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# Reduction of speckle contrast in HDTV laser projection display.

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# Problem Description

Reduction of speckle contrast in laser-based HDTV projection displays

## Introduction

poLight is developing an optical modulator chip for use in HDTV projection display based on laser sources. The technology uses a polymer thin film where the surface can be modulated by use of an electrical field. This effect is exploited when creating a tunable diffraction grating array that by the use of line-scan optics can project a high resolution 2 mega pixel image in rear projection TV.

Coherent laser illumination combined with a diffuse screen gives rise to unwanted speckle in the projected image, which creates noise in the form of a granular pattern and thereby reduces the image quality.

## Master thesis

In the specialization project a general study of the speckle effect in laser based displays was performed and different methods to measure and characterize the effect were identified.

In the master thesis the main goals are to give a theoretical basis to understand speckle, build a setup for characterization of speckle in laser based displays, and perform practical measurements. It is necessary to identify important physical parameters that influence speckle phenomena and determine which quantitative measurements that can be performed (e.g. speckle contrast, speckle size and autocorrelation). Methods to perform the measurements will be evaluated and the setup realized. A main part of the setup will be based on a B/W digital video camera with imaging optics that is adapted to the detector geometry.

Speckle contrast and different methods to reduce the speckle contrast will be studied. A description of the physics behind the speckle will be attempted. Measurements of speckle contrast will be made for different experimental configurations like e.g. an expanded laser beam that illuminates:

1. a diffuse screen
2. a vibrating screen (the frequency will be optimized to reduce the speckle contrast)
3. a stationary diffuser placed in the beam path in front of a stationary screen
4. a diffuser that is modulated in different ways (vibration, rotation) with a stationary screen
5. a diffuser based on poLight's technology
6. a Hadamard matrix (if possible) placed in the beam path in front of a stationary screen

An evaluation of the measurements will be made and based on these results a suggestion will be made for which speckle reduction technique to pursue.





# Abstract

In this thesis the focus has been on laser speckle. It is done in collaboration with poLight. They are developing a projector, where laser light is the source of illumination. In such projectors, laser speckle degrades the image quality. The aim of this project is to construct a speckle reduction device to be used in the laser projector.

The theory covers a description of laser speckle, how to reduce the speckle contrast, and five methods to do so. We explain why speckle arises and which parameters we can manipulate to reduce the speckle contrast. The five speckle reduction methods included in this thesis are; vibrating diffuser, slowly moving diffuser, Hadamard matrices, scattering tube, and vibrating mirror. Large vibrational motions are unwanted, considering the size of the device, generation of noise, and problems with alignment of the optical components in the projector that this would lead to. The quality of the laser beam is prominent in order to produce a sharp image, thus the use of diffusers with large scattering angles is not a good solution. The scattering tubes, designed by poLight, are tubes filled with micro pearls in a polymer gel. The size of the pearls decides the nature of the scattering. Larger pearls will give less back scattering and more light transmitted in the forward direction. If the tubes are rotated in a well balanced device we can avoid generating vibrations. The Hadamard matrices is the only one of the five methods which is not based on a motion. The challenge is to find a SLM to implement the matrices. It requires a low response time in order to present enough matrices during the exposure time of the eye.

The laboratory setup we use to measure the speckle contrast is an improved version of the setup constructed in the specialisation project. A screen was removed from the old setup, and the speckle is now imaged directly from the speckle reduction device. The measured speckle reduction is thus due to the device alone, and not affected by the screen. The results were reproducible and in agreement with what we expected. We implemented a vibrating diffuser, both the single and the slowly moving. A piece cut from a plastic bag and some Scotch Magic tape were used as diffusers. The tape is the strongest diffuser and gives the lowest speckle contrast, however, it also has the largest scattering angle. The single tape diffuser reduced the speckle contrast to  $C = 0.112$ . With two tape difusers in series the intensity

in the images becomes too low to exploit the dynamic range of the CCD sensor. The result is a higher calculated speckle contrast with two diffusers,  $C = 0.131$ , even though it ought to be smaller.

We tested five prototypes of the scattering tube with different concentrations. The tube with the highest concentration has the highest speckle reduction abilities. It also has the strongest scattering effect. The scattering is less than with the tape diffuser, and so is the speckle reduction. The speckle contrast is reduced to  $C = 0.320$  when the tube is rotated, and to  $C = 0.389$  when it is vibrated. The tubes was also tested in series with a ground glass. The ground glass acted as a second diffuser. In this setting, vibration and rotation of the tubes reduced the speckle contrast equally,  $C \approx 0.283$

From the measured speckle contrast of the diffusers and tubes in stationary conditions, a polarization analysis should show a depolarization of the laser beam. This were the case only for the plastic diffuser. It is assumed that the error lays with the polarization analysis. There should be a depolarization in the tape and a partial depolarization in the tubes.

A calculation of the speckle size was performed as well. Based on the theory we expected the size of the speckle grains to be  $\sigma_s = 37.77 \mu m$ . From the Fourier analysis of a speckle image from the setup we calculated the speckle size to be  $\sigma_s = 5.35 \text{ mm}$ , which is approximately 140 times bigger. The expected speckle size is too small, because we did not take into account a small magnification in the setup. The Fourier analysis of discrete and limited sets of data points is probably the main explanation of the difference, but a more thorough study is needed.

# Preface

This project has been conducted at the Department of Electrical Engineering And Tele Communications of NTNU in collaboration with poLight, Horten, Norway. The measurements and study of speckle theory is conducted at NTNU. The prototypes of the scattering tube were manufactured at poLight. The project and preliminary results were presented at the Norwegian Electro-Optics meeting 2008. The poster is included in the appendix, see appendix E. The poster was made in collaboration with doctoral research fellow Sigbjørn Vindenes Egge with guidance from Associate Professor Astrid Aksnes at NTNU and Vladimir Kartashov at poLight.

Astrid Aksnes was my supervisor at the university. I would like to thank her for all the support, guidance, and feedback she gave me. Sigbjørn Vindenes Egge helped me in the laboratory and gave me feedback on my thesis, for which I would like to thank him. Vladimir Kartashov, my supervisor at poLight, has been an inspiration with his dedication to the study of laser speckle. I am regretful for not discussing more of my work with him, but I would like to thank him for responding quickly to the few questions I came around to send him.

My dearest Anne had to endure me spending long hours at school working on my thesis. She remain faithful at my side giving me a lot of support, and for this I am ever so grateful.



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# Chapter 1

## Theory

### 1.1 Introduction

The use of lasers in display technology was proposed early, only a few years after the demonstration of the first laser in 1960 [1]. But at that time, a laser projector was costly and the quality could not meet the standard of the products that were already on the market. Laser projectors have been made since then, but only expensive 'ultra high end' projectors. The laser technology has developed especially with the semi-conductor lasers, cheap but powerful, and today there exist lasers and other technology that make it possible to produce a laser display intended for the consumer market. Mitsubishi Electric, Tokyo, Japan, has developed a rear projection TV. It is announced that it will be available to the consumers in the third quarter in 2008 [2].

In the challenge with Mitsubishi Electric to produce laser displays, there is one main problem that has to be solved – laser speckle. Since the invention of the laser a lot of research has been done on laser speckle. It is a random intensity pattern, and has a disturbing effect that will degrade the quality of the image. A reduction of this effect is essential to meet the standard of today's display technology. The speckle reduction method to be used has to be adapted to the design of the display system.

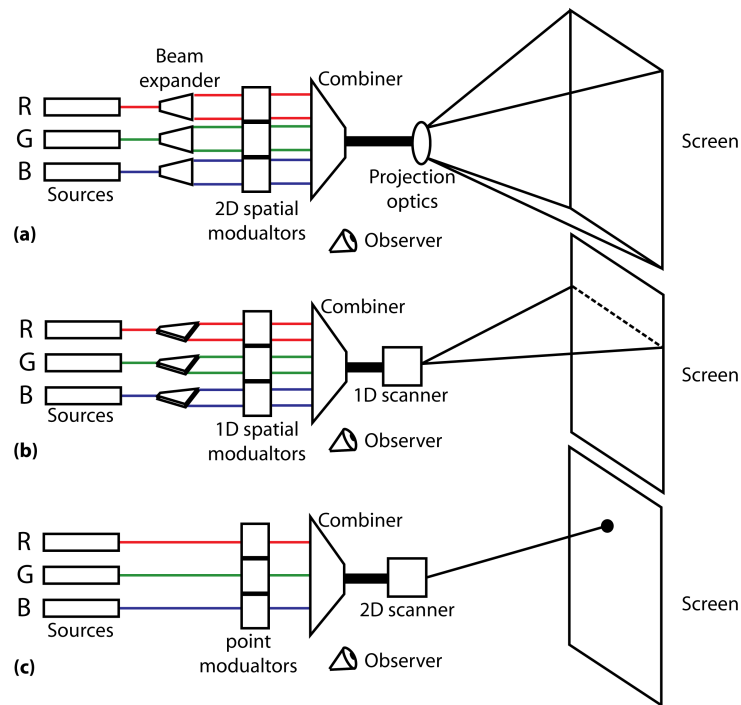
In this thesis we will look at the theory behind laser speckle and some potential methods to reduce it. We will also test solutions in a laboratory setup.

### 1.2 Laser projection displays

A laser projection display consists of a laser source with the three basic colours and a system to form and project the image on a screen as shown in Fig. 1.1. The screen has to be optically rough to allow a large viewing angle. This means that the height fluctuation in the screen surface is comparable

to the wavelength. This surface variation combined with coherent laser light creates speckle that will disturb the image quality. The perception of a speckle pattern is dependent on the observer because it is sensitive to the observers eyesight [3]. Speckle is a clear disadvantage using lasers, but there are four advantages compared to other light sources [4]:

1. higher contrast
2. improved colour gamut
3. potentially greater brightness
4. nearly infinite depth of focus achievable in a special configuration



**Figure 1.1:** A laser projection display with three laser sources emitting the colours red (R), green (G), and blue (B), an image forming system, and a screen. Sketches of (a) full-frame display, (b) line-scanned display, and (c) raster-scanned display.

There are mainly three different ways of making a laser projector [4]. One method is to use a full-frame display projecting the whole optical 2D image at the same time. Figure 1.1 (a) shows a sketch of such a projector. Each laser beam is expanded and passes through a 2D spatial light modulator. The three colours are then combined and projected on to the screen.

Line-scanned displays use a 1D spatial light modulator to make a line of pixels. The principle is demonstrated in Fig. 1.1 (b). The lines from

each colour are combined and then scanned across the screen to form the 2D image, this requires a 1D scanner.

Raster-scanned displays, shown in Fig. 1.1 (c), require only point modulators that vary the intensities of the different coloured laser beams. The beams are combined and a 2D scanner scans the optical spot over the screen forming the 2D image.

It is important to distinguish between these methods, because there are different demands depending on which one we choose. Today's displays must be able to present images with high quality, known as High-Definition Television (HDTV). There are three standards

- 720p (1280 x 720)
- 1080i (1920 x 1080)
- 1080p (1920 x 1080)

'i' and 'p' stand for interlaced and progressive respectively. The frame rate is dependent on the system, and is either 24, 25, or 30 frames per second. 30 frames per second is the most demanding. If we use the resolution 1080p and 30 frames per second, we can estimate the time at hand to reduce the speckle. With a full-frame display we have  $1/30 \approx 33$  ms to work with. In line-scanned displays it would be less. Each line will be held for about  $1/(30 \cdot 1920) \approx 17$   $\mu$ s. With the raster-scanned display there are only  $1/(30 \cdot 1920 \cdot 1080) \approx 16$  ns. The time can also be reduced by the technology used to realize the projector, for instance with the modulators.

There exists a few laser projectors on the market today. But they are expensive and have often been specially designed for the buyer. A company that has developed an RGB laser projector is Corporation for Laser Optics Research, Portsmouth, NH, USA. The laser projector uses the full-frame method, and they claim that it has 'virtually no speckle' [5]. To minimize speckle they have used a laser cavity design which produces a controlled multimode output in the transverse direction [6]. Because of the multimode operation the beam diverges, but with some optical treatment it still produces reasonably crisp images on the screen surface.

### 1.3 Speckle

A speckle pattern is a random intensity distribution that is formed when fairly coherent light is either reflected from a rough surface by random scatterers or propagates through a medium with random refractive index fluctuation [7]. The different points on a rough surface or transparent medium contribute with its own reflected or transmitted wave. The components may have both random lengths (amplitude) and random direction (phase) in the complex plane, or they may have known lengths and random direction. When

we add these components in an observation point, they constitute what is known as a 'random walk'. Depending on the phase of the various elements there is either constructive or destructive interference.

Below we are following a more formal approach to understand speckle. It is based on the book by Joseph W. Goodman [4] and it uses his notation. We are only doing an analysis in the case where we have a sum of phasors with random length and direction, not the cases where we have a constant phasor plus a random phasor sum or a sum of a finite number of equal length phasors.

## 1.4 Phasor

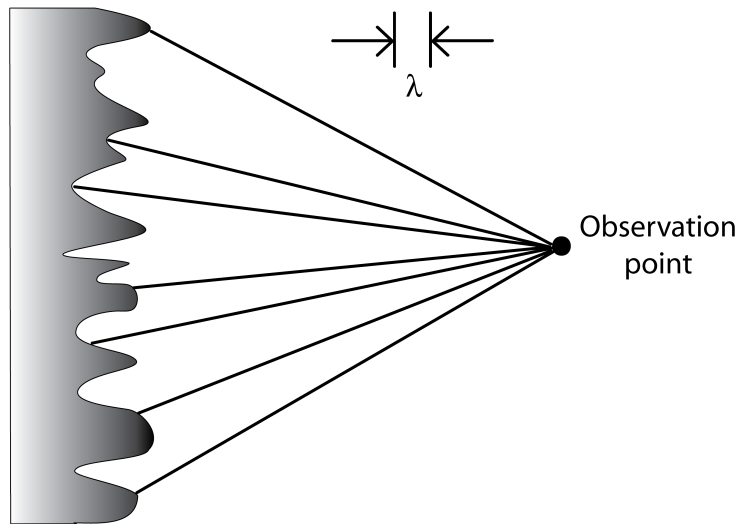
The electric field can be represented mathematically by the wave function

$$U(x, y; t) = A(x, y; t) \cos(2\pi\nu_0 t - \theta(x, y; t)) \quad , \quad (1.1)$$

where  $A(x, y; t)$  is the amplitude,  $\theta(x, y; t)$  is the phase, and  $\nu_0$  is the frequency. This can be simplified by using a complex notation

$$U(x, y; t) = A(x, y; t)e^{j\theta(x, y; t)} \quad , \quad (1.2)$$

known as a complex phasor. The electric field at a single point in space may consist of contributions from different sources, i.e. different scatterers see Fig. 1.2. The field is then given by the sum of the phasor from each scatterer



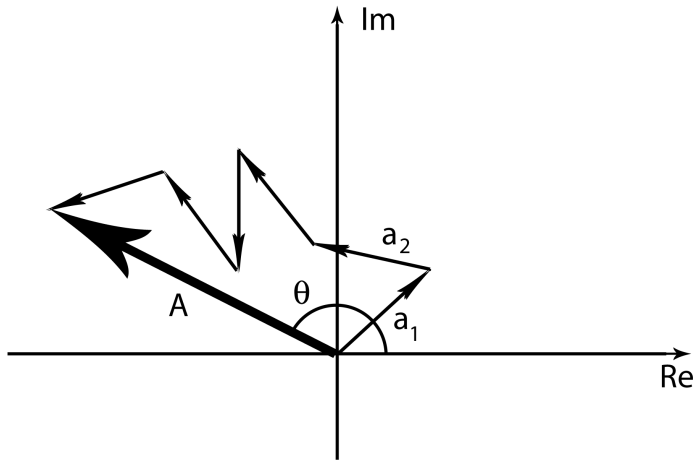
**Figure 1.2:** Contribution on a single point from different scatterers

$$\mathbf{U} = A e^{j\theta} = \sum_{n=1}^N \mathbf{a}_n = \sum_{n=1}^N a_n e^{j\theta_n} \quad . \quad (1.3)$$

This is for a sum of a small number of phasors. In a more realistic situation there will be a very large number of random phasors. The result is a random-phasor-sum

$$\mathbf{U} = Ae^{j\theta} = \frac{1}{\sqrt{N}} \sum_{n=1}^N \mathbf{a}_n = \frac{1}{\sqrt{N}} \sum_{n=1}^N a_n e^{j\theta_n} \quad . \quad (1.4)$$

This sum can be described by the random walk theory as shown in Fig. 1.3.  $N$  represents the number of phasor components and  $a_n$  the length of the  $n$ th component phasor and  $\theta_n$  the phase. We have introduced a scaling factor  $1/\sqrt{N}$ . It preserves finite second moments of the sum if the number of component phasors approaches infinity.



**Figure 1.3:** The sum of random phasors gives the resultant phasor, with amplitude  $\mathbf{A}$  and phase  $\theta$ . This is known as random walk.

Before we continue we have to make some assumptions. This is how they are listed in Joseph W. Goodman's book [4]:

1. The amplitudes and phases  $a_n$  and  $\phi_n$  are statistically independent of  $a_m$  and  $\phi_m$  provided  $n \neq m$ . That is, knowledge of the values of the amplitude and/or phase of one of the component phasors conveys no knowledge about the amplitude and/or phase of an other component phasor.
2. For any  $n$ ,  $a_n$  and  $\phi_n$  are statistically independent of each other. That is, knowledge of the phase of a component phasor conveys no knowledge of the value of the amplitude of that same phasor, and *vice versa*.
3. The phases  $\phi_m$  are uniformly distributed on the interval  $(-\pi, \pi)$ . That is, all values of the phase are equally likely.

We need these assumptions to derive the following statistics. In a case where we have a large number of independent steps,  $N$  in the sum is very large, the probability density function (PDF) of the length and phase is given by

$$p_{A,\theta}(A, \theta) = \frac{A}{2\pi\sigma^2} \exp\left\{-\frac{A^2}{2\sigma^2}\right\} \quad , \quad (1.5)$$

for ( $A \geq 0$ ) and ( $-\pi \leq \theta < \pi$ ), zero otherwise.  $\sigma^2$  is the variance of  $I$ . From this result we can find the PDF for the length  $A$  if we eliminate  $\theta$  by integration over its interval

$$p_A(A) = \int_{-\pi}^{\pi} p_{A,\theta}(A, \theta) d\theta = \frac{A}{\sigma^2} \exp\left\{-\frac{A^2}{2\sigma^2}\right\} \quad , \quad (1.6)$$

for ( $A \geq 0$ ). This is known as the Rayleigh density function.

## 1.5 Optical range

In the optical region we are not capable of measuring the phase and amplitude because of the high frequencies. We are only able to measure the *intensity* of the wave field, rather than the complex amplitude. The human eye is also sensitive to the intensity. The origin of speckle is still a result of a sum of complex amplitudes. We need to derive an expression for intensity based on the phasor theory. First we define the Poynting vector  $\vec{\mathcal{P}}$

$$\vec{\mathcal{P}} = \vec{\mathcal{E}} \times \vec{\mathcal{H}} \quad . \quad (1.7)$$

The Poynting vector is a cross-product of  $\vec{\mathcal{E}}$ , the electric field, and  $\vec{\mathcal{H}}$ , the magnetic field. The time-average of the Poyntings vector is proportional to the time-averaged intensity

$$I \propto |\langle \vec{\mathcal{P}} \rangle| \quad , \quad (1.8)$$

where  $\langle \dots \rangle$  is the infinite time average. This simple result comes from the case where we have a monochromatic plane wave in an isotropic medium. The  $\mathcal{E}$  and  $\mathcal{H}$  are defined as

$$\vec{\mathcal{E}} = \text{Re} \left\{ \vec{\mathbf{E}}_0 \exp \left[ -j(2\pi\nu t - \vec{k} \cdot \vec{r}) \right] \right\} \quad , \quad (1.9)$$

$$\vec{\mathcal{H}} = \text{Re} \left\{ \vec{\mathbf{H}}_0 \exp \left[ -j(2\pi\nu t - \vec{k} \cdot \vec{r}) \right] \right\} \quad , \quad (1.10)$$

where  $\nu$  is the optical frequency and  $\vec{k}$  is the wave vector orthogonal to  $\vec{\mathcal{E}}$  and  $\vec{\mathcal{H}}$  with length  $2\pi/\lambda$ .  $\mathbf{E}_0$  and  $\mathbf{H}_0$  are the complex vector amplitudes. Using Eq.'s (1.9) and (1.10) we can now write

$$|\langle \vec{\mathcal{P}} \rangle| = \frac{\vec{\mathbf{E}}_0 \cdot \vec{\mathbf{E}}_0^*}{2\eta} \quad . \quad (1.11)$$

Here we have used  $\vec{\mathbf{H}}_0 = \vec{\mathbf{E}}_0/2\eta$ , where  $\eta$  is the characteristic impedance of the medium. If we drop a constant we can write

$$I = |\mathbf{A}_{0x}|^2 + |\mathbf{A}_{0y}|^2 + |\mathbf{A}_{0z}|^2 \quad . \quad (1.12)$$

$\mathbf{A}_{0x}$ ,  $\mathbf{A}_{0y}$  and  $\mathbf{A}_{0z}$  are proportional to the amplitude of the elements of the complex vector  $\vec{\mathbf{E}}_0$  in cartesian coordinates. The component  $\mathbf{A}_{0z}$ , in general for paraxial waves, is very small and can be neglected. This leaves the  $x$  and  $y$  components.

$$I = \begin{cases} |\mathbf{A}_{0x}|^2 + |\mathbf{A}_{0y}|^2 & \text{for an unpolarized wave} \\ |\mathbf{A}_0|^2 & \text{for a polarized wave} \end{cases} \quad . \quad (1.13)$$

## 1.6 First order statistics

Now we know how the intensity is connected to the complex wave vector. To find the PDF for the intensity we use this transformation

$$p_v(v) = p_u(f^{-1}(v)) \left| \frac{du}{dv} \right| \quad . \quad (1.14)$$

In our case  $v = I$  and  $u = |\mathbf{A}| = A$  and

$$I = f(A) = A^2 \quad . \quad (1.15)$$

If we have a large number of random phasors which are uniformly distributed on  $(-\pi, \pi)$  we can transform the PDF for the phasor length in Eq. (1.6), using Eq. (1.14).

$$p_I(I) = \frac{\sqrt{I}}{\sigma^2} \exp\left(-\frac{I}{2\sigma^2}\right) \frac{1}{2\sqrt{I}} = \frac{1}{2\sigma^2} \exp\left(-\frac{I}{2\sigma^2}\right) \quad , \quad (1.16)$$

for  $(I \geq 0)$ . The result is a negative exponential distribution. To find the first and second moment we integrate

$$\bar{I}^q = \int_0^\infty I^q p_I(I) dI = (2\sigma^2)^q q! \quad . \quad (1.17)$$

The first moment,  $q = 1$ , gives the mean

$$\bar{I} = 2\sigma^2 \quad . \quad (1.18)$$

Now we can write

$$p_I(I) = \frac{1}{\bar{I}} \exp\left(-\frac{I}{\bar{I}}\right) \quad , \quad (1.19)$$

and

$$\bar{I}^q = (\bar{I})^q q! \quad . \quad (1.20)$$

The second moment is the variance

$$\overline{I^2} = 2\bar{I}^2 , \quad (1.21)$$

$$\sigma_I^2 = \bar{I}^2 , \quad (1.22)$$

$$\sigma_I = \bar{I} . \quad (1.23)$$

We have now found the mean and the standard deviation of a fully developed speckle pattern.

The mean and the variance characterize a speckle pattern. We use these values to define contrast as a measure of the degree of speckle

$$C = \frac{\sigma_I}{\bar{I}} . \quad (1.24)$$

The contrast tells us how much fluctuation of intensity there is compared to the mean intensity. It can be related to the signal-to-noise ratio ( $S/N$ )

$$(S/N) = \frac{1}{C} = \frac{\bar{I}}{\sigma_I} . \quad (1.25)$$

This ratio is a measure of the strength of the average intensity with respect to the fluctuations of intensity. In our case with negative exponentially distributed speckle, fully developed speckle, the contrast and  $S/N$  ratio are both unity,

$$C = 1 , \quad (1.26)$$

$$(S/N) = 1 . \quad (1.27)$$

## 1.7 Sum of speckle patterns

In this project we are looking for a way to reduce the speckle contrast. This is done by summing different speckle patterns. It is not possible to do this on a complex amplitude basis because it would only result in a new pattern. We have to exploit that light sensors measuring intensity integrate over a time interval. During this period we expose the sensor to as many different speckle patterns as possible. The result is a sum of patterns on an intensity basis. The human eye has an integration time of 50 ms. In visual applications like displays, this is the time we have at hand to produce different patterns. Now we are going to find an expression for the reduction when we sum speckle patterns. We will start with two patterns. In the expressions that follow we need the speckle patterns to be independent of one another. There are three ways we can achieve this:

- orthogonal polarizations



- different wavelengths of light
- different angles of illumination

We will go more thoroughly into these methods in the next section.

If  $I_1$  and  $p_1$  are the intensity and PDF of the first speckle pattern and  $I_2$  and  $p_2$  the same for the other pattern, then we have

$$I_s = I_1 + I_2 \quad , \quad (1.28)$$

$$p_s = p_1 * p_2 \quad , \quad (1.29)$$

where  $*$  is the convolution. The Fourier transform of  $p_I$  is

$$\begin{aligned} M_I(\omega) &= \int_0^\infty e^{j\omega I} p_I(I) dI \\ &= \int_0^\infty e^{j\omega I} \left[ \frac{1}{\bar{I}} e^{-\frac{I}{\bar{I}}} \right] dI \\ &= \frac{1}{1 - j\omega \bar{I}} \quad . \end{aligned} \quad (1.30)$$

If we apply this to the two speckle patterns we get

$$M_1 = \frac{1}{1 - j\omega \bar{I}_1} \quad , \quad (1.31)$$

$$M_2 = \frac{1}{1 - j\omega \bar{I}_2} \quad , \quad (1.32)$$

and Eq. (1.29) is transformed to

$$M_s = M_1 M_2 = \frac{1}{1 - j\omega \bar{I}_1} \frac{1}{1 - j\omega \bar{I}_2} \quad . \quad (1.33)$$

The reversed Fourier transform is the new PDF for the sum, which gives

$$\mathcal{F}^{-1} \{M_s\} = p_s(I_s) = \frac{1}{\bar{I}_1 - \bar{I}_2} \left[ \exp\left(-\frac{I_s}{\bar{I}_1}\right) - \exp\left(-\frac{I_s}{\bar{I}_2}\right) \right] \quad , \quad (1.34)$$

when  $(\bar{I}_1 > \bar{I}_2)$  and

$$p_s(I_s) = \frac{I_s}{\bar{I}} \exp\left(-\frac{I_s}{\bar{I}}\right) \quad , \quad (1.35)$$

when  $(\bar{I}_1 = \bar{I}_2 = \bar{I})$ .

The first moment and the second moment is found from the new PDF

$$\bar{I}_s = \overline{I_1 + I_2} = \bar{I}_1 + \bar{I}_2 \quad , \quad (1.36)$$

$$\bar{I}_s^2 = \overline{(I_1 + I_2)^2} = \bar{I}_1^2 + \bar{I}_2^2 + 2\bar{I}_1\bar{I}_2 \quad . \quad (1.37)$$

To get this result we have to assume independence of  $I_1$  and  $I_2$ . In the previous section we found that  $I_1$  and  $I_2$  has a negative exponential distribution, which gives us

$$\sigma_s^2 = \overline{I_s^2} - \overline{I_s}^2 = \overline{I_1}^2 + \overline{I_2}^2 \quad . \quad (1.38)$$

Now we can find a new contrast

$$C = \frac{\sigma_s}{\overline{I_s}} = \frac{\sqrt{\overline{I_1}^2 + \overline{I_2}^2}}{\overline{I_1} + \overline{I_2}} = \frac{\sqrt{1+r^2}}{1+r} \quad , \quad (1.39)$$

where  $r = \overline{I_2}/\overline{I_1}$ . The contrast has its minimum when  $r = 1$ , i.e. when the two intensities have an equal mean

$$C_{min} = \frac{1}{\sqrt{2}} \quad . \quad (1.40)$$

The contrast has been reduced by a factor  $\sqrt{2}$ . It is a start, but we need to reduce it even further. It is likely that a sum of more than two speckle intensities has a larger effect on reducing the contrast.

We can use the same method to find an expression for the sum of  $N$  independent speckle intensities [4]. The result is similar as for two intensities

$$\overline{I_s} = \sum_{n=1}^N \overline{I_n} \quad , \quad (1.41)$$

$$\sigma_s^2 = \sum_{n=1}^N \overline{I_n}^2 \quad . \quad (1.42)$$

This leads to an other equation for the contrast and  $S/N$

$$C = \frac{\sigma_s}{\overline{I_s}} = \frac{\sqrt{\sum_{n=1}^N \overline{I_n}^2}}{\sum_{n=1}^N \overline{I_n}} \quad , \quad (1.43)$$

$$(S/N) = \frac{\overline{I_s}}{\sigma_s} = \frac{\sum_{n=1}^N \overline{I_n}}{\sqrt{\sum_{n=1}^N \overline{I_n}^2}} \quad . \quad (1.44)$$

If we now have  $N$  speckle intensities with the same mean ( $\overline{I_n} = \overline{I_0}$ , all  $n$ ), the contrast and the  $S/N$  ratio are simplified to

$$C = \frac{1}{\sqrt{N}} \quad , \quad (1.45)$$

$$(S/N) = \sqrt{N} \quad . \quad (1.46)$$

By summing  $N$  independent speckle intensities the contrast is reduced by a factor  $\sqrt{N}$ . This is the same result as we obtained for the sum of two. To reduce the contrast to an acceptable level we must produce as many independent speckle intensities as possible. Now we have to find a way to produce these independent speckle patterns.

## 1.8 Speckle size

The size of the speckle grains contains information about the imaging system, and in special setups, the diffusing object. It can for instance be used to measure particle aggregation [8]. There are two ways to observe speckle [9]. The first is when you observe the speckle, reflected from a rough surface, on an optically smooth screen. This is called an objective speckle pattern. When the speckle pattern is imaged on to a screen by the means of a lens it is called subjective, and it is the second way to observe speckle.

