## Department of Precision and Microsystems Engineering

### Validating and Improving a Measurement System for a Deformable Mirror

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Abstract

The semiconductor industry is on an ongoing quest to realize smaller feature size, requiring the constant implementation of new technology. A possible new technology is the use of a spatially controlled heat source to actively deform a mirror substrate to compensate for wavefront aberrations. In order to validate the ability to generate deformations, and to hold them, a measurement system is required.

Although many off the shelf surface measurement system exist, none fulfill all requirements (measurement speed, working environment, mirror size, etc) to be implemented right away. Therefore a dedicated measurement setup is built consisting of an interferometer based fringe projection method. However an initial evaluation of the measurement system showed the performance to be insufficient.

To improve the performance of the measurement system, the system is divided into four subsystems: Illumination system, interferometer, imaging system and data processing which all have been improved. The illumination system is improved by the addition of an optical isolator and polarizer to clean the laser beam, an extra beam expander to improve beam quality and pinhole overlay to reduce reflections. The interferometer is improved with the addition of beam stops to generate calibration images. The imaging system is improved by introducing: An aperture to focus on, a lens is added to improve the focus, the protection window on the CCD is removed and an aperture is introduced to reduce reflections. The data processing is improved by the tuning the filter shapes and introducing another filter to decrease edge effects.

With the improvement the stability error of the measurement system improved from 2.5 nm to 0.29 nm. The reproducibility error decreased from 4.85 nm to 0.80 nm. The spatial resolution of the improved measurement system is 0.4 mm.

To validate the scaling of the measured deformations, an absolute shape measurement is done. This absolute shape measurement requires the system shape (measured shape due to all components in the measurement setup) to be known. While measuring the system shape, the topology of the measurement mirror is assumed to be flat, the topology amplitude of this mirror is validated by an auto-calibration measurement and proved correct. However, the drift in the measurement setup prevents the system from measuring an absolute shape with an high accuracy. Although the accuracy is not sufficient for absolute shape measurements, the scaling of the measured differences is proved correct (order of magnitude).

The improved measurement system is able to validate the viability of deformable mirrors for the use in the semiconductor industry.
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Integrated circuits (ICs) are everywhere around, without them there would not be an Ipad, a laptop
computer and many more technical devices. Through research and development these devices
become smaller and jet more powerful. According to Moore’s law, the number of transistors on an
IC will double approximately every 18 months. Keeping up with Moore’s law can only be possible
by decreasing the size of transistors on ICs. Current lithography machines use Deep Ultra Violet
(DUV) light with a wavelength of 193 \textit{nm} to illuminate the wafer surfaces. To decrease the size of
the transistors even further new technology is developed using Extreme Ultra Violet (EUV) light
with a wavelength of only 13 \textit{nm}.

![Figure 1.1: A possible layout for an EUV lithography machine reflective optical system. In the
future one of the mirrors in this system might be replaced with a new active mirror. Image
modified from [1]](image)

As with all new technologies, using EUV light to expose wafers comes with some challenges. No
glass lenses can be used to focus the light since EUV light is absorbed in glass. However reflective
optics (mirrors) can be used to focus the light onto the wafer. In these mirrors still 30 percent
of the optical power is absorbed, resulting in deformations caused by local thermal expansion of
the mirrors. The transistor size depends on quality of the mirror shapes. To solve the mirror
deformation and decrease the transistor size, an actively controlled deformable mirror can be
used. A novel method of actuating a deformable mirror is described by Rudolf Saathof [2]. The
actuation principle and the deformable mirror design is experimentally tested by J. Schutten [3].
To investigate the viability of the active mirror concept for application in EUV lithography, a
measurement system is build. However, before any conclusions about the viability of the active
mirror concept can be drawn, a proof of the abilities of the measurement system is required. This
report will focus on the improvement and the validation of the measurement system.
1.1 Active mirror concept

The active mirror concept developed by Rudolf Saathof uses the same principle causing the deformations (thermal gradients) to compensate for the problem. As shown in Figure 1.2, the mirror consists of 3 layers, a thick (4 mm) mirror substrate layer, on which first an absorptive coating and then a reflective coating is deposited. An inexpensive spatial controllable heat source (a video projector) is used to illuminate the backside of the mirror, the irradiance of the video projector is absorbed by the absorptive coating. The mirror is first heated to an initial temperature (above room temperature) resulting in an initial bended shape. By lowering the heat input at the locations of EUV hot spots the mirror temperature is kept constant. At a constant temperature there are no thermal gradients and thus no mirror deformations, the active mirror compensates for EUV hot spots. The second function of the mirror is to compensate for wavefront errors (due to deformation of other mirrors) by actively creating thermal gradients and thus deformations of the mirror.

1.1.1 Requirements

The active mirror concept must be evaluated for the use in EUV lithographic machines. This poses some constraints on the working environment of the active mirror. The mirror must operate in vacuum environment and the deformations of the mirror must be up to a maximum of 100 nm. Another constraint for the control of the active mirror is the limited time available to measure the mirror surface. This is only possible in-between wafer exposures (approx. ones every 20 seconds). In lithography machines the Marechal criteria is an important factor. The Marechal criteria states that to distinguish 2 points in the exposure, the wavefront errors cannot exceed 1/14 of the wavelength. However in exposures also the dark regions need to be distinguished, resulting in a
Marechal criteria of $\lambda/20$. The Marechal criteria combined with the 13.5 nm wavelength results in a maximum for wavefront errors of $13.5/20 = 0.675 \text{ nm}$. If a mirror is used to compensate for wavefront errors the mirror deformation must be half the wavefront error since light travels towards and back the mirror. The out of plane resolution of the active mirror must thus be below $0.33 \text{ nm}$, and the mirror must contain the created shape (be stable) in between measurements to within $0.33 \text{ nm}$.

1.2 Project goal

The goal of this research project is to improve the measurement system to a level sufficient to evaluate the active mirror concept for the use in a lithography machine. The measurement system is sufficient if the stability error of the measurement system is below $0.33 \text{ nm}$. The spatial resolution of the measurement system should be above 30 waves over the mirror (measuring bumps of $.4 \text{ mm}$ wide), since this is the limit of the mirror (as described by J. Schutten [3]). To remove wavefront errors the mirror must deform with a resolution below $0.33 \text{ nm}$, the measurement system must thus be able to measure the out of plane (z resolution) below the $0.33 \text{ nm}$.

Another requirement for the measurement system is speed, the measurement system must operate at a minimum of 20 hertz for around 20 seconds to be able to investigate the stability of the active mirror concept. The measurement system must also be able to operate in vacuum environment and be contactless to ensure no damage to the mirror surface finish.

Since the measurement system must prove the mirror can deform and hold it’s shape, a differential measurement (where the shape difference before and after the mirror deformation) is sufficient. However, an absolute shape measurement is required to validate whether the differential measurements are scaled correctly.

1.3 Thesis outline

This thesis will start with an overview of different surface profilers, followed by a description of the basic principles and the performance of the initial measurement system in Chapter 3. Chapter 4 will focus on the improvements done to the measurement system to reach the required performance. An absolute shape measurement will then be described in Chapter 5. This thesis will finish with Chapters 6 and 7 where conclusions on the project and recommendations for future work will be given.
Overview of surface profilers

Although the goal of this project is not to compare different measurement systems, without some background on different surface measurement systems one could wonder why the chosen measurement system is used. The measurement systems can be roughly divided into two groups, contact and non-contact optical surface profilers. Although there are many surface profilers, a choice of most common profilers is presented in this section.

2.1 Contact surface profilers

Tradition profilometers
A profilometer is able to measure surface variations in the z direction (out of plane). The profilometer work by placing a stylus in contact with the surface and dragging this over the surface, while the movement of the stylus is measured. Profilometers are able to measure features sizes from 10 nm to up to a millimeter. Contact forces range from 1 to 50 milligrams while stylus ratios vary from 20 nm to 50 µm. The horizontal resolution of the surface profilers can be controlled by the scan speed and the sampling rate of the data signal. The surface profiles are widely accepted as the standard for measuring surface finishes, the system is robust and can be used in dirty environments where dirt can obstruct optical profilers. The drawbacks of the contact surface profiler are speed, it can only acquire one line of the surface at the time.

Atomic force microscopy
An atomic force microscope is able to measure with very high resolution in the order of fractions of a nanometer. The measurement principle is basically the same as a contact surface profiler, however the atomic force between the tip and the surface is measured with the measurement tip extremely close to the surface, but without touching the surface. Atomic force microscopes are often called a pseudo contact measurement systems. A comparison on resolution and scanning speed between the AFM, a tradition surface profiler and some optical methods is described by Chin Y. Poon [4].

2.2 Optical profilers

There are many types of optical profilers which all work on an optical principle.

Laser triangulation measurements
Laser triangulation is a measurement principle where the location of a reflected laser beam is used to measure a distance. A laser beam is aimed at a target under a slight angle, the reflection of this beam is captured on a detector (an array of light sensitive diodes). The location of the reflection on the detector array, combined with the angle of the laser source determines the measured distance. As found in the data sheet of Mirco Epsilon [5], typical resolutions range starts with a minimum
resolution of 7.5 $nm$ and ends in the meter range. To measure the complete mirror surface, the sensor or measured object needs to be moved. Also a scanning type of sensors are available where the output laser beam is scanning the surface.

**Fringe projection techniques**

As described by Song Zhang [7] high precision fast 3d shape measurements can be made using fringe projection techniques. In these techniques a video projector is used to project a pattern on the test surface. The pattern changes due to the surface topology of the measurement sample. The changed pattern is captured by a digital camera and the distortion of the projected pattern is translated into a surface profile. Fringe projection techniques work with resolutions up to 10 $\mu m$ ($=31$ $nm$).

**Shack-Hartmann Wavefront sensors**

Wavefront sensors can be used to measure the wavefront errors. These sensors work with an array of lenses, the angle of the incoming wavefront determines the location of the focus spot behind the lens. An overview of the development of the Shack-Hartmann wavefront sensor is described by Ben C. Platt [8]. The maximum resolution of a Shack-Hartmann is around $\lambda/20$ ($=31$ $nm$).

**Interferometry**

Interferometry consist out of a range of methods where waves are superimposed to extract information about the waves. Interferometers are used to measure small displacements and surface irregularities. A typical interferometer has a single incoming laser beam which is split into two equal parts by a beam splitter (semi transparent mirror), the light beams travel different paths and when recombining the path length difference results in changes in the combined beam intensity. The measured intensity is translated to a distance change of one of the optical paths. The maximum resolution is in the pico-meter range.

**Stepping interferometers**

Stepping or scanning interferometers are a special group of interferometers. This group uses a lens system to focus on a large part of the measurement object. Comparing the surface with a reference surface results in locations of maximum intensity, by shortening the reference path, different places of maximum intensity will be observed. The change of path length in the reference path relates to the out of plane distance between points where maximum intensity is measured. The shortening of the reference path is often done by a mirror placed on a piezo stepper.

For the validation of the active mirror concept, the contact measurement principles are rejected due to the possibility of damage to the surface, and slow scanning speeds of full mirror surfaces. Laser triangulation and fringe projection techniques are no viable options since the attainable resolution is not good enough. The Wavefront sensor resolution is not sufficient, and the stepping interferometer is to slow to measure stability of the active mirror. Interferometers have a resolution good enough, however the field of view appears not big enough.

To build a measurement system that is fast enough and has a sufficient resolution, a interferometer and fringe projection techniques are combined. The fringes are generated based on the interference of light, combining the full field properties of the fringe projection and the resolution of an interferometer. A more thorough description of the build measurement system can be found in the next chapter.
Chapter 3

Initial measurement system

As stated in the previous chapter, the measurement system is a combination of fringe projection techniques and an interferometric measurement system. The physical measurement setup is a slightly more advanced version of the Michelson interferometer which is thoroughly described in Advanced Mechatronic Systems [9]. The data processing of the measurement system is based on the fringe projection methods as described by Takeda [10] [11]. This chapter describes the basic working principle of the measurement system, followed by a short introduction of the components in the measurement setup, and conclude with an evaluation of the performance of the initial measurement system.

3.1 What’s interference

Interference is a phenomena in which 2 or more waves interact with each other such that the amplitude of the wave changes. Interference takes place in all sort of waves, sound waves, electromagnetic waves (light waves) and even in water waves. A clear imaging of interference can be found when one drops simultaneously 2 stones into a pool of water. From both entrance points a circular wave will propagate outwards. When the waves overlap, new waves form with a different (higher or lower) amplitude. Wave interaction is shown in Figure 3.1 where the superposition of 2 waves results in a new wave with a higher (constructive interference) or a lower (deconstructive interference) amplitude. The resulting amplitude depends on the closeness off both waves. The distance between tops in the wavefront is called phase difference.

![Interference Diagram](image)

(a) Constructive interference  (b) Deconstructive interference  (c) Intermediate case interference

Figure 3.1: Interference is the superposition of 2 waves (blue and dotted red in this example) to form a new wave (green in this example). The new wave has an amplitude varying from zero (deconstructive interference) to the combined amplitude of the original waves (full constructive interference).

The interference of light waves is not as simple as the example given above. Light is interfering all the time everywhere, but this interference is not observed. For example while reading this
report, light is reflected on the paper into your eyes, while on the same time also light is passing from right to left between the paper and your eyes. The light passing from right to left, and the reflective light from the paper interferes. However, luckily one does not observe this interference, and is able to read the report. Only interference taken place on the interface of the detector is detected. An interesting property of light is the quadratic relation between light intensity and the amplitude of the electromagnetic waves.

### 3.2 Michelson interferometer

The used measurement system consist of a Michelson interferometer as shown in Figure 3.2a. A light source delivers a large diameter beam which is split by a beam splitter and directed to the measurement mirror and the reference mirror. The lights reflects back from both mirrors and arrives at the detector. The difference in path length between both the reference beam and the measurement beam result in a phase difference between both beams. The phase difference results in a wavefront with a different intensity as shown in Figure 3.2b. Clearly in this configuration a intermediate case of interference is observed at the detector since there is no complete constructive or deconstructive interference. By shifting the reference mirror slightly forward, the phase difference increases and the intensity at the detector increases. Note that the intensity is not direct measure of the mirror position. If the mirror is shifted forward a complete wavelength, the same phase difference stay the same, resulting in the same captured intensity at the detector.

![Schematic view interferometer](image)

**Figure 3.2**: Shifting the reference mirror slightly forward results in a changed captured intensity at the detector. Note that the intensity is not linear with the intensity but there is a sinusoidal relation of intensity with mirror position.

In Figure 3.3a the reference mirror is tilted. Tilting the reference mirror means moving the upper part backwards and the bottom part forward. The tilted reference mirror results in a sinusoidal pattern of intensity at the detector as shown in Figure 3.3b. The generated pattern is called the carrier fringe, the frequency of the carrier fringe depends on both the laser wavelength and the reference mirror tilt. With the use of the interferometer basically a pattern of fringes is generated and the reconstruction is now the same as used in fringe projection measurement methods. A deformation of the measurement mirror as shown in Figure 3.4a, results in a change of the carrier fringe. The sinusoidal pattern is compressed in some locations, and stretched on other locations.
Figure 3.3: Rotating the reference mirror results in a sinusoidal intensity pattern on the detector. The measurement system uses interference instead of projecting to generate a fringes pattern. This pattern is called the carrier fringe.

Figure 3.4: A deformation of the measurement mirror results in a phase modulation of the carrier fringe. This modulation contains the topology of the measurement mirror.

based on the shape of the measurement mirror. This compression or stretch in the carrier fringe is basically a phase modulation of the carrier fringe. The phase modulation of the carrier fringe contains the shape information used in the reconstruction algorithm to reconstruct the shape of the measurement mirror.

