FLEXIBLE OKO OPTICAL

Flexible Optical B.V.

Adaptive Optics • Optical Microsystems • Wavefront Sensors

Adaptive optical system based on 39-channel PDM: technical passport

OKO Technologies,

OKO Technologies is the trade name of Flexible Optical BV

1 Installation of FrontSurfer software (Windows 2000/XP/Vista/7/8)

1. Start “setup.exe” from “fsurfer” directory of the installation CD to install FrontSurfer to your computer. Follow further installation instructions.
2. Start “Install.exe” from “keylok” directory of the installation CD to install drivers for the protection dongle. Select the option “USB dongle”. Please note that the installation should be completed BEFORE the dongle is connected.
3. Attach the FrontSurfer dongle to a free USB port. The system will recognize the device. Choose for automatic installation of the driver.
4. Under Windows Vista, 7 and 8, FrontSurfer should be started in compatibility mode under administrator access rights. To enable them, right-click on “FrontSurfer” shortcut and locate “Compatibility” property sheet. Enable the options “Run this program in compatibility mode for Windows XP (Service Pack 3)” (optional, maybe omitted on the most recent systems) and “Run this program as an administrator” and press OK to confirm.
5. Now you may start “FrontSurfer” from the Start menu.

2 Wavefront sensor

Parameter	Value
Serial Number	FS1540-0-P150-F3.5-15.06
Camera model	uEye UI-1540SE-M-GL
Camera type	digital CMOS
Camera interface	USB 2.0
Array geometry	square
Array pitch	150 μm
Array focal distance	3.5 mm
Clear aperture	4.5 mm
Subapertures	$\leq$ 729
Maximum tilt, fast mode	$\pm$0.0067 rad
Maximum tilt, slow mode	N/A
Repeatability, PV	$0.024\lambda^*$
Repeatability, RMS	$0.004\lambda^*$
Acquisition rate	$\geq$25 fps
Processing rate, fast mode	$\sim$25 fps**
Processing rate, slow mode	NA
Recommended Zernike terms	$\leq$300
Wavelength	400...900 nm (also sensitive at near IR)

* For $\lambda = 633$ nm.

** For low-order aberration analysis on a PC with Intel i7 1.73 GHz processor and 8 GB RAM.

The repeatability figures can be further improved by averaging over multiple frames. To enable averaging, go to menu "Options ⇒ Camera", press button "Properties" and correct the field "Average over ... frames".

2.1 Using of the absolute and reference measurement modes

- To switch to the absolute measurement mode, go to the menu "Options ⇒ Parameters" and change the "Reference grid" setting to "square". Press "OK".
- To switch to the reference mode, go to the menu "Options ⇒ Parameters" and change the "Reference grid" setting to "get from picture". Press "OK" to complete.

2.2 Interfacing instructions

1. Install uEye camera drivers from "uEye" directory of the installation CD.

2. Connect the wavefront sensor to the computer. The system will recognize the device. Choose for automatic installation of the driver.
3. Start "uEye Cockpit" program and make sure that you can see image from the camera.
4. Configure frame grabber type in FrontSurfer. For this purpose go to the menu "Options ⇒ Camera". In the dialog box "Camera interface" check "Plugin" option. After that, load plugin for the uEye camera by pressing "Load" button and selecting "uEye.dll" file in the FrontSurfer installation directory. Press "OK".
5. Load the wavefront sensor calibration data. For this purpose go to the menu "Options ⇒ Parameters". In the dialog box "Sensor parameters" press "Load" button and load the calibration file "calibration.txt" from the "fsurfer" directory of the CD. Press "OK" to complete. See Fig. 1 for illustration.

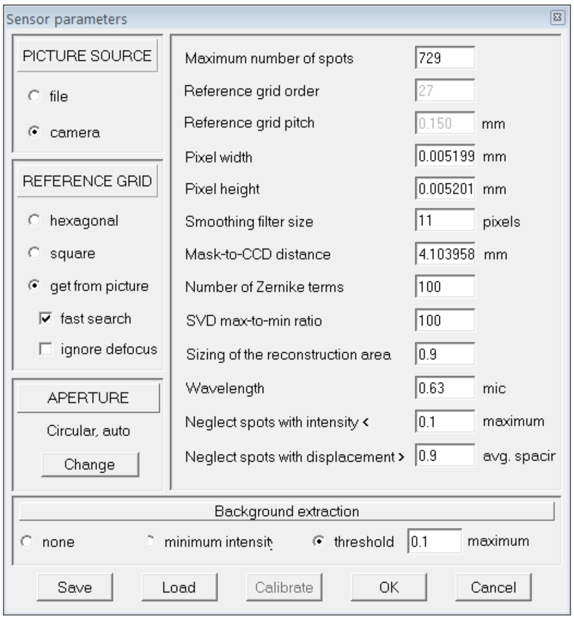

Figure 1: *Sensor parameters window*

6. To increase the processing speed, the sensor can be used with a smaller area of interest (AOI) and/or subsampling mode. To change AOI and subsampling mode, go to menu "Options ⇒ Parameters". In the dialog box "Camera interface" press "Properties" button. In "Area of interest" section, unselect the option "maximize" and adjust the fields "Left", "Width", "Top" and "Height" to set the desired AOI. You need to reduce dark space at the periphery of the frame, keeping the whole pattern of spots visible. A convenient way to set these parameters is to use the Crop tool of uEye Cockpit (see Fig. 2) to chose the desired AOI, jot down the AOI size and coordinates, and insert their values in the FrontSurfer. In "Sampling mode" drop-down menu, chose the desired sampling mode ("Normal", or "Subsampling x2") (see Fig. 4). Load the proper calibration file for the chosen sampling mode.

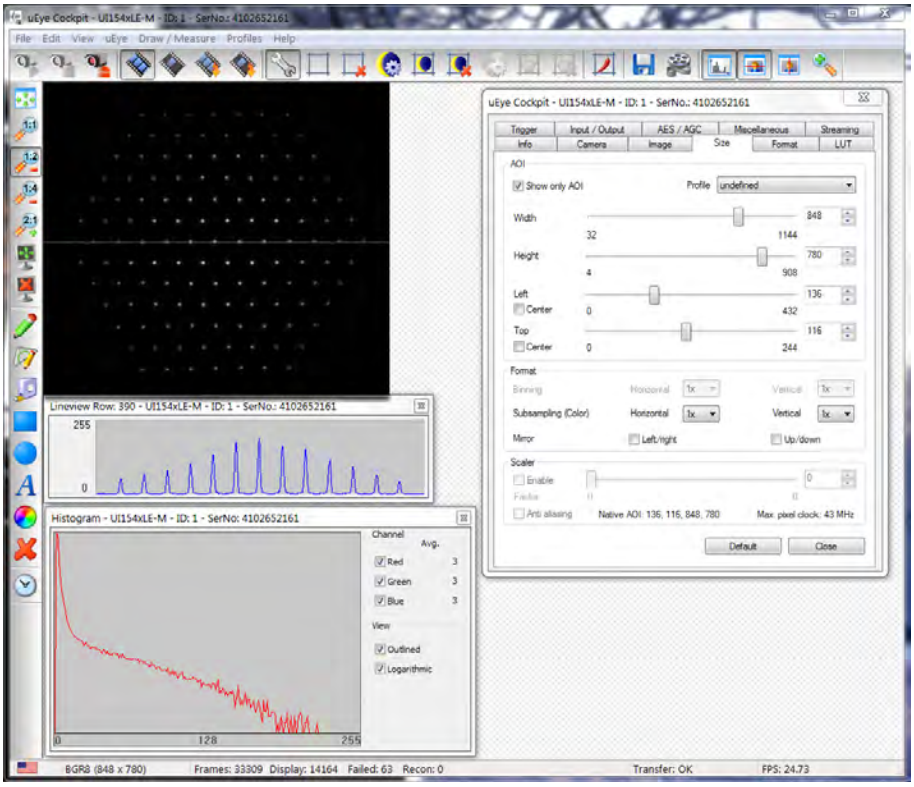

Figure 2: *Reading the AOI values set by the Crop tool of uEye Cockpit (the snapshot was taken wiht 127-lenses hexagonal array).*

The sensor has a microlens array with orthogonal arrangement of microlenses, and is aperture is mostly limited by the image sensor size. Sometimes, it is more convenient to use sensor in this configuration in reference mode with manually defined circular aperture. To define the aperture (area of interest), load the reference pattern first, then click on the reference picture and draw the aperture by dragging the cursor. It will be displayed as a red circle. For more information, refer to section 3.6.3 of the FrontSurfer manual.

