Instantaneous speckle reduction? Yes, but there is no free lunch!

Häusler, Gerd, Dötzer, Florian, Mantel, Klaus

Gerd Häusler, Florian Dötzer, Klaus Mantel, "Instantaneous speckle reduction? Yes, but there is no free lunch!," Proc. SPIE 10834, Speckle 2018: VII International Conference on Speckle Metrology, 108340B (7 September 2018); doi: 10.1117/12.2317925

Event: SPECKLE 2018: VII International Conference on Speckle Metrology, 2018, Janów Podlaski, Poland

Instantaneous speckle reduction? Yes – but there is no free lunch

Gerd Häusler[a], Florian Dötzer[a], Klaus Mantel[b]
[a]Institute of Optics, Information and Photonics, University of Erlangen, Staudtstr. 7, 91058 Erlangen, Germany; [b] Max Planck Institute for the Science of Light, Staudtstr. 2, 91058 Erlangen, Germany

ABSTRACT

We are motivated by the question if scanning laser projection with low speckle noise is possible. Scanning laser projection requires "instantaneous" speckle reduction, within a few nanoseconds – meaning that no moving diffusors can be used. We will argue that instantaneous speckle reduction is possible by conversion of spatial coherence to spatial incoherence - but nature demands for a compensation. The cost can be estimated via the information theoretical concept "channel capacity", which incorporates the etendue as well as the signal-to-noise ratio. We will show that an optical system with low spatial coherence (=low speckle noise) must provide significantly more degrees of freedom than a coherent imaging system. The consequence for the technical optical system is serious: significant speckle reduction can only be achieved by an excessively large projection aperture. This is not just a sophistic consideration, it seriously restricts the design of scanning laser projectors.

Keywords: Speckle noise, speckle noise reduction, laser projection, channel capacity, etendue

1. COHERENCE, SPECKLE AND INFORMATION THEORY

Motivated by the upcoming technology of scanning laser projection[1], we discuss methods for instantaneous speckle reduction and the theoretical and technical consequences of "incoherent laser illumination". Fast scanning of a modulated laser beam by a MEMS mirror enables small, lensless and low-cost video projectors. The projected images, inevitably, suffer from speckle noise. Manufacturers already incorporate some (insufficient) speckle reduction by polarization averaging[2]. Most approved speckle reduction methods[3,4], specifically moving diffusors, cannot be implemented, due to a pixel time of only a few ns, which would require a diffusor speed of several hundred km/sec.

Before discussing scanning projectors, we consider conventional illumination with an incoherent source and some information theoretical consequences[5]. Speckle is caused by spatial coherence (even with white light)[3], so reduction of spatial coherence is the key. Exploiting the Van Cittert–Zernike theorem, we find that the speckle contrast C and the signal-to-noise ratio SNR in the image of a diffusely reflecting object that is illuminated by an incoherent (!) source is given by

$$SNR = 1/C = \sin u_{ill} / \sin u_{obs} \tag{1}$$

where $\sin u_{ill}$, $\sin u_{obs}$ are the illumination- and observation aperture, respectively.
To explain the consequences of eq. (1) for any kind of projection, we consider a realistic geometry, as shown in Fig. 1. According to eq. (1), the chosen apertures allow for a best SNR~8. The apertures together with the screen area A_L comprise a chain of a large "projection etendue" $\Lambda_1 = u_{ill}^2 A_L$ and a small "observation etendue" $\Lambda_2 = u_{obs}^2 A_L$. Normally, in a chain of etendues, the smallest etendue limits the throughput of light, which gives a first hint to the inefficiency of such a configuration. However, the diffuser scatters the light into a large solid angle, such that the throughput solely depends on u_{obs}. Here, we utilize the etendue, because it is connected with information (polarization is neglected):

$$\Lambda/\lambda^2 = \text{Space-Bandwidth Product } SBP = \#\text{pixels} \tag{2}$$

$$CC = \text{Channel Capacity [bit]} = SBP \log_2(1+SNR) \tag{3}$$

The channel capacity is a measure for the maximum transmittable information, and at the same time a measure for the amount of technology that has to be allocated: channel capacity is expensive[6].

