EPFL

Micro-camera and Aberrations

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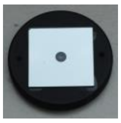
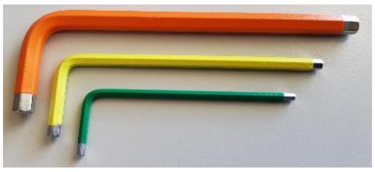
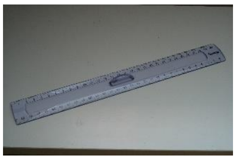
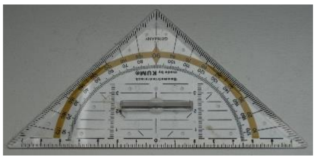
List of material for the TP

1x board	
1x 6 axis stage 1x adapter plate (red part)	
1x camera holder	
1x camera	
1x linear stage 1x adapter plate 1x SM1 lens holder	  
1x lens planconvex on SM1 disc (front and back view)	 
1x grid pattern 1x circle pattern	 
4x large screws with cap 1x small screws with cap	 
4x plastic screws (triangular head) 4x large screws	 

3x Allen keys	
1x slotted screwdriver	
1x SM1 spanner wrench	
1x ruler 1x triangle	 

1 Background

1.1. Aberrations in optical systems

Aberrations in optical systems are the results 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 detectors we use 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 their wavelength dependent properties. An optical system can be corrected for most of its aberrations. One can categorize two main 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 elements. They depend on the change of the refractive index with wavelength for refractive lenses and on the wavelength dependent grating diffraction efficiency for diffractive lenses.

Geometrical aberrations

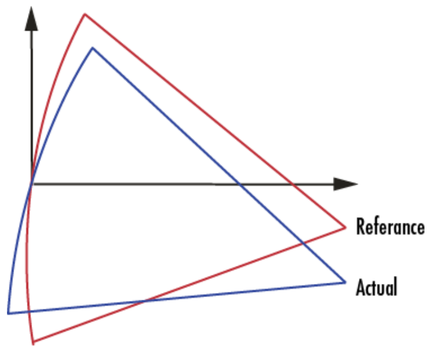
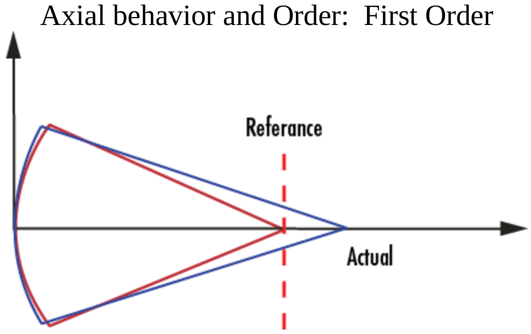
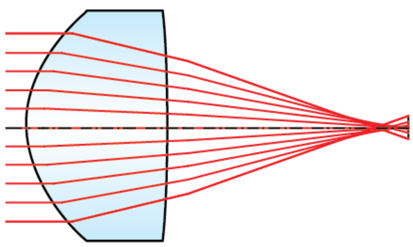
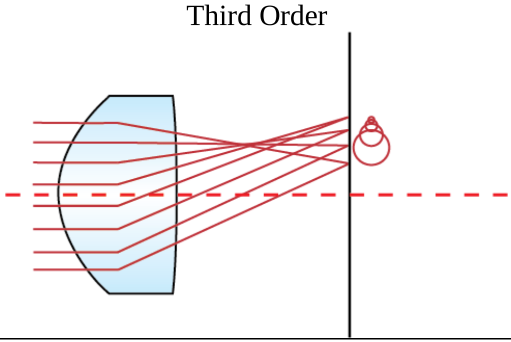
Geometrical aberrations can be classified in various ways. We give them here according to their importance. One finds

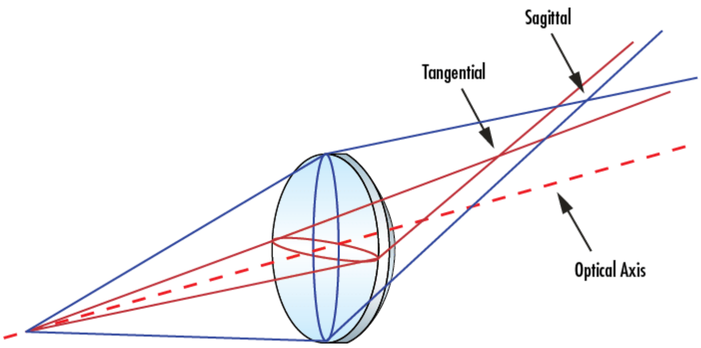
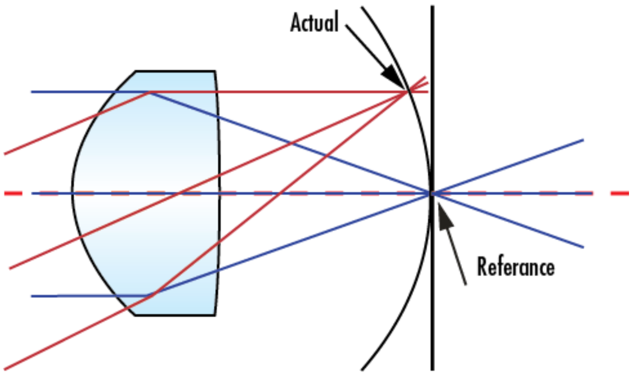
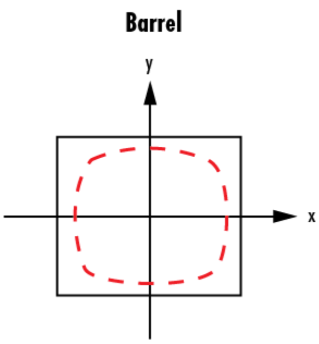
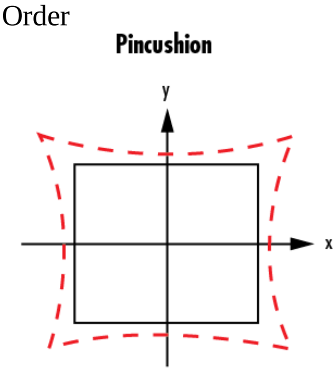
- Distortion
- Field curvature
- Coma
- Spherical aberration

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

The table below gives a summary of the main geometrical aberrations and their 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	Characterization	Corrective action
Tilt – Axial behavior and Order: First Order 	• image has incorrect magnification • caused by actual wavefront being tilted relative to reference wavefront	• change system magnification
Defocus Axial behavior 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 behavior 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 behavior 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 Axial behavior and Order Off-Axis Only, Third order 	• causes two focus 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	• counteract with defocus use spaced doublet lens with stop in center
Field Curvature Axial behavior 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 behavior 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

1.2 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 the 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.