3 Deformable mirror

3.1 Specifications

Please refer to the technical passport of the deformable mirror for its specifications.

3.2 Interfacing instructions

The mirror is supplied with matching high-voltage amplifier, USBDAC40 control unit with USB 2.0 interface and a set of cables. Installation procedure is briefly described below.

1. Connect DAC40USB unit to a USB port of your computer.

   (Optionally; not required for Windows 7 and 8: install the drivers; drivers for this unit can be found in "DAC40USB/Driver" directory of the installation CD.)

   Start "DAC40USB/Program_win2000/TEST_DAC40.exe" to make sure that the unit is recognized by the system.
2. Load configuration of channels for the deformable mirror. With this purpose go to the menu command "Mirror ⇒ Configuration", then press "Configure". In the dialog box "Deformable mirror configuration" press the "Load" button and load the file "PDM50-39_usb.txt" from the CD "fsurfer" directory. Press "OK" twice to complete configuration.
3. Disconnect DAC40USB control unit from your computer.
4. Connect the amplifier units to DAC40USB units using two 20 pins-to-26 pins cables.
5. Connect the mirror to the amplifier unit using two 20 pins-to-20 pins cables. Fix the cables to the optical table.
6. Connect DAC40USB to the computer using a USB cable.

4 Assembling and running of the adaptive optical system

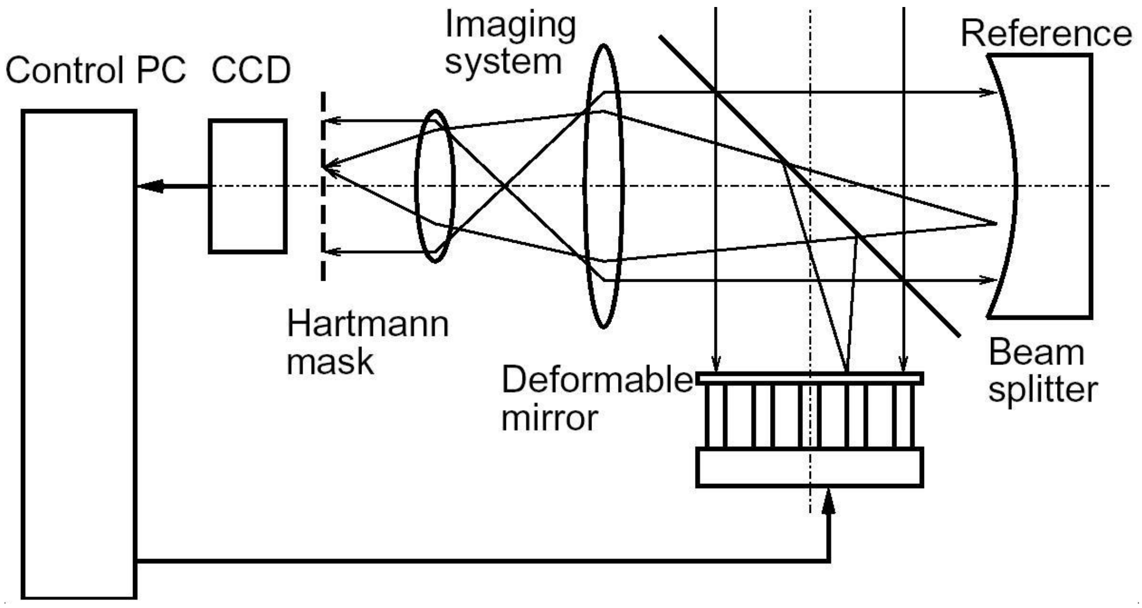

Figure 3: *Scheme of typical adaptive optics setup.*

1. Place the mirror and the wavefront sensor into an optical setup. The optical scheme should satisfy the following conditions.

   a) The optics should re-image the plane of the mirror to the plane of the Hartmann mask (or microlens array).

   b) The scheme should scale the beam in such a way that the working aperture of the mirror (about 35 mm) should be re-imaged to the working area of the Hartmann mask/microlens array (4.5 mm).

   c) The optics should allow for calibration. In the general case, it consists of separate measurement of the complete setup aberration with ideal object or a source of ideal wavefront, replacing the one to be tested.

   The typical setup for functional feedback loop is shown in the Figure 3.

2. Connect the wavefront sensor and the deformable mirror; turn on the amplifier units.

3. Start FrontSurfer. Turn on the preview mode in FrontSurfer and check an image from the Hartmann sensor for both the calibration beam and those reflected from the mirror. It is highly desirable to provide that no spots are missing.

4. Go to the menu command “Mirror → Set values”. Now you may start to use the mirror by applying different control voltages to the actuators. See FrontSurfer manual for instructions on using of the feedback loop operation

mode.

4.1 Practical tips

1. Start FrontSurfer. Go to menu "Mirror → Set values" and set value 0 to all actuators. It corresponds to the bias voltage, which produces slightly concave shape on the mirror.
2. Make sure that the beam is centered on the deformable mirror, wavefront sensor and other components. You can use the supplied "`defocus.exe`" or "`set_channel.exe 1`" command line utilities (supplied on the CD) to facilitate the alignment process.
3. Turn on the preview mode in FrontSurfer and check an image from the Hartmannsensor. Adjust the wavefront sensor position for centering.
4. Adjust the beam brightness with laser diode power potentiometer and/or polarization filter and the wavefront sensor exposure (use menu "Options ⇒ Camera" and then "Properties" button; see Figure 4) to make the spots good visible, avoiding the saturation.
5. Switch on the imaging camera and adjust the exposure to see the focal spot. If needed, adjust the camera position to achieve the best focus.
6. In menu "Mirror ⇒ Feedback parameters", set the parameters according to Figure 5. We recommend setting "Delay" to 100 ms for calibration; it can be reduced to 1 ms for the closed-loop operation.
7. If used in a reference mode, take a reference pattern (use menu "File ⇒ Open Reference" or use a shortcut button "2").
8. Go to menu "Mirror ⇒ Calibrate mirror" to calibrate the system. The calibration data can be saved for further use from menu "Mirror ⇒ Save calibration".
9. Check the eigen modes of the system (use menu "Mirror ⇒ Singular values" and double-click on a singular value marker to see the corresponding mode). They should look similar to the modes shown in Fig. 7. Noisy or low-contrast modes indicate an alignment/calibration problem.
10. Now you may start closed-loop correction from menu "Mirror ⇒ Start feedback". During the correction loop, you may compensate for residual static aberration of the system by manually adjusting Zernike terms, in particular, defocus (C[2,0]) and astigmatism (C[2,2] and C[2,-2]). Spot sharpness should be improved.

Please refer to FrontSurfer manual for further information about the feedback loop operation mode.

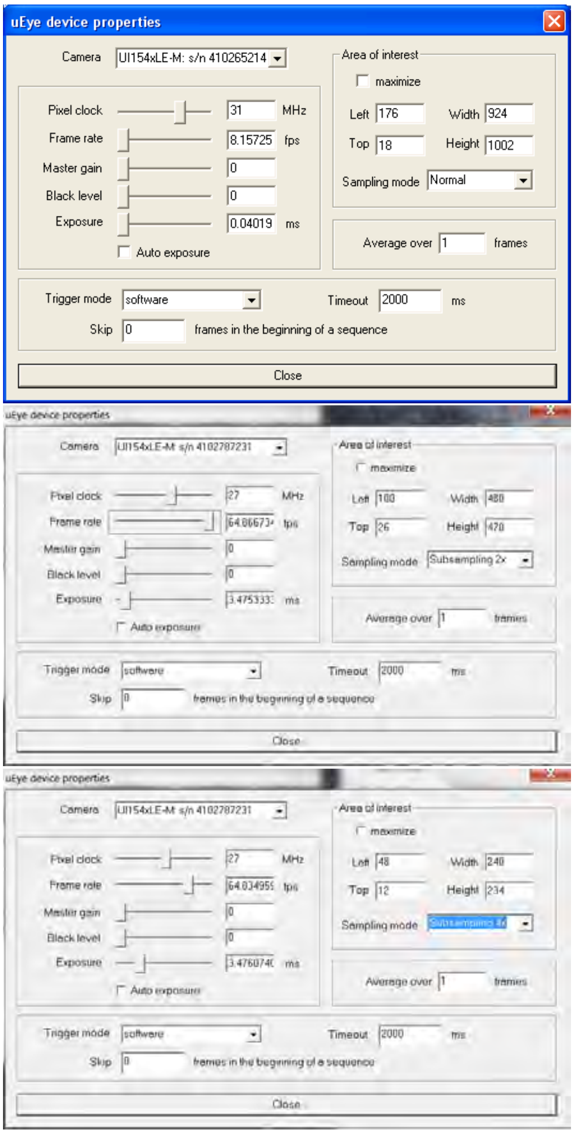

Figure 4: *"uEye" plugin properties; settings for "Normal", "Subsampling x2" and "Subsampling x4" modes (top to bottom).*