Speckle 2018: VII International Conference on Speckle Metrology, edited by Malgorzata Kujawińska, Leszek R. Jaroszewicz, Proc. of SPIE Vol. 10834, 108340B · © 2018 SPIE
CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2317925

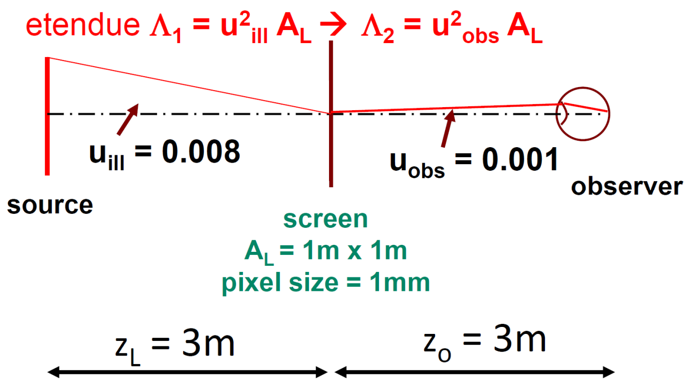

Figure 1. Unfolded geometry of a realistic projection with reduced spatial coherence / reduced speckle noise

Column a) in Table 1 describes the situation where the projection aperture matches the observation aperture. According to Eq. (1), *SNR=1*. Together with the diffraction limit, this leads to a channel capacity of 1 Mbit / frame.

To improve the *SNR* (reduce speckle noise), we increase the illumination (projection-) aperture from 3mm to 24mm, see column b). The diffraction limited projection path now allows for a *SBP* of 64 Mpix, while the observer still resolves 1 Mpix. The averaging over 8x8 projection pixels leads to an 8-fold improvement of the *SNR* in the observed image. Compared to case a), the resulting channel capacity is improved by a factor of three. We are buying a better *SNR*, paying the prize in the currency of information efficiency: we note that we provide much more projection *SBP* (1 Mpix → 64 Mpix) but improve the channel capacity only from 1 Mbit/frame to 3 Mbit/frame.

Table 1. The costs of *SNR* improvement in the currency of *SBP* and channel capacity

	a) Matched apertures	**b) Excess projection aperture**
Projector Aperture	3 mm	24 mm
Observer Aperture	3 mm	3 mm
Projection *SBP*	1 Mpix	64 Mpix
Observation *SBP*	1 Mpix	1 Mpix
System *SNR*	1	8
System *CC* / frame	1 Mbit	~ 3 Mbit

2. INFORMATION LIMITS ARE TECHNICAL LIMITS

The projection lens is commonly not diffraction limited (and doesn't have to be), so the apparent waste of channel capacity does not seriously hurt - it even might be a good deal. Nevertheless, this is not esoteric reasoning - there are serious practical consequences[7, 8]: Even for a traditional projector, the demanded high illumination aperture increases the complexity and cost of the projection lens. For a scanning projector however, the required mirror diameter of 24mm is a deal-breaker: mirrors with 24mm diameter and a reasonable sweep angle do not allow for the required line frequency of 100 kHz. Realistic diameters are of the order of 1mm[9]. So, one must sacrifice either *SNR* or image size and resolution. But even if technological progress would allow for large mirror diameters, major advantages of scanning laser projectors (small size, no lens, no depth of field problems) are gone.

3. SPECKLE REDUCTION WITH LASER ILLUMINATION

Accepting that speckle reduction will cause costs, we now discuss how to implement (virtually) instantaneous spatial incoherence with laser projection. Figure 2 displays the basic idea and a more practical implementation.

