

Operation Manual

Thorlabs Instrumentation

Optical Wavefront Sensor WFS150 / WFS150C



2007

THORLABS

Version: 1.2
Date: December, 2007

Table of Contents

Foreword	3
Part I General	5
1 Safety	5
2 Warranty	5
3 WEEE	6
Waste Treatment on your own Responsibility	7
Ecological Background	7
Part II Getting Started	9
1 WFS150/WFS150C Quick Start-up	9
Software Installation	9
Connection to the PC	18
Start the Application	22
Part III Description	24
1 Shack-Hartmann Functional Principle	27
2 Parts List - Accessories	29
3 Technical Data	31
4 Certifications and Compliances	32
Part IV Operating Instruction	34
1 Preconditions	34
2 Measurement with the Wavefront Sensor	34
Coordinate Definitions	39
3 The Graphics User Interface (GUI)	41
Start the GUI	41
Operating the Wavefront Sensor Software	43
Menu and Toolbar.....	43
Lineview Panel.....	49
Spotfield Panel.....	52
Beam View Panel.....	54
Wavefront Panel.....	56
Zernike Coefficients Panel.....	61
Wavefront Sensor Setup Panel	63
Camera Settings Setup.....	64
Pupil Definitions Setup.....	69
Wavefront Setup.....	72
Zernike Fit Setup.....	74
Miscellaneous Setup.....	77
Measurement Results	80
Measurement Warnings and Errors	83
User Calibration	84
Save Measurement Data	88
Version and other Program Information	92
Save Instrument Settings	92
DataSocket for live data transfer	92
Configuration Panel	95
Available Data Items.....	96

WFS Receiver Application sample.....	98
Printing	99
Part V Service and Maintenance	102
1 Service	102
2 Troubleshooting	102
Part VI Listings	106
1 List of Acronyms	106
2 Addresses	107
Part VII Appendix	109
1 Zernike Fit and Zernike Modes	109
2 Microlens Data	111
3 Typical Wavelength Curves	113
4 Wavefront Sensor Drawing	115
5 WFS Reference Position	116
6 WFS Mounting Adapter	117
Index	118

We aim to develop and produce the best solution for your application in the field of optical measurement technique. To help us to come up to your expectations and develop our products permanently we need your ideas and suggestions. Therefore, please let us know about possible criticism or ideas. We and our international partners are looking forward to hearing from you.

Thorlabs GmbH

This part of the instruction manual contains every specific information on how to handle and use the WFS150/WFS150C Wavefront Sensor.

Attention

This manual contains "WARNINGS" and "ATTENTION" label in this form, to indicate danger for persons or possible damage of equipment.

Please read these advises carefully!

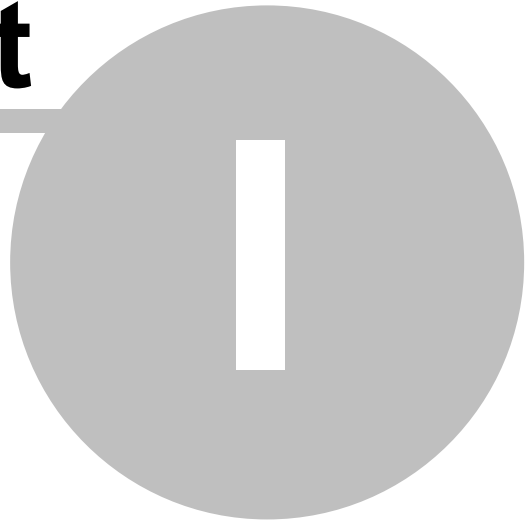
NOTE

This manual also contains "NOTES" and "HINTS" written in this form.

General

WFS150 / WFS150C Manual

Part



1 General

This chapter contains general information about the Wavefront Sensor's safety, warranty and waste treatment.

1.1 Safety

Attention

All statements regarding safety of operation and technical data in this instruction manual will only apply when the unit is operated correctly.

Before applying power to your PC system used to display Wavefront Sensor data, make sure that the protective conductor of the 3 conductor mains power cord is correctly connected to the protective earth contact of the socket outlet!

Improper grounding can cause electric shock with damages to your health or even death!

All modules must only be operated with duly shielded connection USB-Cables delivered by Thorlabs.

Only with written consent from *Thorlabs* may changes to single components be carried out or components not supplied by *Thorlabs* be used.

This precision device is only transportable if duly packed into the complete original packaging including the plastic form parts. If necessary, ask for a replacement package.

**Do not stick something into the aperture at the Wavefront Sensor front!
You may damage the microlens array because there is no covering glass in front of it.**

**Be very careful in handling high power optical beams,
especially if they are focussed!**

**Avoid skin irradiation and use laser
protection glasses the protect your eyes!**

1.2 Warranty

Thorlabs warrants material and production of the WFS150/WFS150C for a period of 24 months starting with the date of shipment. During this warranty period *Thorlabs* will see to defaults by repair or by exchange if these are entitled to warranty.

For warranty repairs or service the unit must be sent back to *Thorlabs* or to a place determined by *Thorlabs*. The customer will carry the shipping costs to *Thorlabs*, in case of warranty repairs *Thorlabs* will carry the shipping costs back to the customer.

If no warranty repair is applicable the customer also has to carry the costs for

back shipment.

In case of shipment from outside EU duties, taxes etc. which should arise have to be carried by the customer.

Thorlabs warrants the hard- and software determined by *Thorlabs* for this unit to operate fault-free provided that they are handled according to our requirements. However, *Thorlabs* does not warrant a faulty free and uninterrupted operation of the unit, of the soft- or firmware for special applications nor this instruction manual to be error free. *Thorlabs* is not liable for consequential damages.

Restriction of warranty

The warranty mentioned before does not cover errors and defects being the result of improper treatment, software or interface not supplied by us, modification, misuse or operation outside the defined ambient conditions stated by us or unauthorized maintenance.

Further claims will not be consented to and will not be acknowledged. *Thorlabs* does explicitly not warrant the usability or the economical use for certain cases of application.

Thorlabs reserves the right to change this instruction manual or the technical data of the described unit at any time.

1.3 WEEE

As required by the WEEE (Waste Electrical and Electronic Equipment Directive) of the European Community and the corresponding national laws, Thorlabs offers all end users in the EC the possibility to return "end of life" units without incurring disposal charges.

This offer is valid for Thorlabs electrical and electronic equipment

- sold after August 13th 2005
- marked correspondingly with the crossed out "wheelie bin" logo (see fig. 1)
- sold to a company or institute within the EC
- currently owned by a company or institute within the EC
- still complete, not disassembled and not contaminated

As the WEEE directive applies to self contained operational electrical and electronic products, this "end of life" take back service does not refer to other Thorlabs products, such as

- pure OEM products, that means assemblies to be built into a unit by the user (e. g. OEM laser driver cards)
- components
- mechanics and optics
- left over parts of units disassembled by the user (PCB's, housings etc.).

If you wish to return a Thorlabs unit for waste recovery, please contact Thorlabs or your nearest dealer for further information.

1.3.1 Waste Treatment on your own Responsibility

If you do not return an "end of life" unit to Thorlabs, you must hand it to a company specialized in waste recovery. Do not dispose of the unit in a litter bin or at a public waste disposal site.

1.3.2 Ecological Background

It is well known that WEEE pollutes the environment by releasing toxic products during decomposition. The aim of the European RoHS directive is to reduce the content of toxic substances in electronic products in the future.

The intent of the WEEE directive is to enforce the recycling of WEEE. A controlled recycling of end of live products will thereby avoid negative impacts on the environment.

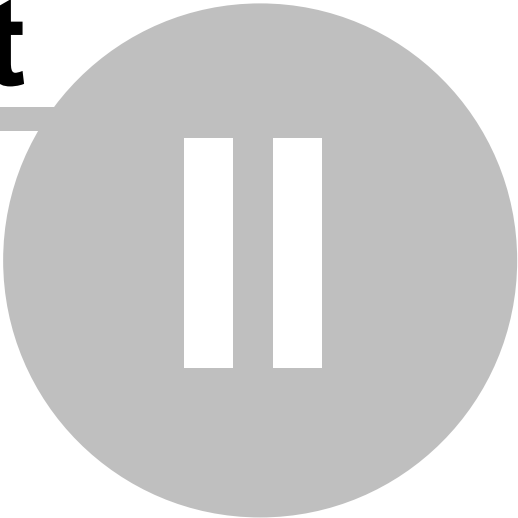


Crossed out "Wheelie Bin" Symbol

Getting Started

WFS150 / WFS150C Manual

Part



2 Getting Started

This section is provided for those interested in getting the Wavefront Sensor up and running quickly. The more detailed description and advanced features are described in the following sections.

2.1 WFS150/WFS150C Quick Start-up

This Quick Start-up guide will lead you through the software installation process and guides you starting the application and introduces the most important functions of the instrument.

Attention

Please, install software prior to connect the instrument to your PC via USB interface.

System requirements

- Operating system: Microsoft Windows 2000®, Windows XP® or higher
- USB 2.0 high speed port (A **USB 1.1** full speed port is **not usable!**)

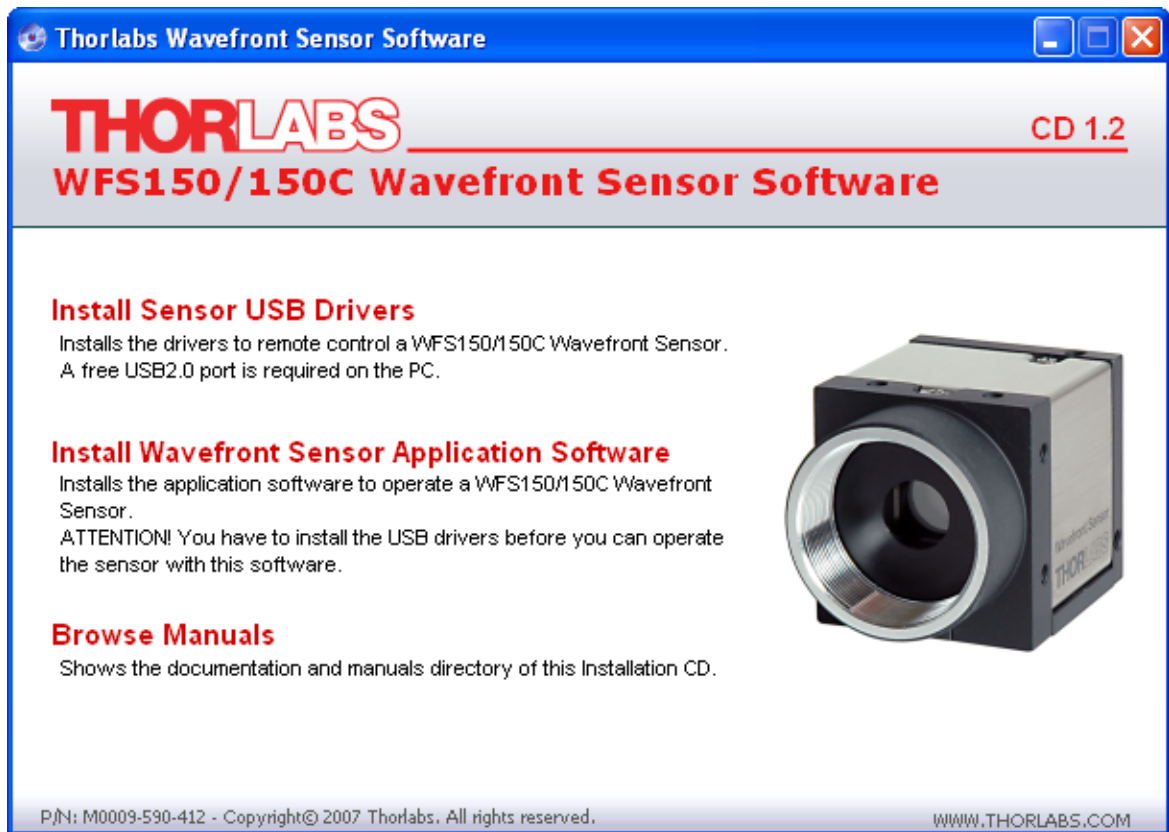
There is only one software component that must be properly installed and activated in order to allow USB control of your WFS150/WFS150C Wavefront Sensor. This software must be installed prior to make any electrical connections between the Wavefront Sensor and PC via USB interface.

2.1.1 Software Installation

Insert the "Thorlabs Wavefront Sensor CD 1.2" (or higher) CD-ROM, included with your WFS150/WFS150C Wavefront Sensor package. It automatically starts up and displays the installation start screen.

In case this 'auto start' feature is disabled on your computer please execute the 'Autorun.exe' file within the folder 'Autorun' on the CD.

The following screen will appear:



There are in total two software components selectable.

Install Sensor USB Drivers	This installs the Wavefront Sensor USB drivers onto your computer. Note, that this driver is identical to the USB drivers for Thorlabs DCU USB2.0 cameras.
Install Wavefront Sensor Application Software	This installs the Wavefront Sensor application and USB drivers onto your computer.

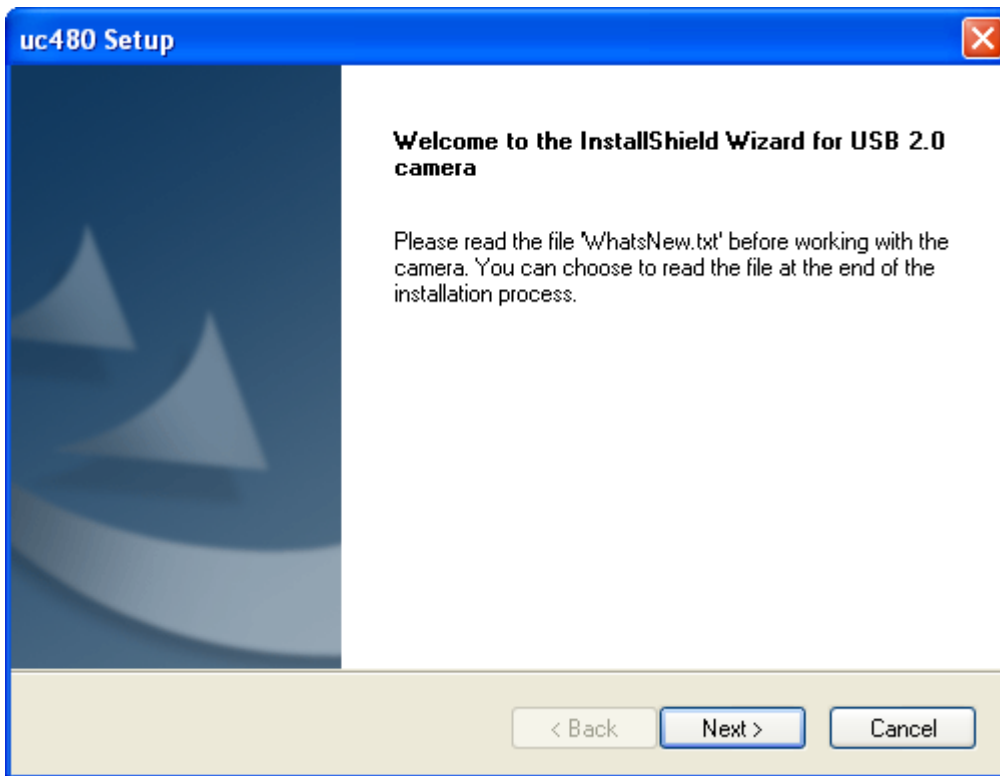
Note: It is recommended to close all other programs on your computer prior to start the installation process. Do install both components in the order:

1. USB Driver
2. Application Program

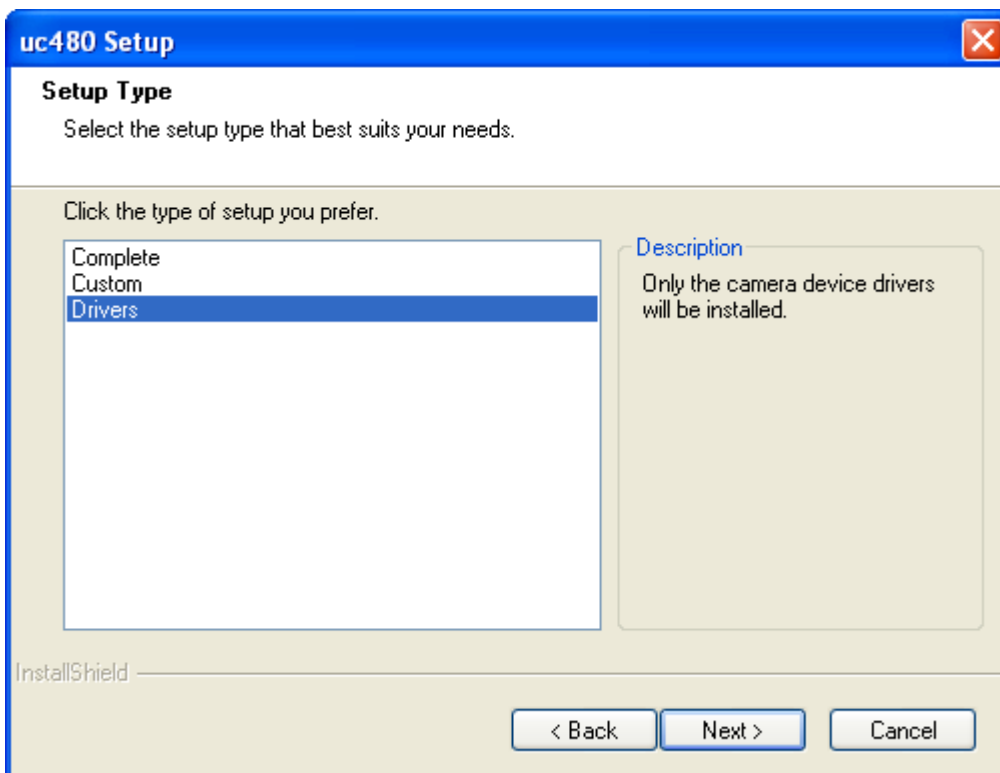
prior to connect the Wavefront Sensor hardware.

1. Installing the Sensor USB Drivers

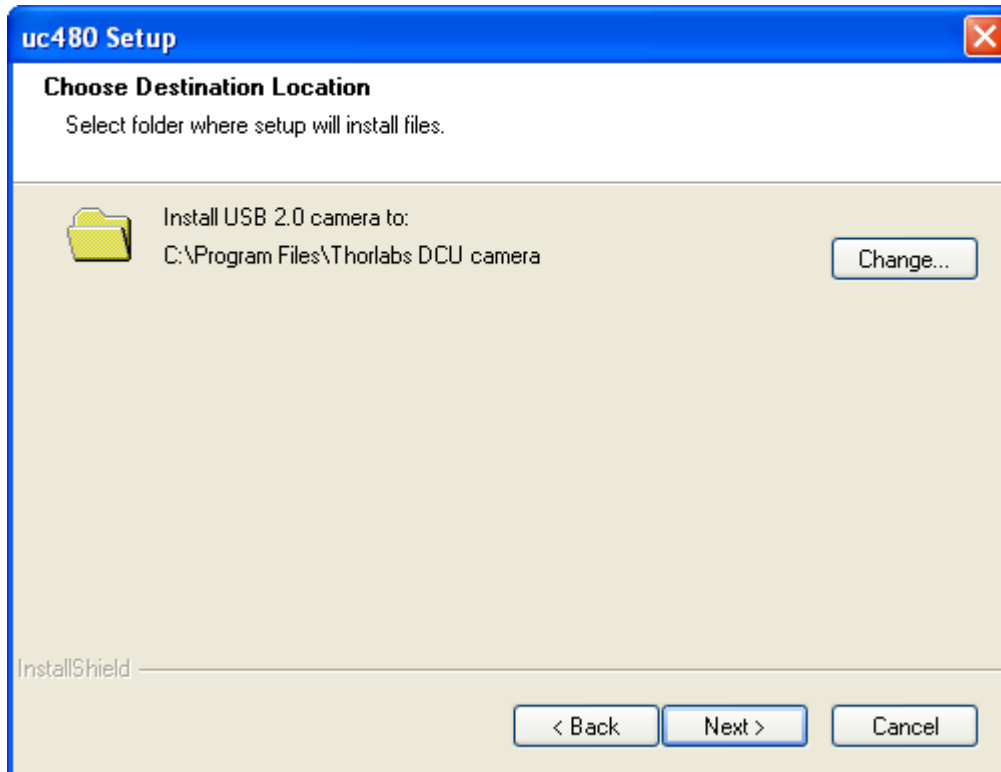
Don't wonder that a driver for a Thorlabs DCU USB2.0 camera is being installed. This is correct because the Wavefront Sensor uses such a camera and therefore the same drivers. 'uc480' is the name of the appropriate camera driver software.



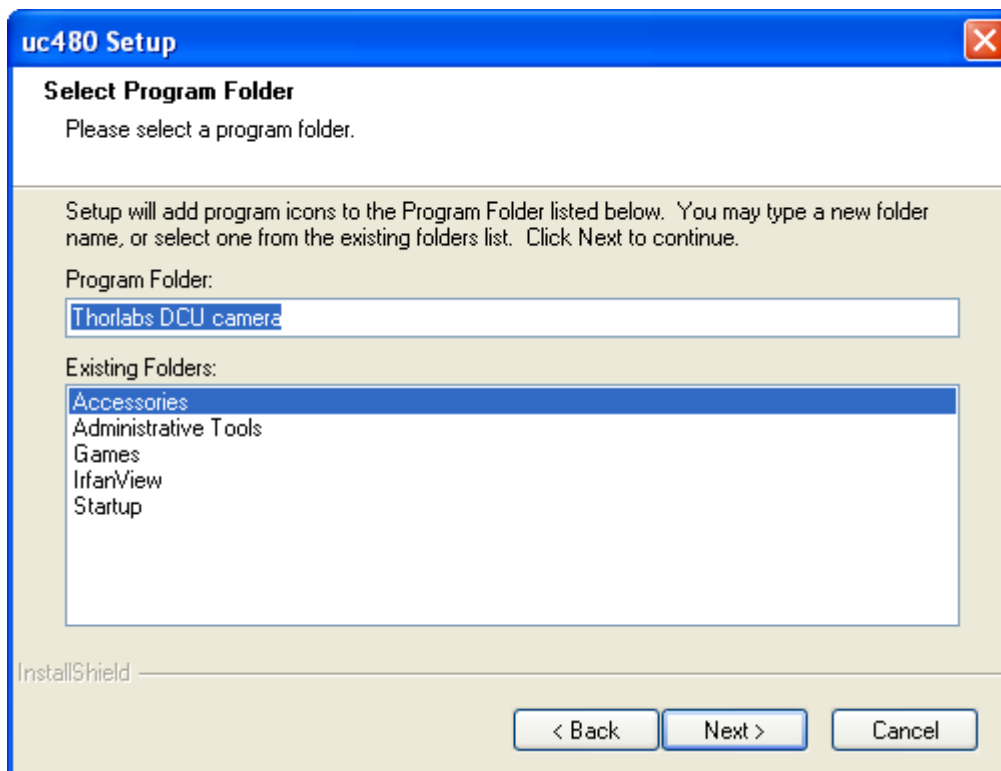
Click 'Next' to proceed.



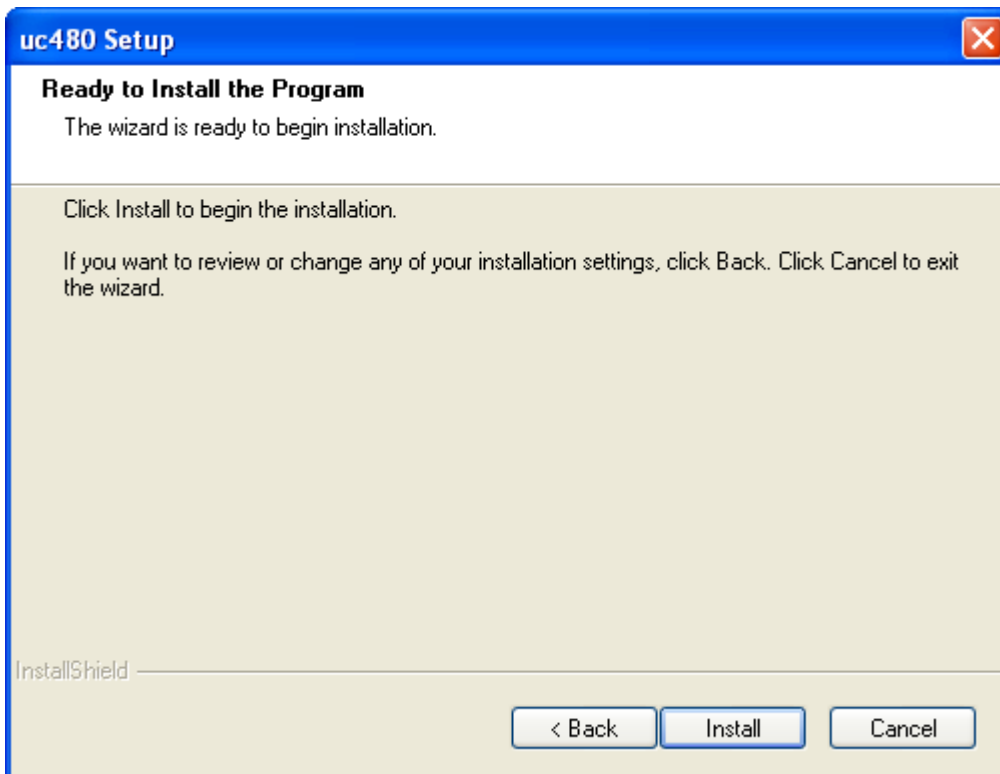
It is sufficient to choose '**Drivers**' in order to install the required camera drivers only. A complete installation of the camera application software and its documentation is not necessary. Click 'Next' to proceed.



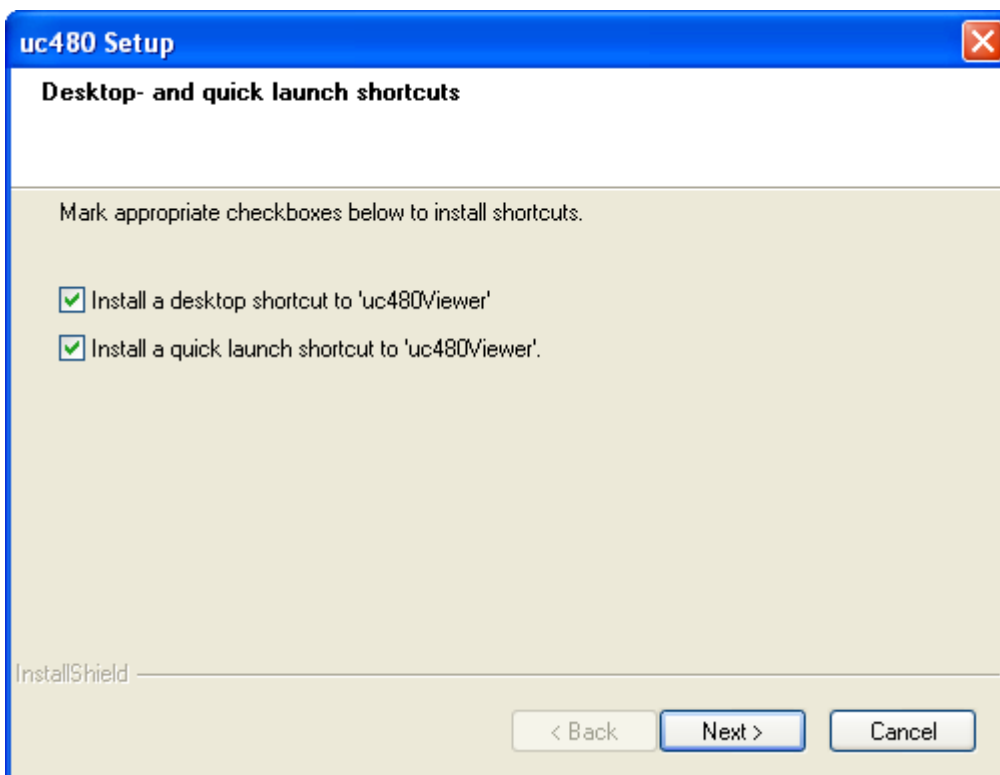
Click 'Next' to proceed or select an alternative folder where to install the driver.



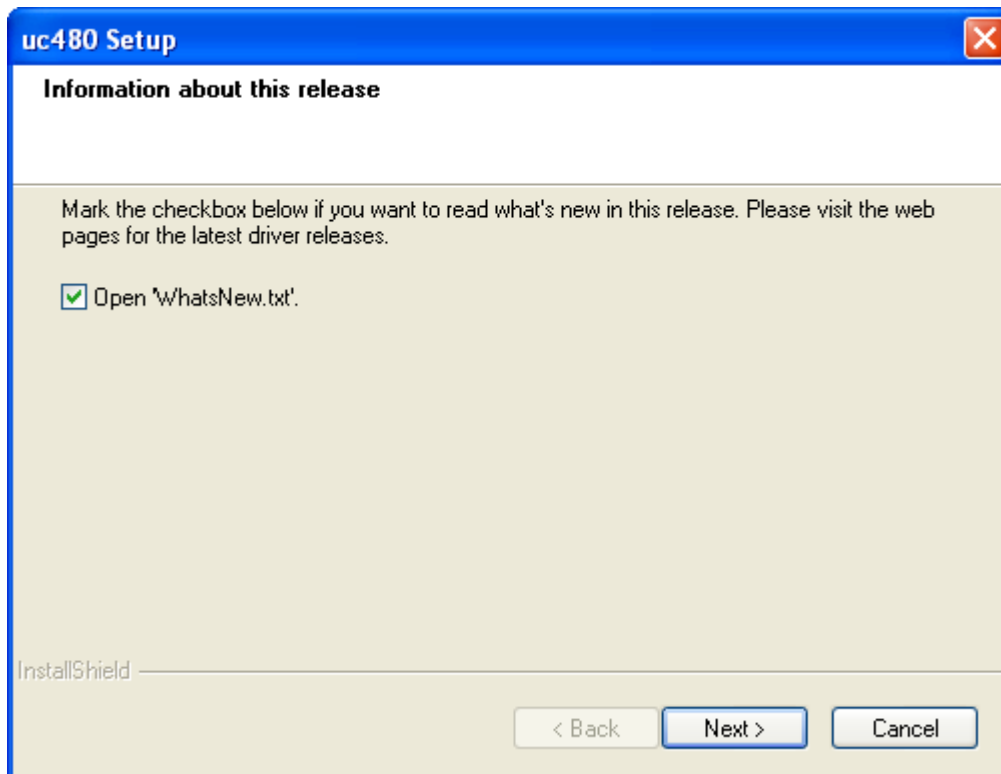
Let the destination folder name unchanged and click 'Next'.