### Objective speckle

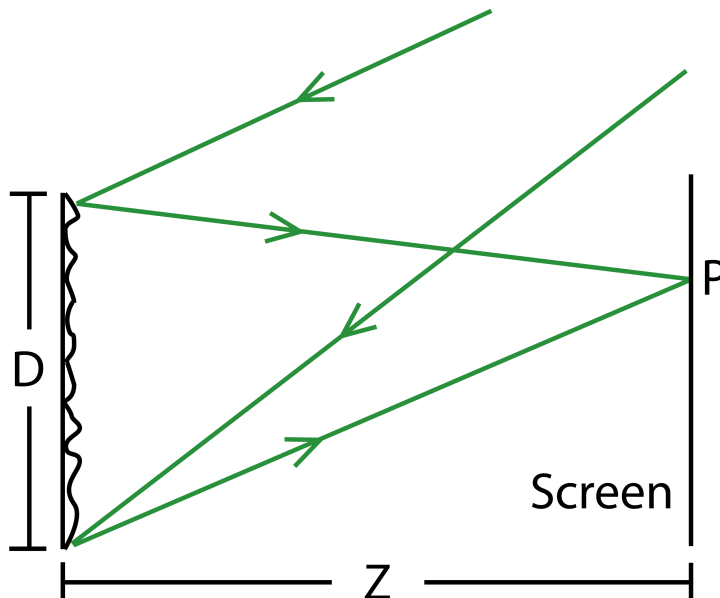


Figure 1.4: Objective speckle [9].

A rough surface is illuminated by laser light as shown in Fig. 1.4. The spot covers a cross-section with a diameter of  $D$ , and the wavelength is  $\lambda$ . The light is scattered and viewed on a screen at a distance  $z$ . An analysis on the  $(y,z)$ -plane shows that two points on the scattering surface, separated by  $l$ , will result in fringes on the screen. This can be any two points separated by this distance, and the frequency of the fringes will be  $f = l/\lambda z$ . The highest possible frequency is obtained by the edge points

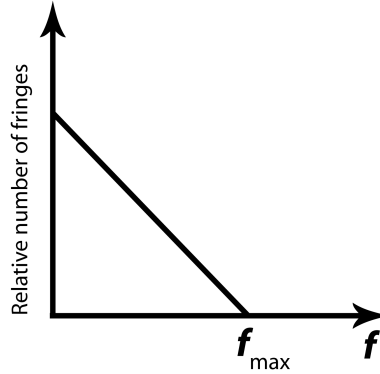
$$f_{max} = \frac{D}{\lambda z} \quad . \quad (1.47)$$

This gives us the smallest possible objective speckle size  $\sigma_o$  in the pattern,

given by the period [9]

$$\sigma_o = \lambda \frac{z}{D} . \quad (1.48)$$

There is only one set of points that will give fringes with this frequency on the screen on the y-axis. For smaller separations  $l$  the number of point pairs increase, and it is proportional to  $(D - l)$ . The fringe patterns add incoherently, because they have individual random phases. This makes the contribution of each frequency to the total intensity proportional to  $(D - l)$ . The frequency and the period are inversely proportional to each other, i.e.  $(D - l) \propto (f_{max} - f)$ , which gives the spatial frequency spectrum a linear shape as shown in Fig. 1.5. In the two dimensional space the spatial frequency spectrum will not necessarily be linear. For a square spot it will have the same shape. In the circular case the shape is slightly different.



**Figure 1.5:** Relative number of fringes with frequency  $f$  [9].

### Subjective speckle

In the setup that we use in the lab, we image subjective speckle. Through the human eye, we also experience subjective speckle. The subjective speckle size is dependent on the imaging optics, and not on the distance to the diffuse object, but the explanation is analogous to the objective speckle. In Fig. 1.6 we image speckle through a lens on to a screen. The minimum size of the speckle grains in the image plane is now

$$\sigma_s = \lambda \frac{b}{D} , \quad (1.49)$$

where  $\lambda$  is the wavelength,  $b$  is the image distance, and  $D$  is the aperture [9]. The aperture number,  $F$ , is defined by

$$F = \frac{f}{D} , \quad (1.50)$$

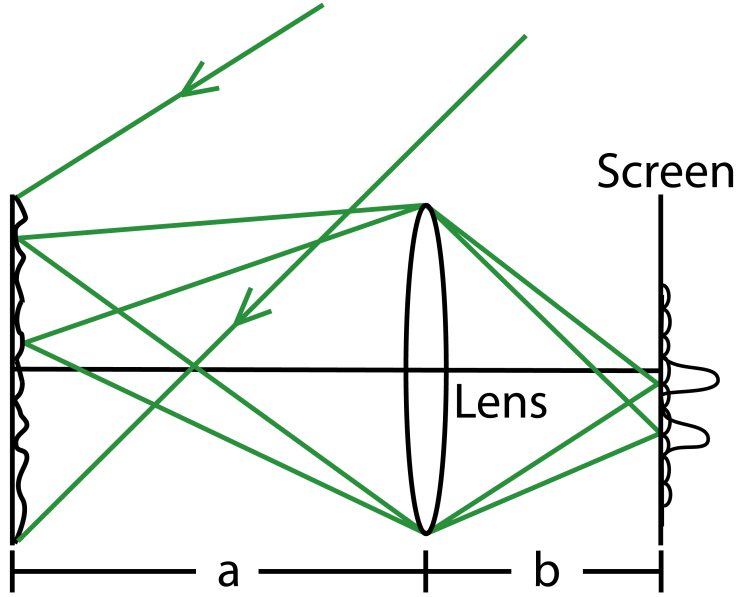


Figure 1.6: Subjective speckle [9].

where  $f$  is the focal length. We also define the magnification as

$$m = \frac{b - f}{f} . \quad (1.51)$$

Using the two definitions Eq. (1.49) can be rewritten

$$\sigma_s = (1 + m) \lambda F . \quad (1.52)$$

It is important to notice that a one-to-one imaging gives  $m = 0$ , and thus

$$\sigma_s = \lambda F . \quad (1.53)$$

Instead of being dependent on the diameter of the scattering area, the speckle size is depending on the lens- or the aperture diameter. It is important to notice that a smaller aperture gives larger speckle grains, the same as with the objective speckle.

If the focal length is much larger compared to the speckle size in the transversal direction, the speckle size in the longitudinal direction will be larger than in the transversal. We can draw this conclusion by comparing the equations for the speckle size in the two directions. In the longitudinal direction the size is [4]

$$(\Delta z)_{1/2} = 6.7\lambda \left(\frac{z}{D}\right)^2 = 6.7\lambda F^2 . \quad (1.54)$$

## 1.9 The autocorrelation function

We have seen that the reduction of the speckle contrast is dependent on the number of independent speckle patterns. In the case with fully developed speckle, independent patterns and uncorrelated patterns are the same [4]. By finding the autocorrelation function of the stationary speckle pattern, we can get an idea of how far the pattern has to be shifted from its original position to be decorrelated, i.e. how much it resembles itself. Under the right conditions there is also a connection between the autocorrelation function and the speckle size. The average width of a speckle grain can be compared to the width of the autocorrelation function [10].

As mentioned in the theory, the intensity in the  $(x, y)$ -plane is a function of the electromagnetic field,  $I(x, y) = |A(x, y)|^2$ . The autocorrelation function of the intensity is given by

$$R_I(x_1, y_1; x_2, y_2) = \langle I(x_1, y_1) I(x_2, y_2) \rangle \quad , \quad (1.55)$$

where  $\langle \dots \rangle$  is the spatial average. There are different approaches to calculate this function.

The easiest way to see this connection is through Fourier transformation and the power spectral density (PSD). With the Fourier transformation we can find the spatial frequency components in the speckle pattern,

$$M_I(\nu_x, \nu_y) = \mathcal{F} \{I(x, y)\} \quad . \quad (1.56)$$

In the previous section, it was shown that the speckle pattern contains mostly low frequencies, and only frequencies up to a cutoff 1.5. It is either the size of the scattering area or the imaging optics that functions as a filter for high frequencies. From  $M_I(\nu_x, \nu_y)$  we can find the PSD

$$\text{PSD}_I(\nu_x, \nu_y) = M_I(\nu_x, \nu_y) \cdot [M_I^*(\nu_x, \nu_y)] = |M_I(\nu_x, \nu_y)|^2 \quad , \quad (1.57)$$

where  $*$  is the complex conjugate. The PSD is also known as the Wiener spectrum. A closer study of the deduction of the Wiener spectrum will lead to the conclusions that, in any speckle patterns, the low spatial frequencies are most common in the speckle pattern [7]. And as mentioned no intensity fluctuations are present beyond a certain cutoff. According to the Wiener-Khinchin theorem we can now find the autocorrelation function by the inverse Fourier transform of the PSD function.

$$R_I(\Delta x, \Delta y) = \mathcal{F}^{-1} \left\{ |\mathcal{F} \{I(x, y)\}|^2 \right\} \quad , \quad (1.58)$$

where  $\Delta x = x_1 - x_2$  and  $\Delta y = y_1 - y_2$  i.e. how far the pattern is shifted from its original position.

In Goodman's work [10], he uses the concept of *mutual intensity* to calculate the autocorrelation. In our case, where we have an optically rough

surface compared to the wavelength,  $A(x, y)$  is a circular complex Gaussian random variable at each point. The autocorrelation of such fields can be used to express the autocorrelation of the intensity. The autocorrelation of the field is

$$J_A(x_1, y_1; x_2, y_2) = \langle A(x_1, y_1) A^*(x_2, y_2) \rangle \quad (1.59)$$

and referred to as the mutual intensity of the fields. If we use the fact that  $J_A(x, y; x, y) = \langle I(x, y) \rangle$  we can rewrite Eq. (1.55) as

$$R_I(x_1, y_1; x_2, y_2) = \langle I(x_1, y_1) \rangle \langle I(x_2, y_2) \rangle + |J_A(x_1, y_1; x_2, y_2)|^2 \quad (1.60)$$

The calculation of  $R_I$  is simplified to calculating  $J_A$ , if the surface fulfills the demand concerning the roughness. In the case of a uniform and square scattering spot with dimensions  $L \times L$ , observed in an image plane at distance  $z$ , objective speckle, the autocorrelation function of the objective speckle intensity is given by

$$R_I(\Delta x, \Delta y) = \langle I \rangle^2 \left[ 1 + \text{sinc}^2 \frac{L\Delta x}{\lambda z} \text{sinc}^2 \frac{L\Delta y}{\lambda z} \right] \quad (1.61)$$

where  $z$  is the distance from the scattering plane to the observation plane. The value of  $\Delta x$  where  $\text{sinc}^2(L\Delta x/\lambda z)$  first falls to zero, denoted as  $\delta x$ , is a reasonable value for the average width of a speckle grain

$$\delta x = \frac{\lambda z}{L} \quad (1.62)$$

We recognize this as the function for objective speckle, with a square scattering spot instead of circular. If we were to use a lens, subjective speckle, the lens should not be able to resolve the microstructure of the scattering surface. Another interesting thing, is that the Fourier transform of a sinc will give the linear frequency as shown in Fig. 1.5. A simulation in Matlab (The MathWorks, Natick, MA, USA) can verify this result.





## Chapter 2

# How to produce independent speckle patterns

There are four different ways to produce independent speckle patterns:

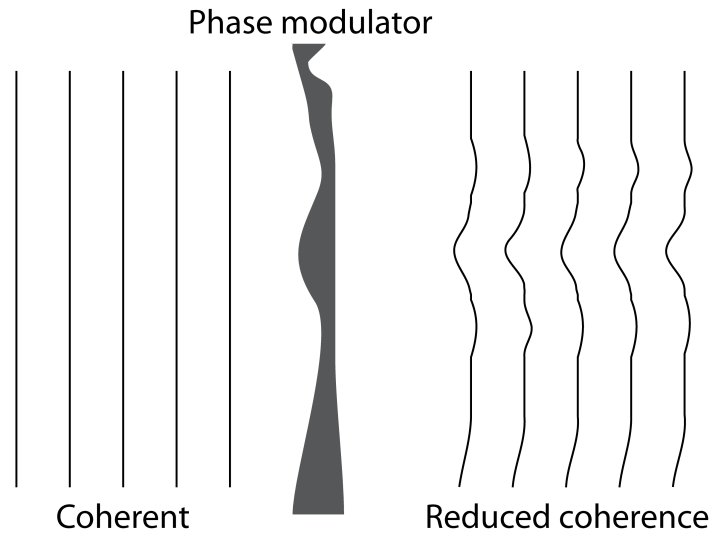
1. Coherence diversity
2. Angle diversity
3. Wavelength diversity
4. Polarization diversity

### 2.1 Coherence diversity

We only have speckle when using coherent light. With incoherent light there will not be a speckle problem. If we want to avoid speckle and we are not dependent on coherent light, we should not use it. Many devices exploit the properties of laser light, a coherent source. In these situations we either have to live with the speckle or we have to find a method to reduce it.

To reduce the speckle contrast we have to remove some of the coherence, either time or spatial coherence. The time coherence is dependent on the spectral width which is dependent on the laser source. The laser we are using in the laboratory is a narrow band diode laser. Diode lasers are cheap and most of them have line width  $\Delta\lambda \approx 2$  nm or less. A laser display intended for the consumer market and mass production has to be cheap, and therefore it is most likely to use diode lasers with  $\Delta\lambda \approx 2$  nm or less. Thus we are not depending on a reduction in speckle contrast due to time coherence in this project.

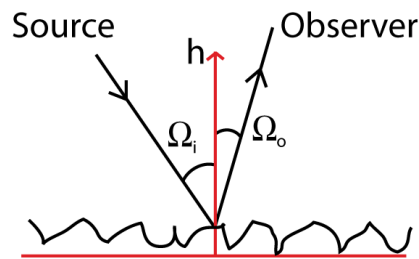
Reduced spatial coherence can be obtained by introducing a phase fluctuation in the cross-section of the beam, i.e. the phase front. Depending on the phase fluctuation it results in a speckle pattern. A new change in the phase



**Figure 2.1:** Sketch of how a phase modulator, i.e. diffuser, destroys some of the wave's spatial coherence passing through.

front leads to a new pattern. A reduction in the speckle contrast occurs if the phase change happens during the integration time of the sensor. The degree of variation, spatial coherence, in the phase front affects the quality of the laser light and it is a trade-off situation – high beam quality or less speckle. Using a diffuser is one example of how to reduce spatial coherence.

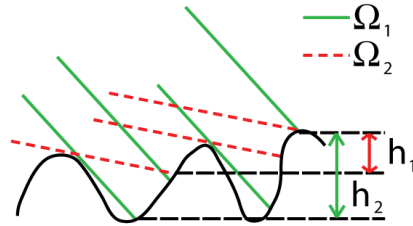
## 2.2 Angle diversity



**Figure 2.2:** The angle of the incident light  $\Omega_i$  and the observation angle  $\Omega_o$ .

We define two angles, the angle of the incident light  $\Omega_i$  and the observation angle  $\Omega_o$  shown in Fig. 2.2. Changing these angles is quite similar to the spatial coherence diversity. While changing the angle to the scattering surface we also change the distance to the scatterers and by that the phase of the incident light or reflected light from a specific point as shown in Fig.

2.3. But it is not always desirable to move the source or the sensor at least not if we are making a display. When watching a display we prefer to sit directly in front of it where the viewing experience is best. It is possible to have the projector produce the image at a large angle of incidence, but it is probably not the best solution. The angle has to be close to ninety degrees to get a good reduction. With this angle we can not allow the screen to curl, and we have to make a special design to reflect the light in the direction of the viewer.



**Figure 2.3:** An increased incident angle ( $\Omega_2 > \Omega_1$ ) results in a smaller height variation ( $h_1 < h_2$ ) and a reduced phase shift.

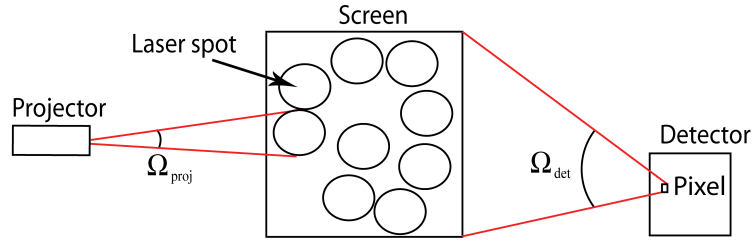
Sensors do not have an infinitely small resolution, not even the human eye. This can be used to produce independent speckle patterns. We can use a digital camera as an example. When you take a picture the image gets divided into pixels. One pixel represents an area in the image. All the details in this area get mixed and are reproduced as one uniform colour. Getting back to the speckle problem, we can use this to produce sub-resolution speckle patterns [11]. If the beam spot is smaller than the resolution of the sensor, we can scan the area with the beam producing independent speckle intensities as shown in Fig. 2.4. The number of uncorrelated patterns we can produce is dependent on the solid-angles subtended by the projector  $\Omega_{proj}$  and the detector  $\Omega_{det}$ . Given that  $\Omega_{det} > \Omega_{proj}$ , we can get a reduction of

$$R_{\Omega} = \sqrt{\frac{\Omega_{det}}{\Omega_{proj}}} . \quad (2.1)$$

To get a reduction we need to sum on an intensity basis. The eye's resolution is also the reason why we are not distracted by speckle when we are using laser pointers. The spot size is small in diameter compared to the eye's resolution. If we expand the spot it will be easier to see the speckle.

## 2.3 Wavelength diversity

The wavelength diversity is related to the coherence diversity. The choice of wavelength affects the speckle pattern. Relative phase change, when reflected



**Figure 2.4:** Solid angles subtended by the projector  $\Omega_{proj}$  and the detector  $\Omega_{det}$  on the screen.

by a rough surface, is proportional to the ratio between the wavelength  $\lambda$  and the height fluctuation  $h$ ,  $\Delta\theta \propto h/\lambda$ . We have a similar connection with transmittance. Smaller  $\Delta\theta$  is better. That is why the surface has to be rough on the scale of the wavelength to produce speckle, otherwise it is considered as a smooth surface. Reduction due to small changes in relative phase is not dependent on summing on an intensity basis. For wavelengths in the visual region even a regular typing paper is rough compared to the wavelength making speckle yet again difficult to avoid in most visual laser devices. It is possible to use lasers with different wavelengths at the same time. They experience different scattering and can produce independent speckle patterns.

## 2.4 Polarization diversity

A rough surface or a diffuser often depolarizes a reflected or transmitted polarized beam.

*When the diffuser or rough surface has the property that different sets of scatterers contribute to the light in two orthogonal polarizations, or when the same set of scatterers exhibits different phases in the two orthogonal polarizations, then the speckle patterns present in the two polarization components of intensity will be independent, and, in accord with the discussion of Section 3.4, the speckle contrast will be reduced. [4]*

It is easy to measure if this reduction is present. We place a polarization analyzer in front of the sensor. If the speckle pattern changes when we rotate the analyzer there will be a reduction in contrast. If the average intensities is the same for the two angles of the analyser we have two independent speckle intensities with equal mean  $N = 2$ , and a reduction factor of  $R = \sqrt{2}$  is likely.

If we rotate the polarization of the beam by 90 degrees, it will produce two new orthogonal polarized speckle patterns. This can be used in a further contrast reduction. You have to switch between the two incident polarizations during the integration time of the sensor. The result is  $R = 2$ . The

same result can be achieved by two different lasers, or a single laser with an optical pathway with a delay longer than the coherence length, with independent polarization. The two beams illuminate the screen at the same time and the reduction in speckle contrast is permanent. We do not have to integrate.



## Chapter 3

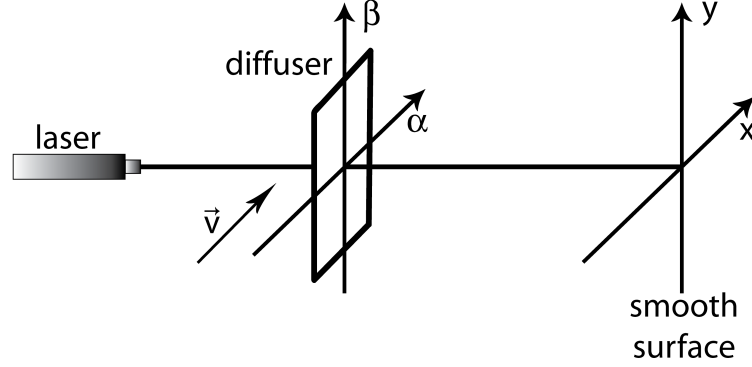
# Methods to reduce speckle

Laser speckle is on the whole a problem in laser applications. There are applications that make use of the phenomenon, e.g diffusive media characterization [12], particle aggregation monitoring [8], vibrations analyses of a rough surface [13]. If the application does not exploit the laser speckle, it is generally a problem. In imaging systems, where the laser light is the illumination source, or in display systems, where the laser light forms the image, it is definitive a problem. Different methods has been developed to reduce speckle contrast in such applications. The simplest and most common is the vibrating diffuser [14, 15]. Although it is a simple method, it is important in the understanding of laser speckle, and it forms a basis for other methods. The use of Hadamard matrices is such a method [16]. Instead of a random diffuser, it is a matrix containing only two different values, which makes it easy to make orthogonal and thus independent matrices. The speckle contrast can also be reduced with the design of the projector, e.g if it uses scanning optics each point on the screen is illuminated over a range of angles [17]. The configuration of the projector is also important for the final design of the speckle reduction device. There are other methods as well, e.g a diffractive optical element [18], ultrasonic waves [19], and multiple tones of illumination [20]. This thesis, however, only covers a few. In this thesis we study one diffuser, two diffusers, Hadamard matrix, a special diffuser designed at poLight, and a vibrating mirror.

### 3.1 Vibrating diffuser

One common method to reduce speckle is to use a diffuser. It destroys the spatial coherence, and produces different speckle patterns if it is moved. With infinite time averaging we would be able to totally destroy the spatial coherence of laser light. But in practice this is not possible, due to the fact that observation time always is finite. Because of the finite time averaging we have to move the diffuser fast to get a large enough displacement. How big

translation we need to develop independent speckle intensities is dependent on the properties of the diffuser. In this first section we will examine the effect of a single diffuser with a random amplitude transmittance, for example milk glass (opaque). Other solutions use diffusers with patterns. A Hadamard matrix may be used as such a diffuser, and will be discussed later.



**Figure 3.1:** Single moving diffuser and an optically smooth surface.

There are a number of different articles on the subject. The following notation is found in Goodman's book [4]. We start with finding an expression for the field in the image plane

$$\mathbf{A}(x, y; t) = \int \int_{-\infty}^{\infty} \mathbf{k}(x + \alpha, y + \beta) \mathbf{a}(\alpha, \beta; t) d\alpha d\beta \quad , \quad (3.1)$$

where  $\mathbf{k}$  is the amplitude point-spread function of the imaging system and  $\mathbf{a}$  is the intensity transmittance. As shown in Fig. 3.1  $(\alpha, \beta)$  are the coordinates at the diffuser and  $(x, y)$  the coordinates at the screen. Because the diffuser is moving,  $\mathbf{A}$  and  $\mathbf{a}$  are time-varying. We assume uniform intensity transmittance. This leaves us with a simple expression for  $\mathbf{a}$  containing the phase contributions from the object  $\Phi_o$  and the diffuser  $\Phi_d$

$$\mathbf{a}(\alpha, \beta; t) = \mathbf{a}_0 e^{j\Phi_o(\alpha, \beta)} e^{j\Phi_d(\alpha - vt, \beta)} \quad , \quad (3.2)$$

where  $\mathbf{a}_0$  is a constant, and the diffuser is moving with speed  $v$  in the positive  $\alpha$  direction.

If we now assume that the image system is space invariant, it is sufficient to calculate the normalized temporal autocovariance of the amplitude  $\mu_{\mathbf{A}}$  at a single point in the image  $(x = 0, y = 0)$ . The squared magnitude of this quantity leads to the normalized autocovariance of the intensity  $\mu_{\mathbf{I}}$ . The speckle suppression is dependent on the degrees of freedom  $M$ . The degrees of freedom is a function of the motion of the diffuser, and is found from the autocovariance of the intensity.



In the situation with a single diffuser and a smooth object we get

$$\mu_{\mathbf{A}}(\tau) \approx 2 \frac{J_1\left(\frac{\pi D v \tau}{\lambda z}\right)}{\frac{\pi D v \tau}{\lambda z}}, \quad (3.3)$$

where  $D$  is the circular entrance pupil and  $z$  the distance from the pupil to the object plane,  $\tau$  is the observation time, and together with the speed  $v$  it gives the displacement.  $J_1(x)$  is the Bessel function of the first order. For a square pupil of width  $L$  we get

$$\mu_{\mathbf{A}}(\tau) \approx \text{sinc}\left(\frac{L v \tau}{\lambda z}\right). \quad (3.4)$$

From these solutions we can find the correlation time of the speckle intensity

$$\tau_c = \int_{-\infty}^{\infty} |\mu_{\mathbf{A}}(\tau)|^2 d\tau. \quad (3.5)$$

This quantity tells us for how long the speckle intensity is related statistically, i.e. how far must the diffuser move,  $X = \tau_c v$ , to be statistically independent of its initial position. In the two cases with square and circular pupils the result is

$$\tau_c = \begin{cases} \frac{8\lambda z}{3\pi^2 v D} & \text{circular pupil} \\ \frac{\lambda z}{v L} & \text{square pupil} \end{cases}. \quad (3.6)$$

To find the number of degrees of freedom we have to use this formula from Goodman's book [4]

$$M = \left[ \frac{\left(\int_{-\infty}^{\infty} P_T(\tau) d\tau\right)^2}{\int_{-\infty}^{\infty} K_T(\tau) |\mu_{\mathbf{A}}(\tau)|^2 d\tau} \right], \quad (3.7)$$

where  $P_T(t)$  is an integration window weighting function and  $K_T(t)$  is the autocorrelation function of  $P_T(t)$ . Using this equation in combination with equation (3.6) and a change of variables,  $\tau = T x$ , leaves us with

$$M = \left[ 2 \int_0^1 (1-x) \frac{J_1\left(\pi \frac{vT}{\lambda z/D} x\right)}{\left(\pi \frac{vT}{\lambda z/D} x\right)^2} dx \right]^{-1}, \quad (3.8)$$

$$M = \left[ 2 \int_0^1 (1-x) \text{sinc}^2\left(\frac{vT}{\lambda z/L} x\right) dx \right]^{-1}, \quad (3.9)$$

where  $P_T(t)$  is a uniform window function  $P_T(t) = \text{rect}\left(\frac{t-T/2}{T}\right)$ . We can see that the degrees of freedom is dependent on the ratio between the distance moved by the diffuser  $vT$  and the dimension of an image resolution cell,

$\lambda z/D$  or  $\lambda z/L$ . If  $T$  grows large, meaning  $1 - \frac{\tau_c}{T} \approx 1$  in the region where the value of  $|\mu_{\mathbf{A}}|^2$  is significant, we get that

$$M \approx \left[ \frac{1}{T} \int_{-\infty}^{\infty} |\mu_{\mathbf{A}}(\tau)|^2 d\tau \right]^{-1} = \frac{T}{\tau_c} . \quad (3.10)$$

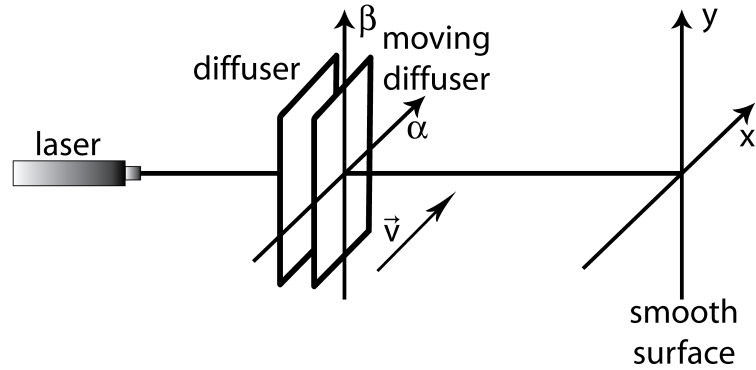
In situations where  $T/\tau_c$  is large, the contrast  $C = 1/\sqrt{M}$  can be approximated to be

$$C \approx \sqrt{\frac{\tau_c}{T}} \approx \begin{cases} \sqrt{\frac{\lambda z/D}{vT}} & \text{circular pupil} \\ \sqrt{\frac{\lambda z/L}{vT}} & \text{square pupil} \end{cases} . \quad (3.11)$$

The speckle contrast reduction is proportional to the square root of the number of resolution widths on the object the diffuser is moved during the integration time. If we compare Eq. (3.11) with Eq. (1.48) it is possible to say that the reduction in speckle contrast is proportional to the square root of the number of speckle sizes the diffuser is moved, i.e. the resolution width on the object is comparable to the speckle size. This is a slow reduction and the diffuser has to move a great distance. We shall now see how we can reduce this distance by inserting another diffuser or a rough object.

### 3.2 Slowly moving diffuser

A moving diffuser in combination with a motionless diffuser can be used to reduce the speckle contrast more efficiently than with just one diffuser. Lowenthal and Joyeux have written an article on this subject [14]. We will use their notation. They derive an expression for the S/N ratio when using the two diffusers, and compare the result with a single moving diffuser in a practical experiment.



**Figure 3.2:** A stationary diffuser and a moving diffuser.

The S/N ratio of the observed illuminance  $\rho$  is  $\sqrt{N}$ , where  $N$  is the

displacement of the diffuser during the integration time. It is measured in length units of the mean size of the speckle in the observation plane.