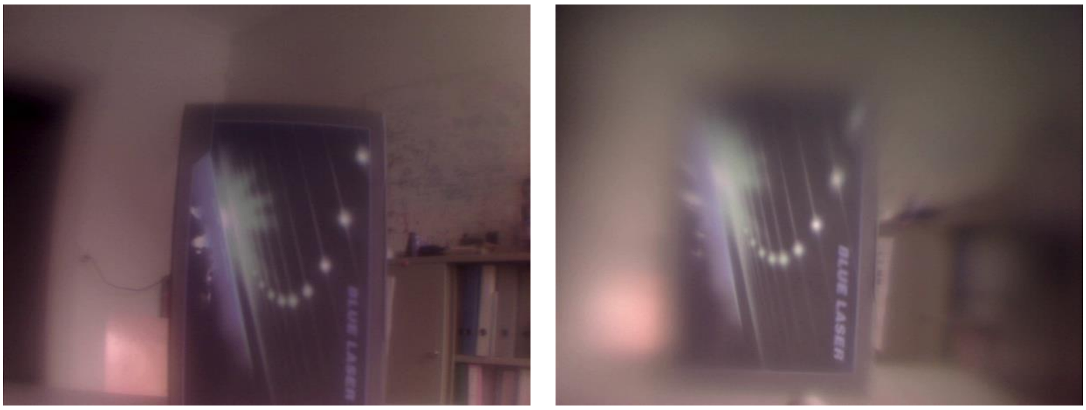
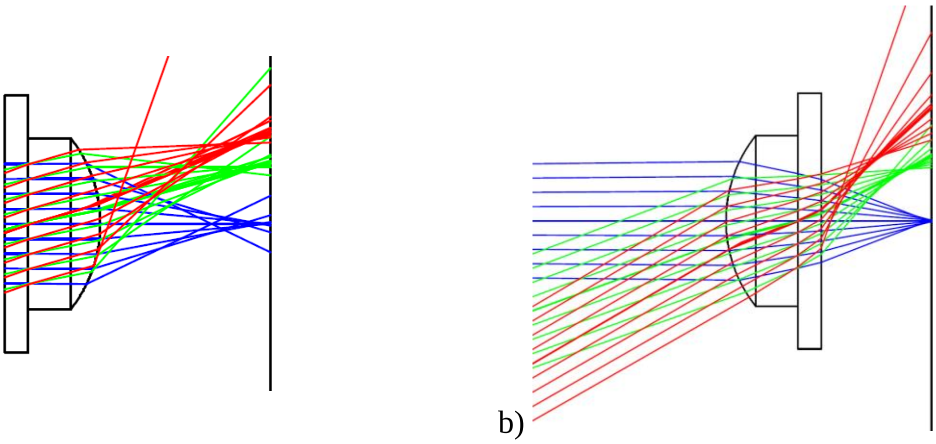


Figure 1. Images taken with a planoconvex lens when the curved surface is oriented towards the detector (left) and towards the object (right). One sees a large difference between both images.

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



a) b)

Figure 2. Focalization of a plan-convex 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. Colors indicate different angles of light propagation and not different wavelengths.

Interpreting the ray images allows to understand the basic feature of focusing for the two cases. On the left, the focal points (crossing of rays of the same color) are found mainly in one plane but the focus points are not very sharp. On 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 that gives values of the focal point positions as a function of the distance from the optical axis (middle of the lens). The results are shown below.

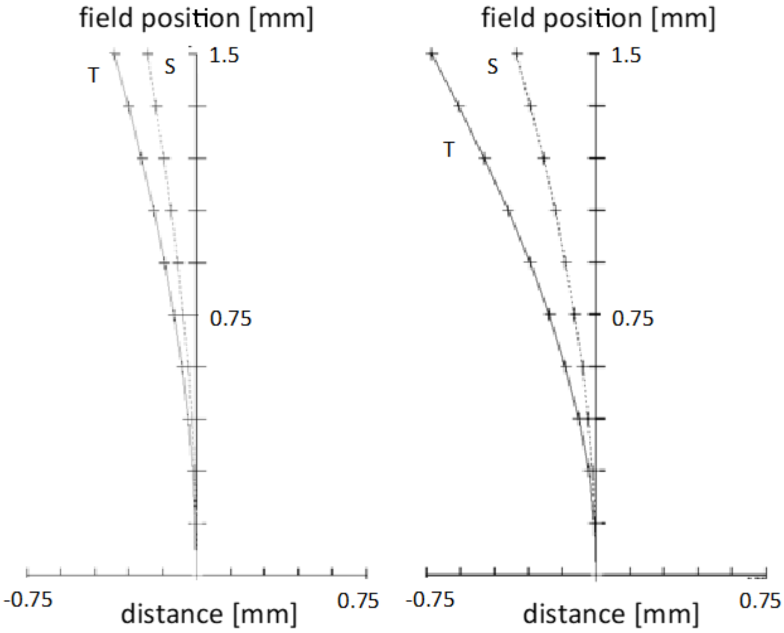


Figure 3 Simulated field curvature for the planoconvex lens used in the experiments. On the left, in landscape orientation, the maximum field curvature is smaller than 0.5 mm and on the right values larger than 0.75 mm could be found. (T – tangential, S – sagittal)

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.

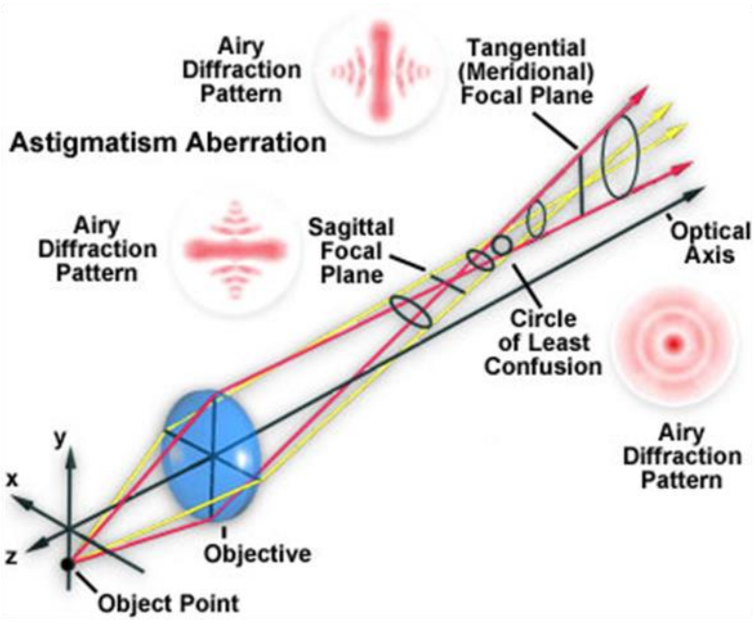


Figure 4 Tangential (T) and Sagittal (S) planes in an optical system. (source: http://www.microscopyu.com/tutorials/java/aberrations/astigmatism/)

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.

