Pinhole camera –

Modulation transfer function

[Version 21.2.2020]

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Contents

1 Objective and overview

The practical work introduces the following subjects to you:

- Pinhole imaging
- Intensity variation in an image
- Measuring the modulation transfer function of an imaging systems

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

PLEASE consult the summary of tasks at the end of the document and control if you have all tasks done!

2 Safety Issues

In this experiments laser sources and low power electrical equipments 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

3.1. Diffraction at circular apertures

A basic limitation of imaging systems is the diffraction of light. Most imaging systems have circular apertures. We review here the basic formulas used in optical engineering.

Pinhole diffraction

Consider a hole with a small diameter. If a plane wave is send onto the hole, light is transmitted and diffracted. Detailed mathematical analysis can be found in supplementary literature (Script O. Martin, Optical Engineering, Saleh Teich, Photonics, Wiley 1991, Chapter 4). As a result of diffraction, light intensity will be not only found in the geometric projection behind the aperture but also aside. The figure below illustrates this effect.

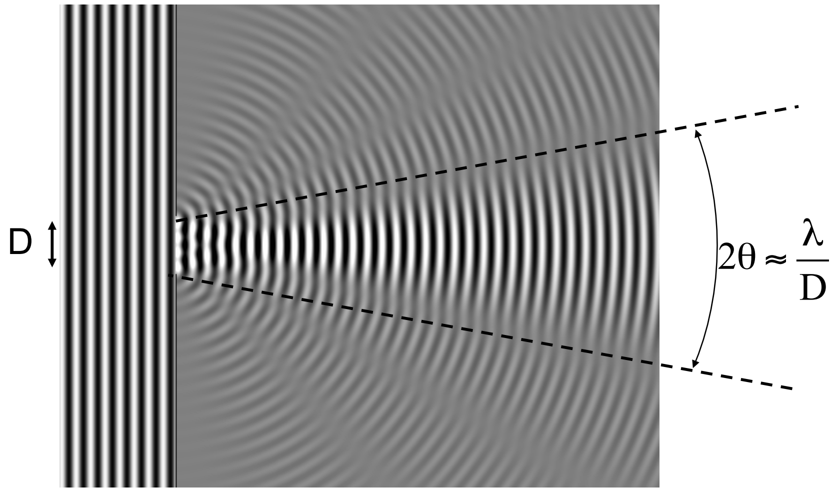

Figure 1. Diffraction at an aperture leads to a spreading of light over a certain angular range. (http://en.wikipedia.org/wiki/File:Wave_Diffraction_4Lambda_Slit.png)

The diffraction sends the light into a solid angle that depends on the wavelength and the size of the aperture. As a rule of thumb one can assume that the angle θ is proportional to the wavelength divided by the size of the aperture.
Diffraction is a wave phenomena. It is also found in water waves. The figure below shows an example of ocean waves passing through slits in Tel Aviv, Israel. (Image taken from *phweb.physics.gatech.edu/gcuo/lectures/.../MP05Diffraction.ppt, 2008)*

Figure 2 Water wave diffraction at "slits". The beach takes the form of the wavefronts. (phweb.physics.gatech.edu/gcuo/lectures/.../MP05Diffraction.ppt)

In a more rigorous description one can derive the exact formulas. Imagine an aperture with a diameter D. The intensity distribution observed at a large distance behind this aperture is an Airy pattern.

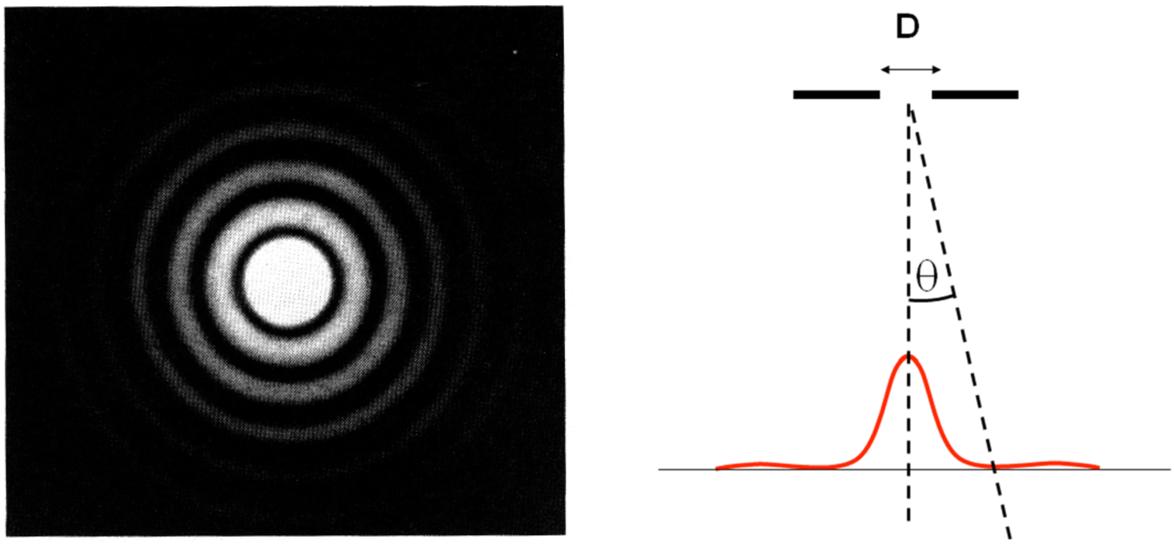

Figure 3: Airy pattern and geometry to describe the different maxima and minima of the intensity.

Such an intensity pattern has several maxima and minima. The first minimum is found at an angle θ

$$\theta = \frac{1.22 \cdot \lambda}{D} \qquad \text{Eq. 1}$$

where λ is the wavelength of light and D the diameter of the aperture.

Example:
For a diameter of D=50 micron and a wavelength λ=0.5 micron (green light) we find

$$\theta = \frac{1.22 \cdot \lambda}{D} = \frac{1.22 \cdot 0.5}{50} = 0.0122 \text{ rad} = 0.7°$$

This angle describes the spreading of the light beam behind the aperture. We define the Airy disk as the area limited by the first zero of intensity of the Airy pattern. About 84% of the light is within the Airy disk. In our example of a 50 micron aperture, at a distance z = 5 mm, the diameter of the Airy disk is given by:

$$D_{5mm} = 2z\sin(\theta) \approx z \cdot 2\theta = 2.44\frac{z \cdot \lambda}{D} = 2.44\frac{5000 \cdot 0.5\mu m}{50} = 122 \text{ micron}$$

This means we would see a disc that is more than twice as large as the original aperture.

Diffraction at lenses

Diffraction limits the minimal spot size that a lens can make. Figure 4 shows the basic imaging geometry. The focal length is f and the diameter of the lens is D.

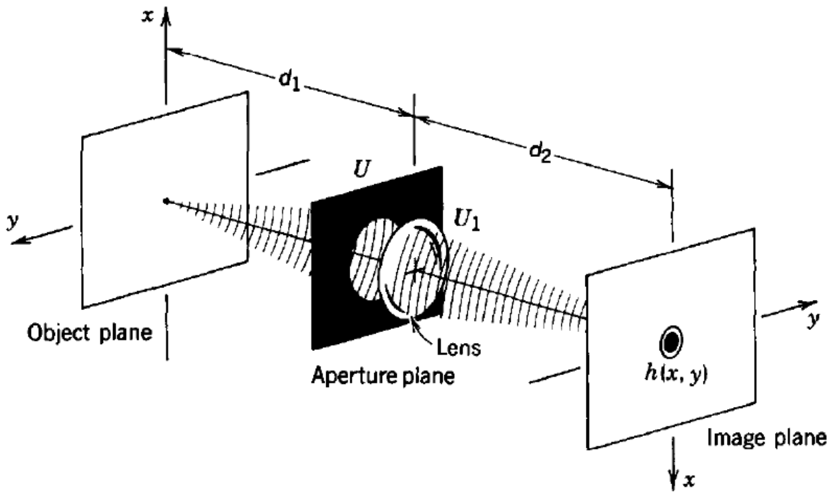

Figure 4. Basic geometry to discuss diffraction limitation for a lens considering imaging with a single lens system (Image from Saleh Teich, Fundamentals of Photonics, Wiley 1991)

