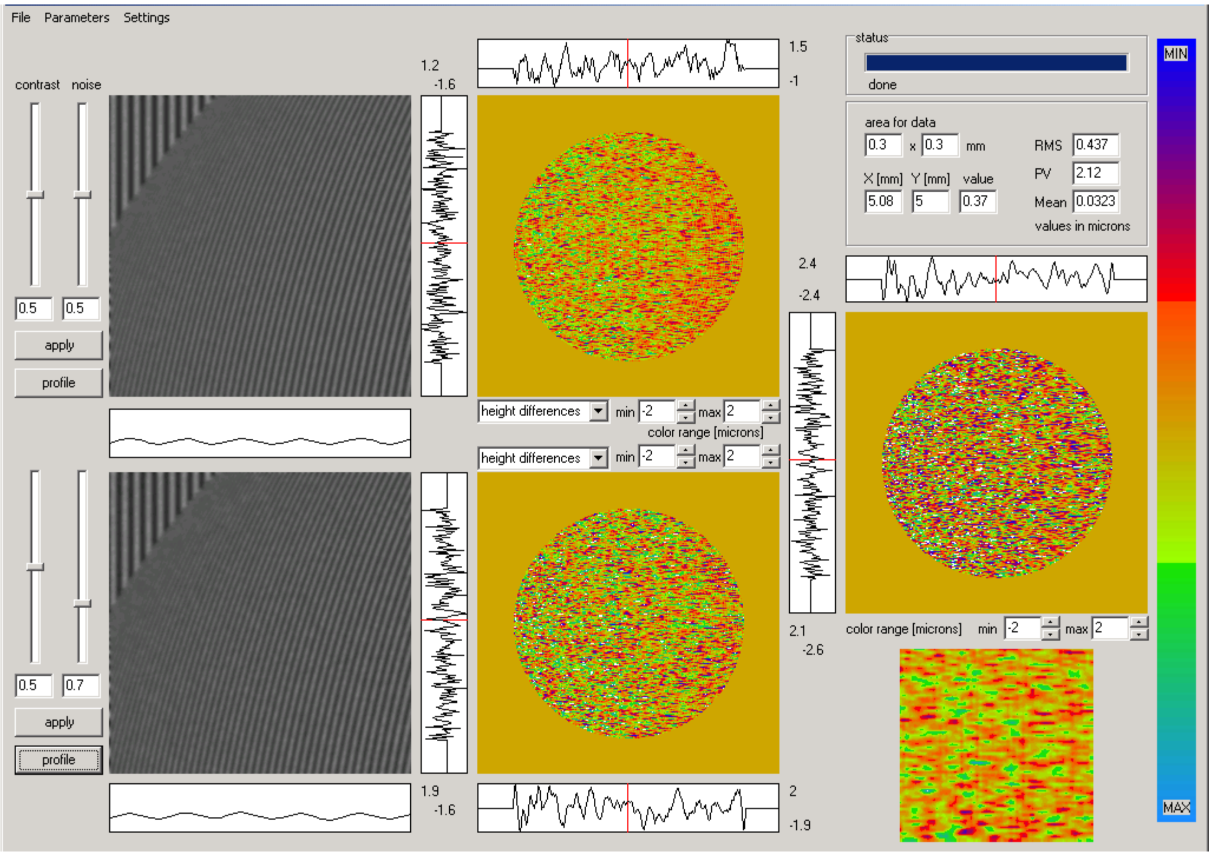
FRINGE PATTERN SIMULATION SOFTWARE

FPSS

Vers. 1.0



contrast 0.5 noise 0.5

contrast 0.5 noise 0.7

height differences min -2 max 2

color range [microns]

height differences min -2 max 2

status: done

area for data 0.3 x 0.3 mm

X [mm] 5.08 Y [mm] 5 value 0.37

RMS 0.437

PV 2.12

Mean 0.0323

values in microns

color range [microns] min -2 max 2

March 2001

BioShape

BioShape AG
Fregestr. 67
D – 12159 Berlin
Germany

Table of contents

1 Executive summary

A simulation software was programmed for use on a personal computer. The software simulates fringe pattern images similar to those that can be obtained from patients' corneas with the intraoperative corneal topographer from BioShape.

The software allows a variation of the relevant parameters that influence the accuracy of the measurement. As a result data is calculated to compare different settings in order to get a feeling for the accuracy of real life application of the technology. The results are displayed graphically and precise figures are given for selectable regions of interest.

The quality of fringe pattern images from the cornea mainly depend on their noise and contrast. Using the software we found that the algorithms prefer high contrast over low noise. Low contrast images are mostly associated with medium noise which makes them difficult to evaluate. High contrast images are not so much bothered by high noise which can easily be reduced by smoothing filters without changing the information.

We thus recommend for the application on patients to use a reasonably high hardware gain for the camera if there is not enough uv light available for the fringe projection. Increasing the gain with software algorithms does not enhance the outcome. The best situation would be to have several millijoules of 193nm laser radiation available at the cornea. This would also allow to decrease the iris diaphragm of the camera lens for an even increased focal depth.

