Flexible Optical B.V.

Adaptive Optics • Optical Microsystems • Wavefront Sensors

# Breadboard adaptive optical system based on 109-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

## 2.1 Specifications

| Parameter | Value |
|---|---|
| Camera model | uEye UI-2210SE-M-GL |
| Camera type | digital CCD |
| Camera interface | USB 2.0 |
| Array geometry | orthogonal |
| Array pitch | 150 um |
| Array focal distance | 3.5 mm |
| Subapertures | 40x32 |
| Tilt dynamic range | ≈180 um |
| Defocus dynamic range | ≈45 um |
| Repeatability, RMS | $\approx \lambda/100^*$ |
| Repeatability, PV | $\approx \lambda/15^*$ |
| Acquisition rate | ≥75 fps |
| Processing rate, fast mode | ≈40 fps** |
| Recommended Zernike terms | ≤300 |
| Wavelength | 400. . . 900 nm |

* For $\lambda = 633$ nm.

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

## 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.

6. To increase the processing speed, the sensor can be used with a smaller area of interest (AOI). To change AOI, 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.

# 3 Deformable mirror

## 3.1 Specifications

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

## 3.2 Interfacing instructions

1. Connect DAC40USB units through a supplied USB hub 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 units are recognized by the system.

2. Connect together ground sockets of the DAC40USB units using the supplied cable.
3. 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 "piezo109usb.txt" from the CD "fsurfer" directory. Press "OK" twice to complete configuration.
4. Disconnect DAC40USB control units from your computer.
5. Connect the amplifier units to DAC40USB units using six 20 pins-to-26 pins cables.
6. Connect together ground sockets of the amplifiers using supplied the cable.
7. Connect the mirror to the amplifier units using six 20 pins-to-20 pins cables. Fix the cables to the optical table.
8. Connect DAC40USB via USB hub to the computer using a USB cable.

# 4 Adaptive optics setup

For proper functioning, the adaptive optics setup should satisfy the following conditions.

1. The optics should re-image the plane of the mirror to the plane of the Hartmann mask (or microlens array).
2. The scheme should scale the beam in such a way that the working aperture of the mirror ($\sim 35\dots40$ mm) should be re-imaged to the working area of the Hartmann mask/microlens array ($\leq 4.5$ mm).
3. (Optional) 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 scheme of the adaptive optics breadboard is shown in Figure 1. A beam from fiber-pigtailed laser diode LD operating at 650 nm wavelength is first filtered by intensity by a couple of film polarizers PF and then collimated with lens L1. Iris diaphragm ID with $\approx 5$ mm opening serves as the entrance pupil of the adaptive optical system. The telescope consisting of lenses L2 and L3 conjugates the entrance pupil to the deformable mirror DM with 2x scaling, and the telescope consisting of lenses L4 and L5 provides conjugation between DM and wavefront sensor (WFS). Imaging camera IC (not included), which is placed after beam splitter BS, allows obtaining an image of the focal spot. An aberration introduced before diaphragm ID can be measured and corrected with the system.

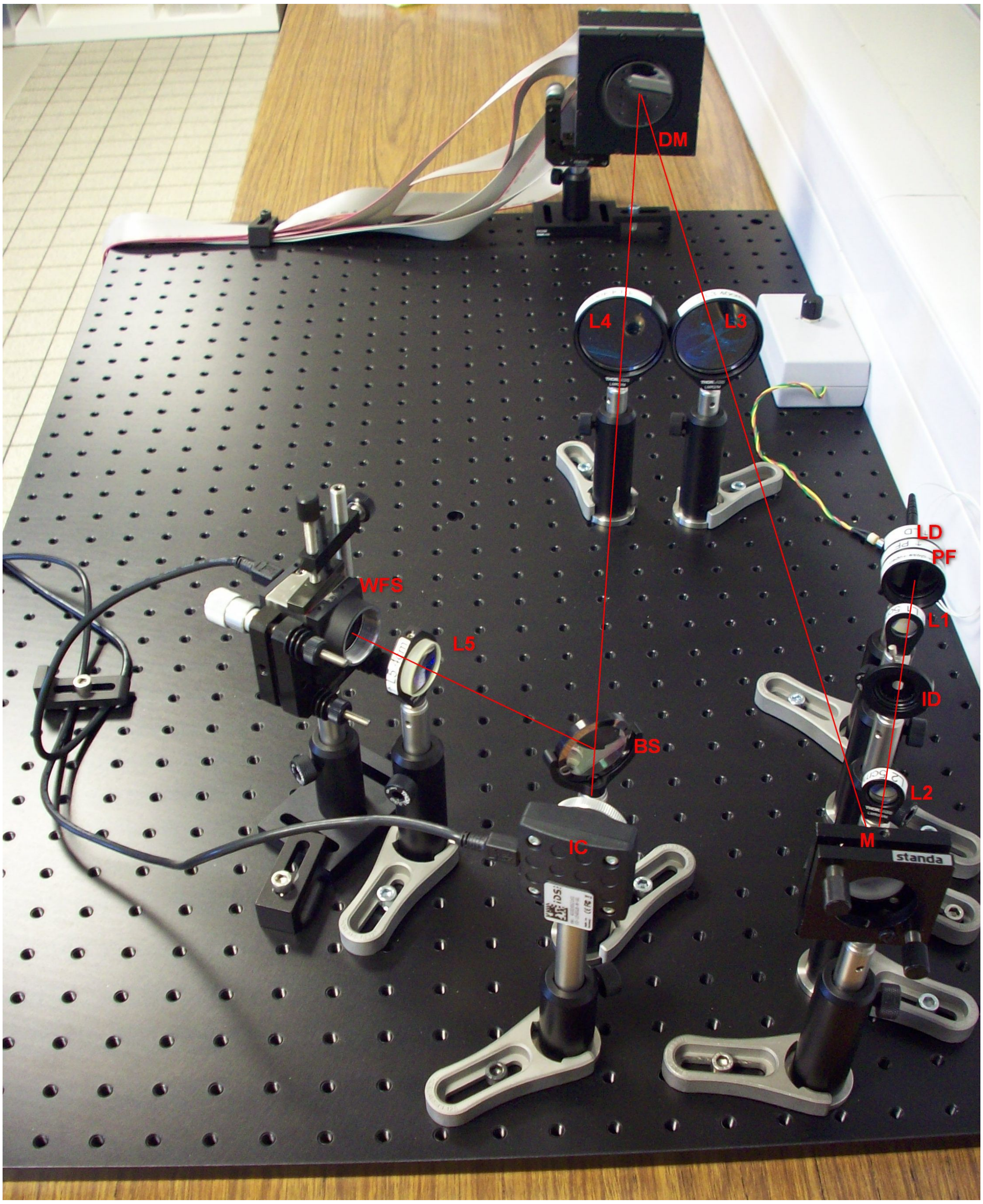


**Figure 1:** *Optical setup. Here LD is the fiber terminal of the laser diode; PF is a couple of polarisation filters; L1-L5 are achromatic lenses with focal distances* $f_1 = f_2 = 5$ *cm,* $f_3 = f_4 = 40$ *cm and* $f_5 = 4$ *cm; ID is the iris diaphragm; M is the flat mirror; DM is the deformable mirror; BS is the beam splitter; IC is the imaging camera (not included); WFS is the wavefront sensor.*

## 4.1 Laser diode

The fiber pigtailed laser diode (LD) serves as a light source. The end of the fiber has SMA connector which attaches to the mount of the collimator. LD is powered by dedicated driver implementing stabilized output. Knob on the upper panel of the unit allows to switch on/off the laser and adjust its power. The device is powered by PP3 9V battery.