The object plane is imaged into an image plane through the lens and the object distance and image distance are d_1 and d_2 respectively. One can define a transfer function (U, U_1) to analytically describe the image formation. A point source on the object plane would create a intensity that can be described by a function h(x,y) that is significant for the Airy pattern (impuls response function). When the aperture is the lens diameter D and the distance from the image plane is d_2 one finds a minimal spot size δ (Diameter) that is given as

$$\delta = 2.44\,\lambda \frac{d_2}{D} \qquad \text{Eq. 2}$$

Often the object distance d_1 is much larger than the image distance d_2 and the focal length and one can use in good approximation the assumption that d_2 is nearly the focal length f of the lens. We rewrite Eq. 2 accordingly and get

$$\delta = 2.44\,\lambda \frac{f}{D} \qquad \text{Eq. 3}$$

More insight into the relation between the different definitions can be get if we further simplify

$$\delta \approx 2\lambda \frac{f}{D} \qquad \text{Eq. 4}$$

which allows to substitute f/D by the F# number. One finds

$$\delta \approx 2\lambda F\# \qquad \text{Eq. 5}$$

For a wavelengths of λ=0.5 micron (green light) one would find that the **F# in micron is the minimal focusable spot size**. A very useful rule of thumb in photography and imaging! We can substitute the F# also by the NA and get

$$\delta \approx \frac{\lambda}{NA} \qquad \text{Eq. 6}$$

The diameter of the Airy disc (minimal spot size δ) is inverse proportional to the numerical aperture and direct proportional to the the wavelength.

Diffraction and resolution

When two neighbouring points are imaged, they can be observed as two points if they are separated, that is, resolved. The image below illustrated different situations.

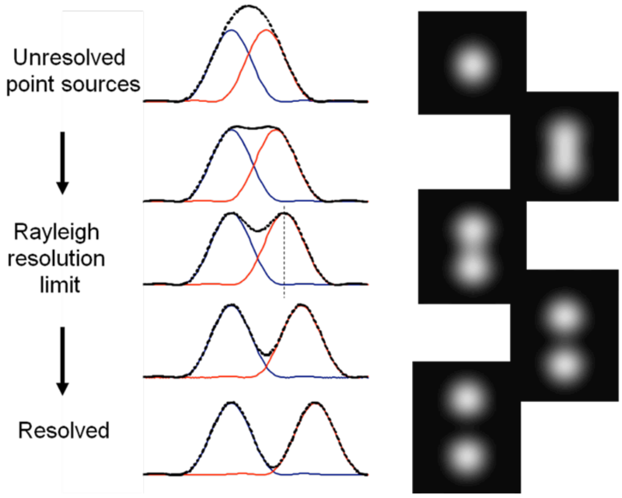

Figure 5. Illustration of a resolution criterion for two point sources. Each source forms an Airy pattern which is here represented as a single spot. If the spots are getting too close they cannot be resolved anymore.

The most common resolution criterion is the **Raleigh resolution limit**. It states that two points in an image can be resolved if the maximum of the diffraction pattern (Airy disc) of the second point is outside the diameter defined by the first zero of the diffraction pattern of the first point. The minimal distance Δx between two points that can just be resolved becomes

$$\Delta x = 1.22\,\lambda \frac{d_2}{D} \qquad \text{Eq 7}$$

which is half the Airy disc diameter. Please note that the **contrast** in such a situation is not 100% as can be seen in the figure above.
An imaging system, therefore, resolves a limited number of points. This number can be limited by the optical system or by the detector. An optimal system has a match between the number of points transmitted by the optical system and the number of pixels of the detector. Usually one defines a disc size that models the resolution of the optical system. Resolution is achieved if the contrast of point images is still 100% which is the case when the discs do not overlap. The figure below illustrates that model.

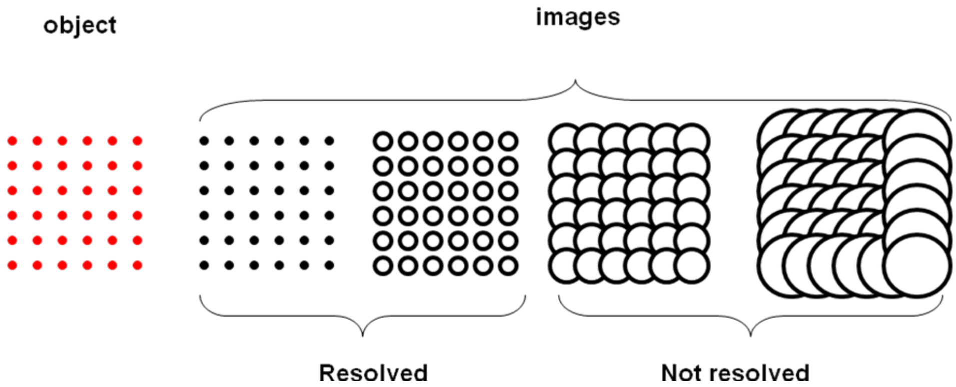

Figure 6. Resolution for an array of points when a minimum resolution disc diameter is assumed. The two cases on the right could not be considered as resolved anymore.

3.2 Pinhole camera principle

The pinhole camera is one of the simplest optical systems. It consists of a small hole and a light sensitive surface to record an image. In a geometrical description, the light reflected or emitted from an object passes through the pinhole and reaches the screen or the detector. The distance from the pinhole to the screen (image distance) is small compared to the objects distance. This situation is illustrated bellow.

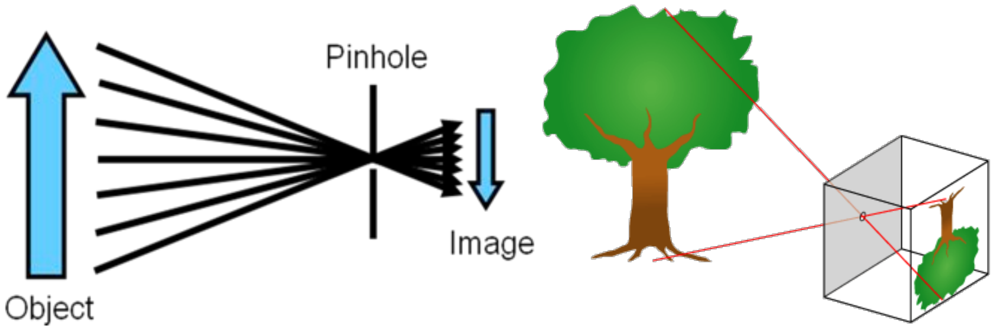

Figure 7. The geometric optics description of the pinhole camera. Light rays passes through the hole and reaches a screen or a photosensitive area. A demagnified and mirrored image appears. (images WEB, Wikipedia)

In opposition to a lens that takes the light diverging from a point of the object and make it converge to a point of the image, a pinhole only limit the angular spread of light. The image formed by the pinhole is not sharp. Its 'softness', however, is almost constant with distance. Therefore, it is said that the pinhole camera has an infinite depth of field. The pinhole has no optical power, therefore the concept of focal length is inappropriate. The magnification is the the image size divided by the object size, or similarly the image distance divided by the object distance $-d_i/d_o$.. It is negative because the image is reversed.

In a purely geometrical description, the pinhole size gives the resolution. The smallest point created on the screen is the shadow of the pinhole size. The smaller it is the better is the resolution. But when the pinhole is small only little light enters and diffraction effects have to be considered.