2 Introduction

The technology employed by BioShape is based on a combination of microscopic triangulation and interferometric evaluation procedures. An ultraviolet fringe pattern is imaged onto the cornea using 193nm laser pulses. The distorted fluorescence pattern observed under a tilted angle is evaluated with phase calculation algorithms derived from interferometric measurement procedures.

The most important question concerns the achievable accuracy and its dependence on the imaging conditions. The user will need to know whether the measured data is reliable and whether he will be able to program the results into his laser to perform an immediate enhancement procedure at the end of the treatment. The laser producer on the other hand needs to have faith in the instrument to eventually let the laser make an automatic final correction.

BioShape has programmed a simulation software that allows a variation of all parameters that have an influence on the measurement accuracy. These parameters include:

- horizontal and vertical pixels per image
- image resolution in microns per pixel
- fringe period in pixels
- triangulation angle
- image contrast
- image noise
- number of Gauss filter iterations

BioShape's intention is to provide a tool which allows to judge the performance of the technology offline. It will give the user a feeling for the measurement accuracy being connected with specific image properties.

3 Background

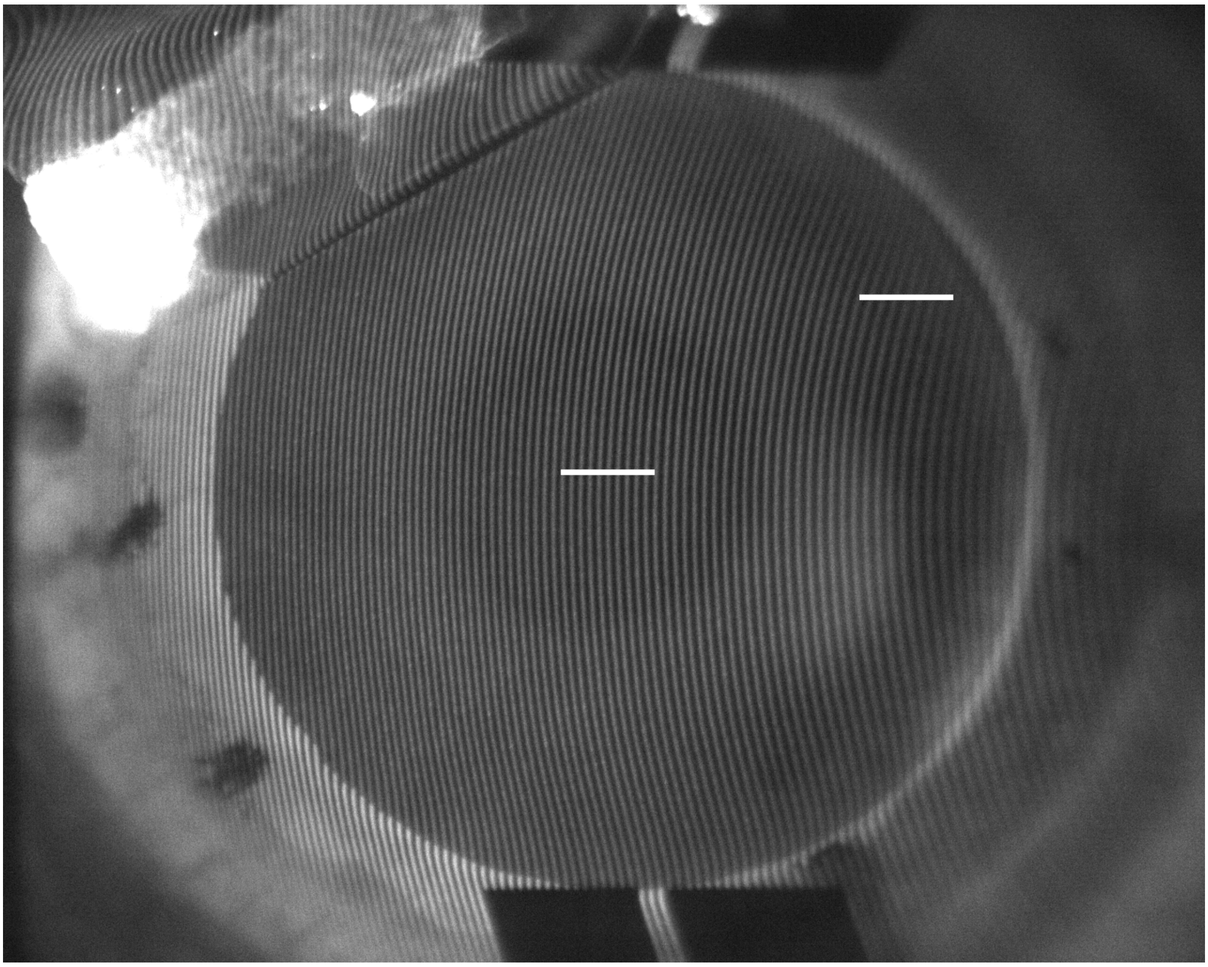
The list of the seven parameters given above can be divided into geometric factors (first four) and image quality (last three). It is obvious that a higher number of pixels results in more information and thus higher accuracy at a given resolution. There is currently one CCD chip of Sony in the market which is very well suited for the technology as it has a high number of pixels (1280x1024) and a comparably high quantum efficiency at the fluorescence wavelengths for a very low price. Given this pixel number a resolution of about ten microns per pixel seems reasonable to cover the whole region of interest of 12.8 x 10.2 mm. As current microkeratomes cut smaller diameters than 10mm the ablated zone should be well within the camera image.

