Speckle sensor

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Contents

1 Objective and overview

The practical work should introduce the following subjects to you:

- Get familiar with the appearance of speckle and with spatial noise
- Evaluate conditions for different speckle sizes and their correlation
- Build a speckle movement sensor and test its performance

To get this done you need to read the reference document provided.

2 Safety Issues

In this experiments laser sources and low power electrical equipment are used. The laser is of class II. Class II: low-power visible lasers that emit a radiant power below 1 mW. The concept is that the human aversion reaction to bright light will protect a person. Only limited controls are specified. (http://www.osha.gov, Laser Hazards)
The laser is safe because the blink reflex of the eye will limit the exposure to less than 0.25 seconds. It only applies to visible-light lasers (400–700 nm). Intentional suppression of the blink reflex could lead to eye injury. In our experiment the laser sources are collimated and should be handled with care. A strongly divergent beam will not be focussed on the eyes retina and represents often no danger. Collimated beams will lead to small focus spots onto the retina special care is needed. ***Do not stare into a collimated beam!***
The electrical equipment used in the experiments is based on USB power (5V, 0.5 A, 2.5 W) and not subjected to any particular security issues. Nevertheless you should **not produce short circuits** on the printed circuit board (PCB) or to the computers USB connection to avoid damage to the material. Make proper use of screwdrivers. Do not force any mechanical parts.

3 Background

Camera

In our experiment we use a pixilated camera. The pixels are arranged in a regular array produced at very high precision. The camera chip has 1600 x 1200 pixels and is 4.536mm x 3.416mm wide and large respectively. The pixel pitch is 2.835 micron in both directions (square). We can safely assume that there is no deviation of pixel position.

Interference and Speckle

The interference of light leads to intensity modulation. But interference appears only under certain conditions, the most important being a high degree of coherence of the light. The coherence of light has two aspects:

- Temporal, and
- Spatial

The temporal coherence is linked to the **spectral properties** of light. A narrow spectrum has a higher degree of coherence than a broad spectrum. It is possible to quantify the degree of temporal coherence by the **coherence length l_c**. Different definitions of coherence length exist, all based on the measurement of the contrast of interference fringes. To calculate the coherence length l_c for a given wavelength λ and spectral $\Delta\lambda$ width one uses the following formula:

$$l_c = \frac{1}{n}\frac{c}{\Delta\nu} = \frac{1}{n}\frac{\lambda^2}{\Delta\lambda} \qquad \text{Eq. 1}$$

where n is the refractive index of the surrounding medium. The coherence length depends on the bandwidth (optical frequency) $\Delta\nu$ and the speed of light c. It can be expressed as a function of the wavelength λ and the spectral width $\Delta\lambda$. We work mainly in air therefore n=1. The table below gives indicative values of the coherence length for the light emitted by the sources used in the course.

Source	Center wavelength	Spectral width	Coherence length
Halogen lamp (visible)	550 nm	300 nm (400 – 700 nm)	1 µm
LED	635 nm	20 nm	20 µm
Monomode laser	635 nm	0.2 nm	2 mm

The spatial coherence is linked to the physical size of a light source. A monomode laser (one wavelength, one polarization) for instance is a coherent source with high spatial coherence because its emission area is very small. A laser beam could be monomode and have a larger diameter which can be explained by the fact that for monomode source the product of emmitaing surface A and solid angle Ω is constant and equal to the square of the wavelength. This can be easily shown for a Gaussian beam for instance and one gets:

$$A\Omega = w^2\pi\,\pi\left(\lambda/(\pi w)\right)^2 = \lambda^2 \qquad \text{Eq.2}$$

(beam diameter 2w, fully coherent, monomode, divergence angle $\theta_{1/e} = \lambda / \left(\pi w_0\right)$)

It nevertheless has a finite (temporal) coherence length. Interferences phenomena can be observed when light having followed different paths, with length difference below the coherence length of the light, are superimposed. **If a spatially extended source is used, the superposition of coherent areas in the spatial domain has to be assured.** This is achieved by observing in the plane where images of the source overlap, hence in the image plane.

Speckles appear when light is reflected from a rough surface or transmitted through rough surfaces. The surface creates phase shifts that lead to constructive or destructive interferences localized in space. Speckles appear overall in space and they have a certain size and extension. A typical image of speckles is shown below.

Figure 1: Speckles in images of a scene illuminated with laser light. Left: incoherent illumination. Middle: coherent illumination. Right: close up that shows the speckle.

The properties of speckle are described through statistics. When the random phase shifts induced by the rough surfaces have a magnitude larger than 2π, the speckle pattern is said to be fully developed. Its statistical properties have been described be different authors (Dainty J.C. (ed.) Laser speckle and related phenomena (chapters 1,2)(Springer, 1975), J. A. Goodman, Speckle Phenomena in Optics, Roberts and Company Publishers; 2010). The probability for the intensity in the speckle pattern follows a negative exponential distribution. This distribution is very broad, that is the speckle pattern shows large variations of intensity. Furthermore as the most probable intensity is zero, the **pattern has a contrast of one**. The speckle pattern generated in this work will be fully developed.
When different speckle pattern generated using different light source or orthogonal polarizations are added the contrast will be altered. This is because the different sources or polarization are not coherent and will not interfere. In such a case intensity images have to be added because there is no interference. The result is another pattern with a reduced contrast.

Speckle size

An important parameter is the size of speckles. The size is the main issue because if the size is very small it might be not visible. If we want to use speckles for measurements, we should adjust its size, which depends on the wavelength of light, the size of the illuminated field (contributing surface area) and the distance from the rough surface to the observation plane. The most important parameter is the maximum angle under which light hits the observation plane. If this angle is large, small speckles are created.

Figure 2: Speckle with different size at different illumination conditions.

The size of the speckle can be calculate by correlating the speckle pattern with itself and make an autocorrelation. This can be done easily numerically. An analytically evaluation gives access to a speckle size that is given by different parameters. Assuming a uniformly illuminated spot of area A_0 , the speckle area A_S is found as

$$A_s A_0 = (\lambda z)^2 \qquad \text{Eq. 3}$$

where z is the distance between the illuminated surface and the observation plane.

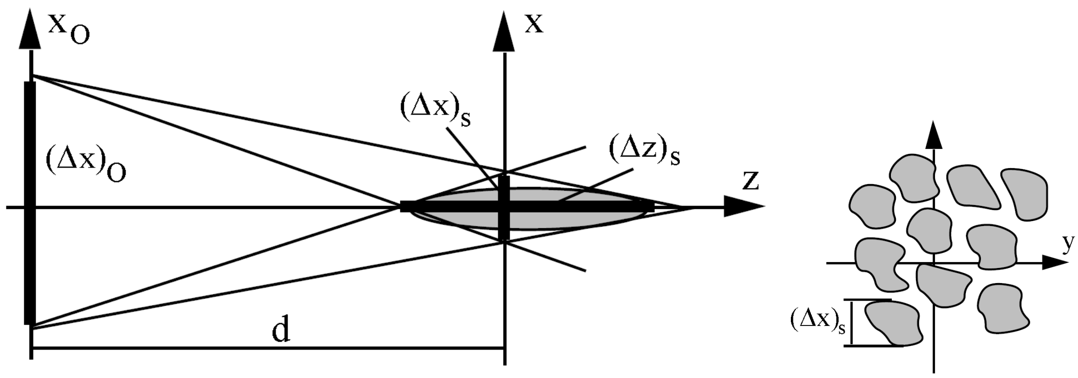


Figure 3: Left: Geometry to calculate speckle size and extension. Right: Visiualization of speckle size Δx_s as seen in the observation plane.