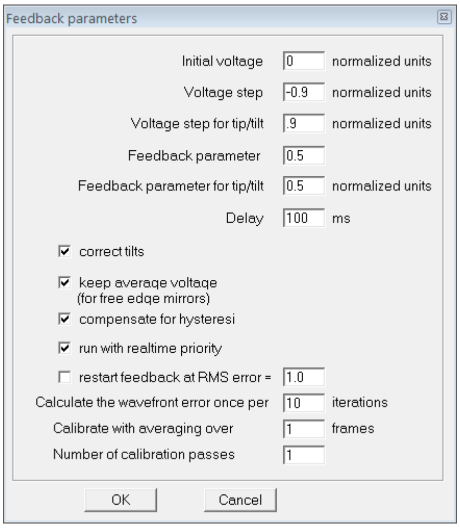

Figure 5: *Feedback parameters for calibration of the mirror*

5 Mirror testing

The mirror was calibrated and tested in feedback loop operation mode before shipping. The results of testing are presented below.

FrontSurfer perform wavefront correction in a series of iterations. If the residual aberration ϕ_n at the n-th iteration corresponds to the set of actuator signals $\mathbf{X}_n$ then the actuator signals at the next step $\mathbf{X}_{n+1}$ will be determined by expression

$$\mathbf{X}_{n+1} = \mathbf{X}_n \text{ - } g\mathbf{A}^{-1}\phi_n,$$

where g is the feedback coefficient with value in the range (0..1], $\mathbf{A}$ is the influence matrix of the mirror, $\mathbf{A}^{-1}$ is its pseudo-inverse given by

$$\mathbf{A}^{-1}=\mathbf{V}\mathbf{S}^{-1}\mathbf{U}^T,$$

$\mathbf{U}$, $\mathbf{S}$ and $\mathbf{V}$ are the singular value decomposition (SVD) of $\mathbf{A}$ which is $\mathbf{A}=\mathbf{U}\mathbf{S}\mathbf{V}^T$ [1]. The columns of the matrix $\mathbf{U}$ make up orthonormal set of the mirror deformations (modes), and the values of the diagonal matrix $\mathbf{S}$ represent the gains of these modes. Discarding those modes having small singular values may improve controllability of the system.

Experimental singular values for the deformable mirror are given in Figure 6; first 20 SVD modes are shown in Figure 7.

A flat mirror was used as a reference. We have used 300:40 mm telescope to conjugate the DM pupil to the WFS plane.

Optimization started from the initial shape of the mirror, which was produced by setting all mirror values to zero; this shape is shown in Figure 8.

In the first test we generated the flat wavefront with respect to the reference mirror. In the following tests we generated various Zernike aberrations with the maximum possible amplitude for which *rms* error was less than $\lambda/14$ (Maréchal criterion); the