3.3 Algorithm

To reconstruct the topology of the measurement mirror an algorithm is build to separate the carrier fringe and the modulation around the carrier fringe. The Algorithm works by transferring the captured interference pattern to the Fourier domain. Inside the Fourier domain the data is filtered and the carrier fringe is removed. Figure 3.5 shows the data from Figure 3.4c transferred to the Fourier spectrum.

If the measurement mirror would be flat, 3 peaks would form in the Fourier spectrum, the average
Figure 3.5: The Fourier spectrum of the data from Figure 3.4b. The captured data is transformed to the Fourier domain to filter the data and remove the carrier fringe. After the carrier fringe is removed a back transformation is done, and the topology information is extracted out of the filtered data.

Intensity peak, in the middle of the spectrum, and two mirrored peaks representing the carrier fringe. The phase modulation of the carrier fringe leads to a spread around the carrier fringe peak. There is no longer a peak, but a lump containing the carrier fringe and the information about the measurement mirror topology. This lump is shifted to the origin to remove the carrier fringe, followed by an inverse Fourier transformation. The angle is then isolated from the total data, and unwrapped to find the shape of the measurement mirror. A full mathematical explanation of the algorithm can be found in Appendix A.

3.4 Initial measurement setup

The initial measurement system is depicted in Figure 3.6. The measurement system can be divided into four subsystem, the illumination system (green), the interferometer (red), the imaging system (blue) and the data processing unit (PC) which is not in the figure. The schematic view of the measurement system as shown in Figures 3.2, 3.3 and 3.4 shows the illumination system as the source and the imaging system as the detector. The illumination system delivers a large diameter laser beam to the interferometer, the laser source first passes a neutral density filter to adjust the laser power. The beam is expanded by a beam expander and the collimated by a lens to have flat wavefronts. The interferometer consist of a beam splitter, reference mirror and measurement mirror. The interferometer is placed in a vacuum chamber to isolate it from airflows. The imaging system consist of a focus lens to focus the beam on the CCD camera.

3.5 Experimental Method

It is easy to check for a number of requirements for the initial measurement system as described in Section 1.1.1. Things as the speed of the measurements (30 hertz based on the camera frame rate), the requirement for contactless measurement and the ability to operate in a vacuum environment are easily checked. However to evaluate the performance of the measurement system, the stability and reproducibility of the measurement system are determined in a series of experiments.
Figure 3.6: The measurement system can be divided into 4 parts: The imaging system containing a laser (1), neutral density filter (2), beam expander (3) and a collimator lens (4). The interferometer part contains a beam splitter (5), reference mirror (6), measurement mirror (7) and is placed in a vacuum chamber (8). The imaging systems contains a focus lens (9) and CCD camera (10). The fourth part is data processing basically a PC which is not in the image.

Figure 3.7: The active area of the ccd chip, with the locations (A) and (B) of the projected fringe patterns to test the CCD position sensitivity.
3.5.1 Stability

The stability of the measurement system is determined by generating 512 shape measurements of the measurement mirror over a timespan of 17 second. The average shape is determined as the average of all the individual measurements. For each measurement point \( n \) the root mean square error \( \sigma_n \) with respect to the average shape is determined. To include all root mean square errors into a single number (RMSE value) the root mean square error is determined:

\[
\sigma = \sqrt{\frac{\sum_{n=1}^{N} \sigma_n^2}{N}}
\]  

(3.1)

where \( N \) denotes the total number of measurement points. The calculated value indicates the ability of the measurement system to measure the same shape over over time, thus indicating the stability of the measurement system.

3.5.2 Reproducibility

A second part in the evaluation of the performance is an experiment of reproducibility. Reproducibility is defined as the ability to measure the same shape while a minimum of one component is exchanged. Instead of exchanging a components the reproducibility is evaluated by selecting an other part of the imaging chip of the ccd. The interferogram is projected on less than half of the surface of the imaging chip as shown in Figure 3.7. Also the move of the ccd camera is relatively easy, and there is no reason to believe moving the ccd changes the shape or alignment of the measurement mirror.

The reproducibility is summed to one value by taking the root mean square difference (RMSD value) between the average measured shapes on locations A and B. Although the alignment of the ccd is done with great care, small differences in alignment result in an unfair representation of the reproducibility. The possible misalignment of the ccd is corrected digitally by shifting the average shapes in both x and y direction until the best match is found.

3.6 Performance of the initial setup

Using the methods described in the previous section, the initial measurement setup is evaluated. Figure 3.8a shows \( \sigma_n \) in nm for all measurement points, while Figure 3.8b shows the difference in nm between the two measurement locations on the CCD. The total RMSE value is 2.5 \( nm \) while the measured RMSD value is 4.85 \( nm \). The RMSE and RMSD values indicating stability and reproducibility are to high to fulfill the requirements of the measurement system as described in Section 1.1.1. Therefor the initial measurement system needs to be improved in order to be useful in evaluating the active mirror concept.
Figure 3.8: The RMSE and difference of the basic measurement setup are too high to fulfill the required specification.
Improving the measurement system

The initial setup as described in Section 3.6 does not meet the requirement on stability described in Section 1.1.1. In order to fulfill the requirements the measurement system needs to be improved. The measurement system is a complex system and in order to improve it, a division into four separate subsystems (illumination system, interferometer, imaging system and data processing) which all fulfill their own function in the measurement system, is made. To set out a red line for the improvement of all four sub systems, some properties of ideal subsystems are formulated. Although the subsystem will never be ideal, the ideal properties stated below make it possible to analyze the subsystems to find where performance gains can be made.

Illumination system

The illumination system is the light source of the measurement system, some properties of an ideal illumination system are:

- The light should have a single wavelength and polarization direction (be a monochromatic light source).
- The output beam should have a large diameter to illuminate the whole mirror surface and the distribution of optical power should be uniform over the complete bundle.
- The output of an ideal illumination system only consist out of the generated light, any reflections or light from other light sources should be adsorb in the illumination system.

Interferometer

The interferometer is the core of the measurement system, some properties of an ideal interferometer setup are:

- The components in the interferometer should have a high stiffness with respect to each other.
- The interferometer should be able to compensate for the initial bended shape of the deformable mirror.

Imaging system

The imaging system is an optical system between the interferometer and the CCD interface. Some properties of an ideal imaging system are:

- The imaging system must decrease the beam size to fit on the CCD imaging chip.
- The imaging system should absorb all light entering the system, so no light is reflected back into the interferometer.
Data processing

The data processing calculates the shapes based on the captured interferograms. Also some statistical tools are used to evaluated the measured shapes, some ideal properties of the data processing are:

- There should be no loss of shape information of the measurement mirror in either capturing or processing of the data.
- The measured shape of a mirror deformation, should be independent of the location of the original deformation.

4.0.1 Method

The improvements done in all of the four subsystem are described using the same structure. For each component in the improved subsystem the function is described. In the case a component is changed or added to the improved measurement setup, a simulation, experiment or both are done to show whether the change is beneficial. Changes in the measurement setup can be quickly assessed by comparing the measurement setup with the ideal measurement setup described above.

Experiments

The experiments done to validate the improvements in the measurement setup are all done using the same methodology. To ensure the sequence of improvements does not influence the review of the component, first the setup is build until it reaches it best configuration. A series of 4 reference experiments is done to validate the system is indeed at it’s peak performance, then the component under investigation is removed and another set of 4 experiments is done. These experiments are all done as described in Section 3.5. Of a set of 4 experiments the RMSE is determined for all 4 measurements and averaged. To generate 4 RMSD values the first and last measurements are done projecting the interferogram on the left side of the CCD chip, while the second and third are done projecting the interferogram on the right side.
4.1 Illumination system

The illumination system functions as the source of light in the measurement system. As stated in the introduction an ideal illumination system has a large diameter monochromatic beam with an uniform distribution of optical power. Improvements of the illumination system are mainly focused on the laser stability, and the optical power distribution. As Figure 4.1 shows, the improved illumination system contains a number of additional components compared to the initial illumination system.

Figure 4.1: The key components of the improved illumination system are: (1) laser, (2) Optical isolator, (3) polarizer, (4) neutral density filter, (5) beam expander, (6) microscope objective, (7) pinhole with anti reflection cover and a collimator lens (8).

The optical path of the illumination system as shown in Figure 4.2, starts with a Helium-Neon laser source, followed by a optical isolator to ensure no reflections of the laser beam reflect back into the laser source. An polarizer is used to ensure the laser beam consist of just one laser mode. The neutral density filter is used to adjust the optical power of the beam. The beam size is enlarged in two steps, first a beam expander increases the beam size, followed by a microscope objective to enlarge the beam even further. The pinhole works as a spatial filter to reduce wavefront errors. On the outgoing side of the pinhole an anti reflective overlay is used to reduce reflections. The last component in the illumination system is a collimator lens to generate a flat wavefront in the output beam.

4.1.1 Laser

The illumination system uses a laser as light source. Lasers are considered one of the purest form of light, although in reality the output is not just a single frequency. The output of a laser, is a spectrum of laser modes which all have slightly different frequency. In the illumination system a typical helium-neon laser, with an central frequency of $632.8 \text{ nm}$ is used. The output spectrum of this helium-neon laser contains 3 modes.

The modes in the laser output spectrum depend on the length of the laser tube, which again depends on the temperature. To ensure the output spectrum always contains the same laser modes, the laser temperature must be stabilized. A large aluminum mount is used to increase the thermal mass of the laser, and thus increase the thermal stability of the laser.
Figure 4.2: A schematic view of the illumination systems optical path. The key components are:
(1) laser, (2) Optical isolator, (3) polarizer, (4) neutral density filter, (5) beam expander, (6) microscope objective, (7) pinhole with anti reflection cover and a collimator lens (8).

The polarization direction of the light differs between the laser modes, successive laser modes have there polarization directions oriented perpendicular to each other.

4.1.2 Optical isolator and polarizer

To stabilize the laser source, reflections of laser light back into the laser must be prevented. This is achieved by the implementation of a Thorlabs IO-3d-633-vlp Free space optical isolator [12]. This optical isolator works with 2 polarizer (entering and exiting polarizer) that are rotated 45 degrees with respect to each other, and a Faraday rotator. The entering polarizer is aligned with the polarization direction of the laser mode in such a way that the light can pass the polarizer. The Faraday rotator rotates the polarization direction of the light with 45 degrees so it can pass the exiting polarizer. Any reflections must pass the optical isolator in opposite direction to reach the laser source. The reflection can pass back to the exiting polarizer, but then the Faraday rotator rotates the polarization direction again 45 degrees resulting in a 90 degrees rotation of polarization with respect to the original polarization. The reflections are unable to pass the ingoing polarizer and are stopped from reaching the laser source.

To ensure there is strictly only one polarization in the output of the illumination system a Thorlabs GTH5-A Glan-Thompson [12] polarizer is introduced into the setup. The Glan-Thompson polarizer consist of 2 Glan-Thompson prisms added together. Birefringence splits the light on entering the prism into two rays, which experience a different refractive indice on the interface of both prisms, thus creating a polarized beam splitter with a rejection ratio of 100,000 to 1.

Aligning the polarization directions

In order to ensure the illumination system delivers a beam of one frequency and one polarization direction, the laser optical isolator and pinhole must be aligned. The alignment of these components cleans the laser output spectrum to just a single mode. The aligning of these components is described in Appendix B.

Qualitative observations show a clear increase in contrast between the fringes after a single laser mode is selected in the illumination system. Figure B.3 shows captured interferograms of both
the setup with and without the correct alignment of the laser, optical isolator and polarizer. To quantify the improvement due to the optical isolator and polarizer, an experiment is done. This experiment compares the optimized measurement system with the measurement system without the optical isolator and polarizer. For the optimized setup an average RMSE value of 0.29 nm and a RMSD of 0.79 nm are measured, while for the setup without the optical isolator and polarizer an average RMSE value of 0.90 nm and a average RMSD value of 1.21 nm is measured, showing the polarizer and optical isolator have a significant contribution to the performance of the measurement system.

4.1.3 Microscope objective, pinhole and collimator lens

The microscope objective (strong lens), pinhole and collimator lens are combined to form a beam expander. A collimated beam enters the microscope objective, and a collimated beam with a much larger diameter leaves the collimator lens. The beam diameter can be expanded by passing either a convex or concave lens, in the setup a convex lens is used, so the beam is first travels through a focal point before it expands. The beam diameter at the collimator lens depends on the distance between the microscope objective and collimator lens and the focal length of both lenses. In the setup the combination of focal lengths is chosen such that the beam size at the collimator lens is (much) larger than the lens diameter, light missing the lens is discarded. The larger than the lens diameter beam size is to ensure the output beam of the illumination system is determined only by the diameter of the collimator lens.

Pinhole as spatial filter

The beam is first focused before it expands, in this focal point a pinhole is located. The pinhole functions as a spatial filter to remove wavefront aberrations. The pinhole has a size of 8 µm and must be positioned very accurately at the focal point. To position the pinhole with respect to the microscope objective a single mount is used to hold both pinhole and microscope objective. Aligning the pinhole is an iterative process, in which the mount is touched multiple times. Since

Figure 4.3: Captured interferograms for one or multiple laser modes. Qualitative there is a better contrast when there is only one laser mode in the illumination system.
Figure 4.4: The lens and pinhole combination is used as a spatial filter to remove wavefront aberrations from the beam.

especially the microscope objective is sensitive to rotational movements, the rotational stiffness of the mount is increased by an additional supporting leg.

Figure 4.4 shows a schematic view of the pinhole as spatial filter. An aberrated wavefront (drawn in green) arrives at the microscope objective. The flat parts of the wavefront are focused at the pinhole and can pass undisturbed, while the wavefront aberrations are focused away from the pinhole (and thus blocked). In this manner the wavefront aberrations are filtered away by the pinhole.

The pinhole is made out of a metal sheet, this results in a high reflective surface. Light reflected in the interferometer is focused back on the pinhole, and the pinhole reflects it back into the interferometer. These back reflections cause a kind of jitter (a fast variation of intensity mostly in the form of circles shapes in the captured images). To remove this jitter from the captured images a paper overlay is placed in front of the pinhole. This paper cover ensures reflections out of the interferometer are absorbed and not reflected back into the interferometer.

**Experimental results**

In Figure 4.5 one observes a qualitative difference between the beam exiting the illumination system with and without the pinhole in place. In the case that only the anti reflective cover is removed one observes jitter in the images. The images also show some speckles which result from removing the CCD window, more on the removal of the CCD window can be found in Section 4.3.

To find quantitative numbers on the improvements due to the spatial filter and the anti reflective overlay, two experiments have been done. A reference experiment in which the improved setup is evaluated is compared to the setup without anti reflective pinhole overlay, and with the setup with the pinhole removed. The reference measurements show an average RMSE of 0.29 nm and an average RMSD of 0.79 nm. The measured average RMSE and RMSD without the anti reflective overlay are 0.97 nm and 0.67 nm. The average RMSE and RMSD values with the pinhole removed are 0.44 nm and 1.16 nm. These numbers indicate that the pinhole decreases the position sensitivity of the ccd camera and thus shows a better reproducibility of the measurement system. Removing the anti reflective overlay results in a much larger noise level of the measurement system.

The removal of the anti reflective pinhole overlay result in lower stability of the measurement...
system. The RMSD value measured without the anti reflective overlay is lower than measured in the reference experiment, there is no theoretical reason to assume the anti reflective pinhole improves the RMSD performance of the measurement system and a possible cause might be the alignment in the imaging system.

