Microcamera and Aberrations

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Contents

1 Objective and overview

The practical work should introduce the following subjects to you:

- Visualize aberrations in optical imaging of a plano convex lens
- Measure the field curvature
- Correct the field distortion with a geometric transformation
- Demonstrate transversal chromatic aberration

Please read the reference documents 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

3.1. Aberrations in optical systems

Aberrations in optical system are the result of different factors. They can appear because of incompatibilities between standard fabrication techniques that deliver mainly spherical lenses or simply by the fact that the detector we are using are flat while the scene we want to capture is not in a plane. The detector geometry influences a lot the appearance of aberrations. In addition the aberrations depend also on the materials and there wavelength depended properties. An optical system can be corrected for most of its aberrations. One can categorize two principle dependencies:

- Material dependent
- Space dependent (field and position dependent)

Chromatic aberrations

Chromatic aberrations are a result of the dispersion of the material that is used for building the optical element. They depend on the change of the the refractive index with wavelength for refractive lenses and on the wavelength dependent grating diffraction efficiency for diffractive lenses.

Geometrical aberrations

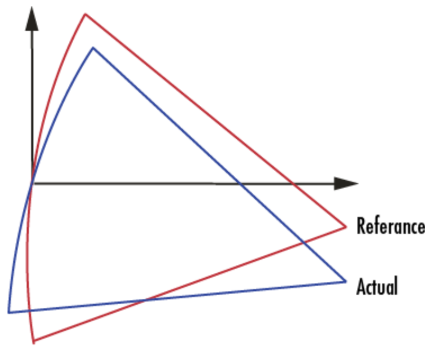
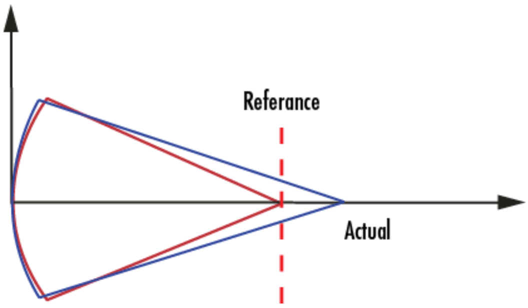
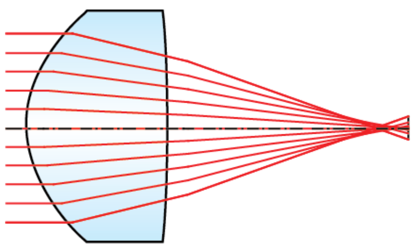
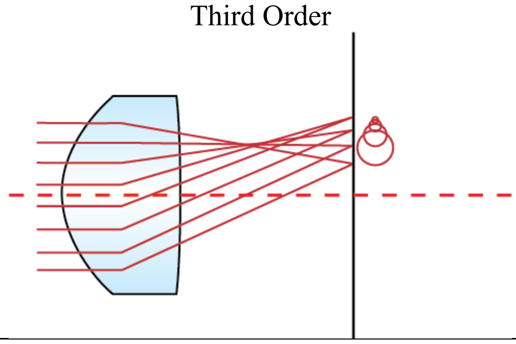
Geometrical aberrations can be classified in various ways. We use here the representation by order them for their visibility. One finds

- Distortion
- Field curvature
- Coma
- Spherical aberration

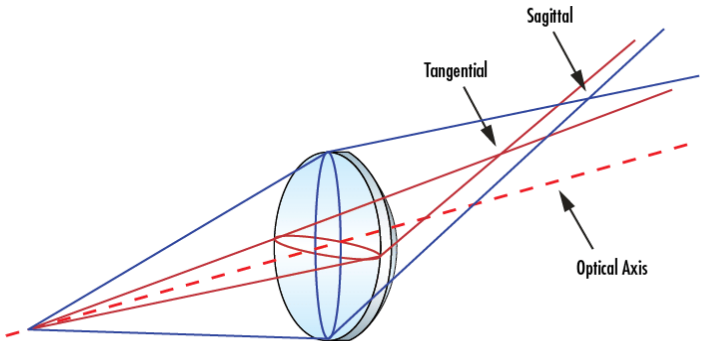
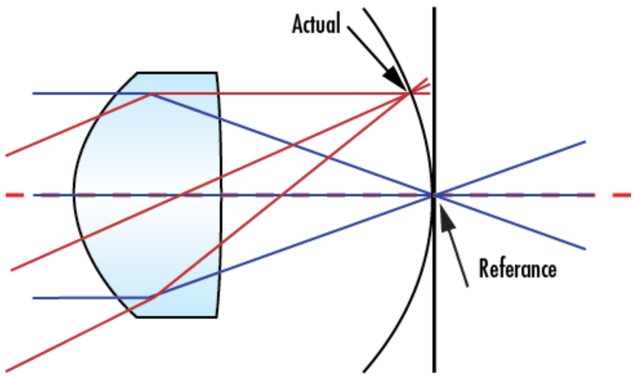
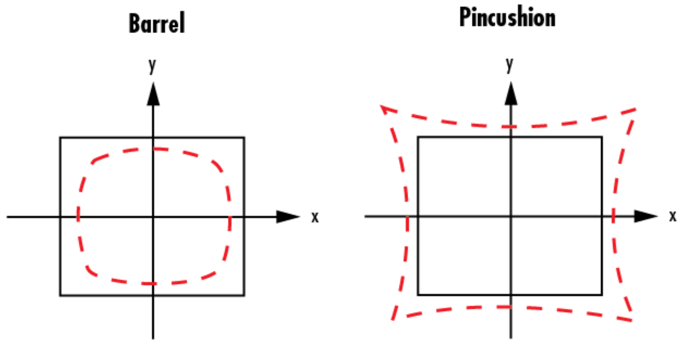
For practical work we will concentrate on the first two aberrations and evaluate their impact. In modern optical designs one uses raytrace programs to visualize the effects of different aberrations. Here we will discuss the basics with results of such simulations.

The table below gives a summary of the main geometrical aberrations and there characteristics. It was assembled using information from Edmund optics technical documentation www.edmundoptics.com and the book:

Dereniak, Eustace, and Dereniak ,Teresa. *Geometric and Trigonometric Optics*. 1st ed. New York: Cambridge University Press, 2008.

Aberration	Characterisation	Corrective action
Tilt – Axial behaviour and Order: First Order 	• image has incorrect magnification • caused by actual wavefront being tilted relative to reference wavefront	• change system magnification
Defocus Axial behaviour and Order: First Order 	• image in incorrect image plane • caused by wrong reference image • used to correct for other aberrations	• refocus system, find new reference image
Spherical Axial behaviour and Order: On-Axis and Off-Axis Aberration, Third Order 	• image appears blurred, rays from edge focus at different point than rays from center • occurs with all spherical optics	• counteract with defocus • use aspheric lenses • lens splitting • use shape factor of planconvex lens • high index
Coma Axial behaviour and Order: Off-Axis, Only Third Order 	• occurs when magnification changes with respect to location on the image • two types: tangential (vertical, y direction) and sagittal (horizontal, x direction)	• use spaced doublet lens with stop in center

Astigmatism	• causes two focus	• counteract

Axial behaviour and Order Off-Axis Only, Third order 	points: one in the horizontal (sagittal S) and the other in the vertical (tangential T) direction • exit pupil appears elliptical off-axis, radius is smaller in one direction	with defocus use spaced doublet lens with stop in center
Field Curvature Axial behaviour and Order Off-Axis Only, Third Order 	• caused by power distribution of optic • image is perfect, but only on curved image plane	• use spaced doublet lens
Distortion Axial behaviour and Order Off-Axis Only, Third Order 	• quadratic magnification error, points on image are either too close or too far from the center • positive distortion is called barrel distortion, negative called pincushion distortion	• decreased by placing aperture stop in the centre of the system

3.2 Field curvature

The field curvature appears to be a problem because detectors are mainly flat and the focalization from different directions is for a simple lens system on a curved surface. If we consider our case of a planoconvex lens we have two possibilities to position the lens in the optical path, the curved side towards the object or the curved side towards the detector. The two options are not equivalent. The figure below shows you example images taken for the two cases.

Figure 1. Images taken with a planoconvex lens when the curved surface is oriented towards the detector (left) and towards the object (right). One sees a large difference between both images.

To better understand the underlying effects, the figure below shows ZEMAX simulations for the lens used in the TP for these two cases.