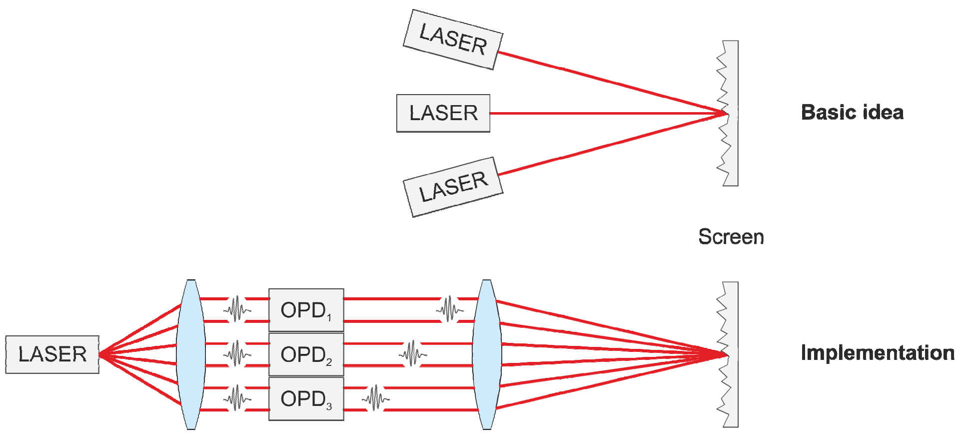

Figure 2. Instantaneous reduction of spatial coherence with laser illumination

The latter requires a little bit of temporal incoherence which is provided by common semiconductor lasers anyway. As shown in Fig. 2 we generate N sub-apertures in the pupil with optical path differences from $OPD_1 \sim l_c$ to $OPD_N \sim Nl_c$, where l_c is the coherence length. The incoherent superposition from N subapertures can be exploited for a better $SNR \sim \sqrt{N}$. A detailed explanation is given in [7, 8]. The coherence reduction is "instantaneous" within a time $\tau \sim Nl_c / c$, with the speed of light c. With $l_c \sim 1mm$ and $N=100$ one could achieve an $SNR \sim 10$ within $0.3\ nsec$.

How many sub-apertures should be implemented for a given illumination- and observation aperture? This is a crucial question, because significant noise reduction demands for many sub-apertures. Where is the limit? As illustrated in Fig. 3, each sub-aperture generates its own, independent (mutually incoherent) diffraction pattern.

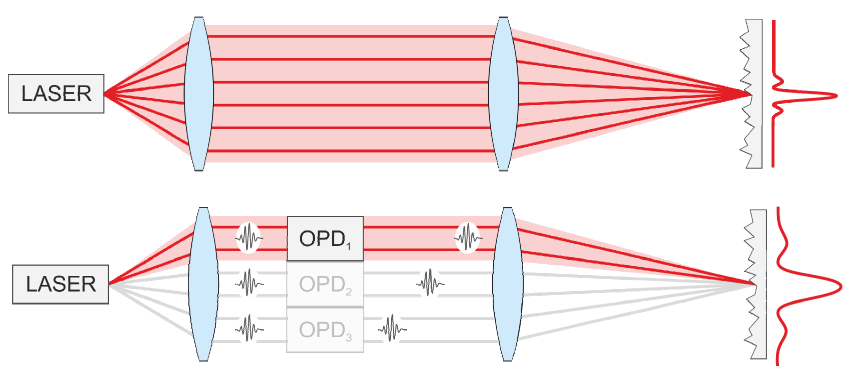

Figure 3. Diffraction patterns of total aperture (top) and of sub-aperture (bottom)

More (and therefore smaller) sub-apertures within a given total aperture lead to a wider diffraction pattern at the screen. For sub-apertures smaller than the observation aperture the corresponding loss of lateral resolution becomes visible for the observer. One may still tolerate this; however, coherence theory tells us that we cannot achieve a signal-to-noise ratio better than $SNR_{max} \sim \sin u_{ill} / \sin u_{obs}$, which is already reached when the sub-apertures are equal to the observation aperture. Smaller sub-apertures do not further improve the SNR, but only reduce the lateral resolution.

4. EXPERIMENTS

As explained, the high but still *finite temporal coherence* of lasers enables illumination with *low spatial coherence*, allowing the reduction of coherent noise. We investigate two possible implementations as shown in Fig. 4. The basic idea is to fill the illumination pupil with mutually incoherent "sources" by introducing optical path differences larger than the coherence length of the laser.