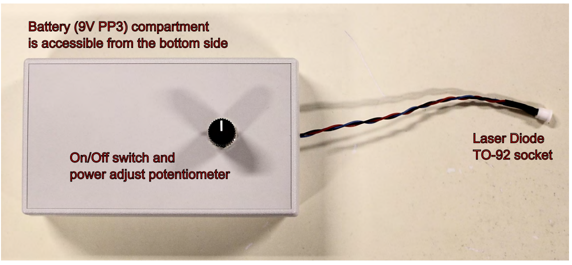


**Figure 2:** *Laser diode driver.*

**Important! The fiber-coupled laser diode (650 nm wavelength, 2 mW maximum output power) is an extremely fragile and static sensitive device. It should be handled with care. Flexible Optical BV is not liable in case of mechanical damage to the fiber or electrostatic damage to the diode. In case you need to replace the diode, please use an antistatic wrist band.**

To start using the laser

1. Check that the LD driver is switched off (rotate potentiometer knob counterclockwise till click).

2. Install the battery if it is not already installed: open battery compartment cover on the bottom of the unit, connect a PP3-style 9V battery observing polarity, insert the battery to the compartment, close the cover.

3. Carefully insert laser diode terminals into TO-92 socket of LD driver unit observing correct alignment of the triangular footprint of the LD and the socket.

4. Connect the laser diode fiber to the system (LD mount);

5. Switch on the laser diode and adjust the power to see the beam. Normally for the purpose of alignments it should be set to maximum (clockwise till stop), but during normal operation of the system output power could be reduced to minimum.

6. For longer battery life and conserving laser diode resource please keep the driver switched off when not in use.

## 4.2 Assembling

During the assembling, the components should be added and adjusted one by one. Several points should be taken into account.

1. The laser beam should be centered with respect to the apertures of all components.
2. The beam should be collimated at the diaphragm ID, deformable mirror DM and wavefront sensor WFS. Its width should be 5 mm in ID plane, 40 mm in DM plane and 4 mm in WFS plane.
3. Check conjugation of the components by observing the image of the stop aperture (ID) in DM and WFS planes; it should have sharp edges.
4. Part of the system behind the deformable mirror (lens L4 and further) should be aligned with the DM turned on and all values set to 0.
5. In order to minimize the astigmatism, all lenses should be placed perpendicularly to the beam.
6. In order to minimize the spherical aberration, orientation of achromatic lenses L1-L5 with respect to the beam should be observed. Generally, the lenses should be oriented with their highest curvature surface in direction of a collimated beam. The lens orientation is also marked with an arrow, that should follow the beam.

## 4.3 Running the adaptive optics loop

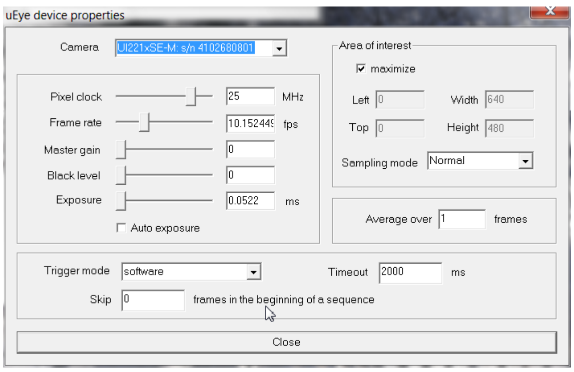


**Figure 3:** *"uEye" plugin properties.*

1. Switch on the laser diode.
2. Connect the wavefront sensor and deformable mirror; turn on the power supplies.

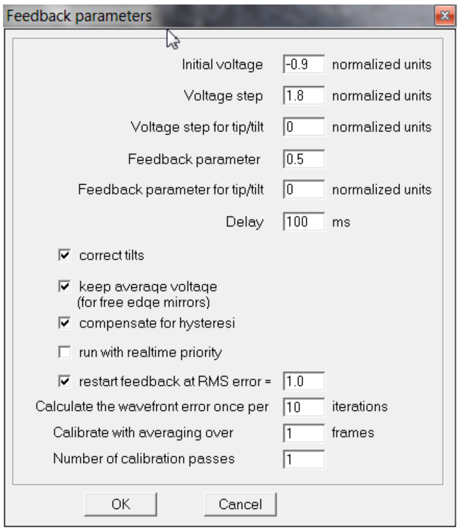


**Figure 4:** *Feedback parameters for calibration of PDM*

3. 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.

4. Make sure that the beam is centered on the deformable mirror, wavefront sensor and other components.

5. Turn on the preview mode in FrontSurfer and check an image from the Hartmann sensor. Adjust the wavefront sensor position for centering.

6. 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 3) to make the spots good visible, avoiding the saturation.

7. 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.

8. In menu "Mirror → Feedback parameters", set the parameters according to Figure 4. We recommend setting "Delay" to 100 ms for calibration; it can be reduced to 1 ms for the closed-loop operation.

9. Go to menu "Mirror → Calibrate mirror" to calibrate the system. The calibration data can be saved for further use from menu "Mirror → Save calibration".

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.

# 5 Closed-loop test

FrontSurfer perform wavefront correction in a series of iterations. If the residual aberration $\phi_n$ 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

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

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.

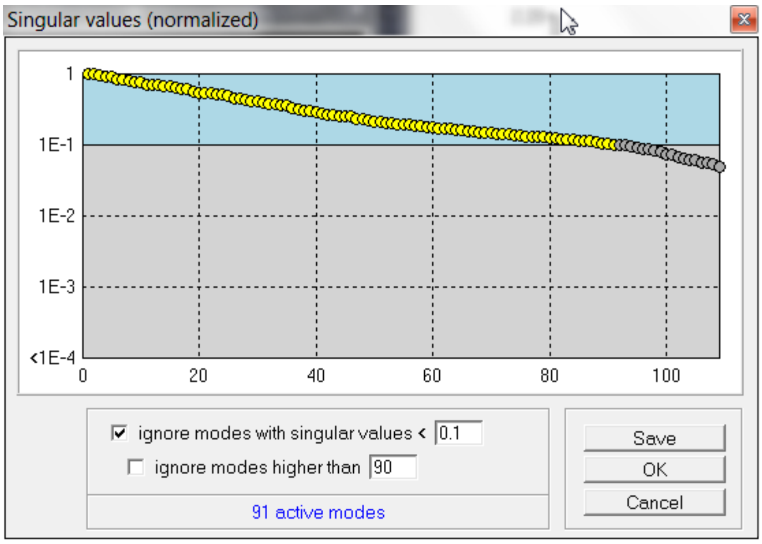


**Figure 5:** *Singular values of the 109-channel mirror.*

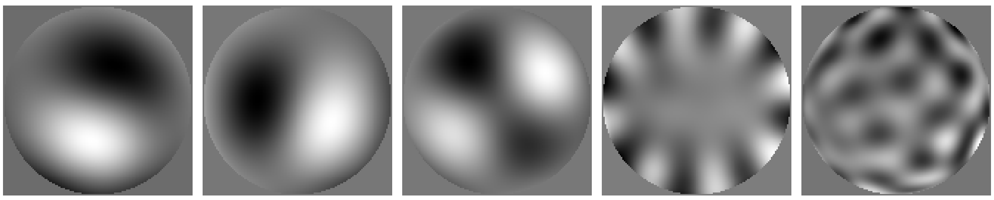

**Figure 6:** *Modes 1,2,3,37, and 64 of the 109-channel mirror.*

Experimental singular values for the deformable mirror are given in Figure 5; some of the SVD modes are shown in Figure 6.

The results of closed-loop testing of the system are shown in Figures 8-24. Optimization started from the initial state produced by setting all mirror values to zero; it is shown in Figure 7. In the first test we have corrected the aberration of the system using ideal grid as a reference (absolute measurement mode); the result is shown in Figure 8. For imaging, we used 1/2" CMOS camera (UI-1540LE-C-GL).