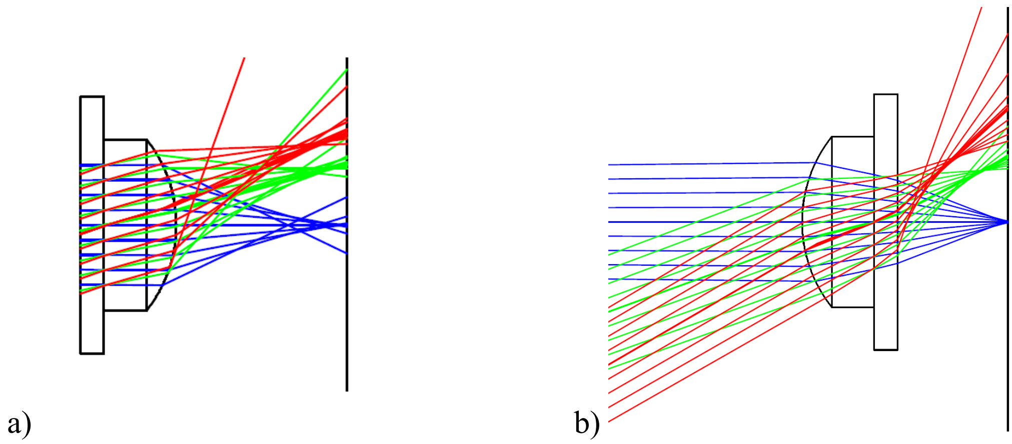


Figure 2. Focalization of a planconvex lens onto a detector for two different orientations of the lens. Light is coming from the left and the detector is on the right. The orientation on the left (a) is also known as landscape lens arrangement.

Interpreting the ray images allows to understand the basic feature or focusing for the two cases. One discusses the field curvature as a quantity that appears over the field size means that one studies effect when going away from the optical axis. On the left the focal point (crossing of rays of the same color) are found mainly in one plane but the focus points are not very sharp. To the right the focal points appear sharper but one can easily see that the focusing appears in different planes. This is called field curvature. With the help of ZEMAX a curve can be drawn the gives values of the focal point position as a function of the distance from the optical axis (middle of the lens). The results are shown below.

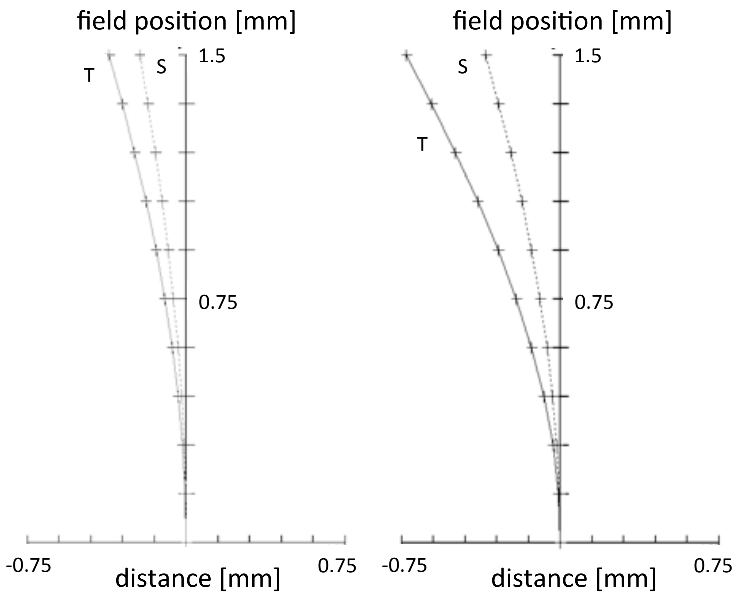


Figure 3 Simulated field curvature for the planoconvex lens used in the experiments. On the left, in landscape orientation, the maximum field curvature is smaller than 0.5 mm and on the right values larger than 0.75 mm could be found. (T – tangential, S – sagittal)

The field curvature is measured for two different case: T – tangential and S – sagittal. This needs to be done because the situation is not symmetric as illustrated in the Figure 4 below.

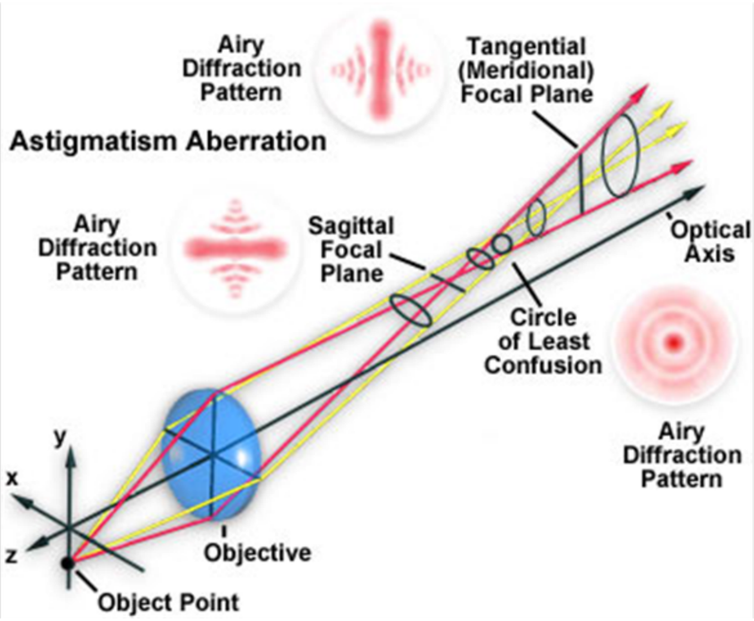


Figure 4 Tangential (T) and Sagittal (S) planes in an optical system. (source: http://www.microscopyu.com/tutorials/java/aberrations/astigmatism/)

The field curvature can be determined in an experiment by observing a test image, changing the distance between lens and detector (focusing) and finding the areas on the detector that appear focused for different of such focusing distances.

3.3 Distortion

In the same manner as shown for the field curvature by propagating rays the simulation of distortion is possible. To do so a sample pattern is converted into light rays and sent through the lens. An image is created by collecting the rays on a detector surface.

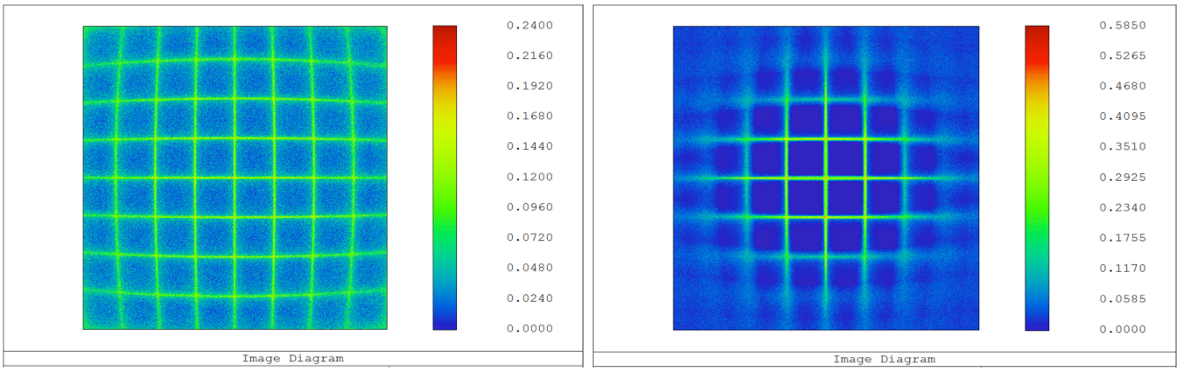


Figure 5. Simulation of an image of a test pattern to visualize effects of field curvature and distortion. The orientation of the lenses is the same as in the figures above.

Figure 5 shows two things. In the landscape like arrangement to the left the grid test pattern appears focused over a large field while it will become defocused for the simulation on the right. An effect that is clearly visible in Figure 1. Secondly, the distortions are very well visible in the landscape lens leading to a so called barrel distortion were the actual magnification becomes less than the paraxial magnification (the one on axis). The corners of the squares seem to be pushed towards the optical axis. There is also the possibility to find the inverse case a so called pincushion distortion (the magnification becomes larger with the field size and the corners are pulled away from the optical axis).
The effects of distortion can be corrected by geometrical transformations and nearly all miniaturized cameras applying that method. The simplest transformation is a quadratic one. One finds first the center of the image, hence the optical axis. Then the image originally in Cartesian coordinates is transformed in polar coordinates. A correction is applied and the result is transformed back into Cartesian coordinates for printing.