If we define according the figure above that the illumination spot area A_0 is circular and that it has a diameter $D=(\Delta x)_O$ and we use the distance d between illuminated surface and observation plane we can write

$$A_s = \frac{(\lambda d)^2}{A_0} = \frac{(\lambda d)^2}{\frac{\pi D^2}{4}} = \frac{(\lambda d)^2}{\frac{\pi D^2}{4}} = \frac{4\lambda^2 d^2}{\pi D^2} \qquad \text{Eq. 4}$$

Illuminated surface area $A_0 = \pi D^2 / 4$

Expected speckle surface area (speckle size Δx_s) $A_s = \pi(\Delta x_s)^2 / 4$

With this we find a speckle size Δx_s as

$$\boxed{\Delta x_s = \frac{4}{\pi}\frac{\lambda d}{D} = 1.27\frac{\lambda d}{D}} \qquad \text{Eq. 5}$$

As an example we calculate the speckle size for a HeNe laser (632 nm) with a collimated beam diameter of D = 1mm. The laser might be pointed to a wall and we observe the point at a distance of d = 10 m, hence far away from the wall. We find

$$(\Delta x)_s = \frac{4}{\pi}\frac{\lambda d}{D} = 1.27\frac{632\cdot 10^{-9}\,\text{m}\,10\text{m}}{1\cdot 10^{-3}\,\text{m}} = 8\text{ mm}$$

If d would be only 5 cm away from the surface (wall) the value would be

$$\left(\Delta x\right)_s = \frac{4}{\pi}\frac{\lambda z}{D} = 1.27\frac{0.635 \cdot 10^{-6}\,\mu m\; 50 \cdot 10^{-3}\text{ m}}{1 \cdot 10^{-3}\,m} = 40\;\mu m$$

Speckles have also a certain depth. From the figure above one can estimate the depth by simple geometrical evaluation. On can set

$$\frac{\left(\Delta z\right)_s}{\left(\Delta x\right)_s} = \frac{d}{D} \qquad \text{Eq. 6}$$

If we approximate the speckle size with $\left(\Delta x\right)_s \approx \lambda d/D$ we get

$$\boxed{\Delta z_s \approx \frac{\lambda d^2}{D^2} = \frac{\left(\Delta x_s\right)^2}{\lambda}} \qquad \text{Eq. 7}$$

As an example we use the same values as above (He-Ne laser 632 nm, collimated beam of D = 1 mm) and find

Distance to observer d= 10 m

$$\left(\Delta z\right)_s \approx \frac{\left(\Delta x\right)_s^2}{\lambda} = \left(8 \cdot 10^{-3}\,m\right)^2 / \, 0.635 \cdot 10^{-6}\,m = 100\text{ m}$$

Distance to observer 5 cm

$$\left(\Delta z\right)_s \approx \frac{\left(\Delta x\right)_s^2}{\lambda} = \left(40 \cdot 10^{-6}\,m\right)^2 / \, 0.635 \cdot 10^{-6}\,m = 2.5mm$$

It is interesting to compare the appearance of interference fringes in the observation plane with the situation of having two point sources that are separated by the diameter D and located at the same distance d from the observer. This reflection lead to the evaluation of the resolution limit of optical devices with a certain numerical aperture, the angle of observation we can observe when being at the observation plane.

Coherent imaging

If a lens is used to image speckle, the speckle size is given by a similar formula. The figure below shows the geometry. Object distance is d_O, image distance d_I, the lens has a focal length f, and imaging can be written using a response function of a point source that lead to h (point spread function). In speckle construction it is important what angles the observers sees. With lens imaging the observer see the lens diameter D_L at a distance d_I. This contains the numerical aperture on the observation side! This will determine the speckle size that is given in such a case as

$$\left(\Delta x\right)_s = \frac{4}{\pi}\frac{\lambda d_I}{D_L} \qquad \text{Eq. 8}$$

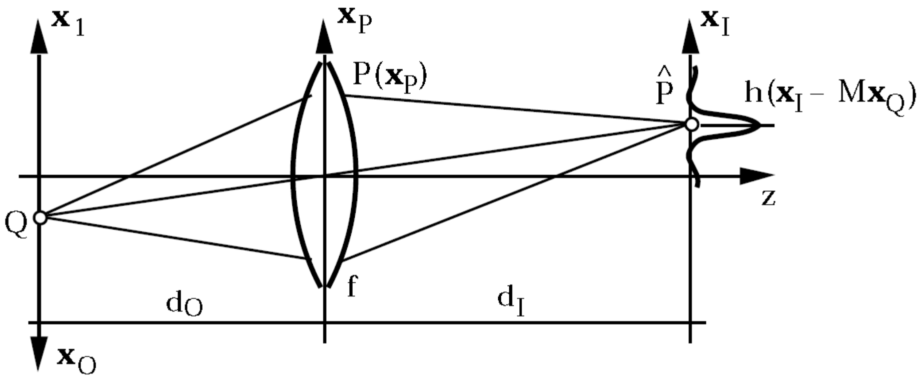


Figure 4: Geometry for coherent imaging. The object distance is d_O and image distance d_I. The diameter of the lens pupil becomes a determining parameter here.

As an example we consider a microscope objective from the imaging side, where we would have our camera. The figure below shows the geometry.

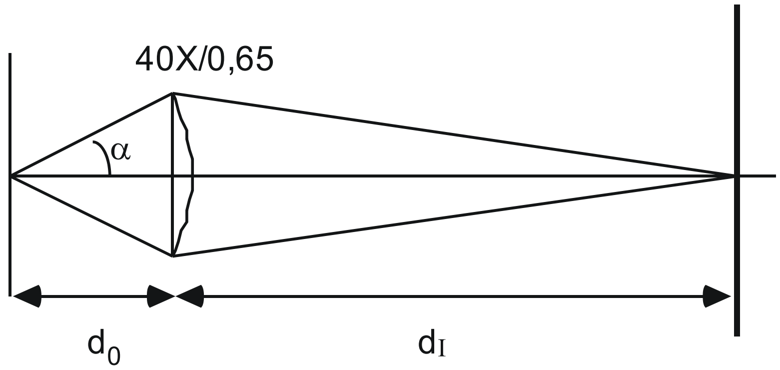


Figure 5 To detemine the speckle size in an image with high magnification.

We use an objective with a magnification of 40x with an object side numerical aperture of NA = 0.65 (in air). We need to determine the expression d_I/D_L. The following equations hold

$$D_L = 2\tan\alpha\, d_0 \qquad \text{Eq. 9}$$

$$M = \frac{d_I}{d_0} \qquad \text{Eq. 10}$$

$$\sin\alpha = NA \qquad \text{Eq. 11}$$

$$\tan\alpha = \frac{\sin\alpha}{\cos\alpha} = \frac{\sin\alpha}{\sqrt{1-\sin^2\alpha}} \qquad \text{Eq. 12}$$

Combining with the speckle size we find

$$(\Delta x)_s = 1.2\lambda\frac{d_I}{2\tan\alpha\, d_0} = 1.2\lambda\frac{M}{2}\frac{\sqrt{1-\sin^2\alpha}}{\sin\alpha} = 1.2\lambda\frac{M}{2}\frac{\sqrt{1-NA^2}}{NA} \qquad \text{Eq. 13}$$

and as the result

$$(\Delta x)_s == 1.2\cdot\frac{40}{2}\cdot 0.633\mu m\frac{\sqrt{1-0.4225}}{0.65} = 17\mu m$$

This has to be compared to the pixel size of the camera that will be in the same order. Speckle reduction becomes for a lot of application very important.

Speckle size evaluation by autocorrelation

A practical way to determine the size of speckle in speckle images is the autocorrelation method. The method is based on performing integrals of the images with itself for different shifts of the image. For pixel images shifts will be done pixel by pixel in both direction and the resulting integral over the surface is then plotted as a function of the shift. To understand what happens we could simulate the situation of a single speckle by assuming it would have circular geometry.