4.1.4 Beam expander and neutral density filter

The final two components in the illumination system are the of the shelf beam expander, and the neutral density filter. The Neutral density filter is used to adjust the optical output power of the illumination system. The beam expander is used to decrease the optical power variation over the beam.

A laser beam has an Gaussian optical power distribution. This distribution of power leads to an uneven distribution of optical power in the output beam of the illumination system. A simple way to reduce the variation in optical power is to use only the center part of the beam. The microscope objective and collimator lens already increase the beam size and discard a part of the beam. Increasing the beam size at the collimator lens even further would result in less variations in the power distribution. To increase the total beam size at the collimator lens an extra beam expander is placed before the microscope objective. This results in a larger diameter beam at the collimator lens, and thus a smaller part with a smaller variation of optical power captured by the collimator lens. The new optical power distribution is shown in Figure 4.6. The decrease of variation in the optical power distribution comes with a cost, the average intensity of the beam is lower (since a smaller part of the beam is used). However, this can be compensated by adjusting the setting of the neutral density filter.

Experimental results

The simulated profiles shows a clear improvement on the distribution of optical power. To quantify this improvement an experiment is done where the optimized setup is compared with the setup

Figure 4.5: The difference between intensity distribution with (a) and without (b) the pinhole. The speckles on both images are glass dust, a result of removing the protection window in front of the CCD chip.
Figure 4.6: By expanding the beam the intensity variation of the part of the beam used is lowered, at the cost of a lower average intensity.

![Diagram showing beam expansion and intensity variation](image)

Figure 4.7: Overview of the performance of all components in the illumination system.

where the second beam expander is removed. For the optimized setup an average RMSE of 0.29 nm and a average RMSD of 0.79 nm are measured. Average RMSE and RMSD values of 0.39 nm and 0.88 nm are measured in the experiment without the extra beam expander.

### 4.1.5 Total error budget of the illumination system

In this section the working principles of the component of the illumination system have been described. The components added (optical isolator, polarizer, beam expander and anti reflection pinhole) to the improved illumination system have all been evaluated by means of simulations and experiments. Figure 4.7 shows an overview of the performance of all component in the illumination system. The optical isolator and polarizer clean the beam to one laser mode. The extra beam expander flattens the distribution of optical power in the beam, and the anti reflective pinhole overlay reduces back reflections in the illumination system.
4.2 Interferometer

The interferometer is the core of the measurement system. Section 3.2 already explains the basic principle on which the interferometer part of the measurement system is working. However, the interferometer contains more components than the ones mentioned in the introduction. This section will describe how air pressure around the interferometer, apertures and vibration isolation influence the performance of the measurement system. Figure 4.8 depicts the interferometer in a photo and a schematic view.

![Interferometer](image)

Figure 4.8: The interferometer is the heart of the measurement system. Key components: Vacuum chamber (1) Beam splitter (2), Reference mirror (3), Active mirror (4) and beam stops (5). The beam splitter splits the incoming light into 2 parts aimed at the reference and active mirror. The mirrors reflect the light back and interference occurs when the beams recombine. Beam stops are placed to be able to stop the light reaching the individual mirrors to generate calibration images.

Since the basic measurement principle is quite simple, at first sight there does not seem to be much to improve in the interferometer. However, the introduction of beam stops, allowing for the possibility of calibration images (see Section 4.5) and the introduction of an additional aperture improve the performance of the measurement system.

4.2.1 Beam splitter

The central component in the interferometer is the Edmund optics Techspec non-polarized cubic beam (50 mm) splitter [13]. This beam splitter splits the incoming light from the illumination system into two equal parts which are directed to the reference and measurement mirror. The specified surface flatness of the beam splitter is $\lambda/8$ ($= 80 \text{ nm}$). The surface flatness is important since the surface topology of the beam splitter deforms the wavefront resulting in a measured shape. To investigate the influence of the beam splitter surface flatness, the beam splitter is rotated around the Z axis. This rotation did not show large differences in the measured shape.
4.2.2 Beam stops

While improving the data processing of the measurement system the need for calibration images arose. In order to capture these calibration images, the beams to the reference and the measurement mirror must be blocked. Two beam stops (black windows which can rotate into the beam) are introduced in the interferometer to block the beam in between the mirrors and the beam splitter. The rotation of the beam stops is accomplished by small servo motors, to block beams while the interferometer operates in vacuum. With the beam stops, calibration images of both the single beams and both beams blocked can be captured. The beam stops operate without disrupting the working principles of the interferometer, and one could argue the beam stops are in fact more part of the data processing system (described in Section: ) then the interferometer.

4.2.3 Mirrors

The interferometer compares the surface topology of both the reference and the measurement mirror. The shape of the reference mirror may not change during the measurements, therefore an Edmund Optics 2 inch precision mirror with a specification on flatness of $\lambda/20 (= 30 \text{ nm})$ is used. To further increase the shape stability of the mirror, a Zerodur substrate, which has a very low $(0.2 \cdot 10^{-7}K^{-1})$ thermal expansion coefficient is chosen.

Although the goal of the measurement system is to measure the deformations of the active deformable mirror, while evaluating the measurement system itself, the measured shape may not change. Therefore while evaluating the measurement system the shape of another zerodur precision mirror is measured.

4.2.4 Vacuum environment

As described in the introduction the final application of the deformable mirror requires the mirror to operate in a vacuum environment. The interferometer itself only needs an environment free of turbulent airflow to operate. In the deformable mirror concept, as described in Section 1.1, thermal gradients are used to generate the mirror deformations. The thermal gradients in the mirror result in a turbulent airflow around the mirror due to convection. To overcome this problem and to simulate the working environment in the final application, the interferometer is placed in a vacuum chamber. In a vacuum environment there is little to no air and thus no airflow.

In this report only the measurement system is evaluated, to ensure the measured shape does not change the shape of a stable zerodur mirror is measured while evaluating the measurement system. The zerodur mirror is free of temperature gradients, so there is no turbulent airflow in the interferometer. Therefore, while evaluating the measurement system, in theory there should be no difference between the interferometer operating in a vacuum or atmospheric pressure environment.

To evaluate the effect of a vacuum environment compared to an atmospheric pressure environment, an experiment is set up. Measurements with a vacuum (9mb) environment results in average RMSE and RMSD values of 0.31 nm and 0.81 nm, while reference experiment at atmospheric (1028 mb) pressure show average RMSE and RMSD values of 0.29 nm and 0.79 nm. The measurements proves that the performance of the measurement system is not influenced by the air pressure in the vacuum chamber. Note this is only valid if there is no heating of the measurement mirror.
Figure 4.9: Edge diffraction of a coherent light source, results in transition zones behind the aperture where interference occurs. Image from [14]

4.2.5 Apertures

Although the illumination system delivers a beam with a sufficient diameter to illuminate the complete mirror surface, there are some apertures in the interferometer causing problems. The apertures in the interferometer are the windows to enter and exit the vacuum chamber and the size of the beam splitter. When light passes an aperture, edge diffraction can occur. The edge diffraction results in a propagation of transition zones behind the aperture where interference occurs, as shown in Figure 4.9. To overcome the problem of edge diffraction, the imaging system must ensure the aperture is in focus (see Section 4.3). The beams pass the beam splitter multiple times, and the optical path length between the first passing and the last passing of the beam splitter is different for both beams. This makes it hard for the imaging system to focus on the aperture.

To ensure the imaging system can focus on a defined aperture, an additional aperture is added just before the beams leaves the interferometer.

4.2.6 Compensation of the initial bended deformable mirror shape

The active mirror concept is based on the generation of temperature gradients. This requires the mirror to first be heated to an initial temperature, causing a bended mirror shape. This initial bended shape must be compensated in the interferometer.

Although most of the compensation is done in the interferometer, first the illumination system is modified so a slightly diverging beam enters the interferometer. The divergence of the beam results in a slightly curved wavefront, however the further we travel the smaller the relative curvature in the wavefront becomes. The curvature in the wavefront doesn’t show up in the measured shape, as long as the optical path length of both the measurement as the reference beam is equal. By introducing a optical path length difference between both beams, the curvature of the wavefront at the detector is no longer equal, resulting in a measured shape with an amplitude equal to the mismatch in curvature. With an correct amount of divergence and optical path length difference, the initial bended deformable mirror shape and the generated shape due to the different curvatures cancels out, as shown in Figure 4.10.
This method of initial mirror shape compensation induces sensitivity for beam intensity fluctuations since the reference and measurement beam travel different distances in the interferometer. As described in the section on mirrors, while improving and evaluating the measurement system, the deformable mirror is exchanged for a stable Zerodur mirror. The compensation of the initial bended shape is still in operation, causing an bended shape to be measured.

4.2.7 Vibration isolation

The real measurement takes place in the interferometer part. Here the shape difference between the reference and measurement mirror is done. Any vibrations of the optical components in the interferometer directly influence the measured shape. The shape of the mirror is not changing, but changes are measured due to vibrations, vibrations are thus a source of noise in the measurement system. Although the total measurement setup is located on a stabilized optical table, additional measures to ensure vibrations in the interferometer are taken.

- The interferometer is placed on an addition breadboard which is supported on four rubber balls. The goal of this independently supported breadboard is to isolate the interferometer from horizontal vibrations.

- The rotational stiffness of the beam splitter is important since the beam splitter act as an cornering mirror ones for both the reference as the measurement beam. A rotation of the beam splitter results in a shift of the beams with respect to each other. To increase rotational stiffness of the beam splitter, the center of mass of the mount and the beam splitter is located directly above the supporting leg and an additional leg is introduced.

- In addition to all measures, additional stiffness between the 3 components is introduced by connecting the components with stiffening rods.

Section 5.2 describes an auto-calibration method for the measurement system. This requires the active mirror to move in both horizontal and vertical direction. The movement of the measurement mirror prevents the use of a stiffening rod. To evaluate the effect of the stiffening rod, an
Figure 4.11: The vibration isolation measures. The interferometer is built on a separate breadboard, supported by 4 rubber balls on an optical table. The stiffness between the optical components is increased by stiffening rods.

experiment is setup. A reference experiment with the rod in place shows average RMSE and RMSD values of 0.29 nm and 0.79 nm, while experiments without the rod show average RMSE and RMSD values of 0.34 nm and 0.81 nm. The experiments done prove the removal of stiffening rod does not significantly decrease the performance of the measurement system. However, this comparison is not complete fair since in actual operation of the active mirror there are additional vibrations from the video projector. These vibrations are absent during both the experiments done to evaluate the influence of the stiffening rod.
4.2.8 Error budget of the interferometer

In this section the interferometer part of the measurement setup is evaluated. The performance of the interferometer is not improved but the flexibility is increased by proving that (see Figure 4.12) the removal of the stiffening rod doesn’t decrease the performance of the measurement system. Operating the interferometer in a vacuum environment does also not increase the performance under the condition that the measurement mirror is not heated. Added to the interferometer is a additional aperture which generates a single plane in the interferometer for the imaging system to focus on. Beam stops have been introduced in order to capture calibration images used in the data processing step.

Figure 4.12: Overview of the performance of the components added in the interferometer
4.3 Imaging system

The imaging system is an important and often forgotten part of an interferometric measurement system. The main function of the imaging system is to focus the interferograms formed in the interferometer on the CCD camera. An ideal imaging system must focus the interferograms, cause no image degradation due to reflections, and must absorb all light entering the system to ensure no back reflections into the interferometer occur. Figure 4.13 depicts the initial and improved imaging system.

![Figure 4.13: The initial and improved imaging system. Components are (1) object plane aperture (not in the image), (2) focus lens (nearly visible), (3) focal plane aperture, (4) collimator lens, (5) CCD camera.](image)

The improved imaging system consists of an object plane aperture (described in the Section 4.2.5), a focus lens to decrease the beam size and an aperture in the focal plane to remove back reflections. Before the light arrives at the CCD it is collimated again by a collimator lens to ensure flat wavefronts arrive at the CCD camera. Although it is not visible in the image of the improved imaging system, the removal of the protection window (5b) in front of the CCD imaging chip improves the imaging system significantly.

![Figure 4.14: A schematic view of the optical path in the improved imaging system. Key components are: (1) Object plane aperture stop, (2) Focus lens, (3) Pupil plane aperture stop, (4) Collimator lens, (5) CCD camera, (5b) CCD protection window.](image)
4.3.1 CCD camera

The imaging system uses a Imaging Source DMK31BF CCD camera which hold an Sony ICX204AL image chip. The working principle of the CCD chip is described in Appendix C. Although the camera has many good properties, two properties cause problems in the imaging system. The first problem is the partly reflective chip interface, and the second problem is internal reflections due to the protective glass cover in front of the imaging chip.

Internal reflections

The combination of the reflective chip interface and the protective glass cover cause internal reflections. Figure 4.15a shows an interference pattern with in the background circular artifacts. These artifacts are expected to be a result of internal reflections in the CCD camera. To validate this theory the camera is tilted with respect to the optical axis, and the shape of the artifacts is monitored. As Figure 4.15b shows, the shape of the artifacts changes from circles into arcs, proving the artifacts indeed originate from the camera.

The amplitude of artifacts can be minimized by introducing a slight tilt in the alignment of the CCD camera. However, the artifacts can’t be totally removed by a CCD tilt. The artifacts influence the measured shape and show up when comparing shapes measured on the left and right side of the CCD. Figure 4.16a shows the difference between two measured shapes on the left and right side of the CCD camera. One can observe an almost sinusoidal pattern with an amplitude of approximately $8 \text{ nm}$ between both shapes, as a result of the artifacts caused by internal reflections in the CCD camera.

To solve the problem of internal reflections the protection window on the CCD is removed. The window removal is done by first grinding away one of the sides of the window, followed by carefully pulled the window off the package. Although the process of removing the window is carefully executed, a small amount of glass dust is left on the CCD imaging chip.
Figure 4.16: (a) The artifacts influence the measured shapes. The comparison of two measurement on different sides of the CCD shows a almost sinusoidal pattern due to the artifacts. (b) To remove the internal reflections the protection window in front of the CCD is removed. An interferogram after the removal shows no artifacts.

CCD tilt

Before the removal of the CCD window, the camera was tilted to minimize the effect of internal reflections. With the CCD window removed this is no longer necessary, since tilt only introduces a sizing error when the CCD camera is shifted through the beam. To quantify the size of this error an experiment is done. With CCD tilt the RMSE values remain the same, while RMSD values increase from 0.79 nm to 1.11 nm for a tilted CCD.

4.3.2 Lenses

The most important function of the imaging system is to decrease the beam size to fit the imaging chip on the CCD camera. To do so the entrance (object plane) and exit (CCD) interfaces of the imaging system must be investigated. The size of the beam at the exiting interface is determined by the size of the pixel size combined with the input of the algorithm. The algorithm as described in Section 4.5 requires a input of 512 by 512 pixels, the beam size at the exiting interface is chosen such that the beam illuminates 540 by 540 pixels. The beam size is larger then the needed 512 by 512 pixels, since the beams from reference and measurement mirror do by definition not totally overlap on the imaging plane. The pixel size of the CCD is 4.65 μm resulting in a beam size of 2.5 by 2.5 mm at the exiting interface. The entrance interface (object plane) of the imaging system has a size of 42 by 42 mm.

If the only requirement of the imaging system would be to decrease the beam size a single focus lens, as used in the initial imaging system, would be sufficient. However an imaging system with only one lens is unable to focus on the object plane. Figure 4.17 shows an captured image of only the reference beam, the light and dark fringes round the sides of the object plane are a typical result of edge diffraction combined with defocus in the imaging system.

