.G. Pelli and B. Farell, “Why use noise?” *Journal of the Optical Society of America A*, **16**, 647-653, 1999.

[2] D. H. Brainard, “The Psychophysics Toolbox”, *Spatial Vision*, **10,** 433-436, 1997.

[3] D. G. Pelli, “The VideoToolbox software for visual psychophysics: Transforming numbers into movies”, *Spatial Vision* **10**, 437-442, 1997.

[4] A.B Watson and D.G. Pelli, “QUEST: a Bayesian adaptive psychometric method”, *Perception and Psychophysics*, **33**, 113-20, 1983.

[5] B.S. Tjan, W.L Braje, G.E. Legge and D. Kersten, “Human efficency for recognizing 3-D objects in luminance noise”, *Vision Research*, 35, 3053-3069, 1995.

[6] P.G.J Barten *Contrast Sensitivity of the Human Eye and Its Effects on Image Quality,* SPIE Optical Engineering Press. Bellingham, Washington, 1999.

[7] N. Drasdo and C.W. Fowler, “Non-linear projection of the retinal image in a wide-angle schematic eye”, *British Journal of Ophthalmology*, **8**, 709-714, 1974.

[8] J.M. Artigas, A. Felipe, and M.J. Buades, “Contrast sensitivity of the visual system in speckle imagery”, *Journal of the Optical Society A*, **11**, 2345-2349, 1994.

[9] J.I. Trisnadi (2004) “Hadamard speckle contrast reduction,” *Optics Letters*, **29**: 11-13.