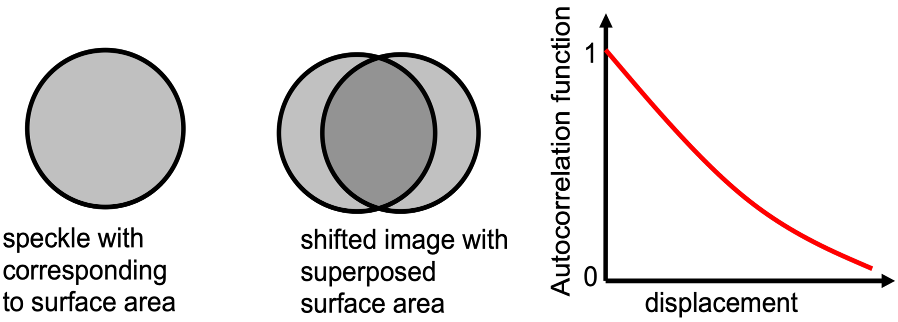


Figure 6: Single speckle and surface area of two shifted speckle pattern. The autocorrelation in the present sitation.

At zero shift the speckle is superposed with itself and the integral is maximum. If one shifts one of the images the superposition becomes smaller. Because the speckle pattern is a statistical pattern only the speckle with itself contributes to the autocorrelation function. All other contributions are averaged out and give a background signal that is not specific. It is of advantage to make a **correction of the background** (DC subtraction) of the initial images to get a direct access to the desired information. The resulting autocorrelation function is 1 for zero shift and decreases for larger shifts until there is no superposition. At this point it becomes zero (!). The autocorrelation function is defined until the whole image has been moved to its extreme and the zero overlap-shift (for the whole image) is reached. The resulting autocorrelation function is two dimensional with a **field size that is the double of the original field**. It is advised to limit the field size in order to reduce the computer memory usage and the computing time. A typical example is shown below.

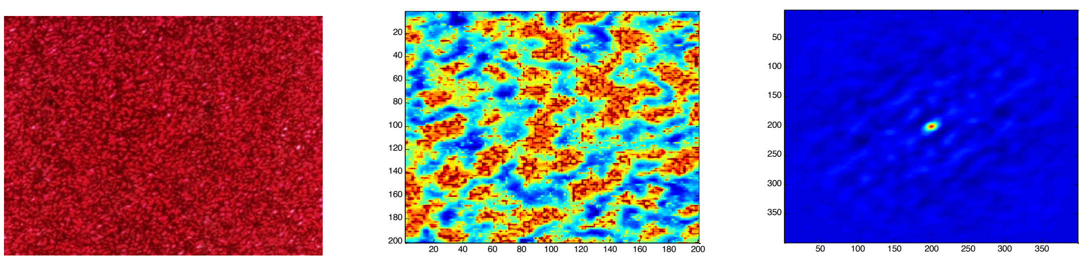


Figure 7: Sequence of the analysis for speckle size evaluation. From the original image (1600x1200) on the left a small region of interest of 200x200 pixels is chosen (middle) and the autocorrelation is plotted on the right.

In practice a speckle images is recorded. A single channel (red, because our laser is red) is used. The average intensity (DC) is subtracted. After reduction of image size (200x200 points) the autocorrelation is done and one finds a peak. In our example that is given in pixels as approximately 20 x 14 pixels. With the pixel size of 2.835 micron of our camera we can calculate speckle size of Δx_s = 20 pxl x 2.835 μm= 56 μm, Δy_s = 14 pxl x 2.835 mm= 40 μm)

Motion sensing with speckles

One of the most interesting applications of speckle phenomena is the measurement of relative displacement and deformation. The basic idea is to observe changes in the speckle pattern after a movement or deformation by correlating different images (cross correlation). There are several aspects to consider: Size of the illuminated area and novelty, speckle size, imaging conditions and boiling speckles.

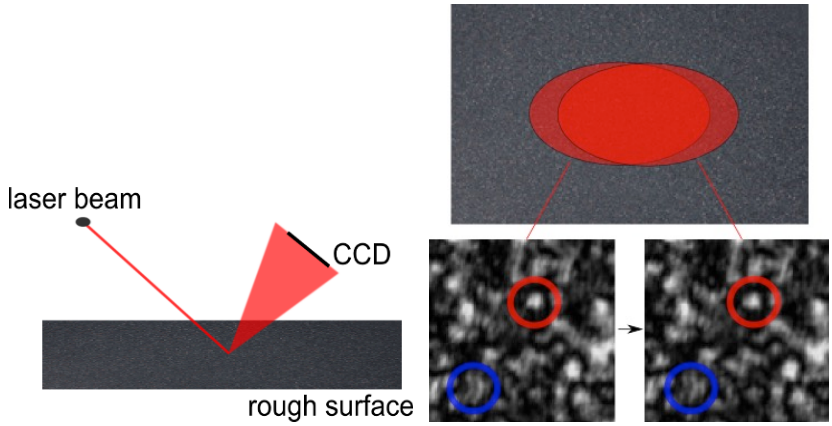


Figure 8: Geometry for speckle movement sensing. If the sample is moved the spot is moved on the surface and the speckle pattern changes its appearance.

Novelty

Imagine we illuminate a spot of certain size with a laser. The spots create speckle patterns on our detector. The spot has a defined size and we will move over the sample. Each illuminated area produces a well defined speckle pattern. When moving, parts of the initial area covered by the spot are not illuminated anymore and new area is illuminated. This means that new information (roughness, statistical surface) is added to the speckle pattern and other is lost. If the movement is small, the new information is little and the speckle pattern changes only a little bit. Crosscorrelation image is similar to autocorrelation and gives high values and a peak. **If the movement exceeds the size of the illumination spot there is no correlation between the initial and final speckle pattern.** The speckle pattern is created by two completely independent (statistically) areas and therefore they are uncorrelated. Crosscorrelation is vanishing and no peak can be found. This effect has to do with the novelty of the illuminated zone. If we want to measure large movements we would need a large spot. Small movements could be detected with smaller illumination spot sizes. Note that the illumination spot size is one important parameter in speckle size calculation.
The some arguments hold for the observation area, hence the camera. Speckle patterns that are independent do not have any correlation and **if one move a speckles pattern more that the cameras (effective detection area) one would be out of range for the measurement**.

Speckle size

Speckle has to be seen in relation to the pixels of the camera. It is possible to construct a sensor where the speckle size matches the camera pixel size and use the camera as a so called “spatial filter”. In our correlation calculation the speckle size and position are given by the peak in the correlation image. It is of advantage to have a peak that has several pixels to correctly perform the evaluation in Matlab.

Boiling speckles

If imaging is used there are particular planes in space that will not contain information about the movement of the surface that creates the speckles. That is the case if the source is imaged onto the observation plane. In such a case speckle patterns are still visible and changing but it is not possible to evaluate the direction of movement. One can define the position of this so called "boiling" plane by imaging the source at a given position. A particular practical position is infinity, which means one works with a collimated beam and boiling will appear at infinity!

Movement evaluation

To measure the relative movement with speckle images one takes several images. To avoid problems with boiling the illumination is adjusted to have the image of the source at infinity, one uses hence a collimated beam. For a collimated beam, the spot radius is equal to the beam diameter. The movement exercised at ones should not exceed the spot diameter or (effective) camera size because of the novelty problem.

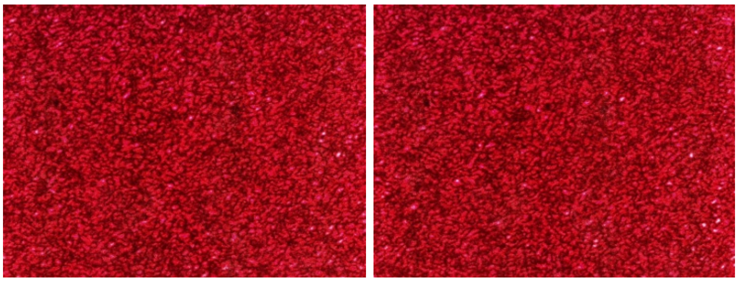


Figure 9: Speckle images before and after movement. The change in the image is hardly visible.