In the following tests we generated various Zernike aberrations; the results are shown in Figures 9-24. Figure 25 shows the settings of the "Feedback parameters" used throughout the tests.

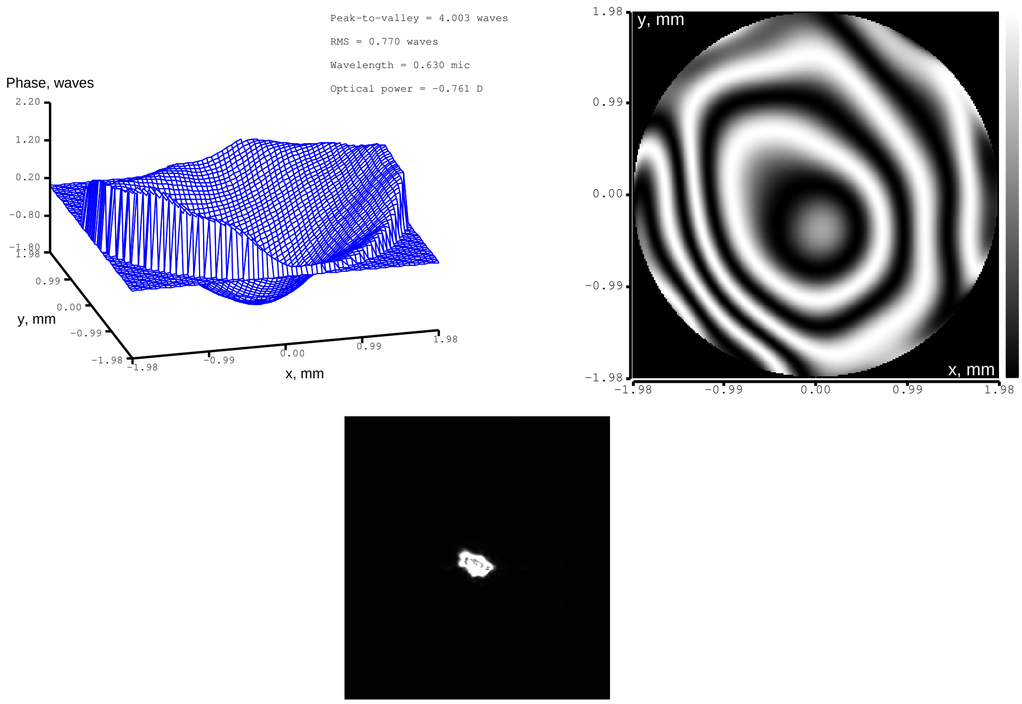


**Figure 7:** *Initial aberration of the system. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

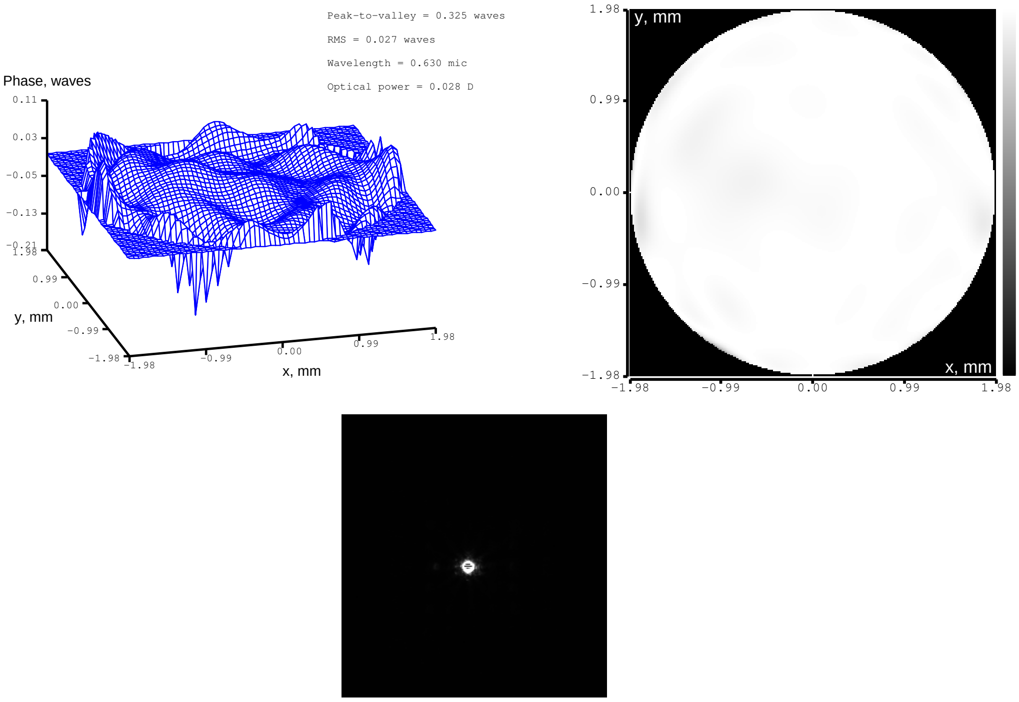


**Figure 8:** *Aberrations in the system after correction. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

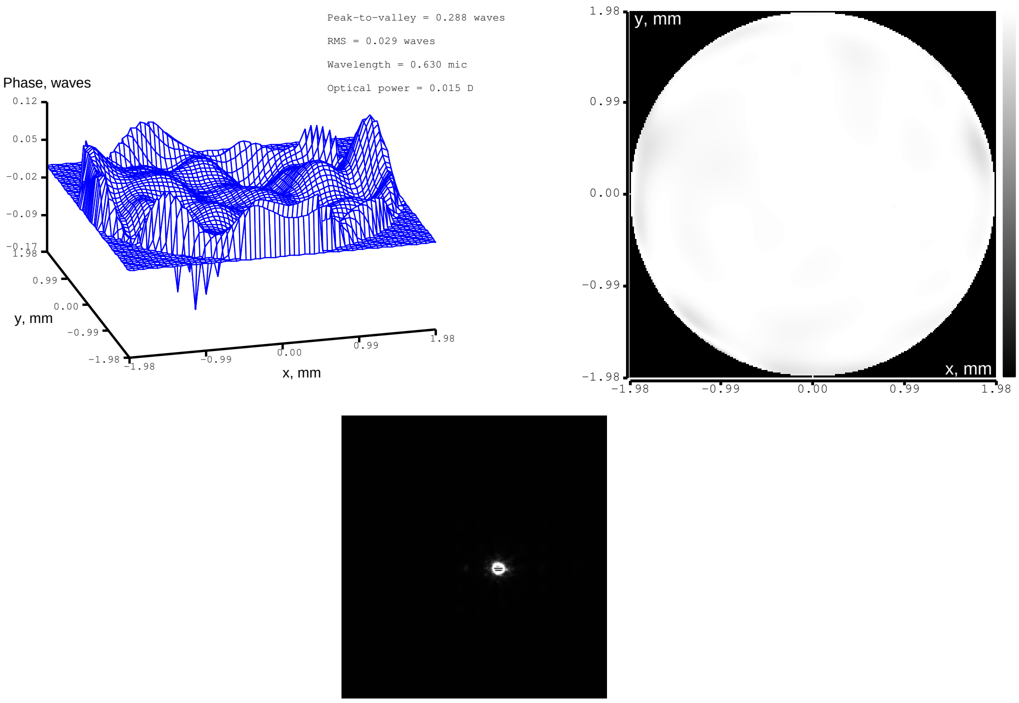


**Figure 9:** *Tip (Zernike term Z[1,0]) of amplitude 8μm generated. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