The evaluation procedure relies on the recognition of a sinusoidal intensity distribution across the fringes. This requires at least five pixels for one period. Currently there are ten pixels per period in the center which corresponds to 50 microns wide lines. The wavelength strongly depends on the position of the cornea due to its curvature. This means that on one side of the center the lines will become thinner and thicker on the other side. The measurements require a good visibility of the fringes also in the thin lines region. The quality of the optics (MTF) plays an important role in this context.

Finally the triangulation angle needs to allow for an optimum between a good visibility and a sufficient distortion of the fringes. 30 degrees is a well suited value considering the curvature of a typical cornea.

Apart from these geometric factors the last three parameters mainly depend on the fluorescence intensity. The more light is falling onto the CCD chip the higher the contrast and the lower the noise will mostly be. As soon as the signal to noise ratio (s/n) decreases the probability of misinterpreting the original image is raised. The reason for the misinterpretation is related to the difficulty of properly recognizing the sinusoidal intensity distribution of the fringes. This results in an increase of the root mean square value (rms) of the measurement which corresponds to more scattering of the data around the real value. One means to reduce the rms value is to flatten the spikes in the image with a Gauss filter. This filter reduces the irregularities without shifting the lines. They appear smoother but they also lose contrast.

Let us take a look at an image taken from an actual patient after a LASIK treatment. The following picture shows the original unfiltered image. The white lines indicate locations of histogram scans. One line crosses the center in which the s/n ratio is high. Further towards the microkeratome cutting edge the s/n ratio decreases considerably in this image as the optics used at that time were unsuited to resolve lines which are a few millimeters below the focal plane. This is improved in the new optics that are currently being built. Nevertheless it is a good example for a lower s/n ratio region which demonstrates the limits of image quality that need to be obeyed for reliable measurements.

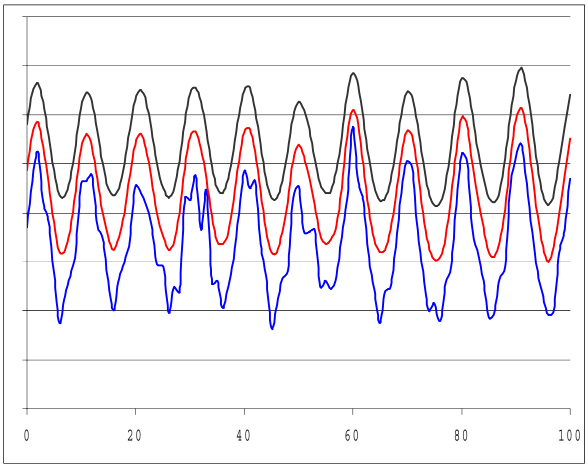


Fringe pattern as observed after a LASIK procedure on a patient's eye with line scans

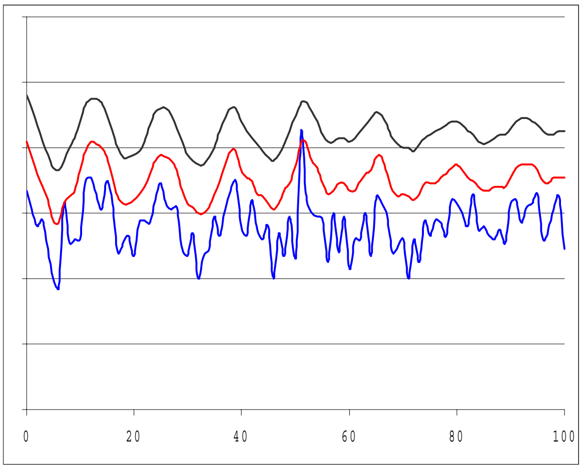
The gray value scans along the lines in the image are shown in the following two graphs. They both give the gray value of the pixels along the lines which correspond to the intensity of the fluorescence signal being modulated by noise.

This superimposed noise is a result of three contributions: noise of the ccd camera (readout and photon/electron conversion), imaging errors of the optics and statistics of the fluorescence emission. The camera readout noise is constant over the whole image. The camera's absolute noise associated with the detection of light is higher in brighter regions. This effect even increases as the fluorescence light noise is also only produced in bright areas. A realistic simulation needs to account for these irregular dependencies of the noise in bright and dark regions of the pattern. The optics errors mainly guarantee a smooth transition between bright and dark which is essential for the evaluation algorithm that requires a sine function.