3.4 Chromatic aberrations

Chromatic aberrations in refractive optical system appear because of the dispersion of materials, hence the dependence of the refractive index on the wavelength of light. Two cases can be distinguished: transverse and longitudinal.

Longitudinal chromatic aberration occurs when different wavelengths focus at different points along the propagation axis as a result of dispersion properties of the glass. In optical terms, 656.3nm (red) is referred to as F light, 587.6nm (yellow) as d light, and 486.1nm (blue) as C light. These designations are historically and arise from emission lines of hydrogen. The refractive index of a glass is wavelength dependent, so it has a slightly different effect on where each wavelength of light focuses, resulting in separate focal points for F, d, and C light.

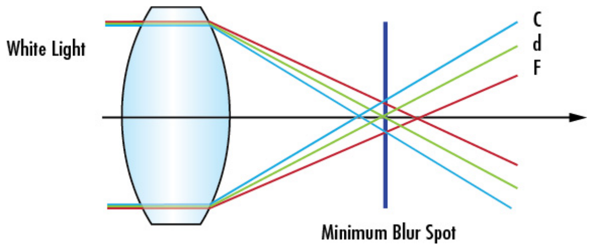


Figure 6: Longitudinal chromatic aberration of a single positive lens (Image: Edmund Optics technical documentation)

Transverse chromatic aberration occurs when the size of the image changes with wavelength. In other words, when white light is used, red (F), yellow (d), and blue (C) wavelengths focus at separate points in a vertical plane

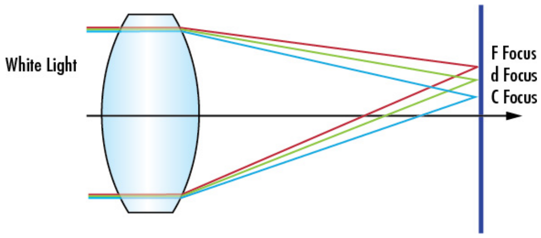


Figure 7: Transverse chromatic aberration of a single positive lens (Image: Edmund Optics technical documentation)

Chromatic aberrations lead to severe image deterioration and need to be avoided. Transverse chromatic aberrations become especially visible in high contrast images with borders or edges. A few examples found on the web below show you the effect.

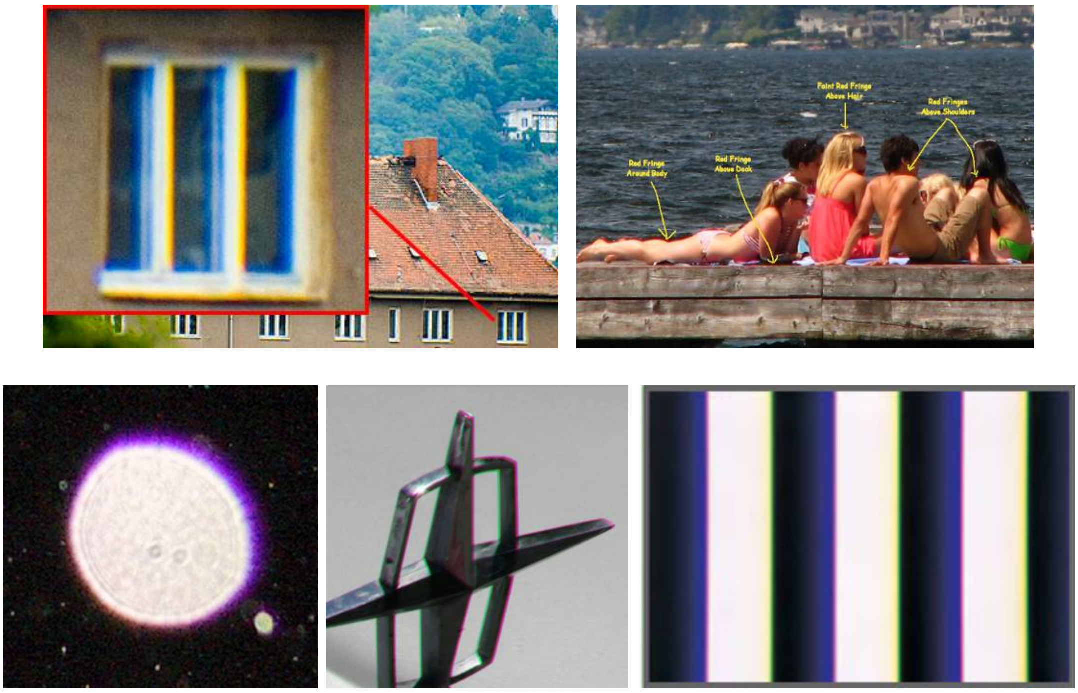


Figure 8: Examples of the effect of transverse chromatic aberrations. Images: WEB

Primary longitudinal correction is usually performed using an **achromatic** doublet lens, which is made of a positive and a negative lens elements of different refractive indices. This type of correction forces light of different colour to focus at the same place by suing an additional active surface. In order to better correct longitudinal chromatic aberration, a more complex lens or lens system must be used to shift the focus to be at the same axial location for more than two wavelengths. This type of correction is usually achieved by using an **apochromatic** lens, which is corrected such that three wavelengths focus at the same point, or a **superachromatic** lens, which is corrected such that four wavelengths focus at the same point.

By correcting the longitudinal chromatic aberrations one adjust the focal length for several wavelengths to the same value and that means that the magnification is adjusted to a single value too. Aberrations that appear due to a different magnification for different wavelengths (transversal chromatic aberrations) will be corrected at the same time. No special measures are usually taken to correct transversal chromatic aberrations.

The correction of aberrations is also possible by means of software and a lot of programs exist that provide this feature. All software corrections need a calibration which depends on the field of view.

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.

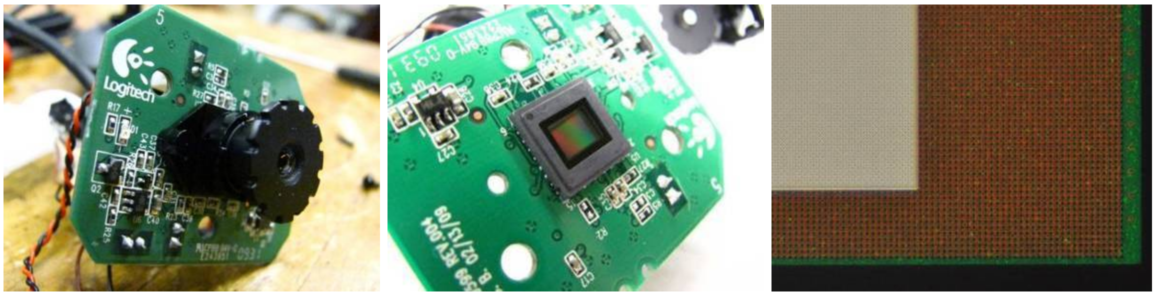


Figure 9: The camera PCB with (left) and without (middle) objective and a microscopy image of the detectors surface

Detector

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

Detector width is 4.536mm x 3.416mm.

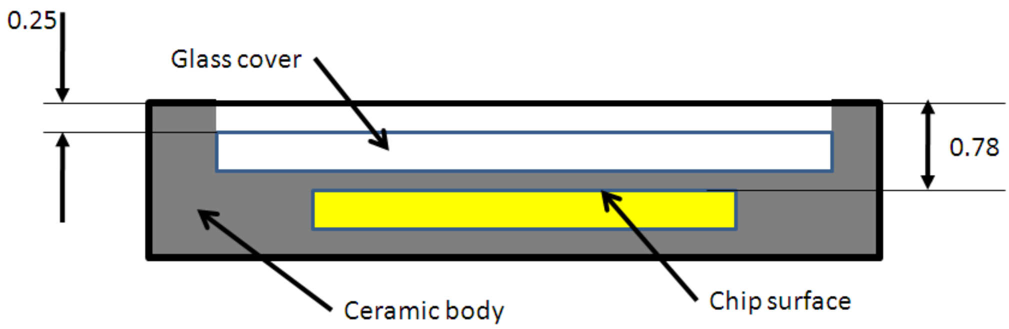


Figure 10: Detector cross section with dimensions (mm).

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

Lens

We will use a planconvex lens from Edmund Scientific **Model: LENS PCX 4MM DIA x 4MM FL UNCOATED** that is glued on a glass plate of 0.55 mm thickness. An aperture of three millimetres in diameter is made by photolithography into a chromium layer. The lens is mounted on the glass plate and assembled on a SM1 disc (Thorlabs).