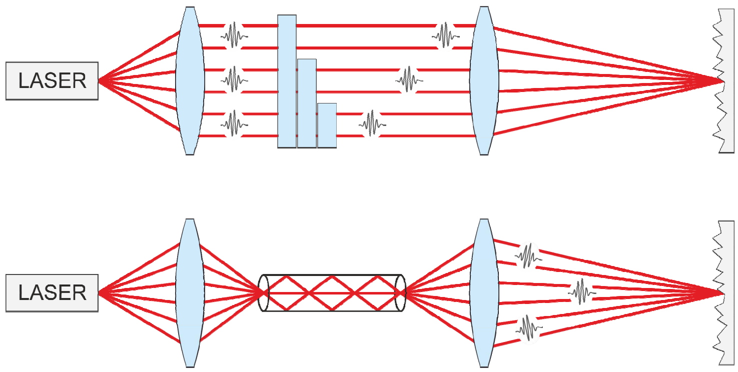

Figure 4: OPD via delay plates or via a multimode fiber

The first implementation introduces the OPDs simply via a stack of glass plates with 3x3 sub-apertures. The second approach exploits the intermodal dispersion of a multimode fiber. The latter method was already used in a similar way for non-scanning projectors by Manni[10], so we will only briefly describe this solution. Figure 5 displays two magnified images of a 62.5µm fiber core, illuminated by a laser with a long and a short coherence length, respectively. If the coherence length is longer than the OPD between the modes, they superimpose coherently and form a speckle pattern. For a sufficiently short coherence length, incoherent superposition takes place, resulting in a more homogeneous intensity distribution.

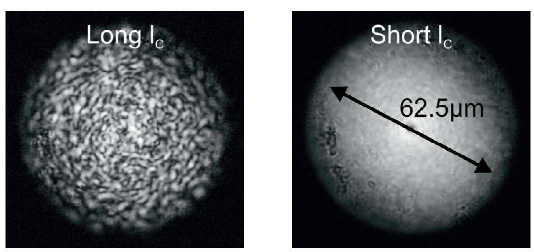

Figure 5. Intensity pattern at the output surface of a multimode fiber, illuminated with long / short coherence length l_c

In the following experiments we use a fiber with 10µm core diameter, an aperture of NA=0.1 and a length of 5m. For the wavelength of our laser (486nm) it supports 7 modes (i.e. sub-apertures) and generates a total OPD of about 10mm. As sketched in Fig. 6, we use a 2D galvo-scanner to project a homogeneously illuminated "image" onto the screen and a camera which mimics the observer.

Figure 7 displays the results of the speckle reduction experiments. Compared to fully coherent laser illumination, the speckle contrast was reduced by a factor of two (multimode fiber) and by a factor of three (delay plates). The measured speckle contrast for the pure laser beam is in good agreement with the simulation. The speckle contrast obtained via the nine delay plates is very close to the expected value of $17\% = 52\%/\sqrt{9}$. The multimode fiber shows slightly higher contrast than expected for seven modes ($20\% = 52\%/\sqrt{7}$). A probable reason is that neither the laser power nor the path differences are distributed evenly among the fiber modes.

The experiments demonstrate that instantaneous speckle reduction is indeed possible with the proposed methods. It should further be noted that only simple technology is required. There are no mechanically moving parts and only a single laser source is necessary.