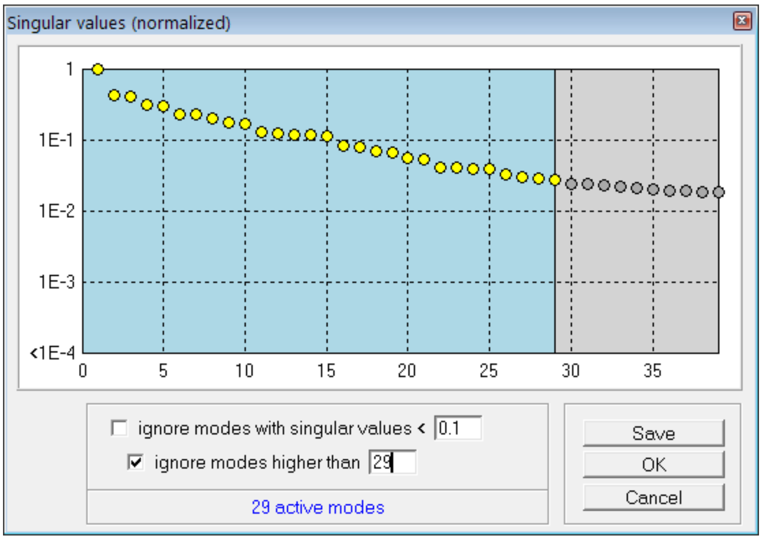

Figure 6: *Singular values of the AO system.*

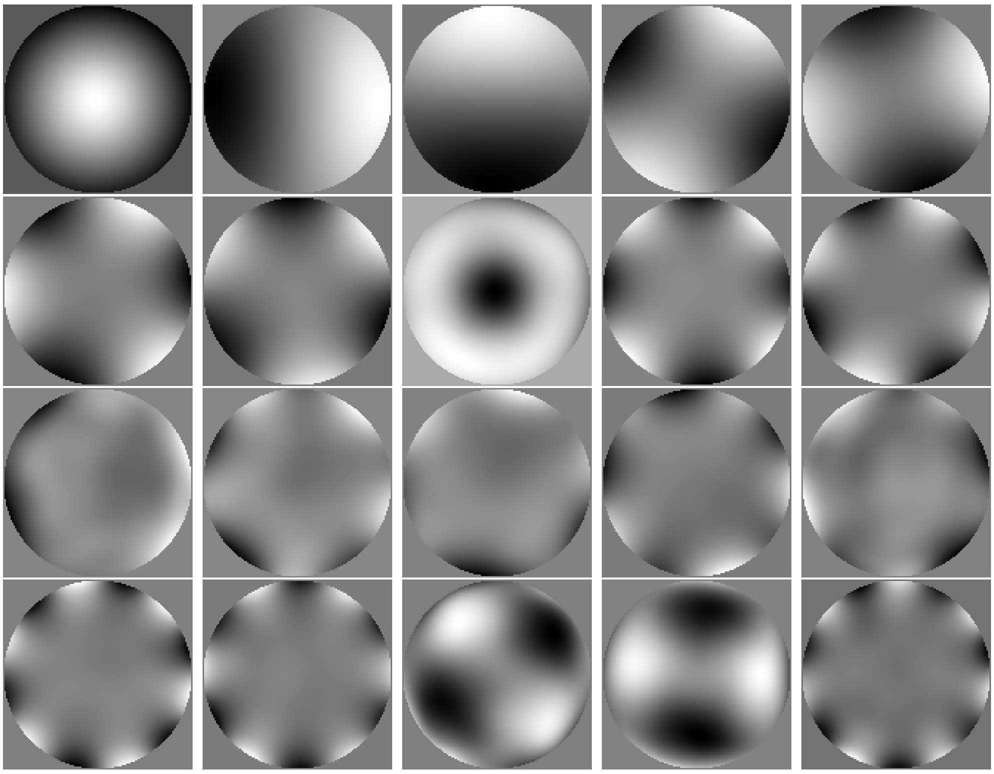

Figure 7: *First 20 modes of the AO system.*

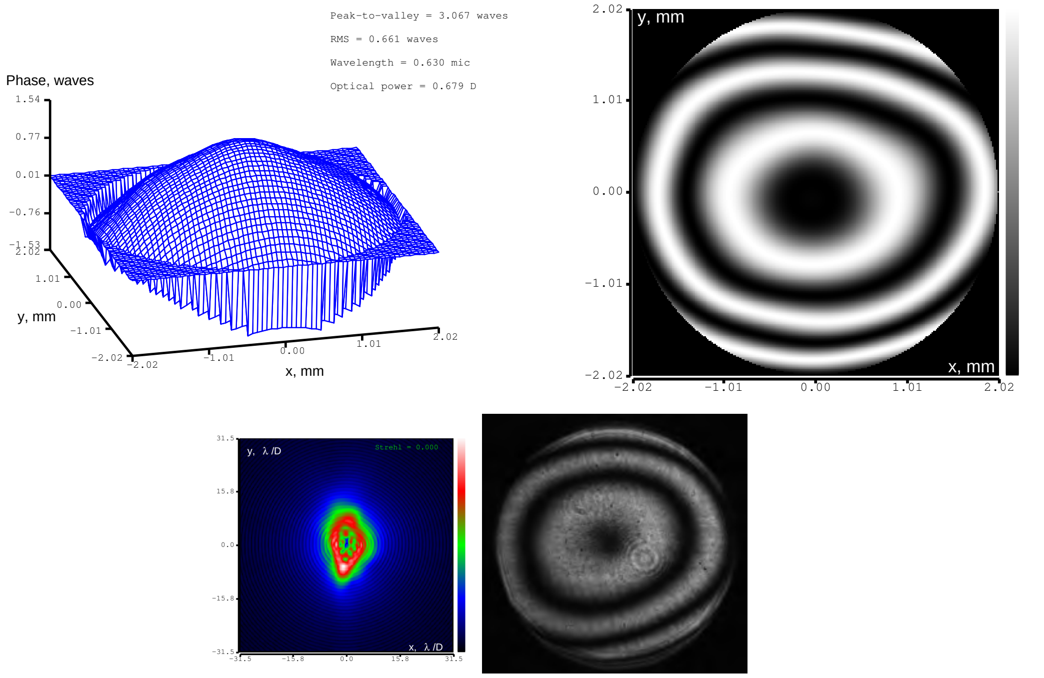

Figure 8: *Initial aberration of the system. top: reconstructed wavefront (left) and simulated interferogram (right); simulated far field (left) and registered interferogram (right) .*

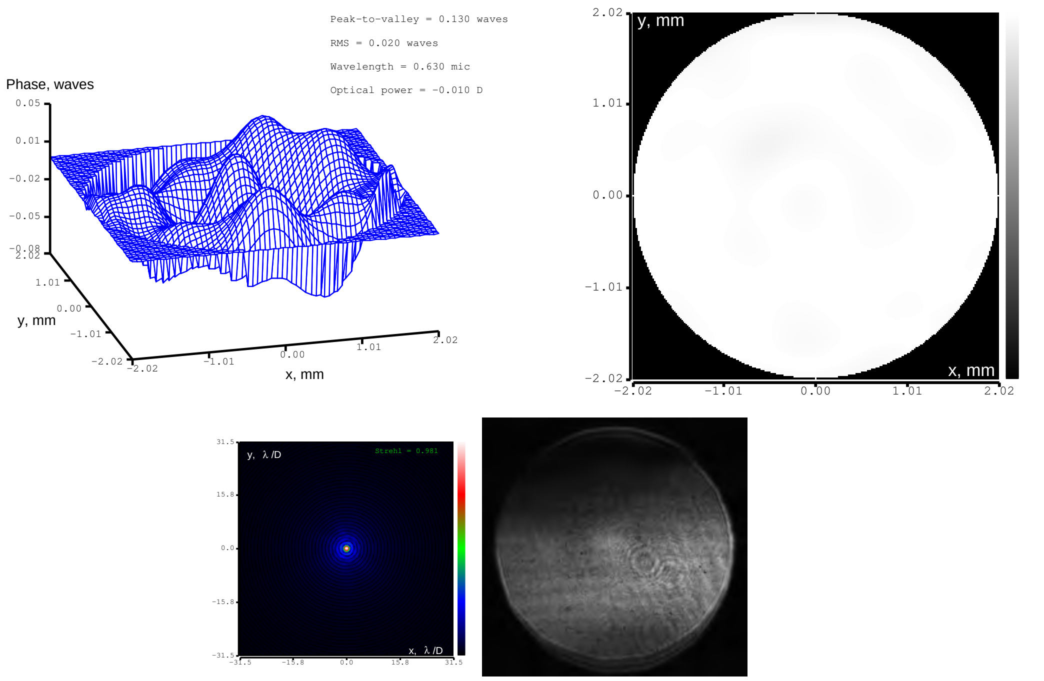

Figure 9: *Flattened mirror top: reconstructed wavefront (left) and simulated interferogram (right); simulated far field (left) and registered interferogram (right) .*

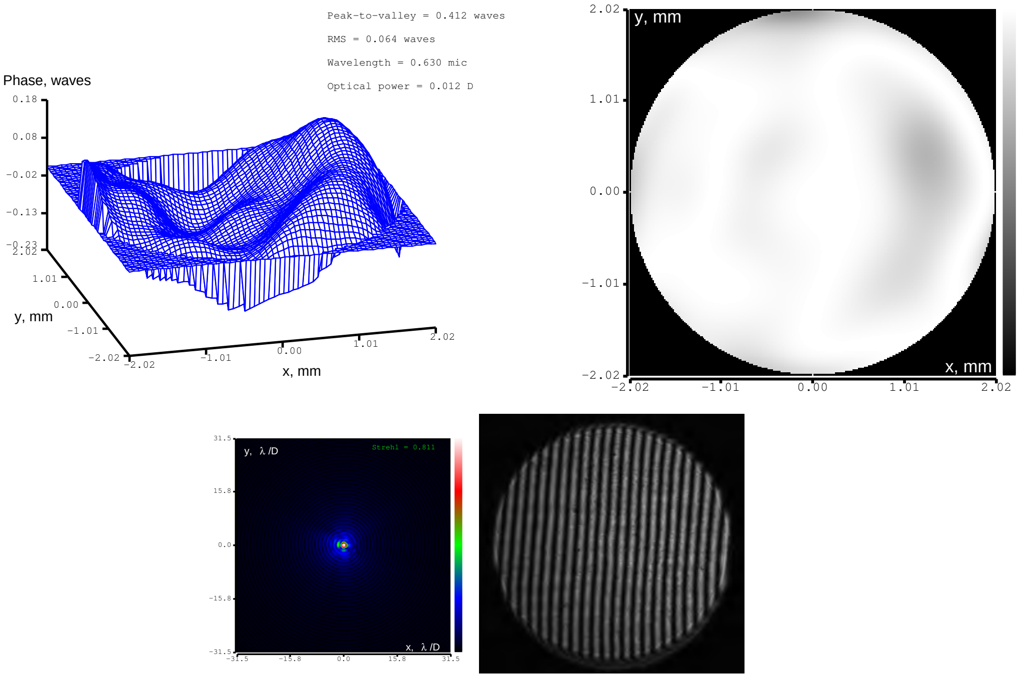

Figure 10: *Tilt (Zernike term Z[1,-1]) of amplitude 7.6μm generated. top: reconstructed wavefront (left) and simulated interferogram (right); simulated far field (left) and registered interferogram (right) .*

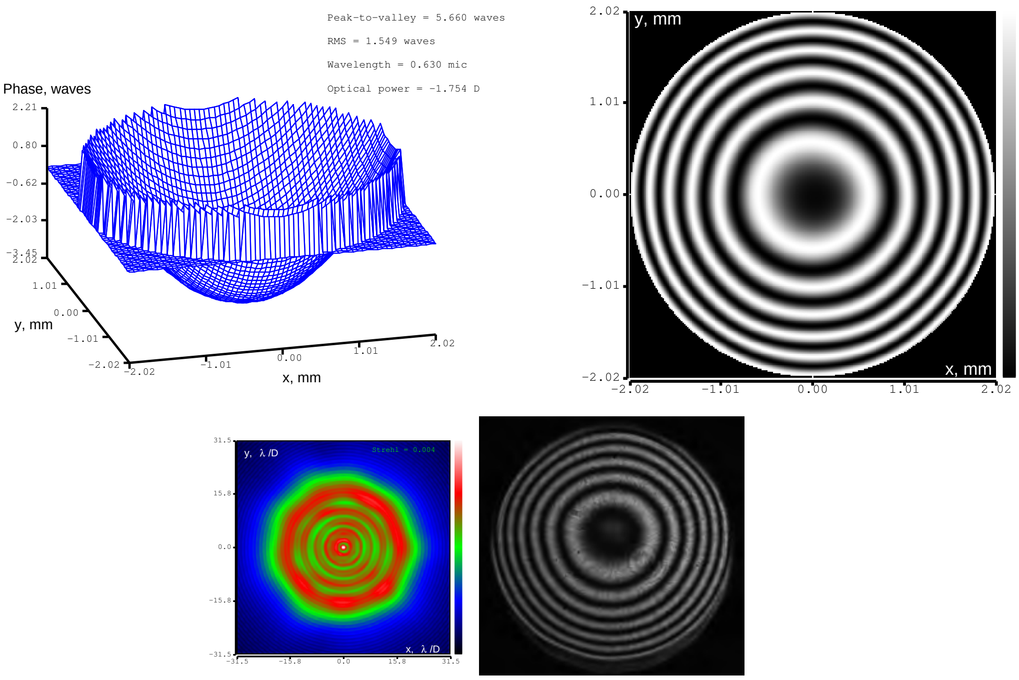

Figure 11: *Defocus (Zernike term Z[2,0]) of amplitude 2.2μm generated. top: reconstructed wavefront (left) and simulated interferogram (right); simulated far field (left) and registered interferogram (right) .*

