Speckle Reduction I: There is no free lunch

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We will introduce options for instantaneous speckle reduction with laser illumination, exploiting the limited coherence length. The costs are that an optical system with low coherent noise has to allocate significantly more channel capacity than exploitable by the observer. We furthermore introduce a novel, simple method to measure the coherence length of a laser.

1 Coherence, Speckle and Information theory

Motivated by the upcoming technology of 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 laser "beamers". The observed images, however, display speckle noise. Manufacturers already incorporate some (insufficient) speckle reduction by polarization averaging [2]. Other approved methods from the speckle reduction toolbox [3], [4], specifically moving diffusors, cannot be implemented, due to a pixel time of only 10 ns, which would require a diffusor speed of several hundred km/sec.

In section 2 we will discuss "instantaneous" speckle reduction with laser illumination. But first we have to discuss standard illumination with an incoherent source. Speckle is caused by spatial coherence, even with much temporal incoherence [3]. So reduction of spatial coherence is the key. Exploiting the van Cittert–Zernike theorem, we find that the speckle contrast C, respectively the signal-to-noise ratio SNR in the image of a diffusely reflecting object that is illuminated by an incoherent (!) source is given by

$$SNR = 1/C = \sin u_{ill} / \sin u_{obs} \,, \qquad (1)$$

where $\sin u_{ill}$, $\sin u_{obs}$ are the illumination- and observation aperture. To explain the consequences of Eq. (1) for any kind of projection, we consider a realistic projector geometry, as shown in Fig. 1.

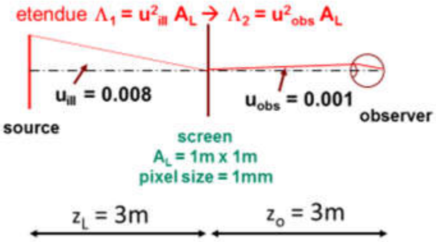


Fig. 1 Geometry of realistic projection with reduced spatial coherence / reduced speckle noise

The chosen apertures allow for a best SNR~8, according to Eq. (1). 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" $\Lambda_2 = u_{obs}^2 A_L$. In a chain of etendues, the smallest will limit the throughput of light. This is a first hint for increased "costs".

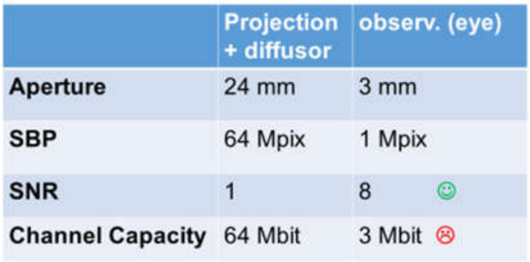
We introduce the etendue for one more reason, because Λ is connected with information:

(2) Λ/λ^2 = *Space-Bandwidth Product SBP = #pixels*

(3) *CC = Channel Capacity [bit] = SBP* $\log^2(1+SNR)$

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 [5].

Figure 2 reveals that for the projection path we have to allocate a channel capacity of 64 Mbit (per frame), although the observer can exploit only 3 Mbit. What happened is that we trade SBP (number of pixels) for better SNR (low speckle noise), paying the prize in terms of information efficiency.



	Projection + diffusor	observ. (eye)
Aperture	24 mm	3 mm
SBP	64 Mpix	1 Mpix
SNR	1	8 ☺
Channel Capacity	64 Mbit	3 Mbit ☹

Fig. 2 Information loss vs SNR in the etendue chain

Of course, illumination optics is commonly not diffraction limited. Nevertheless this is not esoteric reasoning, as there are serious practical consequences [6], [7]: The demanded illumination aperture of 24mm requires a large scanning mirror, which is not available for a required line frequency of 100 kHz. And of course, with a large projection aperture, the major advantages of laser projectors (small size, no lens, no depth of field problems) – are gone.