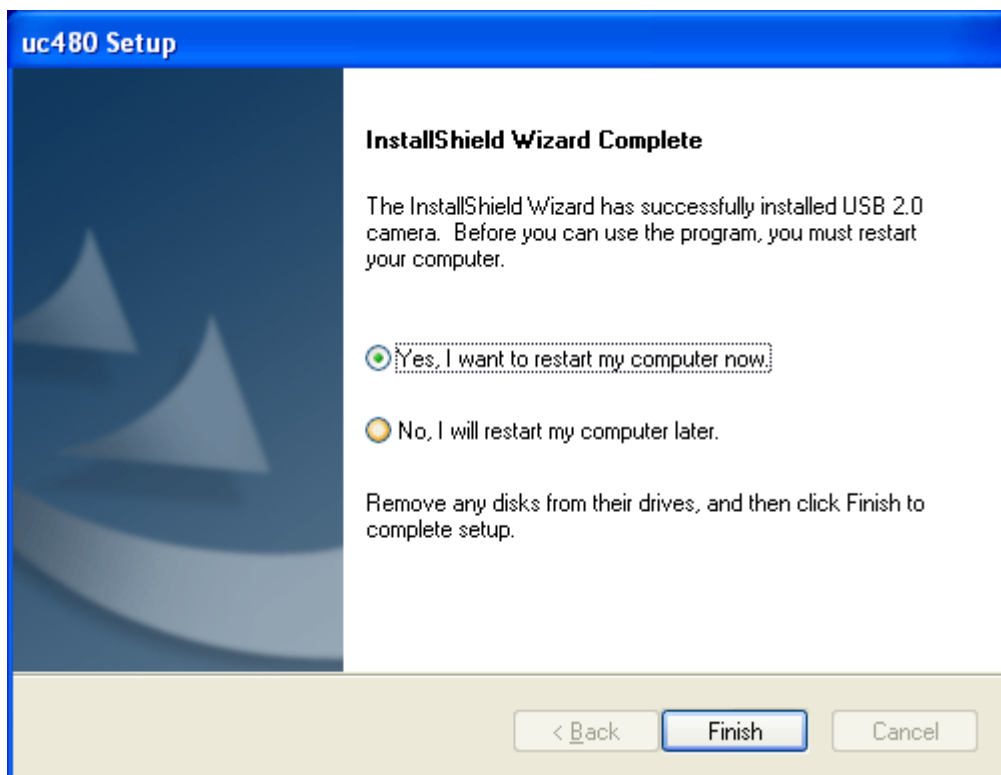
Click 'Next' and the installation process starts.
The following panel will appear. Let the options enabled to generate shortcuts to the uc480Viewer software and click 'Next'.



Click 'Next' to proceed.



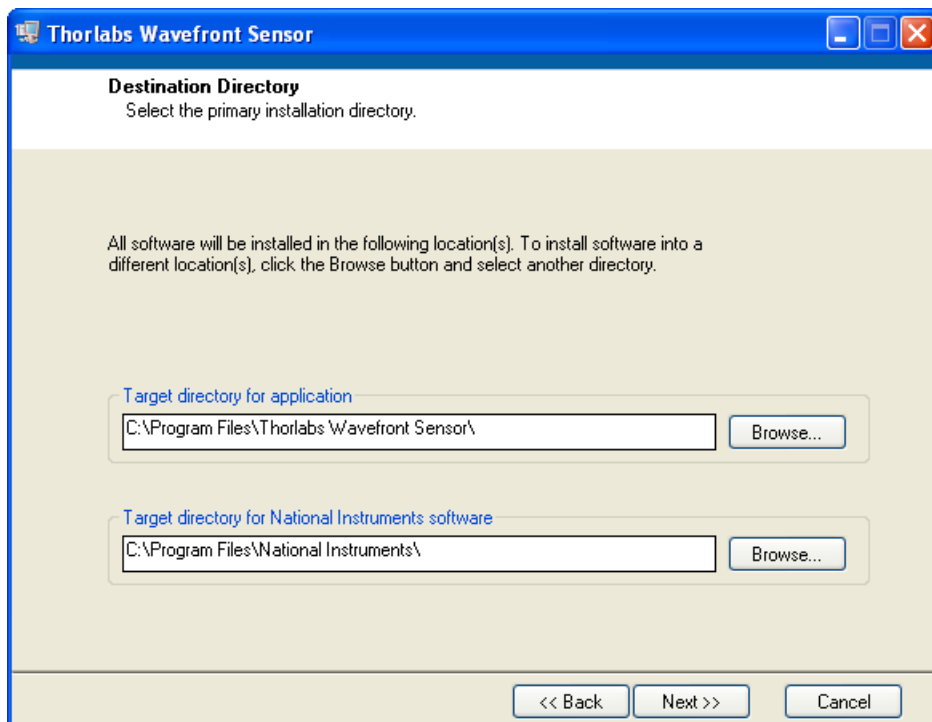
The 'WhatsNew.txt' file will inform you about latest changes of the camera software, it can be disabled. Click 'Next' to proceed.



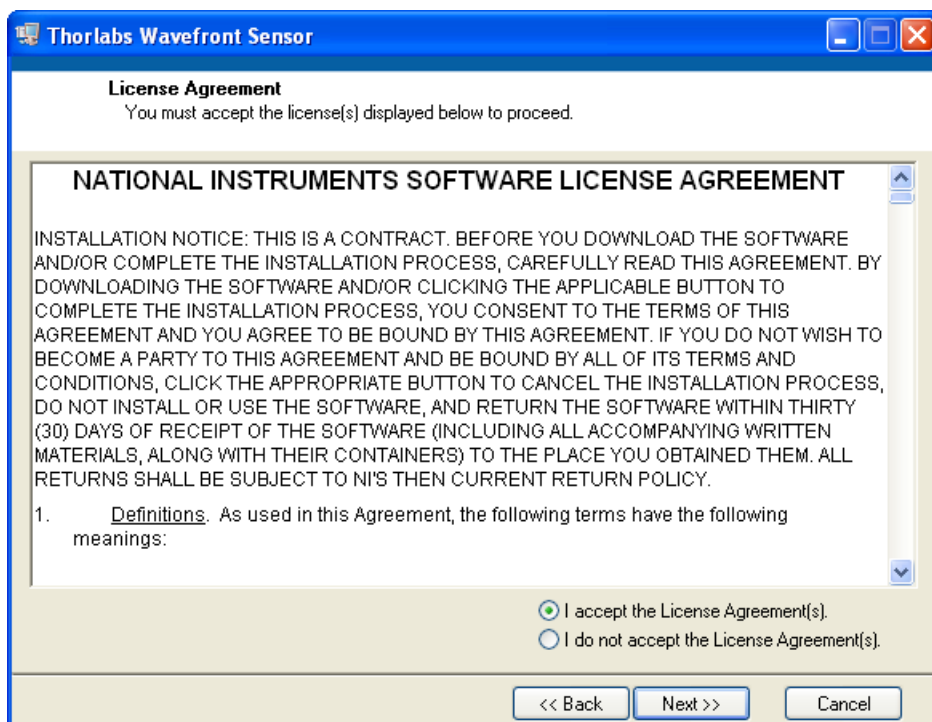
If it is required to restart your computer leave option 'Yes' enabled and click 'Finish' to reboot the computer.

2. Installing the Wavefront Sensor application software

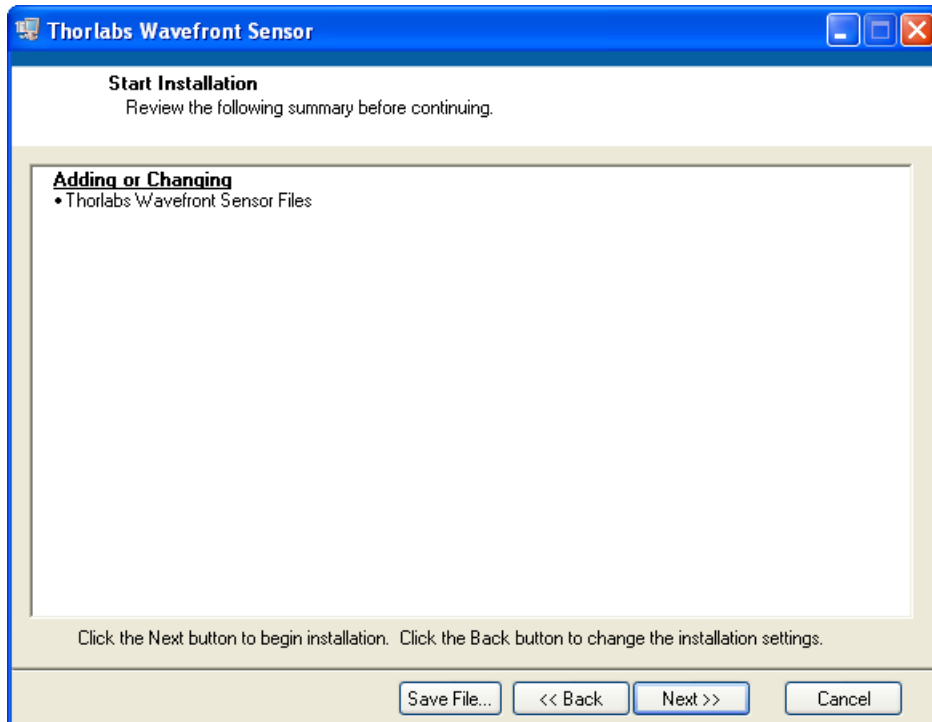
Click on 'Install Wavefront Sensor Application Software' to start the installation procedure. The following opening screen will appear:



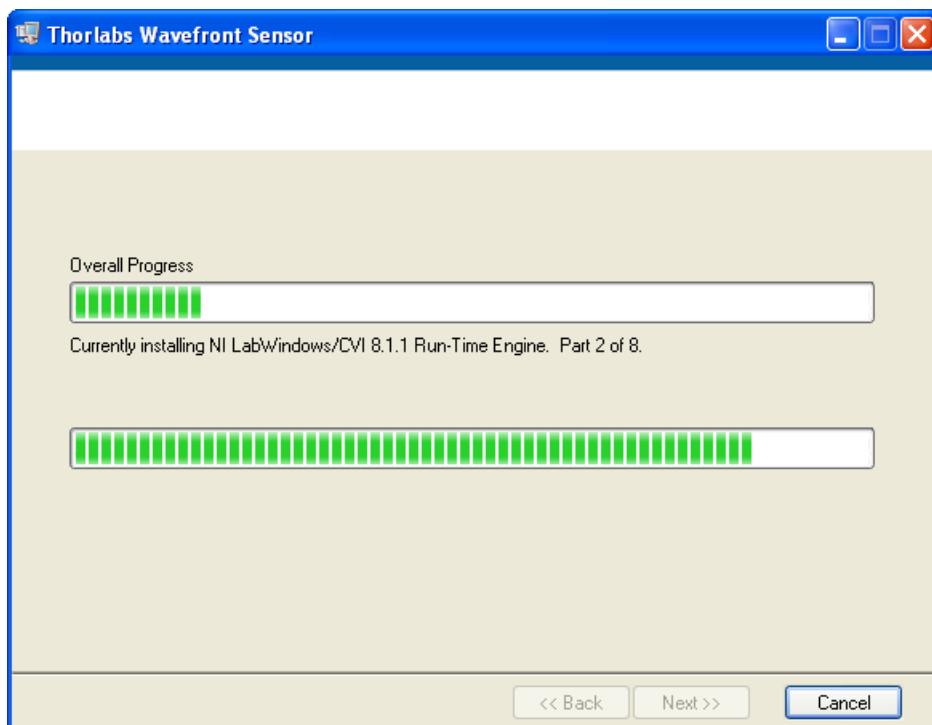
Click 'Next' to proceed.



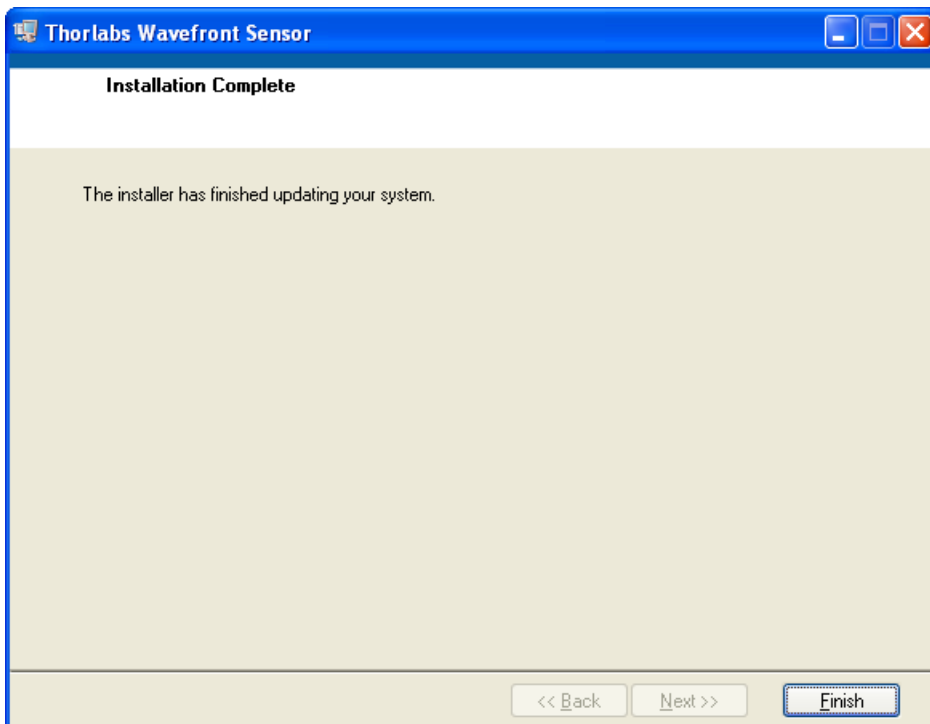
Read the License Agreement carefully. Mark 'I accept the License Agreement' and click 'Next' to proceed.



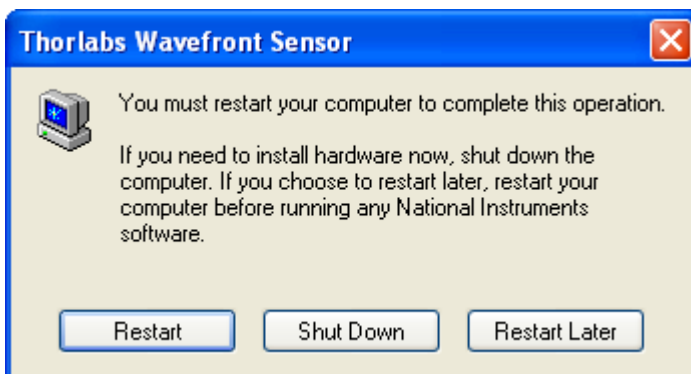
You will be informed about items that are going to be installed. Click 'Next' to proceed.



The installation process will take a minute. If no error occurs the following message appears:



Click 'Finish' to complete the installation process.
Depending on your operating system it may be required to restart your computer.



Click 'Restart' to reboot your system.

2.1.2 Connection to the PC

Connect the Wavefront Sensor to a USB 2.0 high speed port of your computer. Use only the cable that comes with the Wavefront Sensor or a cable qualified for high speed USB2.0 standard.

Attention

**The Wavefront Sensor will not work on a full speed USB1.1 port!
Be sure to connect it to a high speed USB2.0 port.
Do not use cables which are not explicitly suited for
high speed USB data transfer, this can cause
transmission errors and improper instrument operation!**

After connection of the instrument Microsoft Windows® will load the appropriate drivers for the Wavefront Sensor. In fact, since the Wavefront Sensor consists of a modified Thorlabs DCU camera, the driver software is basically the same for both instruments.

Attention

**Don't worry about that a 'Thorlabs DCU camera' is displayed in the device manager. This is because the Thorlabs Wavefront Sensor consists basically of a Thorlabs DCU camera which is also available separately from Thorlabs.
Since both instruments, the DCU camera and the Wavefront Sensor use the same driver software, they are not distinguishable in the device manager, both instruments are displayed as 'Thorlabs DCU camera'.
A differentiation takes place only inside the Wavefront Sensor application program wfs.exe that accepts only WFS150 and WFS150C devices for operation.**

Depending on your Microsoft Windows® settings the 'Found new Hardware Wizard' appears optionally. It will lead you through this process.

Note: You may be prompted to confirm the driver installation.

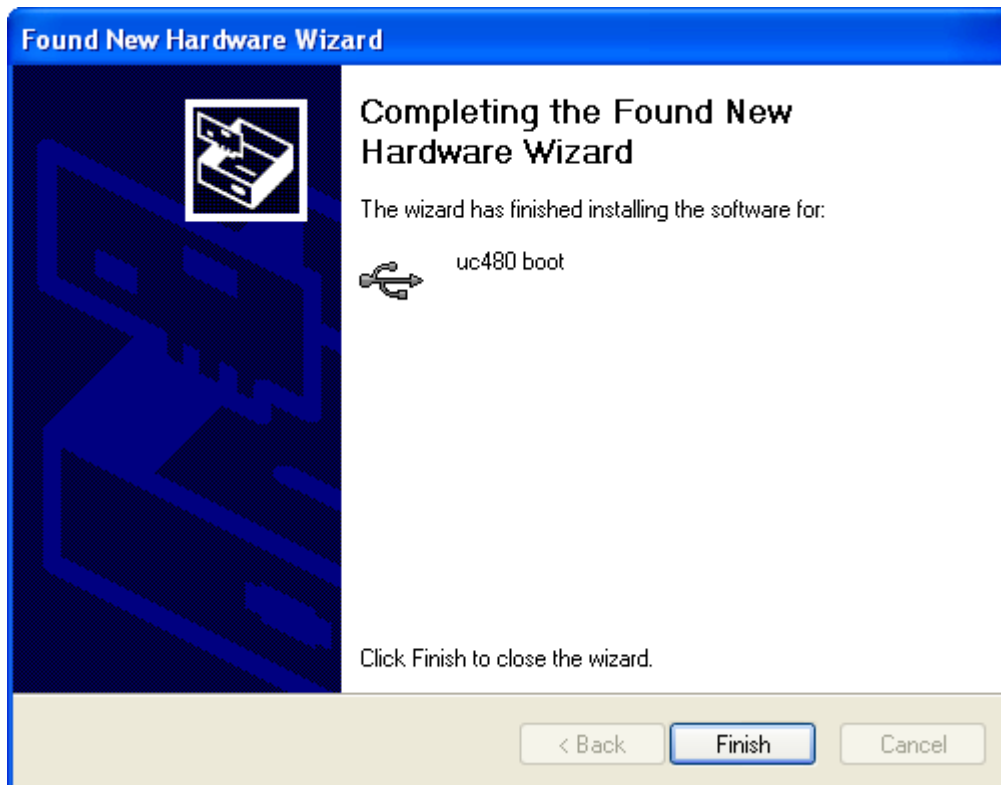
Note: The 'Found New Hardware Wizard' will appear twice, first to assign the installed boot driver and second to assign the real driver for the camera hardware.



Mark 'Install the software automatically (Recommended)' option and click 'Next'.

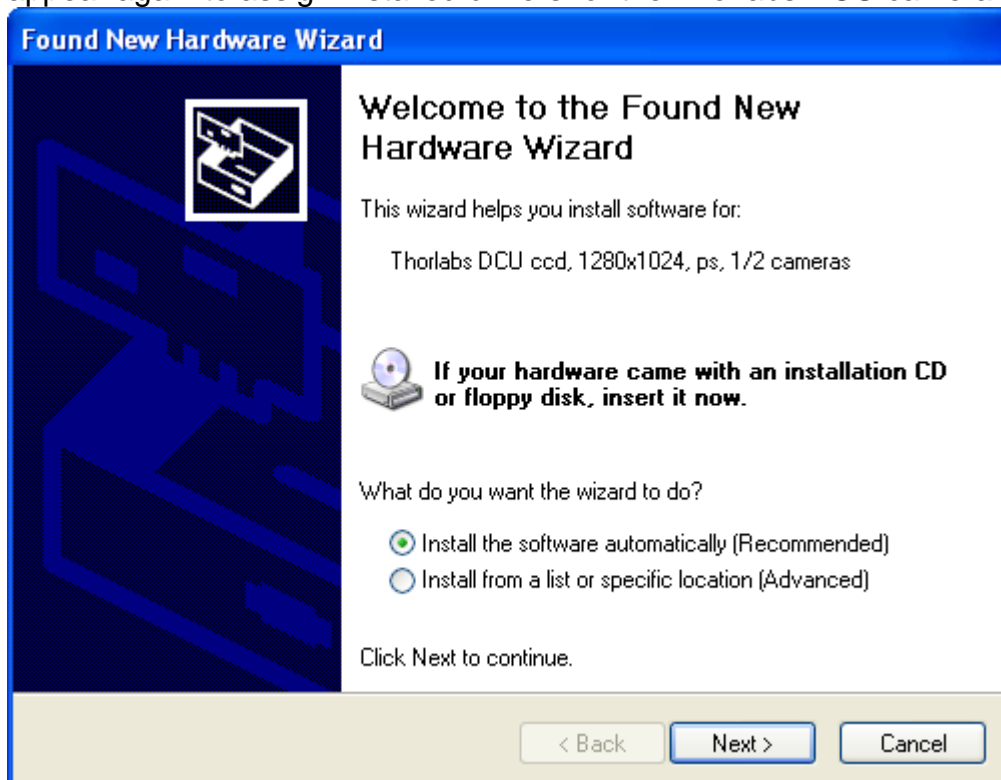


Please ignore this warning '...has not passed Windows Logo testing...' and click on 'Continue Anyway'.



Click on 'Finish' to finalize the first phase.

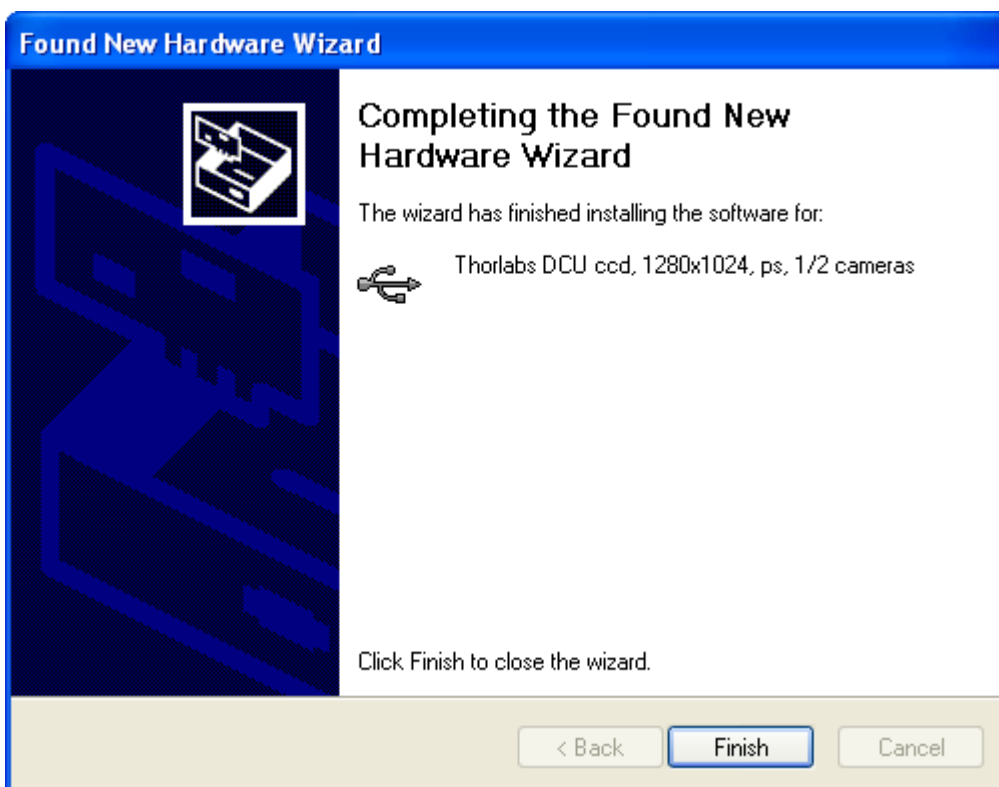
The camera hardware is now booting and the 'Found New Hardware Wizard' will appear again to assign installed drivers for the Thorlabs DCU camera:



Mark 'Install the software automatically (Recommended)' option and click 'Next'.



Please ignore this warning '...has not passed Windows Logo testing...' and click on 'Continue Anyway'.

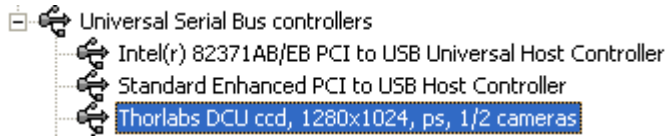


Congratulations!

The USB driver for the Wavefront Sensor is now properly installed. Click 'Finish' to complete this process.

For verification purposes you might check the existence of this instrument in the device manager of your computer.

From the Start button select Control Panel → System → Hardware → Device Manager. The following entry under the USB Serial Bus controllers group indicates that the Wavefront Sensor device is properly installed.



As long as the driver installation is not completed or failed, the instrument will be displayed as 'uc480 boot' or unknown 'USB device'.

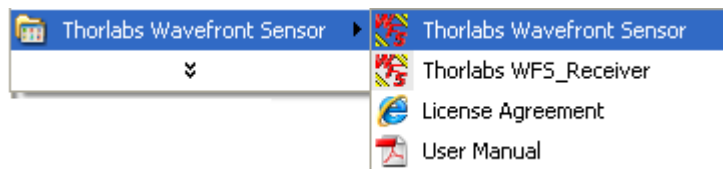


Wait a few seconds to let the driver communicate with the instrument. If you still cannot see the entry 'Thorlabs DCU camera' please check the [troubleshooting](#) chapter.

A successful installation is also indicated by the LED at the back side of the wavefront sensor. It lights up red immediately after connection to the USB bus and goes to green as soon as the driver software has completed the initialisation process and the instrument becomes ready to use by the application program.

2.1.3 Start the Application

Access the Application Programs from the START button. Find the "All Programs" → "Thorlabs Wavefront Sensor" → "Thorlabs Wavefront Sensor" entry.

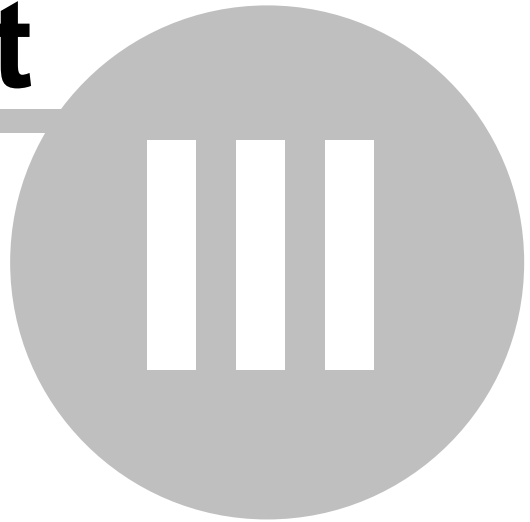


Do not forget to remove the dust cover from the Wavefront Sensor. Refer for [Start the GUI](#) chapter for detailed description.

Description

WFS150 / WFS150C Manual

Part

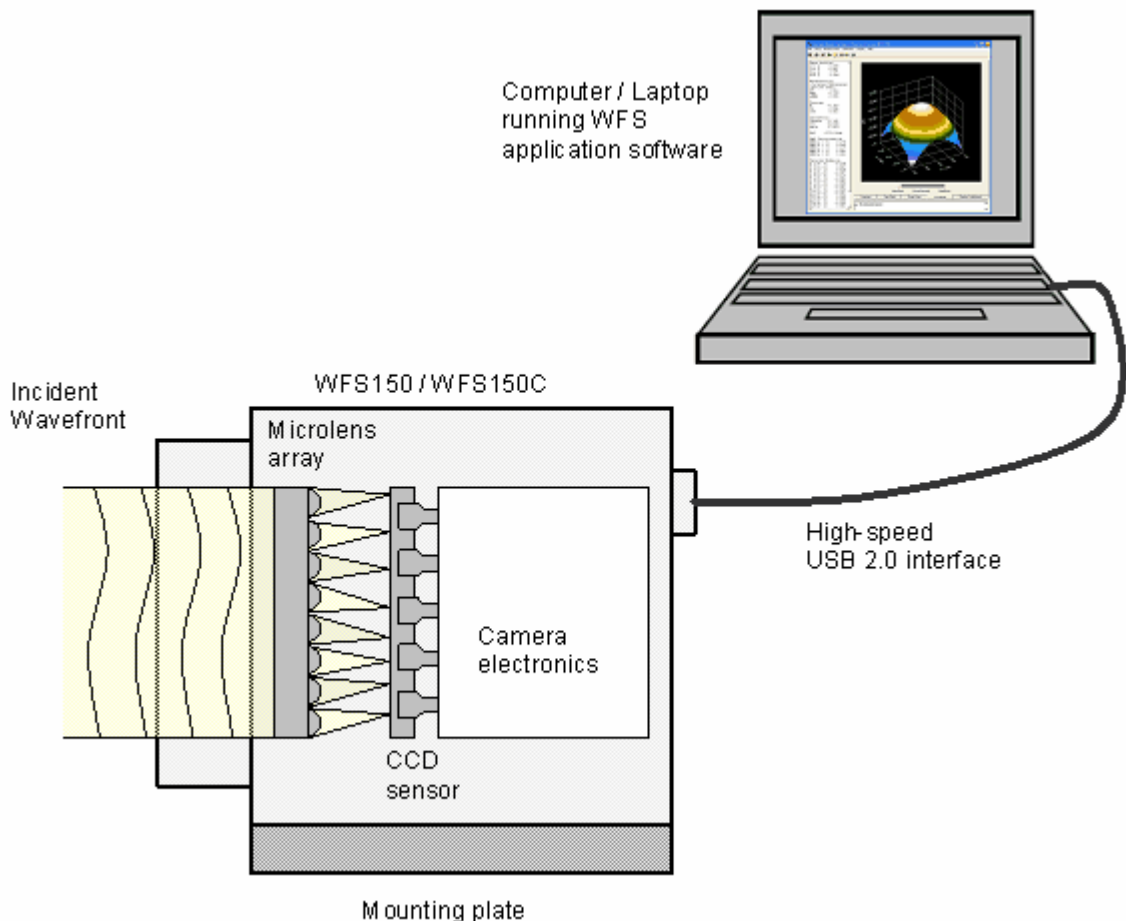


3 Description

Thorlabs Shack-Hartmann Wavefront Sensor

The Thorlabs Shack-Hartmann Wavefront sensor is an indispensable tool for detection and optimization of wavefront distortions that would otherwise impact the beam's focusability and the image definition within an imaging system. It is an economically priced instrument designed for general lab use and production floor testing.