Table: Lens specfications as given by EDMUND OPTICS (http://www.edmundoptics.com)

Diameter DIA (mm)	4.00
Diameter Tolerance (mm)	+0.0/-0.10
Clear Aperture CA (mm)	≥90% of Diameter
Effective Focal Length EFL (mm)	4.00
Back Focal Length BFL (mm)	3.06
Focal Length Tolerance (%)	±1
Design Wavelength DWL (nm)	587.6
Radius R_1 (mm)	3.21
Edge Thickness ET (mm)	1.00
Center Thickness CT (mm)	1.70
Center Thickness Tolerance (mm)	±0.1
Centering (arcminutes)	3 - 5
Surface Quality	40-20
Bevel	0.1mm x 45°
Substrate	N-LaSF44 ()
Refractive index	1.808 (λ = 546.1 nm)
Coating	Uncoated

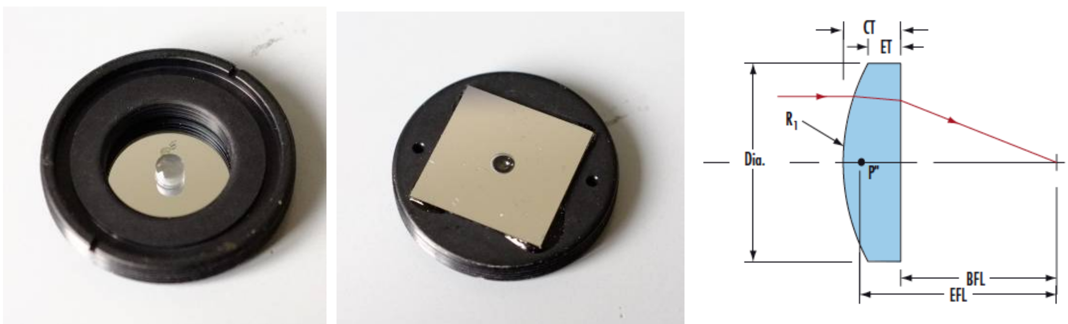


Figure 11: A 3 mm diameter lens on a glass plate and mounted on a SM1 disc. The lens is mounted twowards the inner side of the SM1 disc to protect them and allow short distances to the detector. On the right a technical image is shown to define the parameters of the lens with respect to the table above.

Setup

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.

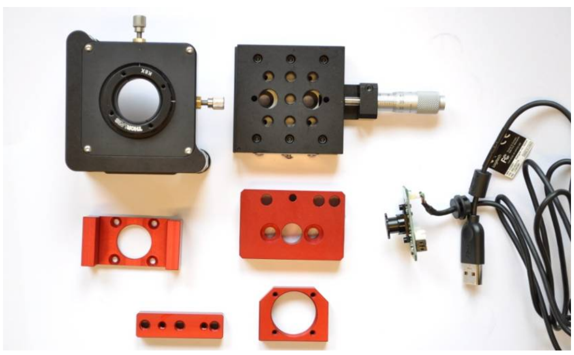


Figure 12. Parts used in this experiment. The six axis stage with x-y positioning, rotation and angular adjustment. The linear stage to set the distance precisely and parts for adjustment.

EPFL

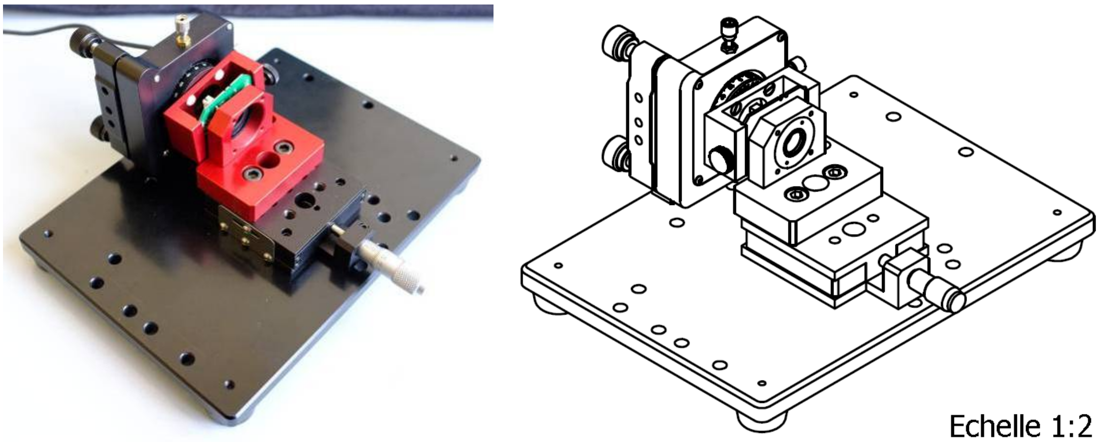


Figure 13. Final setup as mechanical drawig and in reality.

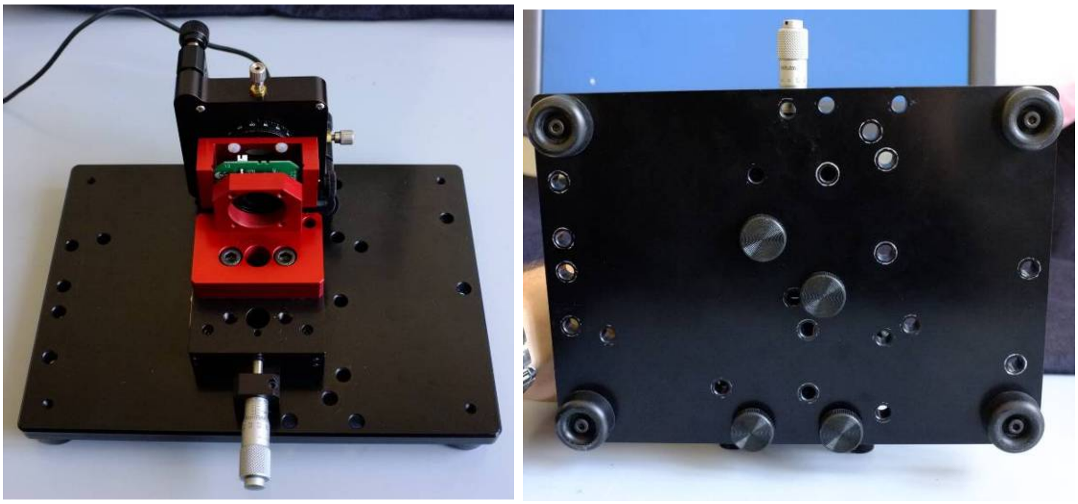


Figure 14. Top and bottom view. The view from below allows to see the fixation of the different components.

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

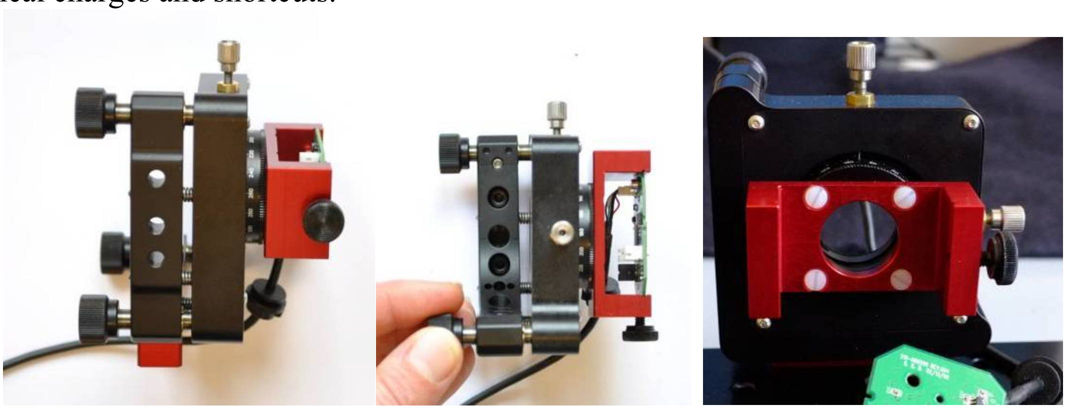


Figure 15. Six axis stage assembly with camera holder (left middle) and plastic screws to fix the camera holder on the stage (right).

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 the 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.