To focus the imaging system an additional collimator lens is required. The collimator lens is
positioned such that the distance between the focus and collimator lens is exact the combined focal length of both lenses. The focal length of the collimator lens is chosen such that the collimated beam after the collimator lens has the required 2.5 by 2.5 mm size.

**What’s focus**

Consider a light ray departing from a single point in the object plane. This light ray passes through the imaging system, and is projected on a single spot on the imaging chip (imaging plane). Now consider a second ray of light departing from the same spot on the object plane but slightly angled with respect to the first ray. This second ray is also projected on the imaging plane. The system is in focus when the first and the second light rays both are projected on the same point.

In the case the imaging system is in focus, the object and imaging plane are called conjugate planes. To calculate the required distances in the imaging system, ray transfer matrix analysis is used. With ray transfer matrix analysis a 2 by 2 RTM (ray transfer matrix) can be constructed, which calculates how light passes through an optical system. The RTM is multiplied by the input plane which consist of a vector which contains the distance $x$ from the optical axis of the ray, and the angle $\phi$ of the ray with respect to the optical axis.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} x_{in} \\ \phi_{in} \end{bmatrix} = \begin{bmatrix} x_{out} \\ \phi_{out} \end{bmatrix}$$ \hspace{1cm} (4.1)

The RTM represents the optical system between the input and output plane, the coefficients A, B, C and D are thus dependent on the components and the position of the components in the optical system. For the imaging system to be focused, the transfer form light from the input (object) plane, to the output (imaging) plane must be investigated. If one now looks at the two rays departing from the same spot on the object plane, both have the same $x_{in}$, but a different $\phi_{in}$. Both rays should be projected on the same spot $x_{out}$ on the image plane. To calculate $x_{out}$ on the image plane, the following formula is used.

$$A \cdot x_{in} + B \cdot \phi_{in} = x_{out}$$ \hspace{1cm} (4.2)
For the system to be in focus we must thus demand that the $B$ coefficient equals zero. The $B$ coefficient of the RTM of the actual imaging system is:

$$B = -\frac{1}{16}d_1 - 16d_2 + 42.5$$

(4.3)

where $d_1$ is the distance between the object plane and the focus lens, and $d_2$ the distance between collimator lens and ccd. Clearly for every distance between the object plane and the focus lens there exist an distance between collimator lens and ccd for which the $B$ coefficient is zero and thus the system is in focus. Figure 4.18 shows a Matlab simulation of the system in focus.

Experimental results

A focused imaging system results in a significant improvement of the average RMSD value of the measurement system. Without focus measurements show RMSD values around $1.7 \text{ nm}$, while for focused systems RMSD values of $1.2 \text{ nm}$ are measured on average. The RMSE values do not change with the focus of the imaging system.

4.3.3 Apertures

The imaging system contains two apertures. The first aperture is the object plane aperture which is described in Section 4.2. The second aperture is placed in the focal plane of the imaging system. This aperture does not fulfill the traditional role of an aperture since it does not reduce the beam size. The function of this aperture is to counter reflections of the CCD. As described the CCD imaging chip is reflective. Reflections from the CCD interface are transmitted back into the measurement system causing jitter. This jitter results in large RMSE values of the measurement system.

To ensure the focal plane aperture does not act as an aperture, the size is an important parameter to control. Lenses act as natural Fourier transformers where the Fourier plane is imaged in the focal plane of the lens. The aperture is also at this location, Figure 4.19 shows the projected
Fourier spectrum of both beams. An aperture in the focal plane act as a filter in the Fourier plane. To ensure no data is lost in the physical setup, the aperture size must be chosen larger than the size of the digital Fourier filter. The final diameter of the aperture is chosen twice the distance between both spots in the focal plane as Figure 4.19 shows.

**Experimental results**

The introduction of the object plane aperture and the focal plane aperture to counter the reflections of the CCD surface are evaluated using experiments. The average RMSE and RMSD values for a reference experiment are 0.29 nm and 0.79 nm. Experiment with the object plane aperture removed do not show significant changes, this might be due to the fact that a part of the outer part of the beam is not used in the reconstruction algorithm. The RMSE and RMSD values with a removed focal plane aperture are: 0.56 nm and 1.38 nm, which is significantly higher than the measured values in the reference experiment.

Figure 4.19: Image of the Fourier spectrum projected in the focal plane of the imaging system. The two red points are the projections of both beams, the distance between both spots, is half of the size of the aperture.
4.3.4 Error budget of the imaging system

The improved imaging system differs on quite a number of point with the initial imaging system. The introduction of the collimator lens reduced the RMSD error significantly, and the removal of the CCD protection window reduced the RMSD value even further. The focal plane aperture is introduced to counter back reflections of the CCD. An overview of the improvement due to all components is shown in Figure 4.20.

![Figure 4.20: The errors for the total imaging system](image)

Figure 4.20: The errors for the total imaging system
4.4 Overall effects in the physical setup

The measurement setup is build in the optics laboratory of the Mechanical engineering faculty of
the TU Delft. Although lab conditions are not bad, this is also not a extreme clean or vibration
free laboratory. For example the buildings air condition system located in the room next door,
induces quite some vibrations.

4.4.1 Temperature control

The laboratory is temperature controlled. As Figure: 4.21 shows the lab temperature is stable
around 22 degrees. The temperature in the lab is especially important for the laser stability and
the alignment of all components, since temperature variations cause the supporting legs of all
optical components to change in length.

![Temperature Graph](image)

Figure 4.21: The measured temperature in the optics lab is constant around 22 degrees Celsius.
Measurements with a resolution of .5 degree are done every 5 minutes.

4.4.2 Vibrations

The measurement system has to preform on the sub nanometer level, therefor vibrations are of
great concern. The complete setup is build on an Thorlabs optical table [12] which is placed
onto 4 air-springs to isolate the optical table from floor vibrations. Another source of vibrations
originates from the actuator. An internal air fan used to cool the video projector generates some
vibrations. During the evaluation of the measurement system the video projector is not used, so
the vibrations due to the projector cooling are not measured.

4.4.3 Airflow

Airflow is an important factor for the stability of the measurement system. There are three sources
of air flows around the setup, turbulence around hot components, air conditioner flow and a airflow
from the actuator cooling. Hot components in the setup are the laser and the CCD camera. The
temperature of these components causes air flow due to convection. Therefor, plastic shields are
mounted around these components, to divert the turbulent air away from the measurement setup. The air conditioning in the optics laboratory generates a down flow of air to ensure dust stays on the floor, this airflow also disturbs the measurement setup. The last source of airflow is caused by the actuator. The video projector generates lots of heat, which is expelled at the side by a strong blower. This heat has to be diverted away from the setup. A series of plastic shields is used to divert the hot air away from the setup.

**Experimental results**

To evaluate the effect of shielding around the measurement setup is setup. Step by step the shielding is removed, and each time the resulting RMSE and RMSD values are measured. Figure 4.22 shows the effect of the removed shielding. The shielding of the interferometer part of the measurement system is the most important since in that section contains totally separated optical paths for both beams. The difference due to shielding of the imaging system is smaller then expected since although the beams travel a nearly common path, there are sections of the path where both beams are completely separated (around the focal point of the imaging system). A possible explanation might be some blocking of the down flow of air due to the storage shelf above the optical table.
4.5 Data processing

The last step in the measurement system is data processing. During the data processing the shape of the measurement mirror is reconstructed from the captured image. The data processing consist of two main sections, the software settings of the CCD camera, and the digital reconstruction algorithm. Both are improved to increase the performance of the measurement system.

4.5.1 CCD Camera

An imaging source DMK31BF CCD camera (see Appendix C) is used to capture the interferograms. The camera software allows for 6 imaging parameters to be set.

- **Frame rate:** The frame rate of the camera can be adjusted. By adjusting the frame rate the dark noise of the camera is influenced. Dark noise is a combination of stray light outside and inside the camera, and the readout noise. Dark noise is called dark noise because it can be measured by blocking all laser light from entering the camera. The frame rate of the camera can be set to 3.75, 7.5 15 or 30 Hz. A frame rate of 30 Hz is chosen so 512 images can be captured in a timespan of 17 seconds to capture a dataset of 512 images.

- **Exposure time:** The exposure time can be chosen for 1/10000 up to 30 seconds in 20 discrete steps. The exposure time chosen for one image capture is 15.6 ms, this is just below the chosen frame rate.

- **Gamma value:** The gamma value is something used in photographic systems to compensate for the non-linearity in especially displays and projectors. The gamma value of the camera should be kept at 1.0 (which corresponds with a software setting of 10) since there is no need for compensation, and compensations is only data distortion.

- **Brightness:** The brightness value of the camera determines the zero point in the system. With this parameter one can shift the zero level of the camera, meaning that no light entering the camera still gives some signal. A shift of 6 intensity values is introduced to ensure that noise is correctly displayed. The shifting of the zero level results in the need for calibration images to generate images with a correct zero level.

- **Contrast:** The contrast of the camera is a parameter which controls the camera gain. The gain in the camera determents the intensity values of the captured image. By increasing the contrast value the intensities on every pixel is increased.

The influence of all software settings of the camera can be found in Appendix D. In order to find the best software settings for the camera, but also to investigate the digital reconstruction algorithm, a Matlab camera model and a 1d version of the reconstruction algorithm are build. The 1D algorithm is build to increase the speed of the simulations. The 1D algorithm using the same filter shapes as the 2D version of the algorithm.

**Camera Model**

The model of the CCD camera contains the several parameters. The *dynamic range* of the camera can be set to different values, for simulation purposes also an infinite dynamic range can be chosen. *Offset* can be chosen as a single value representing a increased of intensity for all pixels. *Camera saturation* is modeled by clipping values higher then the maximum dynamic range of the camera.
The analog digital conversion or quantization is modeled by rounding the input signal. Noise is modeled by adding a random number, taken out of the normal distribution to each pixel.

The input of the camera model is the interferogram, which is a light intensity variation $S(x)$ based on the shape and tilt of both mirrors in the interferometer.

$$S(x) = \frac{1}{2} + \frac{\sin[2R(x) - 2M(x)]}{2} \quad (4.4)$$

where $R(x)$ is the shape of the reference mirror and $M(x)$ the shape of the measurement mirror. Note that $S(x)$ has a value between 0 and 1 where zero means deconstructive interference and 1 constructive interference. This signal is transformed by the camera model to the input signal for the reconstruction algorithm $S_i(x)$.

$$S_i(x) = (\text{Dynamic range} - \text{Offset}) \times \text{Saturation} \times S(x) + \text{Offset} \quad (4.5)$$

In simulations done in this chapter the following reference shape is chosen to represent the system. The main shape is a sinus with a frequency 0.5 and an amplitude of 400 nm, on which a sinus with a frequency of 10 and a amplitude of 20 nm is superimposed. Figure 4.23 shows the mirror shape used in the simulations and a reconstructed shape using the optimized parameters.

Two parameters which can not be adjusted by influence the captured signal are the dynamic range and saturation level of the CCD camera.

**Dynamic range**

The Dynamic range of the camera is limited by the AD (analog digital) conversion to just 256 intensity values. The limited dynamic range results in errors due to rounding the input signal. The effect of dynamic range is tested by a simulation. Figure 4.24a shows the simulated error for cameras with different dynamic ranges. To summarize the errors in a single number, the Root Mean Square (RMS) of all data points is taken. Although the error is decreasing while increasing the dynamic range, this only results in a decrease of RMS error from 0.991 nm to 0.988 nm. This results are quite logical since the algorithm to reconstruct shape is depending on the spatial variation of the measured intensity opposed to the absolute value of the measured intensity. Round off errors only influence the absolute values of the measured intensities.
Saturation level

The camera has a set dynamic range, resulting in a limit of the light intensity that can be captured at each pixel site. If the light intensity is larger than the limit imposed by the dynamic range, the camera saturates. Camera saturation leads to loss of information, because the spatial intensity variation in the captured image no longer matched the real intensity variation. The camera saturation is simulated by multiplying it with the saturation value until the signal becomes larger than the dynamic range of the camera. A saturation of 1.1 means the signal is 10 percent larger than the dynamic range. Figure 4.24b shows the simulated error due to camera saturation. A saturation of 1.1 result in an increase of the error of 16 percent with respect to a saturation value of 1.

4.5.2 CCD initialization

As mentioned in the previous section a number of parameters can be adjusted in the software settings while other parameters can not be set. The values for frame rate, gamma and brightness are chosen for the best image quality (see Appendix: D). The exposure time and contrast combined with the intensity of the laser output beam controls the amount of dynamic range used. In order to capture the best quality of images the maximum dynamic range of the camera should be used, without saturating the camera. An initialization algorithm is build to find and set the best values for both exposure time and contrast. The initialization algorithm uses 2 phases, in the first phase the longest exposure time (without saturating the camera) is found and set. The second phase sets the contrast value such that the maximum dynamic range of the camera is used.
Experimental results

To validate the working principles of the initialization algorithm, an experiment is executed where the camera is saturated on purpose. This experiment is compared to a reference experiment where the initialization algorithm is used. The reference measurement shows an RMSE of 0.29 nm and a RMSD of 0.79 nm, while the saturated experiment shows an RMSE of 0.44 nm and an RMSD of 1.32 nm. The initialization algorithm decreases both the RMSE and the RMSD value, showing the CCD initialization algorithm contributes to the measurement systems improvements.

4.5.3 Frequency leakage

The reconstruction algorithm transforms the captured interferogram to the Fourier domain. The Fourier transformation assumes a periodic signal, but at the begin and the end of the captured interferogram the signal is abruptly cut. This abrupt cut may induce errors which are called frequency (or spectral) leakage. The spectral leakage may be decreased by smoothing out the start and end of the sample interval, which is done by filtering the captured signal. Figure 4.25a shows a simulated fringe pattern, the filter shape and the fringe pattern after the filter is implemented. Figure 4.25b shows the algorithm transfer function with and without the filter implemented. Clearly the errors are smaller if the filter is applied.

4.5.4 Filter shape and number of fringes

In the Fourier domain the data is filtered and shifted. The shift is done to remove the carrier fringe frequency, the filtering is done to remove the peak due to the average intensity of the measured signal. The filter has a circular shape and is located around the peak of the carrier fringe. Figure 4.26 shows the peaks from the carrier fringe and the peak due to the average intensity of the signal in the Fourier plane.

As Figure 4.26 shows, the maximum size of the filter depends on the location of the carrier fringe frequency. This frequency is depended on the number of fringes. The filter size determines the spatial resolution of the measurement system and therefore the amount of fringes must be
maximized. To maximize the amount of fringes, the fringes are aligned perpendicular to the diagonal of the captured image, so the spatial sample frequency is increased to $512\sqrt{2}$, resulting in an optimal carrier fringe frequency of $128\sqrt{2}$ fringes. However, in practice a much lower number of around 100 fringes is chosen.

To investigate the influence of the filter size on the spatial frequency of the measurement system a simulation is done. The original shape chosen in the simulations is a sinusoidal shape of which the spatial frequency is increased. This shape is transformed to fringes by the camera model, run through the algorithm and the RMSD of the reconstructed shape and the original shape is used to summarize the total error. Figure 4.27 shows the RMSD plotted against the spatial frequency of the original signal for both a small and a larger size filter. Figure 4.27 clearly shows the relation between filter size and spatial frequency.