Here are the two line scans through the center (left) and the periphery (right). Each of the horizontal parallel lines corresponds to 20 gray levels. The blue line is the original intensity distribution. The other two lines are derived from the original line by applying a Gauss smoothing filter once or twice. The filtered lines have been shifted vertically for better visibility of the effect. Every filter application reduces the inherent noise but also the signal.



Line scan through the center



Line scan through the periphery

The evaluation of the patient images has shown that two or three consecutive filter application reveal the least noisy topographies. This was confirmed on other measurement test samples. The simulation allows a variation of all these parameters to become familiar with the influence of each of them on the measurement accuracy.

4 Simulation software

4.1 Introduction

With the software simulation we want to provide you a tool to play around with in order to learn how different parameters influence the accuracy of fringe projection measurements. You will be able to change all parameters in a realistic way that play a role for the evaluation process. These parameters were already mentioned in the chapter 'Background':

- horizontal and vertical pixels per image (fixed to 1280 x 1024)
- image resolution in microns per pixel
- fringe period in pixels
- triangulation angle
- image contrast
- image noise
- number of Gauss filter iterations

The CCD pixels were fixed to the realistic dimension of 1280 x 1024 (Sony chip).

In the software calculated spheres from simulated fringe patterns are compared to ideal spheres with an identical radius automatically. This means that you will never get spheres as a result but instead you will always have the differences between your individual sphere resulting from specific simulation parameters and the ideal sphere with the same radius. This difference allows you to estimate the error in the measurement by closely looking at the following parameters:

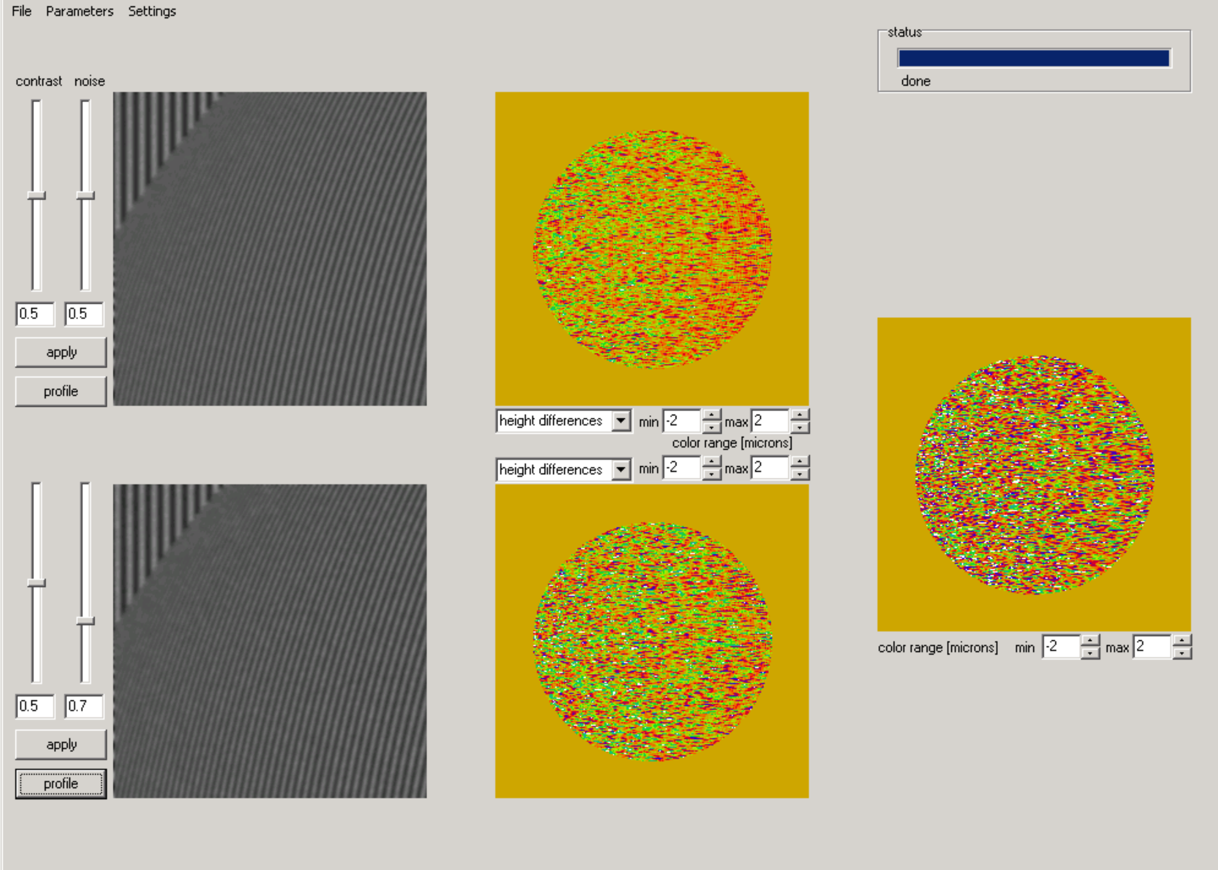
- difference value at a specific pixel (location on the sphere)
- mean value within a region of interest (ROI)
- peak to valley value within a ROI
- root mean square value within a ROI

Corresponding maps of the differences will be provided in color coding to give you a qualitative overview at first glance.