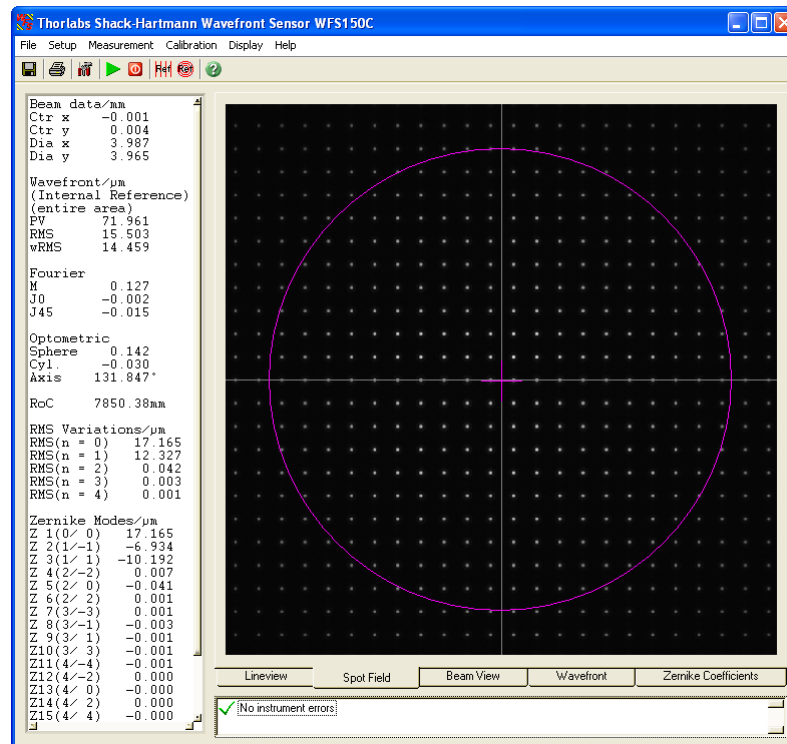
The WFS150 series of Shack-Hartmann wavefront sensors provide accurate, high-speed measurements of the wavefront shape and intensity distribution of beams. This is done by analyzing the location and intensity of spots (spotfield) formed by imaging a beam of light onto a CCD array with a microlens array as shown in the figure below. With Thorlabs' Shack-Hartmann wavefront sensor it is possible to optimize dynamically the wavefronts of laser sources, characterize the wavefront distortion caused by optical components, and provide real-time feedback for the control of adaptive optics.



The sensor operation conforms to **International Standard ISO 15367: "Laser and laser-related equipment - Test methods for determination of the shape of a laser beam wavefront" Part 2: "Shack-Hartmann sensors"**

The Shack-Hartmann Wavefront Sensor consists of a high resolution (1.3

Megapixels) USB 2.0 CCD camera with a microlens array mounted in front of it and a software package for evaluation of the generated spot field. The full featured control and analysis software has a user friendly graphical interface with menu driven tools for camera settings, calibration, analysis, and display options. The C-Mount threading on the face of the CCD camera allows with the help of an adapter (Thorlabs SM1A9) for the convenient mounting of ND filters, to help prevent the saturation of CCD pixel, and lens tubes to reduce scattered light and to allow for the mounting of additional optical components.



Example screen shot showing the spotfield and the pupil border

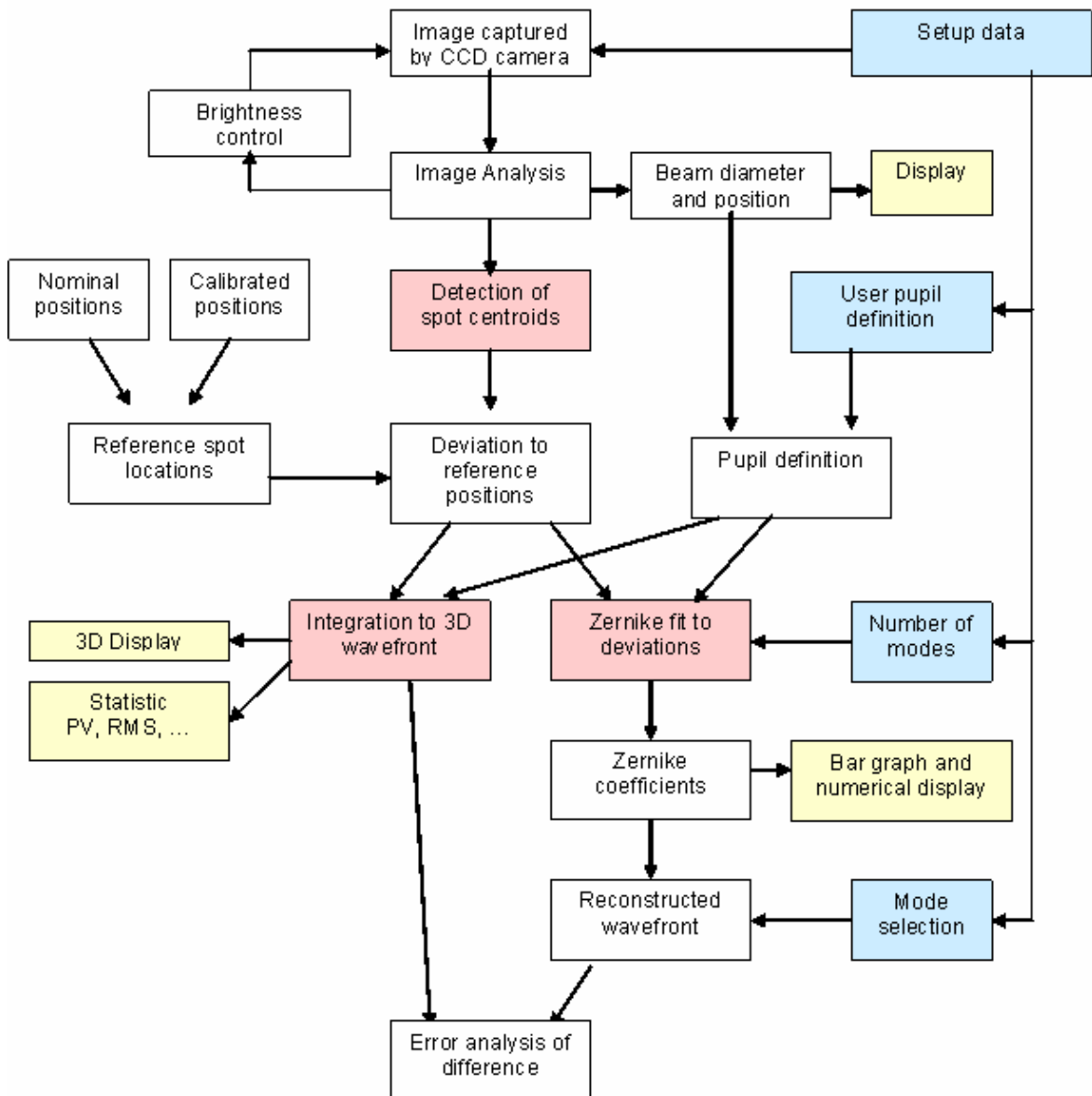
The camera image is transferred via USB 2.0 interface to a computer or laptop that is running the Thorlabs Wavefront Sensor application software. Special algorithms within the software calculate the centroid positions of all detectable spots and the corresponding deviations compared to the appropriate reference positions. A 2-dimensional integration give the wavefront graph displayed in the Graphical User interface (GUI) and a least-squared fit calculates Zernike coefficients that describe the wavefront shape and the amplitude of its deformation.

The visualisation of the measured results can widely be influenced by the user. There are calculated numerical parameters and graphical displays for visualization from the raw camera image to the 3D wavefront graph. The update rate of all numerical results and graphs is bound to the measurement speed of the camera and the selected average mode.

Data flow chart

The following chart will give an overview that shows the data flow within the Wavefront Sensor software and also point out user defined inputs and data outputs.

Color code:



The brightness of the camera image is controlled within a loop to ensure an optimal saturation level. Diameter and position of the beam is detected and these data are used optionally for defining the instruments pupil area. Otherwise pupil data can be defined by the user.

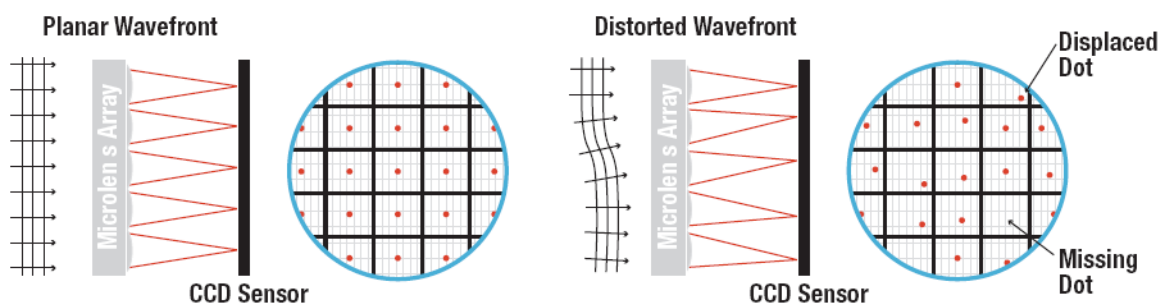
The image is scanned for detectable spots generated by the microlenses and their positions are compared to reference positions. The user select an internal or an user reference table of spot positions.

Spot deviations are calculated and afterwards integrated in order to get a

wavefront array which is displayed in a 3D diagram. All valid spot deviations within the defined pupil region and the desired number of Zernike orders / modes are input data to the Zernike fit that fits the measured wavefront using well-known Zernike functions. Output data are Zernike coefficients which are displayed numerically and within a bar graph panel. All or a few selected Zernike modes are used for the wavefront reconstruction. Also the difference between measured and fitted wavefront data is available.

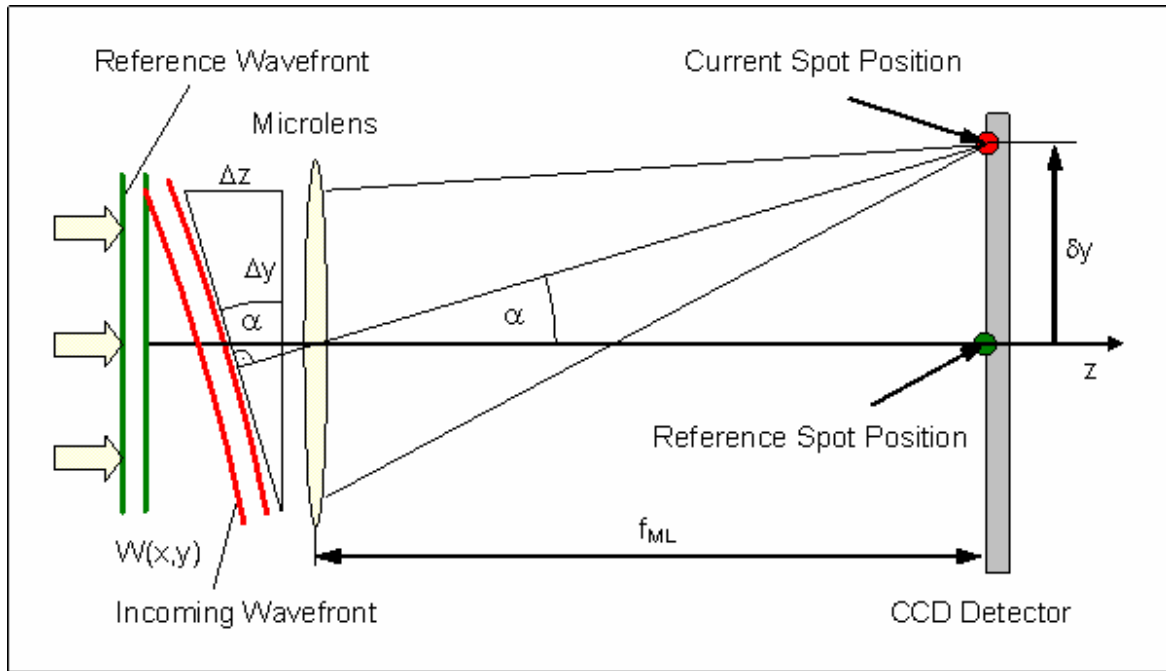
3.1 Shack-Hartmann Functional Principle

The WFS150 / WFS150C Wavefront Sensor consists basically of a CCD camera with a microlens array mounted in a defined distance in front of its sensor chip. Each microlens generates a spot onto the sensor whereas the spot centroid position depends on the wavefront gradient in front of the lens area.



Each microlens of the lenslet array collects the light falling onto its aperture and generates a single spot on the detector plane (CCD camera) that is situated a focal length behind the lenslets. The spot positions are straight behind the lenses only in case the launched wavefront is plane and parallel to the plane of the lenslets. We call these the **Reference Spot Positions** or reference spotfield.

In the common case however, the current spot positions will be deviated in X and Y direction, that is, every spot lies away from the optical axis z of its associated microlens, separated by an angle α .



It can be easily shown that this is caused by an incoming wavefront with the same average angle α compared to the reference wavefront.

$$\tan \alpha = \frac{\Delta z}{\Delta y} = \frac{\delta y}{f_{ML}}$$

When $W(x,y)$ describes the shape of the wavefront so its partial derivation relative to x and y are determined by the spot shift δx and δy , respectively as well as by the distance between microlens and detector which is usually the focal length of the microlens f_{ML} .

$$\frac{\partial}{\partial x} W(x,y) = \frac{\delta x}{f_{ML}} \quad \frac{\partial}{\partial y} W(x,y) = \frac{\delta y}{f_{ML}}$$

Spot deviations δx and δy are determined by calculating the centroid coordinates of all detectable spots and subtracting the corresponding reference coordinates afterwards. These spot deviations are integrated within a 2-dimensional integration process that gives the wavefront $W(x,y)$.

3.2 Parts List - Accessories

A complete wavefront analyzing system consist of a WFS150 or WFS150C sensor, a USB2.0 cable and an PC or laptop. You don't have to install an additional card into your PC and you don't need external power supply.

The shipping package contains:

- Wavefront Sensor instrument as an external measurement head with dust cover
- Mounting adapter plate and 4 mounting screws M3x6
- USB2.0 high speed cable USB A to Mini USB B, 1,5 m
- CD-ROM with the required driver and application software included
- Wavefront Sensor operating manual

The Wavefront sensor comes with different configurations depending on the order code.

Two Wavefront Sensor Models

There are two different versions available which differ in the implemented microlens array (MLA, see data here [Microlens Data](#)) and its distance to the CCD camera sensor.

- **WFS150** uses an anti-reflection (AR) coated MLA that reduces the reflection from the array to **below 1% within the wavelength range 400 - 900 nm**. Note, that the total reflection from the entire instrument can be higher due to reflection from the CCD cover glass and chip itself. This model is well suited **for applications that do not tolerate back-reflections** back into the measurement setup, for instance because it contains a laser without an isolator but parallel beam and long coherence length. Use this model if other ways for preventing back-reflection line tilting the Wavefront Sensor with respect to the input beam are not feasible.
- **WFS150C** uses a MLA with a chrome mask on it that prevents light going in between the microlenses directly to the CCD detector. This increases the image contrast of the detected spotfield and improves the instrument accuracy, especially in case of strong wavefront deformations. The wavelength range is not restricted by an AR coating and covers the full sensitivity range of the Silicon CCD detector **200 - 1100 nm** (with largely reduced sensitivity at the edges). Take into account that such a chrome mask that cannot be anti-reflection coated may **reflect up to 25%** of the input light back to your measurement setup. It can be helpful to tilt the sensor a bit or insert an attenuator in order to reduce the amount of light reflected back into your measurement setup.

Both models are usable within different wavelength ranges. Due to the AR coating used inside WFS150 it is best suited within this range but not outside where the AR coating may have reflective properties! See the following [Technical Data](#) for details.

Mounting Adapter Plate

A mounting adapter is added to the camera housing of the Wavefront Sensor in order to supply standard threads M4 and UNC8-32 which are compatible to the palette of Thorlabs' mounts and posts holders.

Mount this adapter plate on the bottom side of the Wavefront Sensor using the 4 screws M3x6 if you want to use one of the mounting threads M4 or UNC8-32.

Otherwise, this adapter can be omitted. See Appendix [WFS Mounting Adapter](#) for a drawing of this adapter plate.

Optional C-Mount Adapter

The C-Mount threading on the face of the Wavefront Sensor allows with the help of an adapter (**Thorlabs SM1A9**) for the convenient mounting of components utilizing SM1 thread. These are for instance **Neutral density (ND) filters**, to help prevent device saturation or lens tubes to reduce scattered light and to allow for the mounting of additional optical components.

3.3 Technical Data

All technical data are specified at $23 \pm 5^\circ\text{C}$ and $45 \pm 15\%$ rel. humidity

Operating Temperature	+5 ... +35 °C
Storage Temperature	-40 ... +70 °C
Warm-up time for rated accuracy	15 min

Wavefront Sensor Specifications

Parameter	WFS150	WFS150C
Wavelength Range	400 – 900 nm	200 - 1100 nm
Aperture Size	5,95 x 4,76 mm max.	
Camera Resolution	1280 x 1024px max., selectable	
Pixel Size	4,65 x 4,65µm	
Shutter	Global	
Lenslet Pitch	150 µm	
Lens Diameter	146 µm	
Number of Lenslets	39 x 31 max., selectable	
Effective Focal Length	5,0 mm	3,7 mm
Reflectivity	< 1% (400-900 nm)	< 25%
Wavefront Sensitivity	/15 rms (@ 633nm)	
Wavefront Dynamic Range	>100 (@ 633nm)	
Local Radius of Curvature	> 10 mm	> 7,4 mm
Exposure Range	77µs – 66ms	
Frame Rate	15 Hz max.	
Image Digitization	8 bit	
Physical Size	32 x 34 x 45,5 mm	
Power Supply	< 1.5W, via USB	

3.4 Certifications and Compliances

The Thorlabs GmbH, Hans-Böckler-Strasse 6 D-85221 Dachau, declares under it's own responsibility, that the products

Wavefront Sensor WFS150, WFS150C

fulfill the requirements of the following standards and therefore corresponds to the regulations of the directive.

Category	Standards or description	
EC Declaration of Conformity - EMC	Meets intent of Directive 89/336/EEC for Electromagnetic Compatibility. Compliance was demonstrated to the following specifications as listed in the Official Journal of the European Communities:	
	EN 61326:1997 +A1:1998 +A2:2001 +A3:2003	Electrical equipment for measurement, control and laboratory use – EMC requirements: Immunity: complies with immunity test requirements for equipment intended for use in industrial locations ¹ . Emission: complies with EN 55011 Class B Limits ¹ .
	IEC 61000-4-2	Electrostatic Discharge Immunity (Performance criterion B)
	IEC 61000-4-3	Radiated RF Electromagnetic Field Immunity (Performance Criterion A)
	IEC 61000-4-4	Electrical Fast Transient / Burst Immunity (Performance Criterion A)
FCC EMC Compliance	Emissions comply with the Class B Limits of FCC Code of Federal Regulations 47, Part 15, Subpart B ¹ .	
EC Declaration of Conformity - Low Voltage	Compliance was demonstrated to the following specification as listed in the Official Journal of the European Communities: Low Voltage Directive 73/23/EEC, amended by 93/68/EEC	
	EN 61010-1:2001	Safety requirements for electrical equipment for measurement, control and laboratory use.
¹ Compliance demonstrated using a high-quality shielded USB high speed cable shorter than 3 meters.		

Operating Instruction

WFS150 / WFS150C Manual

Part



IV

4 Operating Instruction

This section gives a more detailed description for operating the WFS150 / WFS150C.

4.1 Preconditions

1. You must install Wavefront Sensor application software and USB drivers on your PC according to [Getting Started Quickly](#).
2. You have to connect the WFS150 / WFS150C with your PC by using the USB2.0 cable delivered by Thorlabs.

As soon as the LED at the back of the Wavefront Sensor lights up green the instrument is ready for operation and you can start the application program with its Graphics User Interface (GUI).

Do not forget to remove the dust cover from the Wavefront Sensor.

4.2 Measurement with the Wavefront Sensor

Attention

**Do not stick something into the aperture at the Wavefront Sensor front!
You may damage the microlens array because there is no covering
glass in front of it.**

**Be very careful in handling high power optical beams,
especially if they are focussed!
Avoid skin irradiation and use laser protection
glasses the protect your eyes!**

Measurement results of the Wavefront Sensor are influenced by the user's setting such as the pupil size and other setup parameters of the instrument. It is recommended to study the [Shack-Hartmann Functional Principle](#) as well as the setup options (see [Wavefront Sensor Setup Panel](#)) in order to perform reliable wavefront measurements.

Mounting options

A mounting adapter (see [WFS Mounting Adapter](#)) is added to the camera housing of the Wavefront Sensor in order to supply standard threads M4 and UNC8-32 which are compatible to the palette of Thorlabs' mounts and posts holders. Mount this adapter plate on the bottom side of the Wavefront Sensor using the 4 screws M3x6 if you want to use one of the mounting threads M4 or UNC8-32. Otherwise, this adapter can be omitted.



The C-Mount threading on the face of the CCD camera allows with the help of an adapter (Thorlabs SM1A9) for the convenient mounting of ND filters, to help prevent the saturation of CCD pixel, and lens tubes to reduce scattered light and to allow for the mounting of additional optical components.

Beam Size

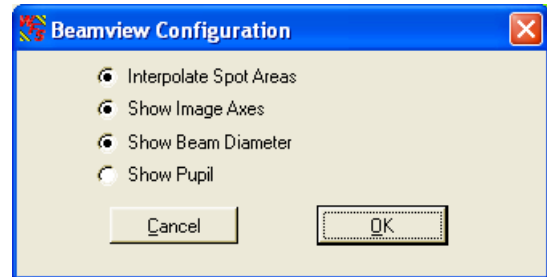
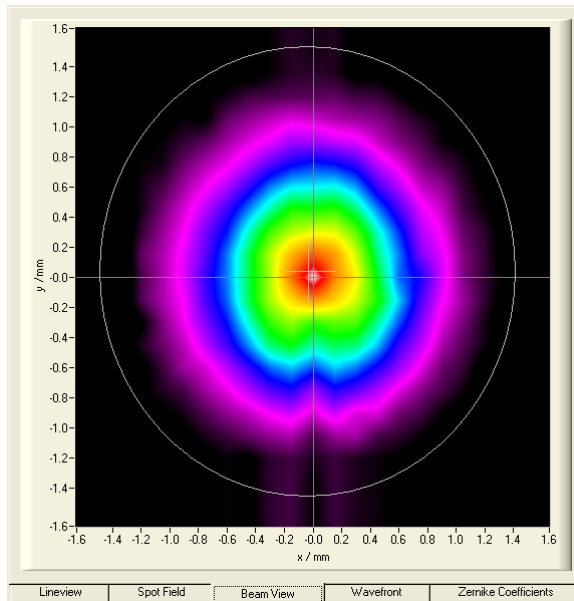
The active area on the CCD camera chip can be selected (see [Camera Settings Setup](#)) in order to adapt it to the actual beam size. Otherwise, a beam much smaller than the sensor area will illuminate only the microlenses at the center and no wavefront data can be retrieved from the ambient area. Also the measurement speed is increased when the camera image size is reduced to fit the real beam diameter.

A beam size larger than the available aperture (5,95 x 4,76 mm) of the WFS150 / WFS150C Wavefront Sensor can be adapted using beam expanders (Thorlabs BE01 - BE20 series).

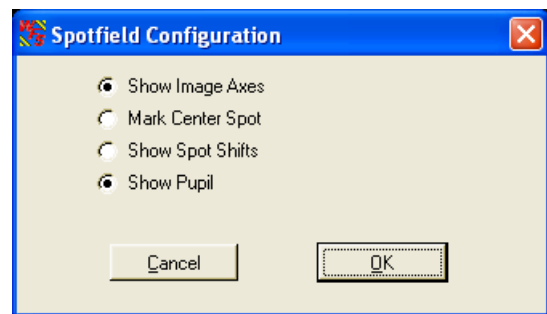
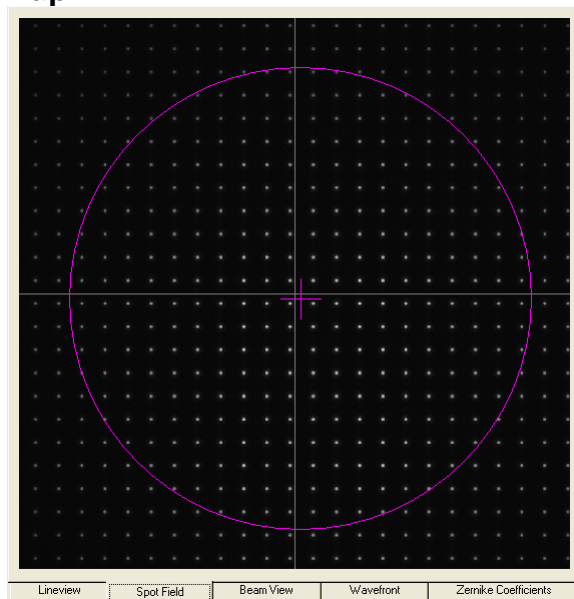
Beam Alignment

Align the Wavefront Sensor so that the beam to be analyzed launches the instrument perpendicular to its front face. In some cases a small tilt angle out of that position can be helpful to prevent unwanted back reflection into the measurement setup.

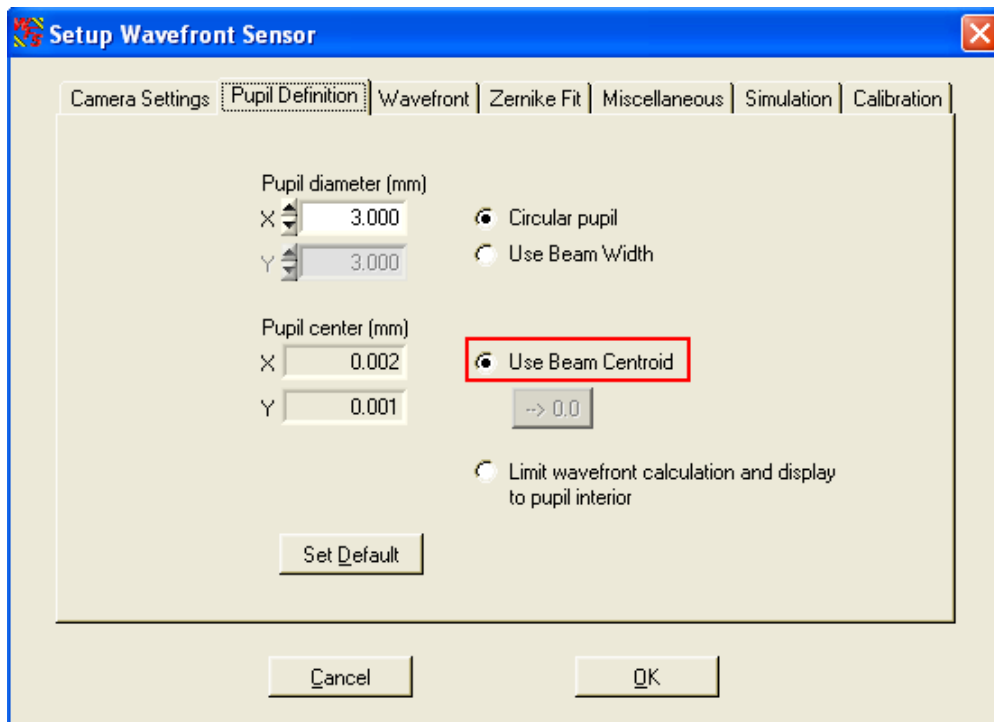
Direct the beam to be analyzed into the center of the entrance aperture of the Wavefront Sensor. Although an off-center beam can also be measured as long as it is not truncated by the active sensor area it is recommended to adjust the beam to be measured so that it hits the center of the Wavefront Sensor. Verify this adjustment by checking the power density distribution displayed within the [Beam View Panel](#). Enable the Beam View options '**Show Image Axes**' and '**Show Beam Diameter**' in order to visualize the beam position and size with respect to the analyzed sensor area.



Alternatively, you can check the correct beam position also using the [Spotfield Panel](#). Enable the diagram options '**Show Image Axes**' and '**Show Pupil**'.



Be sure you have enabled the '**Use Beam Centroid**' option within the [Pupil Definitions Setup](#) panel in order to couple the displayed pupil position to the measured beam centroid position.



Optical Power

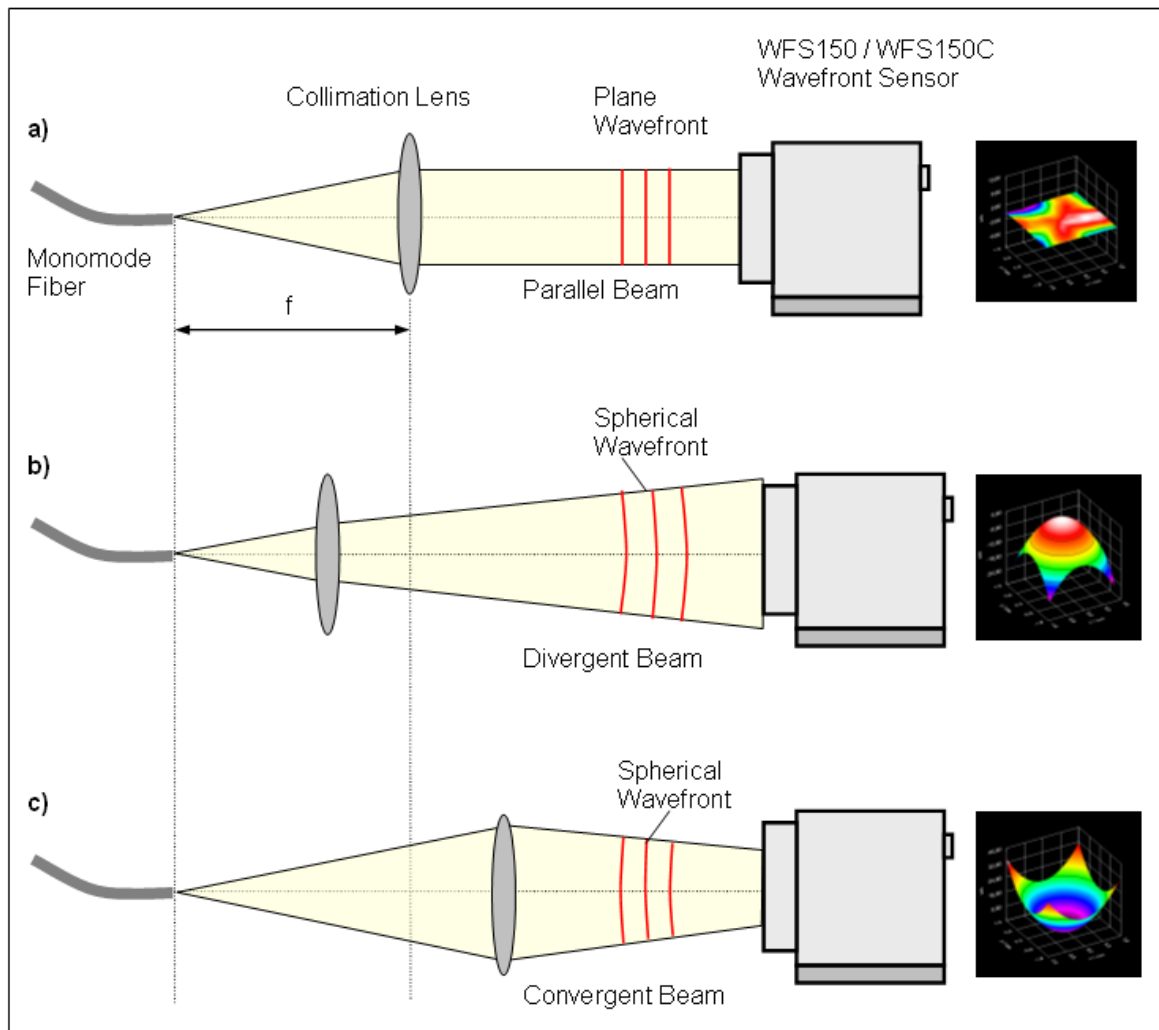
Due to the implemented automatic shutter control of the CCD camera the Wavefront Sensor can handle optical power in a wide dynamic range. Note that the sensitivity is strongly wavelength dependent, see [Typical Wavelength Curves](#). Especially at the edges of the sensitive wavelength range (200 - 1100 nm for WFS150C) there is a drastically reduced sensitivity which allows measurement of higher power sources directly. On the other hand, the Wavefront Sensor can get saturated for small beams at the lower mW levels. Use an external attenuator in that case.