The shape of the filter is also of importance. The filter discards some shape information, since it filters the signal. To ensure the least amount of data is filtered away, the filter should be a big disk around the carrier fringe peak, and zero for all values outside this disk. However the filter is
applied in the Fourier domain, and then an inverse Fourier transformation is applied. The sharp edges on the filter cause reconstruction errors which can be minimized by smoothening the edges. An example of the filter shape with minimal reconstruction error is an blackmann harris window. However, a blackmann-harris shaped filter would result in much more shape information to be filter away. A combination of both filters is made by cutting open the blackmann harris window en introducing a much wider flat top. While optimizing the filter, different combinations of disk width and ramp (from blackmann harris window) width are investigated. Figure 4.28 shows some tested filter shapes and the corresponding Fourier transformations of these filters. A ramp width of 15 pixels is sufficient to ensure little error due to the Fourier transformation are found in the reconstructed shape.

4.5.5 Static noise reduction

The camera captures the interferograms, but not only the interferograms. Also some static noise which is composed of correlated camera noise for example due to non uniform pixel size, stray light, and the offset imposed by the software settings are captured. Another big part of static noise is the non uniform intensity of the output of the illumination system. To compensate for these static noises a compensation algorithm is implemented. This static noise reduction algorithm uses calibration images of: Both the beams in the interferometer blocked (dark image), only the reference beam blocked and only the measurement beams blocked. The beams are blocked by the beam stops introduced in Section 4.2.2

dark frame

The noise reduction starts with the dark frame image. In this dark frame image the laser beam is blocked by both beamstops and no measurement signal arrives at the CCD camera. However the stray light offset and are captured and cause an image to be formed which is called the dark frame. This dark frame is subtracted from all following images captures.
2 Beam interference

In the interferometer basically a 2 beam interference problem occurs for every pixel. 2 Beam interference is described by J.D. Ellis [15] as the following function:

\[ I = I_m + I_r + 2 \sqrt{I_m I_r} \cos[(\omega_m - \omega_r)t - (\phi_r - \phi_m)] \]  
(4.6)

where \( m \) and \( r \) denote the measurement and reference beam, \( I \) is the intensity, \( \omega \) the angular frequency and \( \phi \) the phase. Note that this equation is only valid when both beams have the same polarization direction (yielding the requirement of strictly one polarization for the illumination system). For the full mathematical derivation of this formula see J.D. Ellis.

Since both beams originate from the same laser source, the angular frequency is the same for both and we can thus remove this from Equation 4.6. The phase difference is located within a cosine function, so the minimum and maximum intensity of the two beam interference can be given as:

\[ I_{\text{min}} = I_m + I_r - 2 \sqrt{I_m I_r} \]  
(4.7)

\[ I_{\text{max}} = I_m + I_r + 2 \sqrt{I_m I_r} \]  
(4.8)

The intensity \( I_m \) and \( I_r \) are measured individually for all pixels. With these values one can calculate the maximum and minimum possible intensity if both beams would interfere. With these maximum and minimum values, for each pixel an individual scale can be calculated between constructive and destructive interference. The captured interference pattern can now be enhanced with the information about the minimum and maximum intensity due to interference using the following formula:

\[ S_{\text{enhanced}}(x) = \frac{S(x) - I_{\text{min}}}{I_{\text{max}} - I_{\text{min}}} \]  
(4.9)

Figure 4.29a shows a simulation of the captured intensities of both beams, the resulting fringe pattern and the fringe pattern after enhancing. Note that the intensities of both individual beams have the same shape but not the same amplitude, for example caused by the beam splitter. The captured intensity due to interference is not simply the addition of both intensities since there is a quadratic relation between intensity and electromagnetic field which is actually interfering. Figure 4.29b shows the captured interference pattern (blue) in which the shape of both the individual beams is still visible. The Figure also shows the interferogram after the application of the static noise reduction algorithm, where the interference pattern is enhanced (scaled) to the full dynamic range of the camera.

4.5.6 Minimum feature size

The minimum feature size of deformations the algorithm can detect is an important value. The actual measurement mirror has a quite low spatial resolution, it can produces deformations with an in-plane resolution of around 0.75 mm which equals 10 pixels on the CCD camera. The algorithm must at least be able to detect features of 10 pixels to ensure all mirror topology changes are captured, but a smaller features size of 0.5 mm is aimed for to validate no other effects are influencing the mirror substrate.

Using simulations features of just 1 pixel can be applied. The algorithm is able to detect this peaks, but is unable to match the exact shape due to the maximal spatial frequency as a result of the filter shape. However the filter shape is not the limiting factor in the spatial resolution. The
Figure 4.29: The static noise reduction algorithm used the captured intensities of both individual beams, to calculate the maximum and minimum intensity due to interference for each pixel. The captured data is enhanced (scaled) with using the maximum and minimum intensity to remove intensity variation in the beam.

Spatial resolution is determined by the position dependency of deformations in the reconstruction algorithm. If a small feature is located at the top of an interference peak, the reconstructed amplitude of the feature is smaller than the reconstructed amplitude of the same feature located halfway an interference fringe.

A simulation is done where the position and the width of a feature is varied. Figure 4.30 shows the RMSD between reconstructed shape and the actual shape. For a small feature width the difference between the errors is much larger than for larger feature sizes. The algorithm appears to be able to reconstruct the best for feature size of 9 pixels, while features with a width bigger than 6 pixels can be reconstructed well. This results in a spatial resolution of the measurement system of 0.45 mm.
4.6 Overview of improvements in the measurement system

The previous sections described the improvements of each part of the measurement setup. Inside the illumination system a optical isolator and polarizer, a extra beam expander and a anti reflective pinhole overlay are introduced. The interferometer itself is not improved, but the flexibility is increased by showing that removing the vacuum environment and a stiffening rod does not increase the RMSE and RMSD values. The illumination system is improved by the introduction of an object plane aperture, focal plane aperture (to reduce reflections back into the interferometer), collimator lens and the removal of the protection window in front of the imaging chip. The data processing is increased by the introduction of a static noise reduction algorithm and an improved filter shape. However the biggest improvement in the measurement system is made by shielding all four subsystem from airflows. An overview of the improvements of all components is shown in Figure: 4.31.

Although it’s tempting to sum the improvements due to all the individual components, and generate circle diagrams of the error, this would not be fair since there are correlations between improvement due to different components. A clear example of the correlation is the improvement due to the pinhole and the SNR algorithm. As shown in Figure 4.32, RMSD value of 2.54 nm without the pinhole and SNR algorithm are measured. The improvement due to the pinhole is 1.02 nm, the improvement of the SNR algorithm is 1.3 nm. The total improvement of both measures is 1.75 nm which is much smaller than the value found by simply adding the improvements of the pinhole and SNR algorithm.

In general, the biggest gains are made by shielding the measurement system from airflows. In further improvements the anti reflection measures (the anti reflective pinhole overlay, and the focal plane aperture) result in a lower RMSE. The RMSD value is lowered by the improvements in the imaging system in general and in particular by the removal of the protection window on the CCD.
Figure 4.31: Overview of ALL errors
4.6.1 Performance of the improved measurement setup

The improved measurement setup shows average RMSE values of 0.30 nm. This level of stability in the measurement system is enough to prove the stability of the measurement system, since the stability of the measurement system is below the required Marechal criteria. The RMSD value is improved from 4.85 nm to 0.80 nm. The spatial resolution (minimum in-plane size of a mirror deformation) is 0.45 mm which is sufficient since the deformable mirror attain a spatial resolution is 0.75 mm.
Validating the measurement system

The main function of the measurement systems is to measure shape changes due to deformations generated by the active mirror. The previous chapter evaluated the stability of the measurement system based on the differences in the measured shapes, while the stable shape of a (zerodur) mirror is measured. The calculated value of the stability of the measurement system depends on the scaling of the deformations, however it is still unknown whether the measured shape changes are scaled correctly. To validate the scaling of the measured shape changes, an absolute shape measurement can be used. This chapter will describe an method for absolute shape measurements using the improved setup, followed by an alternative absolute shape measurement method based on gradient measurements, and will conclude with a short peak on drift in the measurement system.

5.1 Absolute shape measurement

As described in Chapter 3 the measurement system measures the shape difference between the measurement and reference mirror. In order to measure the absolute shape of the measurement mirror the shape of the reference mirror, which we will call the system shape must be subtracted from the measured shape to find the absolute shape of the measurement mirror. The ability of the measurement system to perform absolute shape measurements is evaluated by measuring a mirror with a known topology (the VSL mirror), and comparing the measured shape with the known shape of the VSL mirror.

System shape

Although the measurement system in principle measures the difference between the reference and measurement mirror, all (optical) components in the measurement setup contribute to the measured shape. For example the interfaces of the beam splitter, which are passed twice, have a specified surface flatness of $\lambda/8$ (= 80 nm). Also the diverging beam combined with the asymmetric mirror placement (used to compensation for the initial shape of the active mirror) contribute to the system shape when measuring a relatively flat mirror. The measured shape shown in Figure 5.1 is a combination of the system shape (shape resulting of all optical components) and the measurement mirror shape.

Before an absolute shape measurement can be executed, first the system shape must be measured. Measuring the system shape is in principle only possible with an absolutely flat measurement mirror. In a first approximation the system shape is measured using a Zerodur mirror with an specified optical flatness of $\lambda/20$ (= 30 nm). This approximation is valid since the Zerodur mirror topology is much smaller than the system shape (peak valley 434 nm see Figure 5.2a).
Figure 5.1: The measured shape can be divided into 2 parts, the measurement mirror shape, which is the actual shape one want to measure, and the system shape, which is a result of the alignment and interfaces of the optical components in the system.

**VSL mirror**

As described the absolute shape measurement is evaluated by comparing the measurement of a mirror with it’s known surface shape. To acquire a mirror with a known shape, the Dutch Metrology Institute VSL measured the shape of a mirror (from now on called VSL mirror) using a Wyko optical surface profiler (stepping interferometer). Figure 5.2b show the shape of the VSL mirror which has an peak valley amplitude of 3.6 \( \mu m \). The measurement system is not able to measure the full mirror surface, therefor only a part of the VSL mirror is used while evaluation absolute shape measurements. The outline of the used part of the VSL mirror is draw in Figure 5.2b and the used part of the VSL mirror is depicted in Figure 5.2d.

**Measured absolute shape**

With the measured system shape known an absolute shape measurement of the VSL mirror is carried out in the measurement setup. The measured shape (shown in Figure 5.2c) matches the general shape of the VSL mirror on first sight quite well, however if both shapes are subtracted (shown in Figure 5.2e) the RMSD between both shapes is 18.6 \( nm \) and the peak valley difference is even 162 \( nm \).

A possible explanation could be found in the incorrect assumption that the surface topology of the zerodur mirror is negligible. The found peak valley difference is 6 times the specified surface flatness of the zerodur mirror, therefore the shape amplitude of the zerodur mirror must be checked (at least order of magnitude) to judge the errors due to neglecting the zerodur mirror in the system shape.
Figure 5.2: Overview of the system (a), measured mirror (c) and reference shape (b and d) and. The RMSD between measured and reference shape is 18.6 nm and the peak valley difference is 162 nm.
5.2 Auto-calibration

In order to increase the accuracy of the measurement system, the possibility of measuring the system shape of the measurement system without neglecting the zerodur mirror is investigated. Katherine Creath [16] describes a method to calibrate an interferometric surface roughness measurement system by shifting the measurement mirror multiple times with a step size just above the mirror correlation length. However in the measurement setup, not the global shape of the mirror is measured and the surface roughness of the mirror is neglected since the spatial resolution of the measurement system is too low to actually measure the surface roughness. The application of the method described by Katherine Creath is therefore not usable for measuring the system shape.

Another possibility of auto-calibration measurement could be to measure the surface topology of the zerodur mirror by measuring the surface gradients. With the shape of the zerodur mirror known, a better system shape can be generated by subtracting the shape of the zerodur mirror. The use of gradient information to reconstruct surface shapes is for example described by Matthew Harker. He describes a gradient to surface reconstruction using photometric stereo generated gradient fields. Acquiring gradient information is relatively easy by measuring the mirror shape before and after a known mirror shift, subtracting both measurement and dividing by the shifted distance. With the gradient measurement method the shape of the zerodur

5.2.1 Simulation

Before the gradient measurements system is build first an simulation is executed to validated the concept. In this simulation both the VSL mirror shape (Figure 5.2d) and the system shape (Figure 5.2a) are inputs. The output is the reconstructed shape, which is compared with the inputted VSL mirror shape to evaluate the reconstruction algorithm. The simulation consist out of 3 simulated measurements in which the VSL mirror shape is shifted in both x and y direction by 20 pixels.

![Figure 5.3: Auto-calibration simulation. The errors between input and output of the simulation are large but can be explained by the big distance for the gradients.](image)

The difference (Figure 5.3b) between the outputted shape of the simulation (Figure 5.3a) and the inputted VSL mirror shape has a RMSD value of 29.7 nm, the peak valley value of the difference is 134 nm. However there is a correlation between the inputted shape amplitude and the resulting difference, more fair values can be obtained by calculating the error as percentage of the measured shape amplitude. Figure 5.4 shows the RMSD and peak valley of the difference while the inputted shape amplitude is varied. between both the calculated and the actual shape is around 3 percent.
Figure 5.4: Error in percentage of measurement mirror size for varying distances of mirror shifts. The error increases for larger mirror shifts, so small mirror displacements should be used in the auto-calibration algorithm.

With the results obtained in the simulation the gradient measurement method is suitable for a measurement of the system shape.

5.2.2 Setup for auto-calibration

The measurement setup needs a slight modification to be able to perform the auto-calibration. To execute the auto-calibration, the measurement mirror has to move in both the x and y direction by a known distance. These movements are accomplished by placing the mirror on a 2 DOF stage, see Figure 5.5a, while two Mirco Epsilon OptoNCDF [5] laser distance sensors are used to measure the mirror displacement. However, the auto-calibration algorithm requires not the mirror shift but the shift of the mirror projection on the CCD camera (in pixels). For a correct measurement of the relation between mirror movement and the movement of the projection on the CCD camera, an experiment is setup. In Figure 5.5b the mirror is covered by a black cover with two small holes in it. The mirror is moved while simultaneously the location of the projected holes on the CCD is measured. Figure 5.6 shows the relation between the displacement of the mirror and projected mirror. A mirror displacement of 0.071 mm results in a movement of 1 pixel on the CCD.

5.2.3 Gradient to surface algorithm

In the previous section, a simulation is used to validate the working principle of the auto-calibration algorithm. This section will explain the algorithm used to reconstruct the shape from the measured gradients. The algorithm start with the formulation of the surface as a grid of points \( S \). This is a square grid with a length and width of \( i \) points.
Figure 5.5: Setup for auto calibration measurements. Key components are: (1) Laser distance sensors, (2) mirror, (3) 2 DOF stage, (4) mirror cover with 2 small holes.