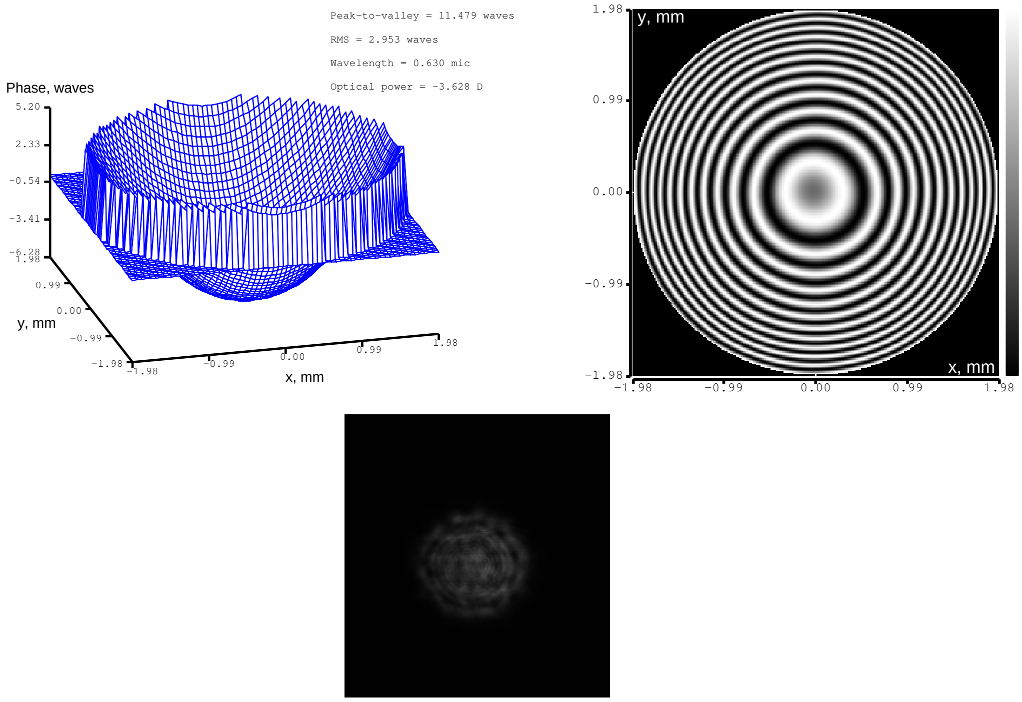


**Figure 10:** *Defocus (Zernike term Z[2,0]) of amplitude 4$\mu$m generated. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

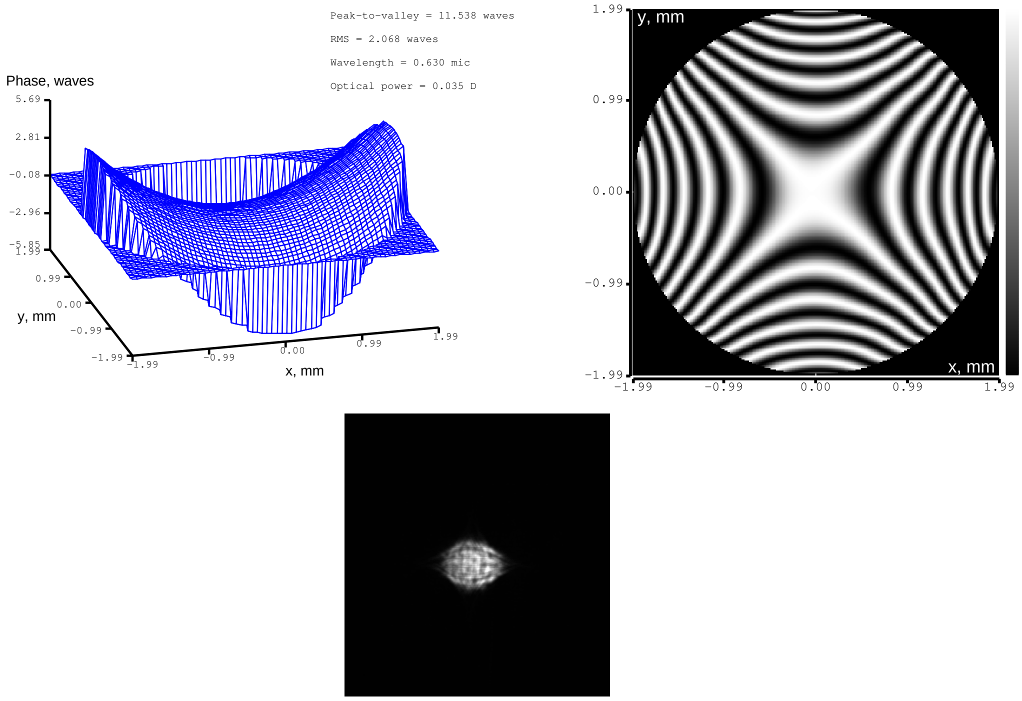


**Figure 11:** *Astigmatism (Zernike term Z[2,2]) of amplitude 4$\mu$m generated. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

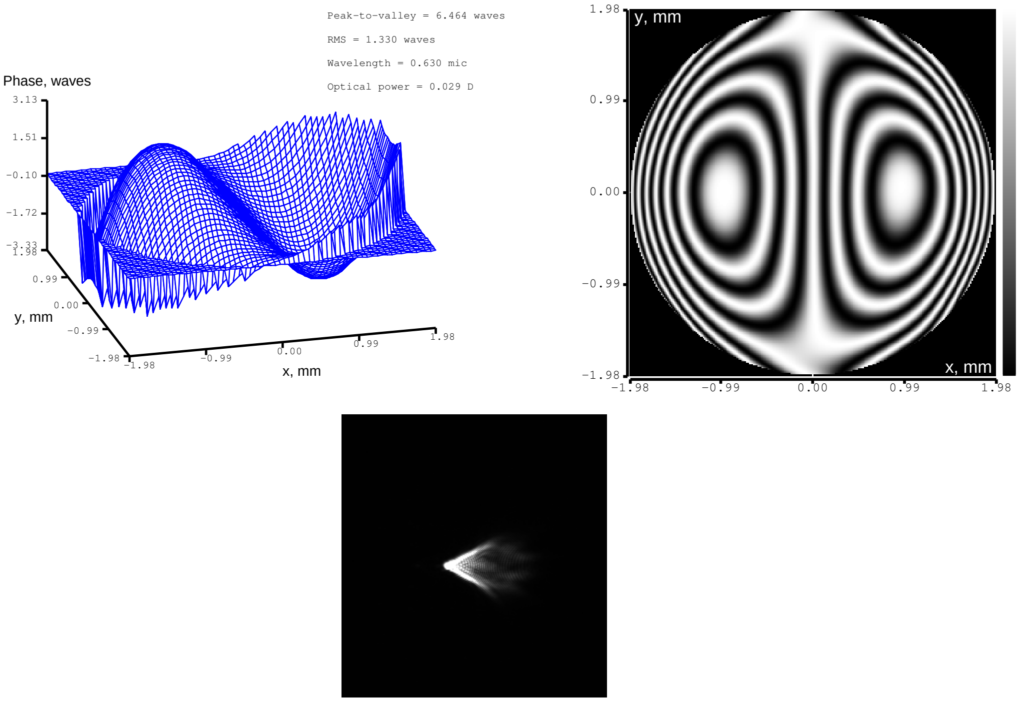


**Figure 12:** *Coma (Zernike term Z[3,1]) of amplitude 3µm generated. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