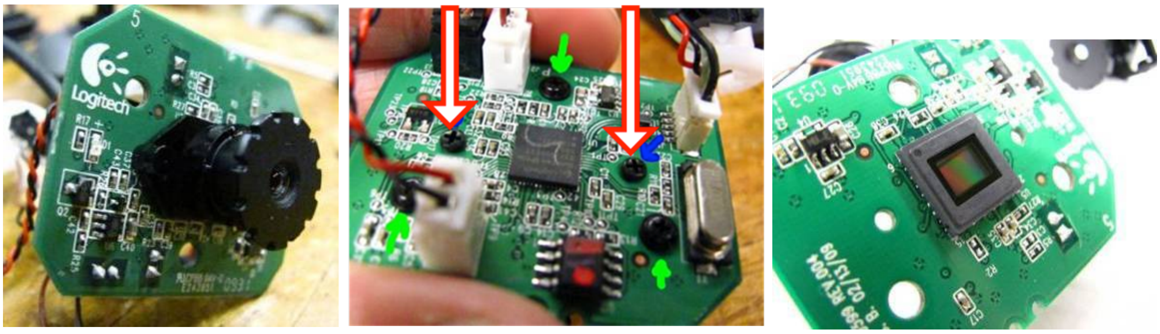


Figure 16. Camera PCB with objective. The red-white arrows show the screws to remove the objective. The PCB with the naked sensor and the objective from the two sides with its IR filter (reddish reflectance).

Adjustment and alignment

- A lens creates an image on the detector. Touching the detector with the lens **should be avoided**. Adjust carefully the system by observing the images and do not force the linear stage movement.
- The translation stage is used to adjust the focalisation.
- 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!

4.2. Imaging with a plan-convex lens for different orientations

Two different situations will be studied: 1) The lens is mounted with its curved surface towards the object and 2) the lens is mounted in Landscape orientation hence with the curved side towards the detector.

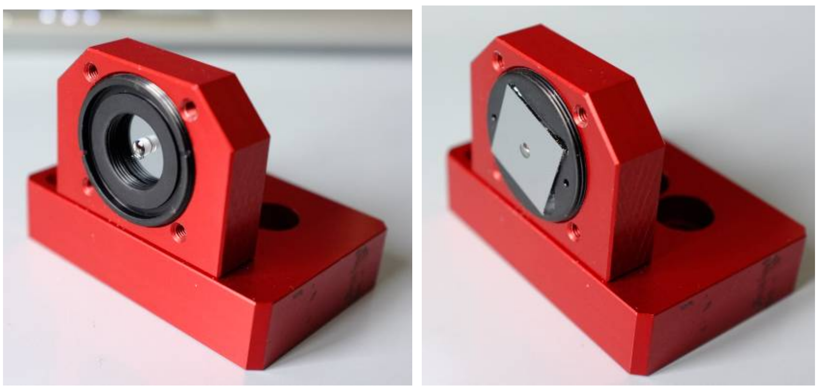


Figure 17. Mount carrying the lens. Two different orientations are shown. Left: Landscape orientation, the lens curved sides will be towards the detector. Right: The curved side of the lens is towards the object space.

In this experiment two images should be taken with different orientation. Proceed as follows:

- Check if the disc SM1 carrying the lens is mounted correctly so that the lens curvature is **towards** the camera chip and in front of the detector (LANDSCAPE).
- Switch on the camera software and use automatic exposure.
- Put an object close to the camera at the position that is defined by the setup as shown below (Fig. 18).

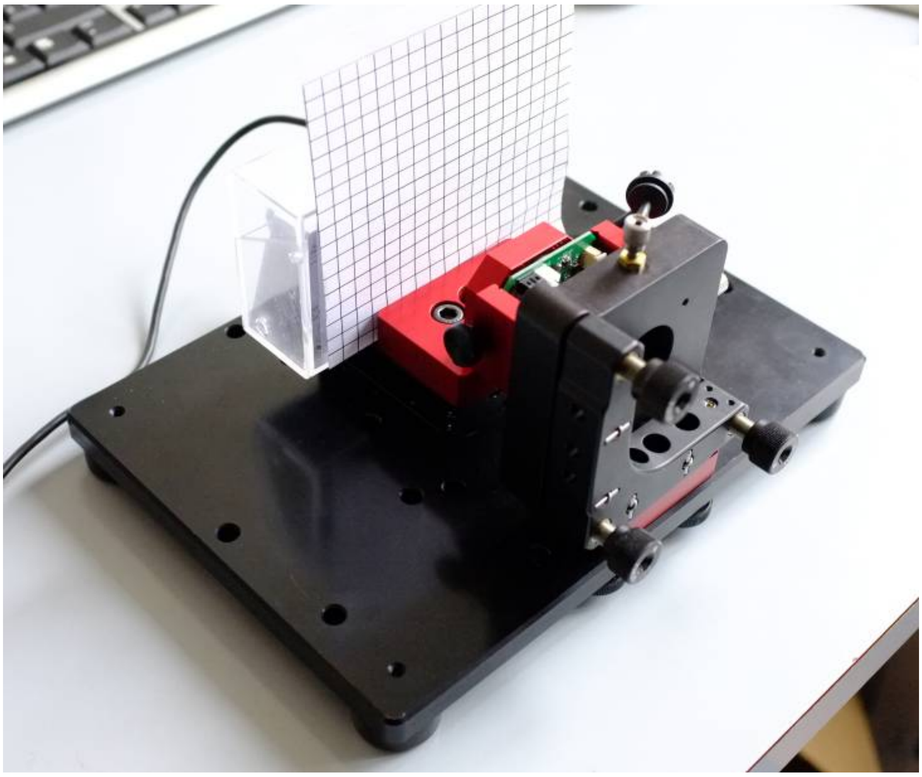
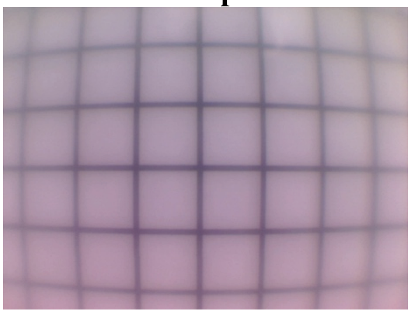


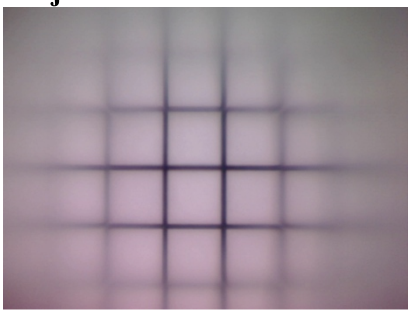
Figure 18. Preferred image position for the camera evaluation. The object is different dependent on the task to be performed.

- Use the GRID as an object for this experiment.
- Move the linear stage until you see an image.
- Note the position and use it as a reference to determine defocusing.
- Take images for different focusing positions.

Landscape orientation



Object curvature orientation



In focus

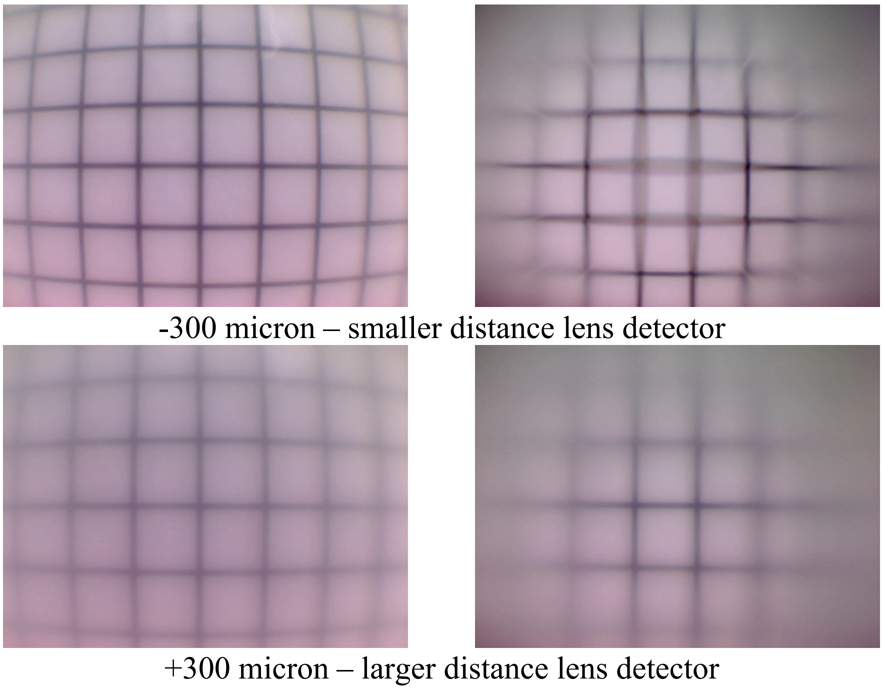


Figure 19. Sequence of images taken with different focalization.