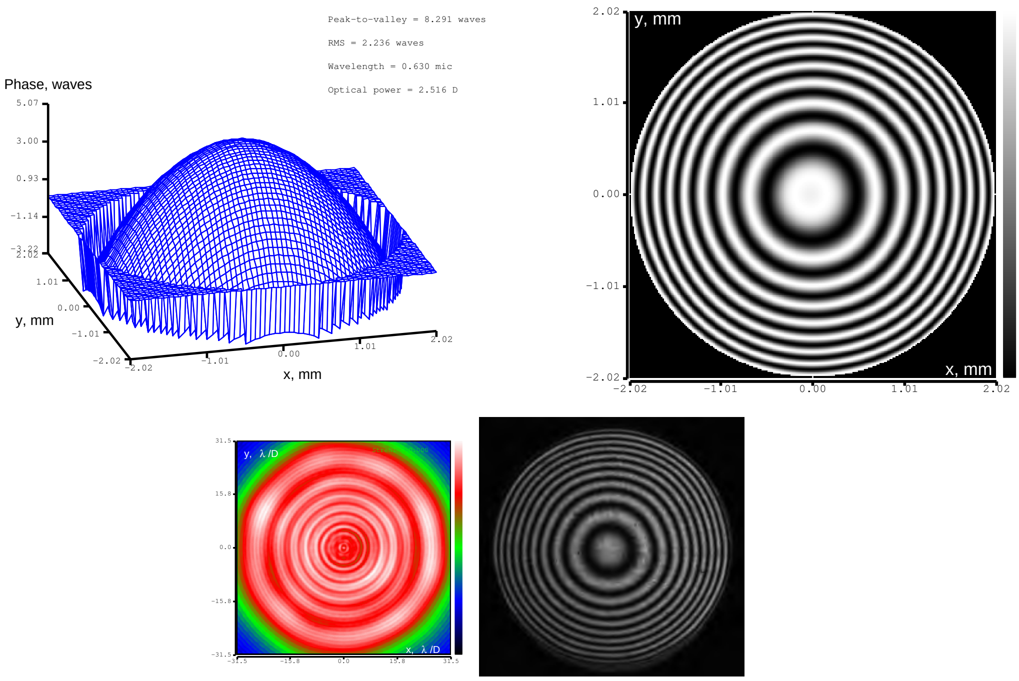

Figure 12: *Defocus (Zernike term Z[2,0]) of amplitude* $-3.2\mu m$ *generated. top: reconstructed wavefront (left) and simulated interferogram (right); simulated far field (left) and registered interferogram (right) .*

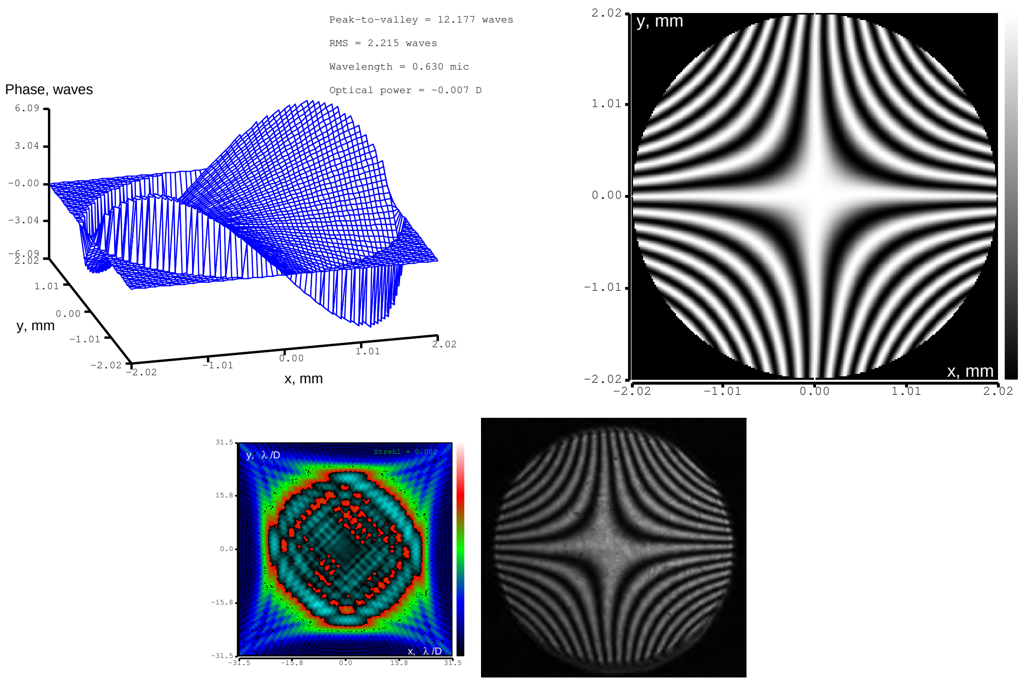

Figure 13: *Astigmatism (Zernike term Z[2,2]) of amplitude* $4.8\mu m$ *generated. top: reconstructed wavefront (left) and simulated interferogram (right); simulated far field (left) and registered interferogram (right) .*

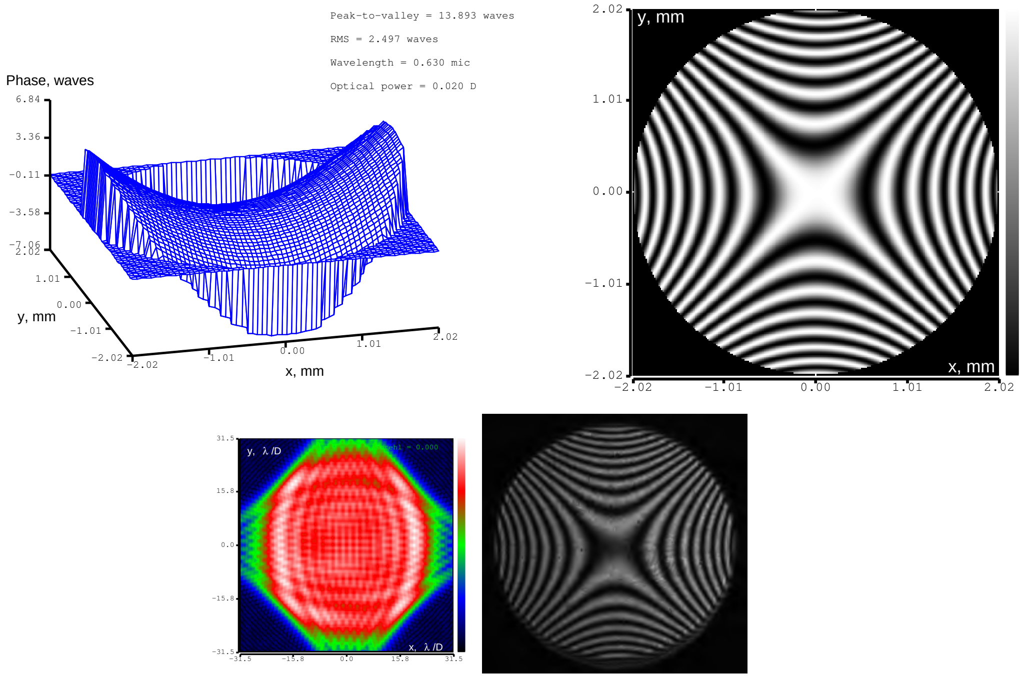

Figure 14: *Astigmatism (Zernike term Z[2,-2]) of amplitude* $-5.4\mu m$ *generated. top: reconstructed wavefront (left) and simulated interferogram (right); simulated far field (left) and registered interferogram (right) .*