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2 Speckle Reduction with Laser Illumination

Accepting that speckle reduction will cause costs, even with “incoherent” light sources, we will now discuss how to implement “instantaneous spatial incoherence” with laser projection. Figure 3 displays the basic idea and the possible implementation.

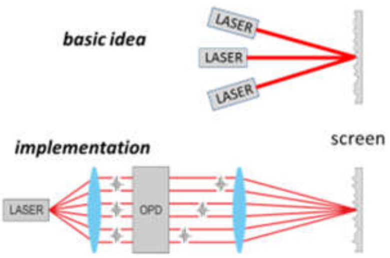

Fig. 3 Instantaneous reduction of spatial coherence with laser illumination

The idea requires a bit of temporal incoherence which is commonly provided by semiconductor lasers. As shown in Fig. 3 we generate *N* subapertures 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 [6], [7]. 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 $N=100$ we could achieve an $SNR \sim 10$ within *0.3 nsec*.

3 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 very simple and fast method to measure this important parameter, via the speckle size, as shown in Fig. 4.

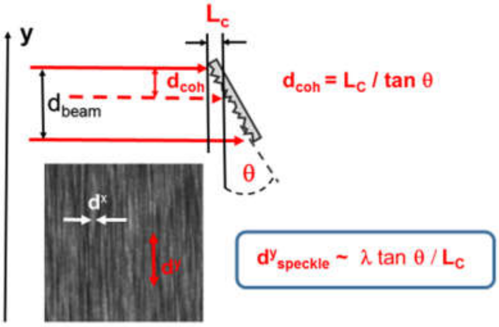

Fig. 4: Coherence length via speckle size

The width of objective speckles at a distance z behind a diffuser is $d_{sp} \sim \lambda z / d_{beam}$, where d_{beam} is the diameter of the illuminated spot. At a diffuser, tilted by θ, d_{beam} degenerates to $d_{coh} = l_C / \tan\theta$, because only the coherent area contributes to the speckles. As shown in Fig. 4, the speckles become anisotropic, with a larger width d_y in y-direction. Figure 5 illustrates the evaluation via the spectrum of the objective speckles, for the untilted scatterer and the tilted scatterer.

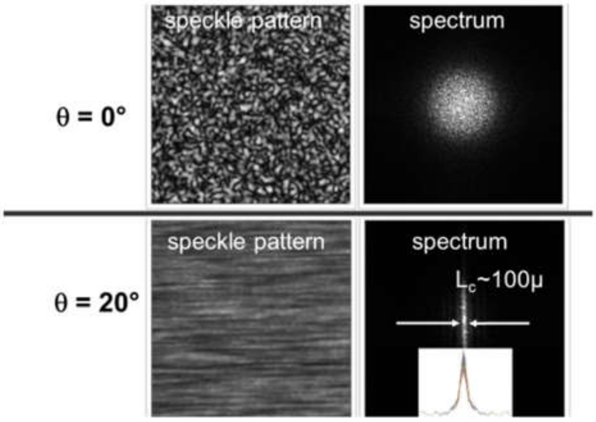

Fig. 5: Temporal coherence function via the spectrum of objective speckles

The speckles from the tilted scatterer display an anisotropic power spectrum. The cross section over the magnitude of the Fourier transform (along the y-direction) corresponds to the magnitude of the temporal coherence function. The scale of the coherence function can easily be estimated via the spectrum for $\theta = 0°$ and the geometry shown in Fig. 4. The coherence length of the used laser was estimated to $l_C^{laser} \sim 100\mu m$. We emphasize that the common method to measure a long coherence length with a tilted-mirror interferometer will be difficult, as too many fringes must be evaluated.

4 Summary

- Instantaneous partial spatial coherence with noise reduction is possible, even with laser illumination.
- The noise reduction demands for an excessive illumination aperture. The demanded channel capacity cannot be fully exploited. Space-bandwidth / lateral resolution is wasted.
- Speckles can be quite easily exploited to measure the coherence length of lasers

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