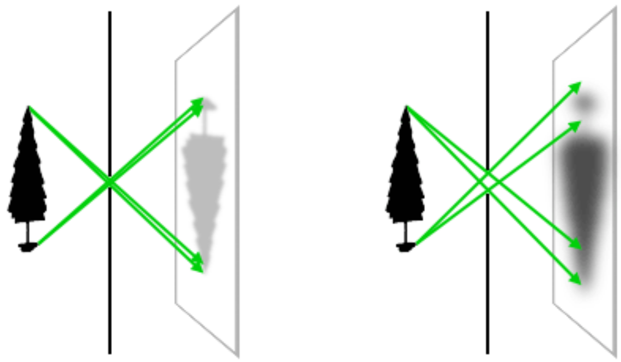

Figure 8. Pinhole influence on resolution in a geometrical model.

In the example of figure 8, the small hole through which the light passes, restricts the possible angles of light reflecting from a certain part of the tree. The overlap of light rays on the projection is very small and the result is a sharp image. A large hole allows a greater variety of angles of reflected light from a particular part of the tree to pass through onto the projection. This means that the light from neighboring parts of the tree overlaps. The contrast of the image is degraded. However, more light gets through and the image is brighter.

The image brightness is not constant over the image. The variation of brightness is the result of the projection of the light rays onto the screen/detector under certain angles.

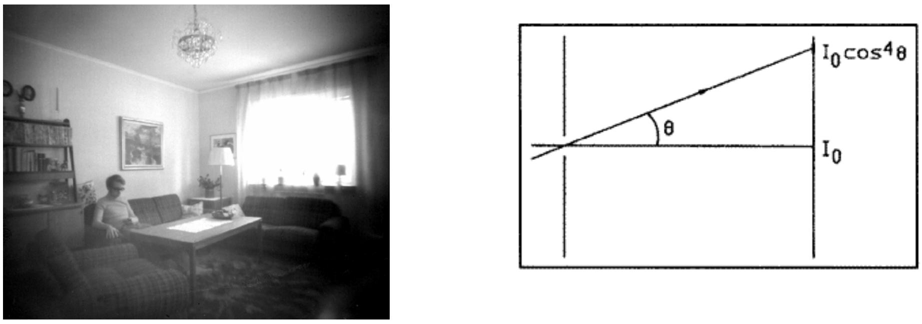

Figure 9. A strong angular dependence of the intensity is visible in images taken with the pinhole camera (Left). The geometry to quantify that effect (right). (image from Kjell Carlsson, Biomedical & X-ray Physics,The Royal Institute of Technology, SCFAB/Albanova, 106 91 Stockholm, Sweden., The Pinhole Camera Revisited)

Consider a small area imaged off axis by an angle θ. From the image plane the pinhole appears as a bright spot of light, a source. The off-axis image is farther from the pinhole, compared with the on axis point, by $1/\cos\theta$. According to the inverse-square law, the irradiance there is reduced by $\cos^2\theta$ compared to the on-axis irradiance. In addition, the pinhole appears smaller by $\cos\theta$ because of the obliquity. Finally, the light falls obliquely onto the film plane, and therefore, it illuminates an area $1/\cos\theta$ larger than the equivalent area on axis. The combination of these three effects results in the cosine to the fourth law.

3.3 Optimum pinhole size

The pinhole camera has a certain resolution that is given by the size of the pinhole. Because the pinhole is small, diffraction of the pinhole influences the resolution. There are several drivers for optimization of the pinhole size.

- The light throughput should be high which needs **large pinholes**.
- One wants to make the resolution as high as possible by using **small pinholes**.
- The diffraction at the pinhole aperture has to be considered which is larger for small pinholes.

Analysis of the diffraction properties lead to an optimal pinhole detector distance d_2 that can be expressed as

$$d_2 \approx \frac{D^2}{4\lambda} = \frac{a^2}{\lambda} \qquad \text{Eq.8}$$

where a the pinhole radius and D the diameter.

Example: Pinhole diameter 300 micron. Wavelength 0.5 micron.

$$d_2 \approx \frac{D^2}{4\lambda} = \frac{300^2}{4\,0.5}\text{micron} = 45\text{mm}$$

3.4 Pinhole camera examples

The pinhole camera is also called camera obscura, which means “dark room” in Latin. The Renaissance painters used camera obscura to achieve realistic paintings (perspective). Vermeer painted “The Girl with a Pearl Earring” (1665-7) using one.

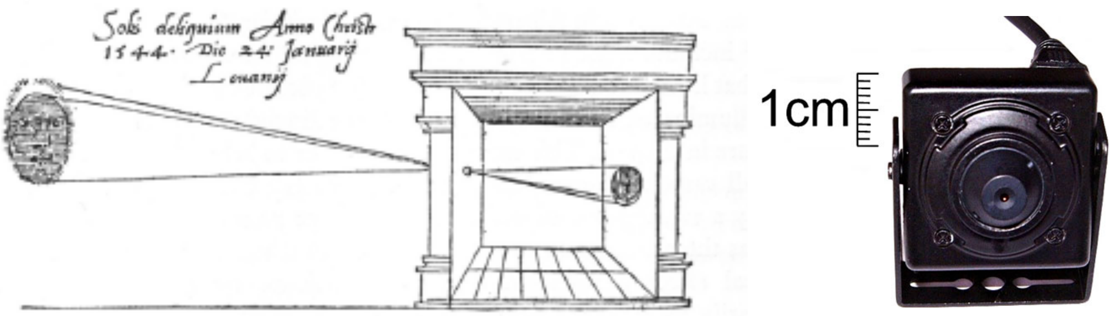

Figure 11. Tow examples of a pinhole camera. Left: A dark room with a small hole in a wall to project images on the wall. Right: A spy camera of small dimensions using a pinhole. (image from Kjell Carlsson, Biomedical & X-ray Physics,The Royal Institute of Technology, SCFAB/Albanova, 106 91 Stockholm, Sweden., The Pinhole Camera Revisited, Web)

Figure 12 A freestanding room-sized camera obscura in the shape of a camera located in San Francisco at the Cliff House in Ocean Beach (San Francisco) (Image Wikipedia).

The advantage of pinhole cameras is that focussing is unnecessary. They might be used as cheap spy cameras to observe scenes with large depth of field. One disadvantage is the very low light throughput.

In 1979, Franke invented the 'widefield' pinhole camera. It is a pinhole and a hemisphere lens. The hemisphere lens acts as a so called **field lens**, or a lens that increases the field of view but does not itself project an image. (M. Young, The pinhole camera, The Physics Teacher, December, 1989, pp. 648-655.) If the index of refraction of the hemispherical field lens is 1.5, the hemisphere (90 deg. field of view) is compressed to a 42º cone. Franke found a slight distortion beyond about 70º and that the optimal index of refraction for aberration free imaging would be 1.3. This is the index of refraction of water, and, in fact, once submerged in water the same effect can be achieved.

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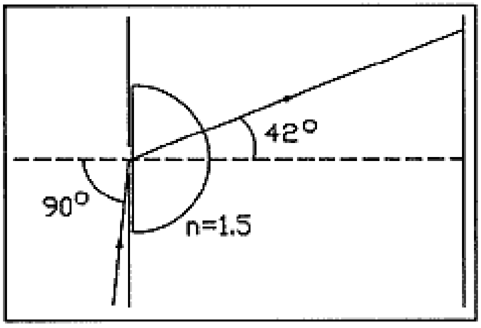

Figure 13. Franke's widefield pinhole camera and a realisation as an on chip multiple channel camera using microlenses and pinholes.

3.5. Modulation transfer function

Using the mathematics of Fourier transforms, an object can be decomposed into so called spatial components, each of these having a given (spatial) frequency, amplitude (modulation or contrast), phase (position), and orientation (See Fig. 14). If the effect of an optical system on all possible spatial components is known, then the aspect of the images it produces could be estimated for any object.