TO BE DONE FOR THE REPORT: Make three images at different de-focalisation positions (-300, 0, 300 micron) for each orientation of the lens (object curvature - Landscape) and plot them in the report. Comment what you see (image quality, focalization over the field of view, aberrations...)

4.3 Direct measurement of the field curvature by defocusing of a test image

It is possible to directly measure the field curvature by refocusing the image at different areas in the field. We will do this for the curvature to object configuration.

- Check if the disc SM1 carrying the lens is mounted correctly so that the lens curvature is **towards** the object (Object curvature position).
- Put the ring system as object close to the camera at the position that is defined by the setup as shown below in Fig. 20.

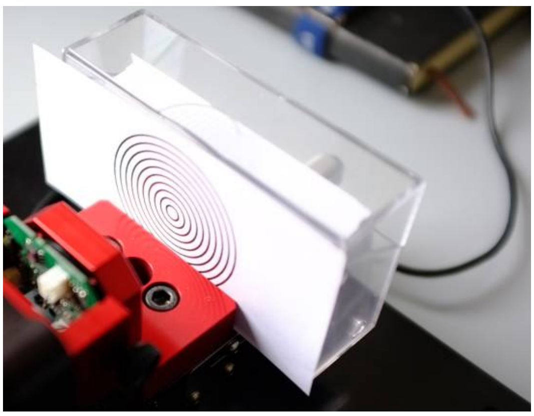


Figure 20. Imaging of rings. The ring system and the camera should be well centered to get reliable results.

- Move the linear stage until you see an image.
- Note the position and use it as a reference to determine defocusing.
- Take images for different focusing positions.

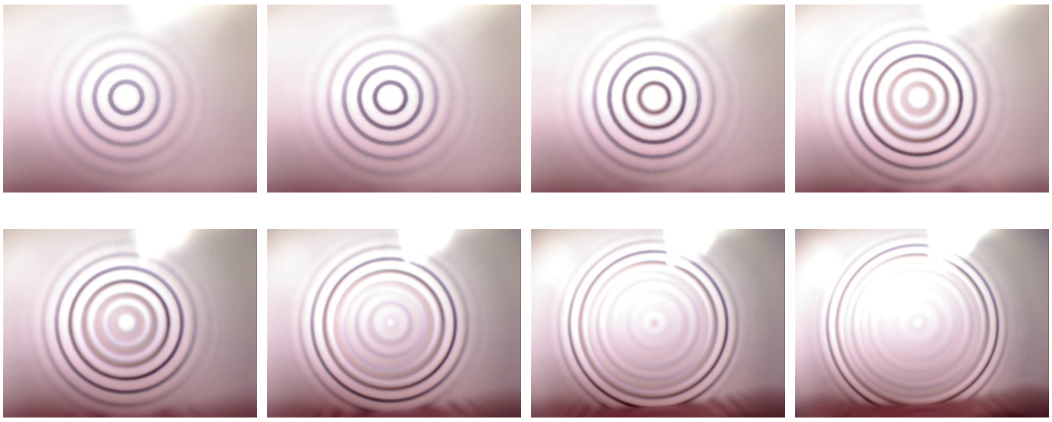


Figure 21: Example images that show that different rings are focused at different position de depending on their ring size.

The field curvature is measured in the image space and traced as a function of the field position. As you can see in the images above if we would measure in the image there would be a lot of deformation. The rings get narrower as we go to larger images fields. To have the right scaling we need to do the following:

- Determine the inner ring diameter in the first image in your camera picture (pixels and than convert into mm). All other rings have N times this diameter
- Plot the de-focalization distance as a function of the calculated ring radius. Do not measure in image space)

The Fig. 22 below shows an example in normalized units (not real values). The plot needs to be in mm at scale please to be compared with the simulations given in Fig. 3 at the beginning.

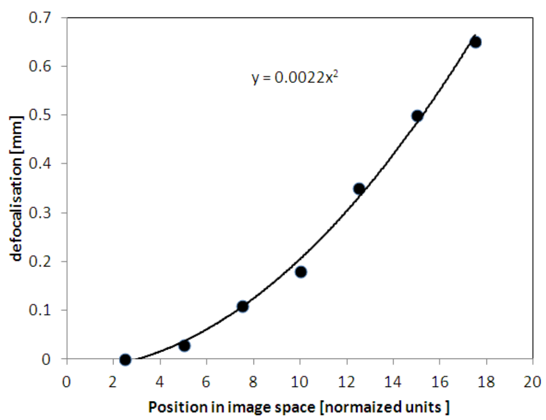


Figure 22. Example plot of measured field curvature against the position in the image space.
NOTE: the plot for the report needs to be done in mm.

For a situation **when astigmatism is corrected** the radius of the field curvature can be calculated by multiplying the focal lengths f with the refractive index n of the lens $\mathbf{R_P = f\ n}$.

This is called Petzval curvature! We want to compare the measure radius of curvature with this value. Different methods to evaluate the radius of curvature can be used from experimental data. Because our system starts at 0,0 a single parameter fit of the type $y= ax^2$ (no linear term nor constant) will allow to find the curvature at the position 0,0. Another possibility is the calculation based on geometry and a section of a circle. Than one uses a two points (center position 0,0 and one extreme point) and calculates the radius that fits this two points. Remember that two points are sufficient to find the radius if one assumes that the circle is tangential in (0,0).

TO BE DONE FOR THE REPORT: Show three images (for instance focusing of ring 1,3,5). Measure the field curvature resulting in de-focalisation for a minimum of 7 rings. Plot the de-focalization distance (to be read at the linear stage) as a function of the position in the image (take care of scaling). Calculate the radius of curvature and compare it with the Petzval curvature R_p= f n (f-focal lengths, n-refractive index of the lens) of the lens. Why is it so different? Compare also with data given in Fig 3.

4.4 Distortion and its correction by coordinate transformation

Distortion is an aberration that depends on the field. It represents a quadratic magnification error which leads to the situation that points on an image are either to close or too far from the center. Positive distortion is called barrel distortion, negative is called pincushion distortion

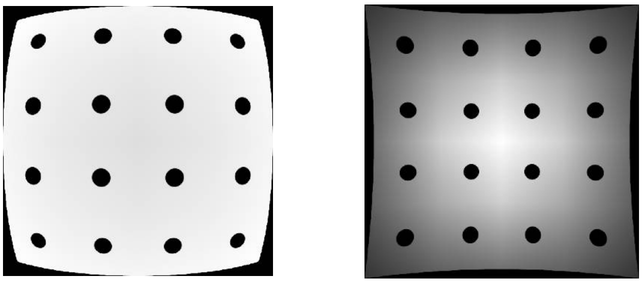


Figure 23. Illustration of barrel (left) and pincushing distortion (right) (Image: Edmund scientific).

- Check if the disc SM1 carrying the lens is mounted correctly so that the lens curvature is **towards** the detector and in LANDSCAPE position.
- Put the square motive as object close to the camera at the position that is defined by the setup as shown in Fig. 18.
- Move the linear stage until you see an image.
- Align the system to the center of the grid. You may need to unscrew and readjust some components such as camera and motive card.

In our experiment we want to correct this distortion by using a two dimensional transformation. The distortion has a center and it is crucial to determine the center to achieve a good correction. PLEASE CAREFULLY ALIGN THE SYSTEM.

The following sequence of transformations has to be applied:

- Define a quadratic region of interest
- Identify the center point (this has to be found by iteration (!) and trial and error)

- The Cartesian coordinates are transferred into polar coordinates by taking care of the center point position (MATLAB: cart2pol)
- Correction of deformation stretching the image as a function of the radius (MATLAB: s = r + a*r.^3;)
- The polar coordinates are transferred into Cartesian coordinates. (MATLAB: pol2cart)
- Re-sampling of data points

The Matlab program "distortion_correction_image.m" performs these steps and prints the corresponding images.
Matlab produces two Figures, one with the original image and a second one that shows the region of interest and the corrected image.

NOTE, that the coordinate transformation needs special care in choosing the region of interest. If the values are getting out of range the program will deliver useless results.