Figure 5.6: The relation between the movement of the mirror and the movement of the projection on the CCD, done for 2 holes. Both measurements show a mirror movement of 0.071 mm results in a shift of 1 pixel.
\[ S = \begin{bmatrix}
  s_{11} & s_{12} & \ldots & s_{1i} \\
  s_{21} & \ddots & \vdots \\
  \vdots & \ddots & \vdots \\
  s_{i1} & \ldots & s_{ii}
\end{bmatrix} \]  
(5.1)

The goal of the algorithm is to reconstruct the surface height of each of the grid points of \( S \). The input of the algorithm are the measured gradients in both x and y direction \( \nabla_x S \) and \( \nabla_y S \). The measured gradients relate the surface height of neighboring grid point of \( S \). For example in the horizontal direction the following relation could be formulated for \( \nabla_x s_{12} \)

\[ 2\nabla_x s_{12} = s_{13} - s_{11} \]  
(5.2)

However, this scheme can’t be used for the gradient \( \nabla_x s_{11} \) since \( s_{10} \) doesn’t exist. Therefore for the gradients on the edge a slightly different relation is formulated.

\[ \nabla_x s_{11} = s_{12} - s_{11} \]  
(5.3)

For each gradient point in the x and y direction a relation between two points in the grid can be formulated. This results to a total number of \( 2i^2 \) relations how the surface heights depend on the gradients. To calculate the surface heights all relations are described in a matrix equation. However, first the surface \( S \) and the measured gradients \( \nabla_x S \) and \( \nabla_y S \) must be transformed to vectors \( s \) and \( \nabla s \). This is done as follows

\[ s = \begin{bmatrix}
  s_{11} & s_{21} & \ldots & s_{1i} & \ldots & s_{2i} & \ldots & s_{ii}
\end{bmatrix} \]  
(5.4)

\[ \nabla s = \begin{bmatrix}
  \nabla_x s \\
  \nabla_y s
\end{bmatrix} \]  
(5.5)

The following matrix equation can now be build describing all relations:

\[ E s = \nabla s \]  
(5.6)

where

\[ E = \begin{bmatrix}
  E_1 \\
  E_2 \\
  E_3 \\
  E_4
\end{bmatrix} \]  
(5.7)

\[ E_1 = \begin{bmatrix}
  -I_i & I_i & 0_{i,(i^2-2i)}
\end{bmatrix} \]  
(5.8)

\[ E_2 = \begin{bmatrix}
  -5I_i^2 & 0_{i^2,(i^2-2i)} + 0_{i^2,(i^2-2i)} & .5I_i^2
\end{bmatrix} \]  
(5.9)

\[ E_3 = \begin{bmatrix}
  0_{i,(i^2-2i)} & -I_i & I_i
\end{bmatrix} \]  
(5.10)

\[ E_4 = \begin{bmatrix}
  E_5 \\
  \ddots
\end{bmatrix} \]  
(5.11)

\[ E_5 = \begin{bmatrix}
  E_5
\end{bmatrix} \]  
(5.12)
where \( \mathbf{E}_1 \) to \( \mathbf{E}_3 \) describe the relations of the horizontal measured gradients and \( \mathbf{E}_4 \) consisting of \( i \) \( \mathbf{E}_5 \) matrices, describes the relations of the vertical measured gradients.

\[
\mathbf{E}_5 = \begin{bmatrix}
-1 & 1 & 0_{1,(i-2)} & 0_{1,i} \\
-.5I_{(i-2)} & 0_{(i-2),2} & 0_{(i-2),2} & -.5I_{(i-2)} \\
0_{1,(i-2)} & -1 & 1 & 0_{1,i}
\end{bmatrix}
\]

This now build matrix equation can be solved, to find the surface height of each grid point. However, the absolute height of the surface can not be determined, there is no absolute reference in the algorithm, in a mathematical sense the absence of an absolute reference result in a rank deficient \( \mathbf{E} \) matrix. The rank of \( \mathbf{E} \) is always \( i - 1 \). The input of the algorithm is consist of gradient measurements in which the gradient is approximated, this results in a system of equations that can not be solved exactly, to overcome this problem a least square approximation on the error is used to find the best match of surface with measured gradients.

### 5.2.4 Measurements

To evaluate the auto calibration measurement before the system shape is determined, an auto-calibration shape measurement of the VSL mirror is done. The measured shape using the auto-calibration method is depicted in Figure 5.7a and compared to VSL mirror shape depicted in Figure 5.7b. The difference (Figure: 5.7c) between the real and measured shape has an RMSD value of 58 \( \text{nm} \) and an the peak valley is 331 \( \text{nm} \). Part of this difference can be explained by a slight rotation (caused by alignment of the mirror in the measurement setup) between the measured and the actual shape.

Although the measurement error of the auto-calibration method is too large to measure better system shapes, the described method can be used to validate the order of magnitude of the surface topology of the zerodur mirror. Figure 5.8 shows the measured surface topology of the zerodur mirror. The peak valley of the measured topology shape is 11 \( \text{nm} \). This value is well below the specified 30 \( \text{nm} \) peak valley of the total mirror surface. The value is below the specified since the topology of only 40 percent of the mirror is measured.

### 5.2.5 Conclusion

Although the auto-calibration algorithm is not sufficient for the use as an absolute shape measurement (the error between measured and known VSL shape differ to much), the auto-calibration can and is used to validate the order of magnitude of the surface topology of the zerodur mirror. The shape amplitude of the zerodur mirror is well below the specified surface flatness. The assumption that the zerodur mirror shape does significantly contributed to the system shape is thus valid.
Figure 5.7: The shape of the VSL mirror and the measured shape using the auto-calibration method are compared. The difference between both has an RMSD of 58 nm and a peak valley of 331 nm. The size of the error disqualifies the auto-calibration algorithm for absolute shape measurements.

Figure 5.8: The shape of the zerodur mirror measured using the auto-calibration algorithm. The peak valley of the measured surface topology is 11 nm, which is as expected well below the specified surface flatness of the total mirror surface since only about 40 percent of the mirror surface is measured.
5.3 Time stability

In the course of the project the measurements obtained by either the absolute shape measurement method or the auto calibration appear to vary over the time. This time dependency in the measurement system lead to the presumption of drift in the measurement setup. To measure the drift in the measurement setup, an experiment is setup. No changes are made to the measurement system and the shape of the VSL mirror is measured on average once every 2 days. Figure 5.9 shows the initial measured shape and the differences between the initial and measured shape on successive days.

![Figure 5.9: Overview of the measured shapes in drift experiment. The drift in the measured values is up to 75 nm peak valley.](image)

The difference depicted in Figure: 5.9 show peak valley errors up to 75 nm. To evaluate the trend in the drift, the development of the peak valley difference is shown in Figure 5.10. The trend is rising so the timespan of the experiment is too short to draw a hard conclusion about the absolute values of drift in the measurement setup.

To identify whether the drift is in the VSL mirror (for example due to creep in ether the clamp or mirror itself) or in the measurement setup, the experiment is repeated (although over a shorter timespan of 4 days) with a shape measurement of a stable Zerodur mirror. Figure 5.11 shows the difference (peak valley 15 nm) between the two shape measurements done in this experiment. The difference between both measurements show that at least a part of the drift is in the measurement setup.
Figure 5.10: The drift in the measurement system shown as the peak valley difference between the measurements. The graph shows no clear range of the drift since the trend is rising during the experiment.

Figure 5.11: A comparison of two shape measurements over a time interval of 4 days. The peak valley of the difference is 15 nm.

The measurements done in this section shows a clear indication of drift in the measurement system. However, the exact cause of this drift is not yet understood. The drift in the measurement system might be responsible for the errors made in the absolute shape measurements and the auto-calibration measurement of the VSL mirror.
The measurement of the deformable mirror topology can be accomplished using a laser interferometer based, fringe projection measurement system.

A measurement system with a precision sufficient to meet the Marechal criteria is build during the research project. In order to reach the Marechal criteria, the measurement system is improved by improving the four subsystems of the measurement system. In the improved measurement setup the stability error decreased from $2.5 \text{ nm}$ to $0.29 \text{ nm}$. The reproducibility of the setup is improved from $4.85 \text{ nm}$ to $0.80 \text{ nm}$.

Based upon the experimental work done during the course of this project, the following conclusions about the four subsystems can be drawn:

1. Relevant components to increase the performance of the illumination system are: The optical isolator and polarizer, cleaning the laser output to a single laser mode, an additional beam expander to flatten the distribution of optical power in the beam and the anti reflective pinhole.

2. The interferometer does not require extra stiffening rods, or a vacuum environment for an optimal performance. The measured performance doesn’t decrease when removing either of them. However, this is only valid in the case there is no heating of the measurement mirror and the video projector is not in use.

3. The performance of the imaging system depends on the focus and reflections in the system. A collimator lens and an aperture in the focal plane, to counter reflections from the CCD improve the performance of the imaging system significantly. The removal of the CCD protection window resulted in a much better reproducibility of the measurement system. The removal of the protection window results in glass dust on the chip surface, so a camera without the window in the first place would be advisable.

4. The filter shape of the data processing is a relevant parameter to optimize in order to improve the performance of the data processing.

Quantitative conclusions about the measurement systems performance are:

1. The stability of the measurement system is improved from $2.5 \text{ nm}$ to $0.29 \text{ nm}$ by improving the four subsystems (imaging, interferometer, illumination system and the data processing) of the measurement system. Most of the performance gain in the measurement system is due to the shielding of air flow in the interferometer (Section 4.4) and the anti reflection measures (Section 4.1.3 and 4.3.3). The stability of the measurement system is sufficient to validate the stability of the active mirror with respect to the Marechel criteria of $0.33 \text{ nm}$. 
2. The reproducibility of the measurement system is improved from 4.85 nm to a value of on average 0.80 nm. This improvement is mainly due to the redesign of the imaging system and the removal of internal reflection inside the CCD by removing the protective glass cover of the imaging chip (Section 4.3.1).

3. The spatial resolution of the measurement system depends on the number of fringes in the interferogram (Section 4.5.4), the digital filter size and the algorithm. The limiting factor in the spatial resolution is the location dependency in the output of the algorithm (Section 4.5.6). However, the spatial resolution of the measurement system is higher than the maximum attainable spatial resolution of the active mirror. The acquired spatial resolution of the measurement system is thus sufficient to measure the mirror deformations.

4. An absolute shape measurement compared with the known mirror shape, a large difference 120 nm peak valley (10 percent of the total shape amplitude)(Section: 5.1). This error can be partly explained by the neglected shape of the Zerodur mirror, which has a shape amplitude of 10 nm (Section 5.2) and the drift in the measurement system (Section 5.3) at least 50 nm, but no definite value is measured yet.
Chapter 7

Recommendation

The following is recommended for future work:

1. This thesis has not focused on influence of the actuator. The actuator in the current total setup is a video projector which induces vibrations on the optical table and shows a large discharge of heat flow used for cooling the projector. The effect of the actuator on the measurement setup should be investigated and alternative ways to connect the projector might be needed to reduce the effect of the projector vibrations.

2. The drift in the measurement system is not fully understood, possible causes might be, shape changes in the measured mirror, a frequency drift in the laser and the alignment and shape of all (optical) components in the measurement system. In order to use the measurement system for an absolute shape measurement, the drift must be fully understood. Therefore an investigation of the shape measurement over a longer time-span must be executed.

3. With the improvements of the measurement system, a next step would be to employ closed loop control to actuate the deformable mirror the the limits of the measurement system.
Bibliography

[1] www.3dit.de/pages/refanimation 12-2-2013


1D Reconstruction algorithm

The actual algorithm used is a 2D reconstruction algorithm, since the total mirror surface topology must be reconstructed. However, the 2D version of the algorithm is only an extension of the 1D algorithm, and the 1D algorithm is much more easily explained. The input signal for the 1D reconstruction algorithm is a data vector containing all intensity values for one line of pixels, as captured by the CCD camera. If the topology of the original mirror is not flat, then the data vector will contain a phase-modulated sinusoidal wave. The topology of the active mirror is hidden in the phase modulation of the fringe pattern in the data vector. In this section, fringe pattern analysis will be used to reconstruct the topology of the original mirror.

A mathematical form describing the input signal is given in equation A.1

\[ g(x) = a(x) + b(x) \cos(2\pi f_0 x + \phi(x)) \]  

where \( a(x) \) is the background intensity, \( b(x) \) the amplitude of the fringes, \( f_0 \) the spatial-carrier frequency, \( x \) the distance to the origin and \( \phi(x) \) the phase modulation containing the information on the original mirror topology. A sample of the content of the data vector is plotted in Figure A.1.

![Sample of the data vector](image)
A.1 Fourier transformation

To reconstruct the topology of the original mirror a Fourier transformation method is used. The Fourier transformation transforms the input data vector to the frequency domain.

A Fourier transformation consist of describing the input signal as a series of cosine functions. All information contained within the data vector is transformed to a series of complex numbers. The first complex number in the series represents a cosine with frequency 0, the next element in the series represent a cosine with frequency 1 and so on. The amplitude and phase of the cosine are stored in the real and imaginary part of the complex number. Figure: A.2 shows how the amplitude and phase of a cosine function are stored in a complex number.

![Figure A.2: How Amplitude and Phase are represented in a complex number](image)

To make further calculations more easy formula A.1 is rewritten using Euler’s formula.

\[
g(x) = a(x) + c(x)e^{2\pi f_0 x} + c^*(x)e^{2\pi f_0 x}
\]

\[
c(x) = \frac{1}{2} b(x)e^{i\phi(x)}
\]

The * denotes the complex conjugate. A multiplication of the signal c(x) by a complex exponential leads to a shift in the frequency domain.

\[
F_x(c(x)e^{2\pi f_0 x}) = C(f_x - f_0)
\]

Now a Fourier transformation with respect to x of the signal g(x) is done, this results in

\[
G(f_x) = F_x(g(x)) = A(f_x) + C(f_x - f_0) + C^*(-(f_x + f_0))
\]

where the capital letters denote the Fourier spectrum, \(f_x\) the spatial frequency and \(f_0\) is the non phase modulated carrier fringe frequency. If compared to \(f_0\) the spatial variations of \(a(x)\), \(b(x)\) and \(\phi(x)\) are low frequent, there will be a separation between the background intensity and the side lumps. In Figure A.3 the Fourier spectrum is depicted. This spectrum is symmetric around the y axis, so either of the both side lumps still contains all information of the input data vector. We are not interested in the average background intensity and only one of the side lumps is needed, a filter is placed over the data in the Fourier spectrum. The shape of the filter is still under investigation, but primary results indicate that a cut open Harris window with the width of 2 times the carrier fringe frequency is a reasonable option. The filter is placed over the right side lump, as shown in Figure A.3. The data under the filter is shifted with \(f_0\) to the origin. This shift is done to remove the carrier fringe frequency out of the data. The new situation is shown in Figure
Figure A.3: The Fourier spectrum of the input data vector. The background intensity is located in the center and two side lumps still contain all information of the input data vector. In the figure a filter over the right side lump is drawn.

A.4. If we take a closer look at the remaining lump we see that it is not symmetric. Actually the left side of the lump colored red shows the information where the carrier-fringe frequency is lowered, the blue colored area contains the information on where the carrier-fringe frequency is increased.

Figure A.4: The filtered and shifted Fourier spectrum. The remaining lump is not symmetric.

Now a reconstruction step has to be made. This is done by applying the inverse Fourier transform to the filtered data. We now obtain

\[ \mathcal{F}_x(C(x)) = c(x) = \frac{1}{2}b(x)e^{i\phi(x)} \quad (A.6) \]

which contains all information about the added phase \( \phi(x) \). We are not interested in the amplitude of the fringes \( b(x) \), but with formula A.7 we can easily free \( \phi(x) \).

\[ \phi(x) = \tan^{-1}\left( \frac{\text{Re}[c(x)]}{\text{Im}[c(x)]} \right) \quad (A.7) \]

The phase \( \phi(x) \) that is now obtained is still wrapped in the range \([-\pi, \pi]\). Using an unwrap algorithm the continuous phase curve is now obtained. With the wavelength of the used laser and
the continuous phase curve, the original mirror topology can be reconstructed.
Appendix B

Alignment of laser, optical isolator and polarizer

A requirement of the illumination system is to deliver light of a single wavelength. Therefore, the laser output spectrum which contains 3 laser modes with a slightly different frequency and perpendicular polarization direction must be cleaned to just one laser mode. The laser mode with the most optical power must be used since then the least amount of energy is removed from the beam. The optical power of each laser mode depends on the location of the laser mode with respect to the laser gain bandwidth. To select the laser mode which contains the most optical power the laser, optical isolator and polarizer must be align correctly. To align these components an experiment is set up in which the optical power and the frequency spectrum of the output beam is measured. Figure: B.1 shows the measurement setup used for the alignment of the laser, optical isolator and polarizer.