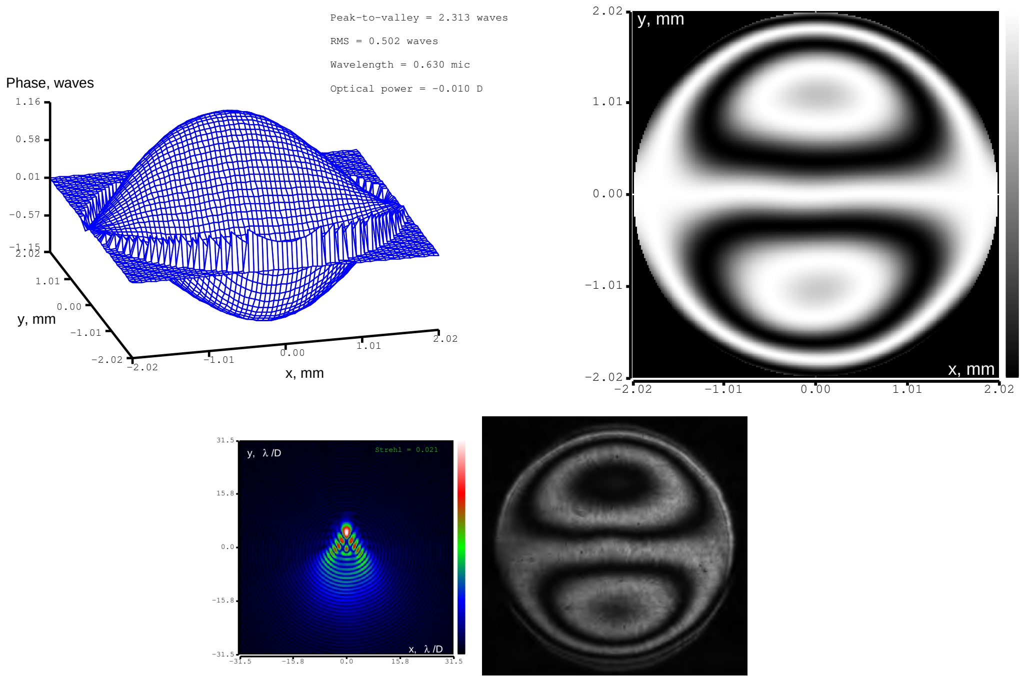

Figure 15: *Coma (Zernike term Z[3,1]) of amplitude* $1.2\mu m$ *generated. top: reconstructed wavefront (left) and simulated interferogram (right); simulated far field (left) and registered interferogram (right) .*

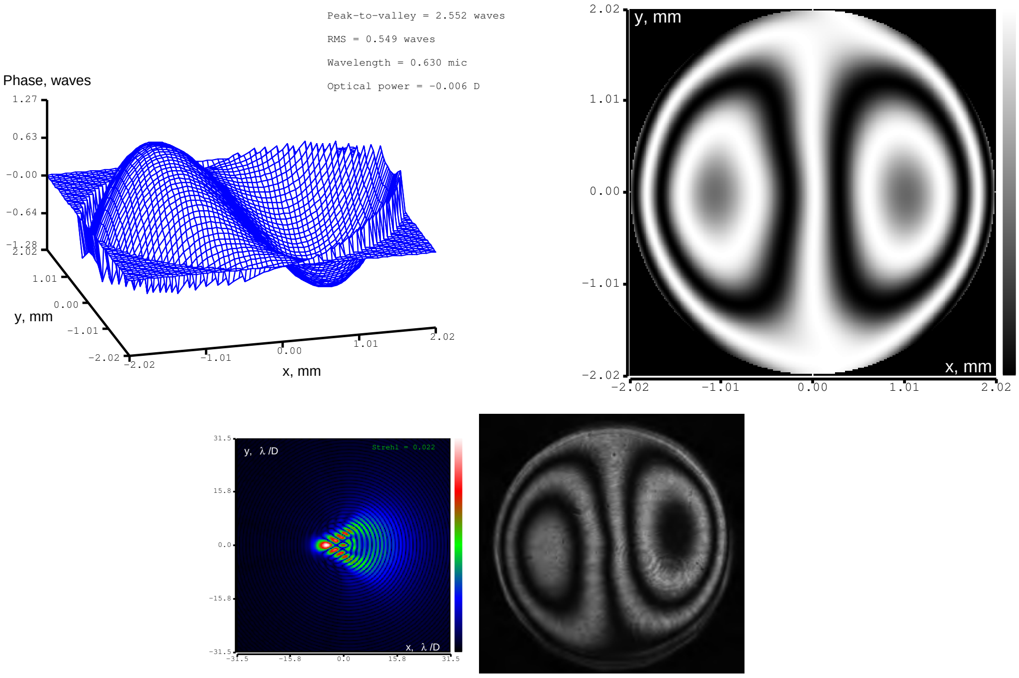

Figure 16: *Coma (Zernike term Z[3,-1]) of amplitude 1.3μm generated. top: reconstructed wavefront (left) and simulated interferogram (right); simulated far field (left) and registered interferogram (right) .*

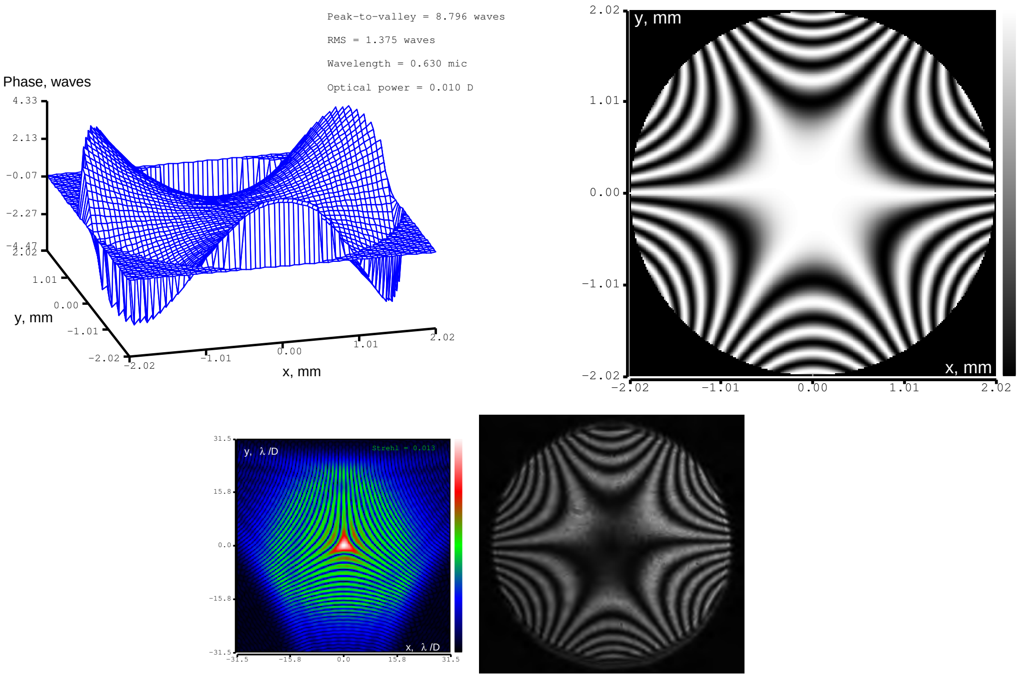

Figure 17: *Trefoil (Zernike term Z[3,3]) of amplitude 3.9μm generated. top: reconstructed wavefront (left) and simulated interferogram (right); simulated far field (left) and registered interferogram (right) .*