1.3 Distortion

Simulation of distortion effects is possible following a procedure similar to that of the field curvature. 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.

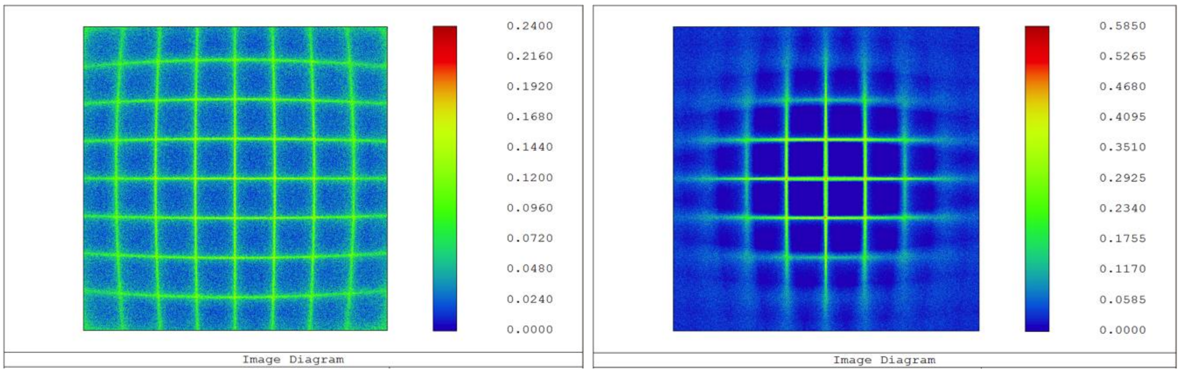


Figure 5. Simulation of an image of a test pattern to visualize the effects of field curvature and distortion. The orientation of the lenses is the same as in the figures above.

Figure 5 shows two things. In the landscape arrangement (left image), the grid test pattern appears focused over a large field whereas it appears defocused for the simulation on the right. An effect that is clearly visible in Figure 1. Secondly, the distortions are very visible in the landscape lens leading to a so-called barrel distortion where 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, i.e., 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 apply that method. The simplest transformation is a quadratic one. One finds first the center of the image, hence the optical axis. Then, the image, which is originally in Cartesian coordinates, is transformed in polar coordinates. A mathematical correction is applied and the result is transformed back into Cartesian coordinates for printing.

1.4 Chromatic aberrations

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

Longitudinal chromatic aberrations occur when different wavelengths are focalized at different points along the propagation axis as a result of the dispersion properties of the glass. Consider the example in Figure 6 where 656.3 nm (red) is referred to as F light, 587.6 nm (yellow) as d light, and 486.1 nm (blue) as C light. These designations are historical and arise from the emission lines of hydrogen. The refractive index of a glass is wavelength dependent, so it has a slightly different values for each wavelength of light being focalized, resulting in separate focal points for F, d, and C lights.

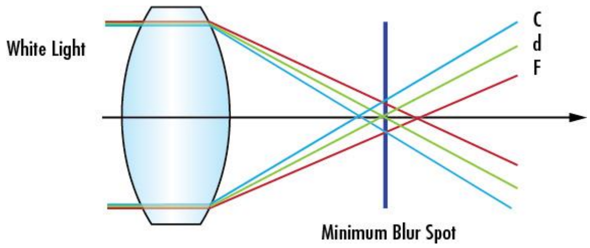


Figure 6: Longitudinal chromatic aberration of a single positive lens (Image: Edmund Optics technical documentation)

Transverse chromatic aberrations occur 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 are focalized at separate points in a vertical plane, as shown in Figure 7.

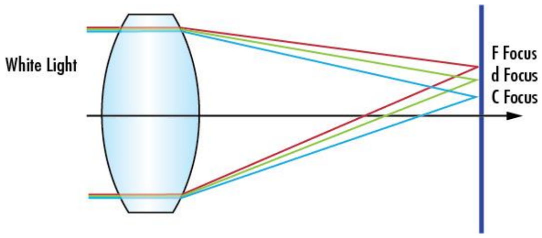


Figure 7: Transverse chromatic aberration of a single positive lens (Image: Edmund Optics technical documentation)

Chromatic aberrations lead to severe image deterioration and need to be avoided. Transverse chromatic aberrations become especially visible in high contrast images with sharp borders or edges. A few example images found on the web are shown below to illustrate these effects.

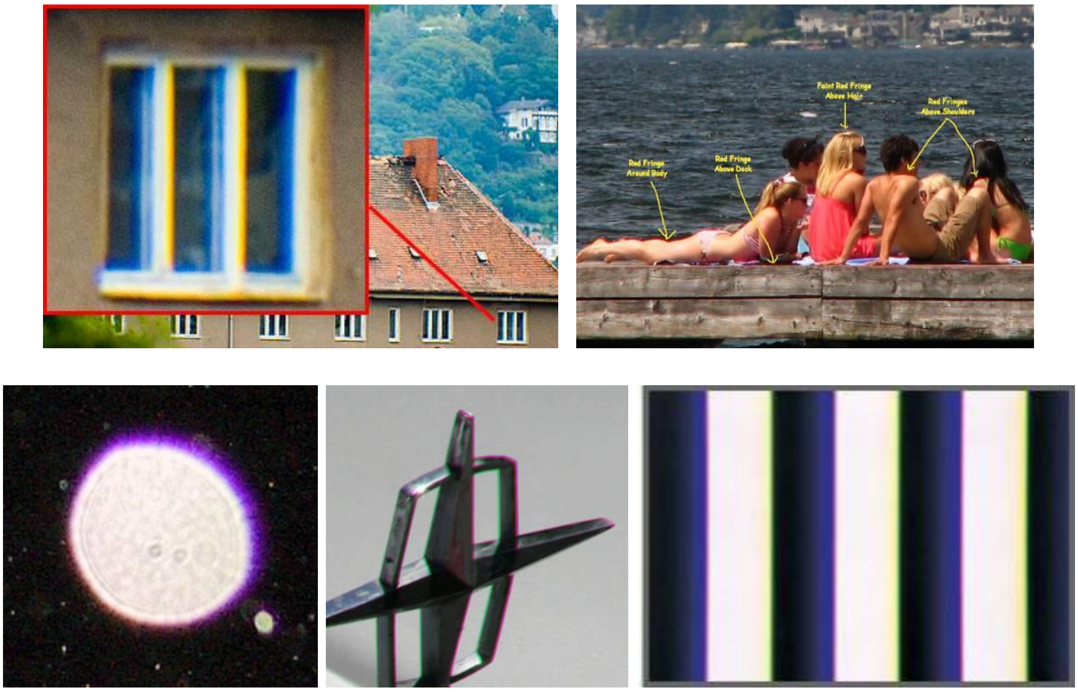


Figure 8: Examples of the effects of transverse chromatic aberrations.