With some assumptions we get an expression for  $\rho$  [14]. We start with finding expressions for the mean and the standard deviation and use them together with Eq. (1.25). In addition we have that  $d_1(\vec{r})$  and  $d_2(\vec{r})$  is the amplitude transmittance of the two diffusers at the point  $\vec{r} = [\alpha, \beta]$ . This leads to

$$\rho = (S/N) = \left[ \frac{1}{T} \int_{-T}^T \left(1 - \frac{\tau}{T}\right) |S_d(\vec{v}\tau)|^2 d\tau \right]^{\frac{1}{2}}, \quad (3.12)$$

where  $T$  is the integration time,  $\vec{v}$  is the speed of the moving diffuser,  $\vec{v}\tau$  gives the displacement, and

$$R_d(\vec{r}) = \langle d_1(\vec{r}_1) d_1^*(\vec{r}_2) \rangle = \langle d_2(\vec{r}_1) d_2^*(\vec{r}_2) \rangle, \quad (3.13)$$

$$S_d(\vec{r}) = \frac{R_d(\vec{r}) * R_d(-\vec{r})}{[R_d(\vec{r}) * R_d(-\vec{r})]_{\vec{r}=o}}. \quad (3.14)$$

$R_d$  is the autocorrelation function of the diffuser's amplitude transmittance and  $S_d$  is the normalized autocorrelation function of  $R_d$ . If the diffuser is not moving  $\vec{v} = 0$  we get that  $\rho = 1$  as we should expect. Choosing a coordinate system in such a way that  $x$  is parallel to  $\vec{v}$  and assuming that the displacement  $X = vT$  is a few times larger than the width of  $S_s(v\tau, 0)$  we can rewrite Eq. (3.12)

$$(S/N) \approx \left[ \frac{T}{\int_{-\infty}^{\infty} |S_d(v\tau, 0)|^2 d\tau} \right]^{\frac{1}{2}} = \left( \frac{vT}{L} \right)^{\frac{1}{2}}, \quad (3.15)$$

where

$$L = \int_{-\infty}^{\infty} |S_d(v\tau, 0)|^2 d\tau. \quad (3.16)$$

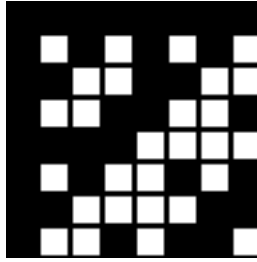
The length  $L$  is approximately the same as the correlation radius of the diffuser. They are of the same order and magnitude.

If we compare this result with the single diffuser, we see that the contrast is reduced proportional to the square root of the ratio between the diffusers correlation length and the distance it has moved. The correlation length is typically many times smaller than the resolution width on the object. With two diffusers we do not have to move the diffuser as much as we do with a single diffuser to obtain the same reduction in speckle contrast. With a single moving diffuser with total diffuser displacement  $X = 0.13$  mm and correlation length  $L = 0.18$  mm the  $S/N$  is almost unchanged  $\rho \approx 1$ . And with two diffusers,  $X = 0.13$  mm and  $L = 6$   $\mu$ m the result is much better  $\rho = 5$ .

We see that we can get good results using diffusers to destroy the spatial coherence and reduce the speckle contrast. But it comes at a price. The diffusers spread the light and destroy the collimation of the beam.

### 3.3 Hadamard matrices

One special kind of diffuser is a Hadamard  $M \times M$  matrix. It is a matrix where each cell either is '+' or '-' as shown in Fig. 3.3. In our case the two values are represented by a phase delay of  $\Delta\phi = 0$  or  $\Delta\phi = \pi$ . If we find two orthogonal matrices and let the beam pass through one matrix at a time, they will produce two independent speckle patterns [11].



**Figure 3.3:** A Hadamard matrix of order 8, where white is + and black is -.

We divide the pixel in  $M \times M = N$  subpixels, and let the contribution from one subpixel on the sensor be  $E_{ij}$ , shown in Fig. 3.4. Then the total intensity will be

$$S_0 = \left| \sum_{i=1}^M \sum_{j=1}^M E_{ij} \right|^2 . \quad (3.17)$$

Now we introduce phase delays in the subpixels using a Hadamard matrix with the same number of cells as there are subpixels. The phase delay in cell  $(ij)$  is  $H_{ij}^a = \exp(j\phi_{ij}^a)$ . The total intensity using the phase matrix is

$$S = \frac{1}{A} \sum_{a=1}^A \left| \sum_{i=1}^M \sum_{j=1}^M H_{ij}^a E_{ij} \right|^2 , \quad (3.18)$$

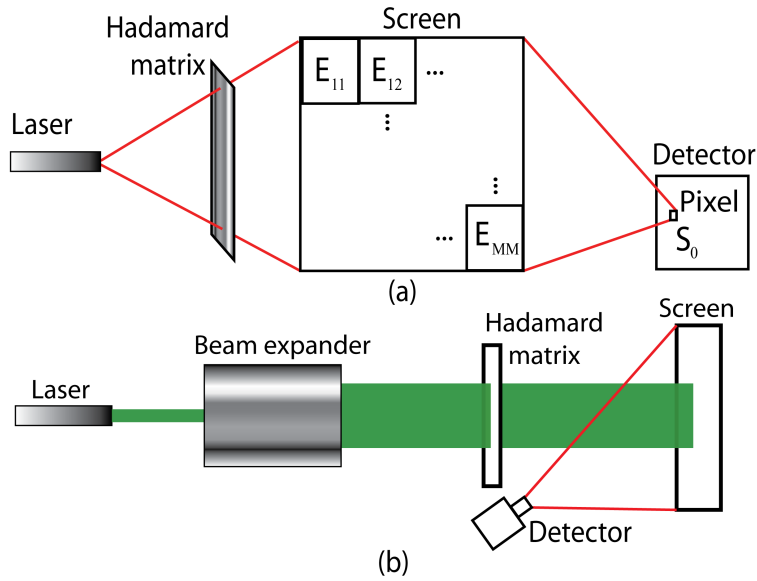
where  $A$  is the number of orthogonal matrices. Since the matrices are orthogonal we can use the decorrelation condition

$$\sum_{a=1}^A H_{ij}^{a*} H_{kl}^a = A \delta_{ik} \delta_{jl} . \quad (3.19)$$

With this condition we can show that

$$\begin{aligned}
 S &= \frac{1}{A} \sum_a \left| \sum_i \sum_j H_{ij}^a E_{ij} \right|^2 \\
 &= \frac{1}{A} \sum_a \sum_i \sum_j \sum_k \sum_l (H_{ij}^{a*} E_{ij}^*) (H_{ij}^a E_{ij}) \\
 &= \frac{1}{A} \sum_i \sum_j \sum_k \sum_l A \delta_{ik} \delta_{jl} E_{ij}^* E_{kl} \\
 &= \sum_i \sum_j |E_{ij}|^2 .
 \end{aligned} \tag{3.20}$$

The cross-terms vanish because of the averaging. Using Hadamard matrices with cells that are decorrelated makes the contributions from each subpixel independent, and they add on an intensity basis. The number of orthogonal matrices gives the reduction  $M$ . To achieve this reduction we need at least  $A_{\min} = M$  phase patterns [11]. If we use a Hadamard matrix with  $N = 8 \times 8 = 64$  cells we may get a reduction of up to  $R = 8$ , i.e.  $C = 0.125$ .

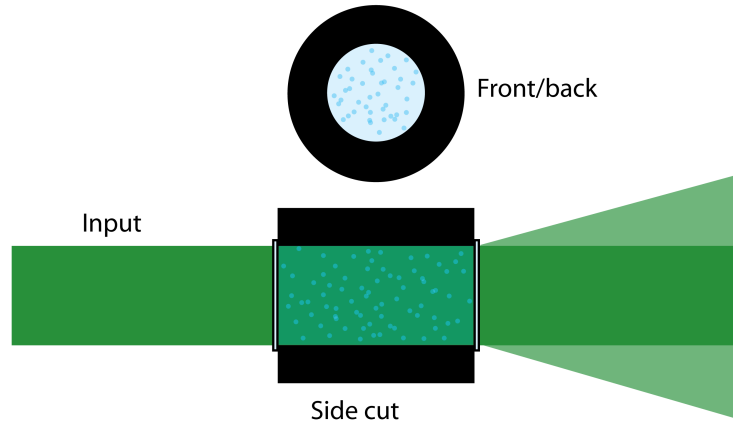


**Figure 3.4:** The Hadamard matrices produces phase variations in the beam cross-section. (a) Each subpixel on the screen contributes to the total intensity  $S_0$ . (b) A practical setup.

The challenge is to present enough phase arrays during the integration time. If the matrices are etched on a plate, we would have to move the plate fast with a large displacement. The displacement needed is determined by the number of matrices and their size. An other method that does not require

mechanical movement is to use a spatial light modulator (SLM). This is an array where the individual cells can be addressed and controlled by electric signals. With a SLM we do not have to deal with large mechanical movement, but there are other problems. The changing between two matrices is not immediate and might be too slow. There is also a risk of burning the SLM because of the high intensity in the laser beam.

### 3.4 Scattering tube

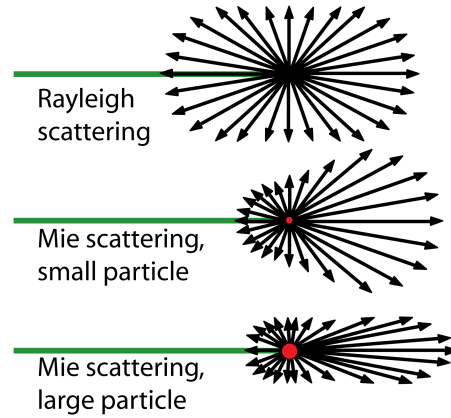


**Figure 3.5:** Diffuser designed by poLight.

poLight has designed a diffuser based on micro pearls and their polymer, see Fig. 3.5. The pearls are mixed into the polymer gel, and the mixture is filled in a plastic tube. The outer diameter of the tube is 17.0 mm, and the inner diameter is 11.0 mm. The ends are covered with thin glass plates. The polymer has a refractive index of  $n_{gel} = 1.4$  at  $\lambda = 589.3$  nm and decreases very slow with increasing wavelengths. The micro pearls are produced by Sekisui, Osaka, Japan, and has a low deviation in diameter. They are normally used as spacers in LCD panels. The refractive index of the pearls is  $n_{part} = 1.57$ , and their diameter is  $25 \mu\text{m}$ . The difference in refractive index between the gel and the pearls, leads to a refraction and phase delay of the part of the beam that passes through a micro pearl. The maximum phase delay through a pearl is

$$d\theta = k_0 (\Delta n) L = \frac{2\pi}{\lambda_0} (n_{gel} - n_{part}) l \quad , \quad (3.21)$$

where  $l$  is the diameter of the pearl, which gives  $d\theta = 50.19 \approx 8(2\pi)$ . A part of the laser beam only has to pass through one pearl to achieve a necessary phase difference.



**Figure 3.6:** Rayleigh and Mie scattering [21].

The size of the pearls are crucial, because the nature of the scattering is dependent on it [22]. When the scatterers are much smaller than the wavelength, Rayleigh scattering is predominant with a high degree of back scattering. For bigger particles we have Mie scattering, where the back scattering decrease with increasing size, see Fig. 3.6. In order to preserve the intensity of the laser beam passing through the tube, the micro pearls has to be large compared to the wavelength. The wavelength in the polymer gel that surrounds the pearls is  $\lambda_{gel} = \lambda/n_{gel} = 380$  nm, and the pearls are more than sixty times larger. The pearls being this much bigger, leads to the assumption that we have Mie scattering by large particles.

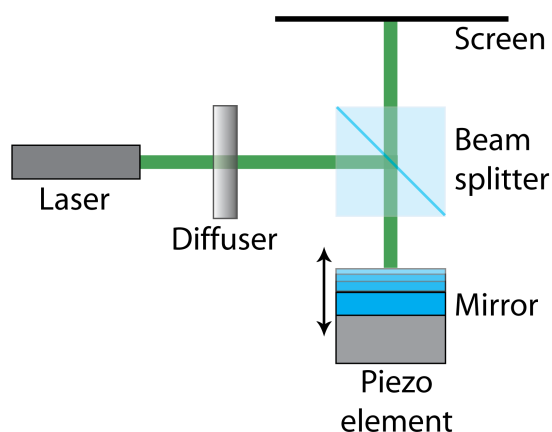
The concentration of particles in the gel and the length of the tube will affect the scattering as well. It is likely that the correlation length of the scattering tubes as diffusers is dependent on these two values. Correlation length is dependent on how far the tube has to be displaced for one part of the cross section of the beam to experience a different phase delay. If the length of the tube is constant, we expect that higher concentration results in lower correlation length. With a very low concentration there can be many areas in the tube where the beam passes through only gel, and does not experience a phase delay. The bigger these areas are, the longer the correlation length is. If the concentration is kept constant, an increased length of the tube will have the same effect as an increased concentration. The longer the tube is, the higher the likelihood of a part of the beam to get scattered increases. The aim must be to find a concentration and a length of the tube that will give a sufficiently small correlation length, however the beam quality is also inflicted. The concentration should not be too high nor the length too long. The more micro pearls the beam passes through, the larger the scattering angle becomes.

Unless the laser beam is depolarized by the scattering, the diffuser itself

will not reduce the speckle contrast without some kind of motion. In the practical part we will look at two ways to use this diffuser - vibration and rotation.

### 3.5 Vibrating mirror

Most of the methods presented in this thesis involve movement transversal to the laser beam. This is done in order to reduce the spatial coherence. With a stationary diffuser and a vibrating mirror, as in Fig. 3.7, it should be possible to do a movement in the longitudinal direction of the laser beam. The diffuser creates a speckle pattern. The speckle pattern upon the surface of the mirror will change dependent on it's displacement.



**Figure 3.7:** Vibrating mirror.

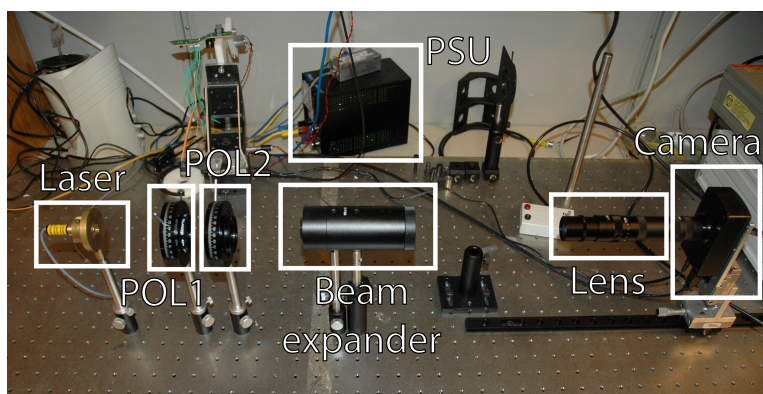
If we assume that we have the same relation between the speckle length and the correlation length in the longitudinal direction as we do in the transversal, we can calculate the displacement needed to create an independent speckle pattern. The longitudinal speckle size is given in Eq. (1.54). From the equation we can see that we need a larger displacement than we do with the vibrating diffuser. This makes this method less interesting. Piezo elements do not normally offer very large displacement, though it is possible to design special stacking of elements to improve this.



## Chapter 4

# Laboratory setup

### 4.1 Measuring speckle contrast



**Figure 4.1:** A picture of the laboratory setup. PSU is the power supply unit for the laser and POL1 and POL2 are the polarizers.

The laboratory setup is fairly simple, see Fig 4.1. Let us first get an overview of the setup, before we look more closely at each component. The setup consists of a laser, two polarizers, a beam expander, a speckle reduction device, a camera with a macro lens, and a computer. The laser is the source for coherent light. It is a diode pumped solid state laser (DPSS), and radiates at  $\lambda = 532$  nm. We control the intensity with the two polarizers, avoiding saturation in the camera. The laser beam is expanded before it passes through the speckle reduction device. The beam continues directly into the camera through the lens. The image is captured by the CCD sensor and grabbed by a Matlab code on the computer, and saved at a preferred location by the user.

When we first built the setup it also contained a mirror and a screen. The mirror only enabled the use of the screen. The screen was a regular typing paper. We imaged the speckle from the screen, instead of the direct

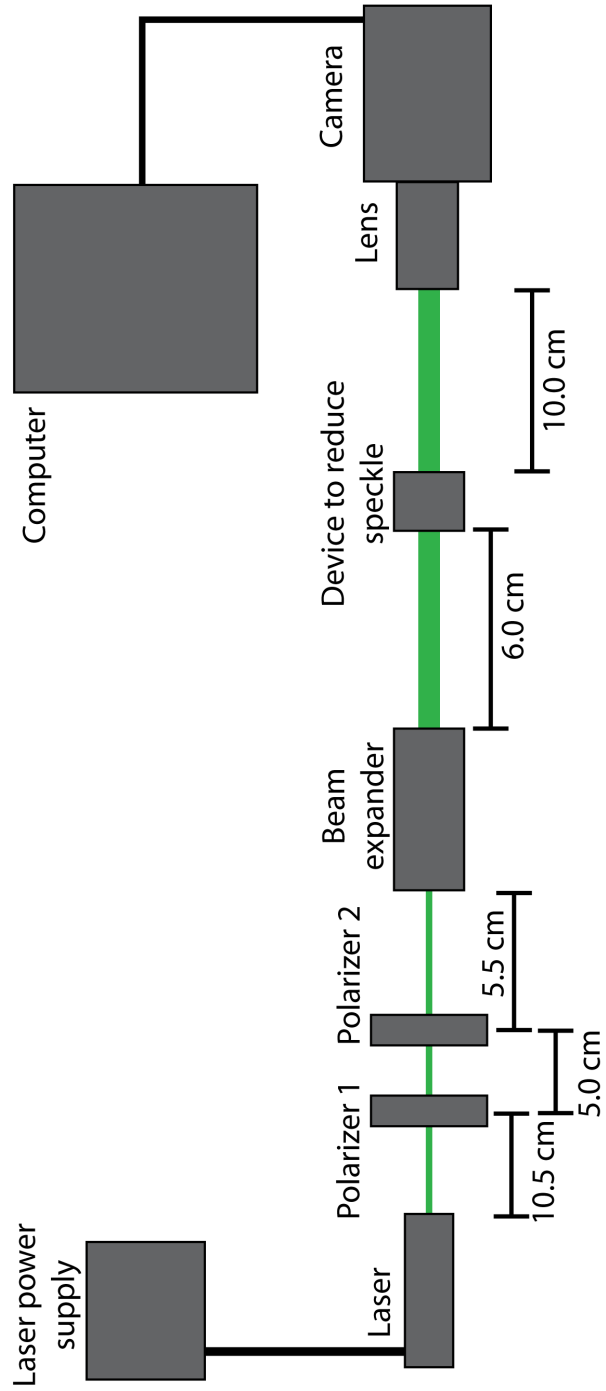


Figure 4.2: Sketch of the setup

version we use now. It was probably a more realistic setup, since our goal is to make a laser projector and the viewer will look at the image reflected from a screen. There were two sides to the use of the screen. We were able to add the speckle effect of a screen, as it will in a laser display, but at the same time we had very little control of what it contributed with in different settings. The results varied from measurement to measurement, and they were difficult to reproduce. In the new setup, we have ruled out the screen as a source of uncertainty. We now know that the speckle reduction device is the sole source of a potential reduction in speckle contrast. This is important in order to be able to characterize the device.

It is possible to reintroduce the screen in later work, after the device has been characterized. Then we can use the screen to adjust the device to reach a satisfying level of speckle contrast in an actual laser display.

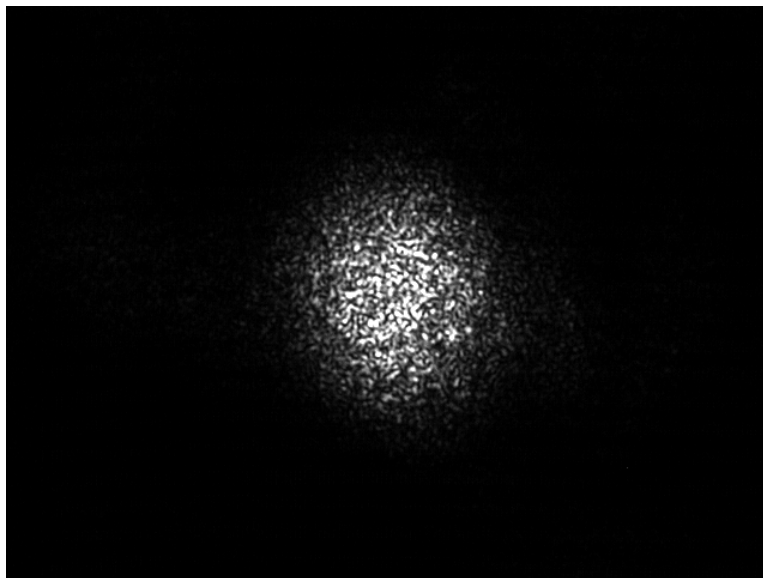
#### 4.1.1 Laser

The human eye is most sensitive to the colour green. Therefore speckle reduction is most critical in this colour area. That is why we have chosen a green laser. We use a DPSS laser from Photonic, Hertfordshire, UK, see appendix D.1. It radiates at wavelength 532 nm. The output power of the laser is 4 mW and the laser mode is  $TEM_{00}$ , which gives a Gaussian beam profile.

#### 4.1.2 Polarizers

To avoid saturation, or worse burning, of the CCD sensor in the camera we use two polarizers, see appendix D.2. If they are crossed, the second polarizer completely stops the light. In parallel the second polarizer transmits almost all the light from the first polarizer. By varying the relative orientation between the two polarizers we can control the intensity of the beam. This is useful, because a saturated pixel in the camera contains little information. It only tells us that there is a very high intensity but not how high compared to unsaturated pixels. At the same time we need the intensity to be as high as possible to exploit the dynamic area of the CCD sensor. The camera does not give an exact value of the intensity in metric units. The image only shows the relative value. The intensity is not a critical parameter when we want to measure the reduction of speckle contrast. To measure the optical power loss in the speckle reduction device, one should use something different than a camera. This work does not cover this problem, but it should be a part of a future work. The intensity could have been controlled with just one polarizer, since the laser light is already linearly polarized from the laser. But the laser is not perfectly polarized, and we have decided to use two polarizers. In this setup, where we image the laser beam directly, we only require a very small portion of the light, and are dependent on almost blocking the beam totally.

### 4.1.3 Beam expander

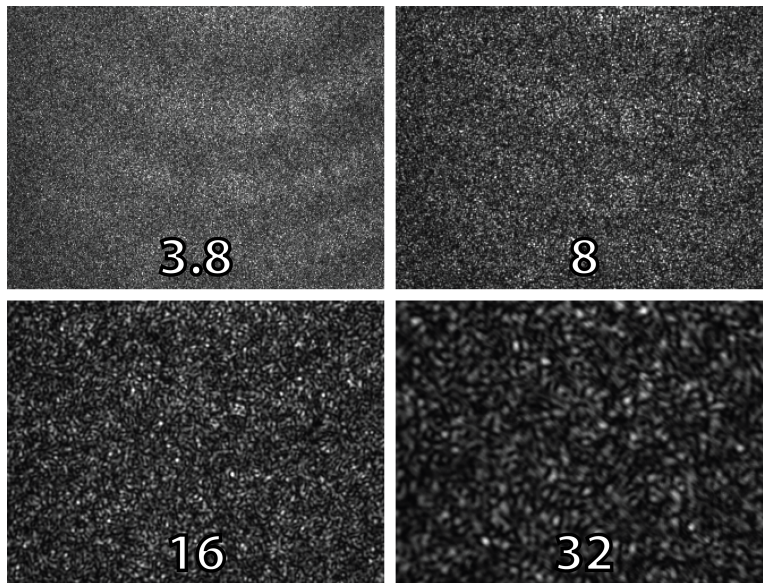


**Figure 4.3:** Laser spot size on the CCD sensor using all the extension rings.

The laser beam has a diameter of 1.2 mm. To fill the CCD array we had to use extension rings on the lens to obtain a field of view (FOV) in the same order of size as the beam. But even when we used all the rings in the kit, 78.5 mm in total, we were not able to fill the sensor as shown in Fig. 4.3. To solve this problem we used a beam expander with  $20\times$  magnification see appendix D.5. The expanded beam spot became larger than the FOV as can be seen in Fig. 4.4. The FOV is  $3.4 \times 2.6$  mm, see appendix A.1 and the laser spot is approximately 12 mm. Choosing a section in the center of the laser spot gives a more uniform speckle intensity distribution in the image due to the expanded Gaussian beam profile.

### 4.1.4 Lens

We use a c-mount lens from VS Technology, Tokyo, Japan, see appendix D.4. The focal length of the lens is 75 mm and it has a variable aperture. We are using a lens to image the speckle on the CCD sensor, and observe subjective speckle, as shown the size of the speckle grains is dependent on the observation method. The subjective speckle size is given in Eq. (1.49). The variable aperture enables us to ensure that the speckle grains covers the minimum number of pixels on the sensor array. The aperture has five options shown in Fig. 4.4.



**Figure 4.4:** Four settings of the aperture in the lens and corresponding f-numbers. Due to the extension rings the actual f-numbers are different, see Tab. 4.2. The fifth setting of the aperture on the lens is closed.

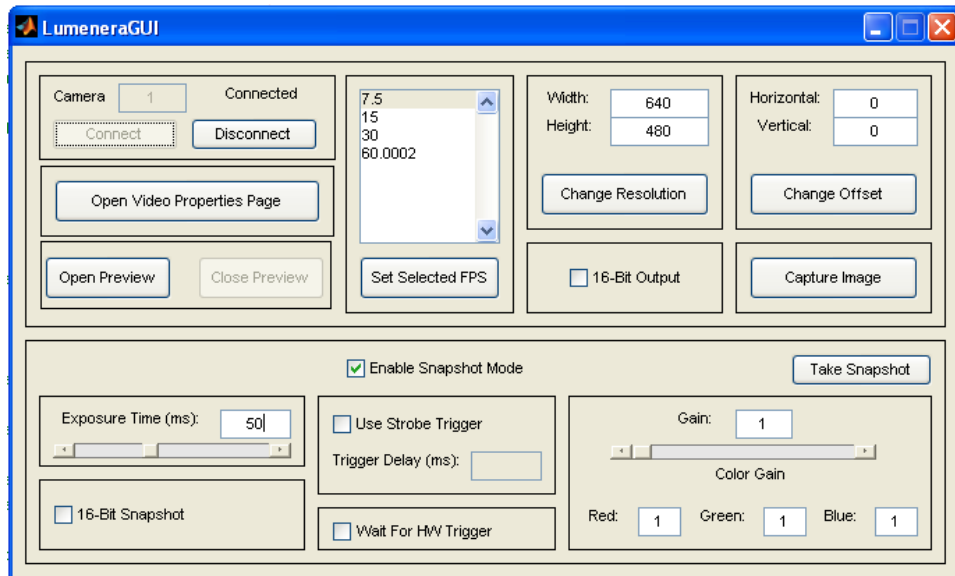
#### 4.1.5 Camera

The camera is a monochrome VGA USB 2.0 camera from Lumenera, Ottawa, Ontario, Canada, see appendix D.3. The format of the CCD array is  $1/3''$  and the resolution is  $640 \times 480$ . We are able to control the camera from a program on the computer called LuCam Capture v4.5.0. Lumenera has also made Lumenera MATLAB Driver v1.1.0 with a graphical user interface (GUI). The driver makes it possible to write scripts that we can run as soon as the image is captured.

The most important settings in this driver are gain, exposure time, and gamma correction. The driver allows both live video and still frames. We use the video mode when we adjust the position of the camera to obtain focus and still frames to save images on the hard drive to be processed in Matlab. The settings have to be adjusted to get good images. The GUI is shown in Fig. 4.5.

Since we only have one camera in this setup, the camera number is 1. Press *Connect* to gain control of the camera, and it will show *Connected* and disable the *Connect* button. The next step is to select a frame rate, frames per second (FPS). A good choice in our case is 7.5 FPS. This frame rate allows an exposure time ranging from 0 ms to 133.5 ms. This makes it possible to use an exposure time of 50 ms, approximately the same as the human eye. This will be our setting unless otherwise stated.

The human eye has two different main types of receptor cells - rods and



**Figure 4.5:** The Matlab driver gives us control of the camera and it's settings.

cones [23]. The sensitivity and response time are different for the two types. The rods are slow and sensitive and useful in poor lighting conditions. Their integration time is up to 100 ms. There are three type of cones that reacts to different wavelengths, and this is what gives colour vision. An overlap in the regions where the cones are sensitive, can explain why the eye is more sensitive to the colour green. The cones are less sensitive than the rods, but they have lower latency. The integration time is approximately 10-20 ms, and they only need a short time to return to the resting potential. They can detect flickering of frequencies up to 80-90 Hz, depending on the illumination. All in all, the response of the eye varies from human to human, and in the setup we have chosen the approximate integration time of the eye, which is 50 ms [15].

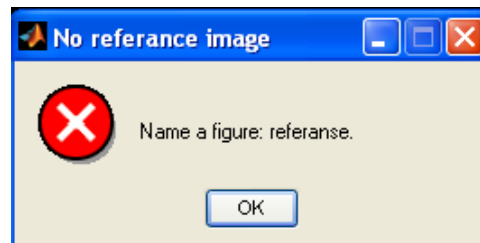
We have found that the speckle reduction is dependent on the number of independent speckle patterns during the integration time. To get an idea of how much speckle reduction a human would experience, it is very important to have control of the exposure. Changing the exposure time can be used to scale the experiment. If we double the exposure time when measuring on a moving diffuser, the displacement would double as well given that the movement has a constant velocity. This means that instead of redesigning the mechanism that moves the diffuser to double the speed, it could be sufficient to double the exposure time. This is only possible to do in the laboratory setup, since it is impossible to alter the eye.

To set the exposure time for the preview (video) mode, press the *Open Video Properties Page* button, see appendix A.3. In the first tab, *Image*

*properties*, you can set the exposure and the gain. The camera's sensitivity to light is set by the gain. In poor light conditions the object can be made visible by increasing the gain. But a high gain is a source of noise in an image, and should be avoided if possible. In this setup the intensity of the laser light can be adjusted in such a way that we do not have to use much gain. The gain is set to the value 1.0, and the exposure time to 50 ms. The *Auto* check box is not supposed to be checked.

The second tab, *Image properties 2*, contains the options for gamma, contrast, and brightness. The gamma value is set to one to obtain a linear response to the intensity of the light. Both the contrast and brightness should be zero. The two last tabs are for more advanced cameras and setups, and are not used.

Now the preview mode will show the speckle reduction live. All you have to do is press the *Open preview* button. This function is also useful when you are aligning the laboratory setup. But we also need to set the same settings for the snapshot mode. The snapshot mode is found in the bottom half of the camera's GUI. Enable the mode, set the exposure time to 50 ms, and the gain to one. Do not check any of the other boxes. To capture an image press the *Take Snapshot* button. We have modified a version of the Matlab driver. When you take a snapshot, it will calculate the speckle contrast and let you save the image and a Matlab figure that contains the speckle contrast in the image.

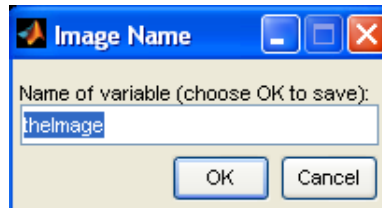


**Figure 4.6:** The first time you take a snapshot, the program remind you to make a reference image for removal of background noise.