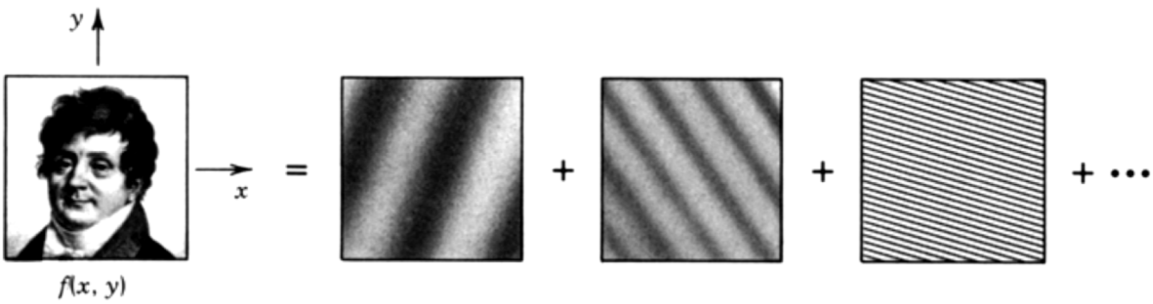

Figure 14. Example of the first orders of a decomposition of an image. Please note that the decomposition is spatially resolved and that the frequency, the contrast and the phase are needed to get a complete description. (image from B. E. A. Saleh, M. C. Teich, *Fundamentals of Photonics.* Wiley 1991)

This concept of spatial decomposition into **spatial frequencies** is extremely powerful to analyses the information transformation in imaging systems. Usually a high contrast pattern loses contrast when transmitted and this means that an optical system acts as a low pass filter on the different spatial components. Figure 15 illustrates this effect for a stripe pattern of black and white lines. The loss of contrast is described by the **modulation transfer function** (MTF).

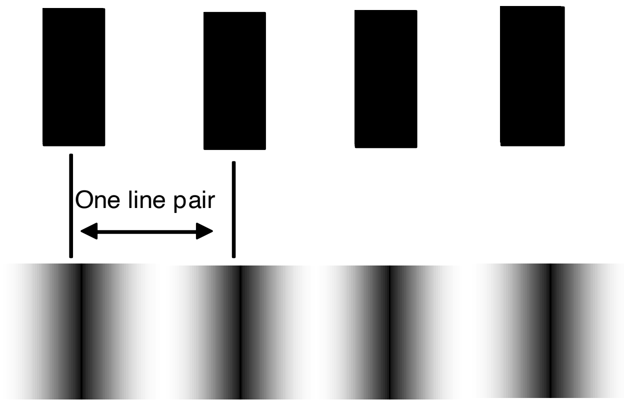

Figure 15. The black and white stripe pattern is transmitted through an optical system with less contrast and “softened”. The contrast in the image for each period of the line pattern is a measure for the quality of the system.

The MTF of a 'perfect' (aberration free) system with circular aperture and an incoherent illumination is given by

$$MTF(\nu) = \frac{2}{\pi}\left(\arccos\left(\frac{\nu}{\nu_C}\right) - \left(\frac{\nu}{\nu_C}\right)\sqrt{1-\left(\frac{\nu}{\nu_C}\right)^2}\right) \qquad \text{Eq. 9}$$

where ν is spatial frequency (mm^{-1}) and ν_c is the so called cutoff frequency that describes the frequencies where the contrast becomes zero:

$$\nu_c = \frac{2NA}{\lambda} \text{ or } \nu_c = \frac{1}{\lambda F\#} \qquad \text{Eq. 10}$$

A normalized plot of Eq. 10 is shown in Figure 16.

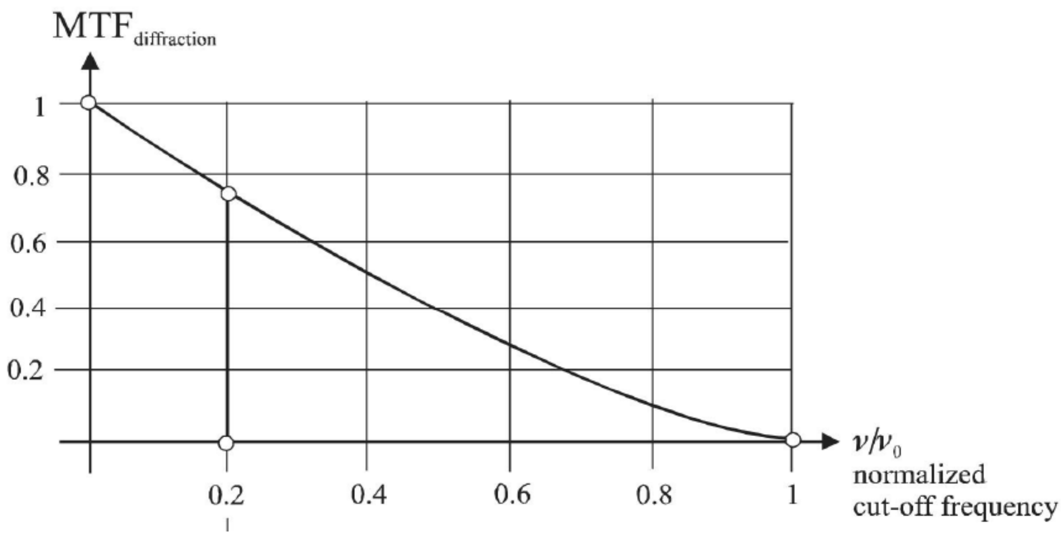

Figure 16. Example of an ideal modulation transfer functions for a diffraction limited system. (picture from: Riedl, Optical Design ISBN 0819477990, SPIE Publishing)

For the visible spectrum with λ = 0.5 µm (green light), the cut-off frequency in line pair/mm is

$$\nu_c\left[\frac{\text{lines}}{\text{mm}}\right]=\frac{2000}{F\#} \qquad \text{Eq. 11}$$

Please note that

1. The MTF is normalised to 1 for ν=0.

2. The MTF reaches 0 for $\nu <= \nu_c$, the cutoff frequency. The cutoff frequency is related to the smallest detail in the image, that is its resolution limit.

For real systems, the MTF is different from Eq. 9:

1. Any optical imperfections (aberrations, vignetting, scattering...) lowers the MTF.

2. For different shapes of the aperture, the MTF depends on the orientation of the spatial components. The MTF is bi-dimensional.

3. Real optical systems are not shift-invariant. In other words, the MTF measured or computed depends on the field position, e.g., on-axis, mid-field, image border.

The quality of an image cannot be reduced to a single number, e.g., the cutoff frequency. **Indeed, the aspect of an image strongly depends on the contrast of all spatial frequencies.** Therefore, the MTF is and will remain an important tool to qualify imaging systems. It has the additional advantage that it can be computed using common optical design softwares and it can be measured.

For measuring the MTF uses the the modulation or contrast that is defined as

$$\text{Contrast}=\frac{I_{max}-I_{min}}{I_{max}+I_{min}} \qquad \text{Eq. 11}$$

To measure the MTF, a test pattern (lines) of high contrast is imaged by the optical system and the contrast of the image is evaluated. This is repeated for a set of pattern spanning the desired spatial frequency range. By definition (in optics), a pattern of 10 lines per mm means that the pattern period is 0.1 mm. Care must be taken that the detector do not limit the measurement range of spatial frequencies. Otherwise, the measured MTF shows the combined effect of the optical system and the detector.

The MTF depends on the position within the image. It is different for the centre and the other positions within the field of view.

As a real example we show the specification of a lens from Edmund scientific: Edmund #32-299.