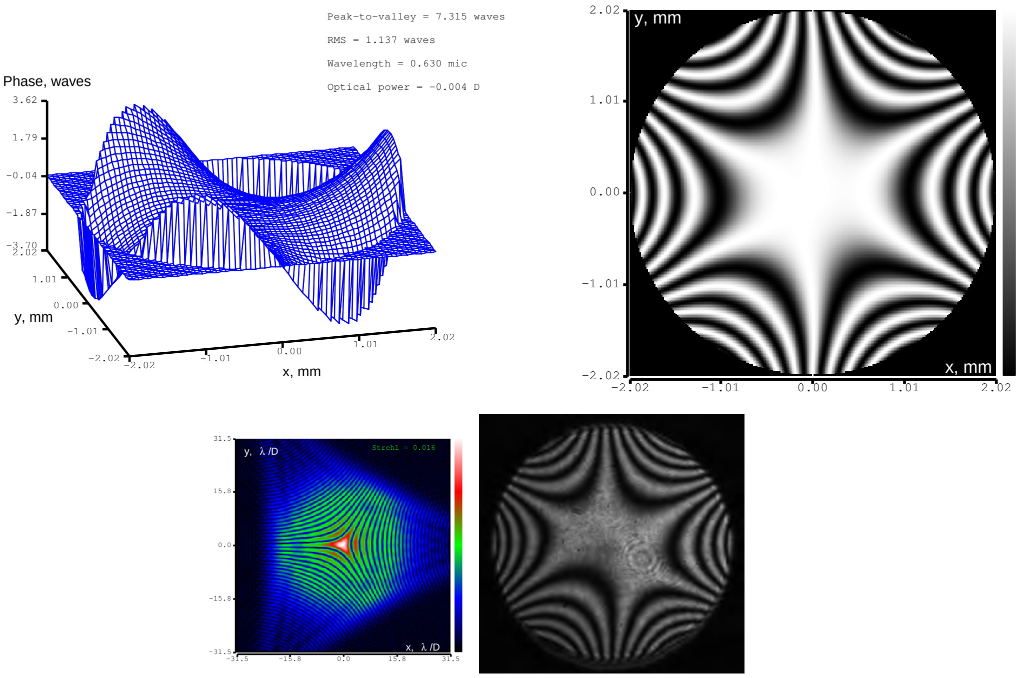

Figure 18: *Trefoil (Zernike term Z[3,-3]) of amplitude* 3.2μm *generated. top: reconstructed wavefront (left) and simulated interferogram (right); simulated far field (left) and registered interferogram (right) .*

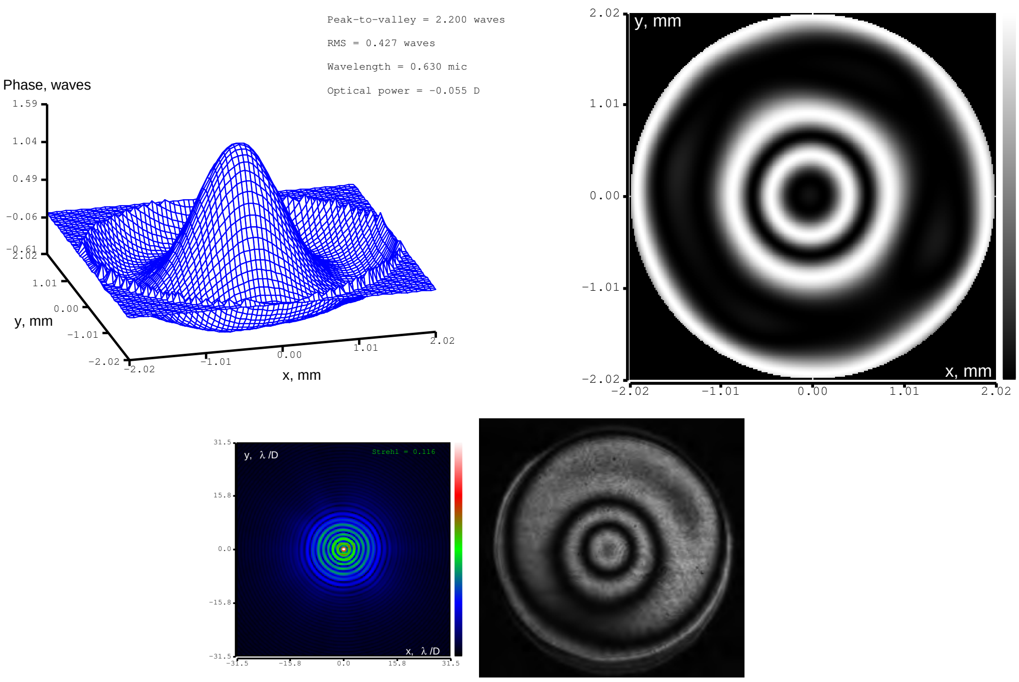

Figure 19: *Spherical aberration (Zernike term Z[4,0]) of amplitude* 0.7μm *generated. top: reconstructed wavefront (left) and simulated interferogram (right); simulated far field (left) and registered interferogram (right) .*

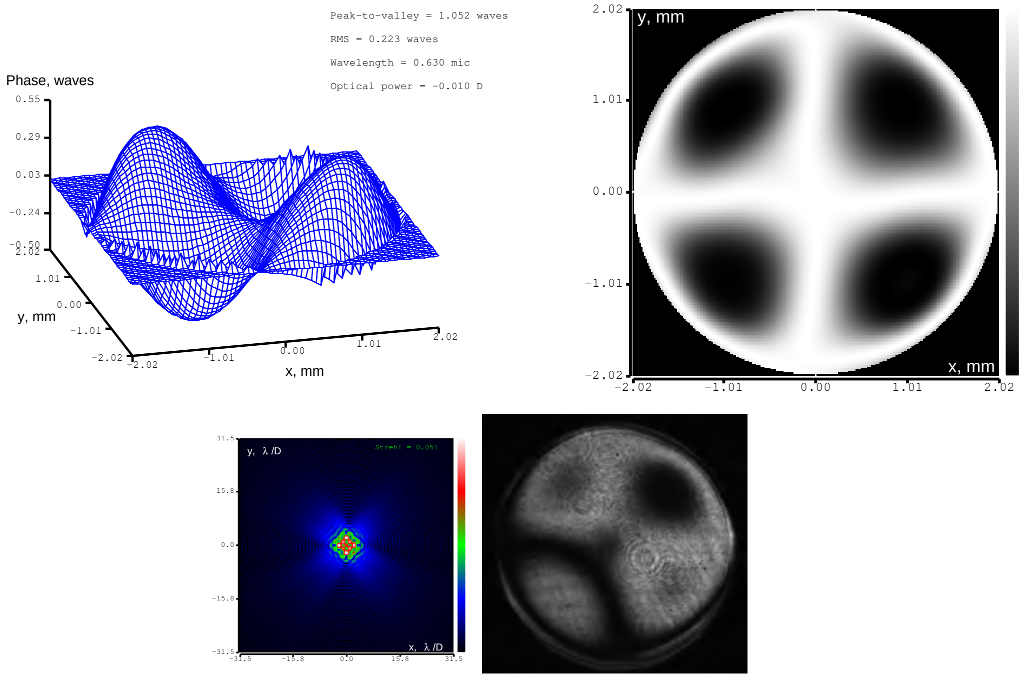

Figure 20: *Zernike term Z[4,2] of amplitude* 0.6μm *generated. top: reconstructed wavefront (left) and simulated interferogram (right); simulated far field (left) and registered interferogram (right) .*