During operation keep in view the on the error window at the bottom. Care about the 'Power too low', 'Power too high' and also 'High Ambient light level' error and find a way to correct the power level accordingly. See [Measurement Warnings and Errors](#) chapter for details.

Example Measurements

The following picture illustrates a very simple example measurement that should establish understanding of what a wavefront is and how it can be influenced.

- a) A collimation lens (e.g. bi-convex) positioned at the distance f (its focal length) from a monomode fiber end face will generate an exactly parallel beam with a plane wavefront.

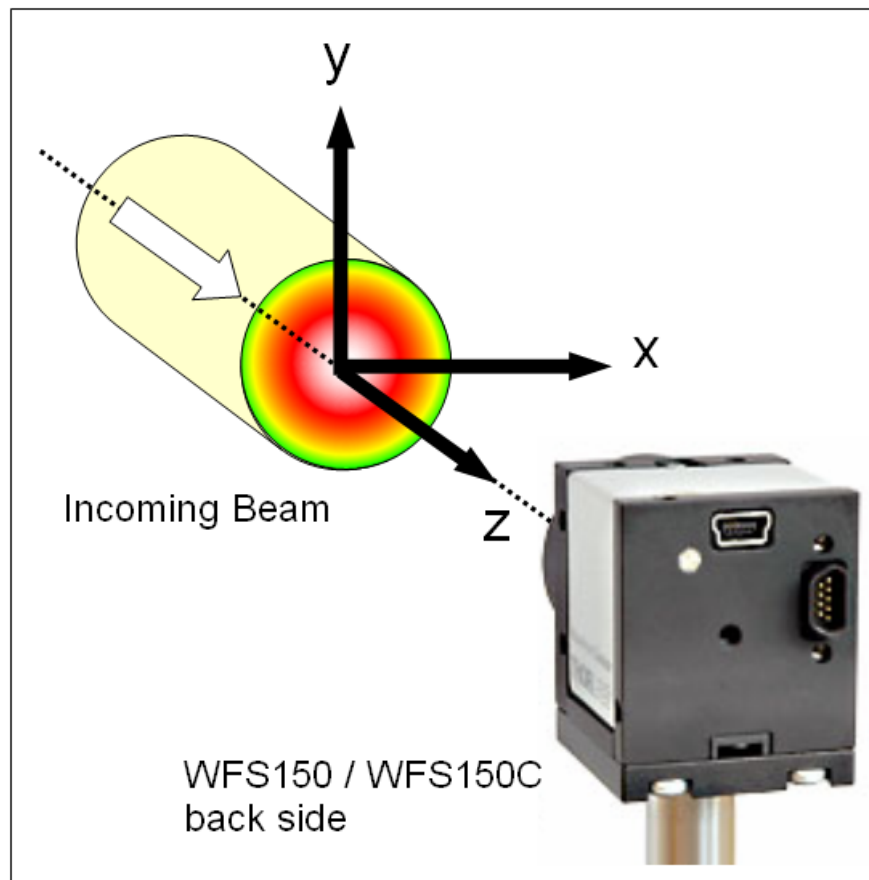


- b)** A movement of the lens towards the fiber end (or even removing the lens) generates a slightly divergent beam which increases in diameter on the way to the Wavefront Sensor. Since the speed of light is the same for all rays within a beam, the wavefront at the outer area falls back behind the center rays. The wavefront is displayed spherical convex, the appropriate Zernike term 'Defocus' is indicating the spherical wavefront.
- c)** A movement of the lens towards the light source will generate a converging beam decreasing its diameter on the way to the Wavefront Sensor. When the Wavefront Sensor would be replaced by a canvas, a focal point would be seen somewhere behind the sensor position. This makes clear that the wavefront before was also spherical but is now displayed spherical concave.

Such an example setup can be used to check the quality of optical fiber collimators. During manufacturing the correct position of the collimation lens is adjusted until the measured wavefront becomes flat and the calculated Zernike coefficient Z_5 describing 'Defocus' becomes zero ($Z_5 = 0$). This procedure is faster and much more precise than the conventional method using a Beam Profiler which is moved back and forth in order to ensure a constant beam diameter.

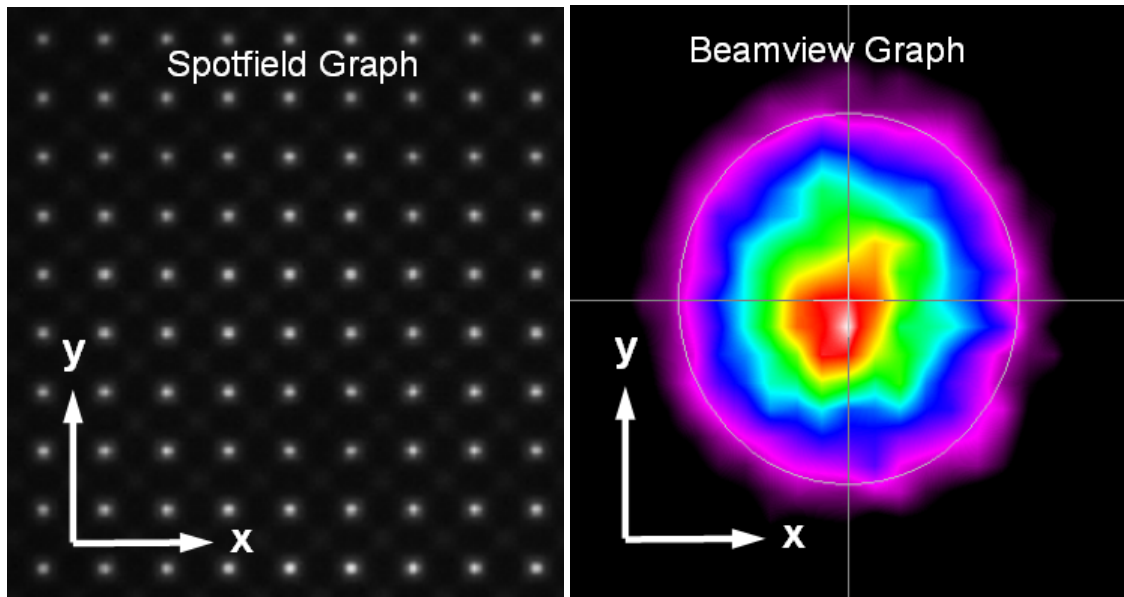
4.2.1 Coordinate Definitions

The WFS150/ WFS150C Wavefront Sensors is using a orthogonal right-hand coordinate system (x,y,z) that is defined as follows:

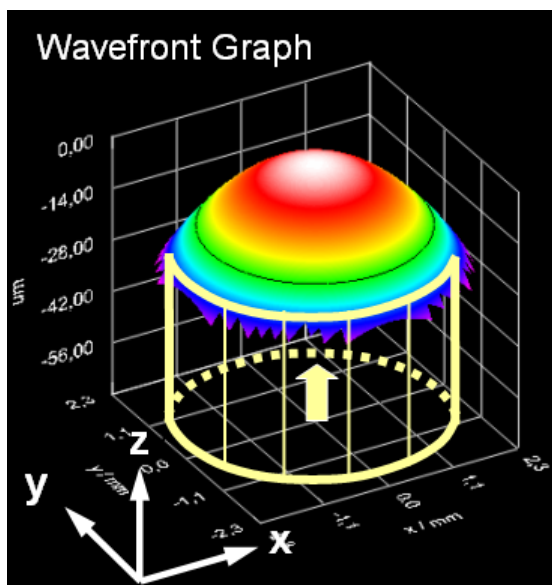


Imagine you are within the Wavefront Sensor and are looking towards the light source. Then the x-direction points towards right and the y-direction points up whereas the optical beam to be analyzed is propagating in z direction towards the entrance aperture of the Wavefront Sensor.

The graphs within the Wavefront Sensor GUI (Spotfield, Beamview) are defined the same way, that is the positive x axis points rightwards and the y axis points upwards.



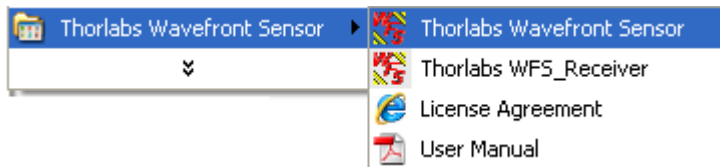
Within the 3D wavefront graph the beam's cross section lies within the x-y-plane that is perspectively drawn at the bottom whereas the z-axis points upwards. Imagine the beam is coming from beneath, so the displayed 3D curve will represent the wavefront at the top of the beam.



4.3 The Graphics User Interface (GUI)

4.3.1 Start the GUI

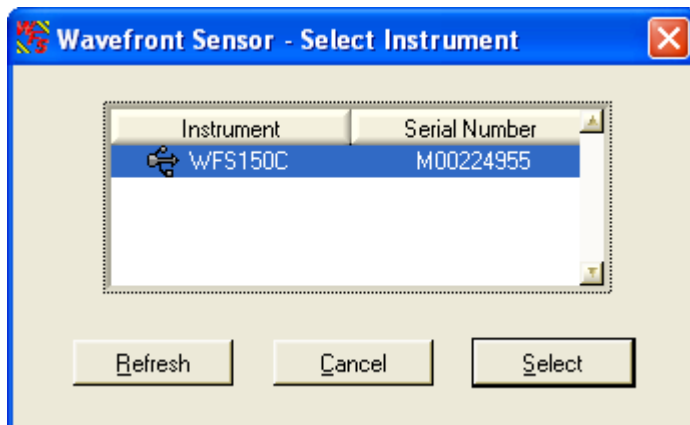
The Graphics User Interface (GUI) is started by running the program wfs.exe in the 'Program Files \ Thorlabs Wavefront Sensor' folder by using either the Wavefront sensor icon on the desktop or from the START menu selecting the "All Programs" → "Thorlabs Wavefront Sensor" → "Thorlabs Wavefront Sensor" entry.



'Thorlabs WFS_Receiver' is a demo program to show the transfer of measurement data to a customer's application that will receive the live data stream.

'License Agreement' will display the License Agreement and 'User Manual' will open the Wavefront Sensor Operating manual using the Adobe Acrobat® Reader.

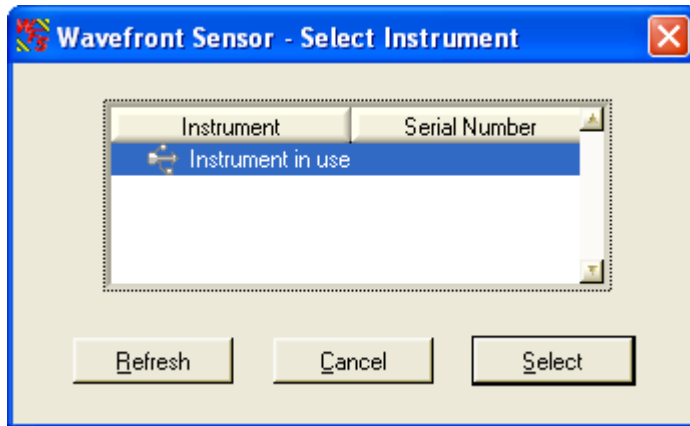
'Thorlabs Wavefront Sensor' is the application program, click on this entry and the Wavefront Sensor software will start with the following dialog box.



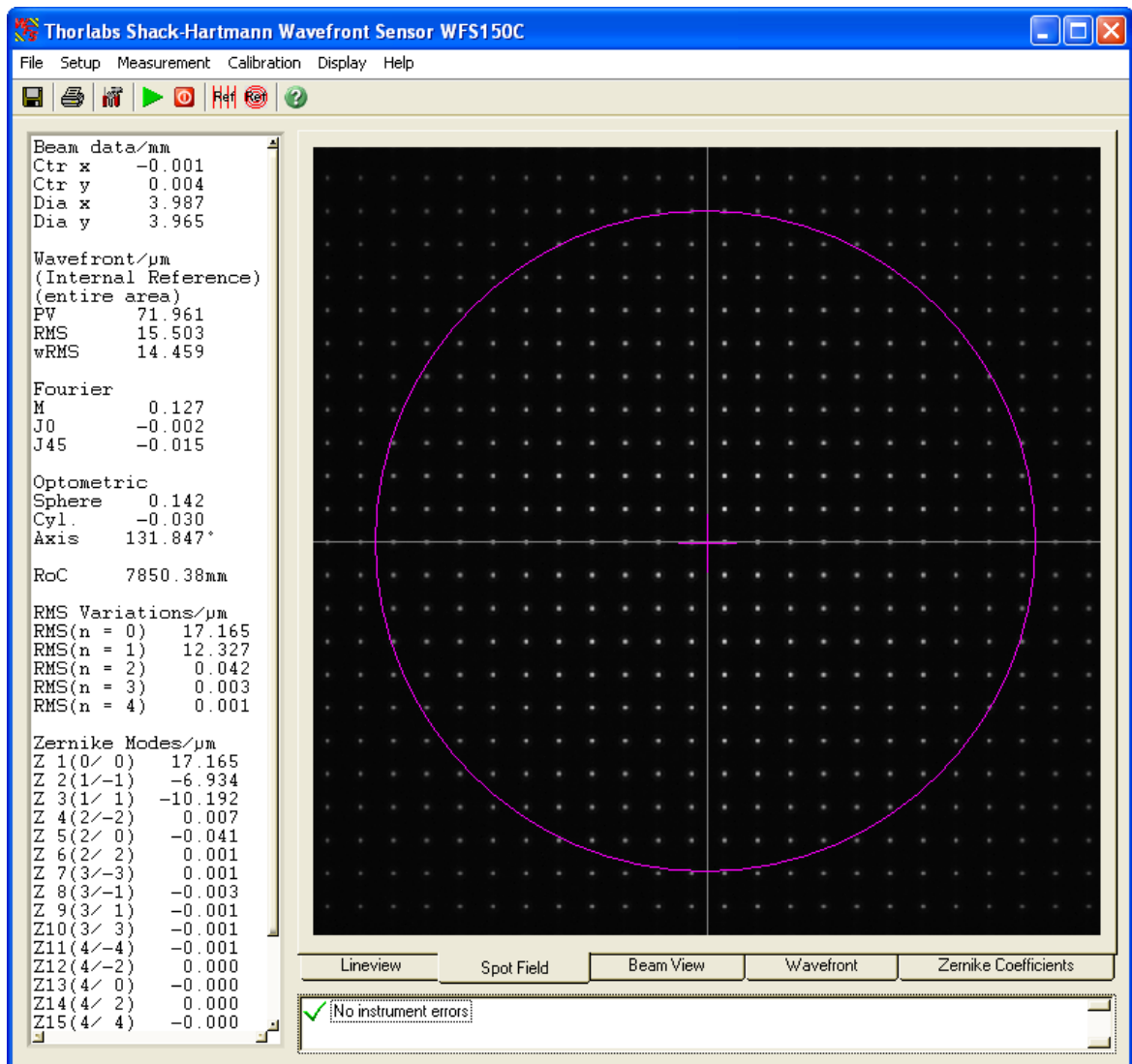
If there is no entry to be seen, click on 'Refresh' to update the list of available Wavefront Sensor instruments. If there is still no instrument displayed please refer to the [Troubleshooting](#) chapter.

You can also operate two or more Thorlabs Wavefront Sensors at the same time on the same computer by starting the application software again. In this case, mark the desired instrument in the list and press 'Select' or just double-click the entry.

An instrument which is already in use is marked correspondingly and cannot be opened as long as the appropriate application was not finished.



The selected Wavefront Sensor starts to work and the Graphical User Interface (GUI) displays the measured data. The GUI looks like this:



The Wavefront Sensor model is displayed in the title bar of the panel. The software starts displaying the actual camera image which is called the 'Spot Field'.

Change the program window size according to your preferences. The actual

setting is stored and is applied when the Wavefront Sensor application software is started again.

At first program start all Wavefront Sensor settings and GUI configurations are set to default values. Read the [Wavefront Sensor Setup Panel](#) chapter carefully and configure the Wavefront Sensor software according to the beam properties and your specifications.

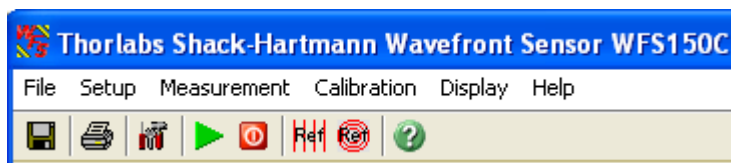
4.3.2 Operating the Wavefront Sensor Software

Now let's get familiar with the Wavefront Sensor GUI.









You can either use the menu or just click a symbol on the tool bar to operate the Wavefront Sensor application software.

4.3.2.1 Menu and Toolbar

The toolbar allows access to the most common menu functions by simply clicking on the appropriate symbol.





Toolbar symbols         are standing for:

	Save Measurement Data
	Print Window
	Setup Wavefront Sensor
	Start Measurement
	Stop Measurement
	Calibrate with Plane Wavefront
	Calibrate with Spherical Wavefront
	Show Help File

The following list contains all menu entries and also lists the appropriate short cut keys and toolbar symbols

File

Measurement File Preferences
 Save Measurement Data (Ctrl + S) 


 Print Window (Ctrl + P) 
 Print Graph Only

 Exit Program

SetupWavefront Sensor 

Configure Lineview
Configure Spotfield
Configure Beamview
Configure Wavefront Graph
Configure Zernike Bar Graph


DataSocket

MeasurementStart Measurement F2 Stop Measurement F3 **Calibration**Plane Wavefront Spherical Wavefront 

Save Spotfield Reference
Load Spotfield Reference

Display

Lineview
Spotfield
Beamview
Wavefront
Zernike Coefficients

HelpContents F1 

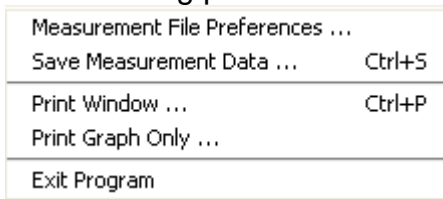
Visit the Thorlabs Website
View License Agreement

About

Explanation of the menu items

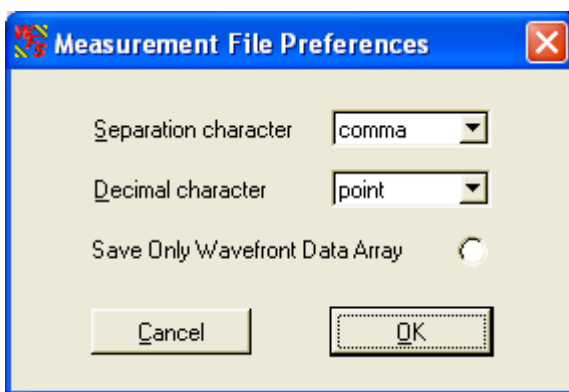
1. File

The following pull down menu occurs:

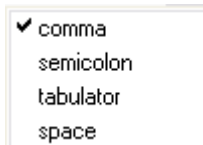


•Measurement File Preferences

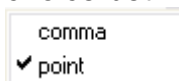
The following popup window occurs, it enables you to set the attributes of the measurement data file:



You can choose a 'Separation character' that separates two successive data values within a text line out of the following:

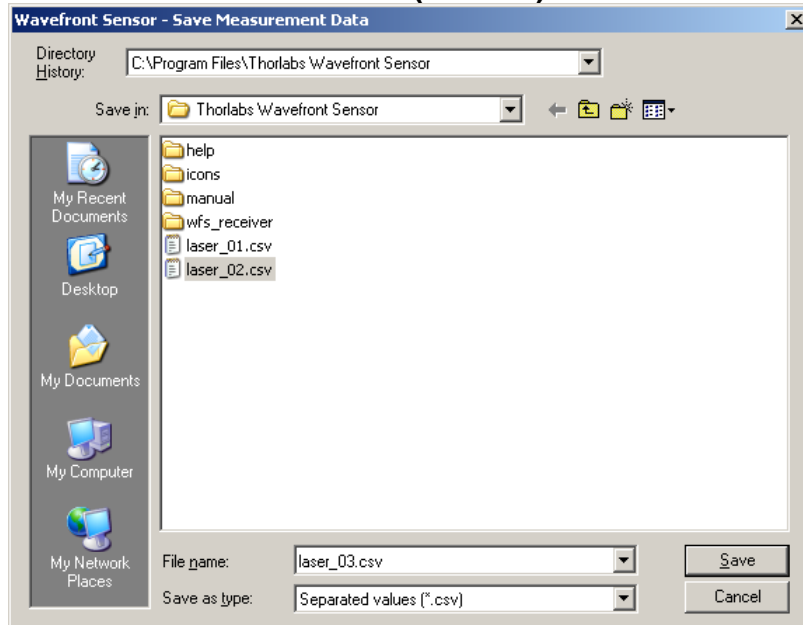


For 'Decimal character' which is whether decimal point or comma you have the choice between the following:



With '**Save Only Wavefront Data Array**' you suppress all single measurement results of the Wavefront Sensor File, and only the measured Wavefront data array will be stored. This option is helpful when you want to process the measured wavefront data for yourself using programs like Microsoft Excel®.

• Save Measurement Data (Ctrl + S)



Choose drive and path for storing data within and type in a name for your Wavefront Sensor data file and click 'Save'. The content and format is defined in the 'Measurement File Preferences' panel, see above.

• Print Window (Ctrl + P)

• Print Graph Only

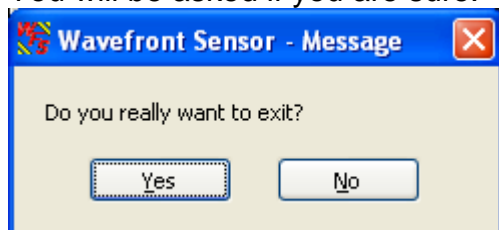
The Wavefront Sensor software enables the user to print out a screen shot of whether

- the entire panel or
- the graph only (the right hand panel with changing content)

on a printer installed under Microsoft Windows®. Refer to the [Printing](#) chapter for a detailed description of the available features.

• Exit Program

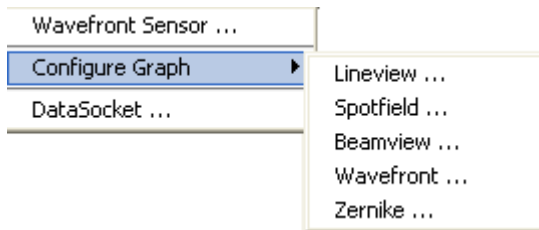
You will be asked if you are sure.



Hit 'Enter' or click 'Yes' for leaving the Wavefront sensor GUI or 'No' for continued operation.

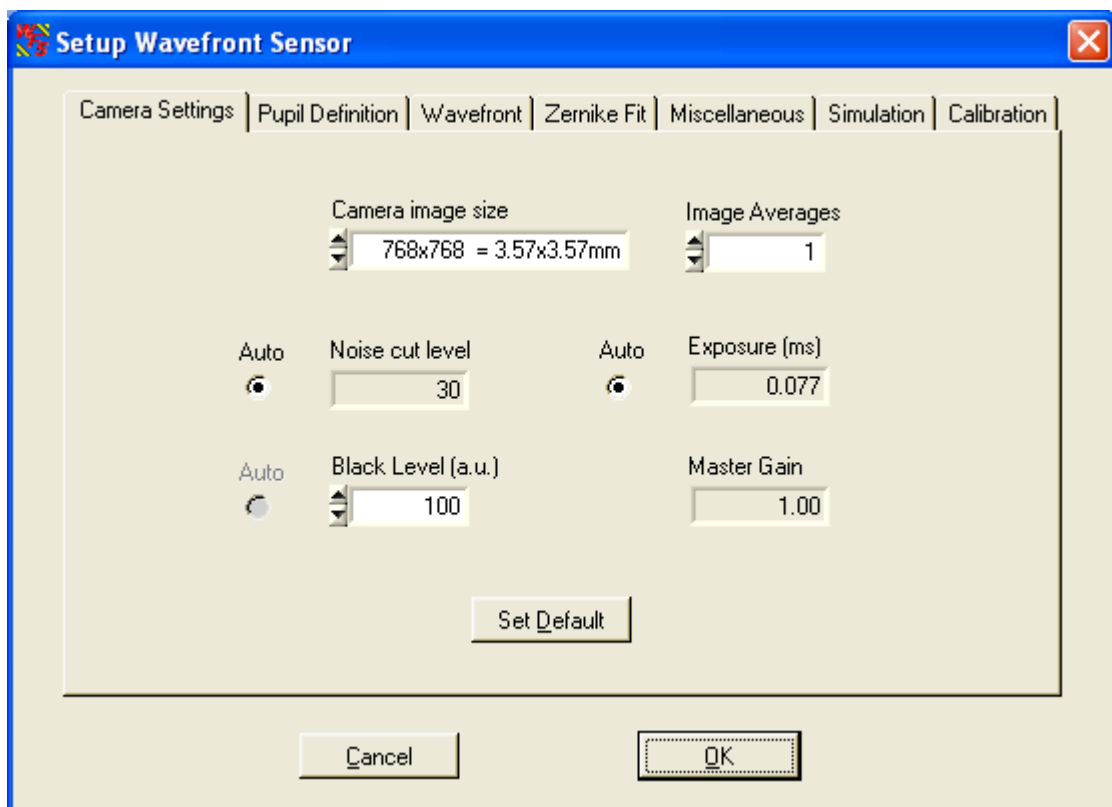
2. Setup

The following pull down menu occurs:



•Wavefront Sensor

Opens the Setup panel of the Wavefront Sensor that will give you the ability to change important setup parameters for the actual wavefront measurement like active camera area, pupil definitions or settings for the Zernike fit.



See the [Wavefront Sensor Setup Panel](#) chapter for a detailed description of all setup controls.

•**Configure Graph** → **Lineview / Spotfield / Beamview / Wavefront / Zernike**
 Opens a configuration panel to the appropriate graphical display. A more direct way to open these configuration panels is to **double-click onto the graphical panel you like to configure**.

•DataSocket

Will display a dialog panel for enabling and configuring the live transfer of measurement data via DataSocket to another application. See [DataSocket for live data transfer](#) for details.

3. Measurement

The following pull down menu occurs:

Start	F2
Stop	F3

•Measurement Start

Starts continuous Wavefront Sensor measurements and displays the results on the screen.

•Measurement Stop

Stops the Wavefront Sensor measurement immediately and terminates the screen updates to keep the actual displayed graphical plots and numerical values to survey and/or save these data.

Note: On occurrence of serious Wavefront Sensor errors the continuous measurement will stop automatically and you will be asked to change settings and to re-start the continuous measurement again.

4. Calibration

The following pull down menu occurs:

Plane Wavefront ...
Spherical Wavefront ...

There are two different ways to perform a User Calibration of the Wavefront Sensor. See chapter [User Calibration](#) for a detailed description.

5. Display

Lineview
Spotfield
Beamview
✓ Wavefront
Zernike Coefficients

See the following chapters for a detailed description of the interchangeable graphical displays. Alternatively click on the tabs below the graphics to see the desired one.

Lineview	Spot Field	Beam View	Wavefront	Zernike Coefficients
----------	------------	-----------	-----------	----------------------

6. Help

The following pull down menu occurs:

Contents ...	F1
Visit the Thorlabs Web Site	
View License Agreement	
About ...	

•Contents

This opens the Wavefront Sensor help file. It contains the same information as the manual but enables the advantage to search for key words.

•Visit the Thorlabs Website

You were directed to the Thorlabs website at www.thorlabs.com that contains information about new software releases or related products.

- **View License Agreement**

The Thorlabs End-User License Agreement you agreed with is displayed.

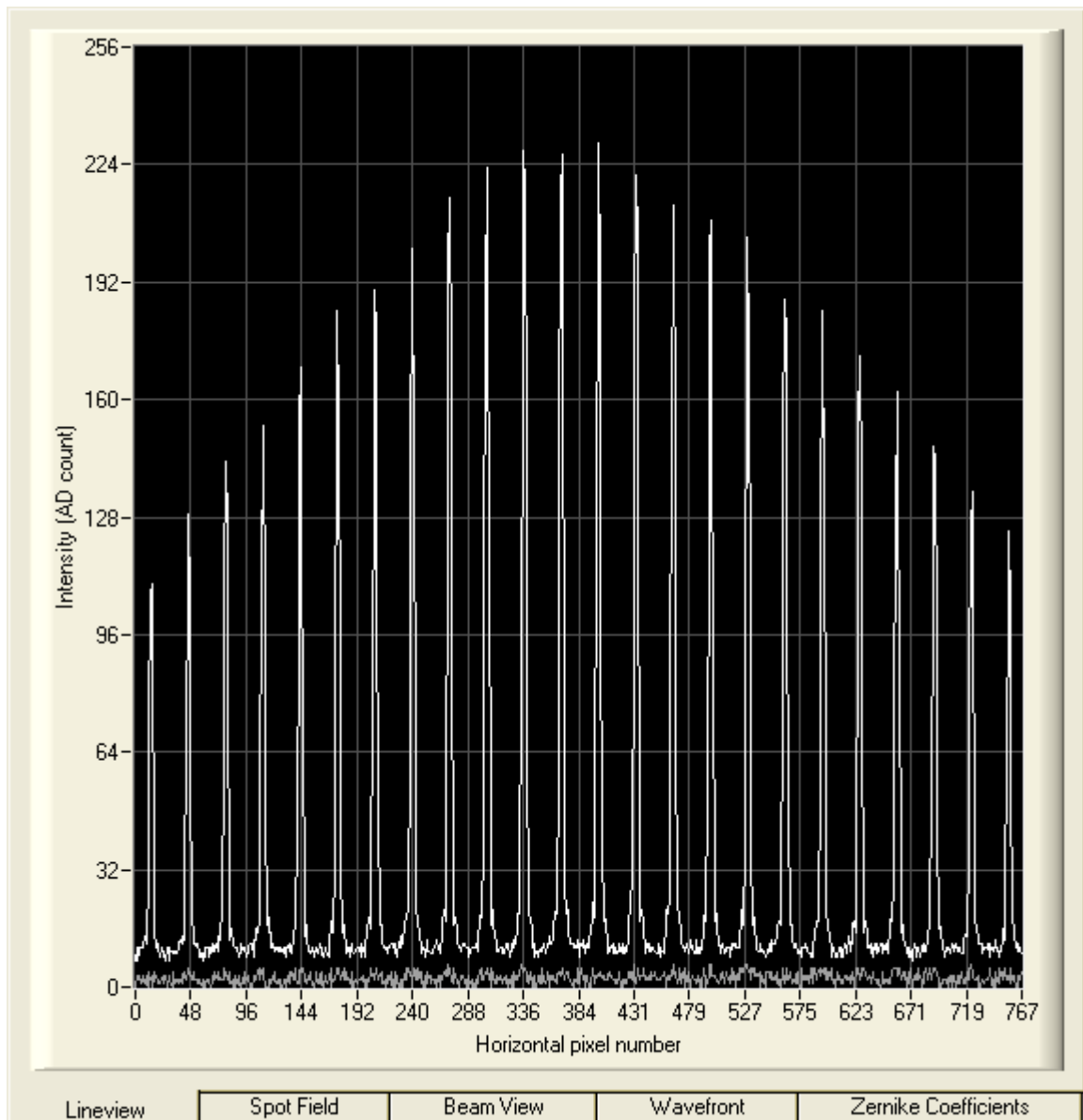
- **About**

Shows you the actual software release versions, the Instrument Name and Serial Number of the used device.