Source : http://www.edmundoptics.com/technical-support/optics/modulation-transfer-function/

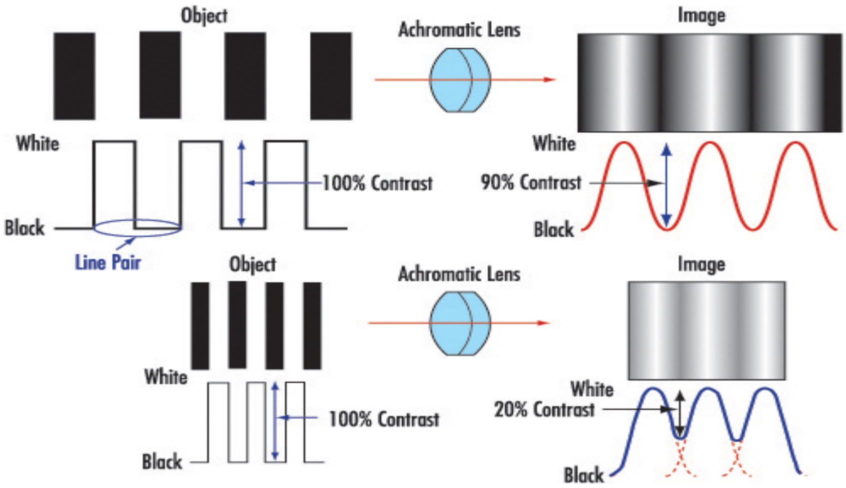

Figure 17. Principle of the evaluation of the MTF as described in the Edmund optics catalogue.

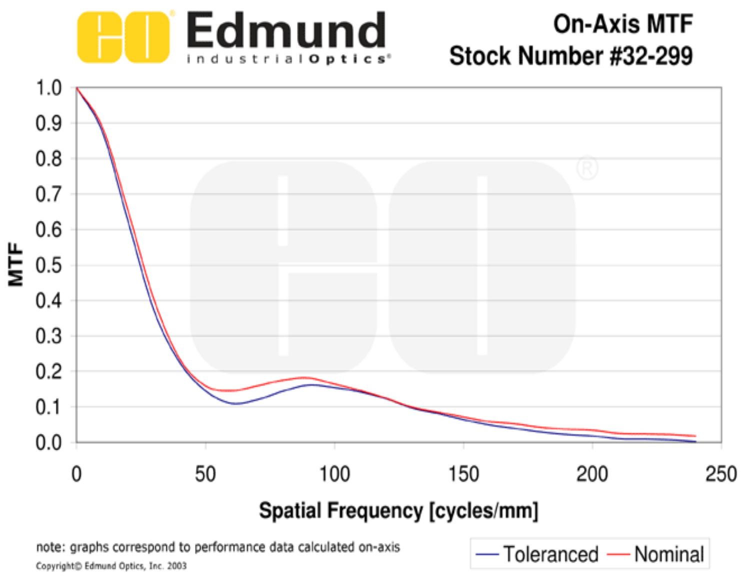

Figure 18. Example of an MTF measurement for the Lens #32-299. Frequencies until 200 cycles per mm are transmitted but at very low contrast. Often a minimal contrast is defined and the spatial frequency at this value is considered as figure of merit.

4 Setup and equipment

4.1. Materials and setup

A camera sensor (1600x1200 pixels, colour, pixel pitch (size) 2.835 um) C600 from Logitech is used as the detector.

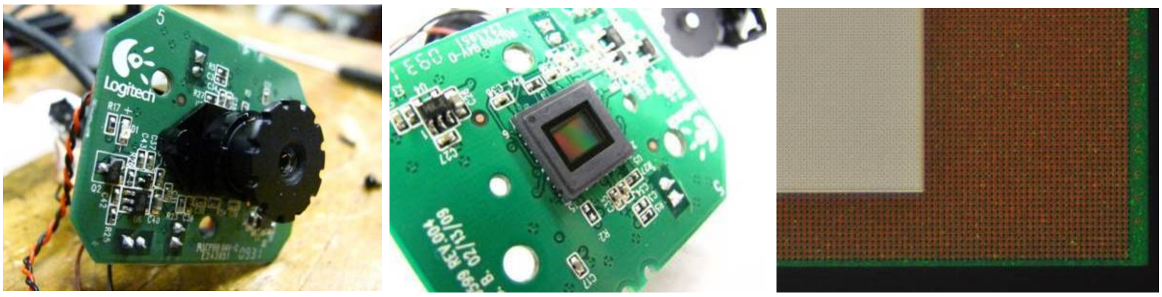

Figure 19: The camera PCB with (left) and without (middle) objective and a microscopy image of the detectors surface

Detector

The sensor appears to be a 1/3.2" Type sensor with 4:3 aspect ratio. Testing seems to indicate that the sensor is a with global shutter.

Detector width is 4.536mm x 3.416mm.

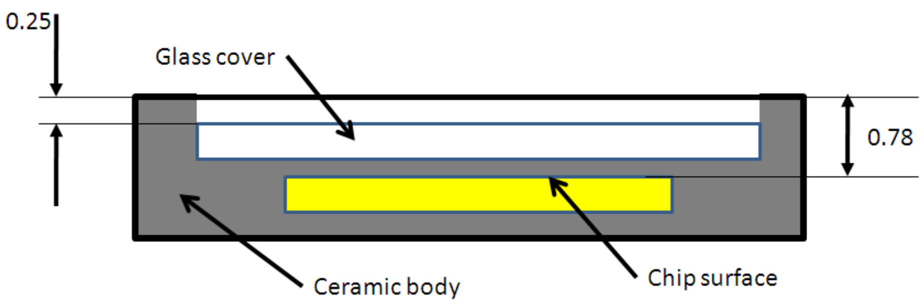

Figure 20: Detector cross section with dimensions (mm).

The distance between the ceramic body top (surface touched with flat specimens) and the chip surface is about 780 micron.

Objectives

We will use a pinhole with a diameter of 100-um mounted on a SM1 disc (Thorlabs) for imaging and to describe the image quality based on brightness, resolution, and MTF measurements.

Figure 21: A pinhole with 100 micron diameter mounted on a SM1 disc.

Setup

The MTF is measured by evaluating the contrast of stripes in images . The result is a curve of contrast versa spatial frequency. Measure such a graph for a pinhole of 100 micron.
The different pieces must be assembled according to the plans. You have to use the camera **without its original objective**, the pinhole and the software provided (Logitech) to acquire an image of the screen. Mount the optical system as shown below.

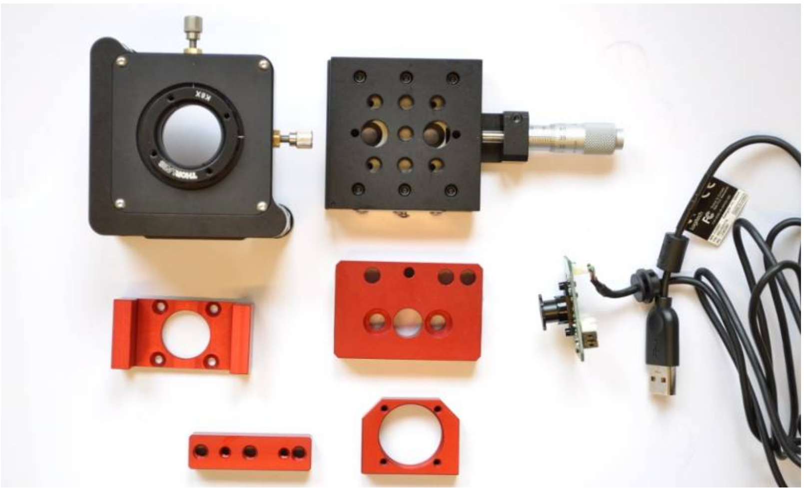

Figure 22. Parts used in this experiment. The six axis stage with x-y positioning, rotation and angular adjustment. The linear stage to set the distance precissley and parts for adjustment.