Primary longitudinal correction is usually performed using an **achromatic** doublet lens, which is made of a positive and a negative lens element of different refractive indices. This type of correction forces light of different color to be focalized at the same place. In order to better correct longitudinal chromatic aberrations, 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 adjusts 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.

2 Setup and equipment

2.1. Materials and setup

A camera sensor is used as the detector.

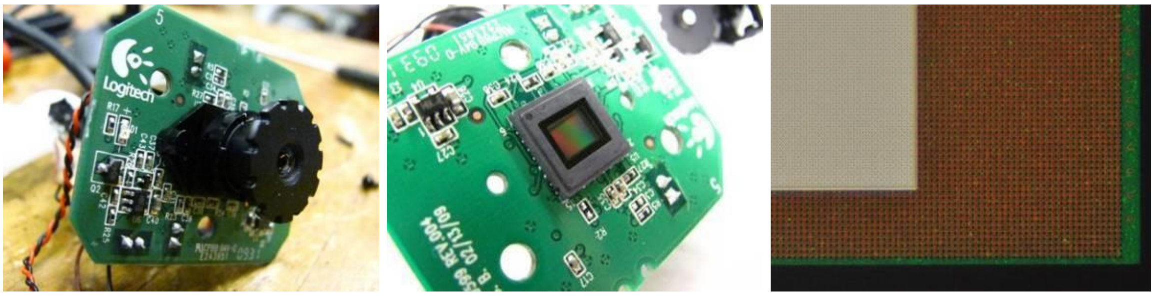


Figure 9: The camera PCB with (left) and without (middle) objective and a microscopy image of the detectors surface

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 millimeters in diameter is made by photolithography on 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

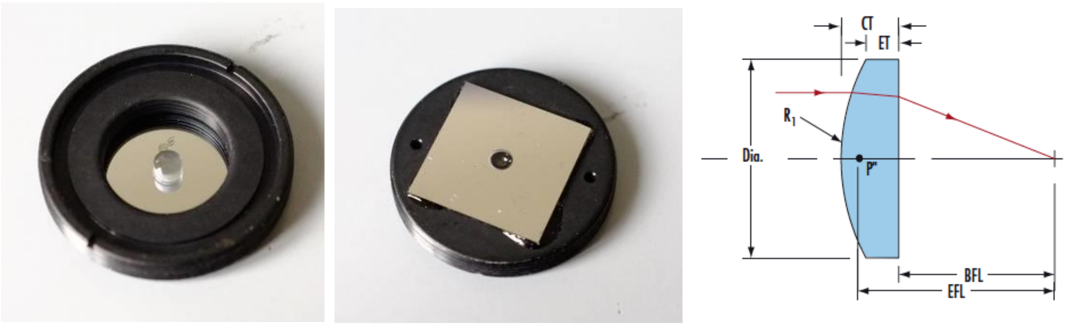


Figure 11: A 3-mm diameter lens on a glass plate and mounted on a SM1 disc. The lens is mounted towards the inner side of the SM1 disc to protect them and allow short distances to the detector. On the right, a technical image is shown to define the parameters of the lens with respect to the table above.

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 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.

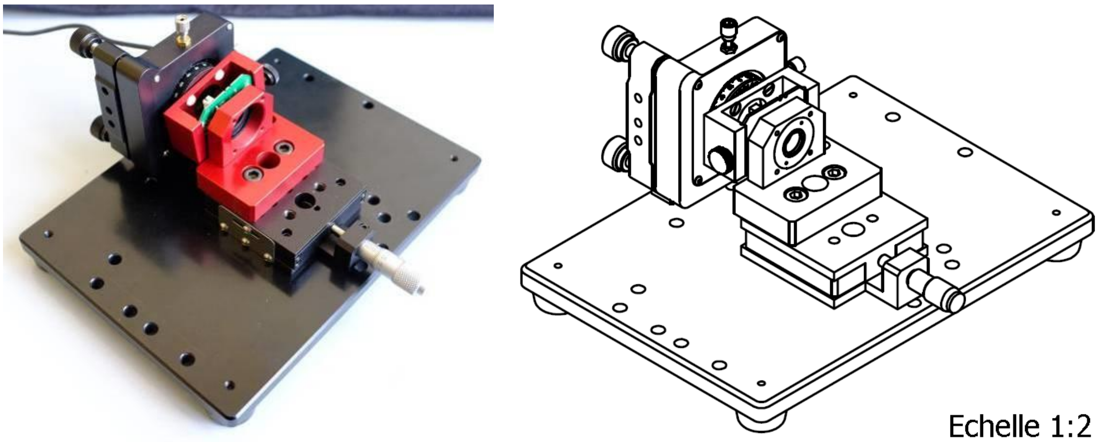


Figure 13. Final setup as mechanical drawing and in reality.

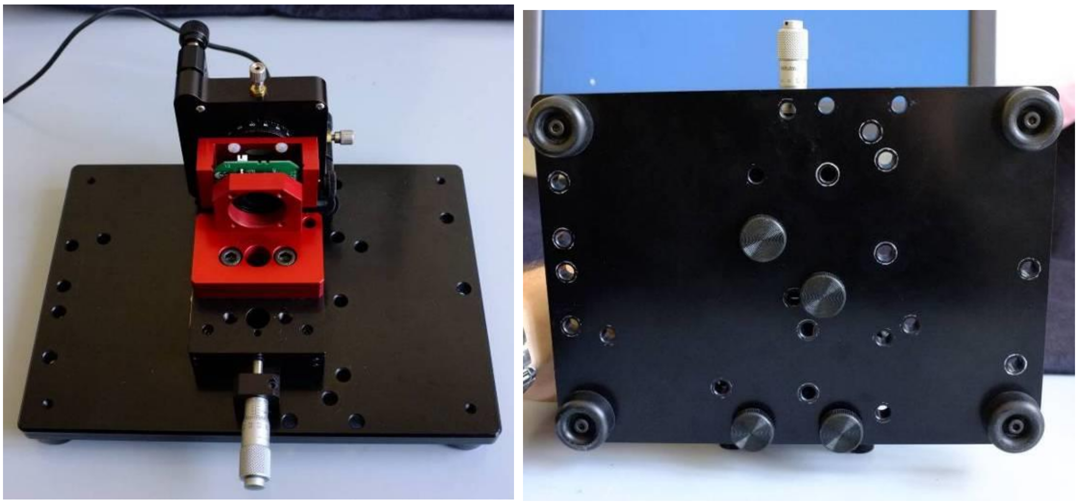


Figure 14. Top and bottom views. The view from below allows to see the fixation of the different components.