4.3.2.2 Lineview Panel

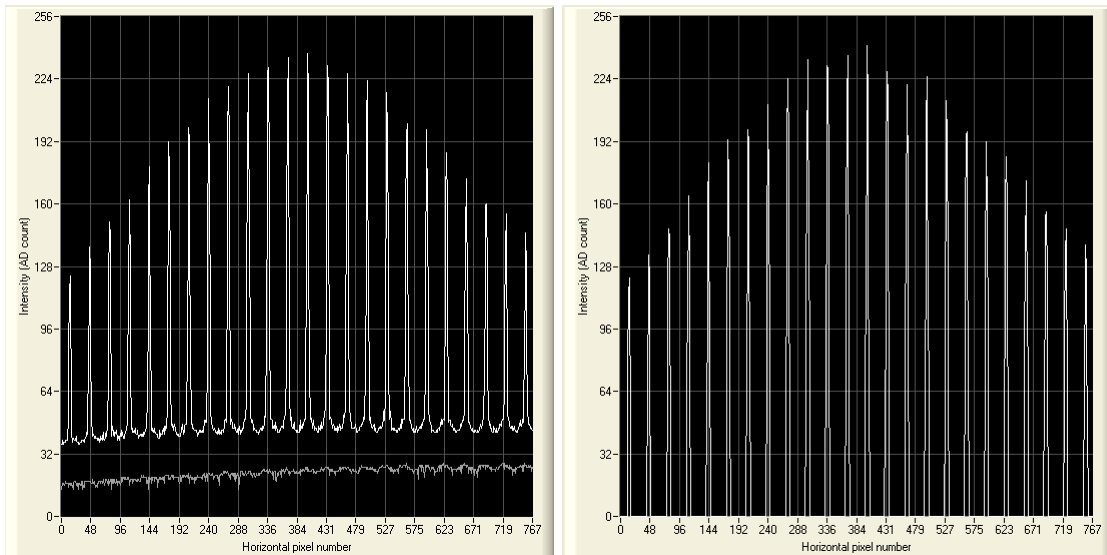
This graph displays the horizontal intensity distribution of the CCD camera. Each point on the horizontal axis of the diagram correspond to one column of the CCD array and displays both the minimum (gray, at the bottom) and the maximum intensity level (white) of the entire pixel column. The peaks are due to the focusing ability of the lenslet array that concentrate the intensity within small spots.



This graph is useful to check the power level of the analysed beam, especially when the automatic brightness control is disabled. Improperly manual camera settings will lead to low or saturated peak intensities or saturation. Prevent both by proper adjustments of the exposure time and master gain (see chapter [Camera Settings](#)).

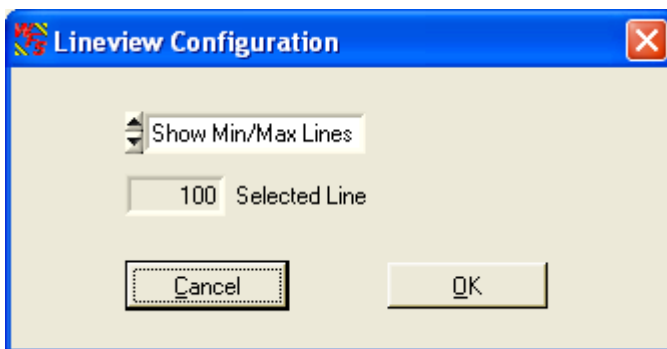
Also the 'Black Level' camera setting adjusts an offset brightness level for all illuminated pixels and should be adjusted so that the minimum line visible within this panel is to be seen above zero. See chapter [Camera Settings](#) for a detailed description.

Furthermore, the effect of choosing a manual '**Noise cut level**' that defines a brightness level in digits which needs to be exceeded by the spots in order to be recognized, can be observed in this Lineview panel. For instance, an increased ambient light level that will influence the determination of spot centroids, can be rejected by setting the 'Noise cut level' to a value higher than the valleys in the diagram.



The example illustrates the effect when the 'Noise cut level' is changed from 0 (left) to 50 (right).

Double click on the graph to see the '**Lineview Configuration**' panel.



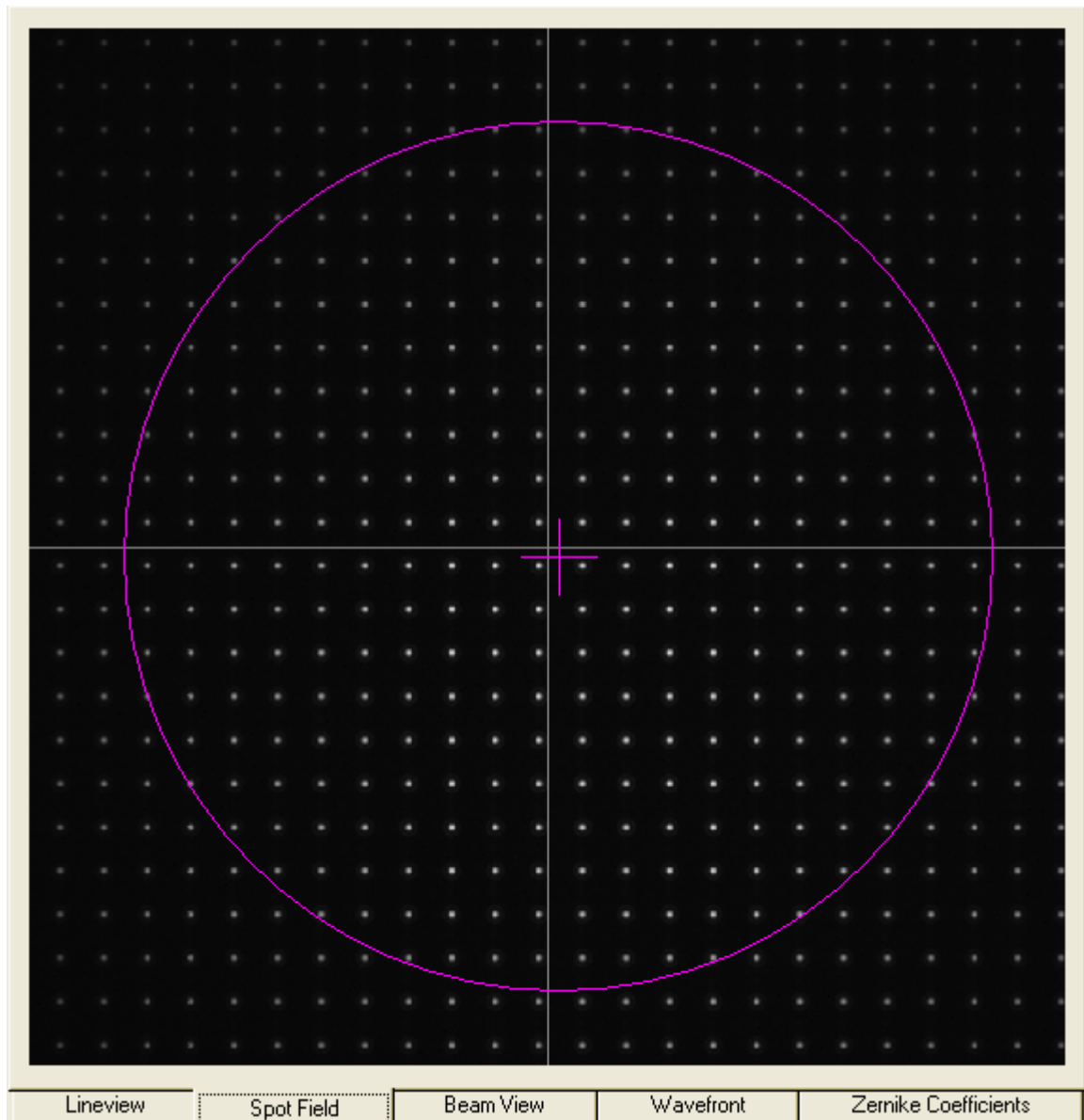
The option '**Show Min/Max Lines**' is enabled by default and will display a graph with two curves. Each point of the upper curve (white) displays the maximum and each point of the lower curve (gray) displays the minimum intensity of the appropriate CCD column.



Switch to '**Show Single Line**' in order to enable selection of a single line out of the CCD array. Enter the line number into the control '**Selected Line**' to see the intensity distribution of the appropriate CCD row. The line number ranges from 0 (bottom) to the number of vertical pixels - 1. The selected line is marked within the [Spotfield Panel](#).

4.3.2.3 Spotfield Panel

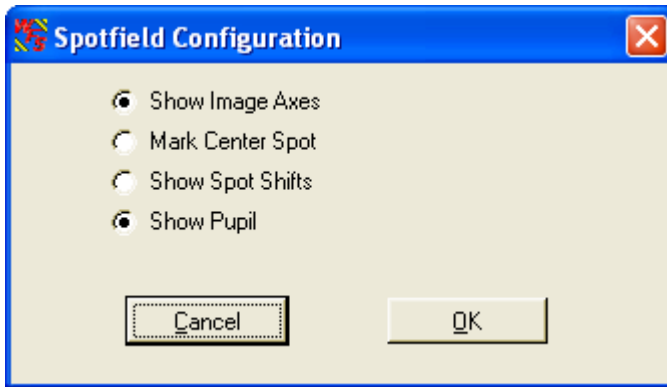
The Spotfield panel allows a direct view of the image taken by the CCD camera. Intensity levels are displayed as gray scale from 0 = black to 254 digits = white and saturation is indicated by red colored pixels.



Select the camera resolution and therewith the number of spots in horizontal and vertical direction using the [Camera Settings](#) panel. It is recommended to select the camera resolution and therewith the active sensor area to be a bit larger than the analyzed beam. A too large area will contain lots of undetectable spots that cannot be converted to wavefront data and also will decrease measurement speed.

In addition a few more graphical elements can be superimposed to the image.

Double click on the graph to see the '**Spotfield Configuration**' panel.

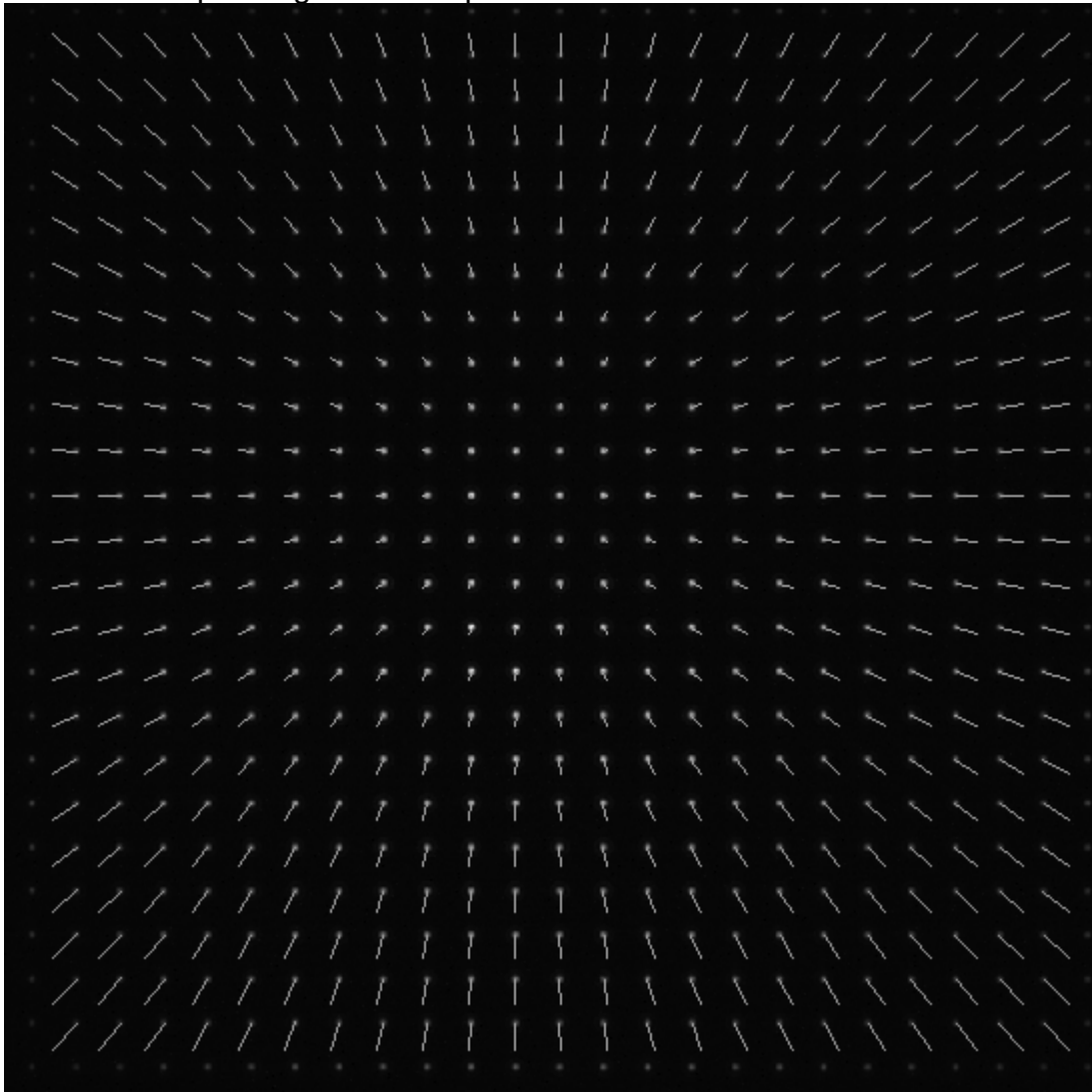


Enable the appropriate option to visualize the graphical items:

'Show Image Axes' displays the center axis in horizontal and vertical direction.

'Mark Center Spot' marks the spot at the image center from that acts as a starting point for the centroid determination algorithm.

'Show Spot Shifts' displays a short gray line between the actual spot position and its corresponding reference position.



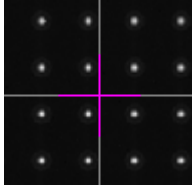
'Show Pupil' displays a circle or an ellipse (magenta) that illustrates the actual

pupil size and position.

Use this panel with activated option 'Show Pupil' for interactive beam alignment to the Wavefront Sensor. Only the spots detected within the pupil will contribute to the calculation of the Zernike fit.

Note: The '[Use Beam Centroid](#)' option needs to be activated in the [Pupil Definitions Setup](#) panel to show the actual beam centroid.

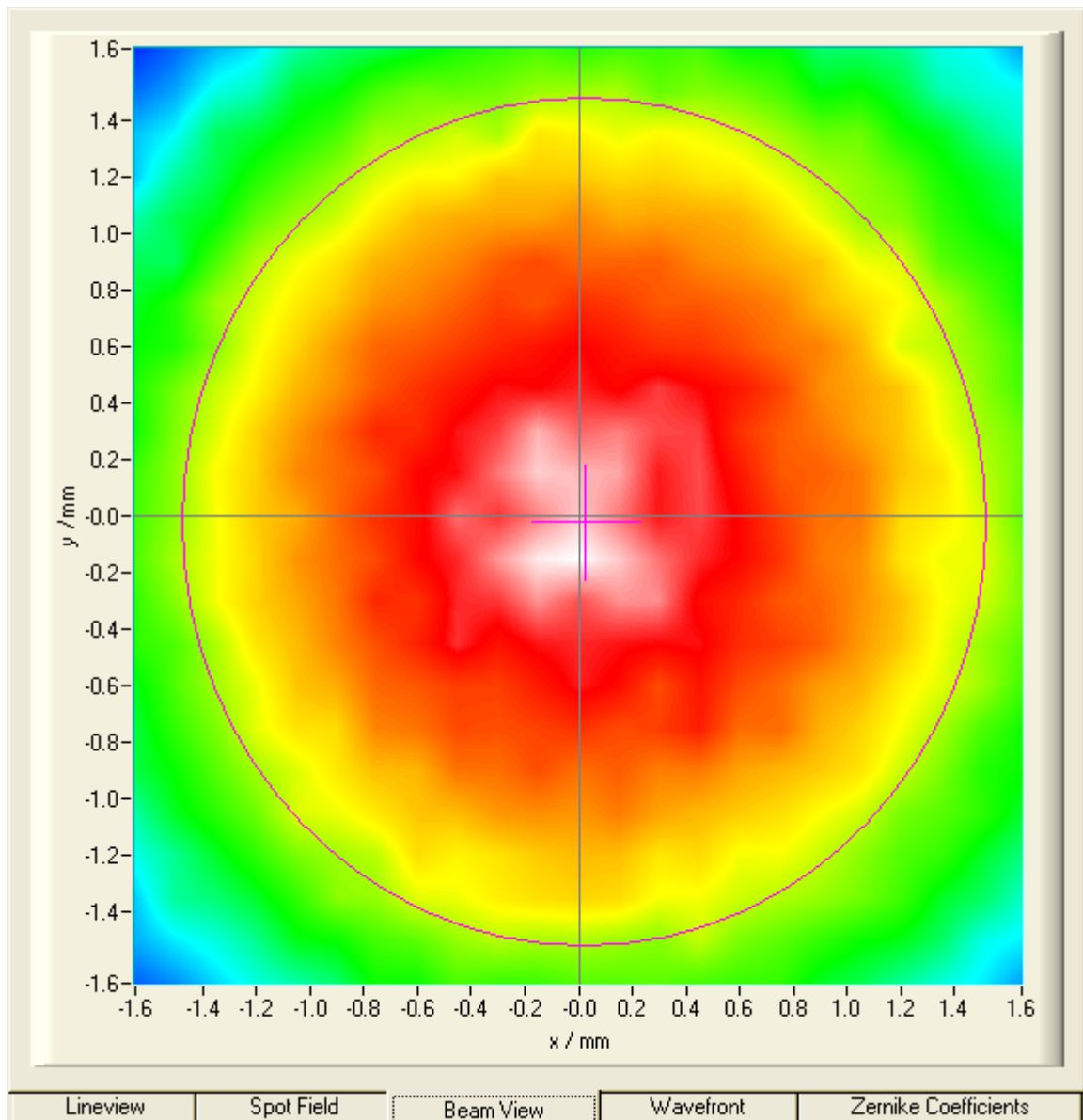
Align the beam so that the center cross of the pupil coincides with the center image axis.



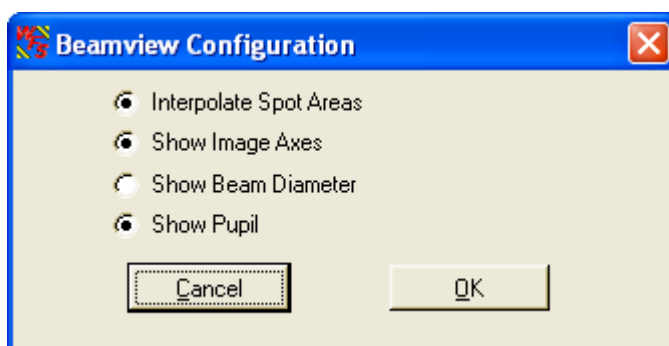
4.3.2.4 Beam View Panel

The Beam View panel gives you an overview about the intensity distribution within the active camera sensor area. This display is comparable to that of a camera based Beam Profiler, but with the constraint of very poor resolution.

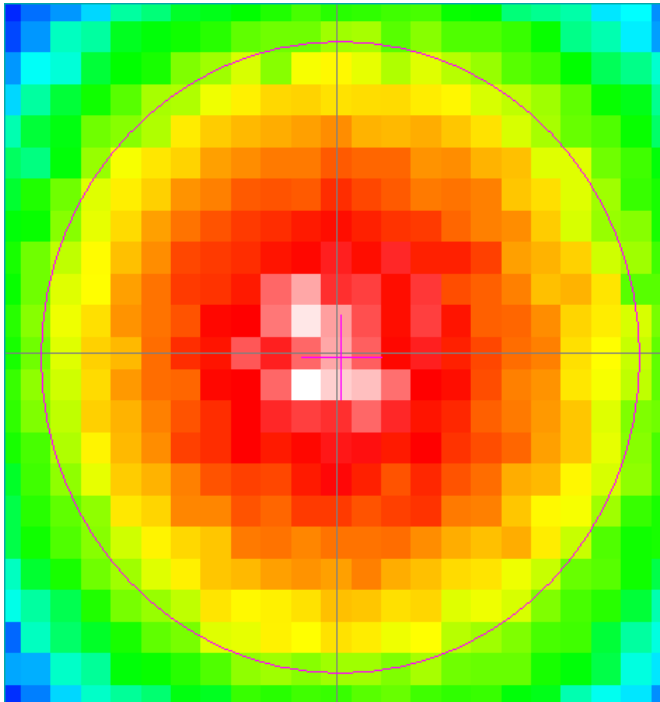
The lateral resolution is not determined by the camera pixel size like in case of a real Beam Profiler, but rather given by the pitch of the lenslet array. One point of the displayed intensity array is derived from the calculated mean intensity of the corresponding spot.



Double click on the graph to see the '**Beamview Configuration**' panel.



'**Interpolate Spot Areas**' will do an interpolation between the coarse array of measured intensity points. If switched off, the real lateral resolution becomes visible.



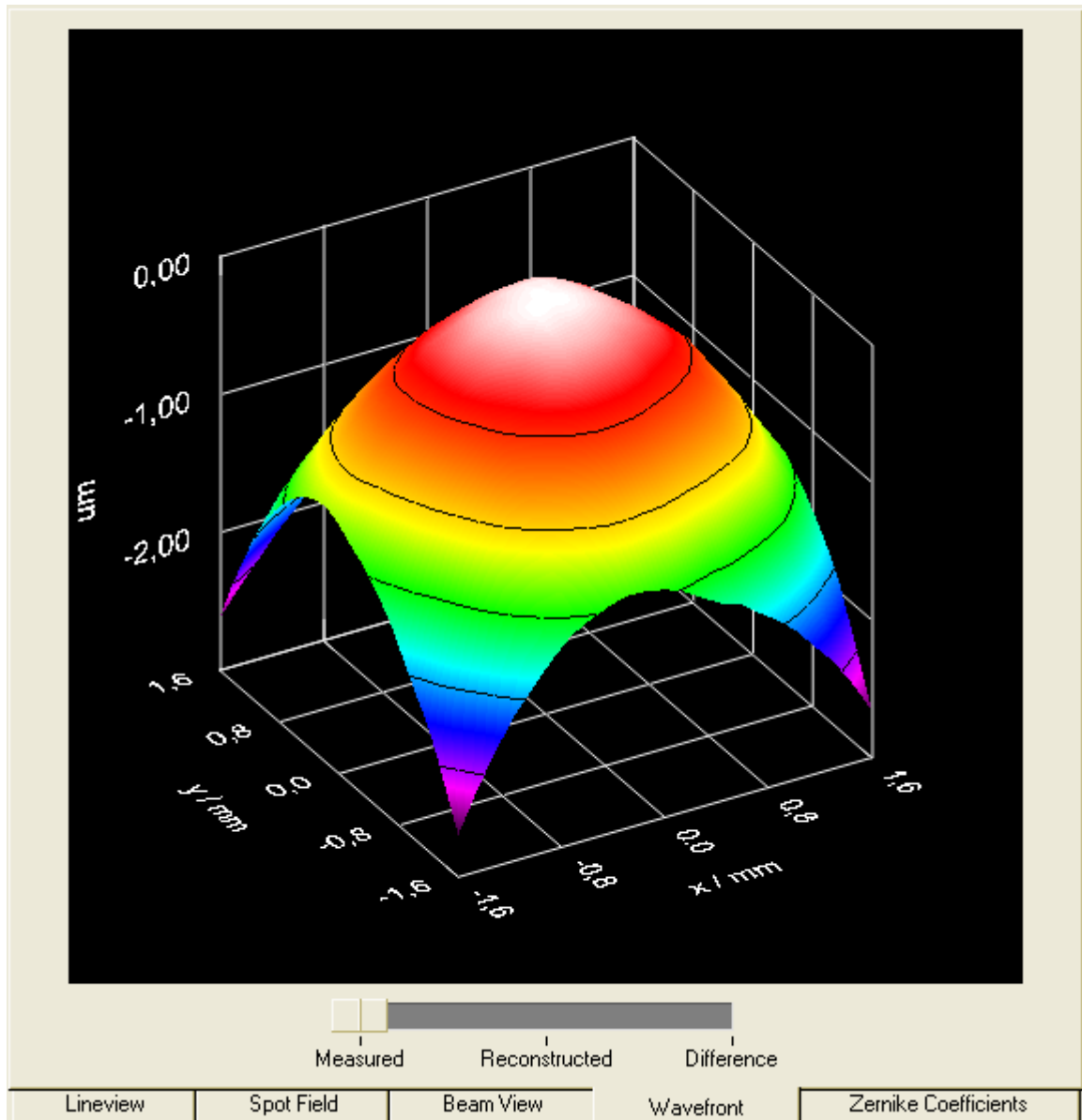
'**Show Image Axes**' displays the center axis in horizontal and vertical direction.
'**Show Beam Diameter**' displays a circle or an ellipse (light gray) that illustrates the actual beam diameter and position.

'**Show Pupil**' displays a circle or an ellipse (magenta) that illustrates the actual pupil size and position.

Note: Usually, there is a difference between the actual beam size and position and the actual pupil size and position. Only in case you marked '**Use Beam Width**' and '**Use Beam Centroid**' options within the [Pupil Definitions Setup](#) panel both parameters coincide.

4.3.2.5 Wavefront Panel

The Wavefront panel contains a 3D diagram that displays the measured wavefront. The wavefront data array is retrieved from the spot shifts which are directly proportional to the local derivatives of the wavefront. A two-dimensional integration process, starting at the center spot, leads to the wavefront data.



The wavefront deformation is displayed in direction of the z-axis and the base surface, defined by the x and y axis, is parallel to the beams cross section. You can choose the wavefront unit to microns (μm) or waves. Refer to the [Wavefront Sensor Setup Panel](#).

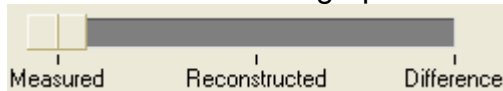
The surface is displayed in a color spectrum whereas the assignment between color and curve height is always the same:

black, magenta	lowest wavefront parts
green	medium
red, white	highest wavefront parts

When the option '**Limit wavefront calculation and display to pupil interior**' is enabled within the [Pupil Definitions Setup](#), only measured wavefront data within the defined pupil are displayed. This can be advantageous in case the wavefront measurement outside the pupil is affected by low light intensity which leads to a noisy behavior.

Wavefront Select Switch

The switch below the graph determines the wavefront type that is displayed.



'**Measured**' shows the wavefront which is directly calculated from the measured spot deviations using a 2-dimensional integration.

'**Reconstructed**' will display a wavefront that is reconstructed using all or only a selected set of the determined Zernike coefficients. The advantages of this display is:

- The wavefront surface is smoothed because noise is cancelled out when only a few low order Zernike modes are selected for reconstruction.
- Lowest order Zernike terms which are always present but are of less interest (for instance piston, tip, tilt) can be cancelled in order to see only the higher order modes of interest.
- Only particular Zernike modes that are enabled within the [Zernike Fit Setup](#) panel can be displayed and analyzed separately.

'**Difference**' displays the difference between the measured and reconstructed wavefront and is therefore an indicator of the fit error.

Note: The actual switch setting is also important to the calculated wavefront statistics **PV**, **RMS** and **wRMS** (see [Measurement Results](#)) because the displayed values refer to the selected wavefront (Measured, Reconstructed or Difference).

Direct rotation, zoom and shifting of the 3D graph

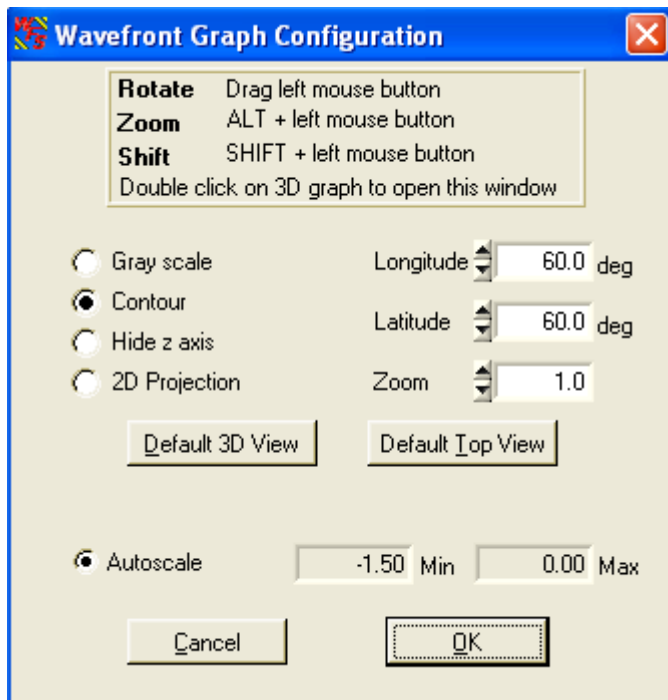
You can zoom and shift the displayed 3D beam profile using the mouse and modifier key Alt and Shift:

To **rotate** the graph about both longitude and latitude angles just click and hold the **left mouse button** on the graph and drag it.

To **zoom** press and hold **Alt** key, then click and hold the **left mouse button** while moving the mouse.