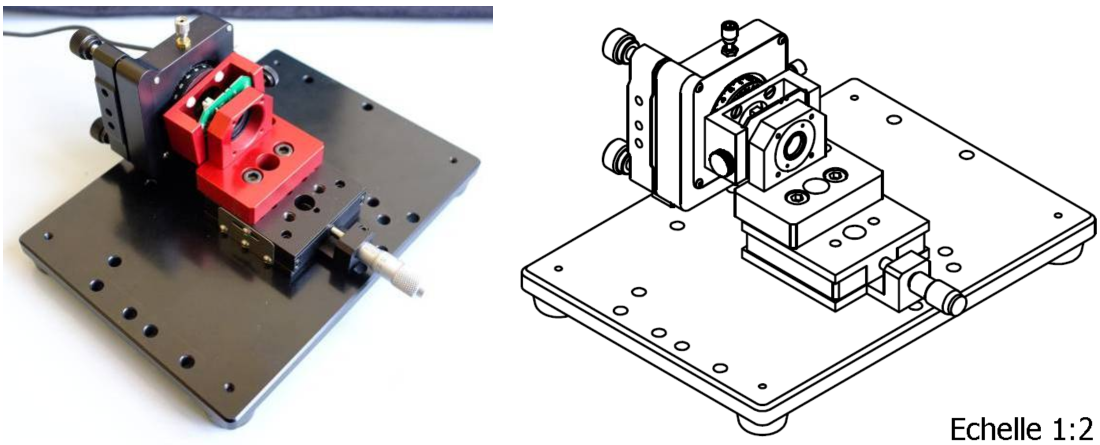

Figure 23 Final setup as mechanical drawig and in reality.

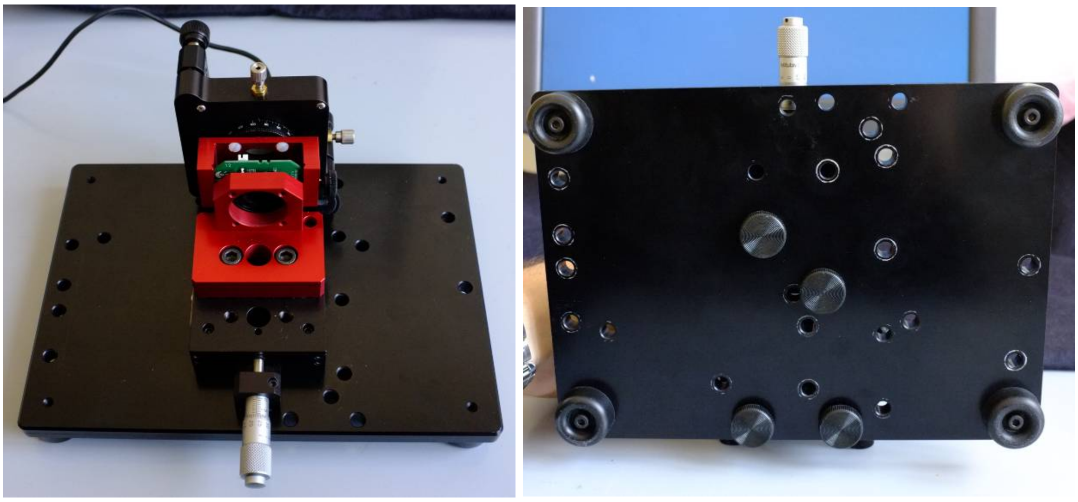

Figure 24. Top and bottom view. The view from below allows visualizing the fixation of the different components.

Start with the translation stage and mount the adapter plate and the holder.

Figure 25 Translation stage carrying the pinhole.

Prepare the 6 axis stage. Attach the adapter bar and the camera holder. Take care the adapter bar is NOT symmetric. Insert the camera. Be careful in handling the camera and prevent electrical charges and shortcuts.

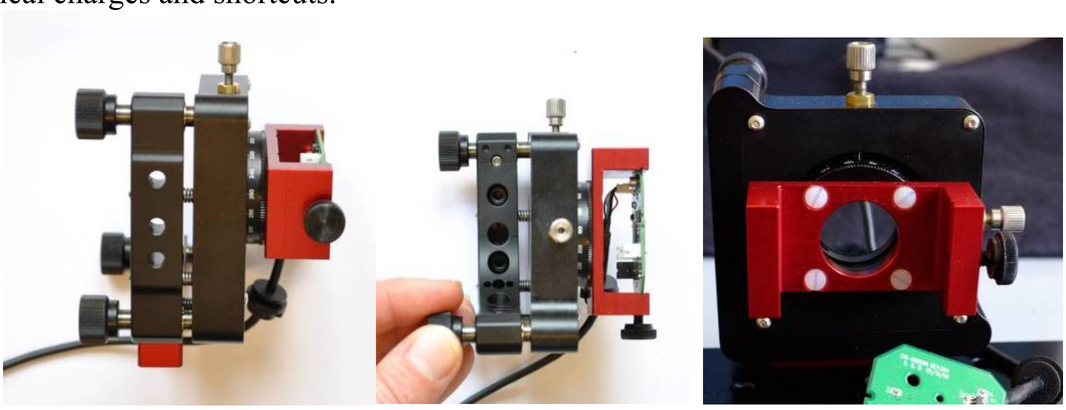

Figure 26 Six axis stage assembly with camera holder (left middle) and plastic screws to fix the camera holder on the stage (right).

NOTE: The camera holder is fixed with PLASTIC screws in the 6 axis stage!

Set everthing together on the base plate. Be carefull to not touching sensitive elements such as lenses, camera chip.
For pinhole camera assembly **remove the original objective** from the Logitech C600. Look at the description "Detector details" for details in appendix C at the end of this document.

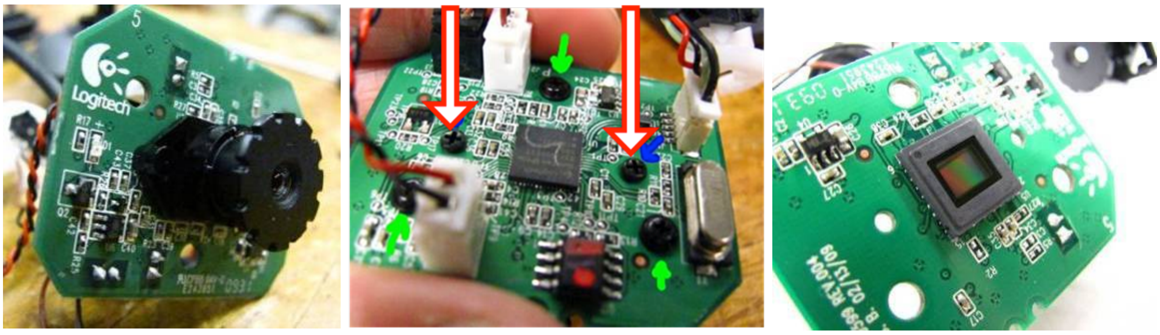

Figure 27. Camera PCB with objective. The red-white arrows show the screws to take of the objective. The PCB with the naked sensor and the objective from the two sides with its IR filter (reddish reflectance)

Adjustment and alignment

- Determine the touching position of the pinhole with the camera. To do so, approach the pinhole and look through the support on the back side of the pinhole membrane when **deformation** becomes visible. Adjust to a **"just touching"** position. With the help of the camera description you know the exact distance of the pinhole and camera (0.78 mm). Note the position of the translation stage.
- The translation stage can be used now to adjust the picture size at your convenience. Observe what happens when you change the position (focussing, resolution, brightness...)
- Choose a position of the pinhole that fills the cameras field of view at best.
- If the image is not well adjusted on your camera chip, improve the alignment of optical components and camera. Move the camera with the 6 axis stage or move the camera in its support. For best results it might be necessary to align the angles too!

Determine the distance between screen and camera for each image you take and note it for recalling. This is needed for evaluation of spatial frequencies.

4.2. Imaging with a pinhole camera

To get an impression of the quality of the images that can be achieved with a pinhole camera you should take images under different conditions. The pinhole diameter is given. The remaining free parameter is the distance from the pinhole to the detector. With the detector dimension given in figure 20 it is possible to find the exact pinhole detector surface position. Proceed as follows:

- Check if the disc SM1 carrying the pinhole is mounted correctly so that the pinhole is in front of the detector
- The pinhole is printed on a membrane. Look from the front of the camera and move the linear stage until until you see deformation of the membrane

Figure 28. If the membrane is touching the detector it deforms. In reflection that is easily visible as shown above. Left: no deformation of the black membrane in the center is visible. Right: The membrane is deformed!