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 (without object and IR filter). Be careful in handling the camera and prevent electrical charges and shortcuts.

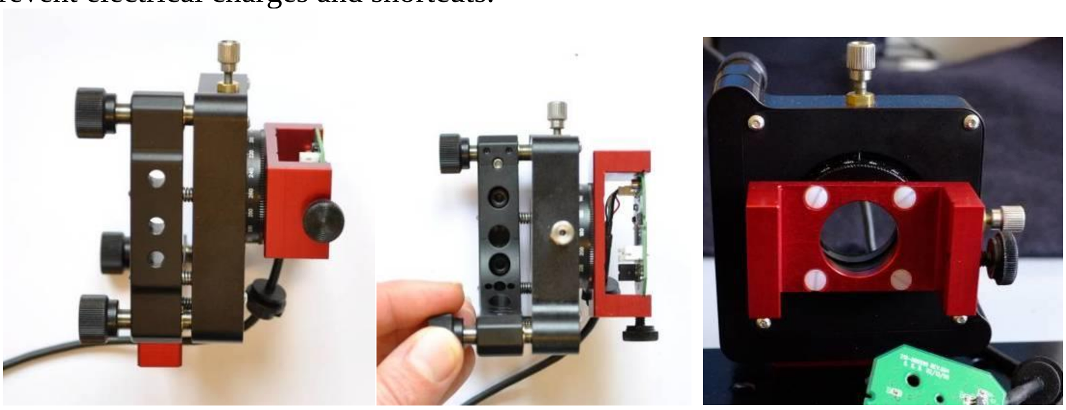


Figure 15. Six axis stage assembly with camera holder (left middle) and plastic screws to fix the camera holder on the stage (right).

NOTE: The camera holder is fixed with PLASTIC screws in the 6-axis stage!
Set everthing together on the base plate. Be carefull to avoid touching sensitive elements such as lenses, camera chip.

For the camera assembly, **remove the original objective** from the camera.

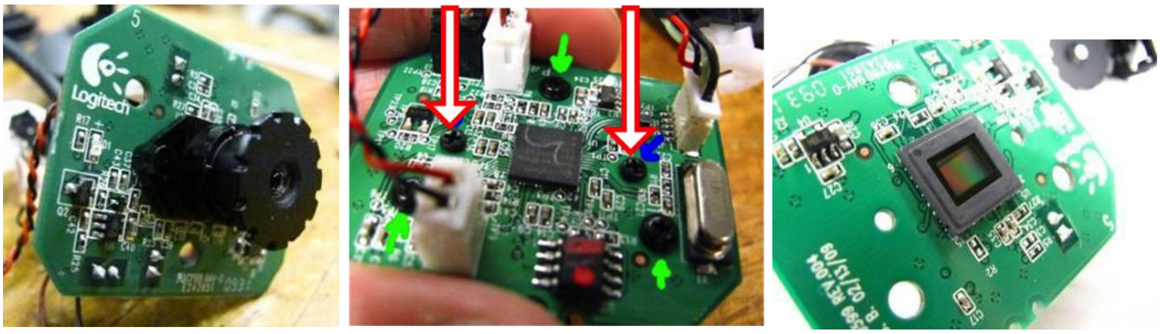


Figure 16. Camera PCB with objective. The red-white arrows show the screws to remove the objective. The PCB with the naked sensor.

Adjustment and alignment

- A lens creates an image on the detector. Touching the detector with the lens **should be avoided (Fig. 16b)**. Adjust carefully the system by observing the images and do not force the linear stage movement.
- The translation stage is used to adjust the focalization.
- 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!

BE CAREFUL WHEN ADJUSTING THE LENS, YOU MAY BREAK THE CAMERA SENSOR!!!!!!!!!!!!!

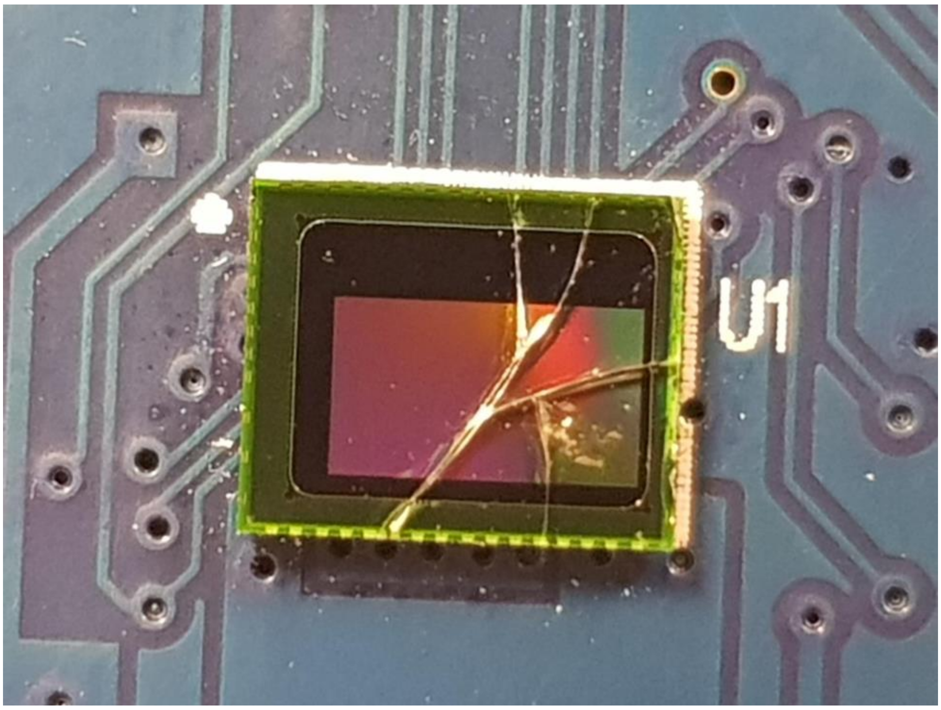


Figure 16b. Broken camera sensor due to a careless student.

2.2. 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.