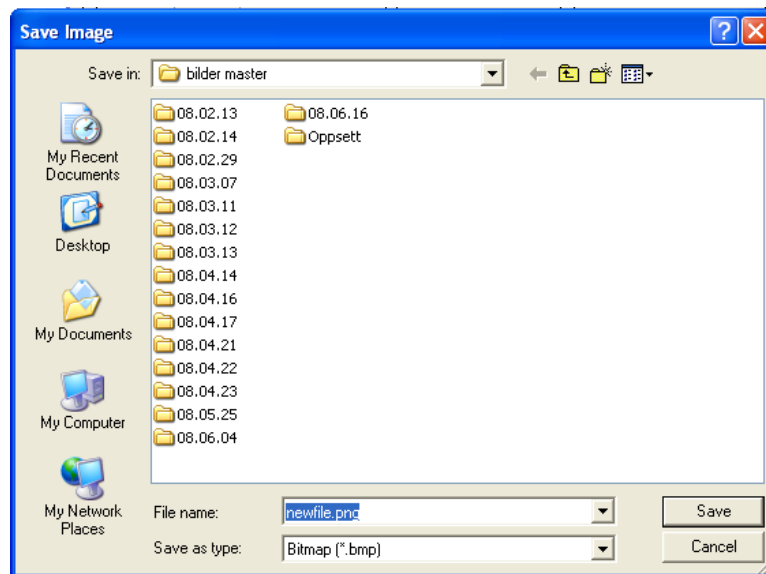
The first time the *Take Snapshot* button is used, the program will remind the user to produce an image for elimination of background noise, see Fig. 4.6. In the next window, see Fig. 4.7, you have to type *referanse* and hit the *OK* button, the rest will be taken care of by the modified program. When you press the *OK* you are allowed to save the image. You have to remember to take new background noise images if you make any changes to the setup. This is done by typing *referanse* in the same text field. It is important to notice that the script does not remove the background noise from subsequent images produced and saved. The noise is only used in the calculation of the speckle contrast, and has to be saved for use in later treatment of the results.

Other images can be saved by using *OK* button when the window in Fig.

4.7 appears. The name in the text field gives name to a variable that are exported to the *Workspace* in Matlab. This feature is not important, and can be used as wanted. You get to chose the location and the name of the image youreself in a new window, see Fig. 4.8.



**Figure 4.7:** Press the *OK* to save the image. To make the image the new reference, type *referanse* in the text field.



**Figure 4.8:** You choose the name and location of the image in this window. (Avoid the use of the period character in the file name.)

Calculating the speckle contrast requires a sufficient amount of statistical data. This is why it is important to use as much of the image sensor as possible. We also need to ensure that we are able to resolve the different speckle grains. This is done by letting a grain cover more than one pixel on the CCD sensor. A reasonable value is a minimum of five pixels per grain. The size of the speckle grains is dependent on the properties of the lens.



$F_L$	D [mm]
3.8	19.74
8	9.38
16	4.69
32	2.34
cl	0

**Table 4.1:** F number on the lens and it's corresponding aperture. The last setting, cl, is closed.

$F_L$	$F_N$	$\sigma_s$ [ $\mu m$ ]	$(\Delta z)_{1/2}$ [mm]
3.8	7.76	4.13	0.215
8	16.34	8.69	0.952
16	32.68	17.39	3.807
32	65.36	34.77	15. 227
cl	cl	-	-

**Table 4.2:** F number on the lens, new F number with extension rings, and expected speckle size.

#### 4.1.6 Speckle size in the setup

We can estimate the speckle size in our laboratory setup with some simple calculations. Because of the extension rings on the lens, we have to find a new F-number. The original focal length of the lens is 75 mm. We use Eq. (1.50) to find the diameter of the aperture for a given F-number setting on the lens, shown in table 4.1. Now that we have found the diameter, we can use the same equation to find the new F-number when we use the extension rings, 78.2 mm, giving us a new focal length of 153.2 mm. The new F-number can be used to calculate an expected speckle size. The transversal speckle size,  $\sigma_s$ , is calculated using Eq. (1.53), and the longitudinal speckle size,  $(\Delta z)_{1/2}$ , is calculated using Eq. (1.54). The result is given in table 4.2.

Given that the CCD sensor is 5.8 mm wide and the resolution in the same direction is 640 pixels, the size of one pixel width is 9.06  $\mu m$ . In the height a pixel is 10.21  $\mu m$ . The active area is smaller, 7.4  $\mu m \times 7.4 \mu m$ . The area of one speckle grain is  $(\frac{\sigma_s}{2})^2 \pi$ . To find how many pixels the speckle grain will cover we divide it's area with the area of one pixel, 9.06  $\mu m \times 10.21 \mu m = 92.50 mm^2$ . For aperture setting  $F = 16$  this gives 2.57 pixels, which is too few. The smallest aperture,  $F = 32$ , gives 10.24 pixels. This is the only aperture setting that will fulfill the demand for number of pixels per speckle grain.

A thorough study of the human eye in the future is necessary to compare the speckle size in the camera with it's size in the eye. This is important for the final speckle reduction device. In order to characterize the different

devices and compare their abilities, it is not crucial.

## 4.2 Matlab code

In this thesis, Matlab (The MathWorks, Natick, MA, USA) has been chosen to collect and process the results. As already mentioned, Lumenera offers a Matlab driver that enables control of their cameras. Matlab has many built-in functions, and is a very powerful tool. In our Matlab-scripts we have used some of these, e.g. functions to find the mean, standard deviation, the fast Fourier transform (FFT), and the inverse fast Fourier transform (IFFT). The help function in Matlab or their home page gives a thorough description of the functions.

### 4.2.1 Calculating the speckle contrast

The code used to calculate the speckle contrast is given in appendix B.1. The function *std2()* uses

$$s = \left( \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2 \right)^{\frac{1}{2}} \quad (4.1)$$

to calculate the standard deviation, where

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad , \quad (4.2)$$

and  $n$  is the number of elements. The function *mean2()* uses Eq. (4.2) to calculate the mean. To calculate the speckle contrast in an image, call the function by using *speckle\_contrast(I)* where  $I$  is a matrix containing the image.

### 4.2.2 Modification of the camera driver

The main script in the Matlab driver for the camera is the *LumeneraGUI.m* file. With a small modification of this file, it calculates the speckle contrast and lets you save an image when you use the snapshot function. This is done by replacing

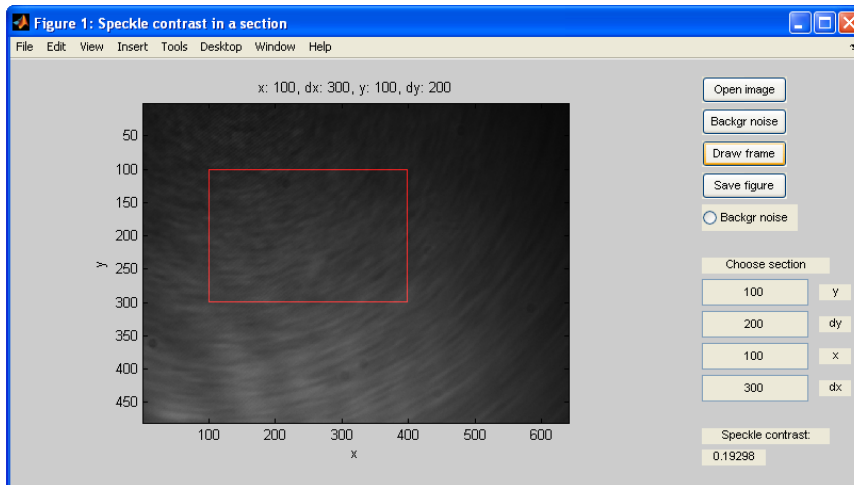
```
figure, image(thePicture);
pictureName = inputdlg({'Name of Image VMatrix:'}, ...
    'Image Name', 1, {'theImage'});
if(length(pictureName) ≠ 0) % check for cancel button
    assignin('base', pictureName{1}, thePicture);
end
```

starting on line 988, with this command:

```
snapshot_picture(thePicture);
```

The *snapshot\_picture()* function is described in appendix B.2. It calculates the speckle contrast, draws a figure, and saves the image and the figure. To save the image it uses the first save function shown in appendix B.3.

### 4.2.3 Speckle contrast in a section



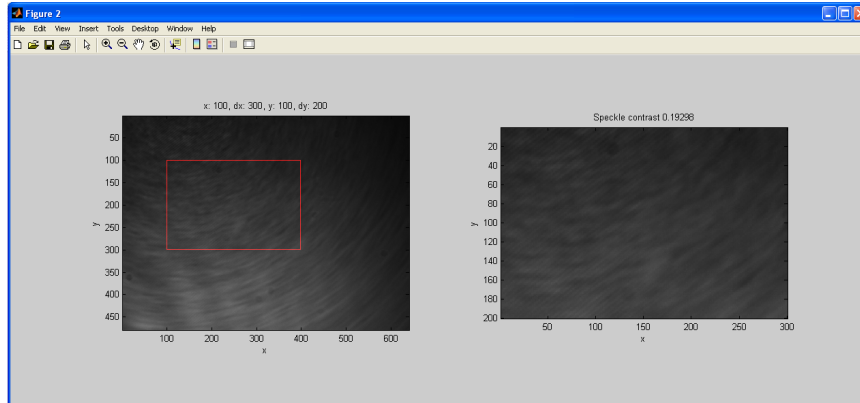
**Figure 4.9:** *behandleGUI.m* lets the user select an area, and it calculates the speckle contrast in this section.

In some of the speckle reduction techniques we use, the reduction of speckle contrast will vary across the image, e.g. rotation of poLight’s diffuser. In this situation it can be useful to select a section of the image to be used in the calculation of the speckle contrast. *behandleGUI.m* is a script, with a graphical user interface shown in Fig. 4.9, that lets the user select a section of the image and calculates the contrast in this section, see appendix B.4. In addition it has two features; load an image to remove the background noise and save the chosen section as an image together with the value of the speckle contrast as shown in Fig. 4.10.

### 4.2.4 Finding the autocorrelation and the PSD

Section 1.9 shows how the speckle size is related to the autocorrelation function and the PSD. By the use of the built-in fast Fourier transformation, the *fft2()*, the *speckle\_size.m* script calculates the PSD and estimates the speckle size, see appendix B.5. The *fft2()* function uses the *fft()* function in the two directions of an image matrix. The transformation is done by using

$$X(k) = \sum_{j=1}^N x(j) \omega_N^{(j-1)(k-1)} \quad , \quad (4.3)$$



**Figure 4.10:** *behandleGUI.m* lets the user save a figure containing information about the selected section.

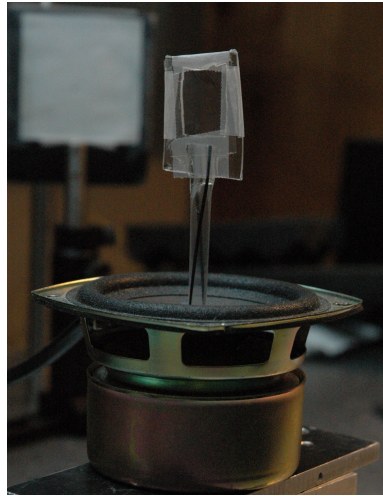
where  $\omega_N = e^{(-2\pi i)/N}$  is an  $N$ th root of unity.

Due to noise the calculated PSD function never reaches zero, and we have to estimate this point to find the speckle size. We expect the PSD to be nearly linear, and the first data points in a calculated PSD follows such a trend. A very simple regression is done based on these data points, which results in a linear line. The point where this line reaches zero is presented as the speckle size.

To present the autocorrelation function, we use another script, *auto-corr.m*, see appendix B.6. The function is obtained by using the *ifft2()* function of the PSD. In this case, the PSD has no imaginary parts, and there will be no difference between the *fft2()* and *ifft2()* functions. The autocorrelation function is divided by it's maximum value, in order to normalize it.

### 4.3 Speckle reduction devices

We have implemented three of the five methods for speckle reduction in section 3; vibrating diffuser, slowly moving diffuser, and the scattering tube from poLight. The vibrating diffuser techniques are mainly included in order to compare the laboratory setup from the specialisation project with the new setup. The SLM that were ordered to implement the Hadamard method, arrived very late due to a long delivery time, and there was not enough time left to include the work in this thesis. In our setup, where the F-number is approximately 65, the longitudinal speckle size is very large,  $(\Delta z)_{1/2} \approx 15$  mm. This advances a demand for a large displacement of the vibrating mirror, and we did not have an instrument that could do this.



**Figure 4.11:** The diaphragm provides the motion to the vibrating diffuser.

#### 4.3.1 Implementation of a vibrating diffuser

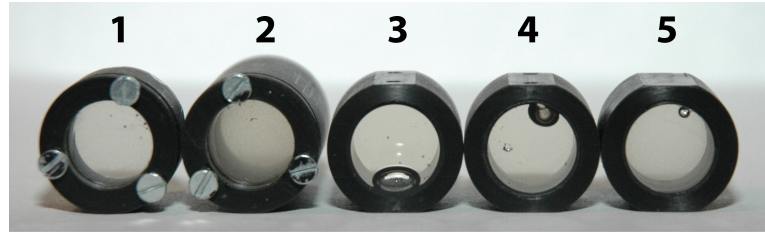
A simple device was constructed in the specialisation project to vibrate a diffuser. It consists of a bass loudspeaker from a pc stereo. The speaker element is removed from its box, which reduces the air resistance for the diaphragm and makes it easier to place it in the setup. A drinking straw with a quadrangular plastic frame is glued on top of the diaphragm, see Fig. 4.11. The opening of the frame is  $1.5\text{ cm} \times 1.9\text{ cm}$ . The plastic frame holds the diffuser. The original power amplifier is used to drive the loudspeaker, and the source is a function generator. The settings of the amplifier is left in one position through out the measurements. It is fed with a sine signal, and the vibration of the diffuser is controlled by the signal's frequency and amplitude. The displacement is dependent on both the amplitude and the frequency of the signal. The deflection increase with the amplitude, but it decrease with increasing frequency. It is quite difficult to measure the displacement of the diaphragm. The comparison of different diffuser is done on the basis of the signal from the function generator. The signal is monitored by the use of a oscilloscope.

A metal frame is used to implement the second diffuser. The opening of this frame is  $5.7\text{ cm} \times 5.7\text{ cm}$ . It is placed after the the vibrating diffuser, because of its larger opening. The first diffuser will disperse the laser beam in such a way that the second diffuser demands a larger aperture. The two diffusers are placed as close as possible to each other, in order to minimize the blurring [15].

Two different household products, a clear thin plastic bag designed for bread and the Scotch Magic adhesive tape, are used as diffusers. The plastic bag was also used in the specialisation project. This will make it possible to

compare the two setups. The Scotch Magic has been used in previous setups as a diffuser, e.g. in holography [24] and in speckle reduction [25]. We have also used a ground glass as a diffuser, Edmund Optics, Barrington, NJ, USA, part number 43725, but we did not try to vibrate it because of its weight.

### 4.3.2 Implementation of the scattering tube



**Figure 4.12:** The scattering tubes.

poLight has made five samples of the scattering tube, see Fig. 4.12 and Tab. 4.3. They first made tubes three through five. The difference in the length of the shortest and longest of these three tubes is 2 mm, and thus the degree of scattering is mainly dependent on the concentration of micro pearls. The concentration was decided by mixing solutions with varying concentrations. A subjective evaluation of the scattering abilities of the solutions were done by regarding the scattering of a laser beam. It was concluded that all the solutions had too high concentrations of micro pearls. The solution with the lowest concentration was chosen and moulded in tube number five. Then the solution was thinned out in two new solutions by two different factors, and moulded in tube three and four. In proportion to the concentration of tube number three, the concentrations are 1:7:17, as shown in Tab. 4.4.

#	Length	Conc.	Adj.	Defects
1	10 mm	A	Yes	Broken glass first surface
2	20 mm	A	Yes	No
3	15 mm	B	No	One big and two small air bubbles
4	14 mm	C	No	Big air bubble, air pocket close to the glass
5	13 mm	D	No	Small air bubbles

**Table 4.3:** There are five tubes from poLight. Each one as a concentration (Conc.) as shown in Tab. 4.4. Two of them can adjust (Adj.) the surface glass at one side.

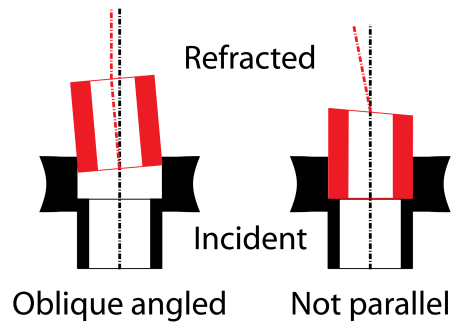
There is a problem with the tubes. When the laser beam passes through one of them, the laser beam exits with an angle, see Fig 4.13. An unexpanded laser beam drew a circle on a screen when the tube was rotated. The circle's diameter increased with the distance from the tube, which confirms the angle.

If the end glasses of the tube are parallel and tube is mounted oblique angled in the holder, the use of Snell's law of diffraction shows that it only leads to a displacement of the refracted beam parallel to the incident beam. This means that this is not the problem. On the other hand, if the end glasses are not parallel, the angle between the glasses will lead to an angle of the refracted beam which is different from the incident, see Fig. 4.13. The producing of these samples did not a sufficient accuracy to deal with this problem, since the glasses only has to be off with a very small angle. If they are off with one degree, they will draw a circle with a diameter of approximately 3.5 mm at a screen 50 cm from the tube.

Concentration	B	C	D
Ratio	1	7	17

**Table 4.4:** Concentration in tube three through five.

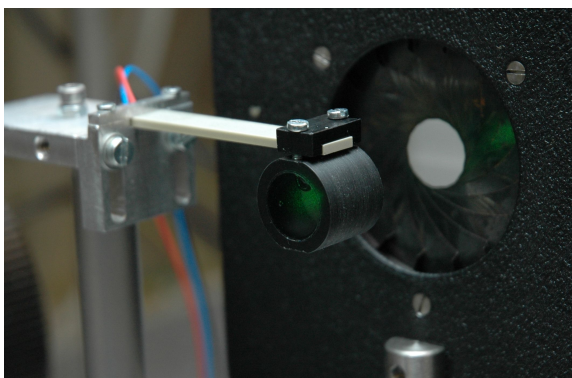
poLight came up with an idea to a solution to the problem of the unparallel end glasses. It was a ring, pressing on the edge of one of the end glasses. By overfilling the tube with gel, the gel acts as a spring for the glass. Three screws holds the ring in place. The screws can be used to adjust the glass. They have made two such tubes, tube number one and two, see Fig. 4.12 and Tab. 4.3. The two new scattering tubes have the same concentration of micro pearls. The length of tube number two is twice the length of tube number one. This leads to a higher scattering in tube two, and probably a smaller correlation length.



**Figure 4.13:** The angle problem with the scattering tubes.

The scattering tubes are used as a reduction device in two manners. The first is vibration by a piezo plate bender as shown in Fig. 4.14, see appendix D.6. The same signal generator that we used with the vibrating diffuser is used with this device as well. The signal is put through a voltage amplifier, A800 (FLC Electronics, Partille, Sweden), see appendix D.7. The plate bender is wired in such a way that it can handle voltages from 0 V to 200 V.

The voltage amplifier has a fixed gain of  $100\times$ , and can handle  $\pm 400$  V. This means that the signal from the signal generator has to be between 0 V and 2 V. This is done by choosing a signal with a 1 V bias and a peak to peak amplitude  $< 2$  V. The displacement is still difficult to measure. It is also dependent on both the voltage amplitude and the frequency, but in this case the deflection increases with both voltage amplitude and frequency. As we get closer to the resonance frequency the displacement increases.

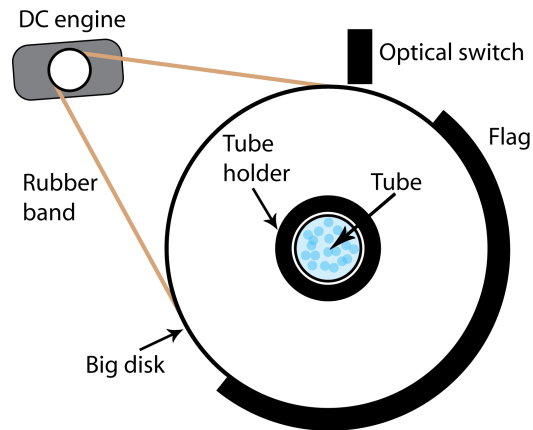


**Figure 4.14:** The piezo plate bender, vibrates the scattering tube.

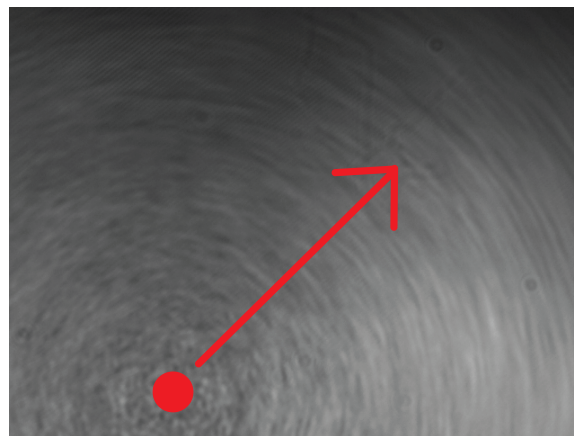
The expanded laser beam has nearly the same diameter as the scattering tubes, and a part of the beam is likely to be able to pass on the outside of the tube when the tube is vibrated. To stop this light from affecting the results, a variable aperture is placed behind the vibrating tube. The FOV of the camera will always be inside of the tube, because the FOV is so small, unless you choose to image a section in either the top or bottom of the tube's opening.

The second manner is rotation, as shown in Fig. 4.15. The scattering tube is placed in a holder which is rotated by a DC engine. The big disk acts as a gear and it also stops any parts of the laser light from passing on the outside of the tube. By measuring the time between each time the flag interrupts the optical switch, it is possible to calculate the number of revolutions per minute (RPM). In the laboratory setup a labView program calculates this value. It measures the time between two interruptions of the optical switch, calculates the RPM, and displays the average of fifteen measurements. This measurement does not have a high precision, but it gives a quite good indication of the RPM. To complete at least one rotation during the integration time of the camera, the tube should rotate with more than 1200 RPM. In most cases it is useful to place the center of rotation in one of the corners of the FOV. Then it will be possible to measure the speckle reduction as a function of distance from the center of rotation, shown in Fig. 4.16.





**Figure 4.15:** Rotation of the scattering tube, done with a DC engine. It also has a system to measure RPM.



**Figure 4.16:** The center of rotation is marked with the red dot. The arrow indicates increasing rotary circumference.



# Chapter 5

## Results

While performing the measurements, we found that the speckle contrast varies with the intensity, see Fig 5.1. A brighter image gives a lower speckle contrast. When the level of intensity is sufficiently high, small variations in the intensity give small variation in the calculated speckle contrast. The intensity is affected by the transmittance of the diffuser and the extent of vibration. To overcome this problem we recorded multiple images with small variations in the intensities. In the following sections, we present the average of the contrast in these multiple images.

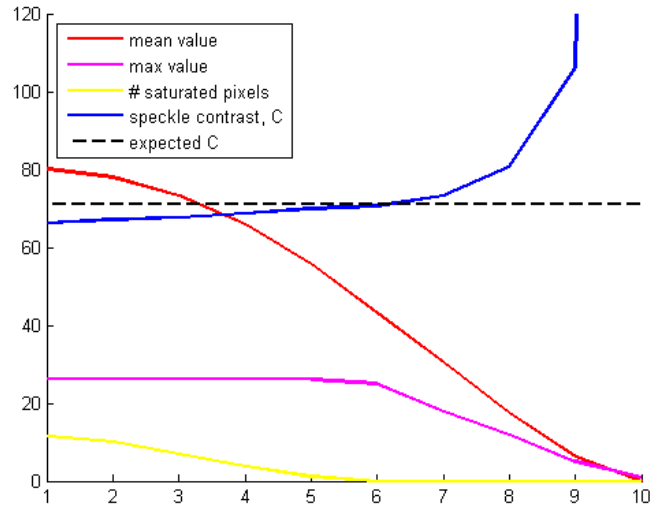
When the intensity passes a lower limit, the calculated speckle contrast increases rapidly, and surpasses the upper limit for a physical value of speckle contrast,  $C = 1.0$ . An image with a too low intensity, will result in a too high calculated speckle contrast. This illustrates the importance of utilizing the dynamic range of the CCD sensor.

The camera produces black and white images. If an image is presented in colours, then the colours are only used to emphasize the speckle pattern. A dark red colour represents the highest intensity, and deep blue colour the lowest intensity. The colourbar is included in appendix C.1.

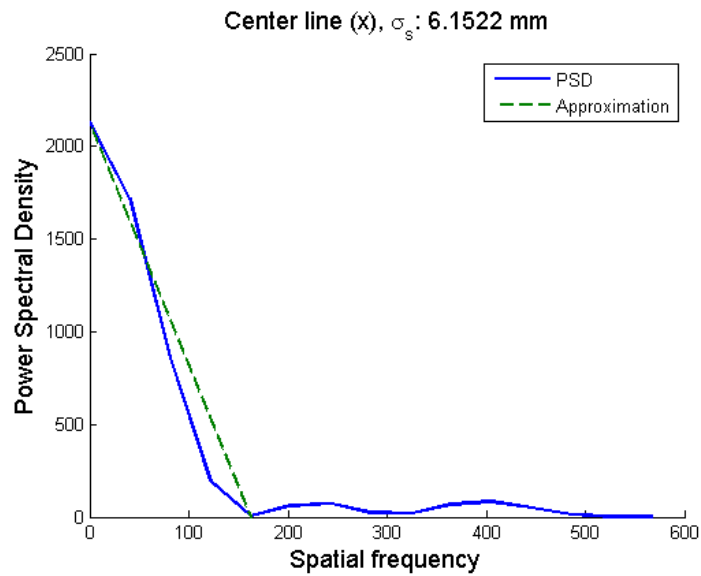
### 5.1 Speckle size

The *speckle\_size.m* script is used to estimate the speckle size in the setup. A part of the power spectral density and the estimation of the smallest speckle size in the horizontal direction,  $\sigma_s$ , is shown in Fig. 5.2. The estimated speckle size is  $\sigma_s = 6.15$  mm. In the vertical direction the speckle size is estimated to  $\sigma_s = 4.54$  mm, see Fig. 5.3. The average of these two is  $\sigma_s = 5.35$  mm.

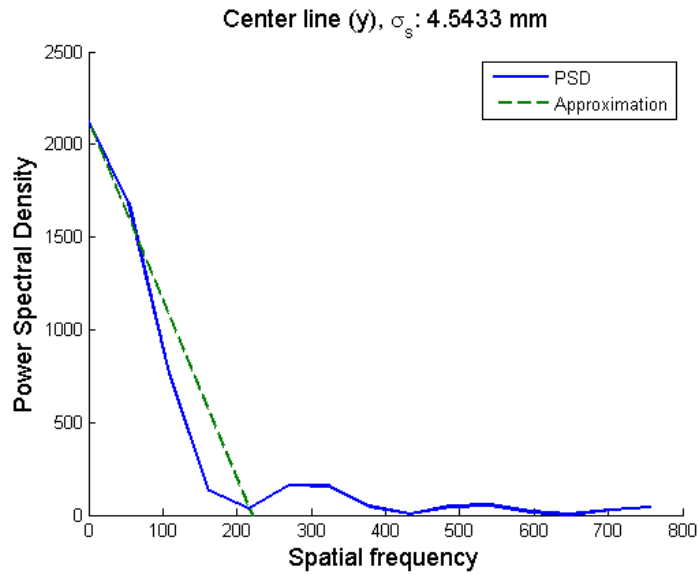
The autocorrelation function is calculated with the *autocorr.m* script. A two dimensional plot is shown in Fig. 5.4. From the profile of this plot, shown in Fig. 5.5 and Fig. 5.6, it is possible to recognize the shape of a  $\text{sinc}^2$ , but there is something wrong with the scaling. The height of the  $\text{sinc}^2$  should be unity, and the offset should be one as well, see Eq.(1.61).



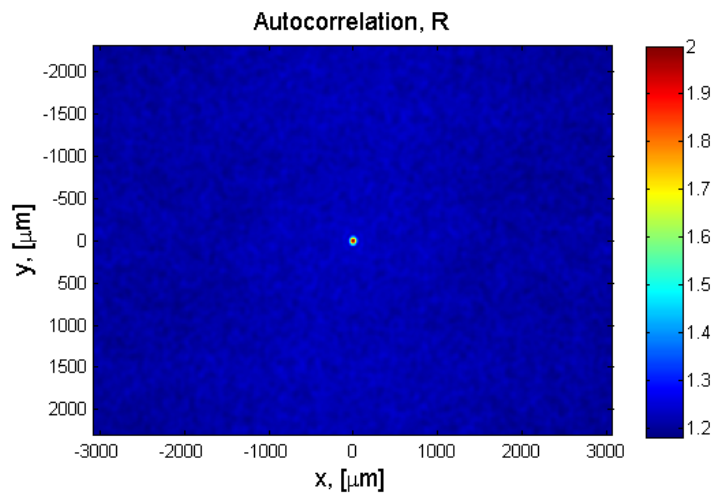
**Figure 5.1:** This plot shows how the speckle contrast is related to the intensity. There are small variations when the intensity is high. When the intensity passes a lower limit, the speckle contrast increases rapidly, exceeding its upper limit of  $C = 1.0$  by far. The speckle contrast is scaled with a factor of 100, and the maximum value by a factor of 1/10. The expected speckle contrast,  $C = 0.71$ , is valid in the case of a depolarized speckle pattern.



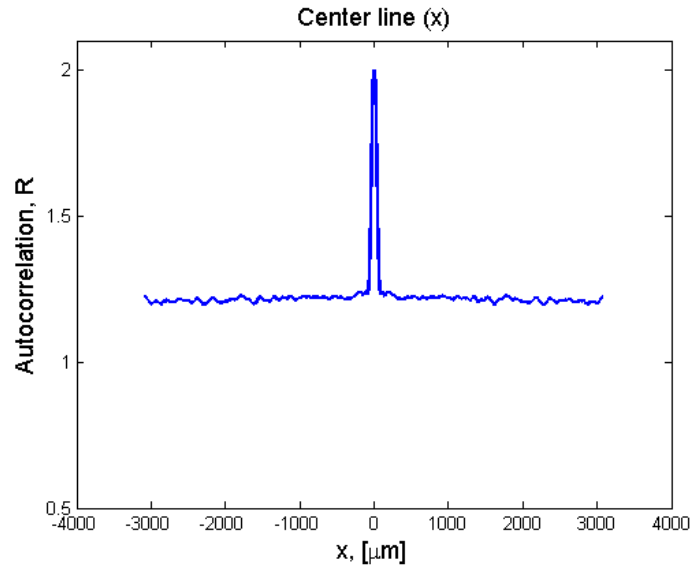
**Figure 5.2:** The PSD function used to estimate the speckle size in the horizontal direction.