The measurement setup contains the components mentioned above, while an additional beam splitter is introduced to the setup to measure the frequency output spectrum of the beam using a Fabry-Perot cavity, and the optical power using a Thorlabs PM100 light intensity meter. Figure B.2a shows the output spectrum of the beam with an incorrect alignment of the laser, optical isolator and polarizer, while Figure B.2b shows the output spectrum with the alignment of the components mentioned above. Note that the intensity measured for each mode is not the optical power of the mode, but the intensity measured inside the Fabry-Perot cavity which depends on the q factor of the Fabry-Perot cavity.

Experimental results

Qualitative observations show a clear increase in contrast between the fringes after a single laser mode is selected in the illumination system. Figure: B.3 shows captured interferograms of both

Figure B.1: The setup used for selecting the mode with the most optical power. Key components are: 1 laser, 2 Optical isolator, 3 polarizer, 4 beam splitter, 5 Fabry Perot resonator, 6 Thorlabs pm100 light intensity meter.
Figure B.2: The laser output spectrum with (dashed) and without (solid) the polarizer and optical isolator in place. The laser output spectrum clearly shows the spectrum of a \( \frac{2}{3} \) mode laser. The measured intensity is not the same as optical power in the modes since the measured intensity is depending on the Fabry-Perot cavity q-factor.

Figure B.3: Captured interferograms for one or multiple laser modes. Qualitatively, there is a better contrast when there is only one laser mode in the illumination system.

the setup with and without the correct alignment of the laser, optical isolator and polarizer. To quantify the improvement due to the optical isolator and polarizer, an experiment is done. This experiment compares the optimized measurement system with the measurement system without the optical isolator and polarizer. For the optimized setup an average RMSE value of 0.29 nm and a RMSD of 0.79 nm are measured, while for the setup without the optical isolator and polarizer an average RMSE value of 0.90 nm and a average RMSD value of 1.2 nm is measured, showing the correct alignment of the polarizer and optical isolator have a contribution to the performance of the measurement system.
A CCD chip consists of a photoactive region (an epitaxial layer of silicon) and a transition region which contains a shift register. An image is projected on the CCD where a grid of capacitors (photoactive region) is located. Each capacitor accumulates electric charge proportional to the light intensity at that region. This effect is called the photoelectric effect, the photons that hit each capacitor can bump electrons out of their atoms causing the capacitor to become charged. Note that the CCD uses the particle properties of light.

The current setup uses the DMK31BF03 firewire CCD camera. An image of the DMK31 can be found in Figure C.2. The CCD chip inside this camera is a Sony ICX204AL which is an interline progressive scan chip [18]. The CCD chip contains shift registers, which are located between the lines of capacitors (interline). The shift registers are shaded from incoming light to make sure the amount of charge stays constant while the charge is stored inside the shift registers. The shaded shift registers result in a low quantum efficiency of the chip since only a relative small part of the chip is photoactive. The progressive scan part tells us that all interline shift registers, shift their charge to a second shift register, which in turn shifts the charge to the output amplifier. More on the working principles of CCD cameras can be found in [19]. Figure C.1 depicts the schematic layout of the Sony CCD chip.

![Schematic layout of the Sony ICX204AL CCD chip](image-url)
Taking a image with the DMK31BF CCD camera basically consist out of four steps.

1. **Resetting:** With a switching signal all capacitors are reset so there is no charge left over in the capacitors. This is the start of the accumulation period and a part of the electronic shutter.

2. **Accumulating:** During the exposure time, a number of photons hits on each pixel. In each pixel a capacitor transforms the photons into an electric charge. The charged is accumulated during the exposure time.

3. **Storing:** As a result of the shutter signal, the accumulated charge of each pixel is transferred to the shift-registers located next to the pixel. The shift registers themselves are shaded from light so that no change in the amount of charged stored is possible.

4. **Reading:** After the accumulated charge is transferred to the shift register the image is read out. The charge is then transported to the output amplifier, where the charge is transformed into a voltage. A shift register works like a bucket line. Each bucket is emptied into the next one, thus transferring the water (charge) to the next bucket until the end of the line is reached.

The sony CCD chip executes step 2 and 4 simultaneous for a faster image capture rate. This method results in a speed of 30 frames a second. To increase the speed of the camera even further there is an option to only read $\frac{1}{3}$ of the pixels. This process increases the speed to 60 frames a second, but at the same time compromises the vertical resolution of the image.

![Figure C.2: DMK31BF03 monochrome fire-wire CCD camera](image-url)
Camera parameters

This chapter contains an analysis of the camera performance. The analysis is split into three parts, software settings, noise sources and camera linearity. The first part on software settings will be about testing the influence of the software settings on the resulting images. The second part will describe the noise sources in the camera. The third part will show that the camera has an almost linear intensity profile.

D.1 Camera software settings

The image capture software allows for 4 parameters to be set. These parameters, gamma, contrast, brightness and exposure time all influence the quality of the image captured. The standard values used in this chapter and the range that can be set for each parameter is listed in Table: D.1.

This section will describe all parameters in the following way. First a sort introduction on the meaning and use of the parameter is given. Then the results of the experiments will be shown in a histogram. Then a conclusions will be drawn. The experiment done for each parameter consist of a series of measurements with a series of different values for the parameter under investigation, while the other parameters are kept constant on the standard values listed in Table: D.1. All measurements are done with an almost uniform illumination of the ccd which is achieved using a laser beam. All experiments are done with two different light intensities (1.4 $\mu$W/mm$^2$ and 3.7 $\mu$W/mm$^2$). At each setting 50 images are taken and first averaged before any further analysis is done.

<table>
<thead>
<tr>
<th>parameter</th>
<th>standard value</th>
<th>range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma</td>
<td>10</td>
<td>10:22</td>
</tr>
<tr>
<td>Contrast</td>
<td>200</td>
<td>180:1024</td>
</tr>
<tr>
<td>Brightness</td>
<td>0</td>
<td>0:255</td>
</tr>
<tr>
<td>Exposure</td>
<td>-10</td>
<td>-12:5</td>
</tr>
</tbody>
</table>

Table D.1: Camera parameters, standard values used in this chapter and range in which each parameter can be set.

D.1.1 Gamma settings

Monitor and projectors generally work non-linear, due to the working principle of these displays. If the light intensity displayed is linearly increased in a certain amount of step, the difference between each step does not look the same for all steps. A second non-linear effect is human perception of intensities. To overcome these problems and show a ‘nicer’ picture, generally the light intensity values are multiplied with an exponential function, to create a linear scale on a monitor or projector.
In the case of interferometry image captures there is no reason to display the data captured by the ccd camera. The gamma correction is in the case of interferometry no more than a distortion of the data. An experiment with gamma values of 10, 14, 18, and 22 is done. The results are plotted in a histogram in Figure D.1. In the histogram the x axis contains all possible pixel values of the camera 0 to 255 and the y axis shows which percentage of pixels has the intensity value. The image should appear like a bell shaped figure.

Figure D.1: Histogram of gamma settings. An increase of the gamma value generates a distortion in the histogram so the lowest value for gamma (10) should be chosen in further measurements.

Figure D.1 clearly show that there is some kind of algorithm inside the camera. Higher gamma values shift the histogram and distort the bell shape. This algorithm inside the camera increases or decreases the amount of pixels with certain pixel values. Figure D.2 shows six images with difference gamma and light intensity settings. Optically only the picture becomes slightly brighter, but nothing dramatic is really happening. A gamma value of 10 (the lowest value possible) will be chosen for further measurements.

D.1.2 Brightness settings

Brightness is a parameter that controls the camera offset. The offset shift the complete histogram shape to higher intensity values. This shift is used to counteract saturation for low pixel values. The pixel values in a captured images are based on the light intensity at each pixel site and a random noise factor which distorts the signal. If the light intensity is zero (no lights hits the camera), the pixel values should all be zero. This is not the case since the noise factor gives some pixel a higher and some a lower pixel value. The AD converter in the camera can not handle pixel
Figure D.2: 6 images with different gamma and settings. Optically the only difference between low and high gamma settings is the brightness of the images, while the image data is distorted values lower than zero and shows these pixels as zero. This results in a zero level saturation and loss of information about the noise in the system.

To counteract zero level saturation an offset can be used to increase all pixel values in the CCD. The range of the brightness can be set from 0 to 255, an experiment is done with brightness settings of 0, 75, 150 and 225. Figure D.3 shows that increasing the brightness values indeed shifts the histogram while maintaining the shape of the histogram.

The noise observed in the camera pixel values has an amplitude around two. A brightness level of 50 shifts all pixel values with a value of four. To make sure no zero level saturation occurs a brightness level of 50 should be used as a minimum settings.

D.1.3 Exposure settings

The camera has a digital shutter. The exposure time relates to the amount of photons that hit the CCD chip. With longer exposure times the camera captures more photons and generates more charge, resulting in a brighter image. When the amount of photons that hit the CCD chip is low, the random character of the arrival times between photons in light generates so called shot noise.
Figure D.3: Histogram of different brightness and intensity settings. A increase of the brightness value of 75 results in a shift of around 6 intensity values in the histogram.

Shot noise is described in section: D.2.1. A long exposure time appears to be favorable, but there is a limitation. Once a certain amount of photons reached the pixel, the pixel can no longer store the charge that is generated on the arrival of the photons and saturated occurs in the image.

The lightest areas in the image should be just below the saturation threshold of the camera. Inside the camera the charge is digitalized using an 8 bit Analog Digital (AD) converter. With the lightest areas just below the saturation threshold the largest part of the camera bit depth is used. With a larger part of the bit depth used the influence of roundoff errors are kept to a minimum.

The exposure time can be set by the exposure value. To convert the exposure value to the exposure time in seconds $2^{\text{exposure value}}$ must be calculated. The light intensity is often not easily changed, but the same effect can be generated by the contrast settings.

D.1.4 Contrast settings

The contrast setting of the camera increases the gain of the camera output amplifier. Increasing the contrast value looks the same as increasing the amount of light captured by the ccd camera. An experiment is done with different contrast settings. Figure D.4 shows the resulting histograms. Indeed with the contrast setting the histogram can be shifted to higher and lower values.

To make sure there is no zero level saturation in the camera, while the largest possible part of the
camera bit depth is used, the right values for the exposure time and contrast have to be chosen. There is no best setting for these parameters because they depend on the light intensity measured.

D.2 Noise

In the ccd camera there are some noise sources. The darker the images becomes the more clear the noise becomes. The measured value is a combination of the actual intensity, correlated and random noise. In this section we will look at the noise sources in the camera.

Measured value = Actual Intensity + Correlated noise + Random noise.

D.2.1 Random noise

Random noise it is already in the name is random. Random noise sources in the camera are mostly electronic noise sources. Electronic noise consist of: Thermal noise, the resistivity of resistors fluctuates with temperature. Shot noise results from the random passage of individual charge carriers across a potential barrier. Excess noise, is the noise in excess of thermal and shot noise. Excess noise is the result of fluctuating conductivity due to imperfect contact between to materials. More on these noise sources can be found in high precision mechatronics [9]. To counteract the random noise present in the camera averaging is used.
Photon noise

Photon noise is a form of shot noise and is the result of the inherent statistical variation in the rate of arrival of photons on the CCD chip. This statistical process is governed by Poisson statistics, and therefore the photon noise is equivalent to the square-root of the signal. Shot noise is typically observed in the darker regions of the image as a speckle pattern. By averaging images the shot noise effects can be counteracted.

D.2.2 Correlated noise

Correlated noise is repeatable over each set of images and can be compensated. Most of the correlated noise sources are an effect of the design and manufacturing of the CCD camera.

Dark and readout noise

Dark noise is a result of dark current. Dark current is the rate that electrons accumulate in each pixel due to thermal action. Dark current depends on the temperature and imperfections in each pixel.

Readout noise results from the readout process of the camera. Each row of capacitors stores the charge in the shift register next to it. A problem in one of the many interline shift registers can result in a distortion in the image. And is thus a source of noise.

In order to test dark and readout noise a dark frame is taken. A dark frame is an image with no light entering the CCD camera. This is done with the following camera parameters, Brightness 20, Contrast 180, Gamma 10. The exposure time is varied, so 8 different exposure times are tested. For each exposure time 200 images are taken and averaged. The results are shown in Figure D.5. The mean values and the standard deviation (std) can be found in Table D.2.

<table>
<thead>
<tr>
<th>Exposure time (ms)</th>
<th>mean</th>
<th>std</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,122</td>
<td>5,87</td>
<td>0,041</td>
</tr>
<tr>
<td>0,488</td>
<td>5,87</td>
<td>0,041</td>
</tr>
<tr>
<td>1,953</td>
<td>5,87</td>
<td>0,042</td>
</tr>
<tr>
<td>7,812</td>
<td>5,86</td>
<td>0,045</td>
</tr>
<tr>
<td>31,250</td>
<td>5,85</td>
<td>0,038</td>
</tr>
<tr>
<td>125</td>
<td>5,85</td>
<td>0,045</td>
</tr>
<tr>
<td>500</td>
<td>5,86</td>
<td>0,121</td>
</tr>
<tr>
<td>2000</td>
<td>5,88</td>
<td>0,384</td>
</tr>
</tbody>
</table>

Table D.2: Mean values and the standard deviation for 200 averaged images for different exposure times.

Figure D.5 shows some strange artifact, there appear some vertical ridges in the images. The CCD chip is readout in a vertical way, so they could well be readout noise. Also the exposure settings change the length of the ridges, different exposure settings give different readout speeds. This result supports the readout noise theory.

Table D.2 shows that the standard deviation of the read out noise is about 0.05 pixel value. The camera pixel value output consists of integer values. If no averaging is used before data processing no influence on the reconstructed image is expected to occur. In a qualitative experiment the influence of the camera temperature is tested. A higher camera temperature results in a slightly
higher standard deviation, but the difference is small, about 20 percent higher values for the standard deviation are found. So again no large impact on the reconstructed shape is expected with higher camera temperatures.

D.2.3 Diode glow

In order to evaluate the performance of the camera a dark frame with an exposure time of 30 seconds is taken. The image taken is digitally enhanced by increasing the brightness by a factor two for a more clearly view of the features in the image. The 30 seconds dark frame is shown in Figure D.6.

The brighter spot observed in the left upper corner is probably caused by so called diode glow. The diodes used in the camera architecture emit a very low amount of photons. Also there are some hot pixels which show a much higher pixel value. These pixels are defective and with longer exposure times always show a much higher pixel value. Although the effect becomes only visible for images taken with a long exposure time.
Figure D.6: Dark frame 30 seconds. No lights enters the camera and a 30 second exposure time is chosen. The image is lighted by a factor 2 to clearly show the results. Bright pixels are highly repeatable.

D.3 CCD linearity

Images taken for interferometric measurements depend on the sinusoidal profile of the fringes for good reconstructions. The quality of the measurements depends on the linearity of the camera used in the setup. In this section the linearity of the camera is tested, the influence of a camera non linearity is simulated and tested in section E.3. To test the linearity of the ccd camera a laser (1) is used to generate a uniform light bundle. The neutral density filter (2) is used to vary the intensity of the laser beam. Then the beam is split by the beam splitter (3), and directed to the Thorlabs PM100 light intensity meter (4) and the ccd camera (5). Figure D.7 shows the test setup used in the experiment.