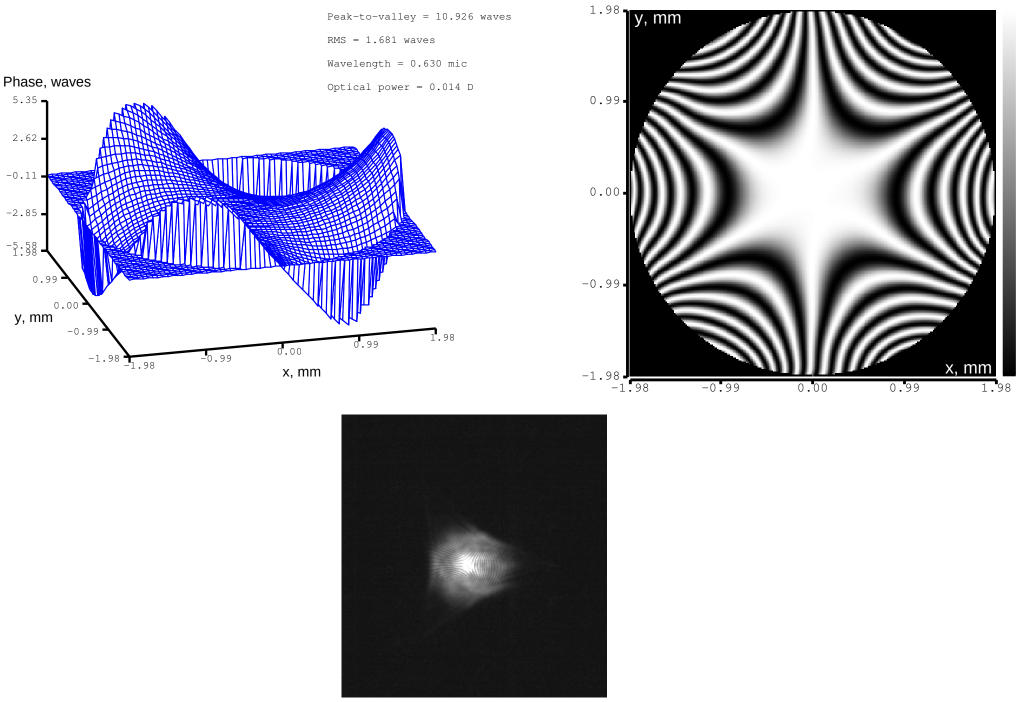


**Figure 13:** *Trefoil (Zernike term Z[3,3]) of amplitude 4µm generated. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

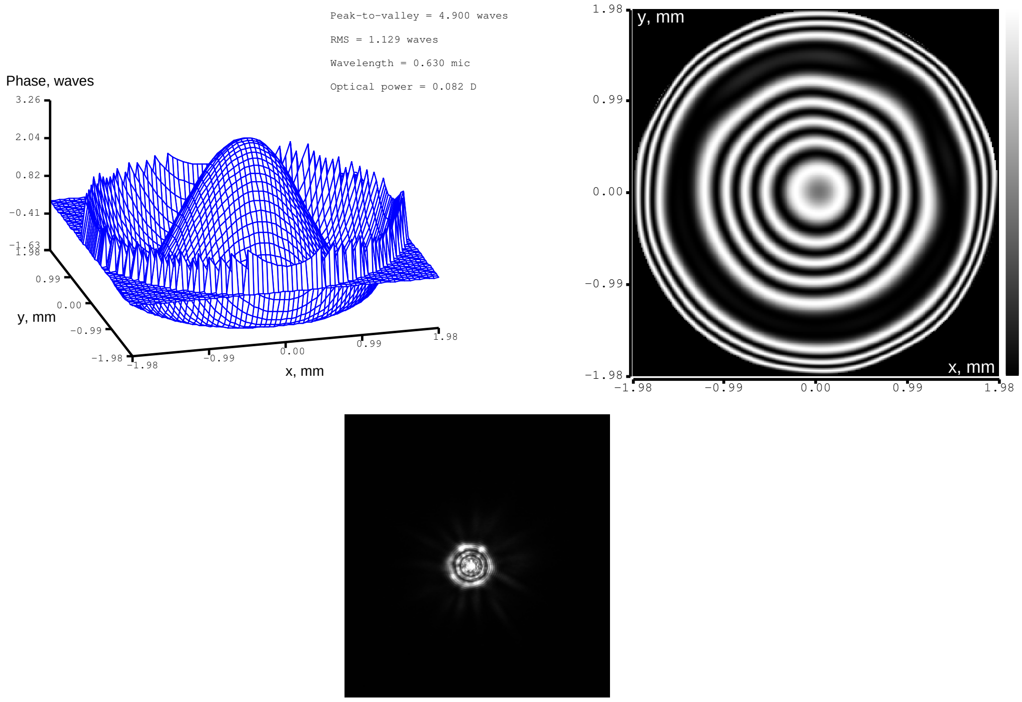


**Figure 14:** *Spherical aberration (Zernike term Z[4,0]) of amplitude 2μm generated. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