Shifting the graph within the drawing area is done with pressing the **Shift** key and holding the **left mouse button** while dragging the mouse.

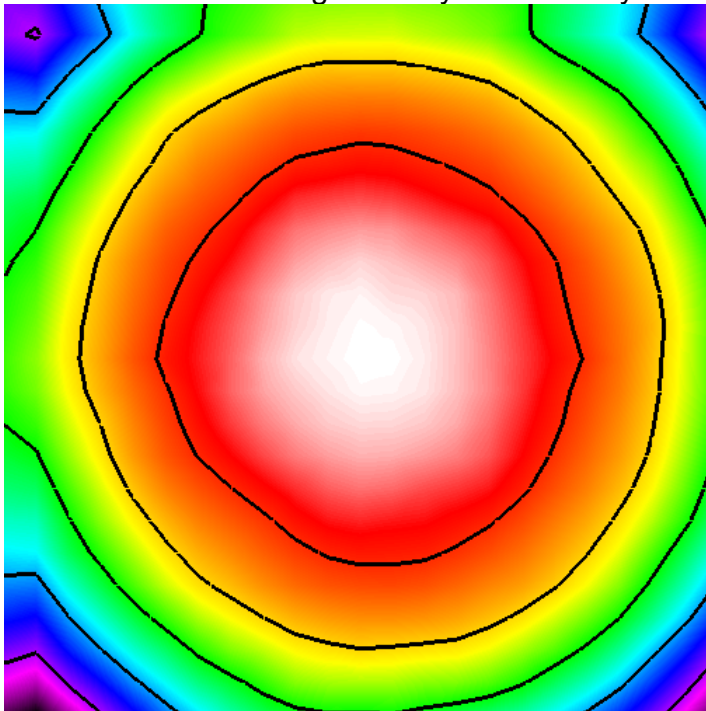
Double click on the graph to see the '**Wavefront Graph Configuration**' panel.



There are two predefined view adjustments, 'Default 3D view' and 'Default top view'.

'**Default 3D view**' arranged the view angles so that all three axis are to be seen and the wavefront can be viewed as a 3D curve.

'**Default top view**' sets the 'Latitude' view angle to zero and allows a view parallel to the z-axis towards the x-y plane. The x-y-plane becomes rectangular and the wavefront height is only indicated by its color.



The following options define the look of the 3D graph

'**Gray scale**' switched between a color spectrum and a graduated gray

color palette

'**Contour**'

wavefront height

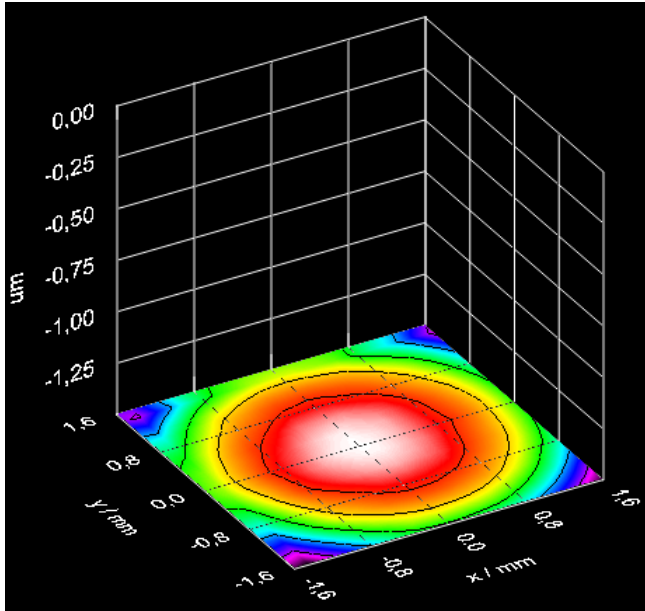
'**Hide z axis**'

'**2D Projection**'

inserts contour lines into the graph indicating lines of equal

hides the z-axis and the corresponding grid and caption

let the 3D graph collapse to the base x-y plane



The following items define the view of the 3D graph

'**Longitude**'

'**Latitude**'

'**Zoom**'

determines the rotation angle about the z axis

determines the view angle to the graph

changes the graph size (range 1...10)

Clicking **Default 3D View** adjusts all controls to the default 3D view whereas **Default Top View** rotated the graph to achieve a top view of the profile. The default top view zoom level of 2 is to visualize the entire active sensor area without its caption.

Autoscale

By default, the graph's z-axis is auto scaled to utilize the full diagram heights, independent of the wavefront dynamic.

Switch the '**Autoscale**' option off to enter manually defined values for the displayed range of the z-axis.



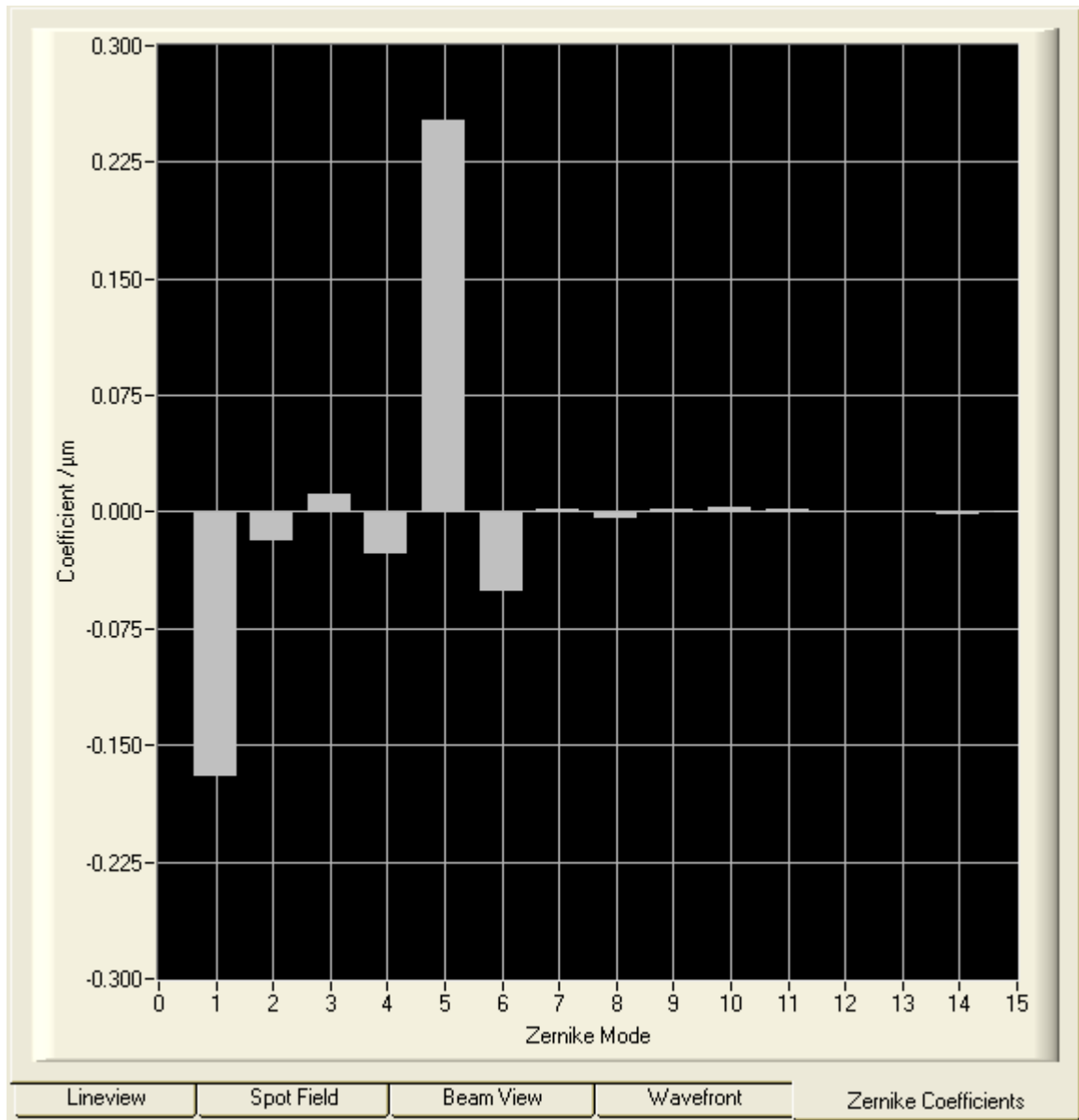
Note: The absolute position of the wavefront surface with respect to the z-axis is determined by the wavefront center that is always set to zero.

Note: Wavefront areas that are not defined because the appropriate spot was not detectable will not be displayed at all.

Click **Cancel** or **ESC** to discard all changes or click **OK** or close the panel if you want to take over the changes.

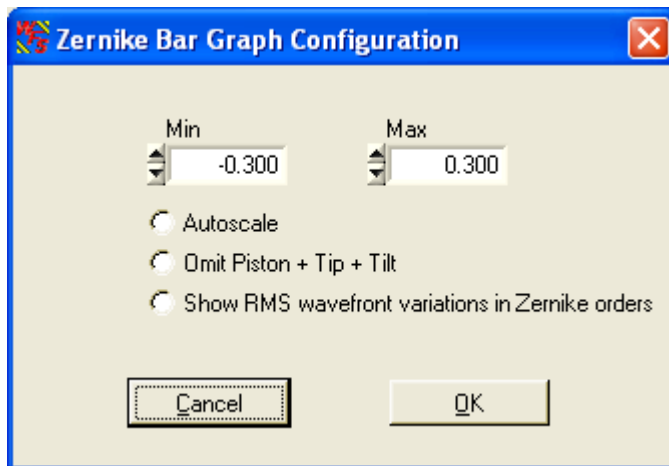
4.3.2.6 Zernike Coefficients Panel

This panel displays a bar graph whereas the vertical bars indicate the Zernike coefficients which are the results of the Zernike fit.



The Zernike coefficients can be positive or negative and indicate that the measured wavefront does contain particular Zernike modes weighted with its coefficient standing for its amplitude.

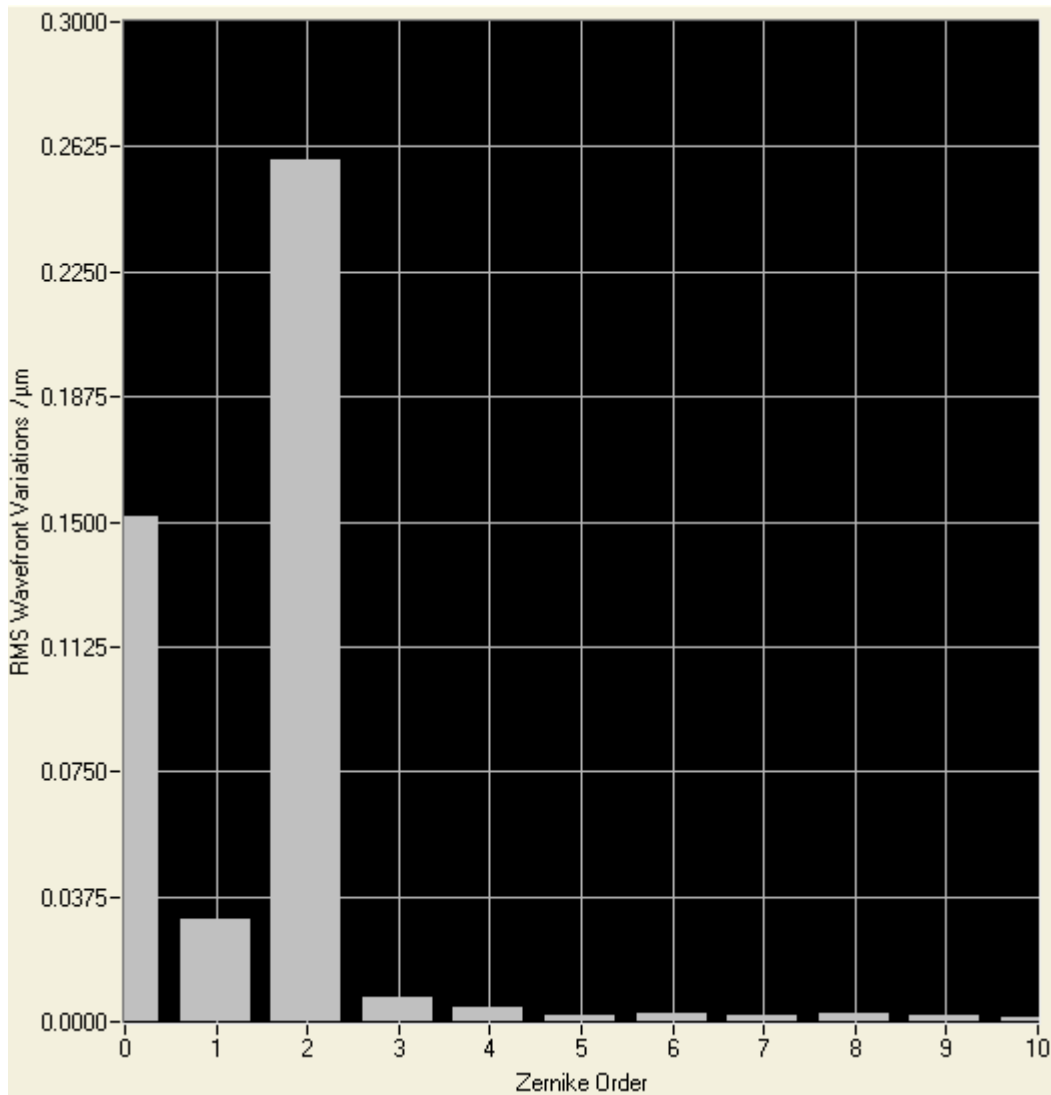
Double click on the graph to see the '**Zernike Bar Graph Configuration**' panel.



By default, the graph's vertical axis is scaled automatically. In case some of the displayed Zernike coefficients are huge compared to other distortions you like to focus on it is advantageous to switch '**Autoscale**' off. Also in case of fluctuating Zernike coefficients that cause a permanently changing vertical scale, it is advantageous to disable 'Autoscale' and to define a fixed range by entering Min. and Max. values manually.

'**Omit Piston + Tip + Tilt**' is normally switched off and all calculated Zernike Modes are displayed. But generally, the lowest order modes Piston and the wavefront's Tip and Tilt are of less interest. Since these lowest order modes may have a considerable higher amplitude than the higher order modes they are disturbing and are dispensable. Enable this option to see only Zernike modes with index 4 and higher.

The option '**Show RMS wavefront variations in Zernike orders**' will change the displayed data content. Not a single Zernike mode is associated to a graphical bar but a summation of all Zernike modes of a particular order.

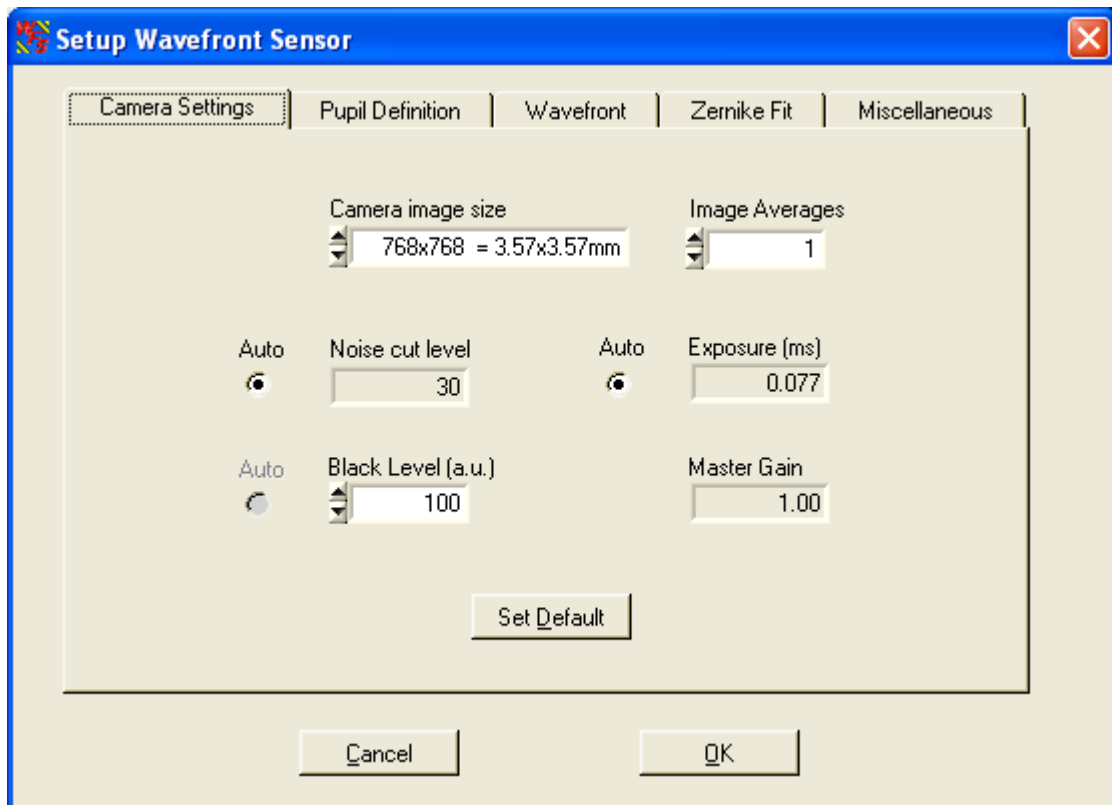


Use the '**Omit Piston + Tip + Tilt**' option to suppress the display of Zernike orders 1 and 2 if they are of less interest.

4.3.3 Wavefront Sensor Setup Panel

The Wavefront Sensor GUI automatically starts measuring the applied wavefront using favorable default parameters. Using these default settings the instrument is able to do first measurements. Nevertheless, it is highly recommended to verify all the applied settings.

To open the setup panel you can use the **Menu** \rightarrow **Setup** \rightarrow **Wavefront Sensor** entry or simply **click right** on one of the graphs on the right hand side of the main panel.



Changing a setup control has immediate influence to the instrument operation or data display. After finalizing changes click '**OK**' to save the actual settings. Also closing the panel will automatically save the settings of all setup controls. By clicking on '**Cancel**' all the changes since opening the panel get lost and the instrument will go back to the state before opening the panel by restoring the previous settings.

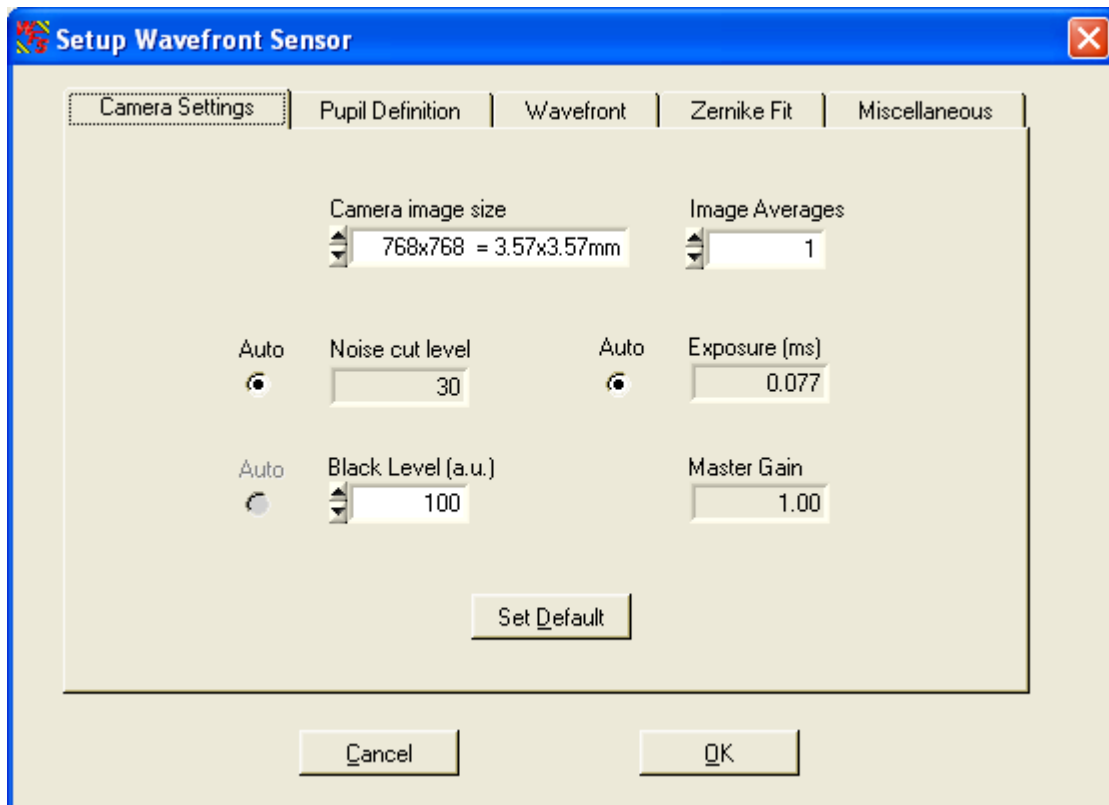
The Setup Panel is divided into five sub panels, accessible by clicking on the corresponding tabs.

- Camera Settings
- Pupil Definitions
- Wavefront
- Zernike Fit
- Miscellaneous

4.3.3.1 Camera Settings Setup

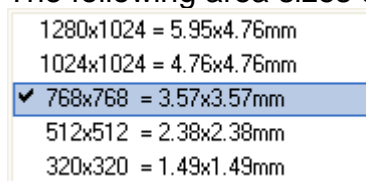
'Camera Settings' handle adjustments concerning the image capturing of the CCD camera.

To open the setup panel you can use the **Menu** → **Setup** → **Wavefront Sensor** entry or simply **click right** on one of the graphs on the right hand side of the main panel. Select the tab '**Camera Settings**'.



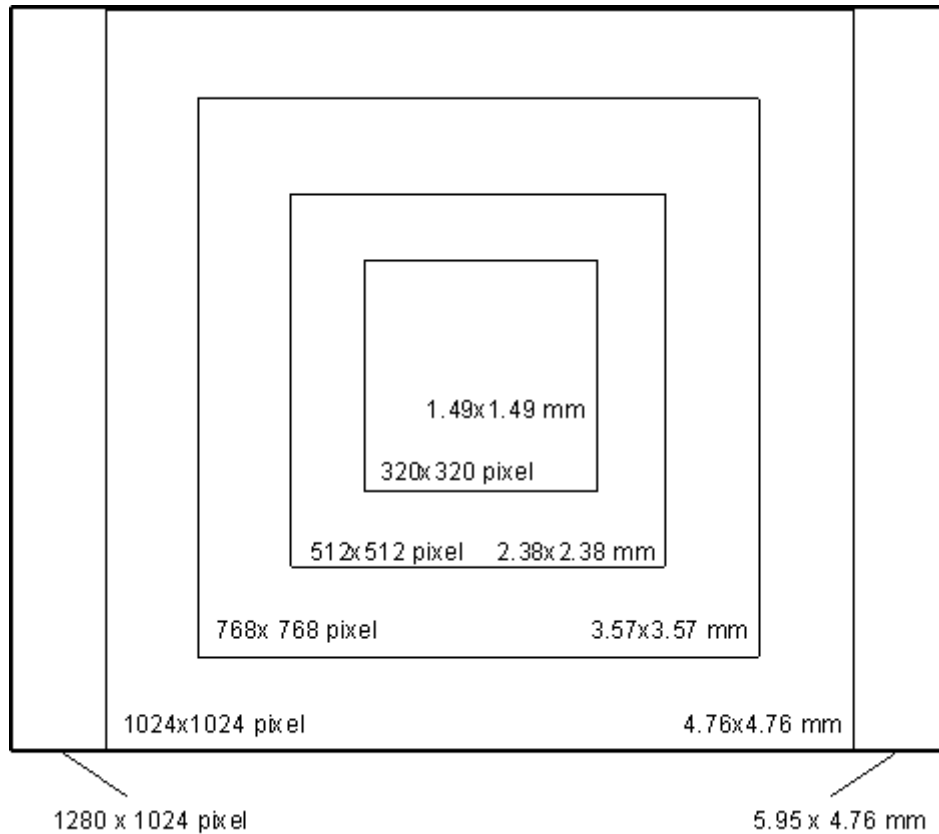
Camera Image Size defines the active area of the camera used for measuring the wavefront. This setting should be adapted to the beam size applied to the instrument. Limiting the used camera size will reduce the unused sensor area and increases measurement speed because of saving time for evaluating the spotfield images.

The following area sizes can be selected:



The camera offers a maximum of 1280 x 1024 pixel = 1.3 MegaPixel on a rectangular area 5.95 x 4.76 mm. For beams that have a larger diameter than 4.76 mm, only a fraction of the beam cross section can be analyzed by the instrument. The Wavefront Sensor is 'over filled' regarding the entrance aperture but can still yield correct results. In this case special care must be taken to the pupil parameters (see [Pupil Definitions Setup](#)).

The following graph illustrates the selectable image sizes.



Note: Changing the camera resolution will also change the number of detectable spots. In case you are working with a 'User Calibrated Reference' a new [User Calibration](#) may be required.

Depending on the selected camera resolution in pixel the resolution of the Wavefront Sensor, that is the number of the calculated microlens spots is also defined thereby. The number of microlens spots in x and y direction is as follows:

Camera resolution in pixel	Wavefront resolution	No. of wavefront points
320 x 320	9 x 9	81
512 x 512	15 x 15	225
768 x 768	23 x 23	529
1024 x 1024	31 x 31	961
1280 x 1024	39 x 31	1209

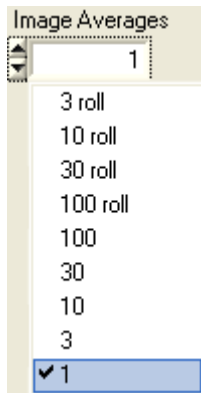
The wavefront resolution is by the factor microlens pitch / pixel size lower than the camera resolution. This means about 32x32 CCD pixels are mapped to one single microlens.

Image Averages

Averages will reduce measurement noise which can be advantageous in case a low-level light source has to be analyzed. An average setting higher than 1 will

take multiple images from the camera, average the pixel intensity pixel by pixel and output an averaged image to the following evaluating routines. Due to reduced intensity noise the accuracy of detected spot centroids is increased.

The available average settings are

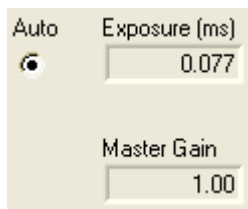


whereas 3, 10, 30, 100 indicate **normal averages** where the average is taken in the background and only after reaching the selected number of averaged images the instrument will continue operation and start data evaluation and display. This type of averaging also reduces the update rate of numerical and graphical data on the main panel. This may be a beneficial effect for better reading the numerics.

Settings 3 roll, 10 roll, 30 roll, 100 roll indicate pseudo **rolling averages**. Here, the average of successive captured camera images is calculated every time a new image is retrieved. A new image is added to a buffer that already contains the averaged image and the summarized image is divided by the number of averages. This way a pseudo rolling average across the last 3, 10, 30 or 100 images is retrieved. This type of averaging does not slow down the update rate on the screen.

Exposure time and Gain

For normal operation it is highly recommended to select the **'Auto'** setting. In this case the Wavefront Sensor application program analyzes automatically the maximum image intensity and adapts the control parameter 'Exposure time (ms)' and 'Master Gain' correspondingly in order to reach a maximum image intensity close to the maximum of 255 digits.



In rare cases of fluctuating light source intensity it may be helpful to deactivate the 'Auto' feature and allow manual adjustments.

The **'Exposure'** time can be set to values between 0,077 ms and 66.501 ms in steps of 0.055 ms. **'Master Gain'** indicates the analogue amplification factor of the CCD sensor signal, it can be set to values between 1.00 and 5.00. It is

advantageous to do the main brightness control using the exposure time and use low Master gain amplification factors only if the exposure control adjustment works too coarse. Otherwise the image noise will be increased needlessly.

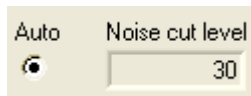
It is recommended to check the actual saturation degree of the camera's AD converter by verification on the **LineView panel**.

Attention

Manual settings of 'Exposure time' and 'Master gain' must not lead neither to image saturations (pixel intensity = 255 digits) nor to low image brightness (max. intensity < half range 128 digits). Otherwise, measurement errors and noise will increase.

Noise Cut Level

'Noise cut level' defines a brightness level in digits which needs to be exceeded by the spots. Ambient light and noise terms below this limit will be set to zero intensity. See the result in the Lineview panel. Since defining such a fix level is problematic for changing beam intensities and ambient light situations, the 'Auto' setting is highly recommended which enables dynamic adaption to the different intensity levels for each spot area and yields best results for centroid calculation.



For a manual definition of the noise cut level, values between 0 and 255 digits may be applied.

Attention

Improper settings of manual 'Noise Cut Level' may lead to increased measurement errors.

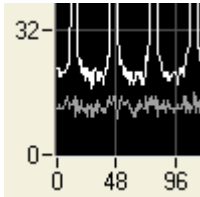
Black Level

'Black Level' is a camera setting that adjusts the offset brightness level for all illuminated pixels and should be adjusted so that the minimum line in the Lineview panel is to be seen above zero. In case of very high noise level reduce the setting.

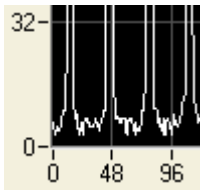


Arbitrary values range from 0 to 255.

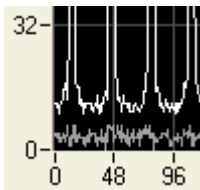
Examples:



Black Level = 255 is too high, lowest intensity pixel show high offset



Black Level = 0 is too low, lowest intensity pixels are below zero and therefore not measurable



Black Level = 100 is optimal setting, lowest intensity pixels are a somewhat above zero and therefore good measurable

An automatic adjustment is not supported by the camera. Therefore, it is suggested to check the correct setting.