The experiment is done using the following settings for the CCD camera: Gamma 10, Brightness 0, Contrast 300, Exposure -11. The light intensity is varied and the average light intensity captured by the CCD is the plotted against the intensity measured by the Thorlabs PM 100. According to the results of the experiment the camera has a nearly linear response. It is unclear whether the slight non linearity measured is due to the CCD camera or the PM100 light intensity meter. The RMS value of the residuals between the linear fit and the measured data is 0.8781. This value can be compared to the non linearity that is introduced in camera simulations in chapter E.
Figure D.7: Setup for camera linearity experiment, key components are: laser (1), neutral density filter (2), beam splitter (3), Thorlabs PM100 light intensity meter (4) and the ccd camera (5)
Figure D.8: Linearity of the ccd camera. In the top figure the data and a linear fit is plotted. The bottom figure shows the deviation between the measured data and the linear fit.
Simulated Camera and Algorithm

Simulations are a fast and simple method to analyse a lot of parameters. The goal of the simulations is to test the performance of the algorithm, how well is the reconstructed shape compared to the original shape. In these simulations, the input of the model is perfect, the image interference pattern is captured by an ideal camera. In reality, there is no such thing as an ideal camera, and a second goal for the simulation is to compare the ideal camera and a realistic camera. All simulations are done using Matlab software.

E.1 Interferometer and camera model

In order to conduct simulations, an interferometer and camera model has to be built. This is done by defining a tilt for the reference mirror and a topology for the original mirror. The shape of the original mirror will be kept constant throughout this chapter, although the amplitude of the shape is varied while testing the performance of the algorithm. The shape of the original mirror can be found in Figure E.2. The interference pattern for the camera is now created, this is done using

\[ S(x) = \frac{1}{2} + \frac{\sin[2R(x) - 2O(x)]}{2} \]  

(E.1)

where \( S(x) \) is the signal, \( R(x) \) the shape of the reference mirror (a tilted flat line) and \( O(x) \) the shape of the original mirror. The interference pattern \( S \) has an amplitude between 0 (destructive interference) and 1 (constructive interference).

E.1.1 Camera model

In the real setup, this interference pattern is captured by the camera. In the camera, there are quite some things going on, therefore the camera model is a bit more complex, it contains 6 setup parameters.

1. **Saturation:** A percentage of the bit depth of the CCD camera is used. If the used bit depth is greater than the actual bit depth of the camera, some pixel values will be clipped. The camera then saturates. The saturation value 1 corresponds to 100 percent of the camera bit depth used.

2. **Bit depth:** The bit depth gives the amounts of steps the AD converter inside the CCD camera can use.

3. **Quantization:** The AD converter inside the CCD camera quantizes the pixel values. This quantization leads to some round off errors.

4. **Offset:** A zero light intensity should result in a zero pixel value. But to generate more useful data, a slight offset can be set with the offset parameter. The offset value just gives the pixel value that is added to all pixels.
5. **Non linearity:** The camera may be slightly non linear. The pixel values are modified according to a lookup table.

6. **Random noise:** A random Poisson noise distorts the data.

The generated interference pattern \( S \) is modified in the camera. First an offset and saturation is taken into account

\[
\bar{S}(x) = (\text{bit depth} - \text{offset}) \times \text{saturation} \times S(x) + \text{offset}
\]

(E.2)

followed by a clipping of the signal if there are values above the bit depth value. Quantization is then implemented by simply rounding the signal \( \bar{S}(x) \). Noise is implemented as for each pixel an addition of a random value taken out of the normal distribution. Finally non linearity is implemented by changing all values according to a look up table. Figure E.1 shows the look up table for three different non linearity values.

![Figure E.1: Look up table for non linearity factors. The intensity is given in percents of the maximum intensity.](image)

The ideal camera uses the full bit depth, so there is no offset and no saturation. There is no random noise and the ideal camera is linear. The ideal camera doesn’t have a AD converter so there is no quantization and thus no roundoff errors. (Matlab still is a numerical computing software so there are some roundoff errors due to the source code of matlab. These are of many orders lower than the quantization error in the camera, and therefore not relevant.)

### E.2 Performance of the algorithm

The algorithm is used to reconstruct the topology of the original mirror from the interference pattern. Inside the algorithm the input signal is filtering and some data manipulation is done. This means that even if a ideal camera is used (so the fringe pattern is perfectly translated to the input signal of the algorithm) the reconstructed shape is not exactly the same as the original shape. In this section an evaluation of the performance of the algorithm is done. Important in the performance of the algorithm is the amplitude of the topology of the original mirror, and the number of fringes used.
To start the analysis of the algorithm performance, first the original mirror surface shape (topology) has to be chosen. The topology of the original mirror can be found in Figure E.2. The topology is translated to an input signal for the algorithm by the ideal camera described in section E.1.1. The reconstructed shape of the original mirror is also showed in Figure E.2.

Figure E.2: Original and reconstructed signal using the ideal camera. An amplitude error and a tilting error can be observed.

**Amplitude of the original mirror topology**

To test the performance of the algorithm the size (peak to peak) of the shape of the original mirror is now varied. Figure E.3 shows the reconstruction error of the algorithm in nm based on the size of the original mirror topology. A topology size of around 100 nm is realistic in the current setup.

<table>
<thead>
<tr>
<th>Size original mirror topology [nm]</th>
<th>RMS [nm]</th>
<th>PTP [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>39.23</td>
<td>2.08</td>
<td>33.99</td>
</tr>
<tr>
<td>78.47</td>
<td>2.97</td>
<td>39.54</td>
</tr>
<tr>
<td>117.70</td>
<td>3.95</td>
<td>45.02</td>
</tr>
<tr>
<td>156.94</td>
<td>4.98</td>
<td>50.38</td>
</tr>
<tr>
<td>196.17</td>
<td>6.04</td>
<td>55.59</td>
</tr>
<tr>
<td>235.40</td>
<td>7.14</td>
<td>60.59</td>
</tr>
<tr>
<td>274.64</td>
<td>8.29</td>
<td>65.34</td>
</tr>
<tr>
<td>313.87</td>
<td>9.49</td>
<td>69.79</td>
</tr>
</tbody>
</table>

Table E.1: RMS and peak to peak error of the reconstructed shape with different original mirror topology sizes.

Figure E.3 clearly shows the error increases with the amplitude of the original mirror topology. The RMS and peak to peak value of the error are shown in table E.1. A look at the original mirror topology size gives a RMS error is 3.95 nm and the peak to peak error is 45 nm.

**Number of fringes**

Although the number of fringes is not a parameter set in the script it does influence the performance of the script. The number of fringes used results from the tilt of the reference mirror inside of the interferometer. In the current setup 25 fringes are used.
Figure E.3: Error of the algorithm based on the size [nm] of the original mirror topology. The larger the size the larger the error becomes. The original mirror topology has a size in the order of 100nm.

Table E.2: Algorithm error with different a varied number of fringes. About 20 fringes gives the lowest error in the algorithm.

<table>
<thead>
<tr>
<th>Number of fringes</th>
<th>RMS [nm]</th>
<th>PTP [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.00</td>
<td>24.83</td>
<td>102.79</td>
</tr>
<tr>
<td>15.00</td>
<td>4.18</td>
<td>34.92</td>
</tr>
<tr>
<td>20.00</td>
<td>3.88</td>
<td>39.43</td>
</tr>
<tr>
<td>25.00</td>
<td>3.95</td>
<td>45.02</td>
</tr>
<tr>
<td>30.00</td>
<td>4.04</td>
<td>50.23</td>
</tr>
<tr>
<td>35.00</td>
<td>4.04</td>
<td>54.78</td>
</tr>
<tr>
<td>40.00</td>
<td>4.03</td>
<td>58.97</td>
</tr>
</tbody>
</table>

Figure E.4 and table E.2 clearly show that the optimum for the amount of fringes is around 20 fringes.
Figure E.4: Error of the algorithm based on the number of fringes. The peak to peak size of the original mirror topology is 117 nm. Clearly a tilting error remains independent of the number of fringes.

E.3 Performance of the simulated camera

This section shows a comparison between the ideal camera and the non ideal (real world) camera. In the simulations with a non ideal camera the error depends on two factors, the algorithm performance and the camera performance. To differentiate between the algorithm and camera performance, the error described in this section is the difference between the reconstructed shape when the ideal and the non ideal camera are used.

Figure E.5 shows three plots, the first plot depicted in blue shows the original mirror shape, the second plot depicted in green is the reconstructed shape using an ideal camera, the final plot depicted in black shows the reconstructed shape using the non ideal camera. The reconstructed shape using the non ideal camera clearly oscillates around the green ideal camera reconstructed shape.

The following camera parameters will now be analysed: Quantization, saturation, bit depth and offset. For each parameter, first a short introduction and the setting of the DMK31BF camera used in the current setup will be given. Then the results of the simulations will be shown in a figure and table. Finally a short conclusion about the parameter is given.
Figure E.5: Original mirror shape and two reconstructed shapes using both the ideal and non-ideal camera. The error is defined as the difference between the reconstructed shape using the ideal and non-ideal camera.

Quantization errors

To quantify the charge captured on the ccd chip an analog to digital (AD) converter is used. All digital cameras systems have an AD converter so there’s no way to overcome roundoff errors. The amount of round off error is dependent on the amount of bits in the AD converter, the total amount of steps in the camera is called the camera bit depth. The DMK31BF camera used in the current setup has an bit depth of 256. Figure E.6 shows the error due to the quantization while different camera bit depths are used.

<table>
<thead>
<tr>
<th>Bit depth [steps]</th>
<th>RMS [nm]</th>
<th>PTP [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>128</td>
<td>0.161</td>
<td>0.853</td>
</tr>
<tr>
<td>256</td>
<td>0.079</td>
<td>0.380</td>
</tr>
<tr>
<td>512</td>
<td>0.035</td>
<td>0.179</td>
</tr>
<tr>
<td>1024</td>
<td>0.020</td>
<td>0.120</td>
</tr>
<tr>
<td>2048</td>
<td>0.010</td>
<td>0.047</td>
</tr>
</tbody>
</table>

Table E.3: Error of quantization with different bit depths given in RMS and Peak to Peak values

Table E.3 shows that a bit depth of 256 gives an RMS error of 0.079 nm. This means the DMK31BF camera currently used has a sufficient bit depth. A camera with a higher bit depth has less error, but the current error of 0.079 nm is not the limiting factor in the camera.
Figure E.6: Error due to quantization with different bit depths. The camera currently used has a bit depth of 256 which gives a RMS error around 0.079 nm, which is sufficiently low.

Saturation errors

Saturation of the CCD camera is clipping of the intensity values captured due to the working principle of the camera. To prevent saturation a correct combination of camera settings and the amount of light in the setup has to be chosen. Finding the correct setting is not always an easy task and data used by J. Schutten [3] shows saturation values of around 10 percent. In Figure E.7 the simulated error is shown while different saturation values are used. Figure E.7 and table E.4 shows that saturation values of 1 and lower don’t give an error (except for some Matlab roundoff errors which are negligible). Saturation values lower than 1 result in a smaller part of the camera bit depth to be used, but since there is no quantization in the simulation this gives no error. A saturation value of 1 means the full range of the camera bit depth is used and thus we are talking about an ideal camera in this case. Table E.4 shows that a saturation of 1.1 (10 percent) gives an RMS error of just below 2 nm. To generate the ‘best’ data, it is better to choose a saturation value below 1 (no saturation in the camera) this lowers the range of the camera bit depth used, but errors due to lower part of the camera bit depth used are far smaller than errors due to saturation.
Figure E.7: Errors due to saturation. The value in the legend shows the range of the camera that is used, ranges above 1 result in saturation. 1.1 means 10 percent of the pixels is saturated. The values of 1 and below have as expected no error.

<table>
<thead>
<tr>
<th>Saturation value</th>
<th>RMS [nm]</th>
<th>PTP [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>.8</td>
<td>7.882e-14</td>
<td>4.235e-13</td>
</tr>
<tr>
<td>.9</td>
<td>7.739e-14</td>
<td>4.235e13</td>
</tr>
<tr>
<td>.95</td>
<td>9.123e-14</td>
<td>5.558e-13</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.05</td>
<td>0.763</td>
<td>4.187</td>
</tr>
<tr>
<td>1.1</td>
<td>1.933</td>
<td>10.676</td>
</tr>
<tr>
<td>1.15</td>
<td>3.175</td>
<td>17.282</td>
</tr>
<tr>
<td>1.25</td>
<td>5.755</td>
<td>31.268</td>
</tr>
<tr>
<td>1.4</td>
<td>9.273</td>
<td>50.038</td>
</tr>
</tbody>
</table>

Table E.4: Error of saturation by varying the amount of saturated pixels given in RMS and Peak to Peak values. The saturation below one is only a Matlab roundoff error, a saturation value 1 is the ideal camera thus zero error is expected.

Offset

The camera offset is necessary in order to characterize the noise in the camera. In the DMK31BF camera a brightness value can be set to create an offset. The brightness value 50 generates an
pixel value offset of about 4. This offset lowers the range of bit depth used in the camera slightly, but since in the simulations only offset and no quantization is taken into account, the offset should not induce any error. Figure E.8 shows only Matlab roundoff errors which are negligible.

Figure E.8: Camera offset, without quantization there is no error except the Matlab roundoff errors.
Camera non linearity

In section D.3 the camera is found to be nearly linear, but there is a small error. To characterize the DMK31BF camera a comparison between the RMS values of the residuals between the measured intensity profile and the linear fit and the RMS value generated by the non linearity factor is done. The residuals have an RMS value of 0.8781, A non linearity factor of 1.011 corresponds with the same RMS value. This section shows how much error is induced by the camera non linearity. Figure E.9 shows the error for different simulated non linearity factors.

For a non linearity value of 1.02 the RMS error is 0.29 nm and the peak to peak error is 1.48 nm. The low RMS error means, the DMK31BF camera is sufficiently linear.
E.3.1 Parameter comparison

All parameters and the algorithm have now been simulated, and after each simulation the realistic value of the simulated parameter is stated. Now a comparison between the error induced by the individual parameters and the algorithm can be made. Figure E.10 shows the RMS and peak to peak errors due to all individual settings. The realistic camera settings used in Figure E.10 are bit depth 256, the offset 2, saturation 1.1 (10 percent) and a non-linearity of 1.02.

Figure E.10: Overview of RMS and peak to peak errors of the algorithm and the different camera parameter settings. The algorithm dominates the RMS and the peak to peak error.

E.3.2 Cross correlation and realistic camera performance

Until now only the individual camera parameters have been simulated. Their could be a cross correlation between camera parameters that gives a bigger error. The cross correlation between all camera parameters is simulated, the largest RMS error found is in the same order of magnitude as the largest RMS error induced by saturation. The saturation error appears to be leading the cross correlation error.

Until now we only looked at the error due to one individual camera parameter. Their could be a cross correlation between camera parameters that give a bigger error. The cross correlation of all camera parameters are simulated, the largest RMS error found is in the same order of magnitude as the largest RMS error induced by saturation. We can thus assume the saturation error to be leading the cross correlation errors.
**Realistic camera**

With the previously stated realistic values for the camera parameters combined with an additional noise factor, taken out of the normal distribution with a zero mu and a sigma of 2, a simulation of the realistic camera is done. Figure E.11 shows the error of the realistic camera, the RMS error is 1.57 nm and the peak to peak error is 9.2 nm, as expected these values are the same order of magnitude as the saturation error.

![Realistic camera error](image)

Figure E.11: Realistic camera error, simulation is done with for all parameters a realistic value.