In addition to evaluating single images you can also compare two simulated spheres with just one differing parameter. This feature enables to recognize the influence of each parameter alone.

4.2 Simple screen

The following image shows a screen shot of the simplest window of the software:



contrast 0.5 noise 0.5

contrast 0.5 noise 0.7

height differences min -2 max 2 color range [microns]

height differences min -2 max 2

color range [microns] min -2 max 2

Simple simulation screen

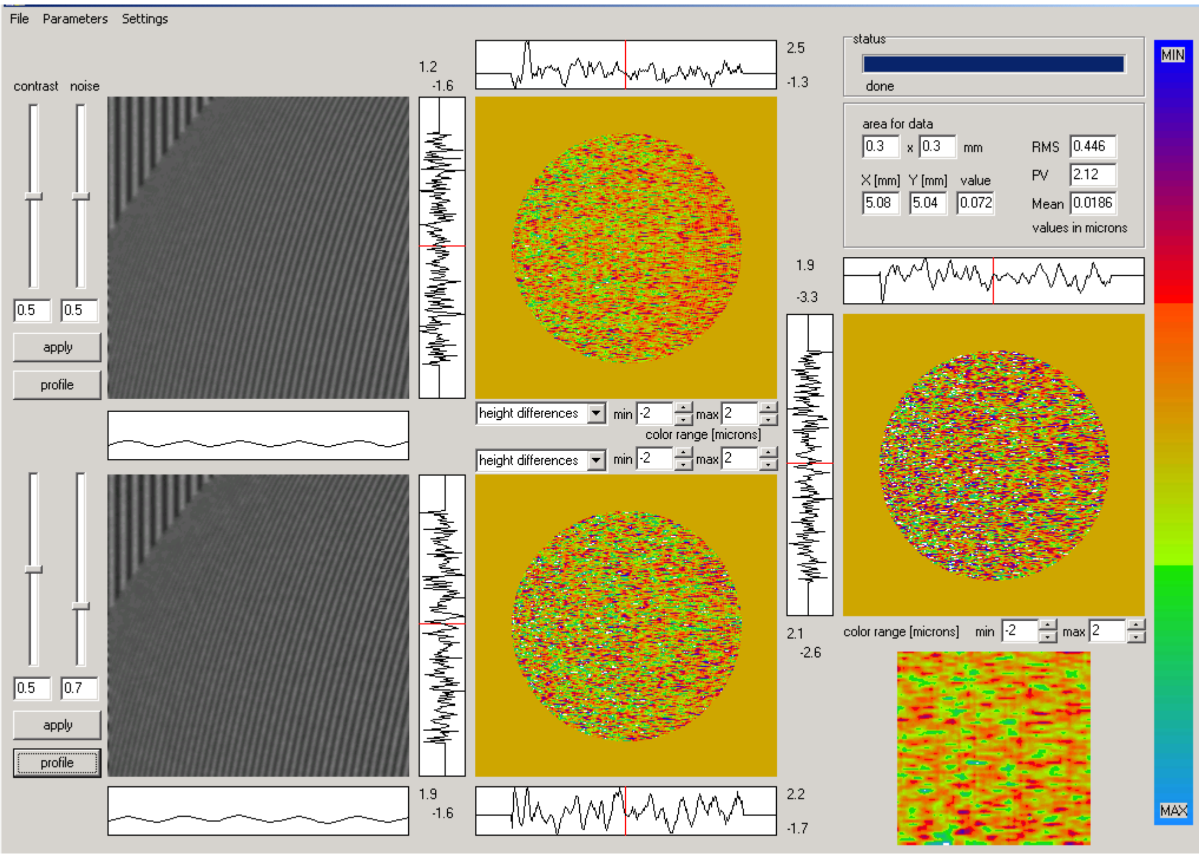
The two fringe patterns on the left show the original images one and two which are considered. Their contrast and noise levels are set on their left. By clicking on the apply button the images are produced using these parameters.

Next to them on the right are the results of the evaluation of the fringe patterns. These images are calculated using the appropriate algorithms after clicking on the profile button under the apply button. The current map shows the height difference between the simulated noisy pattern and the ideal sphere. It thus reveals the accuracy connected with specific settings.

The image on the very right is the difference between the two evaluated maps. Here the user can compare the two maps generated before.

4.3 Complex screen

A more informative screen also contains line scans of each image, statistical data, a magnifier (all live updated) and a color bar. These options can be selected in the settings menu. The screen is shown in the following image:



contrast 0.5 noise 0.5

contrast 0.5 noise 0.7

height differences min -2 max 2 color range [microns]

height differences min -2 max 2

status done

area for data 0.3 x 0.3 mm

X [mm] 5.08 Y [mm] 5.04 value 0.072

RMS 0.446 PV 2.12 Mean 0.0186 values in microns

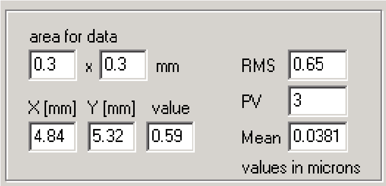
color range [microns] min -2 max 2

Detailed simulation screen

4.3.1 Line Scans

Line scans are live updated when moving the mouse over an image. The y-axis of the line scans of the fringe pattern images are scaled from 0 to 255 gray values. The y-axis of the other line scans are automatically scaled to cover all of the data in the selected line. The corresponding maximum and minimum value are given as captions.