Set Default

Click on 'Set Default' to activate the factory default values:

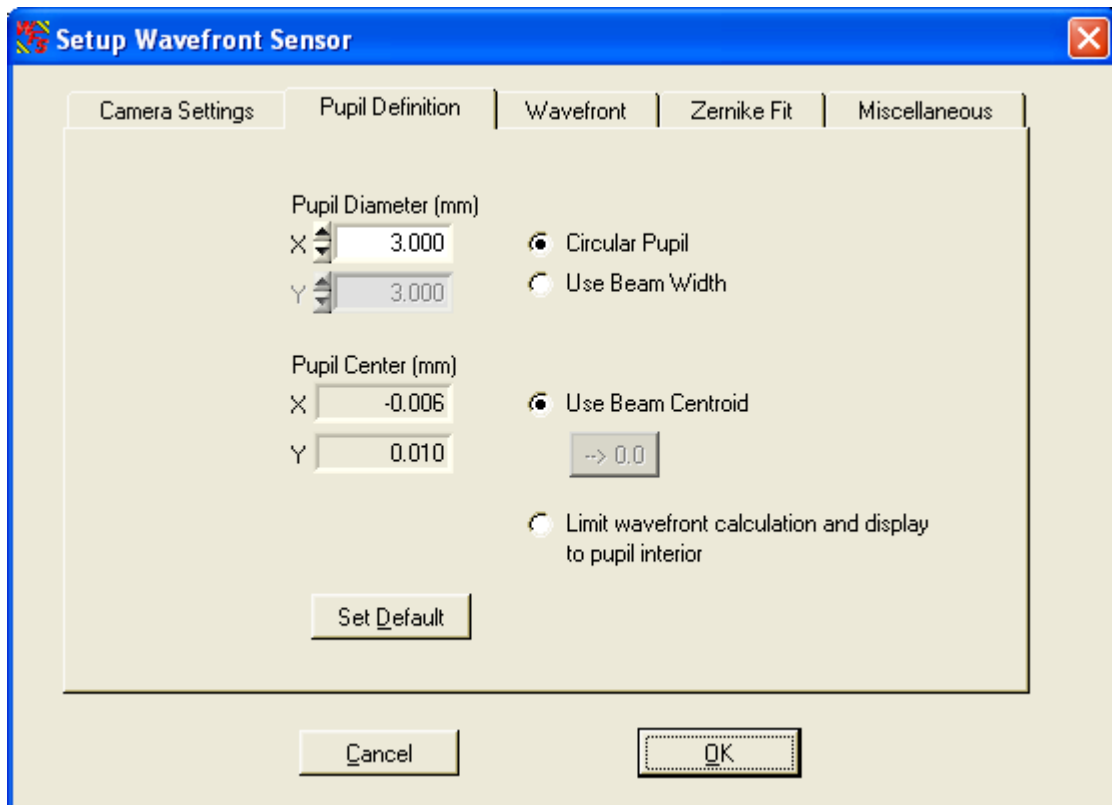
- Cam Noise Level = Auto
- Exposure time and Master Gain = Auto
- Black Level = 100

Settings for Camera Image Size and Averaging remain unchanged.

4.3.3.2 Pupil Definitions Setup

'Pupil Definitions' handle adjustments concerning the pupil which is the image area which is used for wavefront calculations and Zernike fit definitions.

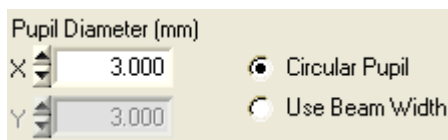
To open the setup panel you can use the **Menu** → **Setup** → **Wavefront Sensor** entry or simply **click right** on one of the graphs on the right hand side of the main panel. Select the tab '**Pupil Definitions**'.



It is required to define a Zernike radius because the Zernike functions fitted to the measured wavefront are normalized to a Unity Radius = 1. Calculated Zernike coefficients refer to the here defined pupil radius (see [Zernike Fit Setup](#)).

Pupil Diameter (mm)

The here defined Pupil Diameter is twice normalized radius (= 1) of the Zernike functions. This Pupil Diameter in mm can be set manually or automatically.



If **'Use Beam Width'** is enabled the pupil diameter is automatically adapted to the measured beam width. The beam width is measured using the second moment method and corresponds to the $1/e^2$ diameter in case of a Gaussian beam shape.

Note: The second moment method will calculate accurate beam widths only when ambient light is shielded from the Wavefront Sensor and the **'Black Level'** of the camera is properly aligned (see [Camera Settings Setup](#)). A positive offset to the beam's intensity distribution will lead to beam diameters larger than real. A manual defined **'Noise Cut Level'** in the [Camera Settings](#) will help to reject an increased dark level.

Let **'Use Beam Width'** unchecked to define the pupil size manually. You may define an elliptical pupil by entering different values for X and Y diameter. Here, the mean diameter defines the Zernike circle.

It is recommended to use a '**Circular Pupil**' by selecting the appropriate option. Here, only the diameter in X needs to be entered and the Y diameter is set to the same value.

Note: The pupil diameter can be defined larger than the active camera area defined with **Camera Image Size** in the [Camera Settings](#). So, a wavefront measurement is enabled also in case of the beam to be analyzed is wider than the sensor area. Please, take into account that such a calculation may suffer from increased uncertainties because the measurement points (spots of the lenslets) are no more equally distributed across the pupil area but are concentrated at the center.

Pupil Center (mm)

The pupil center in mm can also be set manually or automatically.



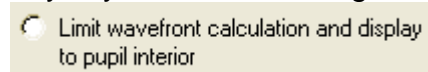
It is recommended to enable '**Use Beam Centroid**' in order to automatically adapt the pupil center to the measured beam centroid coordinates. In case of fluctuations of the beam position during the measurement, the Wavefront Sensor will automatically follow the wandered spot. If you switch to manual input you can use the '**-> 0.0**' button to set the pupil centroid to the center of the Wavefront Sensor.

Note: Manual definition of the pupil center requires a careful and stable beam adjustment, otherwise the measurement results will suffer from increasing errors.

It is recommended to review the pupil size and position using the appropriate functions in the '**Spot Field**' and '**Beam View**' displays. The '**Show Pupil**' option must be enabled in the appropriate configuration panels.

Limit to Pupil Interior

Enabling this option will limit the wavefront calculation and display of it to the pupil interior. Points outside the pupil, that do not go into the Zernike calculation anyway, will not be recognized for statistical wavefront analyses.



The 3D wavefront display on the [Wavefront Panel](#) will show only the wavefront data within the pupil when this option is enabled.

Note: In case the 'Measured Wavefront' is selected for display, this option influences the total measured wavefront distortions (PV, RMS). Distortions only within the defined pupil area are usually lower than the total measured distortions outside the pupil.

Set Default

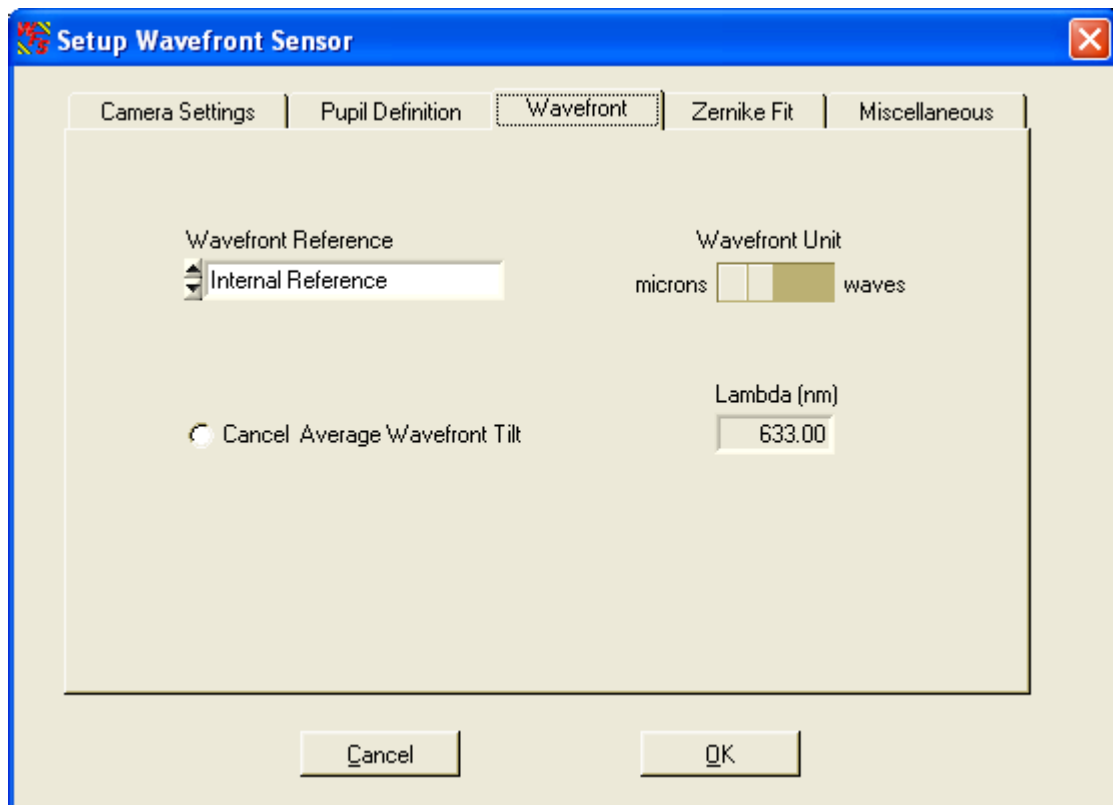
Click on 'Set Default' to activate the factory default values:

- Circular pupil
- Use Beam Width = disabled
- manual Pupil Diameter = 3 mm
- Use Beam Centroid = enabled
- Limit to Pupil Interior = disabled

4.3.3.3 Wavefront Setup

The '**Wavefront**' setup panel contains essential items which determine wavefront measurement and normalization of displayed data.

To open the setup panel you can use the **Menu** → **Setup** → **Wavefront Sensor** entry or simply **click right** on one of the graphs on the right hand side of the main panel. Select the tab '**Wavefront**'.



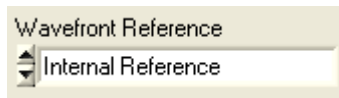
Wavefront Reference

The Thorlabs Wavefront Sensors WFS150 / WFS150C are factory calibrated and provide an internal reference for the measured spotfield centroids. This internal reference is based on the well known and highly accurate parameters

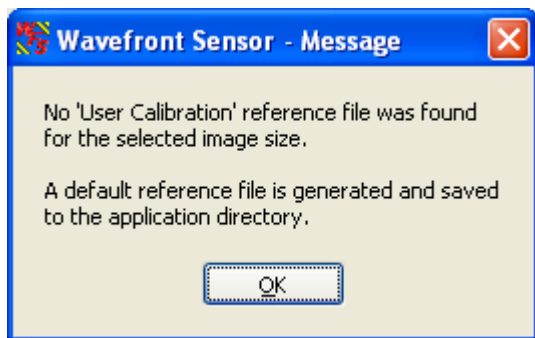
- pixel distance of the CCD sensor = 4.65 μm
- lenslet pitch of the microlens array = 150 μm
- calibrated out-of-center shifts in for a plane wavefront under vertical incidence
- negligible torsion between CCD chip end lenslet array

This means, the centroid positions for all spots created by the lenslet array are

accurately known for a plane wavefront at vertical incidence and acts as an '**Internal reference**'.



It is recommended to use this internal reference unless a perfect plane or spherical wavefront is available to perform a User Calibration. There is no default user calibration delivered with the instrument. Therefore, as soon as the '**User Calibrated Reference**' is activated, you will be informed that such a default reference is created and saved to the application directory.



This default user reference file is identical to the internal reference. Perform a [User Calibration](#) using a plane or spherical wavefront to fill the default file with reference data measured by the user.

There is one user reference file designated for each selectable camera resolution. Correspondingly there are different files named:

wfs_ref_0.ref

wfs_ref_1.ref

wfs_ref_2.ref

wfs_ref_3.ref

wfs_ref_4.ref

in the application directory.

Note: Do not change the content of these reference files, they would become unusable!

Wavefront Unit and Wavelength

Define the desired wavefront unit using this control switch.



You can select either the absolute unit **microns** (μm) or relate the wavefront deformations to the operating wavelength yielding the unit **waves**. In the latter case you are required to input the operating wavelength in nm.



Switch to 'waves' unit and then input the operating wavelength of your light source. The accepted wavelength range is 200 to 1100 nm and corresponds to the wavelength range of model WFS150C.

Cancel Average Wavefront Tilt

In practice, the direction of the input beam is not perfectly perpendicular aligned to the sensor area. The measured wavefront is thereby mainly determined by tip and tilt and the interesting but small wavefront deformations are not seen in the wavefront panel. Since wavefront tip and tilt is often less interesting, this option allows you to cancel the average tip and tilt contribution to be canceled prior to wavefront and Zernike calculation.



Note: The average wavefront tip and tilt will not be removed completely. Small relics are still visible in terms of Zernike coefficients Z_1 and Z_2 . Also note that Zernike terms Z_1 and Z_2 are not related to the original wavefront but the tilt-corrected wavefront when the 'Cancel Average Wavefront Tilt' option is enabled.

Default Settings

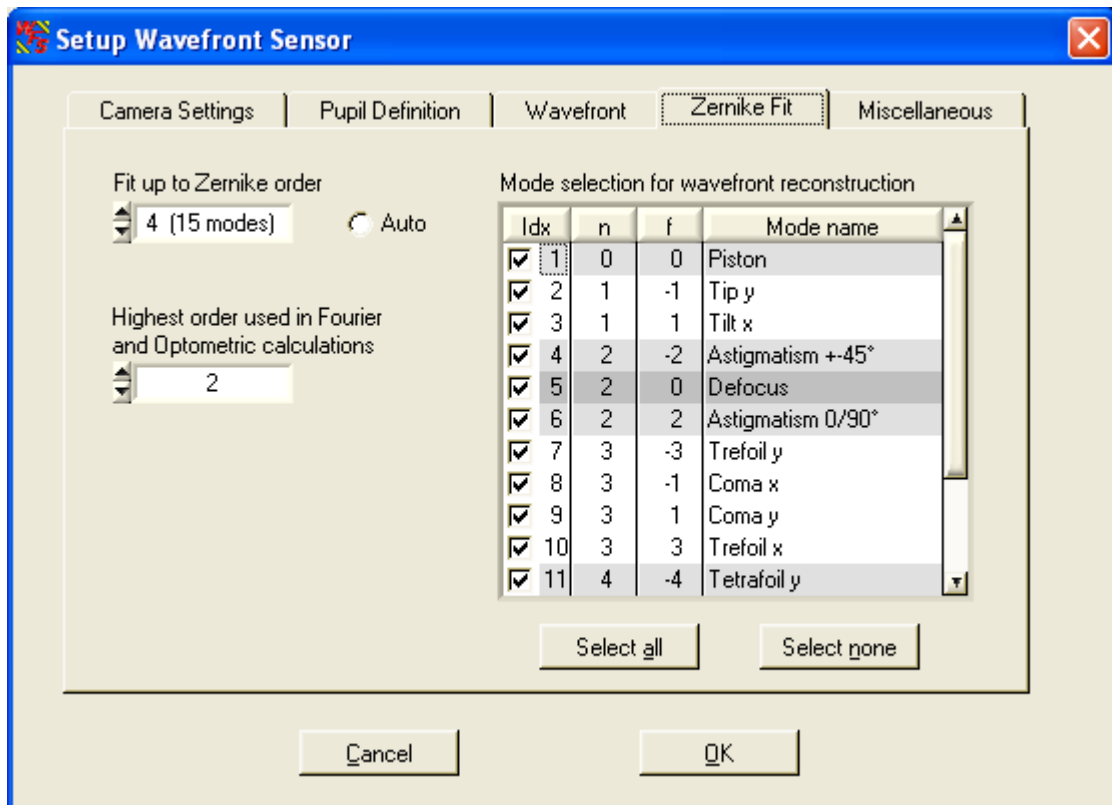
At first program start, the following default settings become active:

- Wavefront Reference = Internal Reference
- Wavefront Unit = μm
- operating wavelength = 633 nm (red HeNe)
- Cancel Average Wavefront Tilt = off

4.3.3.4 Zernike Fit Setup

This setup panel contains definitions of the Zernike Fit that directly influence the wavefront representation in terms of Zernike coefficients and wavefront reconstruction.

To open the setup panel you can use the **Menu** → **Setup** → **Wavefront Sensor** entry or simply **click right** on one of the graphs on the right hand side of the main panel. Select the tab '**Zernike Fit**'.



Fit up to Zernike Order

Use this control to define the highest order of Zernike polynoms that should be used to fit the measured wavefront within the pupil area.

Available settings are:

- 10 (66 modes)
- 9 (55 modes)
- 8 (45 modes)
- 7 (36 modes)
- 6 (28 modes)
- 5 (21 modes)
- 4 (15 modes)
- 3 (10 modes)
- 2 (6 modes)

According to the well known set of Zernike polynoms, the highest radial order (r^n) determines the number of Zernike modes that contain this or lower potencies n of the pupil radius r .

By default, the highest Zernike order is set to $n = 4$ which implies a total number of 15 Zernike modes. The resulting coefficients are displayed in bar graph chart on the Zernike Coefficients panel.

The higher the Zernike order the more Zernike modes are used to reconstruct the measured wavefront shape. The best wavefront reconstruction is obtained using the highest Zernike order 10 utilizing a total number of 66 Zernike modes.

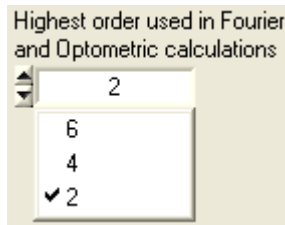
Auto

If 'Auto' is enabled, the Zernike order is set to the highest possible value which is

feasible. The highest number of Zernike modes must not exceed the amount of detected spots within the pupil.

Highest order in Fourier and Optometric calculations

This control can be set to 2, 4 or 6 and forces the numerical calculation of the Fourier coefficients M, J0 and J45 as well as the Optometric parameters Sphere, Cylinder and Axis to consider Zernike terms up to the desired order.



Mode selection for wavefront reconstruction

This table provides a list of all calculated Zernike coefficients each listed in a row. The number of rows is determined by the '**Fit up to Zernike Order**' control. The check box at the left side determines whether this mode should be used for the reconstruction of the wavefront or not. For instance, to see the reconstructed wavefront without primitive modes piston, tip and tilt (which often dominate the 3D graphic) use the following setting:

Idx	n	f	Mode name
<input type="checkbox"/>	0	0	Piston
<input type="checkbox"/>	1	-1	Tip y
<input type="checkbox"/>	1	1	Tilt x
<input checked="" type="checkbox"/>	2	-2	Astigmatism +-45°
<input checked="" type="checkbox"/>	2	0	Defocus
<input checked="" type="checkbox"/>	2	2	Astigmatism 0/90°
<input checked="" type="checkbox"/>	3	-3	Trefoil y
<input checked="" type="checkbox"/>	3	-1	Coma x
<input checked="" type="checkbox"/>	3	1	Coma y
<input checked="" type="checkbox"/>	3	3	Trefoil x
<input checked="" type="checkbox"/>	4	-4	Tetrafoil y

On the other side, in order to focus on a single or a few modes that describe the aberration best, click on '**Select none**' and then mark the modes of interest. To focus on third order ($n = 3$) aberrations, do the following selection:

Mode selection for wavefront reconstruction			
Idx	n	f	Mode name
<input type="checkbox"/>	1	0	Piston
<input type="checkbox"/>	2	1	Tip y
<input type="checkbox"/>	3	1	Tilt x
<input type="checkbox"/>	4	2	Astigmatism +-45°
<input type="checkbox"/>	5	2	Defocus
<input type="checkbox"/>	6	2	Astigmatism 0/90°
<input checked="" type="checkbox"/>	7	3	Trefoil y
<input checked="" type="checkbox"/>	8	3	Coma x
<input checked="" type="checkbox"/>	9	3	Coma y
<input checked="" type="checkbox"/>	10	3	Trefoil x
<input type="checkbox"/>	11	4	Tetrafoil y

Note: Only the selected Zernike Modes are displayed on the Wavefront graphical display with 'Reconstructed' wavefront selected. Also the numerical displays for Peak to Valley (PV) and RMS wavefront distortions will depend on this mode selection.

```
Wavefront/waves
(User Cal. Ref.)
(entire area)
PV      76.482
RMS     18.033
wRMS    18.430
```

For a complete reconstruction using all calculated Zernike modes click on '**Select all**'.

Default Settings

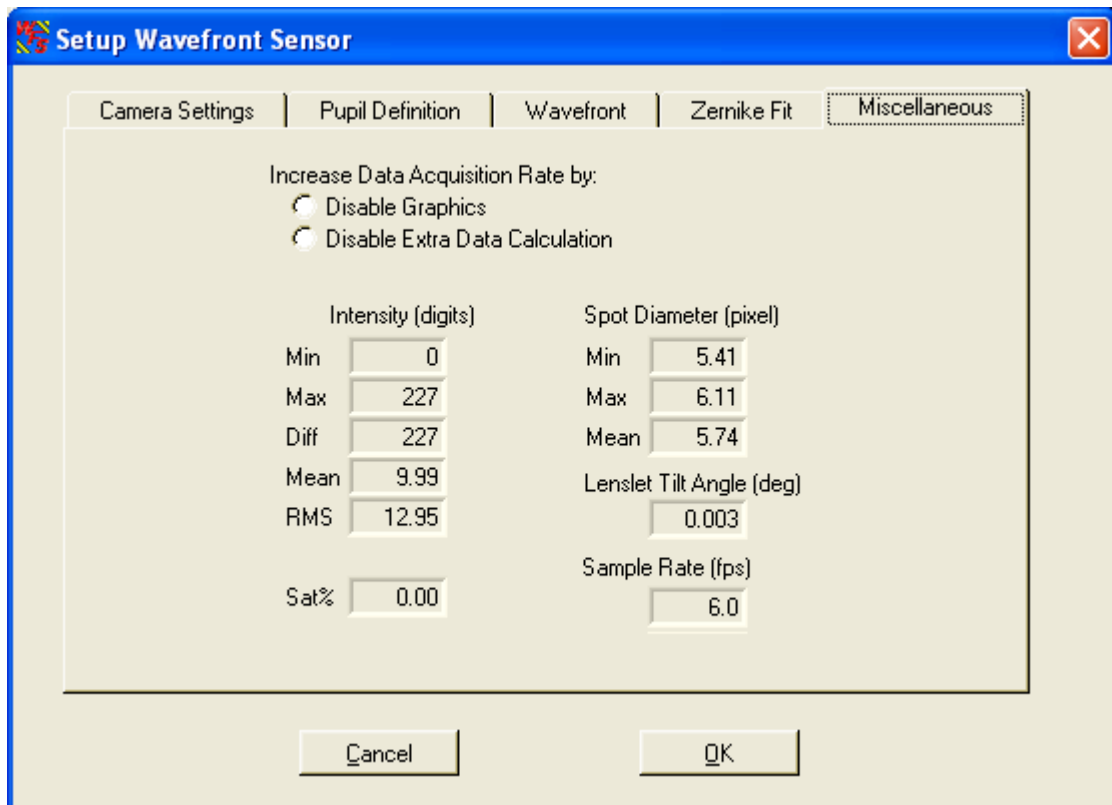
At first program start, the following default settings become active:

- Fit up to Zernike Order = 4 (manual setting)
- Highest order in Fourier and Optometric calculations = 2
- All Zernike modes selected for wavefront reconstruction

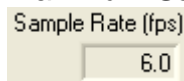
4.3.3.5 Miscellaneous Setup

This setup panel is to display a few statistic data about the captured camera image and allows speed improvement by cancelling unused calculations and displays.

To open the setup panel you can use the **Menu** → **Setup** → **Wavefront Sensor** entry or simply **click right** on one of the graphs on the right hand side of the main panel. Select the tab '**Miscellaneous**'.



There are ways to speed up the Wavefront Sensor software in order to achieve a maximum **Sample Rate** in frames per second (fps).

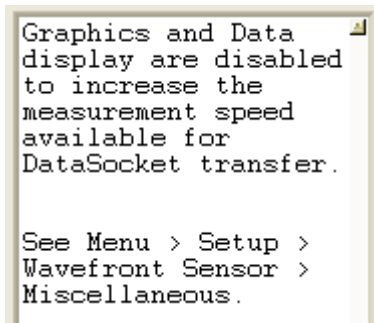


This may be required when the Wavefront Sensor GUI Software is used as a data source to a user application that is connected via the [DataSocket](#) interface. In this case the graphical displays of the Wavefront Sensor GUI become redundant and its updating and can be disabled.

Note: Selecting a lower camera resolution on panel [Camera Settings](#) will result in less spots to be calculated and will increase overall measurement speed.

Display Graphics

Enable this control to disable updates of the GUI graphics. This saves calculation time and increases measurement speed. All graphs including the output box for numerical parameters are cleared. A corresponding message in the parameter box will remind you of this active option and shows the way to deactivation.



Disable Extra Data Calculation

Extra data are the parameters displayed in this tab of the setup panel. Enable this control to prevent time-consuming calculation (e.g. spot diameters) of all these parameters. The last remaining control is the speed indicator 'Sample Rate'.

The extra data consists of statistics about the image. The maximum brightness pixels must be below 255 digits to prevent sensor saturation. 'Sat%' indicates the percentage of saturated pixels.

Intensity (digits)	
Min	0
Max	237
Diff	237
Mean	3.74
RMS	14.12
Sat%	0.00

The calculated values for all spot diameters

Spot Diameter (pixel)	
Min	5.34
Max	5.84
Mean	5.56

and also the tilt angle of the lenslet array with respect to the CCD chip

Lenslet Tilt Angle (deg)	
	0.003

are data to verify the optical quality during assembling.

Especially the lenslet tilt needs to be adjusted to below 0.01 degree in order to ensure accurate measurements of higher Zernike modes.

Default Settings

At first program start, the following default settings become active:

- Display Graphics = off
- Disable Extra Data Calculation = off

4.3.4 Measurement Results

Numerical measurement results are displayed on the left side of the of the main panel. Be sure that there is no error occurred during capturing the camera image and its subsequent analysis.



Note: If not '**No instrument errors**' appears in the status window you cannot rely on the measurement results!

Refer to [Measurement Warnings and Errors](#) for a listing of possibly occurring errors.

Beam Data

Beam data/mm	
Ctr x	0.034
Ctr y	0.039
Dia x	4.103
Dia y	4.071

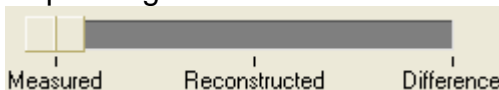
Calculated from the centroid and the second moment of the entire camera image, the beam's center coordinates **Ctr x** and **Ctr y** and beam diameter **Dia x** and **Dia y** in X and Y direction are displayed in mm. In case of a Gaussian beam shape the second moment coincides with beam width at the standard $1/e^2$ a clip level. Please take into account that this data cannot give an exact measure of the beam because the lenslet array in front of the camera and wavefront distortions have changed the intensity distribution between the real beam and the camera image. Furthermore, high ambient light level and improper set camera's 'Black Level' (see [Camera Settings](#)) will distort the beam data results.

Wavefront Data

Wavefront/ μm (User Cal. Ref.) (entire area)	
PV	47.024
RMS	10.915
wRMS	9.478

These wavefront statistics are either displayed in microns or waves, as selected in the [Wavefront Sensor Setup Panel](#). Calculated data is either related to the entire wavefront or to the pupil interior only, according to the settings within [Pupil Definitions Setup](#) panel.

Depending on the actual wavefront switch setting below the wavefront graph



the calculated wavefront statistics refer to the selected wavefront (Measured, Reconstructed or Difference).

PV is the total Peak-to-Valley value, that is the maximum variance of the wavefront in the observed area.

RMS is the Root Mean Squared average value and

wRMS is the intensity weighted Root Mean Square average value. Here higher intensity spots in the pupil center have more weight than lower intensity spots away from the center.

Fourier Constants

Fourier	
M	16.273
J0	-1.029
J45	1.509

Fourier constants are M, J0 and J45 and are derived from the Zernike coefficients. Depending on setting in the [Zernike Fit Setup](#) panel, Zernike orders up to 2, 4 or 6 go into these constants.

Optometric Constants

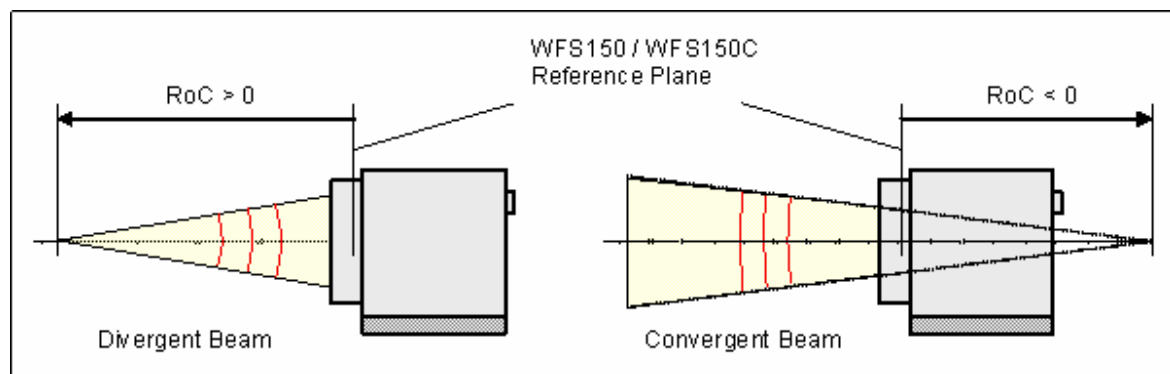
Optometric	
Sphere	18.099
Cyl.	-3.653
Axis	62.148°

Optometric constants are Sphere, Cylinder and the axis angle of the cylinder. Depending on setting in the [Zernike Fit Setup](#) panel, Zernike orders up to 2, 4 or 6 go into these constants.

Radius of Curvature RoC

RoC	61.45mm
-----	---------

This parameter is based on the 5th Zernike term 'Defocus' and describes the degree of curvature of the measured wavefront. All other Zernike terms and corresponding wavefront deformations are left unnoticed and only the spherical term is considered. The Radius of Curvature (RoC) is identical to the distance from a point source which is emitting a spherical wavefront.



Positive RoC distances are standing for divergent spherical wavefronts where the point source is located in front of the Wavefront Sensor reference plane whereas negative values indicate a convergent spherical wavefront which virtual focal point lies behind the Wavefront Sensor reference plane. The higher the absolute RoC value the more flat is the corresponding wavefront and the higher is the parallelism of the beam.

RMS Variations

RMS Variations/ μm	
RMS(n = 0)	5.533
RMS(n = 1)	1.534
RMS(n = 2)	5.351

Since the Zernike modes are normalized to unity variance, all Zernike coefficients of a particular order can be summarized and expressed as total RMS variation of this Zernike order. The number of Zernike orders defined in [Zernike Fit Setup](#) panel will determine the number of output appropriate RMS variation results.

Zernike Modes

Zernike Modes/ μm	
Z 1(0/ 0)	5.533
Z 2(1/-1)	1.050
Z 3(1/ 1)	-1.119

The coefficients of the Zernike modes which are determined by a least square fit to the measured wavefront are either displayed in microns or waves. The mode number is followed by the order and frequency number of the mode in brackets.

Fit Error

Fit error / arcmin	
Mean	5.490e-11
Stddev	1.837e-03

The Fit error describes the difference between the measured and the reconstructed wavefront. A lower value indicates a better fit. Usually, a Zernike fit using more modes will reduce the fit error.

4.3.5 Measurement Warnings and Errors

During capturing of the camera image and its subsequent analysis some errors may arise which needs to be recognized.

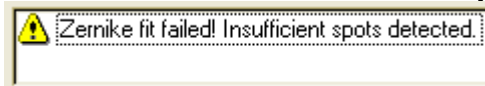


Note: Measurement results are unreliable if an error or warning is indicated within the status window.