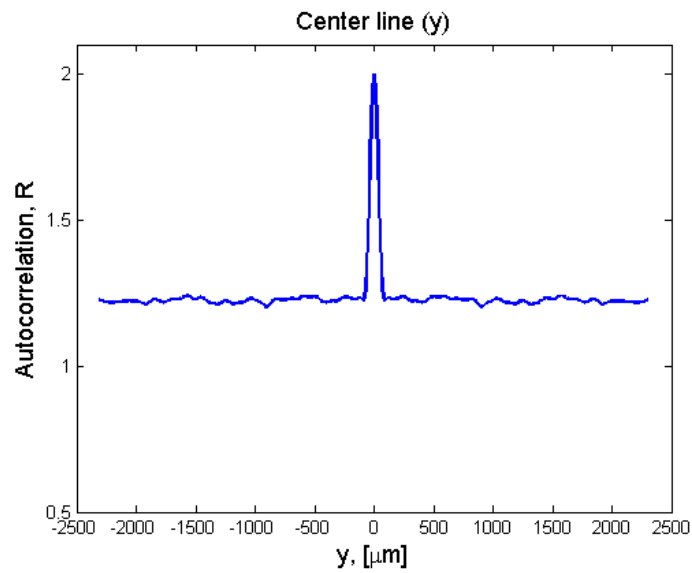
**Figure 5.3:** The PSD function used to estimate the speckle size in the vertical direction.



**Figure 5.4:** The two dimensional autocorrelation function of a speckle pattern in the setup.



**Figure 5.5:** The profile of the two dimensional autocorrelation function along the x axis.

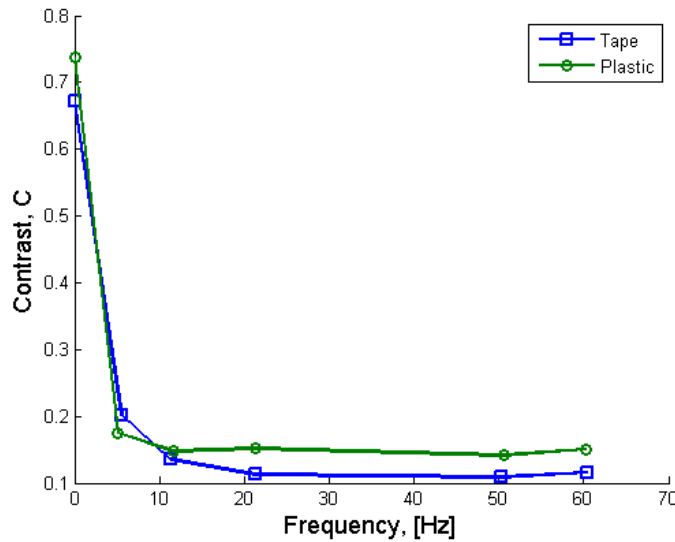


**Figure 5.6:** The profile of the two dimensional autocorrelation function along the y axis.

## 5.2 The diffusers

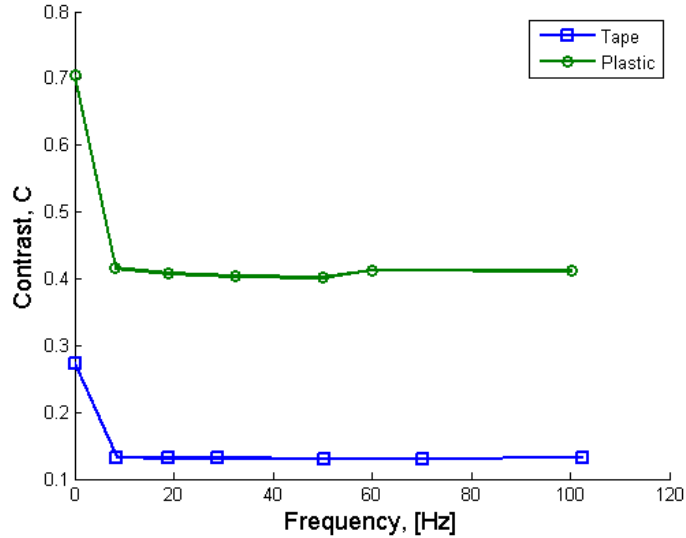
The transmittance of the tape and the ground glass are dissimilar from the plastic cut from the plastic bag. The plastic is transparent, while the tape and glass are opaque. While the diffusers are stationary, they all create speckle patterns. The speckle contrast for the plastic is  $C = 0.801$ , for the tape  $C = 0.744$ , and for the glass  $C = 0.701$ . A polarizer was placed between the diffuser and the lens. The analysis of the polarization of the transmitted light shows that there are little difference in the speckle patterns for either of the diffusers, see appendix C.2. When the polarizers are crossed the glass and the tape almost stops the light, while for the plastic there are transmitted light for all angles of the polarizer. This is the result of a depolarization in the plastic film.

### 5.2.1 One diffuser



**Figure 5.7:** Vibrating diffuser. The pk-pk voltage amplitude is 1.33 V.

In turn, the diffusers are attached to the frame on the speaker element. The measured speckle contrast is plotted with respect to the frequency, shown in Fig. 5.7. The pk-pk voltage amplitude was 1.33 V. The speckle contrast for the plastic stabilizes at  $C \approx 0.145$ , and the tape stabilizes at a lower level,  $C \approx 0.112$ .



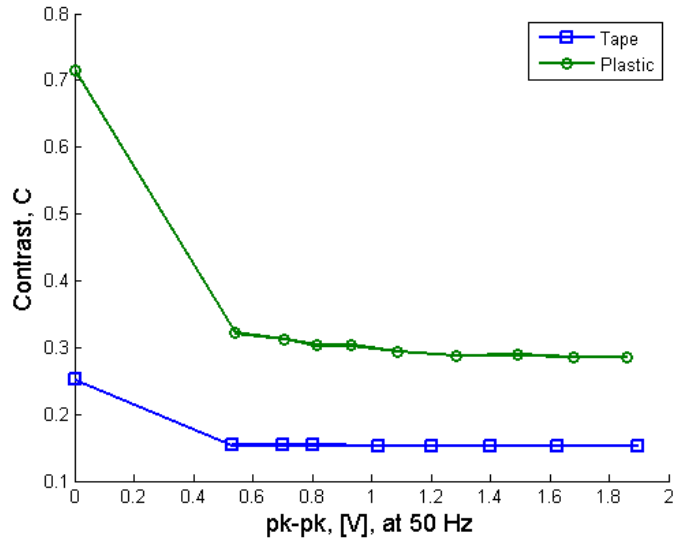
**Figure 5.8:** Two diffusers, plotted against frequency. The pk-pk voltage amplitude is 1.33 V.

### 5.2.2 Two diffusers

The metal frame is used to insert a second diffuser after the vibrating diffuser. The new motionless diffuser is of the same type as the vibrating. The distance between the two is approximately 3 mm. The drinking straw glued to the diaphragm is not perfectly vertical, which inhibits the possibility of placing the two diffusers closer to each other. We have plotted the speckle contrast against both the voltage amplitude and the frequency. The result with respect to the frequency is shown in Fig. 5.8. The voltage pk-pk amplitude from the signal generator is 1.33 V. With a constant frequency, set to 50.0 Hz, the results for varying voltage amplitude is shown in Fig. 5.9.

The vibrating diffuser in series with a motionless diffuser shows the same tendency as in the case with one vibrating diffuser. The tape reduces the speckle contrast more than the plastic. The tape has a low starting point,  $C \approx 0.263$ , and stabilizing at  $C \approx 0.131$  in the frequency- and  $C \approx 0.152$  in the voltage measuring series. In Fig. 5.10, we compare two images of the tape diffuser in motion. In the one diffuser image the mean intensity is 139, and in the two diffusers image the mean intensity is 84. In the latter image the polarizers were parallel, and transmitted the maximum amount of light. The plastic diffuser's starting point is approximately the same as when there is only one diffuser, and it stabilizes at  $C \approx 0.407$  and  $C \approx 0.287$ . This difference can probably be explained by looking at the images in Fig. 5.11 and 5.12. In the image from the voltage measuring series, it seems like there is two speckle patterns superimposed. This is most likely caused by



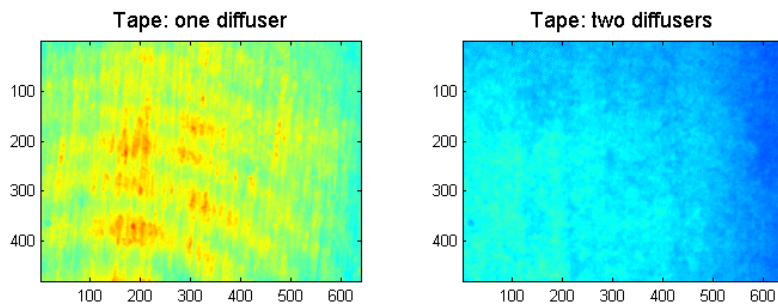


**Figure 5.9:** Two diffusers, plotted against pk-pk voltage amplitude. The frequency is 50 Hz.

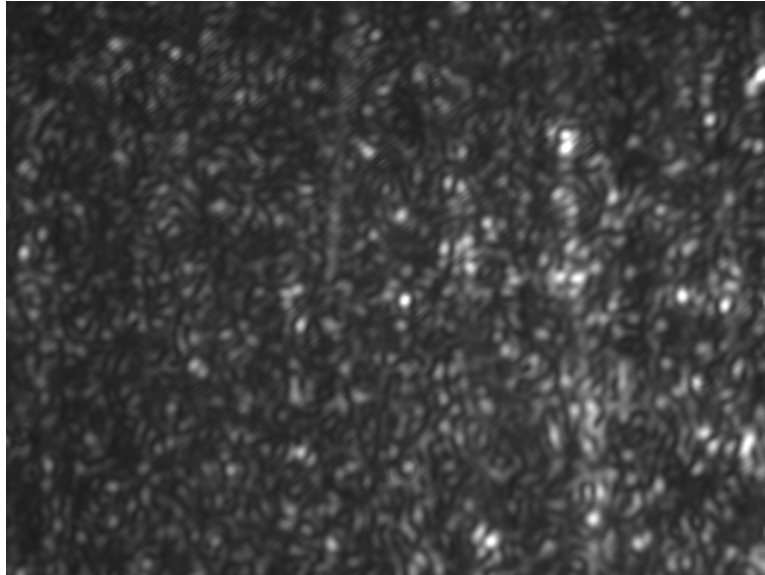
the vibrating diffuser being in contact with the second diffuser, making it vibrate as well. This additional movement take part in a further reduction of the speckle contrast.

### 5.3 The scattering tubes

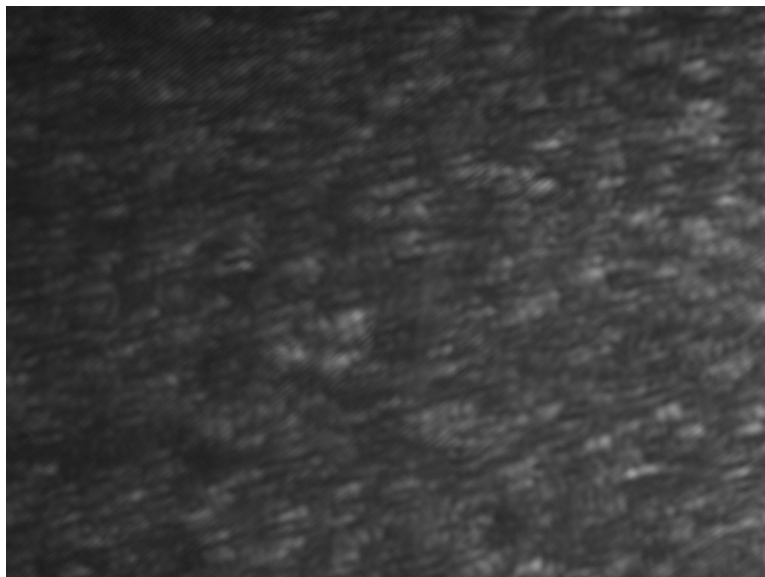
All the tubes, except tube number two, has a defect. When we choose the FOV, we have to take this in to consideration. Air bubbles reflects and scatters the beam. The result is a dark spot in the cross-section of the laser



**Figure 5.10:** There is a difference in the amount of light that reaches the CCD sensor in the camera. Two tape diffusers in series generates heavy scattering.



**Figure 5.11:** Vibrating plastic diffuser, from when measuring speckle contrast with respect to frequency. The frequency is 50.1 Hz and the pk-pk voltage amplitude is 1.33 V.



**Figure 5.12:** Vibrating plastic diffuser, from when measuring the speckle contrast with respect to pk-pk voltage amplitude. The frequency is 50.0 Hz, and the pk-pk voltage amplitude is 1.49 V.

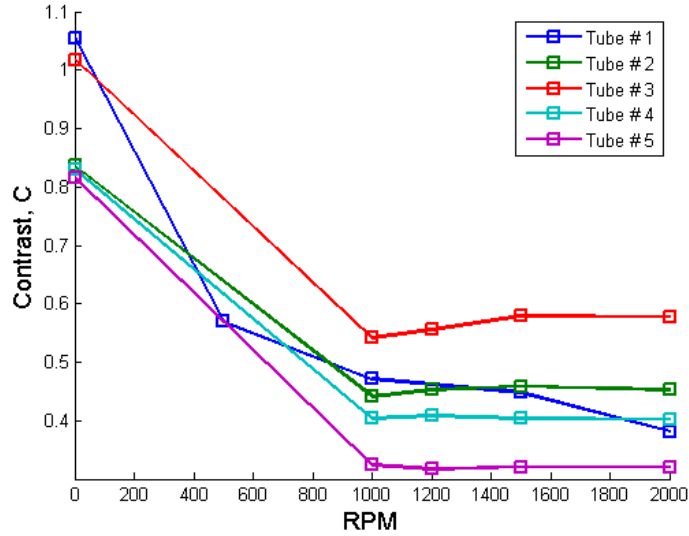
beam. It is mainly a problem when the tubes are stationary or vibrated. The vibration displacement is not larger than the air bubbles, but since the bubbles are situated at the edge of the tubes, the rotary circumference leads to a large displacement of the bubbles when rotated. At high rotary speeds the shadows are not visible in the image because of the integration, but they will still have an effect on the result. The FOV is chosen where there is no defects, if possible. The FOV should be a distance from the edge, in order to minimize diffraction effects disturbing the image. At times, it was difficult to obtain an even intensity distribution in the speckle patterns. This was possible to deal with by adjusting the angle of the beam expander. With tube number three, lowest concentration, this was especially a problem.

An analysis of the polarization of the laser beam after the tubes is found in appendix C.2. The polarizer between the tube and the lens, completely stops the light when it is crossed with the first polarizer, i.e. at 90 degrees. The speckle pattern does not change when we rotate the polarization analyser either. This indicates that there is not any depolarization in the scattering tubes.

### 5.3.1 Rotation of the tubes

The speckle contrast is plotted in respect to the RPM in Fig. 5.13. The results for tube number one deviates from the rest. This is probably because of the broken end glass. The crack in the glass creates a hot spot in the image, and saturates the pixels it covers. The results for the other tubes, has a common tendency. Tube number three has a much higher starting point than the rest, probably because of difficulties in obtaining an even speckle pattern. The speckle contrast, when the tube is rotated, stabilizes at  $C \approx 0.578$ . Tubes number two, four, and five stabilizes at  $C \approx 0.455$ ,  $C \approx 0.401$ , and  $C \approx 0.320$ , respectively.

The measurement is repeated with the ground glass as a diffuser between the rotating tube and the lens. The ground glass is mounted on the rear of the rotary device. It creates an even speckle pattern whether the tubes are rotated or not. This makes it difficult to determine where the FOV is in proportion to the rotary center. Tube number one was left out from this measurement, because of it's broken glass. The starting points are more equal for all the tubes, due to the added diffuser. Tubes number three and four has almost the same speckle contrast at 2000 RPM,  $C \approx 0.375$ . The same happens for the two other tubes, tubes two and five. They have a speckle contrast of  $C \approx 0.283$  at 2000 RPM. The speckle contrast for tubes three, four, and five, does not stabilize as in the other measurements. One possible explanation is that the tube and the device holding the tube starts to vibrate at high speeds. The images taken at 2000 RPM show the same effect as in Fig. 5.12, where there seems to be two speckle patterns superimposed. This effect is seen for tube number two as well, but the speckle contrast does



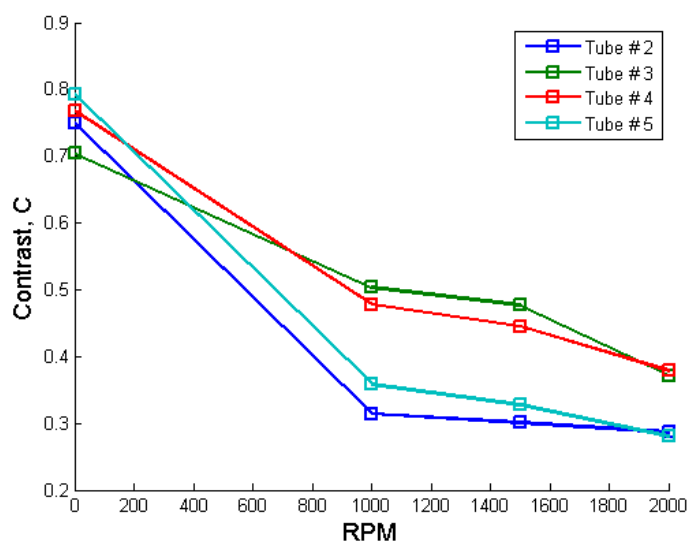
**Figure 5.13:** Rotation of the tubes. The contrast is calculated on the basis of the whole image, and the center of rotation was a part of the FOV, i.e. the speckle contrasts in the plot is an average.

not decrease in the same manner as for the others.

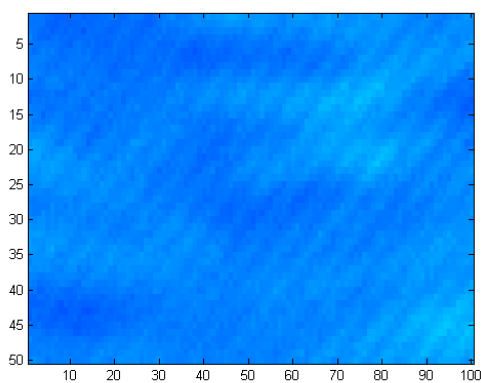
To illustrate the increased speckle reduction as we move away from the rotary center, we have chosen sections along two lines in two images as shown in Fig. 5.16. The images are of tube number two, rotating at 2000 RPM. The difference is the intensity. The speckle contrast in each section is plotted against the y pixel coordinate shown in Fig. 5.17. The size of a section is  $100 \times 50$  pixels. The speckle contrast is reduced with the distance from the rotary center. At vertical pixel number 350, we have an increase in the speckle contrast. If we look at one of the sections, see Fig. 5.15, we can see a stripe pattern hidden in the image. The stripe pattern does not change direction when the tube is rotated, and must be caused by the measuring setup. It may arise from a diffraction effect from the variable aperture in the lens. When the speckle contrast is calculated from a section, the result is generally lower. This is also the case if we choose an image where the speckle reduction is equal in the whole image. This illustrates the problem of capturing images with a uniform intensity distribution. The effect of lower calculated speckle contrast, has to be taken in consideration if we want to compare these results with others.

### 5.3.2 Vibration of the tubes

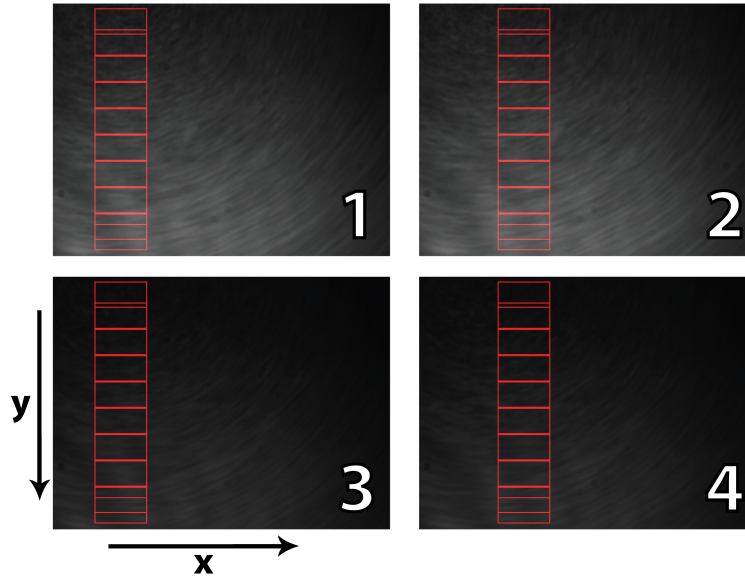
It is only the three oldest tubes, tubes three through five, which have female threads, and can be mounted on the piezo plate bender. The aperture,



**Figure 5.14:** Rotation of the tubes in series with a stationary diffuser. The ground glass is the diffuser.



**Figure 5.15:** The section from vertical pixel number 350 in series number 1. It shows a diagonal stripe pattern in the image.



**Figure 5.16:** Sections chosen for the measuring series. Series one and two is the same image, and series three and four is the same. Both images are of tube number two rotating with 2000 RPM, the difference is the intensity, and the sections are  $(dx, dy) = (100, 50)$  pixels.

to prevent any stray light, is placed as close as possible to the vibrating tube, approximately 5 mm. The diameter of the opening is 12.2 mm. The signal from the signal generator is a sine, with 1 V offset and 1.77 V pk-pk amplitude. An example is shown in Fig. 5.18, where tube number five is vibrated at 80 Hz. From this image we can see that the displacement is small, and it spends more time at the end points during the exposure. The speckle contrast is measured with respect to frequency, shown in Fig. 5.19. The speckle contrast for tube number three at 0 Hz, is out of it's range. The speckle contrast decreases slightly after 50 Hz for all the tubes. At 100 Hz the speckle contrasts are  $C \approx 0.715$ ,  $C \approx 0.525$ , and  $C \approx 0.389$  for tubes three, four, and five, respectively.

The ground glass is used one more time in series with the tubes. The glass is mounted on the aperture. The speckle contrast is only measured for 0 Hz and 50 Hz, and the results are shown in Fig. 5.20. With the diffuser, the speckle contrast is within the range for all the tubes at 0 Hz. At 50 Hz the speckle contrast is  $C \approx 0.613$  for tube three,  $C \approx 0.529$  for tube four, and  $C \approx 0.284$  for tube five.

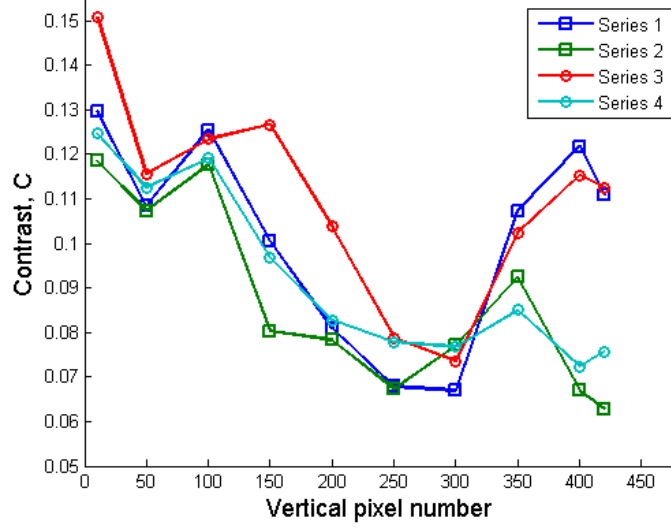


Figure 5.17: Speckle contrast in sections at increasing distance from the rotary center.

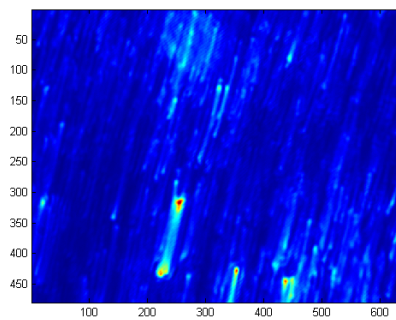


Figure 5.18: Tube number five, vibrated with 80 Hz.

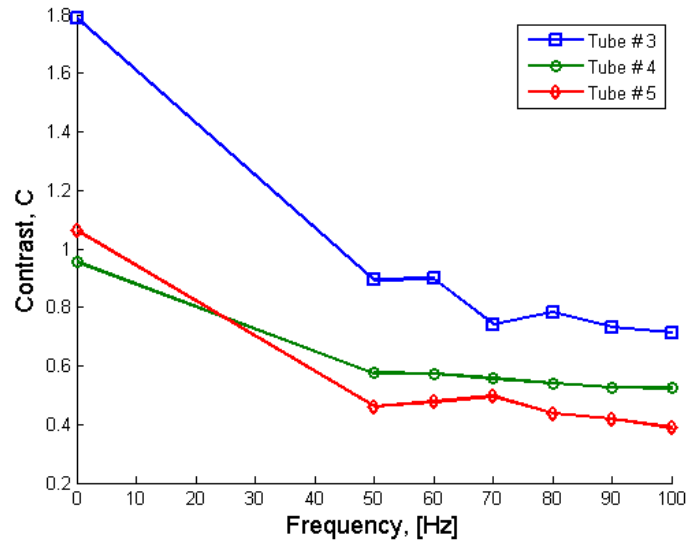


Figure 5.19: Vibration of the tubes.

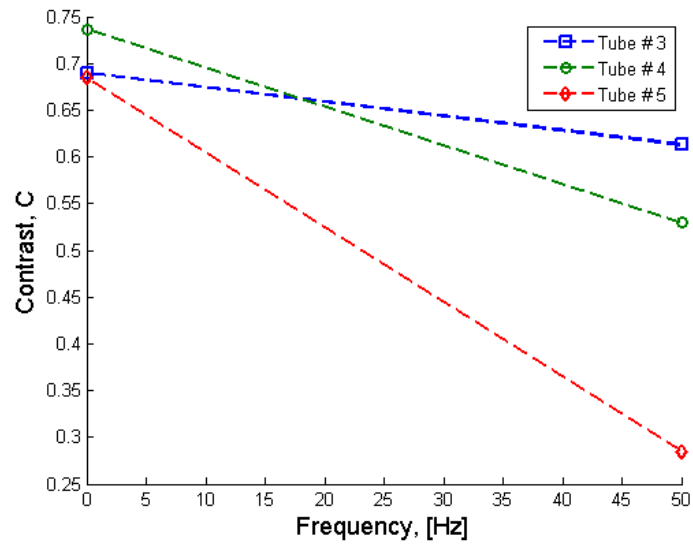


Figure 5.20: Vibration of the tubes in series with a screen. The ground glass is the screen.



## Chapter 6

# Discussion

The speckle reduction methods presented in this thesis are all based on some kind of motion, except for the Hadamard matrices. The speckle in a laser displays arise due to the screen being rough, and thus the screen acts as a second diffuser. This means that we in general have the situation mentioned in the section of the slowly moving diffuser, only in this case the distance between the two diffusers is much larger. It should be safe to assume that the speckle reduction, due to one vibrating diffuser in relation with the screen, is to a certain degree dependent on the correlation length of the diffuser. And not only the number of resolution widths on the object that the diffuser is moved. In order to reach a sufficiently low speckle contrast, we are dependent on either a strong diffuser or a large motion. A strong diffuser is most likely to have a short correlation length, but at the same time it will destroy the qualities of the laser beam. It is also important to take into consideration that the housing of a laser projector should not be too large nor the projector make too much noise. The size of the projector housing restricts the size of the diffuser and it's motion, and in addition the vibration is a source to noise. The rotary movement of the scattering tube has an advantage. It does not have to suddenly change direction, and if the device is properly balanced there will be a minimum of vibration that may produce noise.

The best solution would be to use a stationary device. It would eliminate the problems with the motion, and in addition make the alignment of the projector's optical components easier. The Hadamard matrices can be implemented in a stationary setup. The challenge with this method is to find or create a device that can switch trough enough matrices during the integration time of the eye. The LCD based SLM technology are in general to slow, but can be used to test the Hadamard method in the laboratory.

The modification of the laboratory setup seems to work better than the previous version. The removal of the screen was a good choice. The results are possible to reproduce, and they are in agreement with what we expected. The modified version of the Matlab driver, makes it easier to perform mea-

surements. However, there are still some difficulties with the setup. With weak diffusers, it is difficult to obtain uniform speckle patterns. It can be dealt with by adjusting the angle of the beam expander. In other words, the alignment of the setup should be improved, e.g. there exists equipment which enables us to mount the laser directly to the beam expander. The aperture of the polarizers are large enough to transmit the expanded laser beam. There is also the problem with the stripes appearing in the images. It is most likely an effect in the lens, but the problem has not been properly described yet.

The speckle size we expected was  $\sigma_s = 37.77 \mu\text{m}$ , see Tab. 4.2. From an image of a speckle pattern in the setup, we calculated the size to be  $\sigma_s = 5.35 \text{ mm}$ , which is approximately 140 times larger than the expected. When we calculated the expected size, we did not take into account that we have a small magnification. Another source of error is the script used to find the PSD of the speckle pattern. The Nyquist-Shannon sampling theorem is fulfilled, given that the actual speckle size is in the order of the expected size. But to obtain a smooth PSD function, the fast Fourier transformation needs a high number of points. This is done by expanding the image matrix with elements containing the value zero. The edge of the image matrix will then have an unwanted effect. These are some possible explanations, but a more thorough study is needed.

Another result that is difficult to explain is the polarization analysis. The analysis only shows a depolarization for the plastic diffuser. This should mean that the speckle patterns produced by the other diffusers, including the scattering tubes, are fully developed. In a fully developed speckle pattern, the speckle contrast ought to be  $C = 1.0$ . When the ground glass and the tape are stationary, the speckle contrasts are closer to  $C \approx 0.75$ , which should mean that we have a depolarization of the laser beam. The same goes for the scattering tubes, where the contrasts are  $C \approx 0.8$ . It seems like the problem is with the polarization analysis. Based on the measured speckle contrasts there should be depolarization in the tape and the glass, and partially depolarization in the tubes.