4.3.2 Statistical data



area for data 0.3 x 0.3 mm

X [mm] 4.84 Y [mm] 5.32 value 0.59

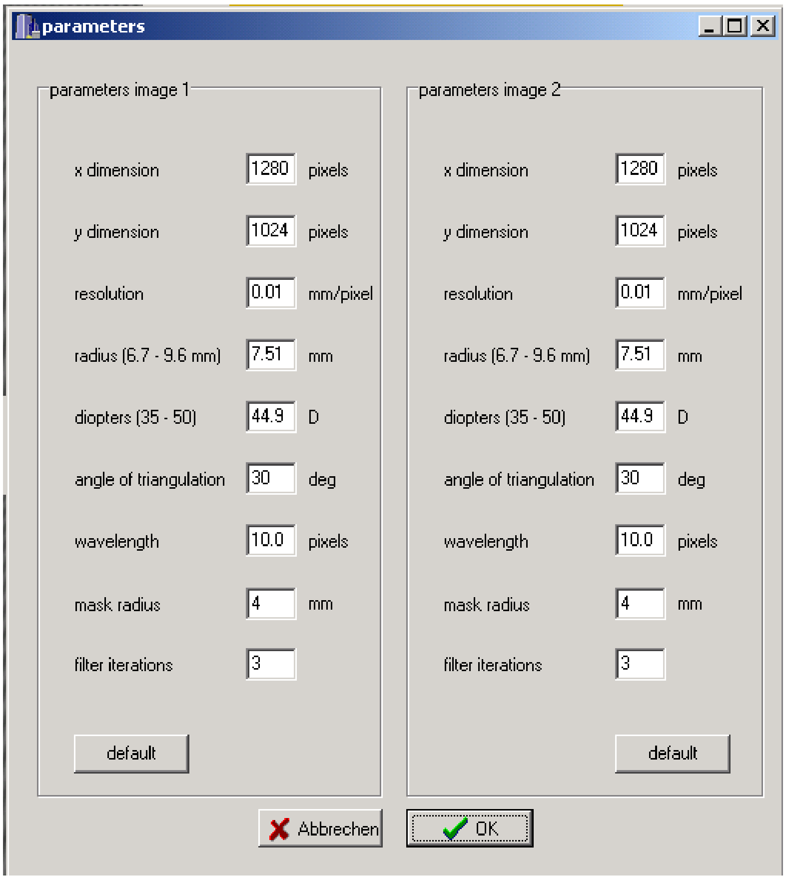
RMS 0.65 PV 3 Mean 0.0381 values in microns

Statistics field

In the upper right of the screen a box with data on the actual mouse location in an image is live updated. The area around the mouse position which is considered for the data can be set. The mouse location and the value at that pixel is given. Root mean square (RMS), peak to valley (PV) and mean values are also live updated.

4.4 Parameter menu

Before generating a fringe pattern the parameters of the image need to be selected in a special menu. Here is a picture of it:



parameters image 1

x dimension 1280 pixels
y dimension 1024 pixels
resolution 0.01 mm/pixel
radius (6.7 - 9.6 mm) 7.51 mm
diopters (35 - 50) 44.9 D
angle of triangulation 30 deg
wavelength 10.0 pixels
mask radius 4 mm
filter iterations 3

parameters image 2

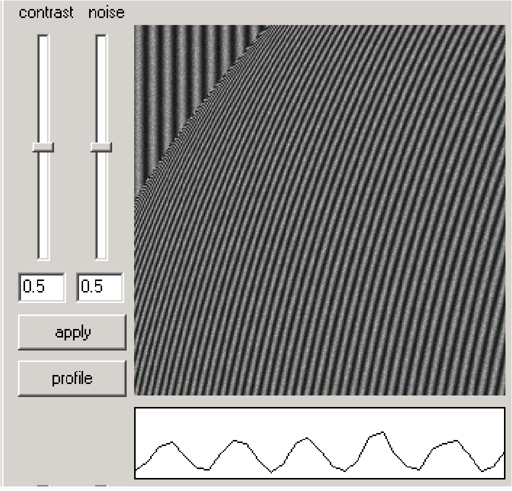
x dimension 1280 pixels
y dimension 1024 pixels
resolution 0.01 mm/pixel
radius (6.7 - 9.6 mm) 7.51 mm
diopters (35 - 50) 44.9 D
angle of triangulation 30 deg
wavelength 10.0 pixels
mask radius 4 mm
filter iterations 3

Parameter window

The x- and y-dimensions are fixed to the size of the currently used Sony CCD chip. Editing the resolution in one image will change them in the other correspondingly to remain compatible for the difference map of both. The resolution determines the region of interest. The radius of the sphere and the corresponding curvature are selectable within ranges that are typical for the human cornea. A refractive index of 1.337 was used for the conversion. The fringe pattern wavelength is considered at the apex. The wavelength changes to both sides of the apex due to the triangulation setup and the shape of the sphere. The mask radius sets the size of the evaluated region of interest. The figure after filter iterations determines how often a 3x3 Gauss smoothing filter is applied to the original image before the evaluation is performed. The fringe pattern image is altered accordingly.