- Determine the touching point by moving the linear stage and by looking at the membrane's deformation.
- Note the position and use it as a reference to determine the exact distance pinhole-detector.
- Take images of the same scene for different pinhole-detector distances.
- Adjust exposure and gain and cover with the black tissue to reduce stray light
- Make a series of images every 0.5 mm with the same exposure conditions!

0.8 mm

1.3 mm

1.8 mm

2.3 mm

Figure 29. Sequence of images taken with different pinhole-detector distances and fixed illumination conditions.

TO BE DONE FOR THE REPORT: Make a series of at least 4 images like in the example given above (start at pinhole touching the camera window, write down the distance camera chip pinhole). Use always the same exposure conditions. Print all 4 images in the report. Describe your findings.

4.3 Intensity distribution over the field

The pinhole camera has a pronounced intensity distribution over the field of view. Theoretically this is a $\cos^4\theta$ function. (Compare to Figure 9). We would like to measure this for the green channel. Use the following procedure.

- Adjust the camera to match the field of view with the camera chip size as shown below.

Figure 30. Left: Adjustment where the field size of the pinhole camera (limited by the pinhole holder) matches the detector chip size. Right: Image of an uniform white paper that shows the intensity change over the field of view.

- Take an image of a uniform (white) scene.
- Charge the later image in Matlab and use the script “FWHM_LINE_GREEN”. You will get two figures as shown below.
- Find the point of maximum intensity with the cursor tool  and note the y value (horizontal position at which the line plot has to be taken)

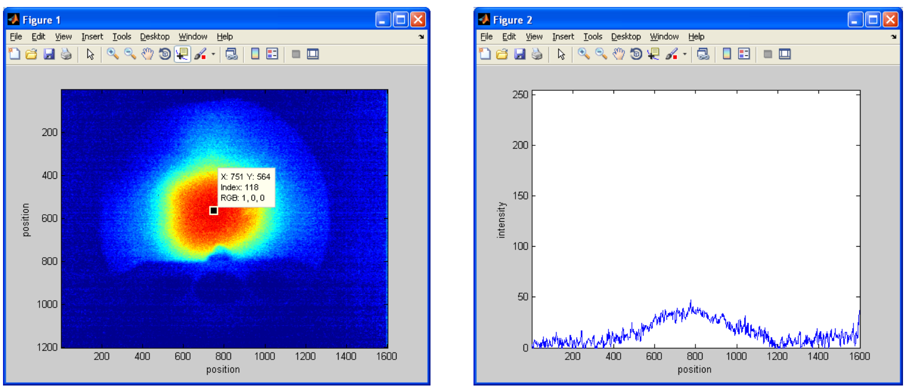

Figure 31 Matlab plots of the intensity distribution of Figure 30 right and line plot of the intensity at a certain horizontal position (here 200). The plot on the right shows the appearance of the cursor data to find the maximal intensity.

- Modify the Matlab script to take the horizontal line plot at the maximum intensity position.

EPFL

- Adapt the parameter "distance" and "peak_position_x" in the Matlab script to have best matching result
- Plot the figures again.

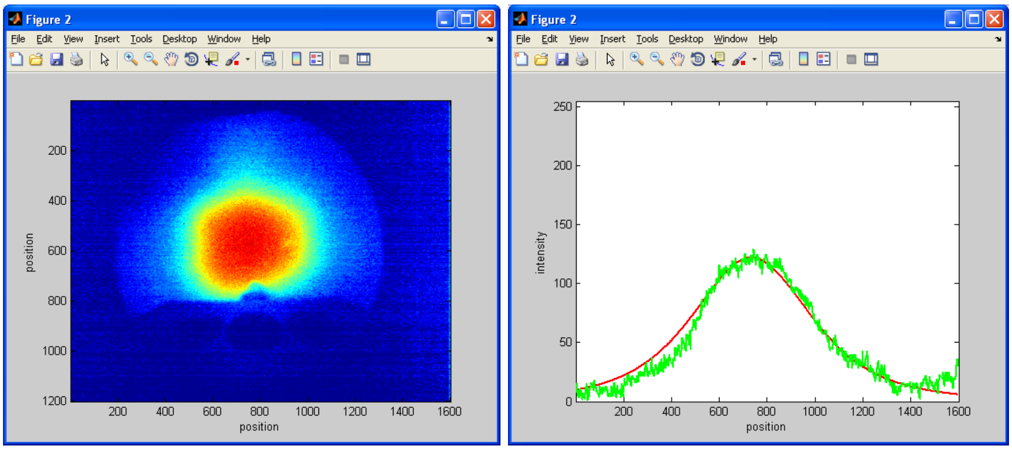

Figure 32. Two dimensional intensity and line plot to evaluate the intensity dependence of the field of view. In red a $\cos^4$ plot.

Matlab script "FWHM_LINE_GREEN" to evaluate the intensity distribution of the pinhole camera of the field diameter

```
% Read image 1
I_1 = imread('picture 73.jpg');
% select a channel (here green)
Green_2 = I_1(:,:,2);
% format conversion
Green_2 = double(Green_2);
%visiualize the image to define region of interest
imagesc(Green_2)
xlabel('position')
ylabel('position')

% select a line of interest ROI (1 x 1600), use the position of the center
of the peak,
Line_number = 571;
x_vector = 1:1:1599;
Line = Green_2(Line_number:Line_number,1:1599);

%plot a cos4theta curve with two parameter : distance pinhole camera and
%max intensity, detector size 4.35,
distance = 1.3;
peak_position_x = 735;
theta = atan((x_vector-peak_position_x)*4.536/1600/distance);
cos4theta = 122 * (cos(theta).^4);

%plot a single line
figure
plot(1:1:1599,cos4theta,'r-',1:1:1599,Line,'g-','LineWidth',2)
xlabel('position')
ylabel('intensity')
axis([1 1600 0 255])
```

TO BE DONE FOR THE REPORT: Take an image of a uniform scene (white paper) and evaluate the intensity distribution of the field of view by plotting the two dimensional intensity distribution. Print it in the report. Compare a horizontal line plot at highest intensity with the cos$^4\theta$ law by presenting a plot that contains both measurements and theory. Adjust the plot parameters if necessary to have a good match. Print it in the report. Do not forget to give the plot parameters (distance pinhole – detector, centre position) and discuss them.

4.4 MTF measurement with the basic method

The MTF is measured by imaging stripe images either displayed on the computer screen or by using printouts. The images are looking like the example below. The images and printouts are provided. If you use the screen for projection please use a 1:1 ratio (1 pixel image = 1 pixel) by pressing CTRL A or by pressing the "Actual size" button .

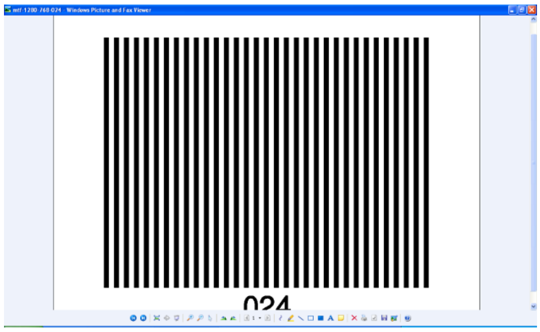

Figure 33: Example stripe pattern to be projected on a screen.

- Choose a convenient distance between the screen and the camera (about 10 -20 cm).
- Display and image each frame labelled mtf-???.tif. Images are found on the server.
- Align the rectangle with respect to the camera chips. This will be useful for averaging.
- Adjust illumination conditions of the camera to get best contrast for large periods. (images called mtf-1280-768-200 or mtf-1280-768-100 for instance)
- Set the camera resolution to the optimal value (1600-1200, 2MP) with the help of the camera software.
- Switch off the camera control LED. (camera software)
- Project one image mtf-xxx .tif after another to simulate different spatial frequencies and take a picture of them. Save the images. Note the distance of the camera to the projection screen
- Take care that the images are **not saturated or underexposed**. In saturation measurement results will be falsified.
- Open the frames with Matlab.