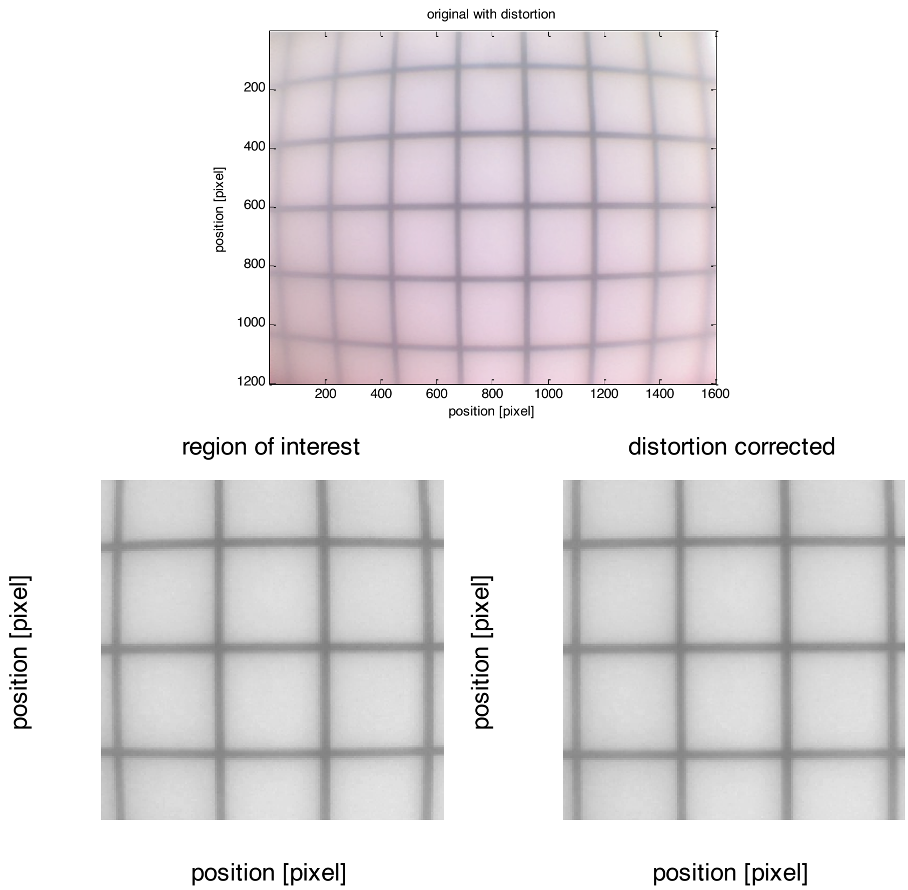


Figure 24. Example of the distortion correction. Above is the original image and below the region of interest and the corrected region of interest. NOTE the that the notation of x (vertical coordinate) and y (horizontal coordinate) in Matlab might cause trouble to define the center point which is here (800,600)

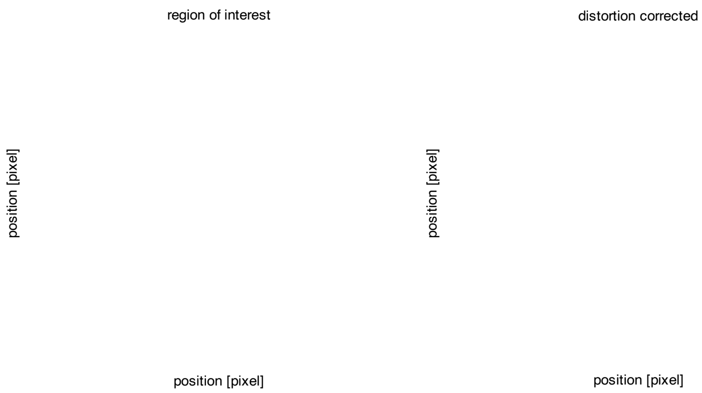


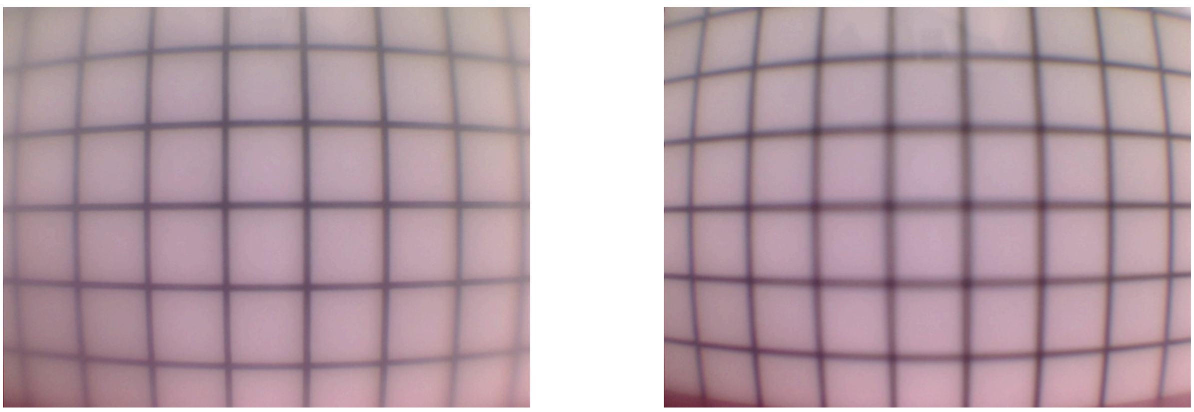
Figure 25. Example of an image sequence that uses the distortion correction value determined above to remove distortion.

TO BE DONE FOR THE REPORT: Show a series of images as given above. Try to find the best correction and give the following values: Position of the center of the transformation (called center_point_x; center_point_y in the matlab script) and the value of the correction (called "a" in the matlab script). Comment on the meaning of the sign of the correction value. Give a real image example by taking an image of a scene and make the correction. Comment your results.

4.5 Observation of transversal chromatic aberrations for large field of views

Chromatic aberrations appear in images often in large field of views, i.e. under large angles. A correction can be done by software. We want to visualize the transversal chromatic aberrations for the landscape lens configuration.

- Check if the disc SM1 carrying the lens is mounted correctly so that the lens curvature is **towards** the detector and in LANDSCAPE position.
- Put the square motive as object close to the camera at the position that is defined by the setup as shown in Fig. 17.
- Move the linear stage until you see an image.
- Align the system to the center of the grid. **Set the grid parallel to the camera detector limits to allow averaging.**
- Control the exposure parameters of the camera and especially the WHITE BALANCE. Click on RETURN TO DEFAULT SETTINGS. It is recommended to switch from automatic to manual here after exposure adjustment.



Focused for the center position

500 micron defocused image (towards detector)

Figure 26. Example images to demonstrate chromatic aberrations. The defocused image shows color effects at its outmost areas.

Transversal chromatic aberration can be made visible by considering the three channels red green and blue of the camera separately. It is necessary to have a well focused image to see the effect and for large fields of view that means that one has to correct the field curvature and defocusing the image. The figure above shows you an example with a de-focalization of 500 micron. The color effects are visible at large field angles.

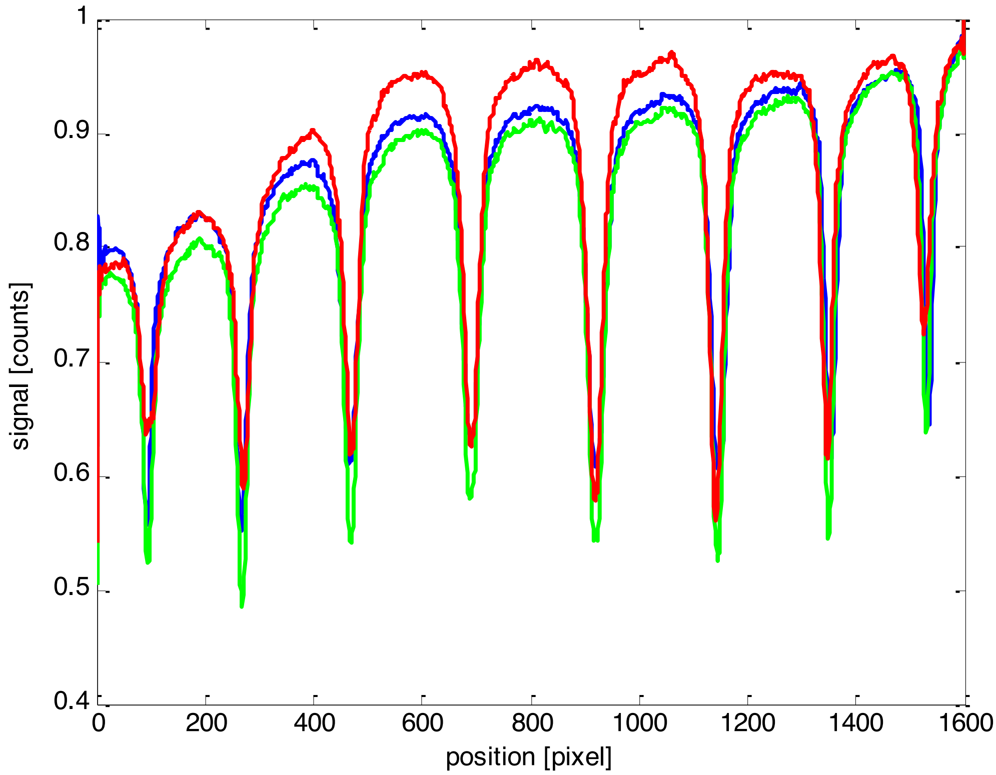


Figure 27. Normalized line plot of the RGB signals at position 655-670 (averaged) giving the peak positions of the grid. Careful evaluation will show that the peak positions (minimal intensity) are different for red green and blue.