4.5 Contrast and Noise

Let us now take a closer look at the simulated fringe pattern.



Simulated fringe pattern with central line scan and parameter bars (here: unfiltered)

Patterns are generated by varying contrast and noise to simulate a real life situation. Both bars can be set between zero and one. Contrast one corresponds to eight bits gray scale or 256 gray values. With contrast 0.5 there are only 7 bits or 128 gray scales. Below this value the smallest gray value will always be at 32 as this comes closer to real world patterns. Usually images with low contrast are quite dark depending on the offset of the camera.

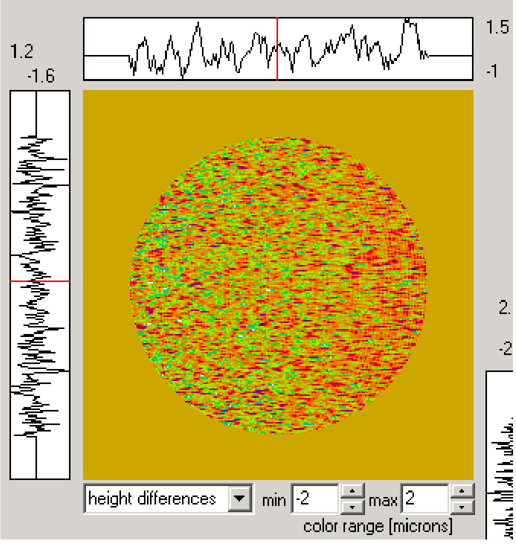
The noise has a much more complex dependency on the brightness of the image. Again this is derived from patient data. We found that the noise of bright regions of the pattern is usually much higher than the noise in the dark regions. This can be explained with the statistical emission of the fluorescence light inducing an variable amount of electrons in the CCD. Here the readout noise is added to the detection noise. The bright regions thus fluctuate more pronounced than the dark regions in which only the dark current of the camera produces little noise. This effect can be observed in histograms of all our patient images. It was accounted for by applying higher noise to brighter region than to darker ones. The noise itself corresponds to a Gaussian distribution around the optimum value depending on the actual gray value. The expectation value sigma of this distribution is set with the noise bar.

A left mouse click on the truncated image will open a new window with the whole image. Clicking on this image will close it again. The whole image is saved into the directory of the program as a bmp-file. Changing the parameters will update this file. If a Gauss smoothing filter is applied the new and the original image are saved. The filenames are sim00.bmp and sim00_filtered.bmp for the first image. The second image files are called sim01.bmp and sim01_filtered.bmp.

The line scan below the image runs through the central region of the pattern with a length of 50 pixels.

Evaluated maps

Once the patterns are simulated they are evaluated by clicking on the profile button. This generates the following color coded height difference image:



height differences

min -2

max 2

Color coded difference map with line scans and range selectors

The color range of the map is changed by using the arrows or typing in new values for min and max. The captions next to the line scans indicate the current range of the values along the corresponding vertical and horizontal lines. The selector allows to choose between six different settings:

- Height difference map
- Peak to valley map (PV)
- Root mean square map (RMS)
- Mean value map
- Binary view
- Save data

The binary view sets a threshold at zero microns at marks all values below this threshold in one color and those above in another color.

When clicking on Save data the user is requested to enter a filename without extension. This creates eight files: two bitmaps and six text files. The bitmaps are the color coded map that was displayed before clicking on save data and the original fringe pattern. The text files are: 1. a parameter file with all the settings and five ASCII files with height data.