You should find images like the ones shown below (pictures and the line plots from Matlab).

```
Read an image
I = imread('Picture 2.jpg');
% display an image
figure
imagesc(I);
% convert to B&W
I = mean(I,3);
 % select a region of interest ROI, averaging will be over h lines in
% this example.
x = 1;
y = 200;
w = 1599;
```

```
h = 100;
I = I(y:y+h,x:x+w);
%control plot to check the quality of the regoin of interest. Assure that
%the features are vertical!!
figure
image(I);
xlabel('position')
ylabel('position')
% vertical average over the ROI
M = mean(I);
% plot the average profile
figure
plot(M);
xlabel('position')
ylabel('intensity')
```

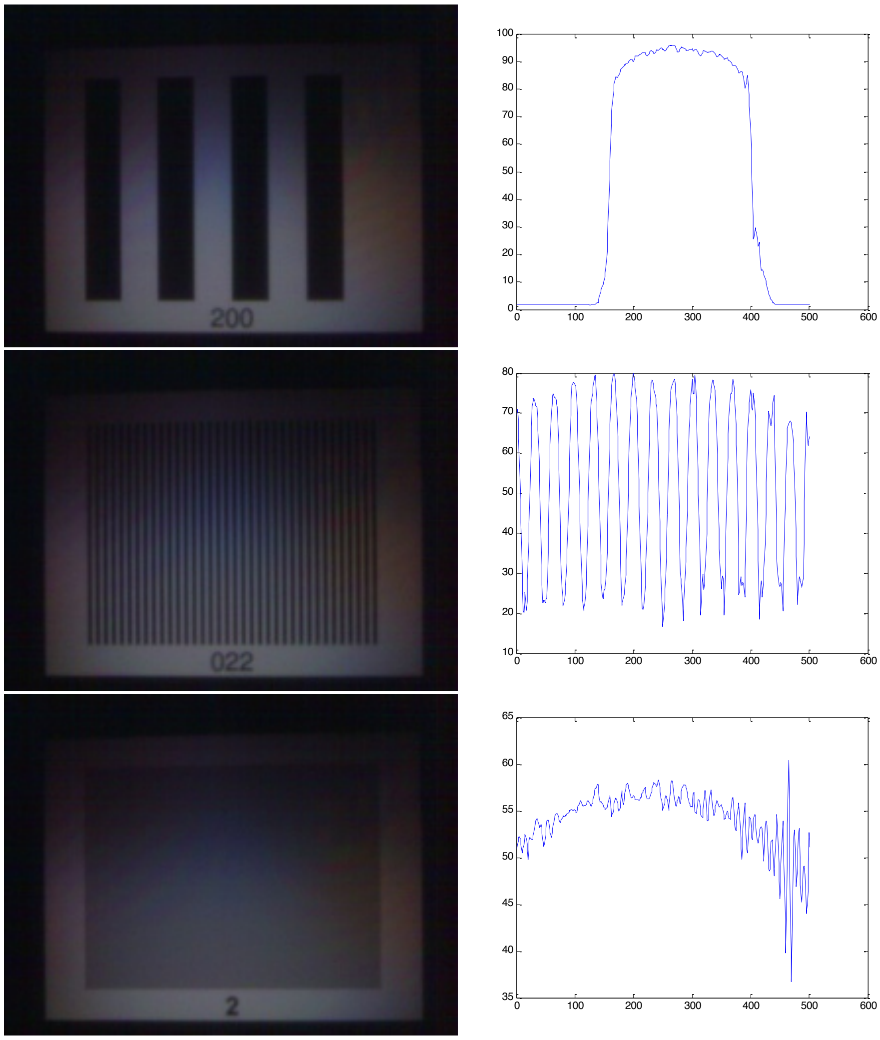

Figure 34: Typical images and intensity line plots to be seen with the pinhole camera for different spatial frequencies.

The MTF measurement depends on the position where it is taken within the field of view. Choose only one position (preferable the **center**) and measure the contrast always at the same position in the image. The contrast C is the modulation intensities relative to the mean intensity and defined in equation 15

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \quad \text{Eq. 15}$$

Use the Matlab scripts attached to this document to plot images and evaluated the contrast (also found on the server for your convenience). Make measurements and plot the contrast versus the spatial frequency in line/mm (image space). The spatial frequency is the reciprocal of the period. **The period is measured in the image** by considering the distance between lines, their width in pixels in the image and the width of pixels of the detector. If your image period is for instance 100 pixels your real period in space is 100 x 2.835 micron = 283.5 micron which leads to a spatial frequency of 3.53 lines per mm.

Please take care that you have a real measurement: **AVOID saturation, DO NOT work in the noise** regime of you camera. Adjust the exposure conditions properly. Use the possibility to make **averages** over several vertical lines to improve your measurements signal to noise ratio. The Matlab script gives you that possibility. As a result you should plot for each stripe pattern the contrast. An example curve is given below.

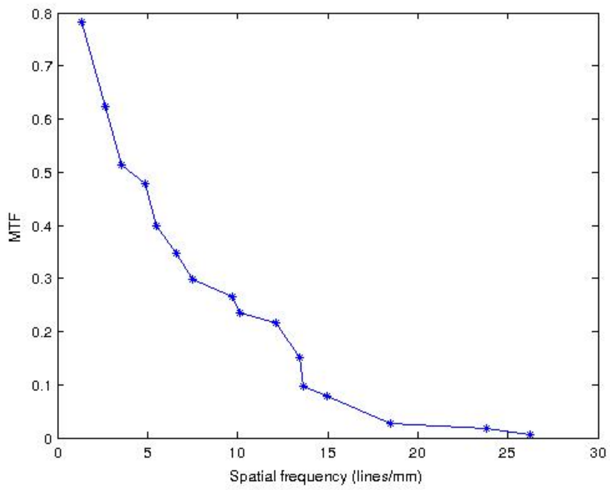

Figure 35: Contrast (here called MTF) as a function of spatial frequency for a pinole camera. **Note**: you should evaluate the spatial frequency in lines/mm. The scale in the image is in angle.

TO BE DONE FOR THE REPORT: Document the procedure by showing typical pictures and line plots (three images – max contrast, medium, no contrast). Measure the MTF and find a plot as a function of **image frequency** on the detector (**lines/mm**) similar to the plot above. Find the spatial frequency for 10% contrast and compare the value with the pinhole diameter by writing a short comment!

NOTE: The frequency in lines/mm on the detector can be calculated with the number of pixel for one period (black and white) in the image and pixel pitch of the camera. The spatial frequency is the inverse of the period! See the example above!

5. Summary of tasks

4.2. Imaging with a pinhole camera. (40 min)

Make a series of at least 4 images like in the example given above (start at pinhole touching the camera window, write down the distance camera chip pinhole). Use always the same exposure conditions. Print all 4 images in the report. Describe your findings.

4.3 Intensity distribution over the field (20 min)

Take an image of a uniform scene (white paper) and evaluate the intensity distribution of the field of view by plotting the two dimensional intensity distribution. Print it in the report. Compare a horizontal line plot at highest intensity with the $\cos^4\theta$ law by presenting a plot that contains both measurements and theory. Adjust the plot parameters if necessary to have a good match. Print it in the report. Do not forget to give the plot parameters (distance pinhole – detector, centre position) and discuss them.

4.4. MTF measurement with the basic method (60 min)

Document the procedure by showing typical pictures and line plots (three images – max contrast, medium, no contrast). Measure the MTF and find a plot as a function of **image frequency** on the detector (**lines/mm**) similar to the plot above. Find the spatial frequency for 10% contrast and compare the value with the pinhole diameter by writing a short comment!

4.5 Example from the WEB

Find a MTF chart and the corresponding objective in the www web and print both the chart and an image of the objective (not an image taken with the objective!) in your report. Be prepared to explain the parameters given in the chart. Cite correctly!

The time indicates the time to be spend on experimental task without evaluation!