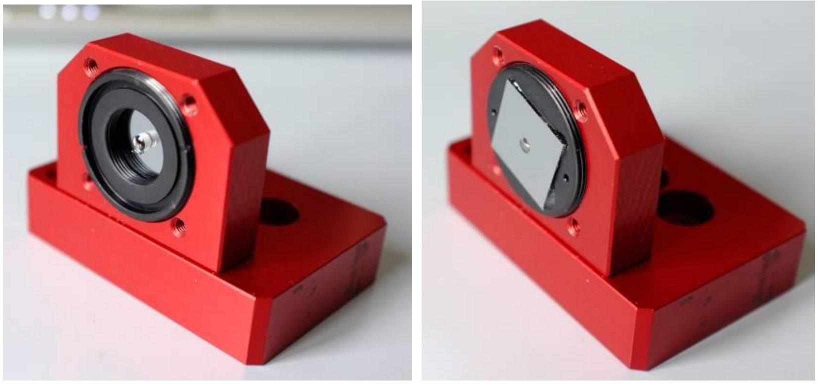


Figure 17. Mount carrying the lens. Two different orientations are shown. Left: Landscape orientation, the lens curved side is towards the detector. Right: The curved side of the lens is towards the object space.

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 the default exposure.
- Put an object close to the camera at the position that is defined by the setup as shown below (Fig. 18).

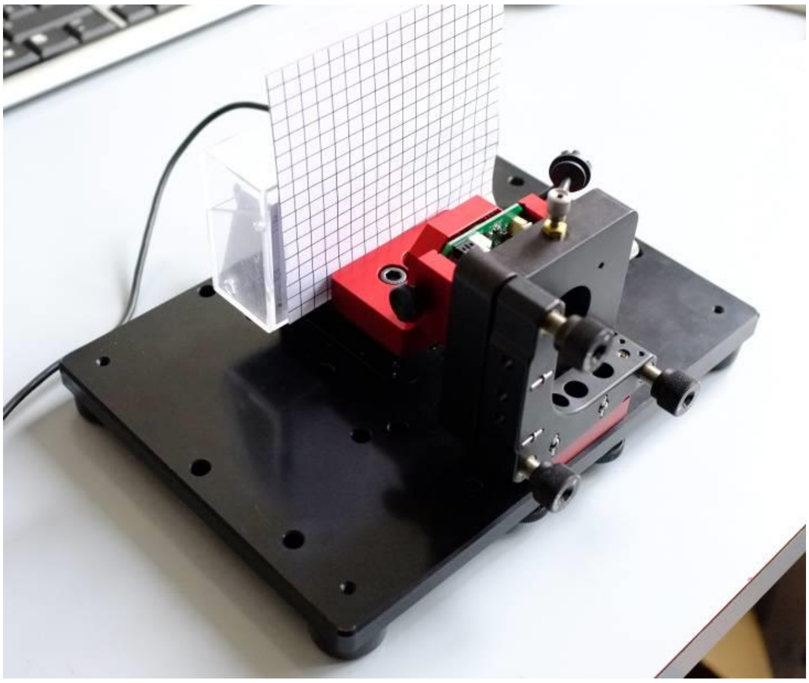
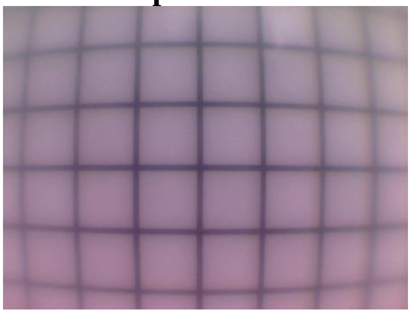
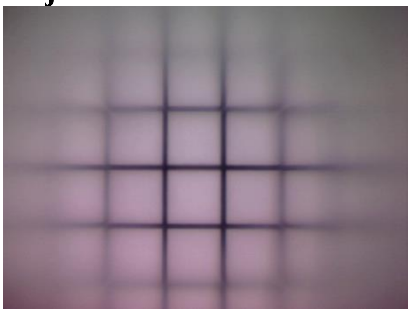


Figure 18. Preferred image position for the camera evaluation. The object is different depending on the task to be performed.

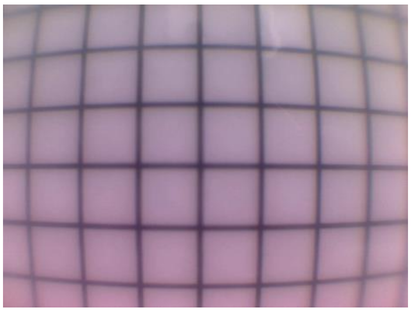
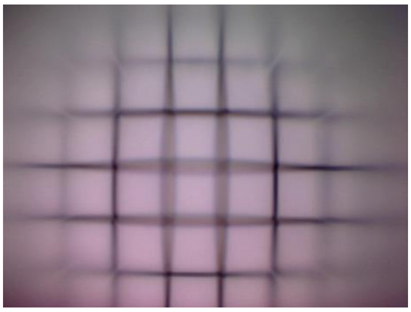
- Use the GRID as an object for this experiment, as in Fig. 18.

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

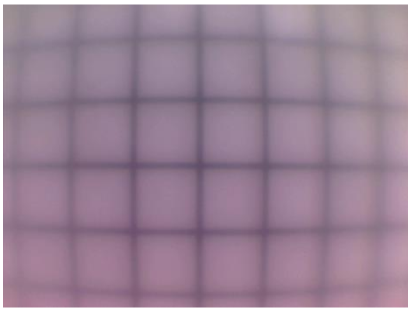
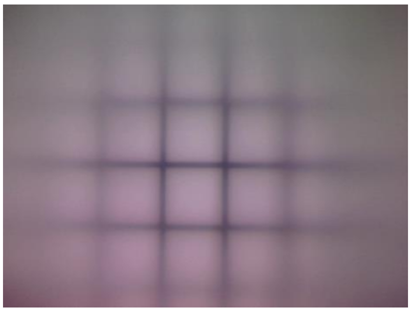
Landscape orientation **Object curvature orientation**

In focus

-300 micron – smaller distance lens detector

+300 micron – larger distance lens detector

Figure 19. Sequence of images taken with different focalization.

2.3 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.

- 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 image with rings close to the camera at the position that is defined by the setup as shown below in Fig. 20.

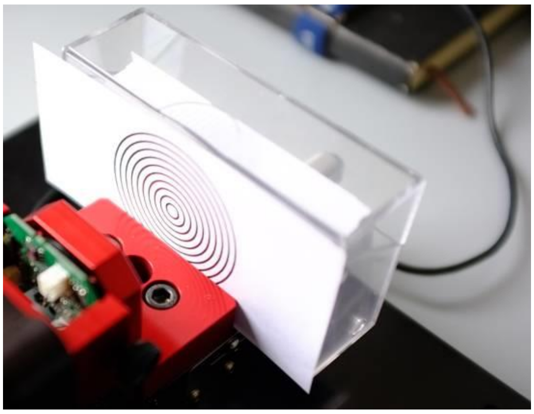


Figure 20. Imaging of rings. The rings and the camera should be well centered to get reliable results.