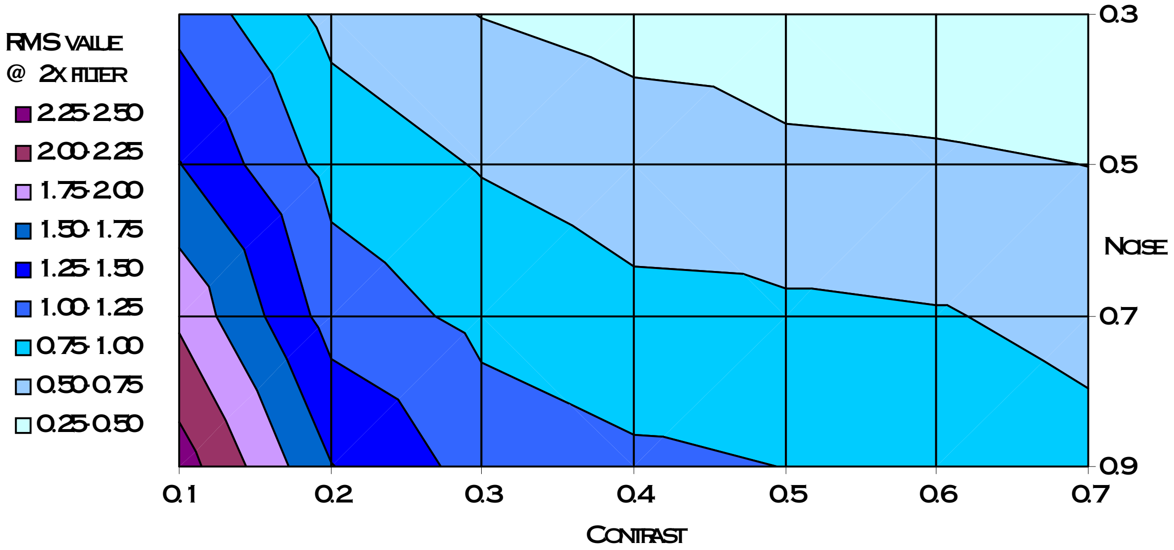
One ASCII file contains the whole surface. In the first line the number columns and rows, in the second line the resolution are given. The following lines contain the values in mm. There are four files, two each for two vertical and horizontal scans. The scans run through the difference map and the height profile of the sphere, respectively.

5 Results

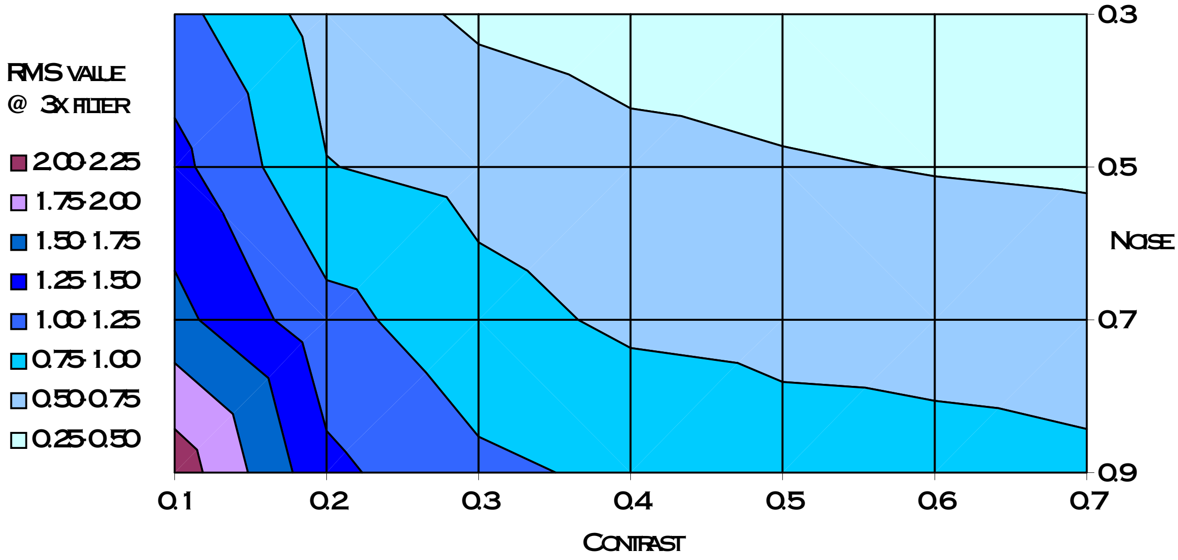
Using the simulation systematically reveals remarkable results that will give an advice on relevant image parameters that have an influence on the measurement accuracy.

We evaluated the RMS value within a field of 1 x 2 mm (x/y) for different noise and contrast settings. This evaluation was done for two and three smoothing filter applications. The following graphs show the results of this evaluation.

The upper graph is for two filter applications, the lower for three. The image quality increases when moving further right and upwards in the graphs as the contrast is increased and the noise is reduced. The graphs indicate that three filter applications give better results than just two. The RMS value at 0.6 contrast and 0.5 noise for example is higher than 0.5 microns for two filter applications and smaller than 0.5 microns for three.



RMS value for different noise and contrast settings with two Gauss filter iterations



RMS value for different noise and contrast settings with three Gauss filter iterations

Another parameter that has a large influence on the measurement accuracy is the fringe period or wavelength. One would expect smaller wavelengths to provide more accurate data. Unfortunately reality looks different. A decrease of the wavelength is usually associated with an increase in noise and a decrease in contrast. This is especially important when considering the periphery of a fringe pattern where the wavelength is changed dramatically due to the triangulation angle.

Let us take a look at an example of a 7.5 mm radius sphere. The noise in these measurements was kept constant at 0.6 and the fringe patterns were Gauss filtered three times. With a central wavelength of 10 pixels at 7.5mm sphere radius the fringe wavelength is reduced in x direction at -3mm to 7 pixels and at +3mm it is 14 pixels. There seems to be an optimum wavelength around eight pixels. Further studies with different noise levels will be performed soon.