The tape is a stronger diffuser than the plastic, and the results confirms this. It becomes especially clear in the two diffuser setup. The tape has a larger scattering angle, and because of the relative large distance between the two- diffusers, the contrast is reduced by blurring without any motion. The plastic diffuser has nearly the same speckle contrast, whether there are one or two diffusers. The measured speckle contrast is found to be higher in the case of two tape diffusers compared to one tape diffuser, when they are vibrated. If we compare the images from the two situations, we can see that the intensity is much lower when there is two diffusers. The laser beam experience heavy scattering by the two diffusers in series. The amount of light that reaches the CCD sensor is not able to exploit it's dynamic range, and the calculated speckle contrast becomes higher.

In the specialisation project, where we used the setup with the screen, the plastic diffuser reduced the speckle contrast from  $C \approx 1.0$  to  $C = 0.631$  with one vibrating diffuser. In series with a motionless diffuser, the speckle contrast was reduced to  $C = 0.676$ . In the project we had problems with the structure in the plastic. It created hot spots in the images. The hot spots in combination with the unknown effects of the screen, lead to strange results. The results varied from measurement to measurement, and were difficult to reproduce.

The scattering tubes, designed by poLight, are in reality special diffusers. The difference is in how they scatter and transmit the light. The results follow the same trends as the diffusers. The most powerful scatterer reduces the speckle contrast the most. A direct comparison between the results of the diffusers and the scattering tubes is difficult, since the speckle contrast varies across the image taken while rotating the tubes. The tape reduces the speckle contrast to a lower level than tube number five, with the highest concentration of micro pearls. On the other hand the quality of the laser beam is better preserved in the scattering tube.

The results we have obtained are in good agreement with the theory. Without a proper way to measure the displacement of the diffusers or the tubes, it is difficult to do any exact calculations based on the results. We have also verified the new setup as more stable than the previous, but it has some problems of its own.



## Chapter 7

# Conclusions

In order to develop a speckle reduction device to be used in a laser display, it is important to have a basic understanding of both laser projectors and laser theory. We have made a study of the most fundamental speckle theory. The theory explains why speckle arises and how it behaves. It is important to know which parameters to manipulate, when trying to reduce the speckle contrast. This knowledge was obtained through a study of research done in the field of laser speckle. We have concentrated on methods for speckle reduction in laser displays.

We have concentrated on five methods; vibrating diffuser, slowly moving diffuser, Hadamard matrices, scattering tube, and vibrating mirror. The aim is to find a speckle reduction device that does not destroy the quality of the laser beam. This is not so important if we use the screen itself to reduce the speckle. This is possible in rear projection displays, where we have reasonable small screens that can be vibrated. The screen is supposed to scatter the light to obtain a large viewing angle. In displays with large screens, this is not a feasible solution. When the speckle reduction device is placed in front of the imaging optics the quality of the laser beam becomes prominent. If the laser beam diverges, the projected image may become diffuse. Thus diffusers with large scattering angles are not a good choice. The diffuser should be able to introduce a random phase delay in the cross-section of the laser beam without too much scattering. In theory, the Hadamard matrices and the scattering tube looks promising.

The Hadamard matrix is the only of the five presented methods that does not require a motion, e.g. vibration or rotation. This gives it an advantage with a view to the alignment of the laser projector's optics and to noise. The theory and experiments with the vibrating diffusers give an important understanding of how we can reduce the spatial coherence to reduce the speckle. And together with the scattering tube, they have been tested in a practical setup. A SLM was ordered to implement the method of Hadamard matrices, but it arrived too late due to a long time of delivery. The vibrating

mirror was not tested either. This method required a very large displacement of the mirror, and we did not have the equipment to implement this.

There was made a change in the laboratory setup, compared to the one used in the specialisation project. The screen was removed, and the the speckle is imaged directly from the speckle reduction device. The modified laboratory setup is much more stable, and the results are possible to reproduce. The setup has some problems that need to be resolved.

A subjective speckle size was estimated. It was compared to a calculated speckle size based on a speckle image from the setup. In the calculations we used the power spectral density to find the speckle size. The calculated speckle size based on the PSD was 140 times larger than the estimated. The inverse Fourier transform of the PSD gave us the autocorrelation function. The autocorrelation function found from an image was compared to the theory. The shape of the function was close to what we expected, but it deviated with respect to the offset and amplitude.

The vibrating diffusers were implemented with a frame mounted to the diaphragm of a loudspeaker. We used a piece of a tape and a section of a thin plastic bag as diffusers. A ground glass was also tested, but it was not vibrated. Except for the polarization analysis, the results were in good agreement with what we expected. The tape has a larger scattering angle than the plastic, and the speckle reduction was greater with the tape.

The scattering tubes had less depolarization than the diffusers, if we look at the speckle contrast. They showed the same tendencies as the diffusers. The tube with the highest concentration, i.e. highest scattering, also had the largest reduction in speckle contrast. The scattering angle of this tube was smaller than the tape, but the tape were able to reduce the speckle contrast further.

The plastic diffuser is not able to reach a sufficiently low speckle contrast, but the scattering is weak. The tape offers the highest speckle reduction, but also the strongest scattering. With two tape diffusers in series, there was not enough intensity reaching the CCD sensor of the camera. The scattering tubes placed somewhere in the middle. The tube with the highest concentration had the highest reduction in speckle contrast. It would be very interesting to see the effects of the scattering tubes if the laser beam was expanded after the scattering tube. Before this can be done, we need to improve the design of the tubes to reduce the refraction angle caused by the end glasses.

## Chapter 8

# Outlook and future work

We have studied the foundation of laser speckle and built up knowledge in the field, this covers some of the existing methods to reduce speckle. The project will be continued in the doctorate study of Sigbjørn Vindenes Egge at NTNU. He will start by trying to simulate speckle in order to find a speckle reduction method.

Speckle reduction with the scattering tube should be tested without expanding the laser beam and the scattering angle ought to be found as well, in order to decide if this is a good method to reduce speckle. The most promising method, is the Hadamard matrices. The principle can be verified with the use of the SLM that was ordered to be a part of this thesis. This SLM, however, does not support a high enough frame rate to be used in real time. The measuring setup has been improved, but it still needs some adjusting and improvements of both the optical elements and the in the processing of the results. Perhaps the foremost subject to study is the speckle in the human eye. The speckle reduction is dependent on how the speckle is imaged in the eye.





# Bibliography

- [1] Charles H. Townes. The first laser.  
[http://www.press.uchicago.edu/Misc/Chicago/284158\\_townes.html](http://www.press.uchicago.edu/Misc/Chicago/284158_townes.html).
- [2] Home page for Mitsubishi's laser tv.  
<http://www.believingisseeing.tv>.
- [3] A. E. Ennos. Laser speckle experiments for students. *Physics Education*, 31(3):138–142, 1996.
- [4] Joseph W. Goodman. *Speckle Phenomena in Optics : theory and applications*. Roberts and Company Publishers, 2006.
- [5] Home page of Corporation for Laser Optics Research.  
<http://colorvision-lasers.com/default.aspx>.
- [6] Masayuki Karakawa, Robert J. Martinsen, and Stephen R. McDowell. Laser video display system and method, November 2002.
- [7] J. W. Goodman. Some fundamental properties of speckle. *Journal of the Optical Society of America*, 66(11), 1976.
- [8] Yann Piederrière J. Le Meur J. Cariou J. Abgrall and M. Blouch. Particle aggregation monitoring by speckle size measurement; application to blood platelets aggregation. *Optics Express*, 12(19):4596–4601, 2004.
- [9] Kjell J. Gåsvik. *Optical Metrology*. John Wiley & Sons, 2002.
- [10] Joseph W. Goodman. Statistical properties of laser speckle patterns. In J. C. Dainty, editor, *Laser Speckle and Related Phenomena*, pages 9–75. Springer-Verlag, 1984.
- [11] Jahja I. Trisnadi. Speckle contrast reduction in laser projection displays. [www.siliconlight.com/webpdf/Speckle\\_SPIE.pdf](http://www.siliconlight.com/webpdf/Speckle_SPIE.pdf), 2007.
- [12] Charles A. Thompson Kevin J. Webb and Andrew M. Weiner. Diffusive media characterization with laser speckle. *Applied Optics*, 36(16):3726–3734, 1997.

- [13] Yu. P. Presnyakov and V. P. Shchepinov. Use of the speckle effect to analyze vibrations of a rough surface. *Technical Physics*, 42(8):919–922, 1997.
- [14] Serge Lowenthal and Denis Joyeux. Speckle removal by a slowly moving diffuser associated with a motionless diffuser. *Journal of the Optical Society of America*, 61(7), 1971.
- [15] Eric G. Rawson, Antonio B. Nafarrate, Robert E. Norton, and Joseph W. Goodman. Speckle-free rear-projection screen using two close screens in slow relative motion. *Journal of the Optical Society of America*, 66(11), 1976.
- [16] Jahja I. Trisnadi. Hadamard speckle contrast reduction. *Optics Letters*, 29(1), 2004.
- [17] David T. Amm and Robert W. Corrigan. Optical performance of the grating light valve technology. *Photonics West-Electronic Imaging*, 1999.
- [18] Lingli Wang, Theo Tschudi, Thorsteinn Halldórsson, and Pálmi Pétursson. Speckle reduction in laser projection systems by diffractive optical elements. *Applied Optics*, 37(10), 1998.
- [19] Lingli Wang, Theo Tschudi, Markus Boeddinghaus, Alexander Elbert, Thorsteinn Halldórsson, and Pálmi Pétursson. Speckle reduction in laser projections with ultrasonic waves. *Optical Engineering*, 39(6), 2000.
- [20] Nicholas George and Atul Jain. Speckle reduction using multiple tones of illumination. *Applied Optics*, 12(6), 1973.
- [21] Hyperphysics.  
<http://hyperphysics.phy-astr.gsu.edu/Hbase/atmos/blusky.html>.
- [22] H. C. van de Hulst. *Light scattering by small particles*. Dover, 1981.
- [23] Arne Valberg. *Lys, syn, farge*. Tapir Forlag, 1998.
- [24] W. J. Dallas. Deterministic diffusers for holography. *Applied Optics*, 12(6):1179–+, 1973.
- [25] C. S. Ih and L. A. Baxter. Improved random spatial phase modulation for speckle elimination. *Applied Optics*, 17(9):1447–1454, 1978.

# Appendices

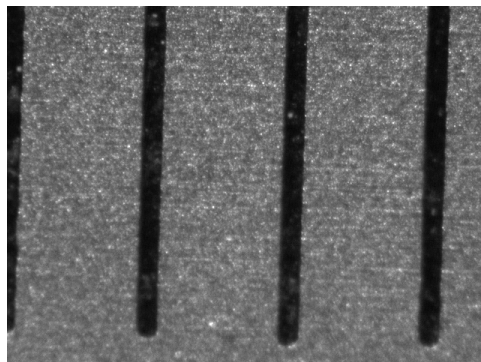


# Appendix A

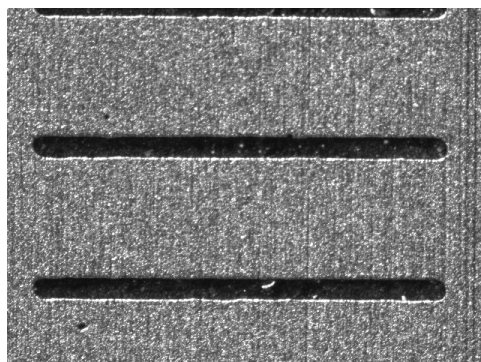
## The laboratory setup

### A.1 Field of view

To measure the FOV we used a ruler. The distance between each line on the ruler is 1 mm.



**Figure A.1:** The horizontal field of view: 3.4 mm.



**Figure A.2:** The vertical field of view: 2.6 mm.

## A.2 How to use the laboratory setup

To make it easier to repeat the measurements or use the laboratory setup for the first time, we have made a check list to follow.

1. Make a test plan.
2. Log on to the computer.
3. Check the setup
  - Make sure it is ready to test what you want.
4. Block the laser beam.
  - Insert a paper sheet in the laser path.
  - Cross the two polarizers.
5. Turn on the laser.
  - The laser has a five minute warm up time.
  - While the laser light is blocked and the laser is warming up, you have time to finish adjusting the setup.
6. Start Matlab and run the script (\*.m-file) to control the camera.
  - Folder: D:/HICFODS/knutoyvind/matlab/Matlab\_lumenera\_modified/
  - Script: LumeneraGUI.m
7. Initiate the preview function.
8. Use the preview function to adjust the focus of the camera.
  - Large lens aperture
  - Long exposure
9. Adjust the lens' aperture.
10. Set the correct properties in Matlab for the measuring images.
  - Exposure time: 50 ms
  - Gain: 1
  - Gamma: 1
11. Dim the lighting in the room
  - Try to keep the lighting to a minimum

- Some light is ok
12. Remove the paper sheet blocking the laser beam.
  13. Adjust the system to optimize the measurements.
    - Adjust the first polarizer, avoid saturation
    - Check if you have the desired FOV, a uniform speckle pattern in the center of the laser beam.
    - If there is not enough light reaching the lens
      - Block the laser after the second polarizer.
      - Remove the first polarizer.
      - Set the rotary holder of the second polarizer to zero degrees.
      - Try to maximize transmittance through the second polarizer, turning the polarizer and not the holder.
      - Reinsert the first polarizer.
      - Set the rotary holder to ninety degrees.
      - Rotate the first polarizer, not the holder, until the transmittance through the second polarizer is at a minimum.
      - Now maximum transmittance is achieved with both the polarizers at zero degrees.
      - Change the settings of the camera if necessary
      - Make a notation in the laboratory diary.
  14. Block the beam again.
  15. Capture a background noise image.
    - Make a folder for this particular measurement
    - Save the image in the folder with the name *reference.bmp*
    - If you change the lighting in the room or the setup, you will need a new reference image.
  16. Remove the blocking of the laser beam.
  17. Start the measuring.
    - Save the images in the in the folder you just made.
    - Make notes of the results.
    - Follow your test plan.

### A.3 Properties tabs for the camera GUI

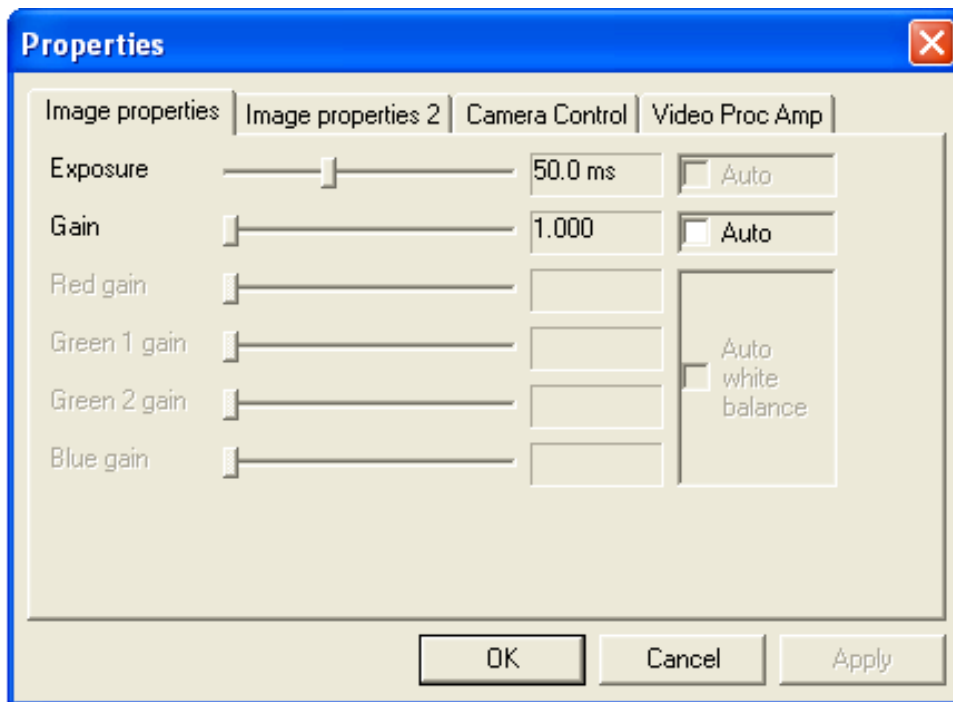


Figure A.3: GUI properties, tab number one.

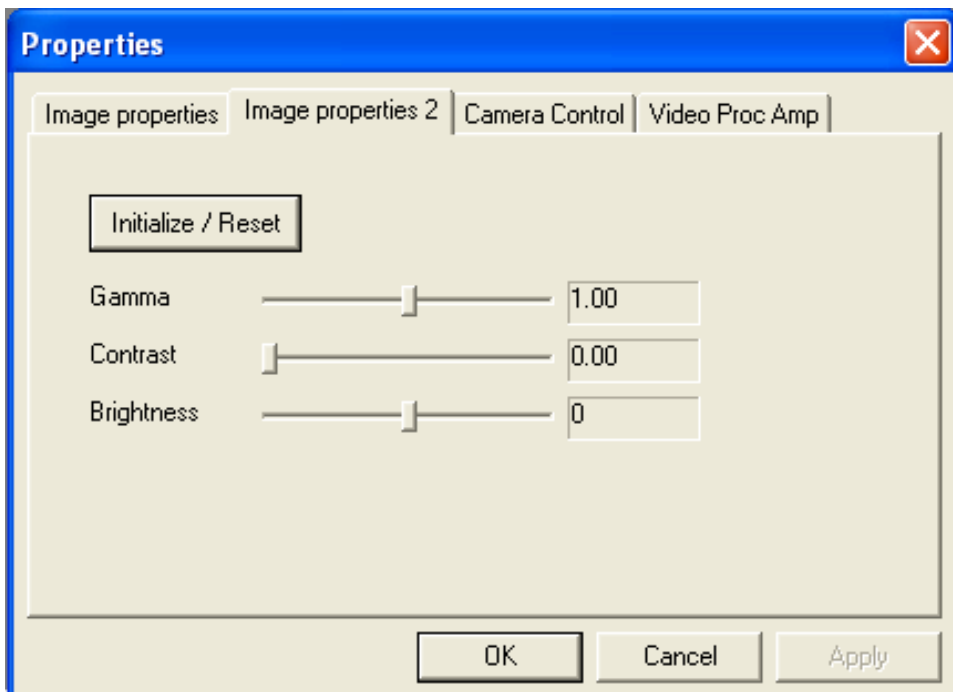


Figure A.4: GUI properties, tab number two.



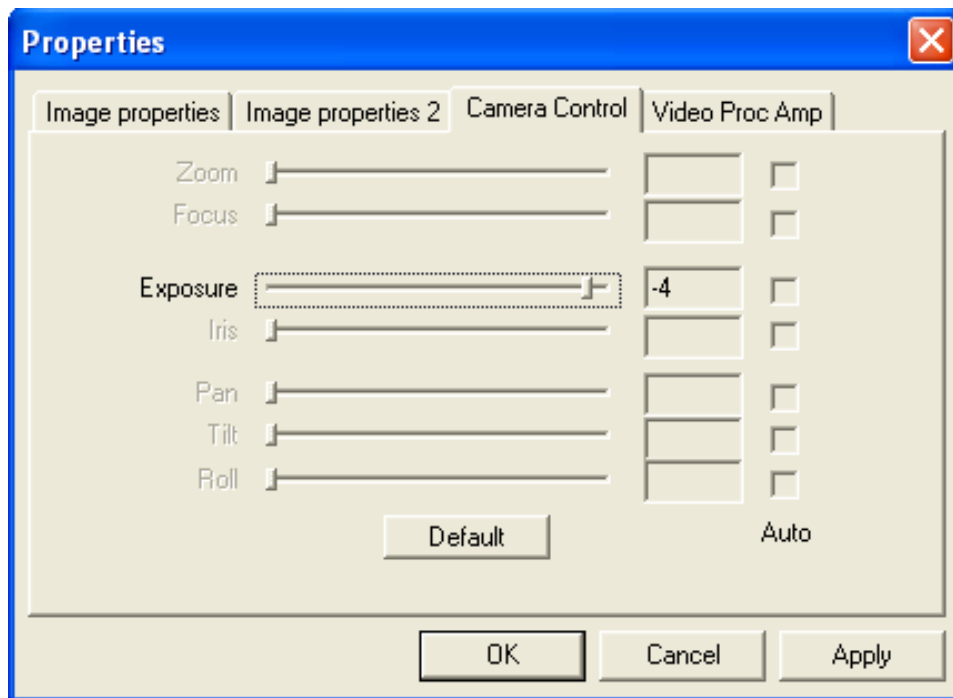


Figure A.5: GUI properties, tab number one.

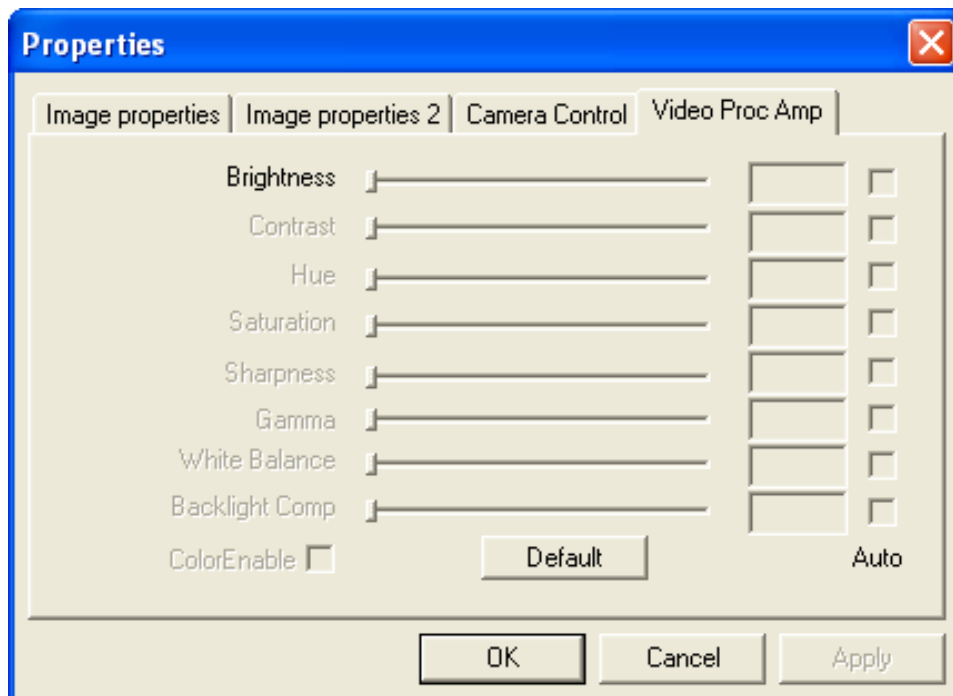


Figure A.6: GUI properties, tab number one.



## Appendix B

# Matlab code

### B.1 Speckle contrast

```
function [C]=speckle_contrast(I)
% Calculates the speckle contrast in
% the image matrix I.

% Finds the standard deviation in the image matrix.
s=std2(I);
% Finds the mean value in the image matrix.
m=mean2(I);
% Computes the speckle contrast.
C=s/m;
```

### B.2 Modification for LumineraGUI.m

```
function snapshot_picture(thePicture)
% snapshot_picture Accepts an image, calculates
% it's speckle contrast and lets the user save
% the image and a figure containig the image
% and value of the speckle contrast. The
% function also asks for a reference image
% in order to remove the background noise.

% Boolean variable, indicates whether there
% is a background noise image or not.
persistent ref
% Variable that contains the background noise
persistent referanse

% Checks if 'referanse' contains any data
if isempty(referanse)
    ref = 0;
end
```

```

% Calculates the speckle contrast, compensating
% for background noise if 'ref' = 1. It puts
% out an error message if the 'ref' = 0, but it
% still calculates the speckle contrast.
if (ref == 1)
    thePicture2 = double(thePicture)/255;
    thePicture2 = thePicture2 - referanse;
    resultat=speckle_contrast(thePicture2);
else
    resultat=speckle_contrast(thePicture);
    errordlg('Name a figure: referanse.', 'No reference image');
    uiwait
end
% Generates a figure
h = figure;
% Draws the image in the figure
image(thePicture);
axis image;
% Inserts the value of the speckle contrast in the figure
title(['Speckle contrast ',num2str(resultat(1))]);
% Demanding a varibel name for the image
pictureName = ...
    inputdlg({'Name of variable (choose OK to save):'},...
            'Image Name', 1, {'theImage'});
% If the user push the OK button it saves the image,
% and exports it to the image as a variable to
% the Matlab Workspace.
if(length(pictureName) ≠ 0) % check for cancel button
    assignin('base', pictureName{1}, thePicture);
    lagreBilde(thePicture,h);
end
% Checks if the variable name is 'referanse'
if (strcmp(pictureName(1),'referanse'))
    referanse = double(thePicture)/255;
    ref = 1;
end

```

### B.3 Save image

```

function lagreBilde(I,h)
% lagreBilde Accepts an image and a handle of a
% figure. It saves the two objects to a
% userspecified location.

% Asks the user for a location
[FileName,PathName,dill] = uiputfile({'*.bmp','Bitmap (*.bmp)';...
    '*.jpg','JPG (*.jpg)';...
    '*.*','All Files' },'Save Image',...
    'D:\HICFODS\Knut Oyvind\bilder master\newfile.bmp');

% Checks if Cancel is pushed. If not, it saves

```

```

% the objects to the location.
if isequal(FileName,0) | isequal(PathName,0)
    disp('User selected Cancel')
else
    FileName2 = strrep(FileName, '.bmp', '');
    % Looks for '.bmp' in the filename, and removes it.

    imwrite(I, strcat(PathName,FileName), 'bmp');
    % Saves the image as a 'bmp' file.

    hgsave(h, strcat(PathName,FileName2));
    % Saves the Matlab handle as a 'fig'.

    disp(['User selected', fullfile(PathName,FileName)])
end

function lagreBilde2(I,I2,h)
% lagreBilde2 Is the same function as lagreBilde,
% only it accepts two images and a handle of a
% figure. It saves the objects to a userspecified
% location.

% Asks the user for a location
[FileName,PathName,dill] = uiputfile({'*.bmp','Bitmap (*.bmp)';...
    '*.jpg','JPG (*.jpg)';...
    '*.*','All Files' }, 'Save Image',...
    'D:\HICFODS\Knut Oyvind\bilder master\newfile.bmp');

% Checks if Cancel is pushed. If not, it saves
% the objects to the location.
if isequal(FileName,0) | isequal(PathName,0)
    disp('User selected Cancel')
else
    FileName2 = strrep(FileName, '.bmp', '');

    imwrite(I, strcat(PathName, 'cut_',FileName), 'bmp');
    % Adds 'cut_' to the FileName and saves it as a 'bmp' file.
    imwrite(I2, strcat(PathName,FileName), 'bmp');
    % Saves the second image as a 'bmp' file.
    hgsave(h, strcat(PathName,FileName2));
    % Saves the Matlab handle as a 'fig'.

    disp(['User selected', fullfile(PathName,FileName)])
end

```

## B.4 Speckle contrast in a section of an image

```

function behandlegui
% behandlegui Lets you load an image, then
% choose a section and calculate the contrast
% in the section. It also allows removal of

```

```

% background noise by loading the image that
% contains this information. It has
% a function to save the section and a figure
% that contains the contrast and the size
% of the chosen section .

% Create and then hide the GUI
% as it is being constructed.
f = figure('Visible','off','Position',...
    [360,500,800,400]);

% Construct the components.

openi = uicontrol('Style','pushbutton',...
    'String','Open image',...
    'Position',[650,360,80,25],...
    'Callback',{@openi_Callback});
openbn = uicontrol('Style','pushbutton',...
    'String','Backgr noise',...
    'Position',[650,330,80,25],...
    'Callback',{@openbn_Callback});
frame = uicontrol('Style','pushbutton',...
    'String','Draw frame',...
    'Position',[650,300,80,25],...
    'Callback',{@frame_Callback});
savef = uicontrol('Style','pushbutton',...
    'String','Save figure',...
    'Position',[650,270,80,25],...
    'Callback',{@savef_Callback});
backgr = uicontrol('Style','radio',...
    'String','Backgr noise',...
    'Value',0,...
    'Position',[650,240,90,25],...
    'Callback',{@bn_Callback});
htext = uicontrol('Style','text','String',...
    'Choose section',...
    'Position',[650,200,120,15]);
xtext = uicontrol('Style','text',...
    'String','x',...
    'Position',[760,110,30,15]);
dxttext = uicontrol('Style','text',...
    'String','dx',...
    'Position',[760,80,30,15]);
ytext = uicontrol('Style','text',...
    'String','y',...
    'Position',[760,170,30,15]);
dyttext = uicontrol('Style','text',...
    'String','dy',...
    'Position',[760,140,30,15]);
speckletext = uicontrol('Style','text',...
    'String','Speckle contrast:',...
    'Position',[650,40,120,15]);
speckleval = uicontrol('Style','text',...
    'String','- ',...