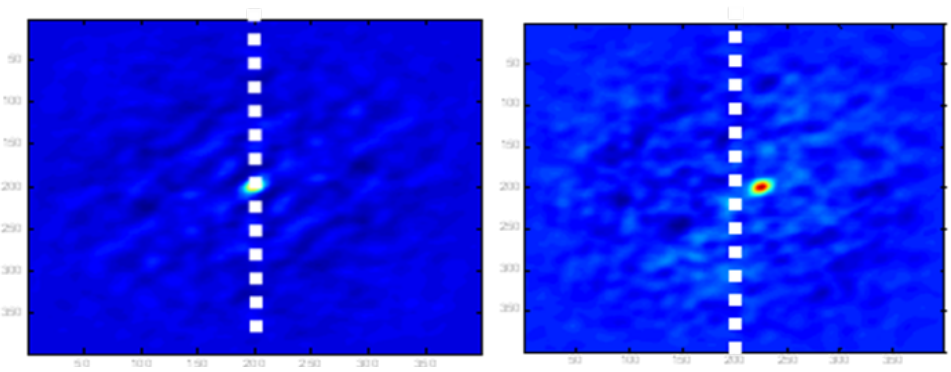


Figure 10 Movement evaluation procedure: The two speckle images are taken and evaluation is done for a region of interest. The crosscorrelation is performed and a peak is visible. On the left the crosscorrelation of an image with itself is the autocorrelation and gives a centered peak with a width corresponding to the speckle size. Right: Crosscorrelation of the two images lead to a shift of the peak position that corresponds to the movement.

If one uses collimated light the movement of the speckle patterns corresponds directly to the movement of the object because there is no magnification involved. That makes measurement very convenient. If an imaging system is used, the speed of movement of speckles on the detector plane depends on the magnification and the position of the detection plane and might vary considerably from the speed of movement of the object.

OPTIONAL READING: Spatial noise

When the speckle pattern is not under study the high contrast and small size of the speckle pattern is a nuisance. Indeed, a small translation of the speckle pattern relative to the detector (pixel) results in an unwanted intensity variation: a spatial noise. This can be particular annoying if one wants to measure a distance of an object or the intensity in a part of an image, a case common in microscopy. The main problem is that within a certain detection area different number of speckles might fall and this falsifies the measurement. As an example we will evaluate the effect of different numbers of speckles in an area on the measurement precision.

Let a detector of surface area AD be illuminated with a speckle pattern. This is illustrated below.

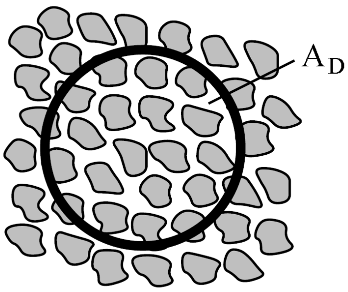


Figure11: Spekle pattern compared to detector size if several speckles are projected one a single pixel.

The power P detected is the integral of the intensity I(x) over the surface area A_D:

$$P = \int_{A_D} I(x_I)\, d^2 x_I \qquad \text{Eq. 14}$$

The average power is intensity times the surface.

$$< P >= A_D < I(x_I) > \qquad \text{Eq. 15}$$

The total power and the average power obtained for different speckle patterns of identical speckle size vary and the magnitude of these variations is related to the ratio between speckle size (number of speckles in the active detector area) and detector size. Keep in mind that the speckle pattern has always a contrast of one. We find zones with no intensity beside zones with high intensity in the speckle pattern.

We can determine the number of speckle on the detector, that is

$$N = \frac{A_D}{A_s} \qquad \text{Eq. 16}$$

The speckle surface $A_s = \pi(\Delta x_s)^2/4$ is given by the condition how speckle are created (imaging or free space). In an imaging situation we found that the speckle size was $(\Delta x)_s = \frac{4}{\pi}\frac{\lambda d_I}{D_L}$ and we find for the speckle surface

$$A_s = \frac{\pi}{4}(\Delta x_s)^2 = \frac{\pi}{4}\left(\frac{4}{\pi}\frac{\lambda d_I}{D_L}\right)^2 = \frac{4}{\pi}\frac{\lambda^2 d_I^2}{D_L^2} \qquad \text{Eq 17}$$

with the lens or aperture diameter D_L and the image distance (distance lens camera) d_I. The number of speckles N on the detector can be found to be

$$N = \frac{\pi}{4}\frac{A_D D_L^2}{\lambda^2 d_I^2} = \frac{A_D A_P}{\lambda^2 d_I^2} \qquad \text{Eq. 18}$$

where we used the surface of the aperture A_P given as $A_P = \pi D_L^2 / 4$. The formula shows that the apertures are related to the distance and the wavelengths hence to geometrical parameter and wavelengths to find the ratio.

The signal quality is given by the fluctuations δP of the power P. It can be shown that in the present situation the fluctuations are approximately proportional to the square root of the number of speckles found on the detector. One finds

$$\boxed{\frac{\delta P}{P} \approx \frac{1}{\sqrt{N}} \approx \frac{(\Delta x)_s}{D_L}} \qquad \text{Eq. 19}$$

The formula shows that if we have many speckles the fluctuations are small. For only a few speckles variations are large which can be easily understand if consider the case of a detector that has only one speckle – that might fall on the detector (full signal) or not (no signal). If we add speckles this effects becomes smaller.

The aim of the experiment is to determine the power (intensity) fluctuations over different surface areas for a selected speckle pattern and find the relation with the speckle number.

4 4. Setup and equipment - tasks of the experimental work

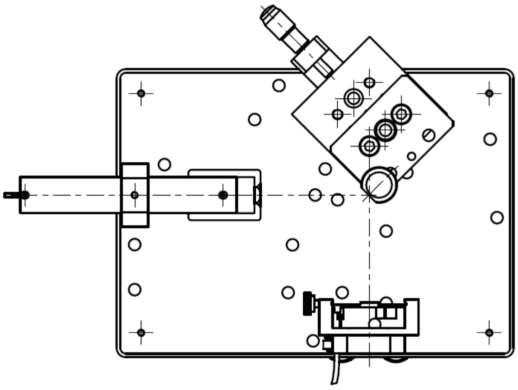
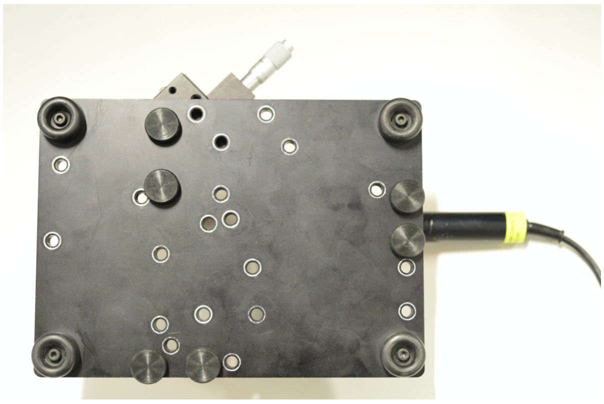
Objective

The purpose of this lab is to evaluate the influence of speckles in measurements and to build up a speckle motion sensor. Speckles motion sensors are used today in handheld devices like optical mice. The aim is to build a speckle motion sensor and measure displacements. Image correlation should be used to evaluate the speckle size and the movement over 1 mm distance.

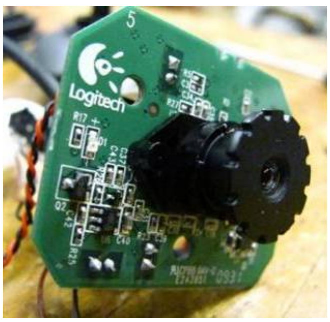
4.1. Materials, mechanical holders and setup

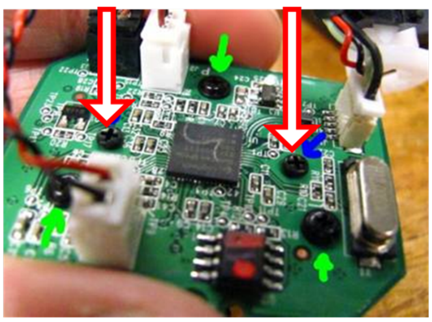
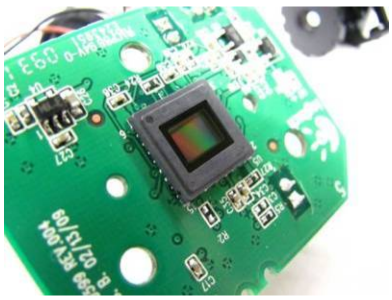
- A CMOS camera (1600x1200 pixels, colour, pixel size 2.835 um) C600 from Logitech
- Laserdiode, USB driven
- Objective lens Logitech C600
- Planconvex lens diameter 9 mm, f=12 mm
- Tape to change the illumination spot

Speckle sensing is based on interference and a laser has to be used. The light is directly projected on the camera sensor and the objective is not needed. Set up the laser source, camera and motion object as shown in the CAD drawing below.