The evaluation will only be qualitative. To do so two peaks symmetric to a center peak will be compared by zooming in and plot the graph. We use the center peak at position. Two peaks are chosen: the one at 360 and a second at 1300 approximately.

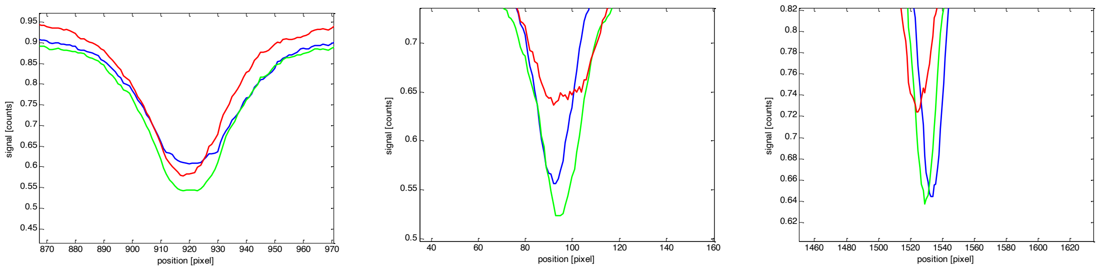


Figure 28. Peak positions for peaks at 920, 90 and 1530 pixels. At 920 all RGB peaks have the same position and this is taken as the center of the field. The position can be measured directly in the image by Matlabs “curser” function.

Looking at the results in the figure above one can easily see a difference of the peak center positions for the three different colors.

The table below gives the measured values:

direction	Blue peak position	Green peak position	Red peak position	Blue peak relative to position of center peak (920)	Green peak relative to position of center peak (920)	Red peak relative to position of center peak (920)
left	93	94	96	???	???	???
right	1533	1529	1524	???	???	???

TO BE DONE FOR THE REPORT: Present two images and show transversal aberrations like in Figure 26. Choose a convenient position in the image (middle) and plot the normalized line plot as given in Fig. 27. Use averaging to improve the quality of the measurement. Demonstrate the shift of the peaks for two positions (peaks) within the field of view by showing two graphs like in Fig 28 (Zoom plots of Fig. 27). Present a table that gives the peak positions for red green and blue as in the example above. Compare the values with Fig 6 or 7.

5. Summary of tasks of the experimental work

4.2. Imaging with a plan-convex lens for different orientations (30 min)

Make three images at different de-focalisation positions (-300, 0, 300 micron) for each orientation of the lens (object curvature - Landscape) and plot them in the report. Comment what you see (image quality, focalization over the field of view, aberrations...)

4.3 Direct measurement of the field curvature by defocusing of a test image (45 min)

Show three images (for instance focusing of ring 1,3,5). Measure the field curvature resulting in de-focalisation for a minimum of 7 rings. Plot the de-focalization distance (to be read at the linear stage) as a function of the position in the image (to be read in the image). Calculate the radius of curvature and compare it with the Petzval curvature R_p= f n (f-focal lengths, n-refractive index of the lens) of the lens. Why is it so different? Compare also with data given in Fig 3.

4.4 Distortion and its correction by coordinate transformation (20 min)

Show a series of images as given above. Try to find the best correction and give the following values: Position of the centre of the transformation (called center_point_x; center_point_y in the matlab script) and the value of the correction (called "a" in the matlab script). Comment on the meaning of the sign of the correction value. Give a real image example by taking an image of a scene and make the correction. Comment your results.

4.5 Observation of transversal chromatic aberrations for large field of views (25 min)

Present two images and show transversal aberrations like in Figure 26. Choose a convenient position in the image (middle) and plot the normalized line plot as given in Fig. 27. Use averaging to improve the quality of the measurement. Demonstrate the shift of the peaks for two positions (peaks) within the field of view by showing two graphs like in Fig 28 (Zoom plots of Fig. 27). Present a table that gives the peak positions for red green and blue as in the example above. Compare the values with Fig 6 or 7.

4.6 Example from the web

Find an image taken with a fisheye lens and print it into your report. Print also an image of the lens model as shown below so that one can read the parameters of the lens! Cite correctly!

MATLAB Scripts

distortion_correction_image.m

```
%read an image 1200x1600
Original = imread('picture 232.jpg');

%define a square region of interest with the distortion in the middle

figure
imagesc(Original)
title('original with distortion')
xlabel('position [pixel]')
ylabel('position [pixel]')

%define a square region of interest with the center of distortion in the
middle
center_point_x = 600;
center_point_y = 750;
image_size = 800;

% Note: Maximum "image_size" is given by distance center to border

I  = Original((center_point_x-
(image_size/2)):(center_point_x+(image_size/2)),(center_point_y-
(image_size/2)):(center_point_y+(image_size/2)));

% Pplot the region of interest
figure
subplot(121)
imshow(I)
title('region of interest')
xlabel('position [pixel]')
ylabel('position [pixel]')

% In what follows the radial distortion is corrected via transformation in
% radial coordinates - multiplication - back transformation

imid= round(size(I,2)/2); % Find index of middle element
[nrows,ncols] = size(I);
[xi,yi] = meshgrid(1:ncols,1:nrows);

xt = xi(:) - imid;
yt = yi(:) - imid;
%transformation in polar coordinates
[theta,r] = cart2pol(xt,yt);

 % Try varying the amplitude of the cubic term. This "a" value has to be
% noted in the reported. please give a two number precission. The sign is
% important
a = -0.00000035;

%Transformation (stretching) of the polar coordinate image - quadratic
coorection
s = r + a*r.^3;
```

```
% back transformation polar - cartesian, resampling
[ut,vt] = pol2cart(theta,s);
u = reshape(ut,size(xi)) + imid;
v = reshape(vt,size(yi)) + imid;

tmap_B = cat(3,u,v);
resamp = makeresampler('linear','fill');

I_distortion_corrected = tformarray(I,[],resamp,[2 1],[1 2],[],tmap_B,.3);

% Plot of corrected image
subplot(122)
imshow(I_distortion_corrected)
title('distortion corrected')
xlabel('position [pixel]')
ylabel('position [pixel]')
```

RGB_SpectraLinePlot.m

```
% Read image
I = imread('picture 166.jpg');

figure
imagesc(I)

% convert to RGB signals
I_B = I(:,:,3);
I_G = I(:,:,2);
I_R = I(:,:,1);

%average over several lines (vertical)
% select a region of interest ROI y_start, y_end with several number of
lines here 30 lines are averaged
%normalization of intensity by devision through the maximum

y_start = 655;
y_end = 670;

ROI_Line_B   = I_B(y_start:y_end,1:1599);
N_Avg_Line_B = mean(ROI_Line_B)/nanmax(mean(ROI_Line_B));

ROI_Line_G   = I_G(y_start:y_end,1:1599);
N_Avg_Line_G = mean(ROI_Line_G)/nanmax(mean(ROI_Line_G));

ROI_Line_R   = I_R(y_start:y_end,1:1599);
N_Avg_Line_R = mean(ROI_Line_R)/nanmax(mean(ROI_Line_R));

%plot the averaged lines all at once
figure
plot(1:1:1599, N_Avg_Line_B,'b-',1:1:1599, N_Avg_Line_G,'g-',1:1:1599,
N_Avg_Line_R,'r-','LineWidth',2);

xlabel('position [pixel]')
ylabel('signal [counts]')
```