```

```

        'Position', [650, 20, 60, 15]);
yedit = uicontrol('Style','edit',...
    'String',{'1'},...
    'Position', [650, 170, 100, 25],...
    'Callback', {@edit_Callback});
dyedit = uicontrol('Style','edit',...
    'String',{'480'},...
    'Position', [650, 140, 100, 25],...
    'Callback', {@edit_Callback});
xedit = uicontrol('Style','edit',...
    'String',{'1'},...
    'Position', [650, 110, 100, 25],...
    'Callback', {@edit_Callback});
dxedit = uicontrol('Style','edit',...
    'String',{'640'},...
    'Position', [650, 80, 100, 25],...
    'Callback', {@edit_Callback});

ha = axes('Units','Pixels','Position',...
    [50, 60, 550, 300]);
align([xedit, xtext], 'None', 'Middle')
align([dxedit, dxtext], 'None', 'Middle')
align([yedit, ytext], 'None', 'Middle')
align([dyedit, dytext], 'None', 'Middle')

% Initialize the GUI.
% Change units to normalized so components resize
% automatically.
set([f, ha, frame, openi, savef, ...
    htext, xedit, dxedit, yedit, dyedit], ...
    'Units', 'normalized');

%Defining som variables to be used.
pathname = ...
'D:\HICFODS\Knut Oyvind\bilder master\myfile.bmp';
scrsz = get(0, 'ScreenSize');
I = []; % Original image
I2 = []; % Copy of original image
        % to be manipulated.
Id = []; % Double version of the
        % image. Used to calculate
        % the speckle contrast.

Ibn = zeros(480, 640); % Double version of
        % the background noise image
bn = 0; % Boolean value that indicates if the
        % user has loaded a back ground image

x = 1; % Coordinates for the choosen section
dx = 640;
y = 1;
dy = 480;

```

```

C = 1;           % The speckle contrast

% Assign the GUI a name to appear in the window title.
set(f, 'Name', 'Speckle contrast in a section')
% Move the GUI to the center of the screen.
movegui(f, 'center')
% Make the GUI visible.
set(f, 'Visible', 'on');

% Callbacks for behandlegui. These callbacks automatically
% have access to component handles and initialized data
% because they are nested at a lower level.

% frame push button callback. Checks if
% the defined area is within the limits
% of the image. If it is, it draws the frames
% of the area and calculates the speckle
% contrast.
function frame_Callback(source, eventdata)
    %Reading the values
    x = str2double(get(xedit, 'String'));
    dx = str2double(get(dxedit, 'String'));
    y = str2double(get(yedit, 'String'));
    dy = str2double(get(dyedit, 'String'));
    %Checking the limits
    if((x>0) && (x<641) && ((x+dx)>0) && ((x+dx)<642) ...
        && (y>0) && (y<481) && ((y+dy)>0) && ((y+dy)<482))
        % Eliminates background noise
        Itemp = Id - Ibn;
        % Extracts the defined area
        samp = Itemp(y:(y+dy-1), x:(x+dx-1), :);
        % Calculates the speckle contrast in this area
        C = speckle_contrast(samp);
        % Displays the value in the GUI
        set(specklevel, 'String', num2str(C(1)))
        % I is unaltered, we can do whatever we want to I2
        I2 = I;
        % Draws the top horizontal line
        I2(y:(y+1), x:(x+dx-1), 1) = 255;
        % Draws the bottom horizontal line
        I2((y+dy-2):(y+dy-1), x:(x+dx-1), 1) = 255;
        % Draws the left vertical line
        I2(y:(y+dy-1), x:(x+1), 1) = 255;
        % Draws the right vertical line
        I2(y:(y+dy-1), (x+dx-2):(x+dx-1), 1) = 255;
        % Shows the image in the GUI
        image(I2);
        xlabel('x');
        ylabel('y');
        axis image
        title(['x: ', num2str(x), ', dx: ', num2str(dx), ...
            ', y: ', num2str(y), ', dy: ', num2str(dy)]);
    else

```



```

        r = errordlg('Index out of range', 'Index error');
        uiwait(r);
    end

end

% Text edit callbacks. It has no function.
function edit_Callback(source,eventdata)
end

% Radio button callback. It impossible
% for the user to change the value
% without opening an image, which should
% contain the backgrounds noise.
function bn_Callback(source,eventdata)
    set(backgr,'Value',bn);
end

% Background image push button callback. Lets the
% user choose an image to open.
function openbn_Callback(source,eventdata)
    [filename, pathname] = uigetfile({'*.bmp',...
        'Bitmap (*.bmp)'; '*.jpg;*.tif;*.png;*.gif',...
        'All Image Files'; '*.*', 'All Files' },...
        'Choose backgruond noise image',...
        pathname);

    if isequal(filename,0)
        disp('User selected Cancel')
    else
        disp(['User selected', fullfile(pathname, filename)])
        Ibn = imread(strcat(pathname, filename));
        Ibn = double(Ibn(:,:,1))/255; % Allows negative values
        bn = 1;
        set(backgr,'Value',1);
    end
end

% Open image push button callbacks. Lets the user choose
% an image to open.
function openi_Callback(source,eventdata)
    [filename, pathname] = uigetfile({'*.bmp', 'Bitmap (*.bmp)';...
        '*.jpg;*.tif;*.png;*.gif', 'All Image Files';...
        '*.*', 'All Files' }, 'Velg bilde til å behandle',...
        pathname);

    if isequal(filename,0)
        disp('User selected Cancel')
    else
        disp(['User selected', fullfile(pathname, filename)])
        I = imread(strcat(pathname, filename));
        Id = double(I(:,:,1))/255;
    end
end
% Shows the image in the GUI.

```

```

    image(I);
    xlabel('x');
    ylabel('y');
    axis image
end

% Save figure push button callbacks. It makes
% a new figure and saves it to a user
% specified location together with two images,
% the image with the frame and the section
% in the frame.
function savef_Callback(source,eventdata)
h = figure('Position',...
    [10 scrsz(4)/3 (scrsz(3) - 20) scrsz(4)/2])
% Plots the original image with the frame.
subplot(1,2,1);
image(I2)
xlabel('x');
ylabel('y');
title(['x: ',num2str(x),' dx: ',num2str(dx),...
    ', y: ',num2str(y),' dy: ',num2str(dy)]);
axis image;

Itemp = Id - Ibn; % Removes background noise
% Picks out the chosen area.
samp = Itemp(y:(y+dy-1),x:(x+dx-1),:);
% Calculates the speckle contrast.
C = speckle_contrast(samp);
% Picks out the section from the image to be plotted.
dI = I(y:(y+dy-1),x:(x+dx-1),:);
% Plots the section.
subplot(1,2,2);
image(dI);
xlabel('x');
ylabel('y');
title(['Speckle contrast ',num2str(C(1))]);
axis image;
% Saves the selected section, the original image
% with the frame.
lagreBilde2(samp,I2,h);
end

end

```

## B.5 Estimation of the speckle size

```

% speckle_size.m is a script that estimates
% the speckle size. It uses the power spectral
% density (PSD) to do this.

% Loads the speckle image

```

```

I = imread('path to image');

% The average spatial sampling frequency of the pixels
fs = 1/(9.635e-6);

%Finding the autocorrelation
% Choosing one of the layers in the image
b = double(I(:, :, 1))./255;

% m and n are the numbers of points in
% the fast Fourier analysis
m = 2560;
n = 1920;

% Finding the Fourier transform
B = fft2(b,n,m);
% Finding abs^2, i.e the PSD
PSD = B.*conj(B);
% Sorting the result after using fft
PSD2 = fftshift(PSD);

% Singels out the center line along x
y = PSD((n/2+1), (m/2+1):m);
% The frequency axis
f = fs/m*(0:(m/2));

% We expect a linear PSD. To estimate the point
% where the PSD reach zero, we singel out the points
% that follow a linear trend, i.e. the first points
% as long as the slope is negative.
run = 1;
i = 1;
while run
    if y(i)<y(i+1)
        run = 0;
        disp(i);
    else
        i = i + 1;
    end
end

% We do a very simple regression based on
% these points.
% Slope:
a = (y(i)-y(1))/(i-1);
% The point where it crosses the x-axis,
% i.e. y=0, is the max frequency.
fm = -y(1)/a;
s = fm*fs/m;
% The invers of the max frequency gives
% the smallest speckle size.
xwidth = (1/s)*1e+3;

```

```

% The data set needed to plot the line
y2 = [y(1) 0];
f2 = [0 s];
%Plotting the PSD and the line
figure;
hold all
plot(f(1:15),y(1:15),'LineWidth',2);
plot(f2,y2,'—','LineWidth',2)

title(['Center line (x), \sigma_s: ',num2str(xwidth),' mm'],...
      'FontSize',13);
legend('PSD','Approximation')
ylabel('Power Spectral Density','FontSize',13);
xlabel('Spatial frequency','FontSize',13);

% We repete the calculations along y
% Singels out the center line along y
y = PSD((n/2+1):n,(m/2+1));
% The frequency axis
f = fs/n*(0:n);
run = 1;
i = 1;
while run
    if y(i)<y(i+1)
        run = 0;
        disp(i);
    else
        i = i + 1;
    end
end
a = (y(i)-y(1))/(i-1);
fm = -y(1)/a;
s = fm*fs/n;
ywidth = (1/s)*1e3;
y2 = [y(1) 0];
f2 = [0 s];
figure;
hold all
plot(f(1:15),y(1:15),'LineWidth',2);
plot(f2,y2,'—','LineWidth',2)

title(['Center line (y), \sigma_s: ',num2str(ywidth),' mm'],...
      'FontSize',13);
legend('PSD','Approximation')
ylabel('Power Spectral Density','FontSize',13);
xlabel('Spatial frequency','FontSize',13);

```

## B.6 Calculating the autocorrelation function

```

% autocorr.m is a script that calculates
% the 2D autocorrelation function of a
% speckle image.

```

```

I = imread('path to image');

%Finding the autocorrelation

% m and n are the numbers of points in
% the fast Fourier analysis
m = 2560;
n = 1920;
% Choosing one of the layers in the image
b = double(I(:, :, 1))/255;
% Finding the Fourier transform
B = fft2(b,n,m);
% Finding abs^2, i.e. the PSD
PSD = B.*conj(B);
% Inverse Fourier transform
r = ifft2(PSD);
% Sorting the result after using ifft
r = ifftshift(r);
% Finds the maximum value
maks = max(max(r));
% Normalizing the result
r2 = (r./maks).*2;

% The values on the axis
xx = 9.6350*(-(m/2):(m/2-1));
yx = 9.6350*(-(n/2):(n/2-1));

% Draws an image of the 2D autocorrelation
figure;
colormap(jet(256));
imagesc(xx,yx,r2);
axis image
title('Autocorrelation, R', 'FontSize', 13);
xlabel('x, [\mum]', 'FontSize', 13)
ylabel('y, [\mum]', 'FontSize', 13)
colorbar;

% Plots the center line along y
figure;
plot(yx,r2(:, (m/2 + 1)), 'LineWidth', 2);
ylim([0.5 2.1]);
title('Center line (y)', 'FontSize', 13);
xlabel('y, [\mum]', 'FontSize', 13);
ylabel('Autocorrelation, R', 'FontSize', 13);

% Plots the center line along x
figure;
plot(xx,r2((n/2 + 1), :), 'LineWidth', 2);
ylim([0.5 2.1]);
title('Center line (x)', 'FontSize', 13);
xlabel('x, [\mum]', 'FontSize', 13);
ylabel('Autocorrelation, R', 'FontSize', 13);

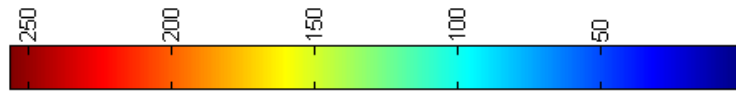
```



# Appendix C

## Results

### C.1 Colourbar



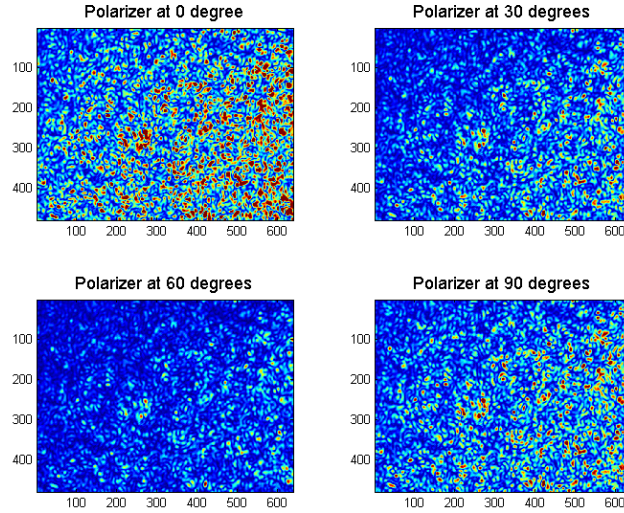
**Figure C.1:** The colourbar maps the intensities to colours.

The camera produces 8-bit images, and thus the intensities are represented by values from 0 to 255. The mapping of the values of the intensities to colours is given in Fig. C.1.



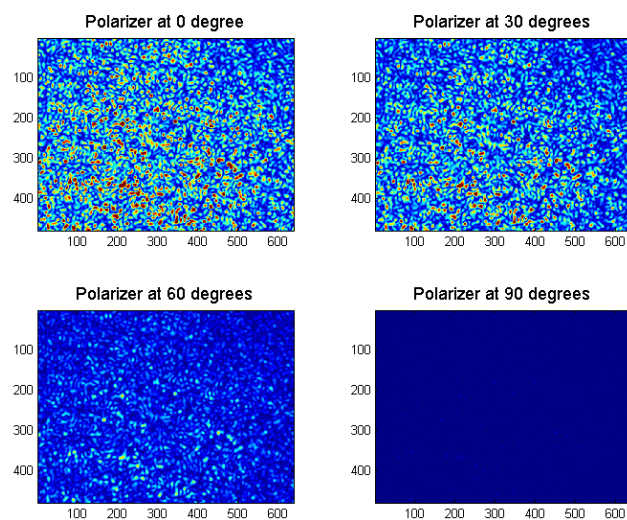
## C.2 Polarization analysis

A polarizer was placed between the diffuser or tube. With out any change in the polarization of the laser beam, there should be full transmittance at 0 degrees and total blocking at 90 degrees.

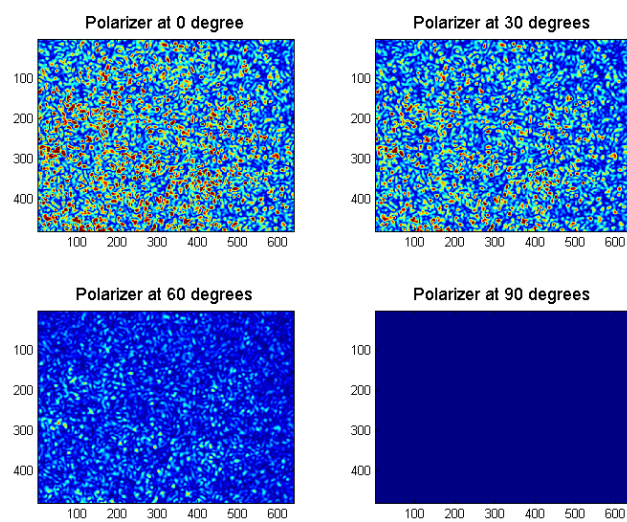


**Figure C.2:** Polarization analysis with the plastic as the diffuser. The exposure time is 5 ms.

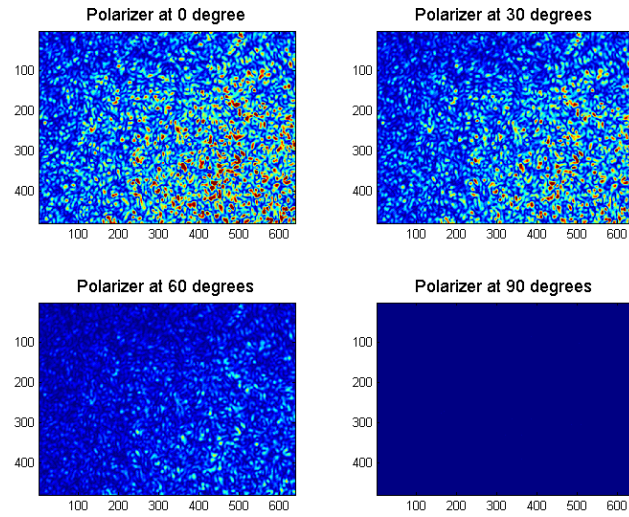
The polarization analysis for the plastic is shown in Fig. C.2. It shows that the plastic depolarize the laser beam. There are very few changes in the speckle pattern at various angles. The result is differnt for the tape as shown in Fig. C.3. The laser beam is blocked by the polorizer at 90 degrees. There is almost no depolarization. And the speckle patterns does not depend in the angle of the polarizer. The grund glass gives the same result as the tape, see Fig. C.4. There is no depolarization or change in the speckle pattern. Fig. C.5 and Fig. C.6 show the polarization analyses for tube number two and three, respectively. we have the same results in these cases as for the tape and the glass. This means that the plastic is the only medium, of these five, that depolarizes the laser beam, however, none of them has a change in their speckle pattern worth mentioning.



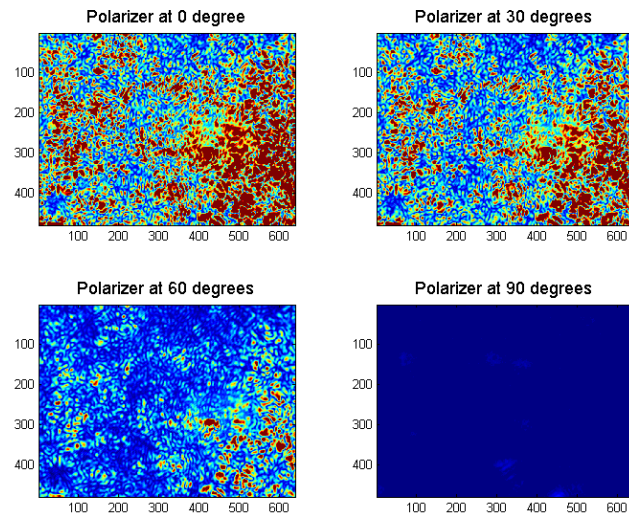
**Figure C.3:** Polarization analysis with the tape as the diffuser. The exposure time is 10 ms.



**Figure C.4:** Polarization analysis with the ground glass as the diffuser. The exposure time is 10 ms.



**Figure C.5:** Polarization analysis of tube # 2. The exposure time is 2 ms.



**Figure C.6:** Polarization analysis of tube # 3. The exposure time is 50 ms.

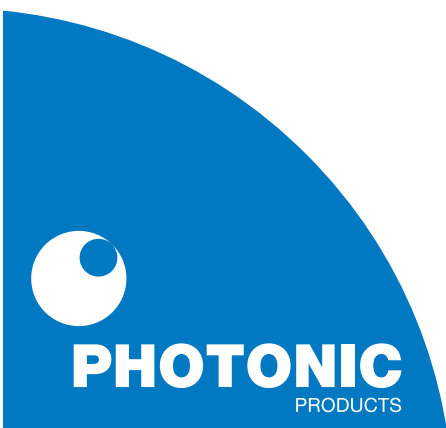
## Appendix D

# Datasheets

### D.1 Datasheet for the laser

# sheet

# data



## DPSS green laser diode module 532nm

### Key features

- Visible light  $\lambda = 532\text{nm}$
- Output power 0.9mW and 4mW
- Circular beam 1.2mm typ.
- Adjustable lens
- Modulation 0-1kHz
- Compact and self-contained
- High reliability

### Applications

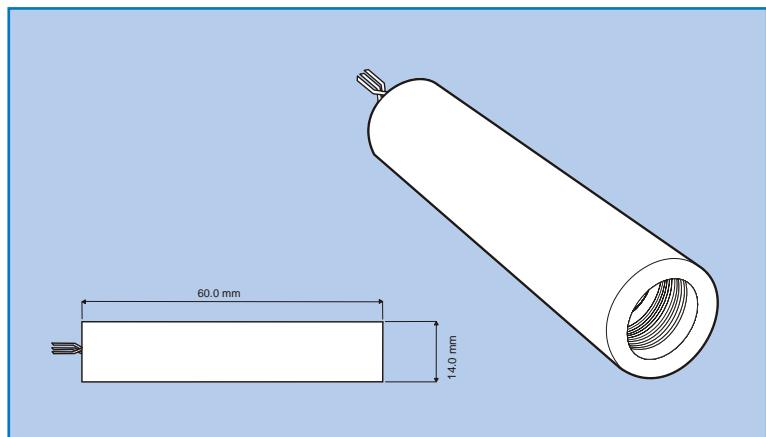
- Industrial alignment
- Medical alignment
- Scientific equipment

### 532nm DPSS Green Laser Diode Module

The 300-0088 series DPSS green laser diode module offers a circular output beam of 1.2mm diameter with beam divergence of  $<2.0\text{mrad}$ , output power of 0.9mW or 4mW, an operating voltage of 4-6V at an operating current of 350mA maximum, and operating temperature from  $+10^{\circ}\text{C}$  to  $+30^{\circ}\text{C}$ . Power stability is better than 5% over 7 hours.

The DPSS (Diode Pumped Solid State) laser diode module has been designed as a complete laser diode solution for OEM use.

It consists of an anodised aluminium housing, laser diode, drive circuit and user-adjustable collimating lens. Electrical connections are made via external flying leads.



laser diode solutions

## DPSS green laser diode module 532nm

### Specifications (Tc=25°C)

ITEM / PART no.	300-0088-00	300-0088-01
Wavelength	532nm	532nm
Output Power (±10%)	0.9mW	4.0mW
Beam Size (typ 1/e <sup>2</sup> )	1.2 mm	1.2 mm
Beam Circularity	≤ 1.3:1	≤ 1.3:1
Beam Divergence	≤ 2.0 mrad	≤ 2.0 mrad
Warm up Time	4-5 minutes	4-5 minutes
Power Stability (over 7 hours after warm up at constant temperature)	< 5%	< 5%
Power Stability (over operating temperature range)	≤ 20%	≤ 20%
Mode	TEM <sub>00</sub>	TEM <sub>00</sub>
Operating Voltage	4-6V DC	4-6V DC
Operating Current (25°C)	< 300mA	< 350mA
Operating Temperature (ambient)	+10°C to +30°C	+10°C to +30°C
Storage Temperature	-40°C to +60°C	-40°C to +60°C
Housing Material	Anodised Aluminium	Anodised Aluminium
Weight	40g	40g
Lifetime MTTF (typ)	5000 hours	5000 hours
Modulation	0 to 1kHz, 5V=ON, 0V=OFF 0 to 1kHz, 5V=ON, 0V=OFF	
Mechanical	14mm ± 0.1mm diameter, 60mm length (66mm including rear cable strain relief)	

#### Heat Sinking

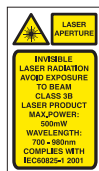
If the case temperature of the laser diode exceeds its maximum specification, premature or catastrophic failure may occur. To ensure the maximum life of the laser diode, it is recommended that an additional electrically insulated heatsink of at least 50 sq cm be used. Thermal transfer cream can be used to improve contact and heat dissipation. Do not restrict air circulation around the device.

#### Power Connections

These DPSS laser diode modules require a regulated input voltage of 4-6V. Connections are made via the 3 pre-tinned external flying leads, (red is positive, black is negative, yellow is modulation).

**WARNING:** The housing is internally connected to the positive supply rail. Damage to the external anodised surfaces will result in the housing being at positive potential.

Specifications subject to change without notice. E&OE



### Laser Safety

The light emitted from these devices has been set in accordance with IEC60825. However, staring into the beam, whether directly or indirectly, must be avoided. IEC60825 classifies laser products into three different categories depending on light emitted, wavelength and eye safety.

#### CLASS II

"Caution", visible laser light less than 1.0mW. Considered eye safe, normal exposure to this type of beam will not cause permanent damage to the retina.

#### CLASS III R

"Danger", visible laser light between 1.0mW and 5.0mW. Considered eye safe with caution. Focusing of this light into the eye could cause some damage.

#### CLASS III B

"Danger", infrared (IR), and high power visible lasers considered dangerous to the retina if exposed.

NB: It is important to note that while complying with the above classifications, unless otherwise stated, our laser diode products are not certified and are designed solely for use in OEM products. The way in which the device is used in the final product may alter its original design classification, and it is the responsibility of the OEM to ensure compliance with the relevant standards.

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PRODUCTS

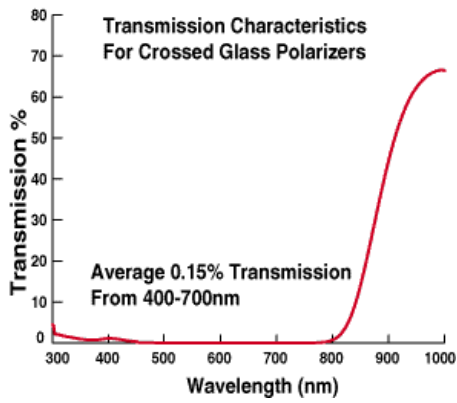
## D.2 Datasheet for the polarizing filters



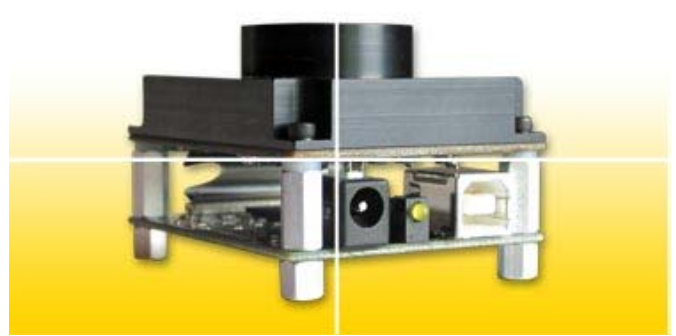
## Specification Table

<b>Diameter Tolerance</b>	Threaded diameter $\pm 0.1$ mm
<b>Clear Aperture</b>	Outer Dia - 5mm (typical)
<b>Operating Temperature</b>	-15° to 70°C (5° to 158°F)
<b>Polarization Efficiency</b>	95%
<b>Transmission, single</b>	30% typical over 400-700nm
<b>Transmission, crossed</b>	0.15% average over 400-700nm

## Technical Images



### **D.3 Datasheet for the camera**



## Outline

Lumenera's Lu070 series of cameras are designed to be used in a wide variety of industrial applications, particularly in low light conditions. Both color and monochrome product models are available.

With 640x480 resolution and on-board processing these cameras deliver outstanding image quality and value for industrial and scientific imaging applications.

Electronic Global Shutter provides capabilities similar to a mechanical shutter, allowing simultaneous integration of the entire pixel array, and then stopping exposure while image data is read out. Ideal for capturing objects in high-speed motion.

Uncompressed images in live streaming video and still image capture are provided across a USB 2.0 digital interface. No framegrabber is required. Advanced camera control is available through a complete Software Developer's Kit, with sample code available to quickly integrate camera functions into OEM applications.

Hardware and software based synchronization trigger is provided standard. On-board memory is available for frame buffering. Lu070 series cameras are offered in both enclosed and board-level form. Custom form factor (sizes) can be provided.

All Lumenera products are supported by an experienced team of software developers and application engineers. We understand your imaging needs and are here to help you with your integration and development. Products come with a full one (1) year warranty.