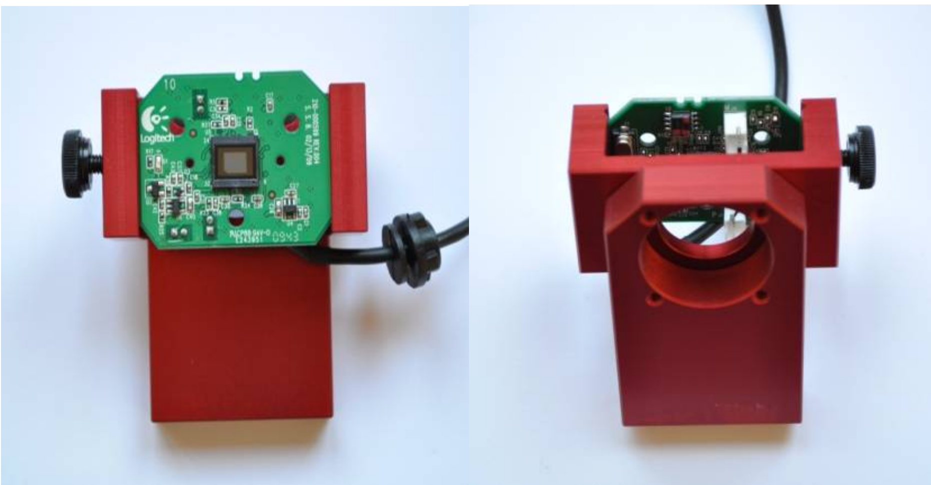



The linear stage has to be mounted with 45° movement direction with respect to the source and the camera. The camera is used without objective and IR filter to allow direct access to the camera chip.



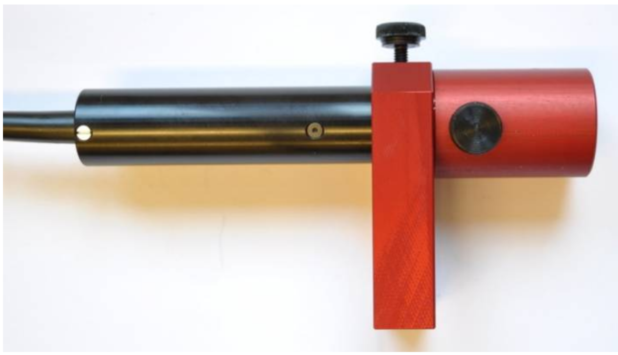



Camera is mounted in the long holder as seen below.



The flat of the cylinder **(do not touch the beam splitter!!)** is mounted parallel to the movement direction of the linear stage.

Figure 12 The cylinder is mounted on the attachment piece to have its machined flat side parallel to the movement direction.



The source is fixed with its special holder. The lens for collimation is put over the laser source end.

4.2 Speckle size measurement

First we want to evaluate conditions for different speckle sizes. The speckle size depends on the light cone (the numerical aperture) the camera sees.

The following procedure has to be applied.

- Build up the mechanics
- Apply a diffusing tape on the beam splitter holder. This can also be the BLACK tape!

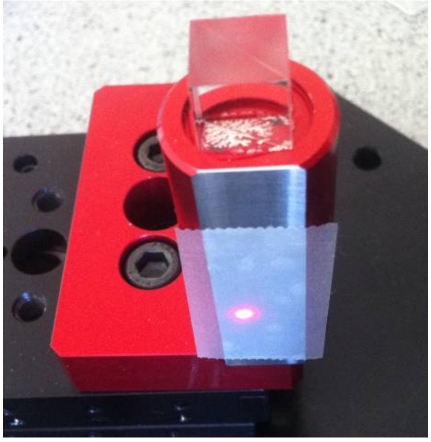


Figure 13 To increase the diffusion properties of the holder a tape (black tape or similar) has to be applied.

- Maximize the intensity by rotating the lens cap
- Focus the laser on the tape and observe the camera image for different spot sizes

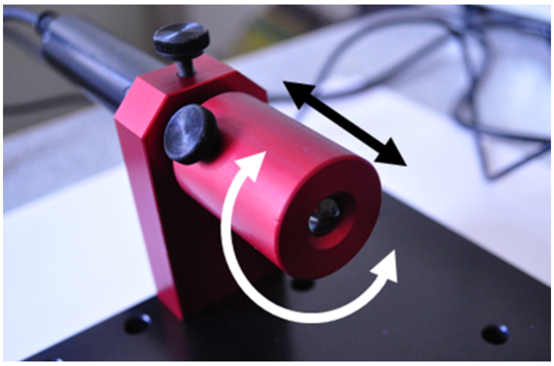


Figure 14. Focalization (black arrow) and intensity adjustment with the lens cap.

Good speckle images should look like examples given below. Try to adjust the exposure condition to use the full dynamic range of the camera (bright spots close to saturation but no saturation)

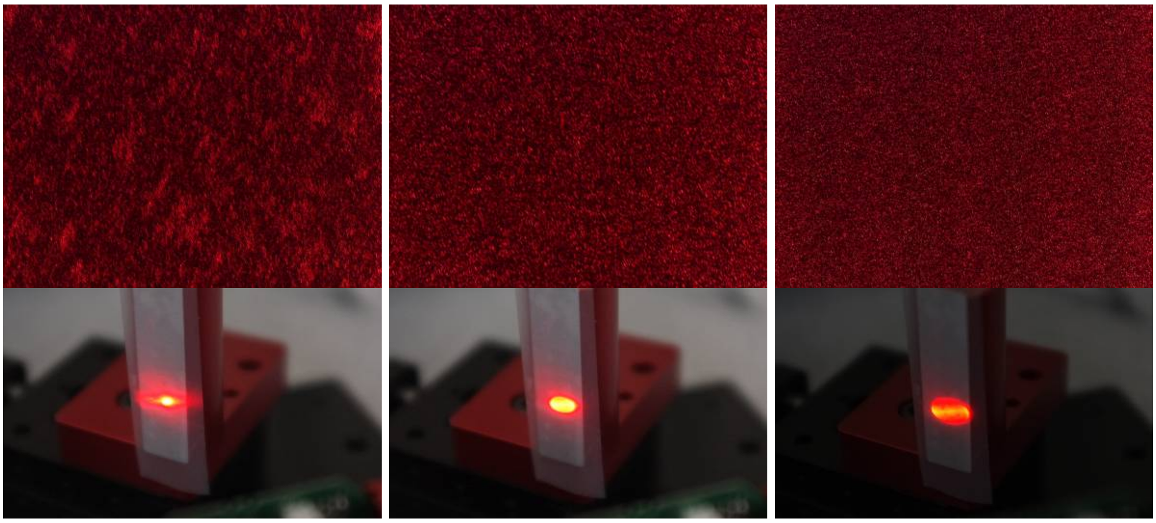


Figure 15: Speckles of different sizes found for different spot sizes on the beam splitter holder. The spot sizes are shown below. Left: small spot, medium spot size, large spot.

The evaluation is done with Matlab. You have to read the image, select a channel (here the red one because the laser is at 635 nm) and transform the format of the image before making the autocorrelation.
The autocorrelation calculates the product of two images as a function of their displacement. If this is done in two directions the final result is an image twice as large as the original. For instance, if we start with an image of 200x200 pixels, we end up with an image of 400x400 pixels. It is convenient to limit the field size to 200 x 200 pixels because of this. The background subtraction is necessary to avoid unwanted superposition of a non-significant signal.