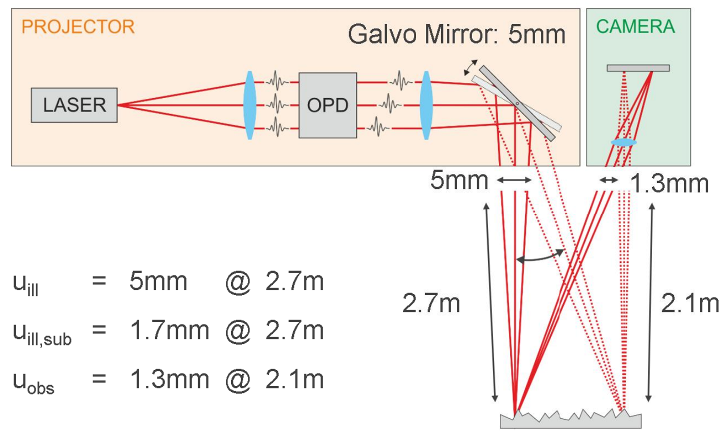

Figure 6. Experimental setup, mimicking a realistic scanning projection scenario

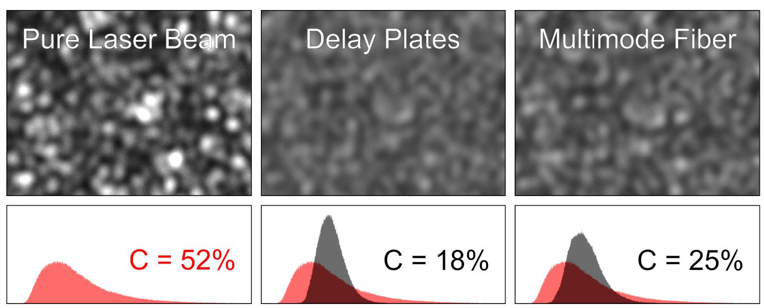

Figure 7. Speckle pattern, intensity histogram and contrast

5. MEASURE THE COHERENCE LENGTH IN A BREATH

For the reduction of spatial coherence we exploit the limited coherence length of lasers. Here we will describe a quite simple and fast method to measure this important parameter, exploiting laser speckle: when shining a laser beam onto a diffuser, a slight increase of the laser's wavelength slightly stretches the resulting (objective) speckle pattern around the axis of specular reflection. If only a small off-axis area is observed, the stretching degenerates into a lateral shift. This can be used to determine the wavelength change of a monochromatic source, as proposed by Chakrabarti[11]. Accordingly, a non-monochromatic source produces elongated speckles. Looking at the scatterer instead of looking at the speckles gives an intuitive insight how to measure the coherence length of a laser or other light sources within the blink of an eye, see figure 8.

The width of objective speckles at a distance z behind a diffuser is given by $d_{sp} \sim \lambda z / d_{beam}$, where d_{beam} is the diameter of the illuminated spot. However, for a tilted diffuser, d_{beam} degenerates to $d_{coh} = l_c / \tan\theta$, because only the coherent area contributes to the speckles. (For observation from the laser position, there is an additional factor ½, because of the forward- and back travel of the light). As shown in Fig. 8, the speckles become anisotropic, with a larger width d_y in y-direction.

Figure 9 illustrates the evaluation via the Fourier-spectrum of the objective speckles, for the untilted and tilted scatterer. As a consequence, the speckles from the tilted scatterer display an anisotropic power spectrum. The cross section (along the y-direction) over the magnitude of the Fourier transform corresponds to the magnitude of the temporal coherence function. The scaling of the coherence function can easily be estimated via the spectrum for $\theta = 0°$ and the geometry shown in Fig. 8. The coherence length of the used laser was estimated to $l_c^{laser} \sim 100\mu m$.