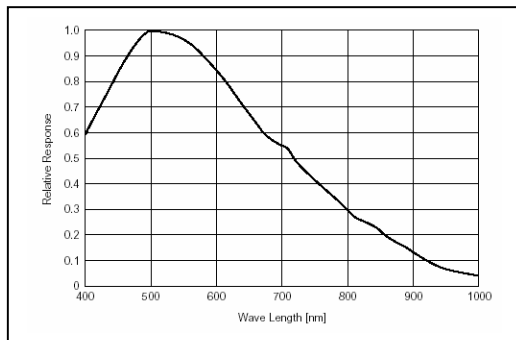
## Performance Features

- Global electronic shutter**
- Excellent sensitivity**
- High speed USB 2.0 (480Mbps/sec)**
- Color or monochrome, interline, progressive scan, 640x480 resolution**
- 60 fps at full 640x480  
+100 fps 320x240 (binning mode)**
- Auto white balance & s/w adjustable exposure**
- On-board image buffer**
- GPI/Os for control of peripherals and synchronization of lighting (4in/4out)**
- FCC Class B, CE Ready**
- Select 8 or 12-bit pixel data**
- Simplified cabling - video, power and full camera control over a single USB cable**
- DirectShow compatible**
- C-Mount provided**
- USB cameras are software compatible with Windows™ 98 SE, Windows ME, Windows 2K and Windows XP operating systems**
- Complete SDK available**

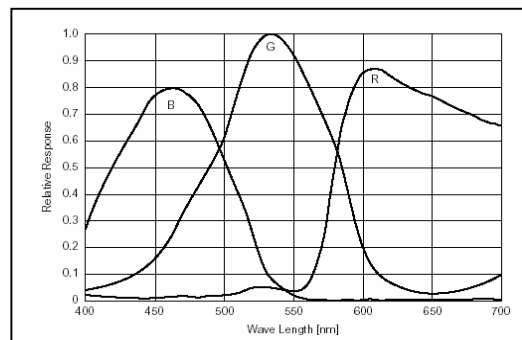
# Specifications

# Lu070

Image Sensor	<b>1/3" format, 5.8mm x 4.9mm array</b>
Effective Pixels	<b>640 x 480, 7.4um square pixels</b>
Frame Rate	<b>60 fps at 640x480, 100+ fps 320x240 (binning)</b>
Sensitivity	<b>High</b>
Dynamic Range	<b>60dB</b>
Exposure	<b>Auto / Manual</b>
White Balance	<b>Auto / Manual</b>
Dimensions (W x H x D)	<b>2.00 x 2.50 x 1.63 inches (board level)</b> <b>2.25 x 3.85 x 1.56 inches (enclosed)</b>
Mass	<b>~150g / 300g with enclosure</b>
Power Requirement	<b>USB bus power, or external 6VDC, 700mA</b>
Power Consumption	<b>~4 Watts</b>
Operating Temperature	<b>0°C to +50°C</b>
Operating Humidity	<b>0% - 95%, Non-condensing</b>
Interface Connector	<b>Standard USB cable</b>
Lens Mount (Lens not included)	<b>C-Mount, (CS-Mount option)</b>



Monochrome Response



Color Response

**Full customization  
available to meet your  
exact needs!**

### Ordering Information

Lu070M	– Monochrome Camera Module
Lu070C	– Color Camera Module
Lu075M	– Enclosed Monochrome Camera
Lu075C	– Enclosed Color Camera
LuSDK	– Software Developer's Kit

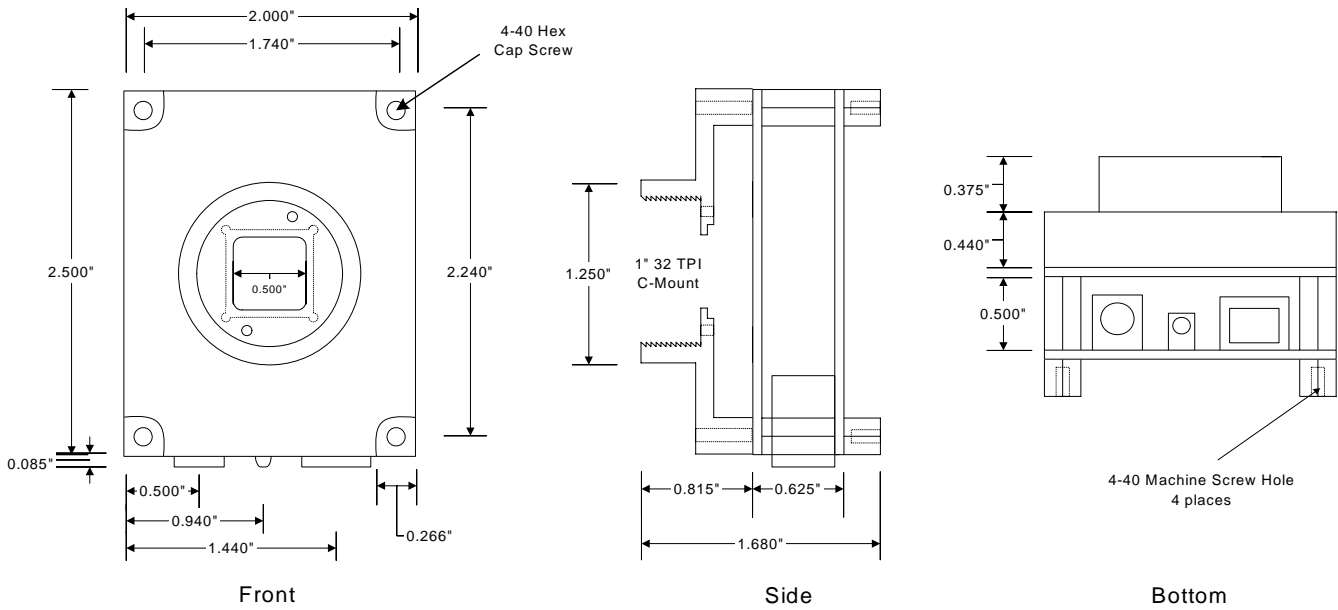
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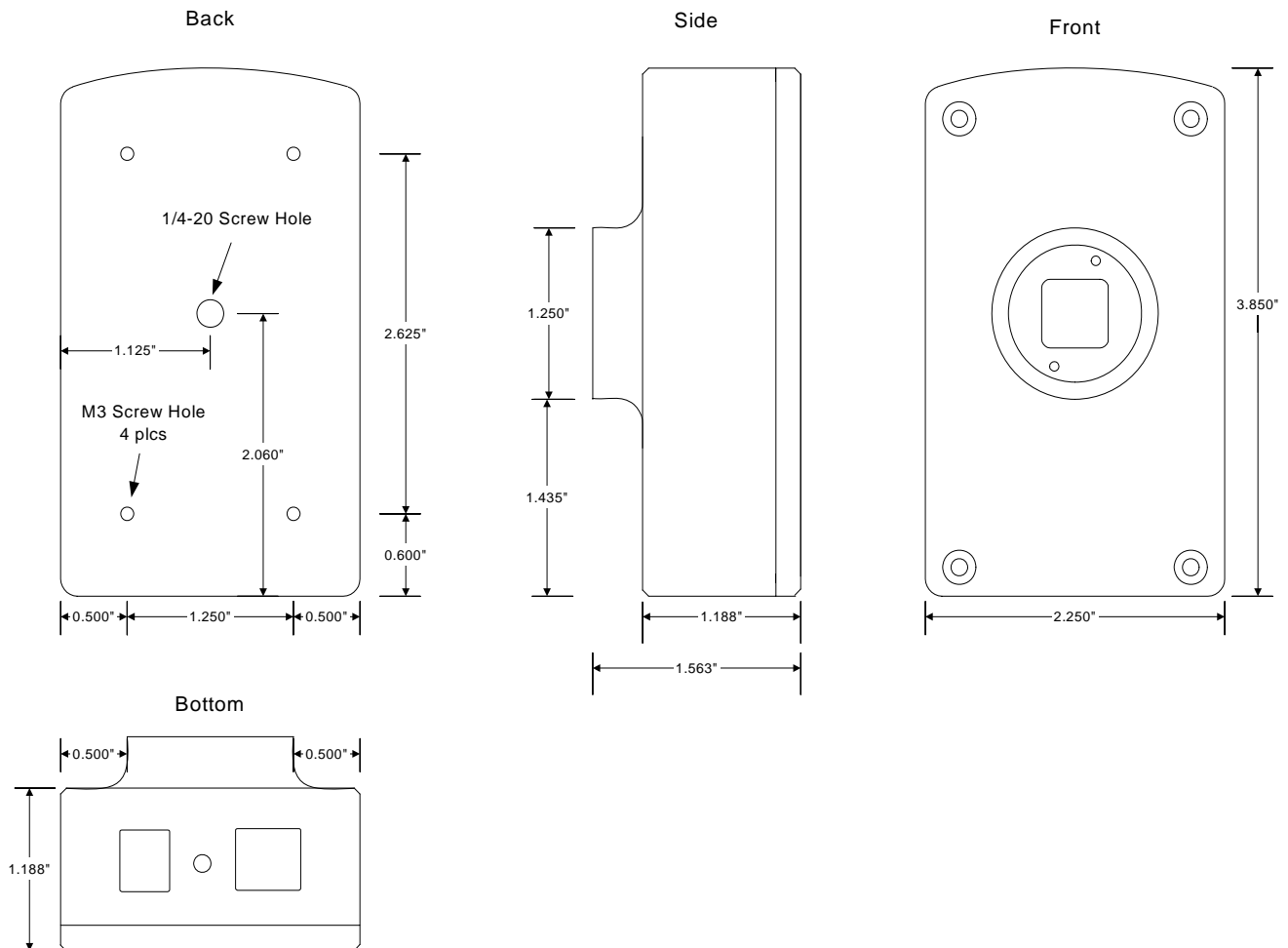
# Mechanicals

# Lu070

## OEM Board-Level Camera



## Enclosed Camera



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## D.4 Datasheet for the lens

# Lenses for Large Sensors / Distortionless Lenses



## SV-L-Series for 1" CCD's

- especially designed for large sensors
- small F-number, large aperture
- usable for low-light situations

## L-Series for 1" Sensor with Lock-Screws for Focus and Iris

P. O. No.	Max. Sensor Size	Mount	Focal Length	F-Stop	MOD in mm	Dimension in mm (ØDxL)	Filter Threat
L-SV-L12513	1"	C	f=12.5mm	F:1.3-C	300	47.0 x 59.0	M43 P=0.75
L-SV-L2514	1"	C	f=25mm	F:1.4-C	500	45.0 x 28.0	M43 P=0.75
L-SV-L5013	1"	C	f=50mm	F:1.3-C	1.000	52.0 x 52.0	M49 P=0.75
L-SV-L5018	1"	C	f=50mm	F:1.8-C	1.000	42.0 x 48.5	M40.5 P=0.5
L-SV-L7513	1"	C	f=75mm	F:1.3-C	1.000	60.0 x 71.3	M58 P=0.75



## VS-LD-Series – Distortionless Macro Lenses

- especially designed for macro applications
- changeable magnification, working distance brightness
- iris with click balls
- nearly no tv-distortion
- compact size, little shading

## Megapixel Distortionless Macro Lenses

P. O. No.	Max. Sensor Size	Mount	Focal Length	F-Stop	MOD in mm	Dimension in mm (ØDxL)	Filter Threat	TV Distortion
L-VS-LD10	1/2"	C	f=10mm	F:2.2-C	89.3-500.1	32.0 x 25.8	M27 P=0.5	< -0.05%
L-VS-LD25	2/3"	C	f=25mm	F:1.9-C	90.8-190.5	32.0 x 26.35-30.5	M27 P=0.5	< +0.02%
L-VS-LD35	2/3"	C	f=35mm	F:1.8-C	95.7-142.4	32.0 x 36.5-43.5	M27 P=0.5	< -0.03%
L-VS-LD50	2/3"	C	f=50mm	F:2.5-C	213-503.7	32.0 x 46.4-53.7	M27 P=0.5	< +0.05%
L-VS-LD75	2/3"	C	f=75mm	F:3.5-C	245.9-527.7	32.0 x 70.8-85.5	M27 P=0.5	< -0.02%

## SV-PH Series Pinhole Lenses

P. O. No.	Max. Sensor Size	Mount	Focal Length	F-Stop	MOD in mm	Dimension in mm (ØDxL)
L-SV-PH085	2/3"	C	f=8.5mm	F:2.8	0.9	20.5 x 86.7
L-SV-PH04	1/2"	C	f=4mm	F:2.5	0.2	23 x 121.6



## VS-MC-Series – Machine Vision Macro Lenses

- especially designed housings for machine vision use
- vibration resistant, less shading, high resolution very small distortions
- UV and IR lenses available

## Vibration-Resistant Macro Lens (Megapixel Distortionless)

P. O. No.	Max. Sensor Size	Mount	Optical Magnification	WD in mm	TV Distortion	Dimension in mm (ØDxL)
L-VS-MC0510 *1	2/3"	C	x0.5 – x1.0	75.2 – 121.2	0%	Length 49.4 – 72.5
L-VS-MC0510S *2	2/3"	C	x0.5 – x1.0	72.3 – 118.3	0%	31 x 64.5 – 87.6
L-VS-MC024	2/3"	C	x0.24 – x0.8	121.2 – 213.3	< 0.1%	Length 49.3 – 65.9
L-VS-MC024S *2	2/3"	C	x0.24 – x0.8	118.3 – 210.4	< 0.1%	31 x 52.2 – 68.8
L-VS-MC0103	1/2"	C	x0.1 – x0.3	182.7 – 489.7	< 0.1%	Length 42.9 – 52.1
L-VS-MC0510-"x" *3	2/3"	C	x0.5 – x1.0	75.2 – 121.2	0%	Length 49.4 – 72.5

## D.5 Datasheet for the beam expander

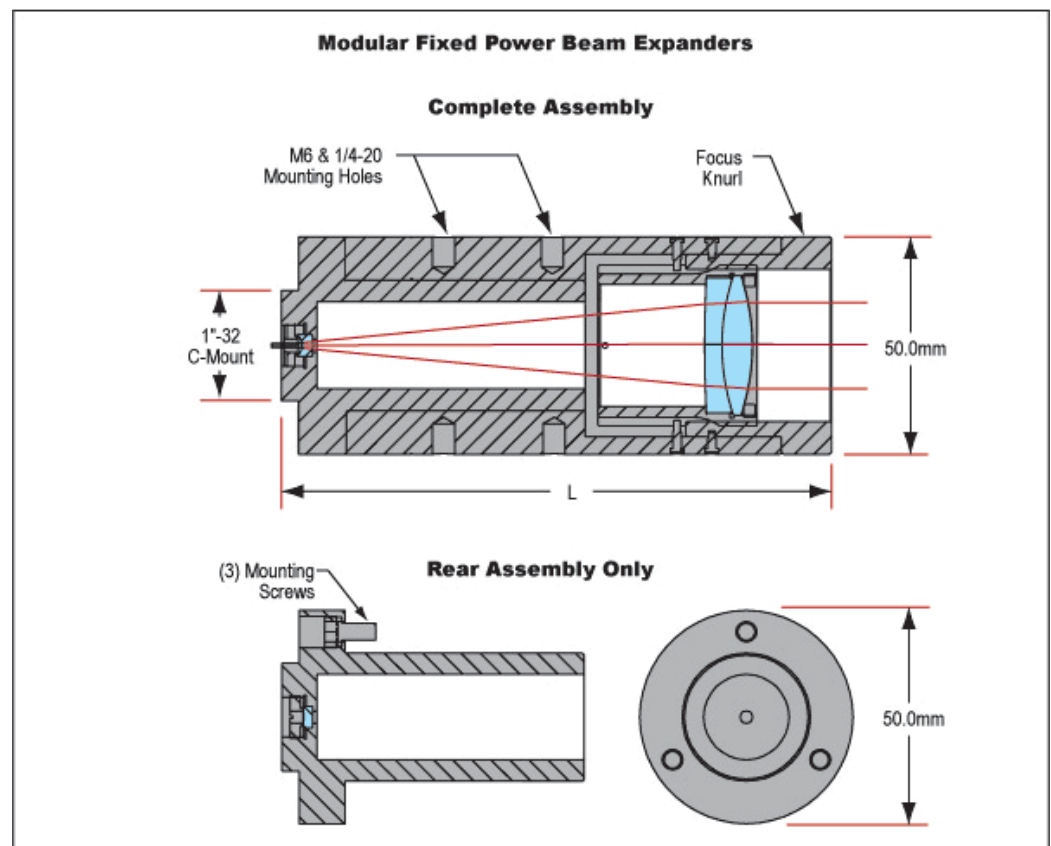


## Specification Table

<b>Beam Expansion Power</b>	3X, 5X, 10X, 15X, or 20X
<b>Entrance Aperture</b>	2.0mm maximum [Optimized for 1.0mm (1/e <sup>2</sup> )]
<b>Exit Aperture</b>	Entrance Beam x Magnification (27mm Max)
<b>Focus Range</b>	1.2m to Infinity
<b>Optics Coating</b>	1/4 wave MgF <sub>2</sub> @ 632.8nm
<b>Design Wavefront Error</b>	1/4 wave @ 632.8nm
<b>Length (L) of Complete Assembly</b>	
	<b>3X</b> 118.95mm
	<b>5X</b> 111.5mm
	<b>10X</b> 122.0mm
	<b>15X</b> 124.5mm
	<b>20X</b> 126.5mm
<b>Diameter</b>	50.0mm
<b>Mount</b>	C-Thread (1"-32 TPI)
<b>Housing</b>	Black Anodized Aluminum
<b>Collimated Beam Size</b>	<a href="#">See primer</a> <

[More Information](#)

## Technical Images



**D.6 Datasheet for the piezo plate bender**

Home > Standard products > Piezo actuators > Search by spec

Recommend this page Print

### Plate bender 9 (CMBP09)

Noliac CMBP's are typically used when a large displacement at low force is required. Noliac CMBP's are cofired monolithic piezoelectric low voltage actuators that convert an electrical input to a very high-resolution bending movement at one end of a plate shaped actuator.

Noliac CMBP's are manufactured with ceramic layer thickness down to 67µm as standard in order to facilitate very low operating voltage for full performance of the piezo material. Noliac CMBP's are mostly made to customer specifications, but a wide range of parts is available from stock as well.

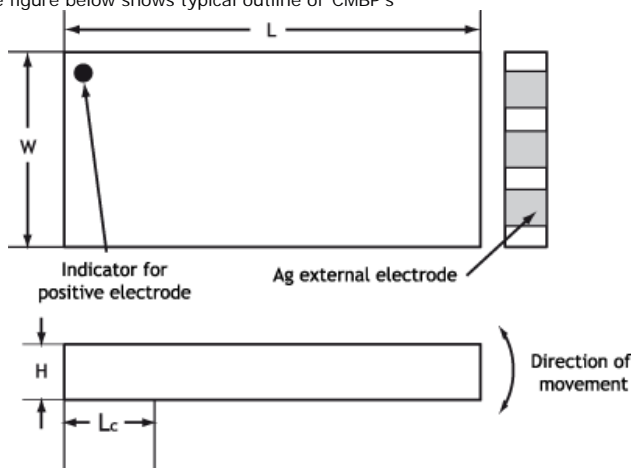
► Search for the specific actuator you need

**Product facts:**

	Value:	Tolerance:
<b>Length/outer diameter</b>	50 mm	+/-1.00 mm
<b>Width/inner diameter</b>	7.8 mm	+/-0.15 mm
<b>Height</b>	1.8 mm	+/-0.10 mm
<b>Operating voltage</b>	200 V	
<b>Free stroke</b>	+/-635 µm	+/-15%
<b>Blocking force</b>	2.9 N	+/-20%
<b>Capacitance</b>	2 x 750 nF	+/-15%
<b>Stiffness</b>	0.0046 N/µm	+/-20%
<b>Maximum operating temperature</b>	150 °C	
<b>Curie temperature</b>	350 °C	
<b>Material</b>	S1	
<b>Unloaded resonance frequency</b>	>265 Hz	
<b>External electrodes</b>	Ag	
<b>Wires</b>	28 AWG x 200 mm (+/-20 mm) Teflon	

**Typical outline:**

The figure below shows typical outline of CMBP's

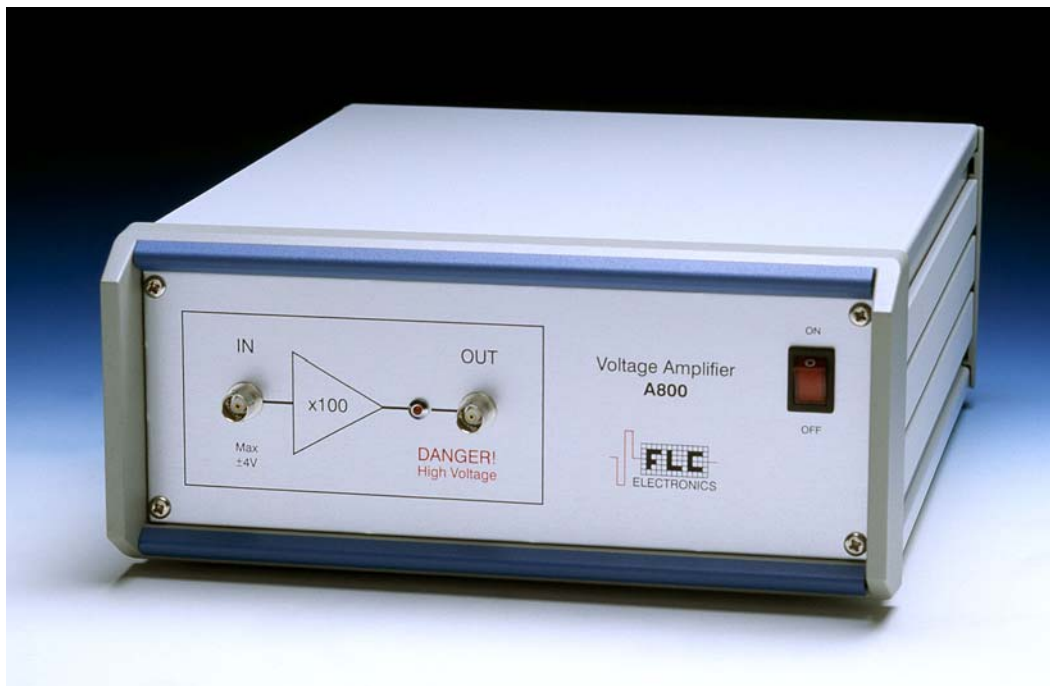


Symbol	Parameter	Unit
L	Length excluding external connections	mm
Lc	Clamping length = 3.5	mm
W	Width	mm
H	Height	mm

**D.7 Datasheet for the voltage amplifier**

# LINEAR AMPLIFIER

## MODEL A800



HIGH VOLTAGE

$\pm 400$  V

FIXED GAIN

100 X

BROADBAND

DC to 200 kHz

HIGH SLEW RATE

$200$  V/ $\mu$ s

LOW OUTPUT IMPEDANCE

$< 1$   $\Omega$

**Address:**

FLC Electronics AB  
Sippedalsvägen 8  
S - 433 31 Partille  
Sweden

**Fax:**

+46 (0)31 340 1848  
+46 (0)31 741 2630

**Electronic mail:**

flce@flce.se

**VAT No:**

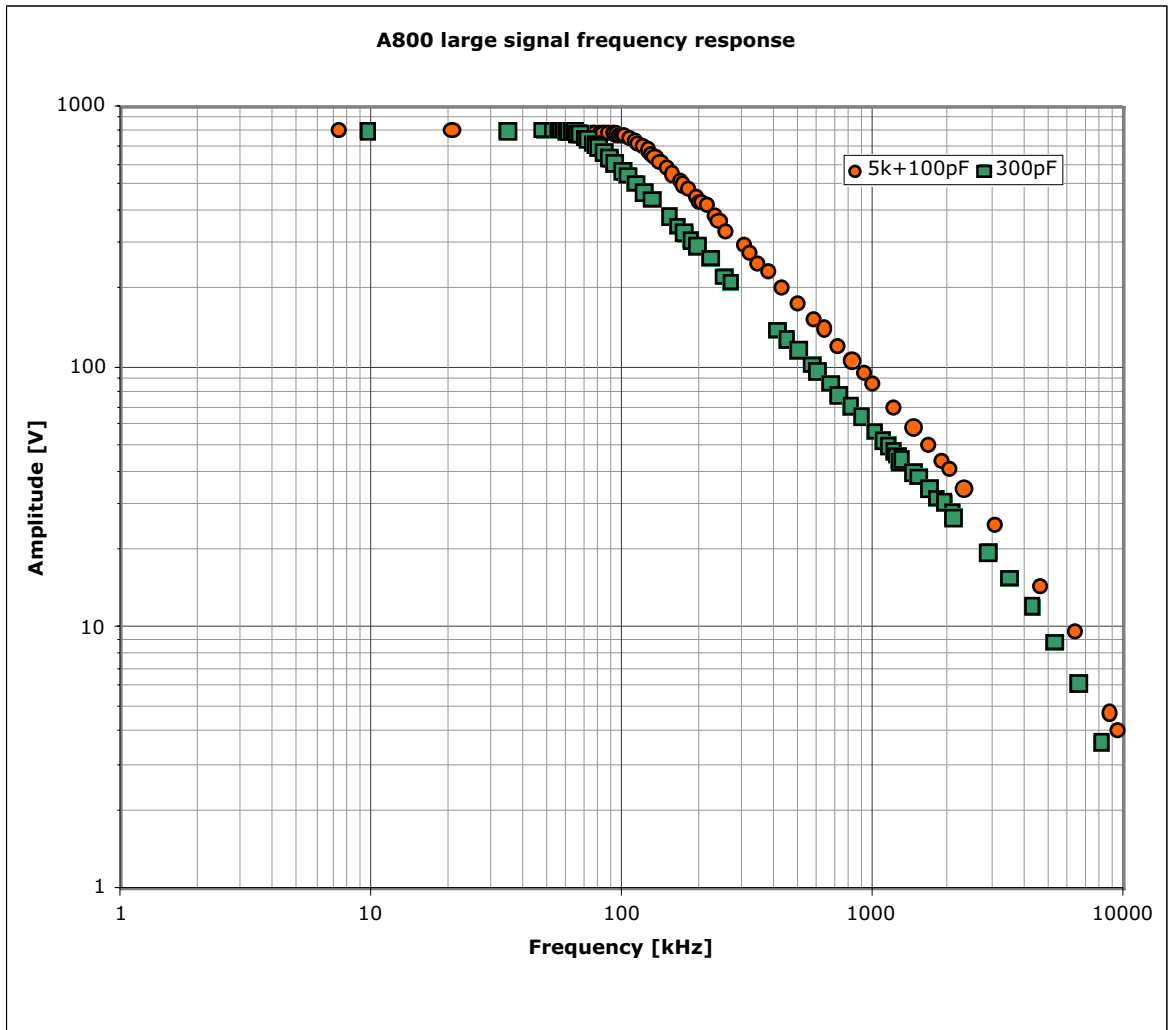
SE556506606401

**Web:**

<http://www.flce.se>

## FREQUENCY RESPONSE

The graph below shows full-scale frequency response of A800 with 5 kΩ in series with 100 pF load (red circles) and with 300 pF pure capacitive load (green squares):



## SUMMARY OF TECHNICAL DATA

<b>Bandwidth:</b>		DC to ca 200 kHz at 800 V <sub>pp</sub>
<b>Amplification:</b>		100 times, fixed
<b>Load:</b>	type	resistive    capacitive
<b>Impedance:</b>	input	1 MΩ    <30 pF
	output	<1 Ω in the linear mode
<b>Voltage:</b>	input	nominal ±4 V
		absolute maximum 20 V peak
<b>Current:</b>	output	60 mA continuous,
<b>Slew Rate:</b>	output	ca 200 V/μs without load
		ca 150 V/μs with 300 pF load
<b>Input protection fuse:</b>		15 mA (Littelfuse, part number 272.015)
		one spare fuse provided inside the instrument, additional fuses available from FLC Electronics AB
<b>Operating Ambient Temperature:</b>		0°C to 30°C
<b>Storage Temperature:</b>		0°C to 60°C
<b>Relative Humidity:</b>		up to 90% (operation)
		30% to 50% (storage)
<b>Power Requirements:</b>		either 100/110 V or 220/230 V, 50/60 Hz (factory set)
<b>Fuse:</b>		100/110 V: 3.15 A (slow),
		220/240 V: 1.6 A (slow)
		cooling fan 315mA (slow)
<b>Dimensions (H/W/L):</b>		112 x 255 x 316 (mm)
<b>Weight:</b>		5 kg
<b>Country of Origin:</b>		Sweden

*Note:* Specifications apply to instruments operating at 23°C±5°C ambient temperature after 2 min. warm-up time. Due to ongoing product development, specifications are subject to change without notice.

**WARNING** It is not allowed to connect the 100...240V AC line power input of the amplifier to DC-AC converters or solid state AC generators with non-sinusoidal output.





## Appendix E

### The poster

The poster which Sigbjørn Vindenes Egge and I presented at the Norwegian Electro-optics meeting 2008.

# Speckle Reduction in Laser Projection Displays

Knut Øyvind Apeland<sup>1</sup>, Sigbjørn Vindenes Egge<sup>1</sup>, Vladimir Kartashov<sup>2</sup>, Lars Henriksen<sup>2</sup>, Ketil Gartmann<sup>2</sup>, Thomas Spatschek<sup>2</sup>, Astrid Aksnes<sup>1</sup>

<sup>1</sup> Norwegian University of Science and Technology (NTNU), Department of Electronics and Telecommunication  
<sup>2</sup> poLight AS, Postboks 163, 3192 Horten

## Introduction

HICFODS (Hybrid Integrated Components for Optical Display Systems) is a co-operative project between HiVE, NTNU, poLight AS, and other industrial partners. The aim of the project is to use lasers as the illumination source in display projectors. Compared to conventional projectors based on lamps or LEDs, lasers offer several intriguing prospects: higher contrast, improved color gamut, greater brightness, and reduced cooling needs. However, a great challenge with laser display projectors is speckle – a random interference pattern that degrades the quality of the image.

## Laser speckle

Before the light from a projector is received at the retina, it has to be scattered from a random surface to obtain an adequate viewing angle. The surface has to be rough on the scale of visible wavelengths. A laser beam incident on this surface results in different parts of the beam being reflected at various heights and angles (random walk). Since the laser light is coherent, the reflected rays will interfere with each other and produce random intensity variations across the retina. This pattern is called speckle, and is a great challenge with laser projection displays.

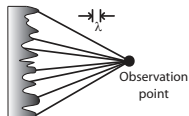


Figure 1: Scattering of coherent light at a rough, random surface.

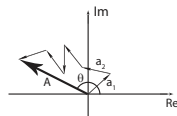


Figure 2: The scattering in figure 1 pictured as a random walk in the complex plane.

Given  $N$  independent speckle patterns superimposed on each other, the contrast is defined by

$$C = 1/\sqrt{N}$$

Thus, in order to reduce speckle contrast to a desired  $C$ , one should shift between  $1/C^2$  independent speckle patterns during the integration time of the eye. According to literature,  $C$  should be less than 0.10 to obtain a good image quality.



Figure 3: The speckle pattern produced by a sheet of paper.

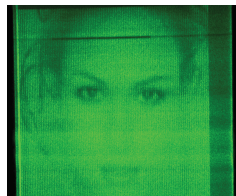


Figure 4: A speckled image produced by a prototype of a laser projector at poLight AS.

## Laboratory setup

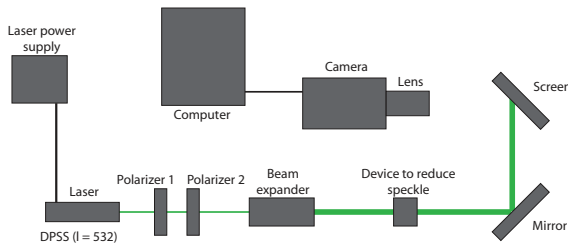


Figure 5: A sketch of the laboratory setup.

A laboratory setup has been built to measure the speckle contrast. A CCD camera is used to image speckle from a screen. The light source is a green DPSS laser. Two polarizers control the intensity, making it possible to avoid saturation of the CCD sensor. A beam expander makes the laser spot larger than the field of view of the camera's lens. When imaging only a section of the laser spot, a fairly uniform speckle pattern is obtained across the image. This is important in order to be able to calculate the speckle contrast. The image is analyzed with Matlab. To study a speckle reduction device, it is placed in the beam path. The setup can measure the reduction abilities and a relative optical loss.

## poLight diffuser

poLight has produced a diffuser which consists of a tube containing a polymer gel with micro pearls embedded. These particles will scatter incoming light and thus reduce the coherence. The amount of speckle reduction has been examined by rotating the tube. Later, other methods of displacement will be investigated, starting with vibration of the tube perpendicular to the incoming ray.

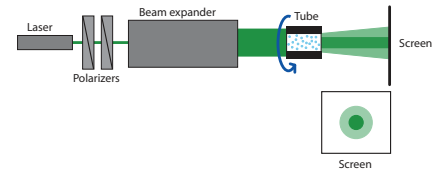


Figure 6: The tube with polymer gel and micro pearls is rotated about the laser beam.

## Results

Initial experiments with the rotating gel with micro pearls show a reduction in speckle contrast. The speckle contrast is then 0.42, compared to 0.74 when the tube is stationary.

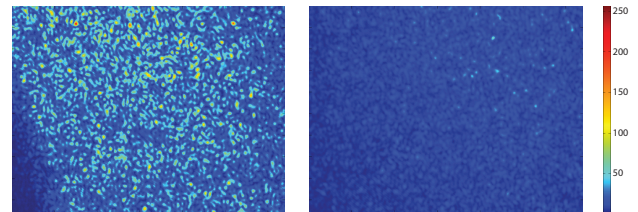


Figure 7: The reduced speckle pattern produced by the tube, when stationary (left) and rotating (right). The values on the colour bar are proportional to the intensity.

There were some problems with the diffuser. The laser spot rotated on the screen, and the radius of rotation increased with distance from the tube to the screen. Calculations show that refraction due to unparallel glass plates at the ends of the tube will cause this effect.

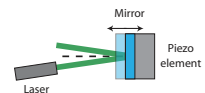
## Future work

poLight's diffuser is not the only method to reduce speckle that will be studied in this project. To examine other ideas simulations and practical experiments will be performed. Other methods include:

**Hadamard matrices** – A spatial light modulator (SLM) creates a phase variation across the wave front. If the phase variation introduced by the SLM is organized as Hadamard matrices there are a certain number of orthogonal matrices. Each matrix creates an independent speckle pattern.



**Vibrating mirror** – A mirror mounted to a piezo element can destroy the coherence in the longitudinal direction. It uses the same principle as when speckle is used to measure surface vibrations.



## Acknowledgements

Thanks to the Research Council of Norway and poLight AS for funding the project (project number 182667/140).