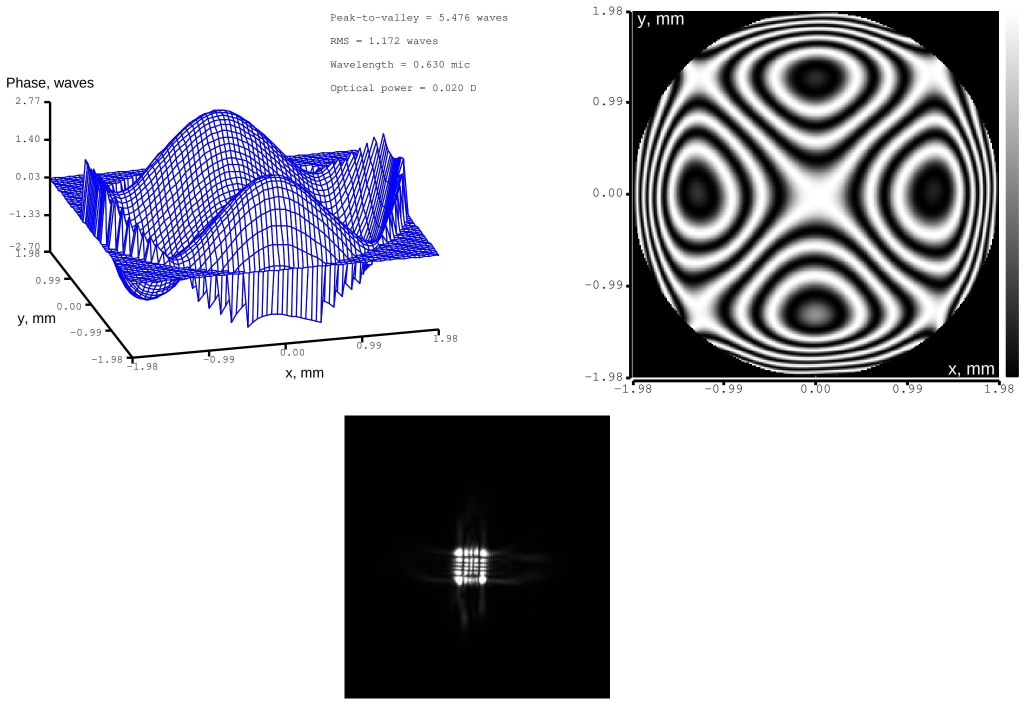


**Figure 15:** *Zernike term Z[4,2] of amplitude 3μm generated. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

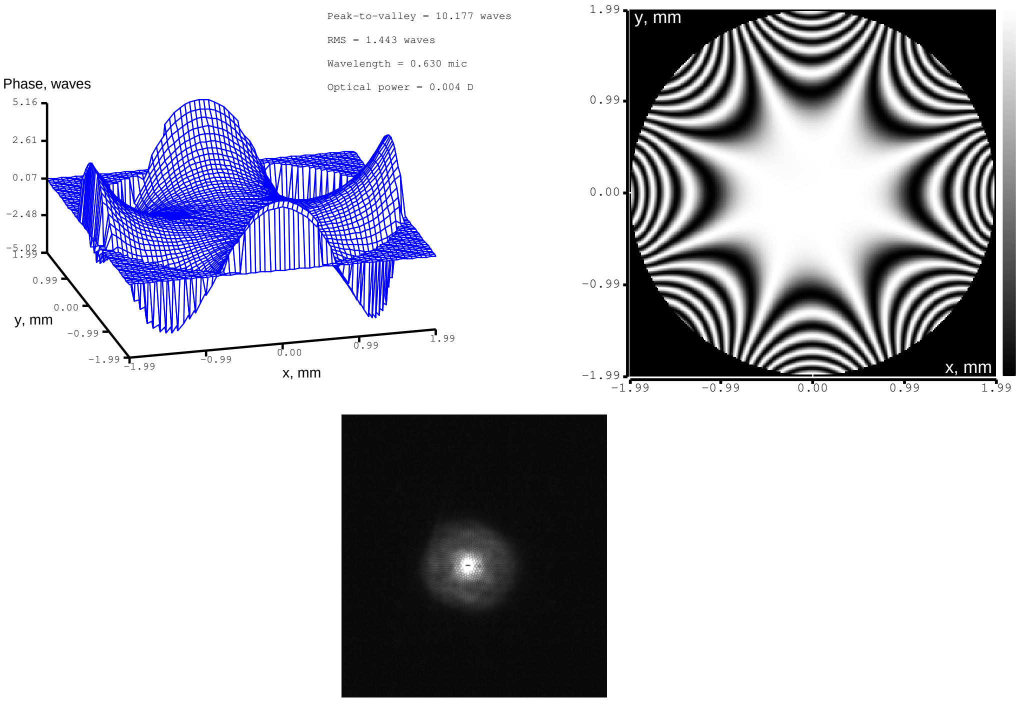


**Figure 16:** *Zernike term Z[4,4] of amplitude 43μm generated. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

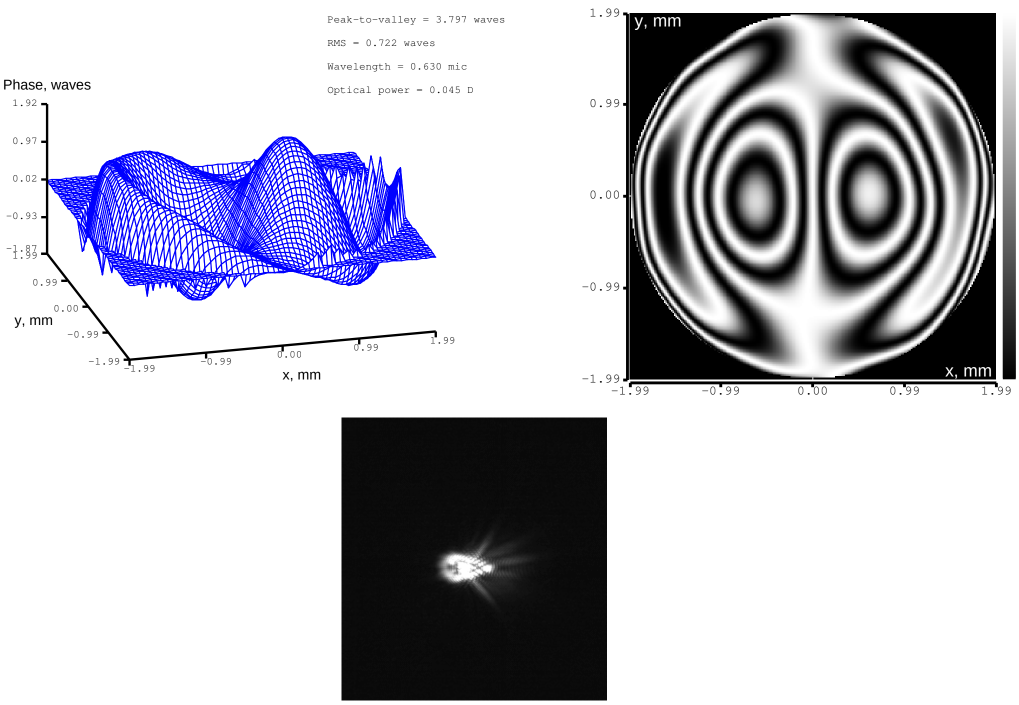


**Figure 17:** *Zernike term Z[5,1] of amplitude 2μm generated. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

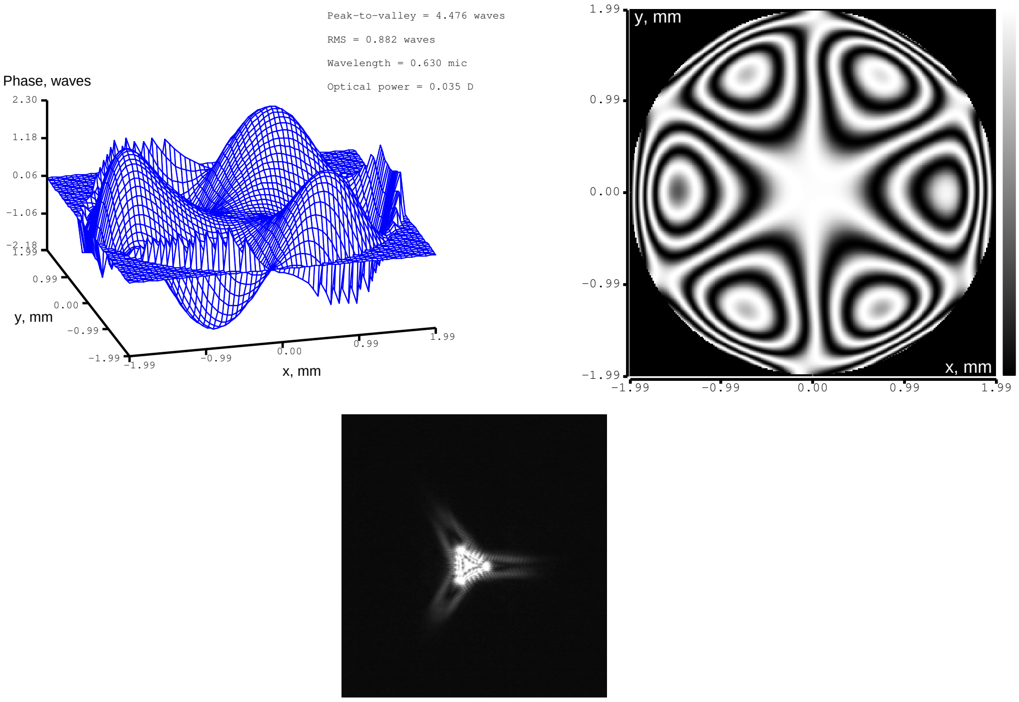


**Figure 18:** *Zernike term Z[5,3] of amplitude* $2.5\mu m$ *generated. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