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

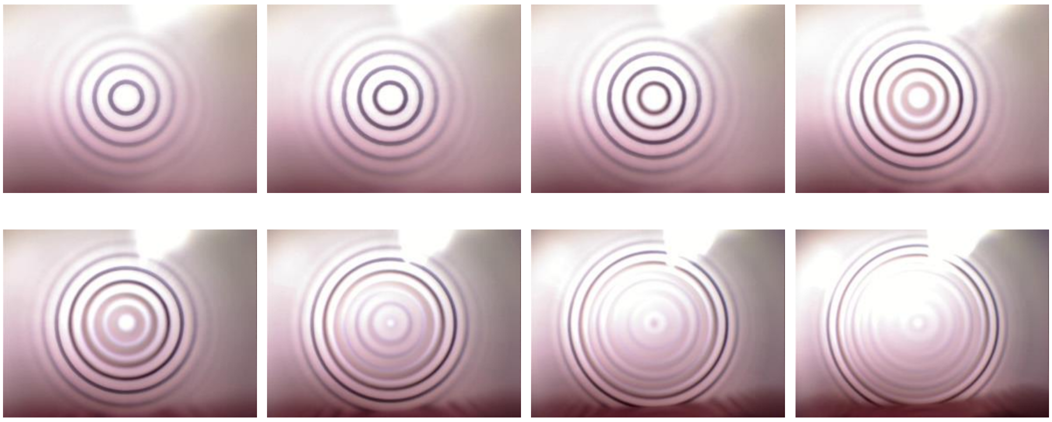


Figure 21: Example images that show that different rings are focalized at different positions depending on their ring size.

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, there is substantial 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 then 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).

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

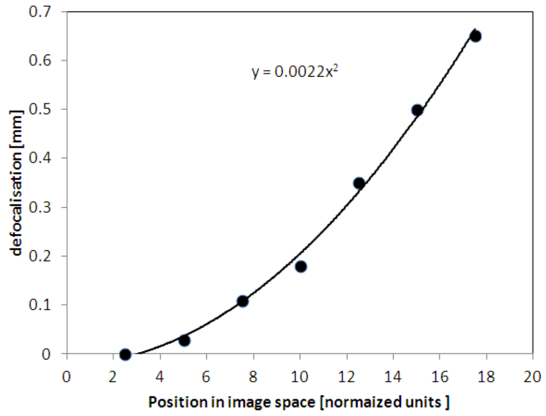


Figure 22. Example plot of measured field curvature against the position in the image space. **NOTE: the plot for the report needs to be done in mm.**

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 **R_P = f n**. This is called the Petzval curvature! We want to compare the measured 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) may be used to find the curvature at the position 0,0. Another possibility is a calculation based on geometry and a section of a circle. Then, one uses two points (center position 0,0 and one extreme point) and calculates the radius that fits these two points. Remember that two points are sufficient to find the radius if one assumes that the circle is tangential in (0,0).

2.4 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 where points on an image are either too close or too far from the center. Positive distortion is called barrel distortion, negative is called pincushion distortion

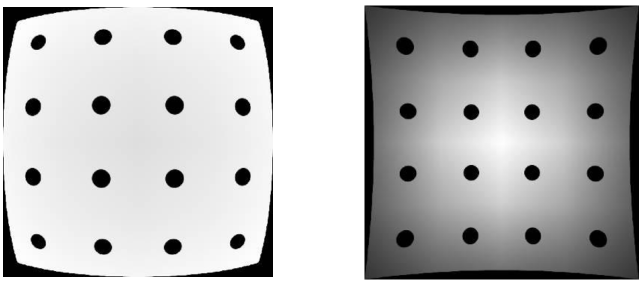


Figure 23. Illustration of barrel (left) and pincushing distortion (right) (Image: Edmund scientific).

- 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 pattern 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 the camera and/or the object card.

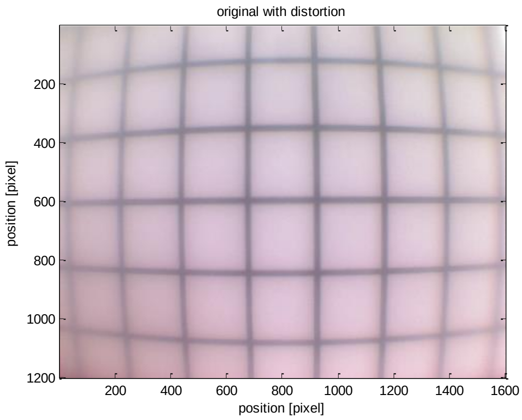
In our experiment, we want to correct this distortion by using a two-dimensional transformation. The distortion has a center and it is crucial to determine the center to achieve a good correction. **PLEASE CAREFULLY ALIGN THE SYSTEM.**

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.
- Correction of deformation by stretching the image as a function of the radius (MATLAB: s = r + a*r.^3;)
- The polar coordinates are transformed back 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 three figures, one with the original image, a second one that shows the region of interest and finally sthe 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.



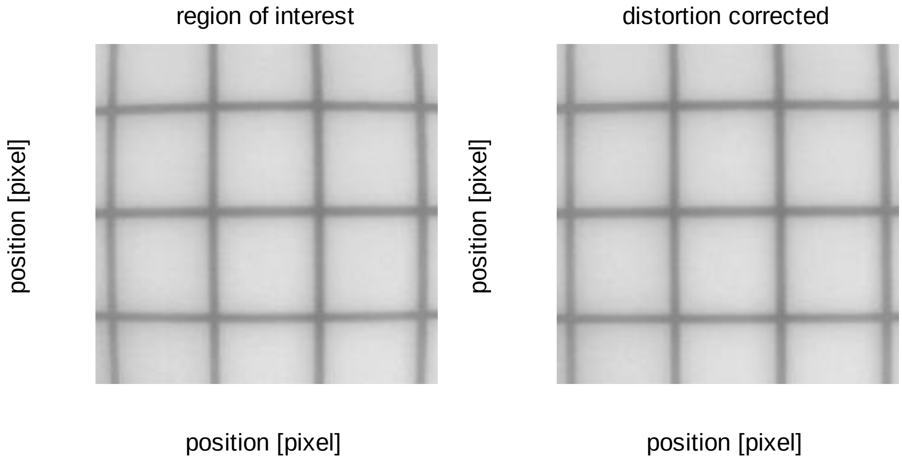


Figure 24. Example of the distortion correction. Above is the original image and below the region of interest and the corrected region of interest. NOTE that the notation of x (vertical coordinate) and y (horizontal coordinate) in Matlab might cause trouble to define the center point which is here (800,600).