The sample Matlab script shows the different steps: (filename: speckle_autocorrelation_line_plots.m)

```
% close images
fclose ('all');
% Read image
I_1 = imread('picture 120.jpg');
% select the red channel
R_1 = I_1(:,:,1);
% format conversion
R_1 = double(R_1);
% background subtraction 1 - mean intensity
R_1 = R_1 - mean(mean(R_1));
% select region of interest ROI (200 x 200)
R_1_ROI = R_1(501:700,701:900);
% plot selection
figure
imagesc(R_1_ROI);
% axis description
xlabel('position')
ylabel('position')
% autocorrelation
A_R_1 = xcorr2(R_1_ROI,R_1_ROI);
% plot autocorrelation
figure
imagesc(A_R_1);
% axis description
xlabel('position')
ylabel('position')
% select center line
% definition of axis value 100 -300 (center at 200)
CenterLine_vertical= A_R_1(100:300,200:200);
CenterLine_horizontal= A_R_1(200:200,100:300);
%plot a single line
figure
plot(CenterLine_vertical);
% axis description
xlabel('position')
ylabel('signal')
xlim ([0 200])
ylim ([0 max(max(A_R_1))])
figure
plot(CenterLine_horizontal);
% axis description
xlabel('position')
ylabel('signal')
```

```
% axis scaling to max y value
xlim ([0 200])
ylim ([0 max(max(A_R_1))])
```

The result of the autocorrelation is a peak at the center of the image. The lateral extension gives the speckle size in pixel. To get the physical size one has to multiply this by the pixel pitch (size) that is 2.835 micron.

- Evaluate the speckle size in your case for the x (horizontal) and y direction (vertical) direction

An example is given below:

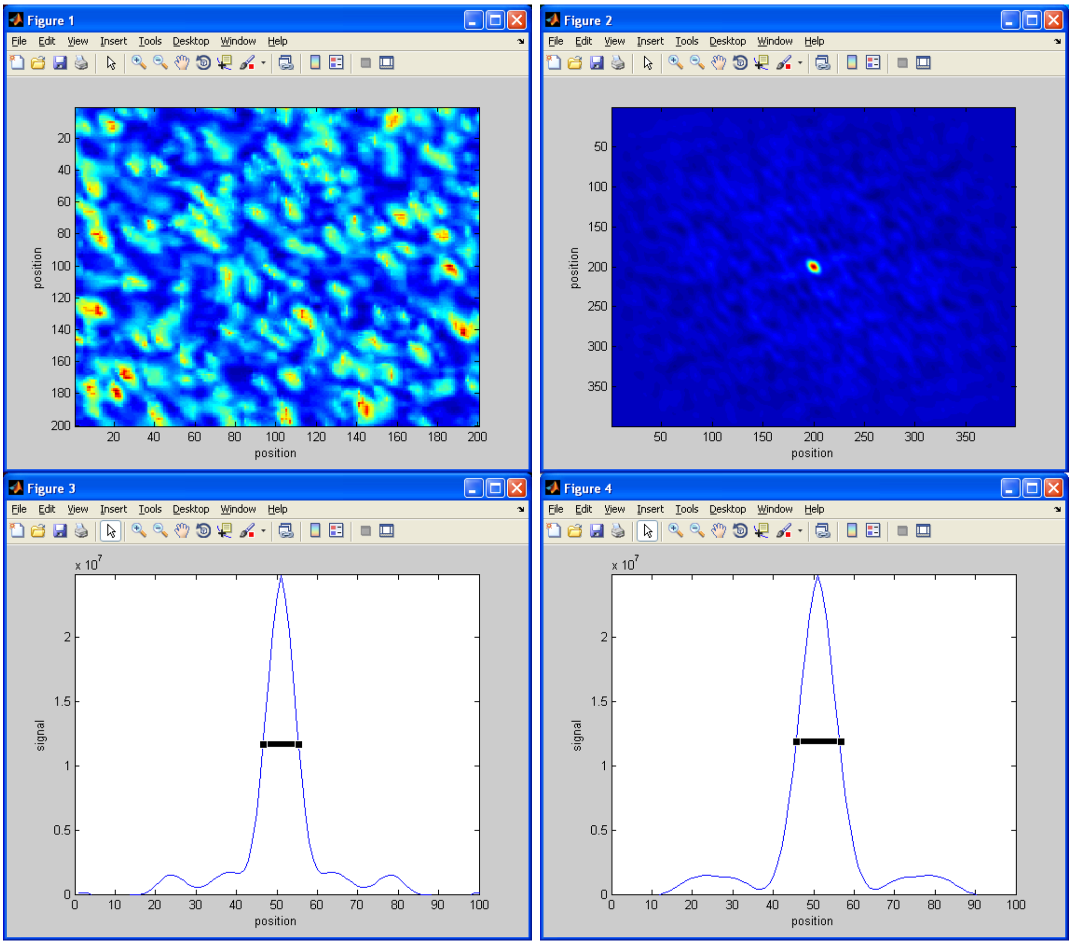


Figure 16 Top left: region of interest with 200x200 pixels. Top right: Autocorrelation function of the image on the left. Bottom: Line plots in the center of the autocorrelation function for two different directions, vertically and horizontally.

As a measure the pixel count at half height is taken to avoid the problems with the baseline noise. The black line guides the eye for both images. In our example we find

- 8 pixels in on vertical direction (Figure 3), FWHM size = 8 x 2.835 micron = 22.68 micron
- 10 pixels in horizontal direction (Figure 4) FWHM size = 10 x 2.835 micron = 28.35 micron

The distance is best evaluated with the curser directly in the curve.

The aim here is to create 3 different speckle patterns with distinct speckle size. You should proceed as follows:

- Focus the beam onto the diffusing surface
- Measure the distance of your camera chip to the diffusing light spot (between 50-60 mm)
- Observe the speckle pattern on the camera chip. (Use the black tissue if straylight becomes to large)
- Defocus slightly to get large speckles, take a picture and evaluate the speckle size.
- Increase the defocus and try to measure the spot approximately with the ruler, take a picture and evaluate the speckle size.
- Increase the defocus further, measure the spot approximately with the ruler, take a picture and evaluate the speckle size.

To be done for the report: Present one complete evaluation cycle as in the figure above. (4 graphs). Set three (3) different speckles size and make a table with spot size and corresponding speckle size and theoretical speckle size. Do not forget to measure the distance between scattering surface and detector as well as the spot size to make the theoretical speckle size calculation. Make error estimation.

4.3 Speckle motion sensor

As already mentioned above it is important to control the position of the image plane of the source and to work with flat wavefront, hence with a collimated laser. But in such a situation the control of speckle size is difficult. We use a different approach. The speckle size depends on the light cone (the numerical aperture) the camera sees. In a real system it is given by the size of the source that scatters (spot size D) and the distance to the observation plane (z), the camera plane. To achieve a reasonable speckle size with the collimated beam one has to reduce the beam diameter.

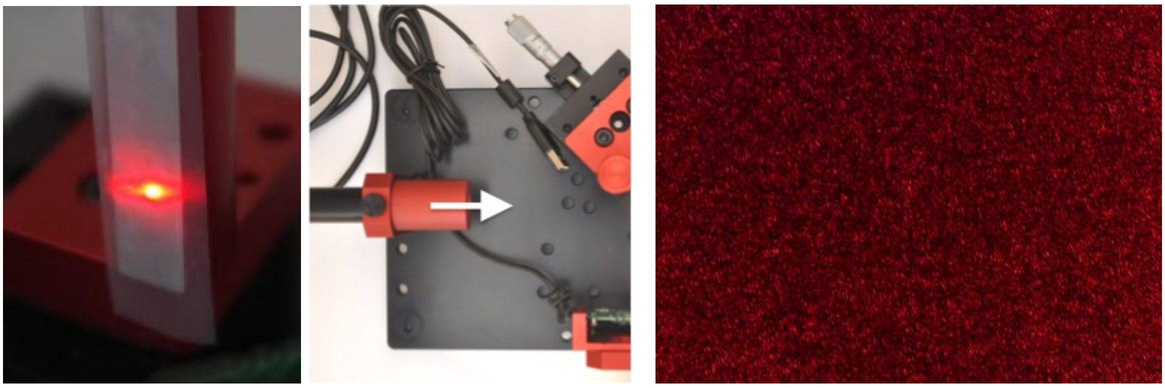


Figure 17: A focused light spot on the left should be defocussed by moving the lens cap as shown in the middle. The speckle size should be adjusted as seen in the image on the right!