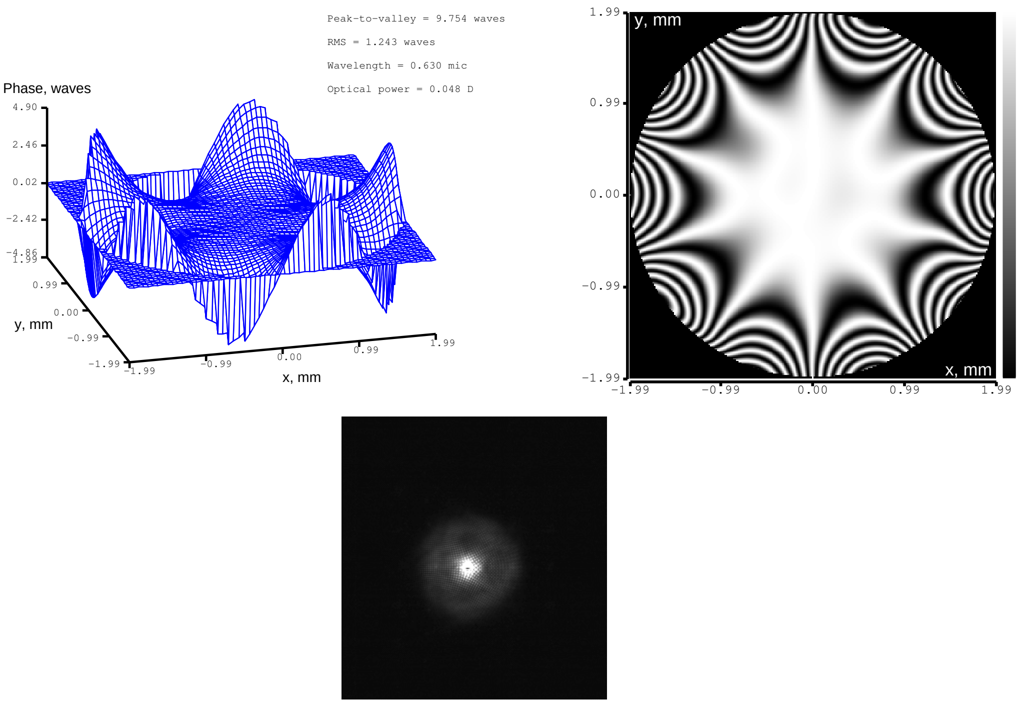


**Figure 19:** *Zernike term Z[5,5] of amplitude* $4\mu m$ *generated. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

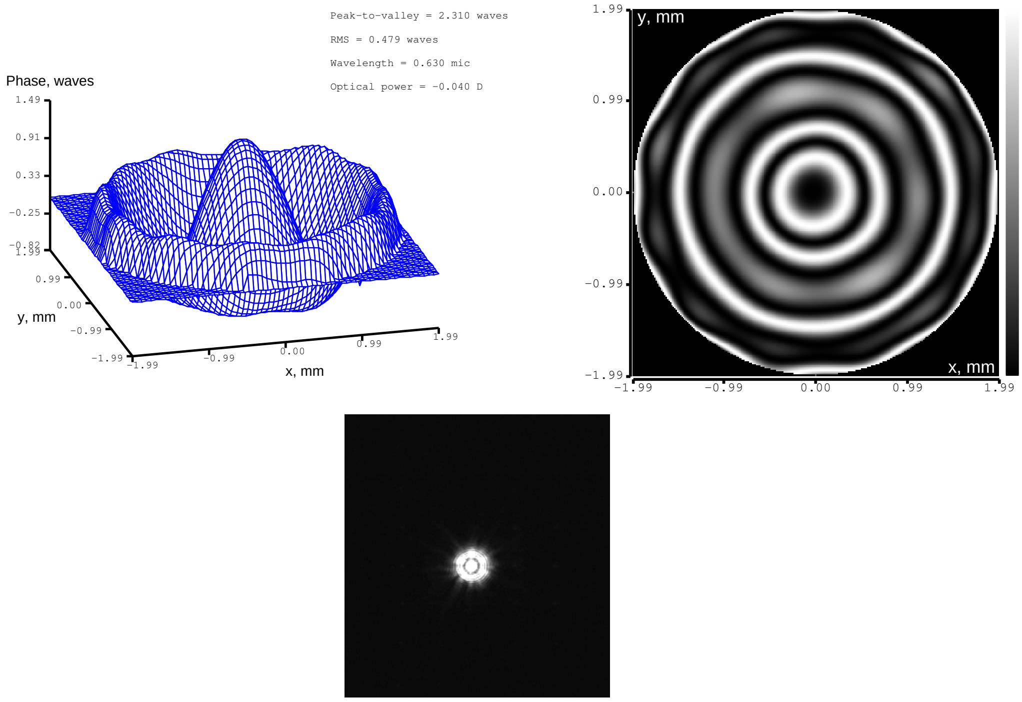


**Figure 20:** *Zernike term Z[6,0] of amplitude* $-1\mu m$ *generated. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

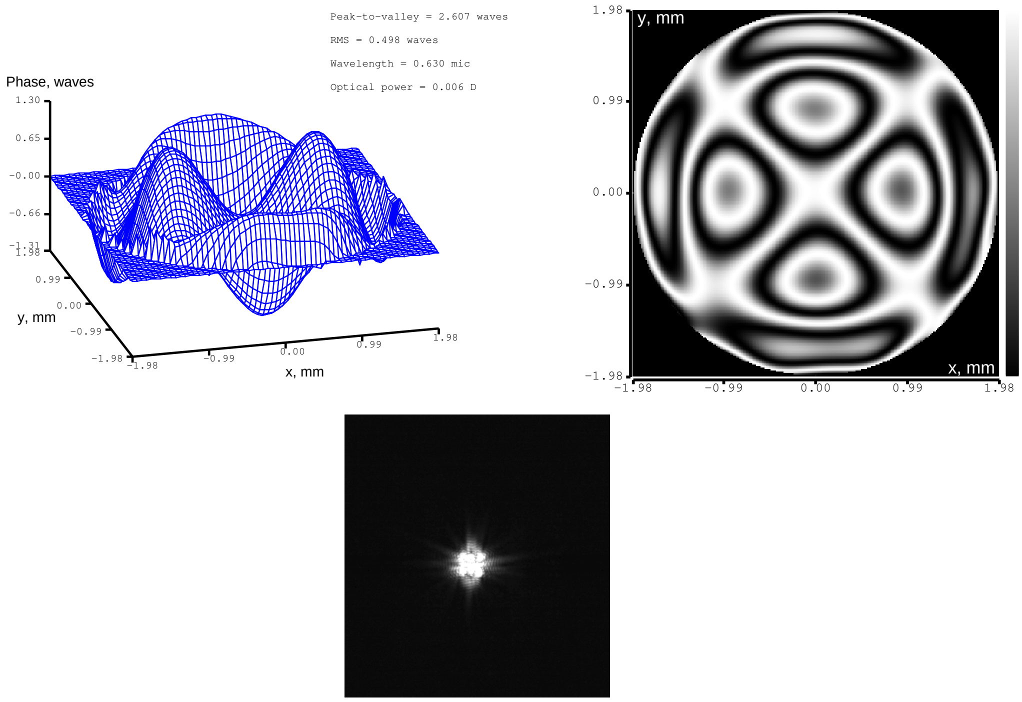


**Figure 21:** *Zernike term Z[6,2] of amplitude* $1.5\mu m$ *generated. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

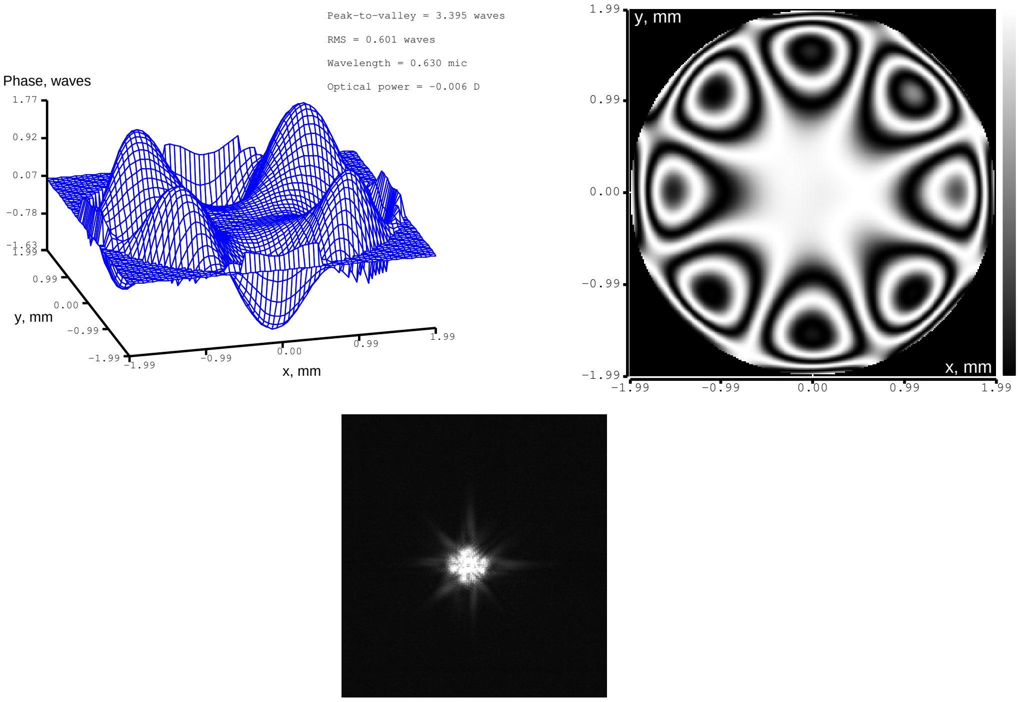


**Figure 22:** *Zernike term Z[6,4] of amplitude* 1.5$\mu m$ *generated. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