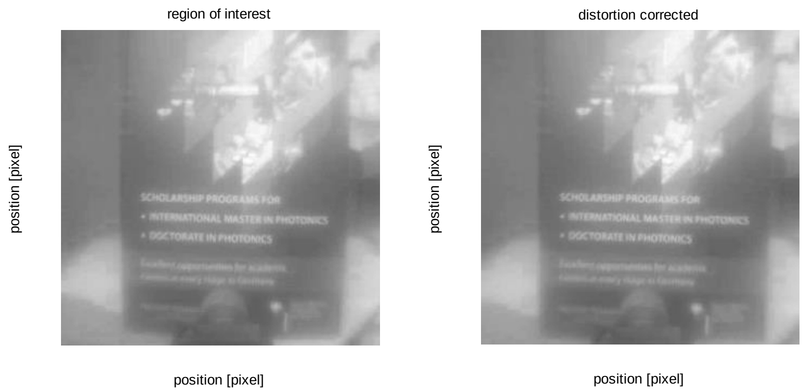
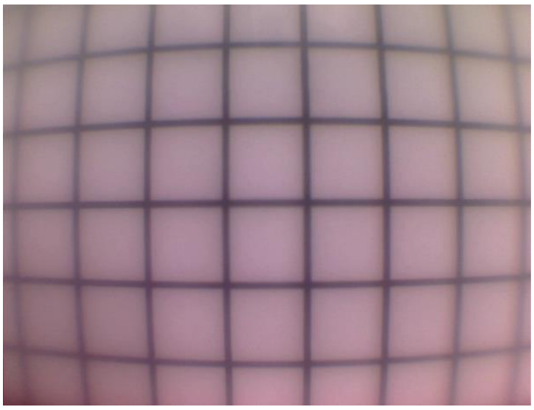


Figure 25. Example of an image sequence that uses the distortion correction value determined above to remove distortion.

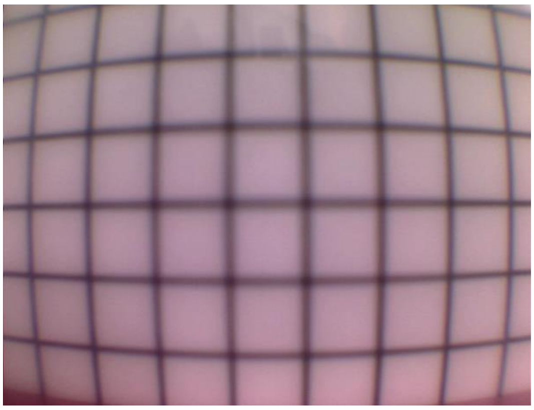
2.5 Observation of transversal chromatic aberrations for large field of views

Chromatic aberrations often appear in images with 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 pattern 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 to allow averaging.**
- Control the exposure parameters of the camera and especially the WHITE BALANCE.



Focused for the center position



500 microns defocused image (towards detector)

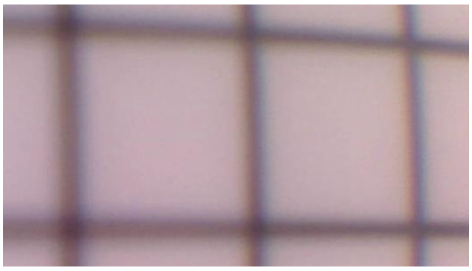


Figure 26. Example images to demonstrate chromatic aberrations. The defocused image shows color effects at its outmost areas.

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 microns. The color effects are visible at large field angles.

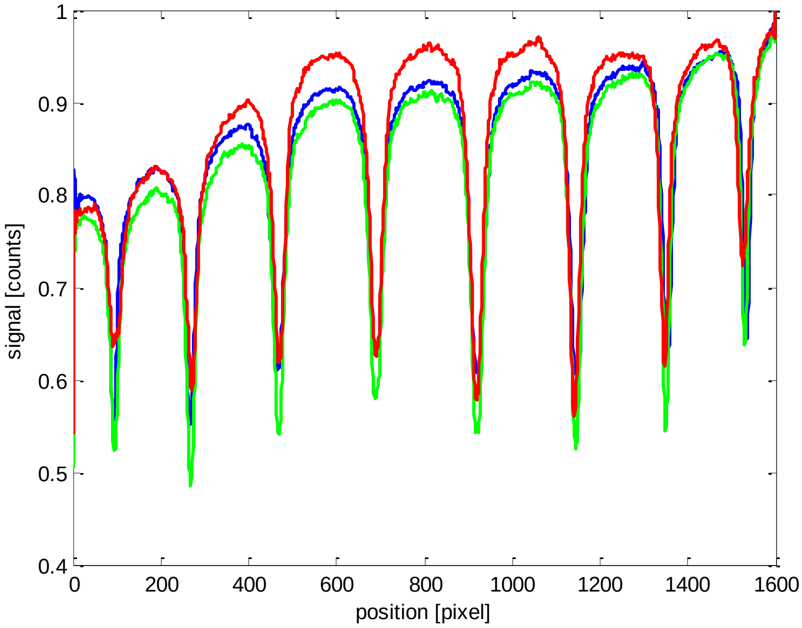


Figure 27. Normalized line plot of the RGB signals at position 655-670 (averaged) giving the peak positions of the grid. Careful evaluation will show that the peak positions (minimal intensity) are different for red green and blue.

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

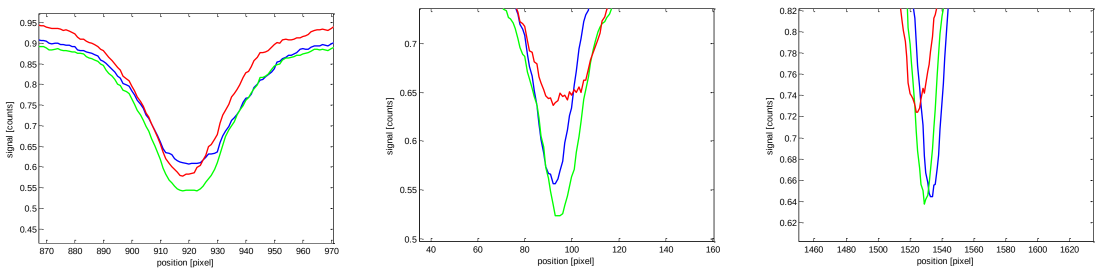


Figure 28. Peak positions for peaks at 920, 90 and 1530 pixels. At 920 all RGB peaks have the same position and this is taken as the center of the field.

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 an example of 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	???	???	???
	1533	1529	1524	???	???	???