Proceed as follows:

- Choose the maximum intensity and focus the laser on the support by rotating and shifting the lens cap as in Fig. 17!
- Move the lens cap towards the support to defocus.
- Observe the speckle size and choose a size similar to the images in Fig. 17 and 18

- Move the linear stage and check if the speckle pattern follows the movement by turning back an forth.

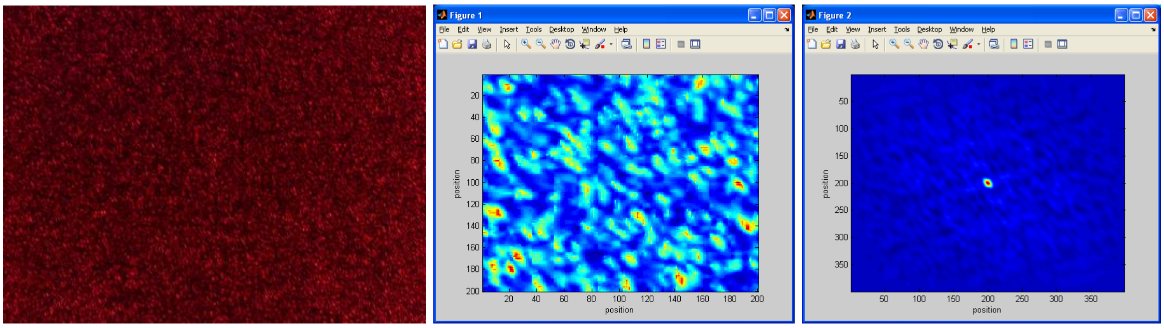


Figure 18: Convenient speckle size and its autocorrelation for the motien sensor experiment.

- Adjust the camera settings (low gain, adjust exposure, no saturation) to get the best conditions

Speckles are used to detect and measure relative motion. The process is based on cross correlation and can be done with the same setup without any modification. Instead of making an autocorrelation a crosscorrelation of two images is done.
A first image is recorded at a defined position of the sample. The sample is moved and second image is recorded. One has therefore to charge a second image, prepare the image (conversion, roi...) and make the cross correlation. In our case the images represented different positions of the linear stage.

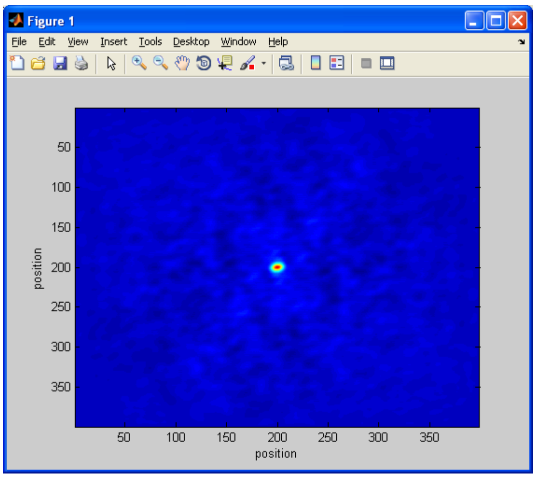
- Record a first image
- Move the linear stage by a small distance (< 100 micron) and note the distance at the linear stage
- Record a second image
- Evaluate the result with Matlab

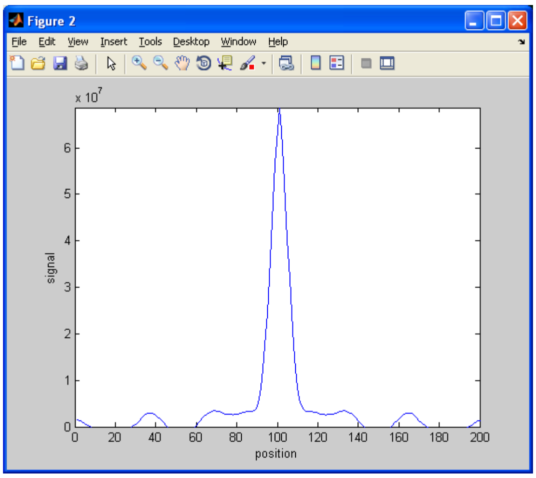
The sample script below gives you an idea of the necessary steps:
(filename: speckle_crosscorrelation_line_plots.m) It allows you to see the crosscorrelation function and delivers line plots to find the shift.

```
% % close images
fclose ('all');
% Read image 1
I_1 = imread('picture 121.jpg');
% select the red channel
R_1 = I_1(:,:,1);
% format conversion
R_1 = double(R_1);
% background subtraction 1 - mean intensity
R_1 = R_1 - mean(mean(R_1));
% select region of interest ROI (200 x 200)
R_1_ROI = R_1(501:700,701:900);

% Read image 2
I_2 = imread('picture 121.jpg');
% select the red channel
R_2 = I_2(:,:,1);
% format conversion
```

```
R_2 = double(R_2);
% background subtraction 1 - mean intensity
R_2 = R_2 - mean(mean(R_2));
% select region of interest ROI (200 x 200)
R_2_ROI = R_2(501:700,701:900);

% plot selection
%figure
%imagesc(R_1_ROI);
% axis description
%xlabel('position')
%ylabel('position')

% crosscorrelation
A_R_1 = xcorr2(R_1_ROI,R_2_ROI);

% plot crosscorrelation
figure
imagesc(A_R_1);
% axis description
xlabel('position')
ylabel('position')

% select center line
% definition of axis value 100 -300 (center at 200)
CenterLine_horizontal= A_R_1(200:200,100:300);

%plot a single line
figure
plot(CenterLine_horizontal);
% axis description
xlabel('position')
ylabel('signal')
% axis scaling to max y value
xlim ([0 200])
ylim ([0 max(max(A_R_1))])
```

The evaluation will lead to the following sequence of sample pictures:





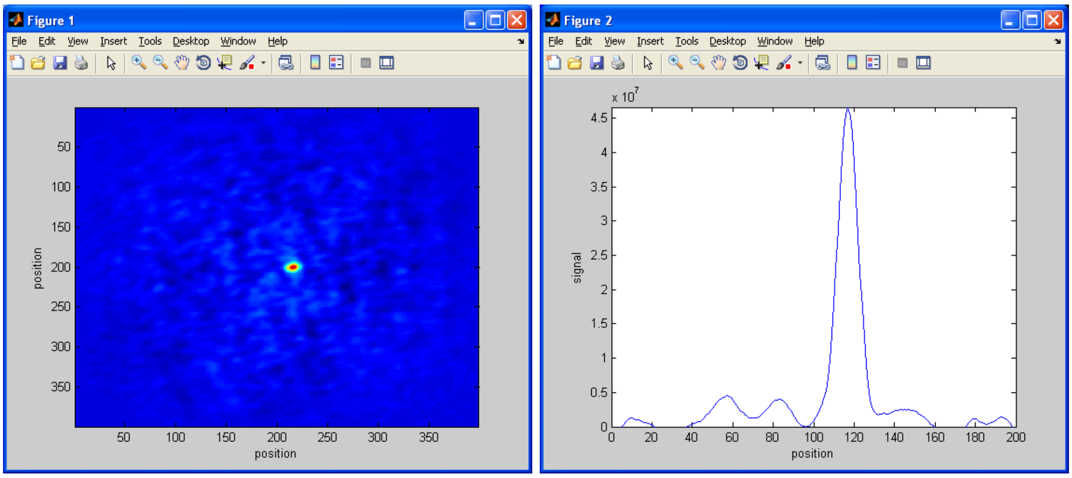


Figure 19: Autocorrelation (one and the same image is used in crosscorrelation Matlab script) and crosscorrelation after small movement. The peak has shifted by about 17 pixels.