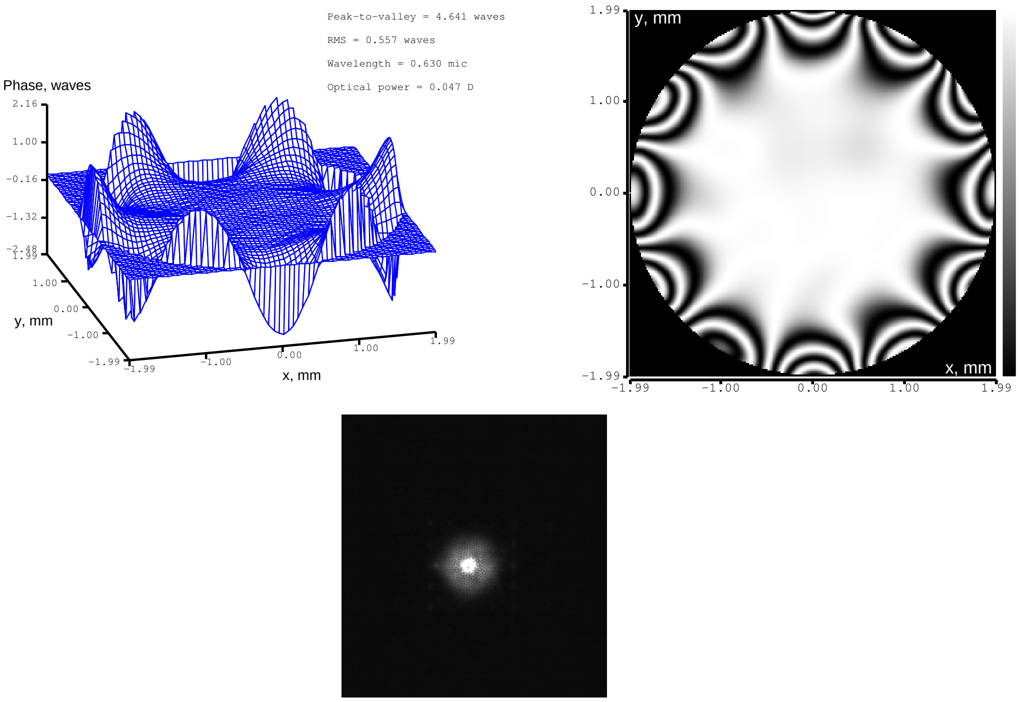


**Figure 23:** *Zernike term Z[6,6] of amplitude* 2$\mu m$ *generated. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

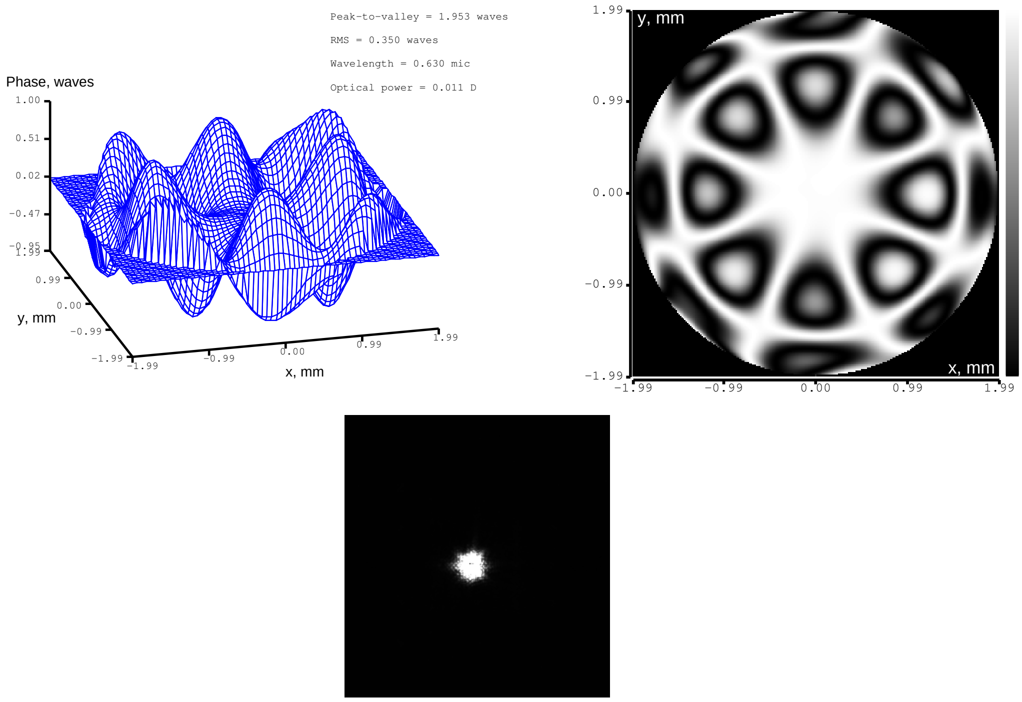


**Figure 24:** *Zernike term Z[8,4] of amplitude* $1.2\mu m$ *generated. Top row: reconstructed wavefront (left) and simulated interferogram (right). Bottom: image of the fiber tip as seen through the system.*

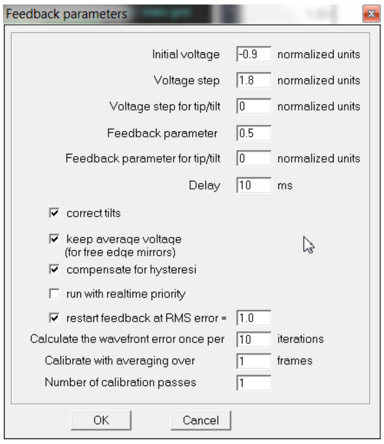


**Figure 25:** *Settings in the "Feedback parameters" dialog box used throughout the tests.*

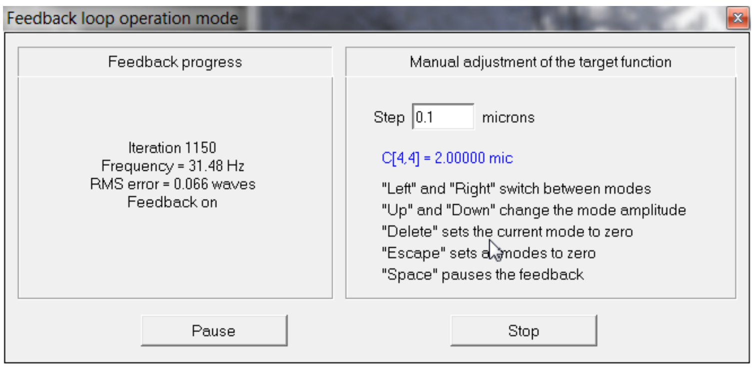


**Figure 26:** *Closed feedback speed and rms in mode*

# References

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

# 6 Contact

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

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