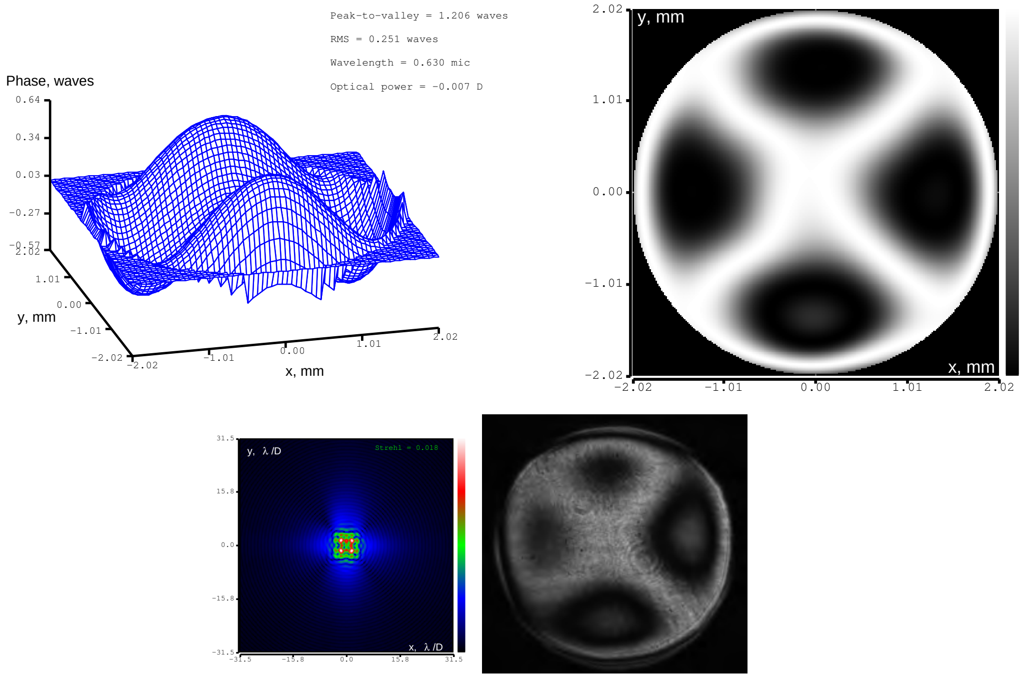

Figure 21: *Zernike term Z[4,-2] of amplitude* 0.7μm *generated. top: reconstructed wavefront (left) and simulated interferogram (right); simulated far field (left) and registered interferogram (right) .*

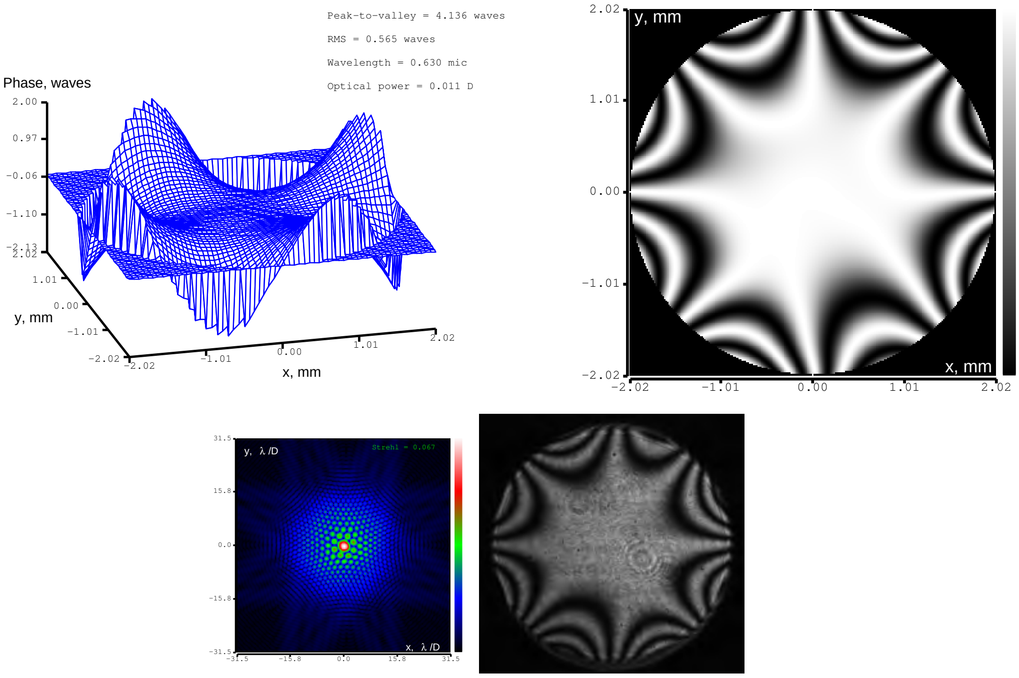

Figure 22: *Zernike term Z[4,4] of amplitude* 1.9μm *generated. top: reconstructed wavefront (left) and simulated interferogram (right); simulated far field (left) and registered interferogram (right) .*

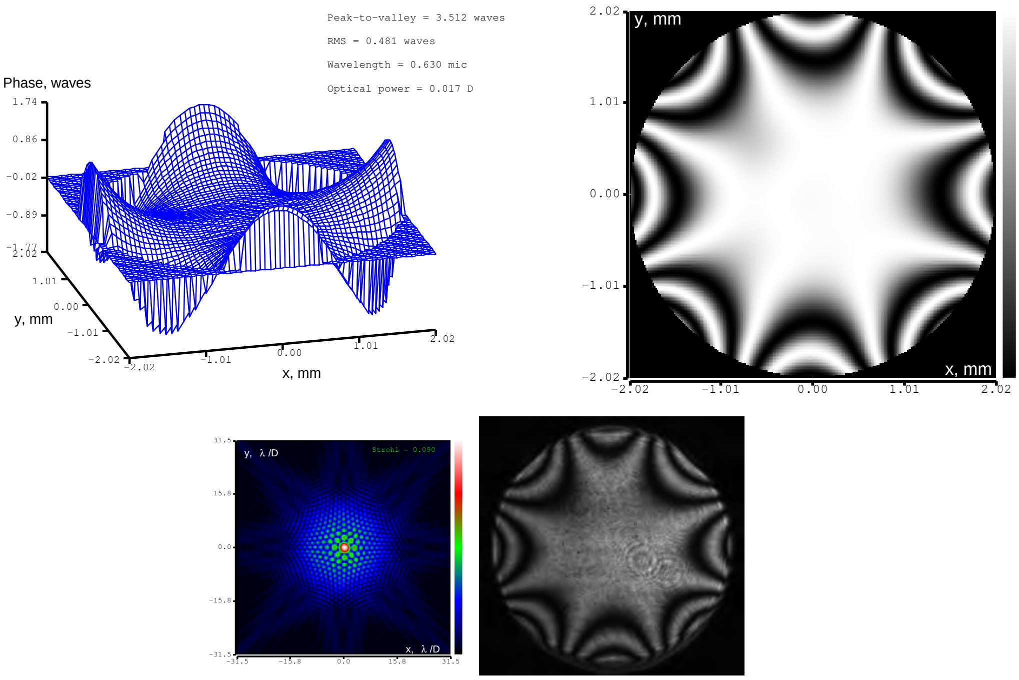

Figure 23: *Zernike term Z[4,-4] of amplitude* 1.7μm *generated. top: reconstructed wavefront (left) and simulated interferogram (right); simulated far field (left) and registered interferogram (right) .*

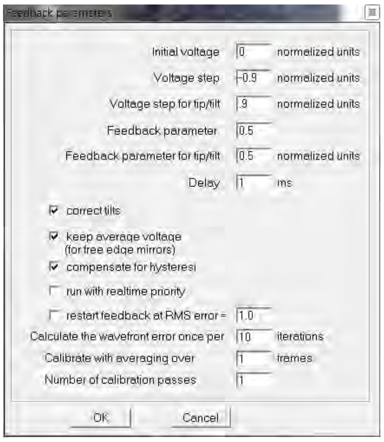

Figure 24: *Settings in the "Feedback parameters" dialog box used throughout the tests.*

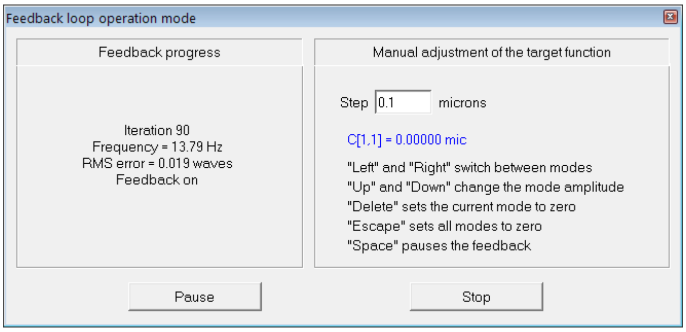

Figure 25: *Fedback*

results are shown in Figures 11-23. Figure 24 shows the settings of the ”Feedback parameters” dialog box used throughout the tests, and Figure 25 shows the feedback speed achieved during the test (“normal”sub-sampling mode).

6 Contact person

All questions about the technology, quality and applications of adaptive mirror should be addressed to:
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References

[1] C. Paterson, I. Munro, C. Dainty, A low cost adaptive optics system using a membrane mirror, Optics Express **6**, 175-185 (2000).