The result is a peak that shows a displacement. Use the maximum peak position as criteria. **Measure this displacement and compare it with the set value. Evaluation is done in the autocorrelation plots and not in the line plots.** If the movement becomes larger de-correlation appears because of the novelty effect. Measure the displacement over a larger distance to see the degeneration of correlation. Choose steps between 20 to 100 micron. Determine the point where the images are not correlated anymore. This is the maximum measurement distance.
The cross correlation image sequence might look like this:

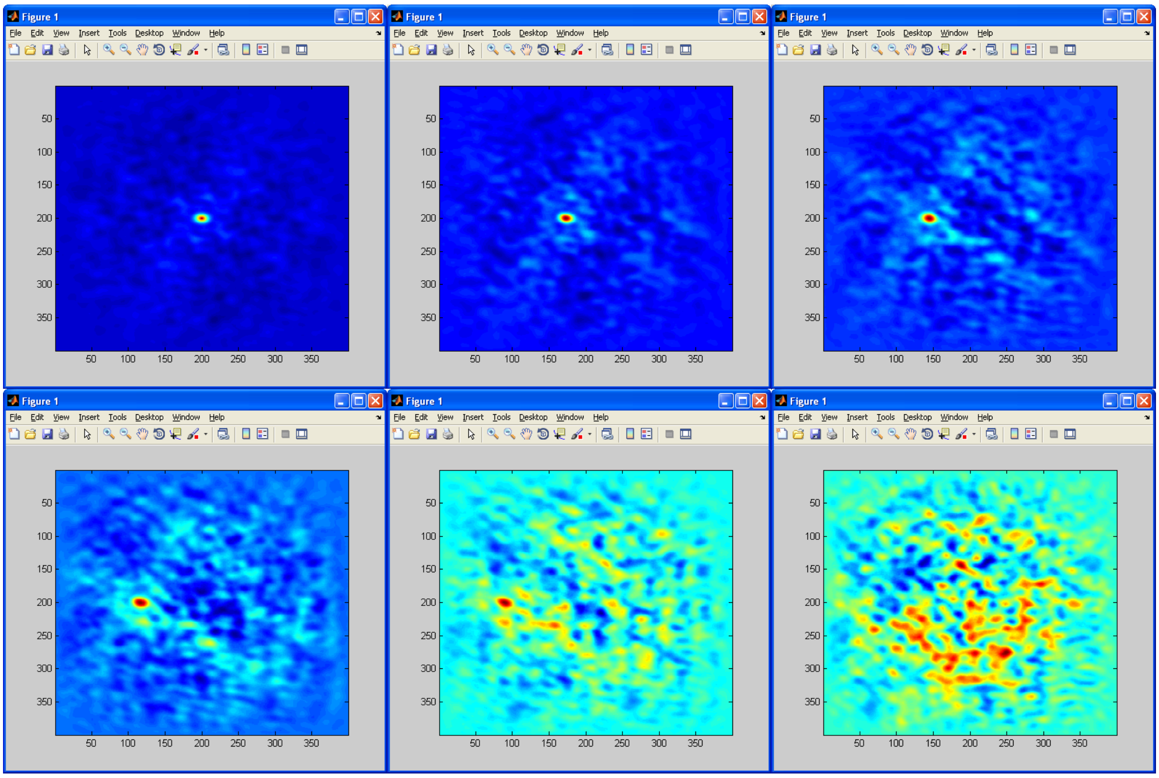


Figure 20: Crosscorrelation for large distance moves.

The first images show a well defined correlation peak while the last one does not anymore. Find the maximum movement distance.

To be done for the report: Find the maximum displacement (no information content) and read the value on the linear stage. Document the de-correlation with three images: Autocorrelation, intermediate value, fully de-correlated. Measure the displacement within the measurement range by speckle autocorrelation for a minimum of **ten** positions at the linear stage and draw a graph (plot – position of the stage against position evaluated by speckle sensor, print it in the document).

Max movement distance:

4.4 Boiling speckles

There exists a situation when the speckles field does not give any movement direction information. This is the case if the source is focused onto the detector. The configuration can be set up as:

- Remove the black tape that stops down the beam
- Remove the diffusing Scotch tape from the beam splitter holder
- Focus the laser beam onto the detector. This will give a line of focus. Be careful in adjusting the focalization position to assure best focusing.
- Apply the diffusing scotch again
- Evaluate the speckle images by taking a first image (speckle size)
- Move the object with the translation stage only very little.
- Evaluate the cross correlation between the two images.

Your will find a result similar to this:

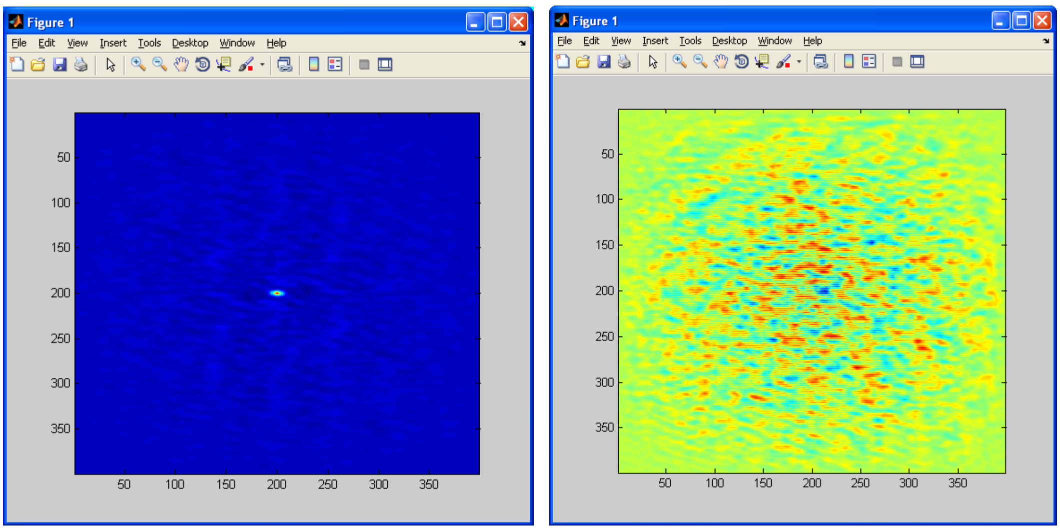


Figure 21 Crosscorrelation of speckle images in boiling speckle situation. Left autocorrelation of the initial speckle pattern. Right Crosscorrelation. A movement of only 10 micron led to complete de-correlation.

A small movement will lead to complete de-correlation. **This can be seen already by naked eye by looking at the speckle pattern and moving the stage.** If the system is well adjusted one is not able to divine the direction of the movement. Find this boiling position and take images for approval. Note the minimal movement distance to obtain full de-correlation.

To be done for the report: Show **three** (3) correlation images, one in autocorrelation and two for boiling crosscorrelation when the movement is in opposite directions. Give the minimal movement distance for the fully de-correlated image.

5. Summary of tasks of the experimental work

4.2 Speckle size measurement (40 min)

Present one complete evaluation cycle as in the figure above. (4 graphs). Set three (3) different speckles size and make a table with spot size and corresponding speckle size and theoretical speckle size. Do not forget to measure the distance between scattering surface and detector as well as the spot size to make the theoretical speckle size calculation. Make error estimation.

4.3 Speckle motion sensor (60 min)

Find the maximum displacement (no information content) and read the value on the linear stage. Document the de-correlation with three images: Autocorrelation, intermediate value, fully de-correlated. Measure the displacement within the measurement range by speckle autocorrelation for a minimum of **ten** positions at the linear stage and draw a graph (plot – position of the stage against position evaluated by speckle sensor, print it in the document).

Max movement distance:

4.5 Boiling speckles (20 min)

Show **three** (3) correlation images, one in autocorrelation and two for boiling crosscorrelation when the movement is in opposite directions. Give the minimal movement distance for the fully de-correlated image.