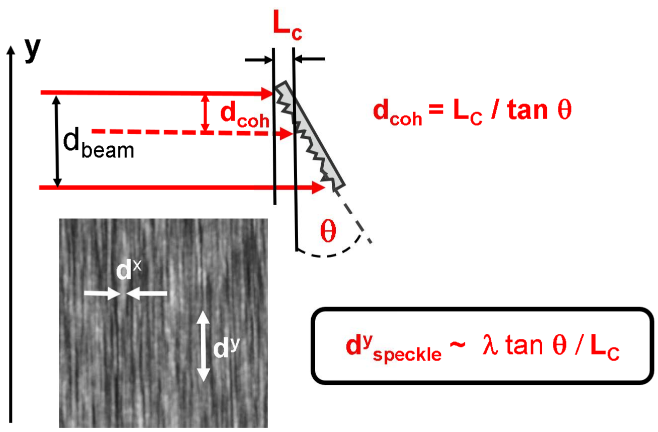

Figure 8. Coherence length via speckle size anisotropy

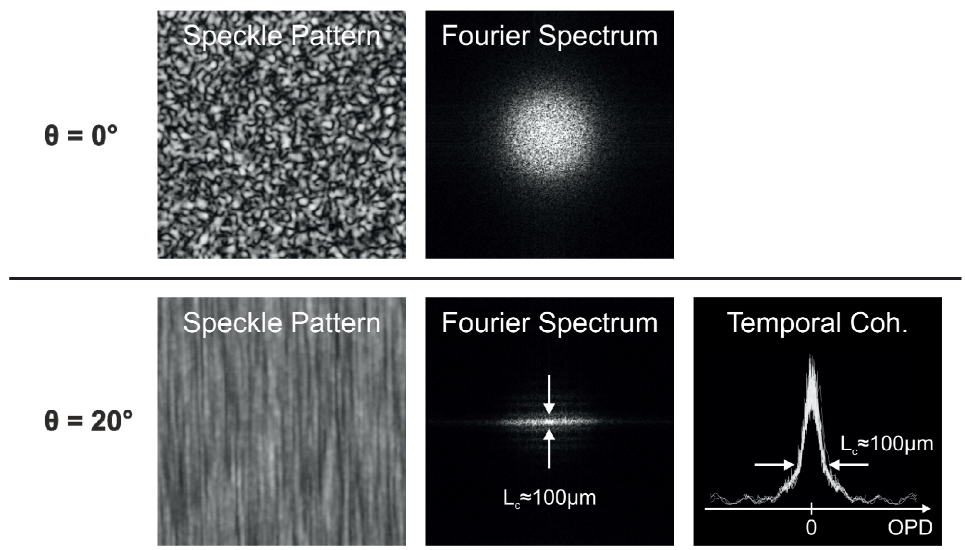

Figure 9. Temporal coherence function via the Fourier spectrum of objective speckles

We emphasize that the common method to measure the coherence length with a tilted-mirror interferometer requires a much more complicated setup and becomes increasingly difficult for larger coherence lengths, as the number of fringes to be evaluated may become extremely large.

6. SUMMARY AND CONCLUSIONS

Instantaneous speckle reduction for scanning laser projectors is possible. The technology is simple and low cost. However, the required large illumination etendue causes significant technological problems. As an interesting information theoretical aspect, the excessive (and "expensive") space-bandwidth provided by the large projection etendue cannot be fully exploited by the observer and the increased *SNR* can only make up for a small fraction of the "wasted" channel capacity.

REFERENCES

[1] Microvision, Inc., www.microvision.com (1 June 2018)

[2] Abelé, N., Le Gros, C., Masson, J., Kilcher, L., „Speckle reduction technique for embeddable MEMS-laser pico-projector“, Proc. SPIE Vol 8977, (2014)

[3] Häusler, G., “Speckle and Coherence”, Encyclopedia of Modern Optics, Elsevier Ltd., Oxford, Vol. 1, pp 114-123, (2004)

[4] Falko, R., “Speckle Reduction in Projection Systems”, Dissertation, Universität Karlsruhe, (2009)

[5] Häusler, G., Dötzer, F., Mantel, K., „Speckle Reduction I: There is no free lunch“, DGaO Proceedings 2017 – http://www.dgao-proceedings.de – ISSN: 1614-8436 – urn:nbn:de:0287-2017-B001-9

[6] Wagner, C., Häusler, G., „Information theoretical optimization for optical range sensors“, Applied Optics, Vol. 42, 27, pp. 5418-5426, (2003)

[7] Dötzer, F., „Speckle Reduction in Laser Scanning Projection Systems“, Bachelor Thesis, Friedrich-Alexander Universität Erlangen-Nürnberg, (2016)

[8] Dötzer, F., Mantel, K., Häusler, G., „Speckle Reduction II: Laser Projection Without Speckle Noise? Experimental Investigation“, DGaO Proceedings 2017 – http://www.dgao-proceedings.de – ISSN: 1614-8436 – urn:nbn:de:0287-2017-B002-3

[9] Fraunhofer IPMS 2D mirror design space, https://www.micro-mirrors.com/en/pic/Designspace_2D_Elliptical.jpg (1 June 2018)

[10] Manni, J. G., Goodman, J. W., “Versatile method for achieving 1% speckle contrast in large-venue laser projection displays using a stationary multimode optical fiber”, Opt. Expr., Vol. 20, 10, pp.11288-11315, (2012)

[11] Chakrabarti, M., Linde Jakobsen, M., Hanson, S. G., “Speckle-based spectrometer”, Opt. Lett., Vol. 40, Issue. 14, pp.3264-3267, (2015)