Read the error message carefully and find a way to remove the reason of it.

Error List

Zernike Fit failed! Insufficient spots detected.

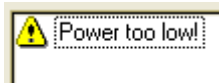


This error occurs if the number of detected spots within the pupil is lower than the number of Zernike modes to be calculated in the least square Zernike fit.

To prevent this error

- check the analyzed beam that it is properly aligned and its intensity dominates the ambient light level and/or
- increase the pupil diameter within the [Pupil Definitions Setup](#) panel and/or
- reduce the number of Zernike orders in the [Zernike Fit Setup](#) panel

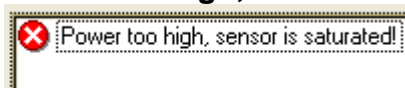
Power too low!



The detected spot intensity is too low so that the analysis of its centroid positions becomes incorrect. Check if 'Exposure Time' and 'Gain' settings within the [Camera Settings Setup](#) of the camera are fixed to a manual entered level. Change the manual setting or enable automatic control of these camera parameters.

When this error occurs also for the highest 'Exposure Time' and 'Gain' setting or if 'auto' is already enabled, the light intensity of the beam to be analyzed is too low for the Wavefront Sensor. Increase the power of your light source or reduce attenuation in front of the Wavefront Sensor.

Power too high, sensor is saturated!



The detected spot intensity is too high so that the camera image is saturated and the analysis of the spot centroid positions becomes incorrect.

Check if 'Exposure Time' and 'Gain' settings within the [Camera Settings Setup](#) panel of the camera are fixed to a manual entered level. Change the manual

setting or enable automatic control of these camera parameters.

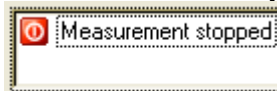
When this error occurs also for the lowest 'Exposure Time' and 'Gain' setting or if 'auto' is already enabled, the light intensity of the beam to be analyzed is too high for the Wavefront Sensor. Decrease the power of your light source or insert an attenuator in front of the Wavefront Sensor.

High ambient light level!



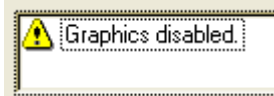
The captured camera image is overlaid a high amount of ambient light that decreases the contrast between the spot peaks and the dark areas between. Reduce the stray light by shielding its incident from the Wavefront Sensor or increase the power of the analyzed beam.

Measurement stopped



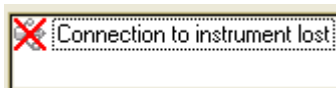
This message is not an error or warning but will notice the user that the continuous measurement has been stopped either by the user or due to occurrence of an other error so that the displayed data and graphs do not indicate actual wavefront data.

Graphics disabled



This warning is a reminder that all graphics and also the numerical parameter box are disabled in order to speed up the sampling rate. Switch off the option 'Disable Graphics' within the panel Menu → Setup → Wavefront Sensor → Miscellaneous to enable the graphical and numerical outputs again.

Connection to instrument lost



An USB interface error is occurred by what the GUI lost the connection to the Wavefront Sensor hardware. Check the USB cable and ensure that it is qualified for high speed USB2.0 transmission. Then reconnect the USB cable and start the Wavefront Sensor application again.

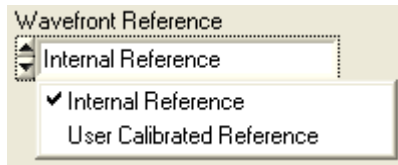
4.3.6 User Calibration

Besides the internal Wavefront Sensor calibration the user has the ability to perform a wavefront calibration using his own setup and light sources. This can increase the instruments accuracy.

A user calibration can be reasonable in case a wavefront should work as a reference but already shows small distortions. In that case do the user wavefront calibration and the distorted wavefront acts as a reference and is displayed as ideal. Following measurements are based on this user reference and allow accurate measurements of further wavefront distortions that come along with

optical elements inserted afterwards.

Go to the tab 'Wavefront' within the [Wavefront Sensor Setup Panel](#) switching between internal and user calibration.




Note: You will increase the accuracy of the calibration when the Wavefront Sensor works with averages > 1 , see [Camera Settings Setup](#) panel.

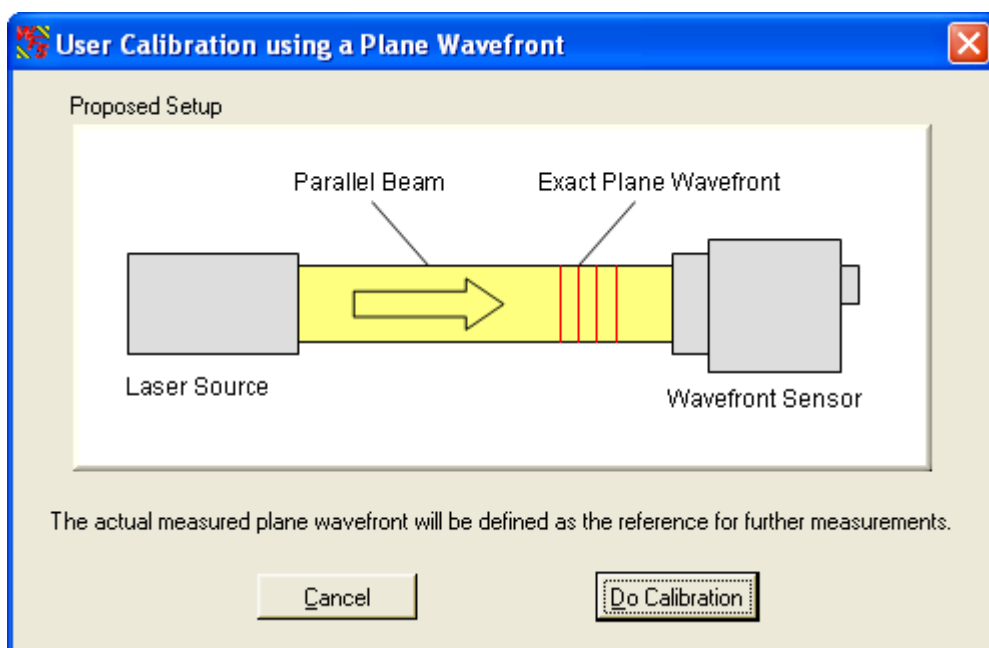
Note: The generated user calibration data are only valid for the actual camera image size, selected in the [Camera Settings Setup](#) panel. Switching to an other camera resolution will require a new calibration!

User Calibration using a Plane Wavefront

In order to perform this user calibration you need to apply a high quality beam with having a perfect plane wavefront. Be sure the beam is properly aligned to the Wavefront Sensor and fills the selected active camera area completely.

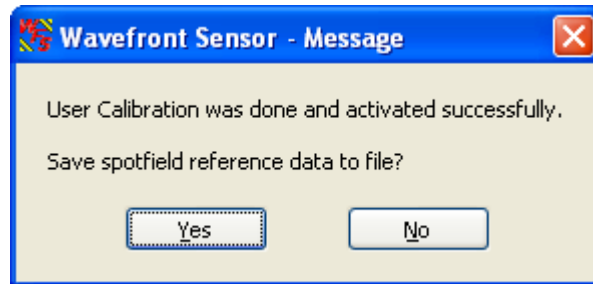
Note: The calibration fails for positions that are insufficient illuminated. Although no error occurs the according area will be excluded in further wavefront measurements.

Start the calibration procedure using **Menu** → **Calibration** → **Plane Wavefront** or simply click on the appropriate symbol  in the toolbar. The following panel illustrates the required calibration setup.



Click '**Do Calibration**' to perform the user calibration and the following message

verifies successful operation.



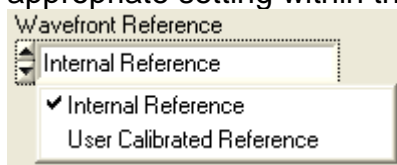
You are asked to save the reference data to a file. Click '**Yes**' to store this user calibration to a predefined file within your application directory to have it available in following Wavefront Sensor sessions. Otherwise, if you click '**No**' the calibration remains in memory and active but is lost as soon as the program is terminated. Also when the sensor resolution (see [Camera Settings](#)) is changed and the appropriate reference file is loaded, the current reference in memory get lost.

User Calibration using a Spherical Wavefront

In order to perform this user calibration you need to apply a high quality divergent beam that originates from a point source having a perfect spherical wavefront. A monomode fiber output without any collimators or lenses is ideally suited for that purpose. Be sure the beam is properly aligned to the Wavefront Sensor and fills the selected active camera area completely.

Note: The calibration fails for positions that are insufficient illuminated. Although no error occurs the according area will be excluded in further wavefront measurements.

Setup the Wavefront Sensor to work using the internal reference. Do the appropriate setting within the [Wavefront Sensor Setup Panel](#).




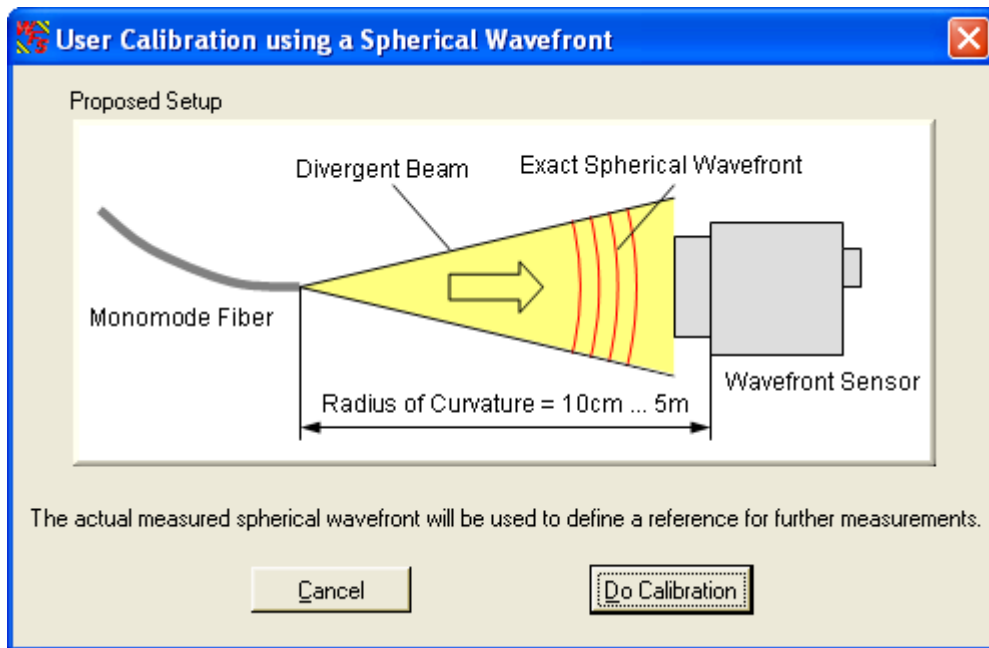
Adjust the point source straight in front of the Wavefront Sensor at a distance in the range 10 cm to 5 m. The Wavefront Sensor will measure the distance and displays it as Radius of Curvature RoC.

RoC 300.11mm

Larger distances are better suited for calibration because the wavefront curvature is lower and closer to a plane wavefront

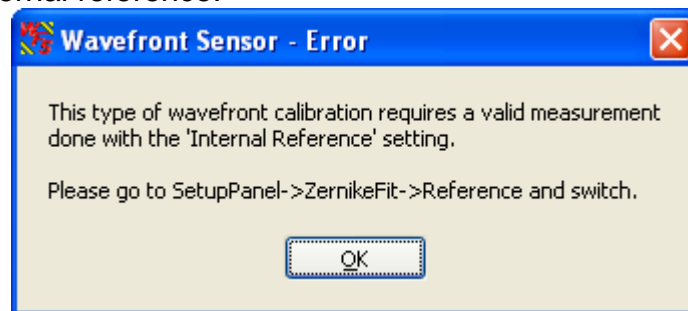
Start the calibration procedure using **Menu → Calibration → Spherical**

Wavefront or simply click on the appropriate symbol  in the toolbar. The following panel illustrates the required calibration setup.

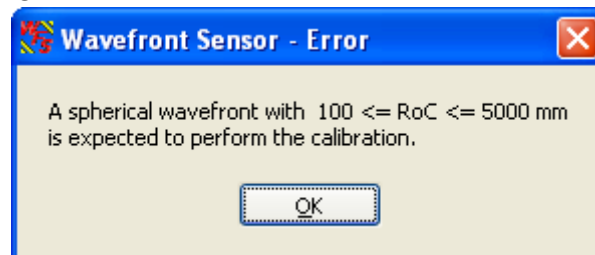


Click '**Do Calibration**' to perform the user calibration.

In case you are currently working with an user reference you will be reminded to switch to the internal reference.

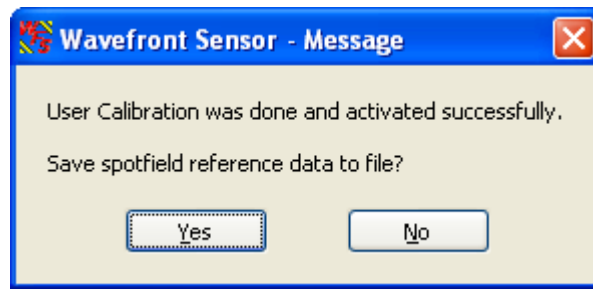


In case the distance to the point source is measured too short or too far the following error occurs.



Change the setup accordingly and repeat the calibration.

After successful calibration you are asked if the reference data should be saved to a file.



Click '**Yes**' to store this user calibration to a predefined file within your application directory to have it available in following Wavefront Sensor sessions. Otherwise, if you click '**No**' the calibration remains in memory and active but is lost as soon as the program is terminated. Also when the sensor resolution (see [Camera Settings](#)) is changed and the appropriate reference file is loaded, the current reference in memory gets lost.

The user calibration data is stored in a file with predefined file name whereas for each selectable camera resolution exists a separate file.

wfs_ref_0.ref
wfs_ref_1.ref
wfs_ref_2.ref
wfs_ref_3.ref
wfs_ref_4.ref

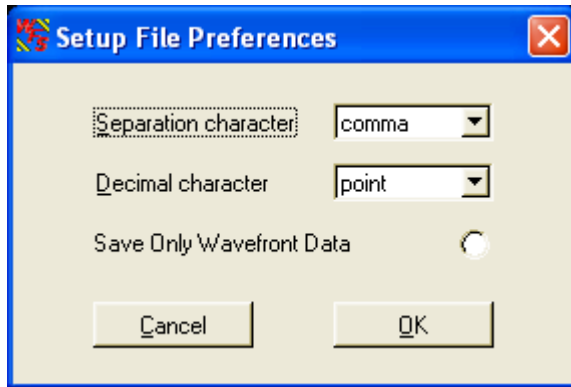
Note: Do not edit the content of these reference files, they would become unusable!

The stored file for an particular camera resolution is loaded automatically at program start and every time the camera resolution is changed but only if '**User Calibration**' option is enabled.

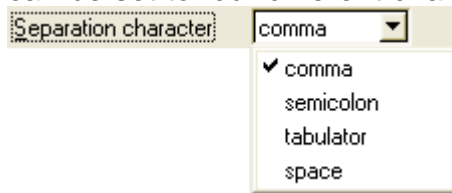
4.3.7 Save Measurement Data

The measured wavefront data can be saved to a text file. The preferred file extension is .csv (comma separated values). This file type can be loaded directly into Microsoft Excel®.

You may define some file preferences before storing the measurement data file. Choose the menu item **File** → **Measurement File Preferences**.

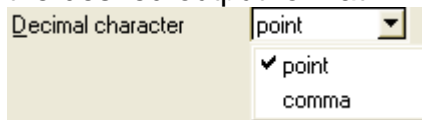


The separation character between the parameter name and the appropriate value can be set to four different characters:



'Comma' is selected by default.

The decimal character can be set to a decimal comma or point in order to achieve the desired output format.



'Point' is selected by default.

If the option '**Save Only Wavefront Data**' is enabled the entire header including the listing of single wavefront and Zernike fit results is omitted and only the wavefront data array is saved. This wavefront data array is surrounded by x- and y-scale information, whereas the first column indicates the x coordinates and the last row indicates the x coordinates of the wavefront array.

Choose menu item **File** → **Save Measurement Data** or just press Ctrl + S to save the wavefront data file to disk using the defined preferences. For the file content see this printout of a sample file:

```
Thorlabs Shack-Hartmann Wavefront Sensor

Model           ,      WFS150C
Serial Number   ,      M00224955

Date MM-DD-YYYY ,      10-11-2007
Time HH:MM:SS   ,      11:15:17

*** CAMERA ***
Camera Type     ,      Thorlabs DCU224M
Camera SN       ,      4002677159
Resolution X    ,      320
Resolution Y    ,      320
Exposure Time [ms] ,      0.132
Master Gain     ,      1.089
Averages        ,      1
Average Type    ,      Normal
```

*** BEAM ***

Beam Center X [mm] , -0.003
 Beam Center Y [mm] , 0.011
 Beam Diameter X [mm] , 1.670
 Beam Diameter Y [mm] , 1.712

*** PUPIL ***

Circular , 1
 Use Beam Centroid , 1
 Use Beam Dia , 0
 Wavefront Calc In Pupil, 0
 Pupil Diameter X [mm] , 1.500
 Pupil Diameter Y [mm] , 1.500
 Pupil Center X [mm] , -0.003
 Pupil Center Y [mm] , 0.011

*** ZERNIKE FIT ***

Zernike Orders Auto , 0
 Zernike Orders , 4
 Zernike Modes , 15
 Unit , μm

Index	Order	Frequency	Coefficient
1,	0,	0,	0.251
2,	1,	-1,	0.000
3,	1,	1,	0.021
4,	2,	-2,	0.001
5,	2,	0,	-0.270
6,	2,	2,	-0.003
7,	3,	-3,	0.000
8,	3,	-1,	0.000
9,	3,	1,	0.000
10,	3,	3,	0.001
11,	4,	-4,	-0.001
12,	4,	-2,	-0.001
13,	4,	0,	-0.001
14,	4,	2,	-0.001
15,	4,	4,	0.001

Fit Error Mean [arcmin] , 9.500e-13
 Fit Error StdDev [arcmin], 7.437e-05

*** RMS WAVEFRONT VARIATIONS ***

Unit , μm

Order	Variation
0,	0.251
1,	0.021
2,	0.270
3,	0.001
4,	0.002

*** FOURIER NOTATION ***

Fourier Order , 2
 Fourier M , 3.328
 Fourier J0 , 0.029
 Fourier J45 , -0.009

*** OPTOMETRIC NOTATION ***

Optometric Sphere , 3.358
 Optometric Cylinder , -0.061
 Optometric Axis [deg] , 171.672

Radius of Curvature[mm], 300.501

*** WAVEFRONT ***

Reference , Internal Reference
 Unit , μm
 Wavelength [nm] , 633.000
 Type , Measured
 Calculation Area , entire area
 PV , 1.230
 RMS , 0.342
 RMS weighted , 0.326
 Spots X , 9
 Spots Y , 9
 y / x [mm], -0.600, -0.450, -0.300, -0.150, 0.000, 0.150, 0.300, 0.450,
 0.600,

```

0.600, 1.103, 1.087, 0.876, 0.740, 0.668, 0.655, 0.671, 0.739,
0.860, 0.450, 1.119, 1.147, 0.866, 0.662, 0.527, 0.496, 0.539, 0.654,
0.830, 0.300, 0.931, 0.897, 0.615, 0.405, 0.283, 0.252, 0.280, 0.386,
0.563, 0.150, 0.809, 0.712, 0.431, 0.227, 0.106, 0.064, 0.092, 0.198,
0.378, 0.000, 0.752, 0.597, 0.321, 0.121, 0.000, -0.044, -0.015, 0.084,
0.265, -0.150, 0.733, 0.561, 0.285, 0.086, -0.035, -0.083, -0.044, 0.053,
0.229, -0.300, 0.750, 0.603, 0.329, 0.132, 0.004, -0.046, -0.008, 0.091,
0.267, -0.450, 0.807, 0.711, 0.444, 0.246, 0.117, 0.064, 0.093, 0.200,
0.376, -0.600, 0.931, 0.897, 0.628, 0.431, 0.304, 0.249, 0.277, 0.382,
0.564,

```

In case the option '**Save Only Wavefront Data**' was enabled the file content is limited to the following lines:

```

Spots X , 9
Spots Y , 9
y / x [mm], -0.600, -0.450, -0.300, -0.150, 0.000, 0.150, 0.300, 0.450,
0.600, 0.600, 1.103, 1.087, 0.876, 0.740, 0.668, 0.655, 0.671, 0.739,
0.860, 0.450, 1.119, 1.147, 0.866, 0.662, 0.527, 0.496, 0.539, 0.654,
0.830, 0.300, 0.931, 0.897, 0.615, 0.405, 0.283, 0.252, 0.280, 0.386,
0.563, 0.150, 0.809, 0.712, 0.431, 0.227, 0.106, 0.064, 0.092, 0.198,
0.378, 0.000, 0.752, 0.597, 0.321, 0.121, 0.000, -0.044, -0.015, 0.084,
0.265, -0.150, 0.733, 0.561, 0.285, 0.086, -0.035, -0.083, -0.044, 0.053,
0.229, -0.300, 0.750, 0.603, 0.329, 0.132, 0.004, -0.046, -0.008, 0.091,
0.267, -0.450, 0.807, 0.711, 0.444, 0.246, 0.117, 0.064, 0.093, 0.200,
0.376, -0.600, 0.931, 0.897, 0.628, 0.431, 0.304, 0.249, 0.277, 0.382,
0.564,

```

4.3.8 Version and other Program Information

The menu entry **Help** → **About** displays application relevant data.



Visit Thorlabs website www.thorlabs.com for downloading available updates.

4.3.9 Save Instrument Settings

The actual settings of the Wavefront Sensor GUI including configurations of the graphical displays and the instrument setup are automatically saved when you leave the program. When you start the Wavefront Sensor GUI again your last settings are automatically loaded and you are able to go on with your work as if there newer was a break.

4.3.10 DataSocket for live data transfer

DataSocket is a program interface designed for live data exchange between different applications on one system or even on separated computers connected by a TCP/IP network. The Wavefront Sensor GUI application is able to send its measurement results to a computer or database receiving the data for further usage. Both, measured **Wavefront and Zernike parameters** including the complete **data arrays** as well as the appropriate **setup data** are available via DataSocket transfer.

Note: The Data Socket implementation on the Wavefront Sensor is **not** designed to control measurement parameters of the Wavefront Sensor! Only sending measurement data to a DataSocket receiver is implemented.

See this website <http://www.ni.com/datasocket/> for details and applications of DataSocket.

The following configurations are feasible:

- a) PC A runs the Wavefront Sensor application which sends the measurement data to the local DataSocket server running on the same machine. An application on the same PC A retrieves the data.
- b) PC A runs the Wavefront Sensor application which sends the measurement data to the local DataSocket server on the same machine. An application on another PC B retrieves the data. PCs A and B are connected via a network.
- c) PC A runs the Wavefront Sensor application which sends the measurement data to the distinct DataSocket server running on PC B. An application PC B retrieves the data.
- d) PC A runs the Wavefront Sensor application which sends the measurement data to a DataSocket server running on PC B. An application on a third PC C retrieves the data. All PCs A, B and C are connected via a TCP/IP network.

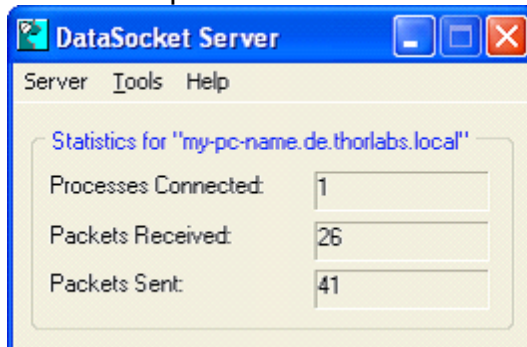
The following explanations are related to the National Instruments® DataSocket server. It comes with the LabWindows/CVI® and LabView® packages or is available from the National Instruments® download website <http://digital.ni.com/public.nsf/allkb/40295802535E31B686256E91001859AB>.

Starting the DataSocket server

When the National Instruments® DataSocket server is installed on a local machine it can be started from the Start prompt of the PC:

Start → Program Files → National Instruments → DataSocket → DataSocket Server

The server panel looks as follows



Even when the panel is closed the server will remain active and is visible within the task bar:



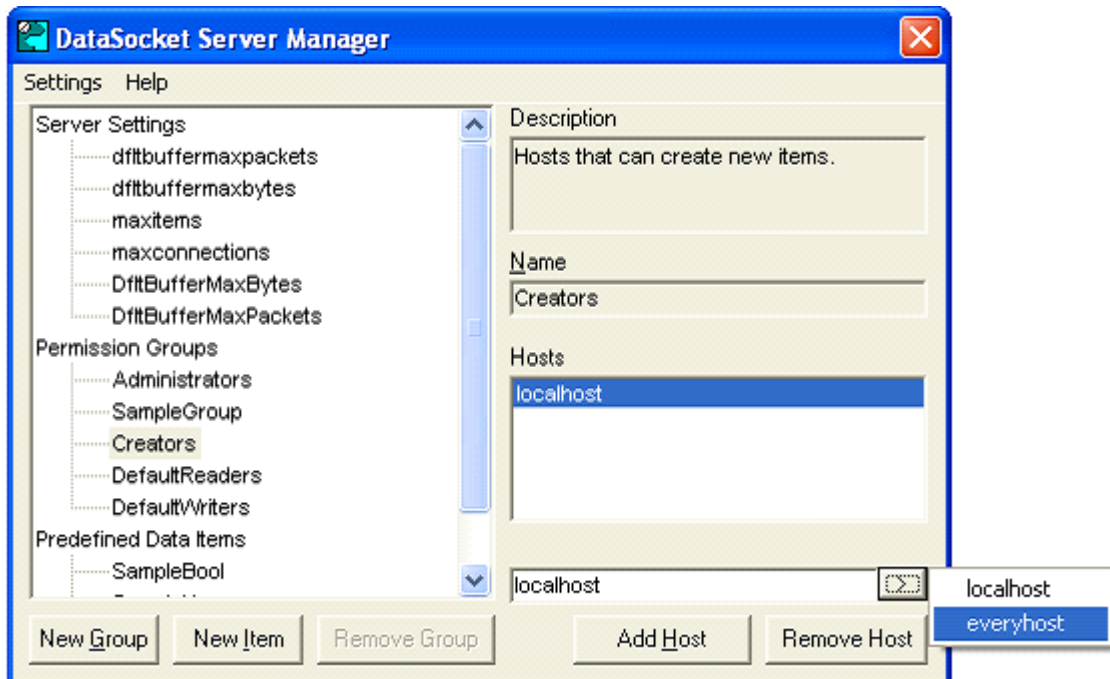
Before using the DataSocket server for Wavefront Sensor data transfer it has to be configured.

DataSocket Server Configuration

The DataSocket server needs to be configured to allow Read and Write access

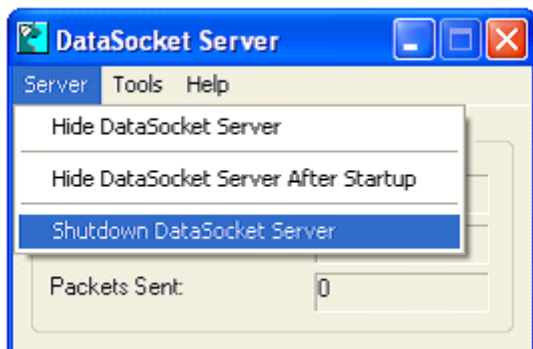
from the connected computers. In addition, the writer application (the PC driving the Wavefront Sensor) requires rights as a creator of new data items.

Open the DataSocket Server Manager using **Start → Program Files → National Instruments → DataSocket → DataSocket Server Manager**. Click on 'Creators' and set 'everyhost' to be allowed to create new data items. Repeat this also for the groups 'Default Readers' and 'Default Writers'.



Save the changed settings (Ctrl+S) and close the panel.

In order to update the DataSocket server using these settings it is required to **shutdown** the DataSocket server by using the appropriate menu entry.



Note: It is not sufficient to close the server panel only, the DataSocket server needs to be relaunched to accept the new configuration!

Firewall configuration

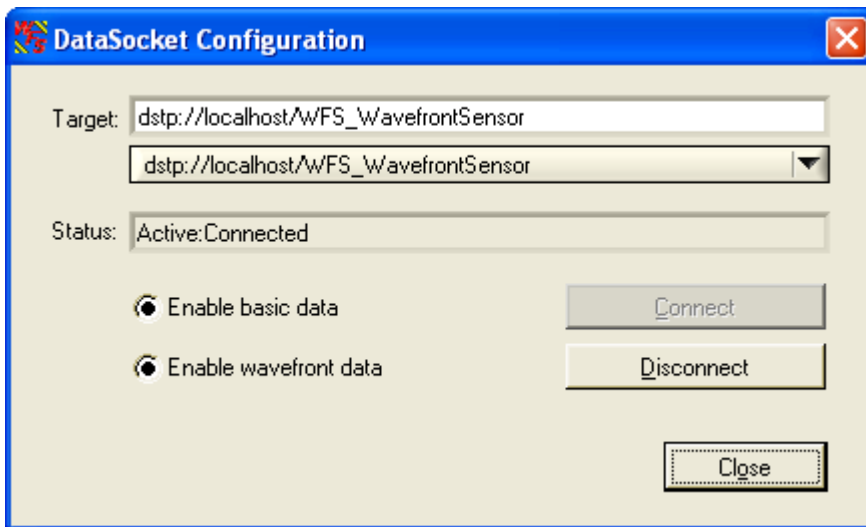
The integrated firewall software in Microsoft Windows® XP and higher operating systems may be configured to block access to the DataSocket server. Open the firewall configuration panel and go to the 'Exceptions' tab. Look for the 'National

Instruments DataSocket Server' entry and mark the appropriate check box to allow an exception.

- Datei- und Druckerfreigabe
- National Instruments DataSocket Server
- National Instruments Example Finder

4.3.10.1 Configuration Panel

To configure the Wavefront Sensor GUI software for DataSocket transfer open the appropriate configuration panel from the menu '**Setup → DataSocket**'.



Local DataSocket server

If you want to use the local DataSocket server running on the same PC just use the default setting '**dstp://localhost/WFS_WavefrontSensor**' and click '**Connect**'. The software will automatically start the server if it is available. The status window will inform you about success or failure.

Separate DataSocket server

If you want to use a DataSocket server on a separate machine connected via a TCP/IP network you have to start the DataSocket server on the remote machine **first** and configure it according to the description in [DataSocket for live data transfer](#). Now type in the correct network name of this computer hosting the DataSocket server, for example **dstp://my-pc-name.de.thorlabs.local/WFS_WavefrontSensor**.

The name of this computer is displayed on the appropriate DataSocket server panel. Then click '**Connect**'. In case of failure look for firewalls blocking the data transfer ([DataSocket for live data transfer](#)).

Click '**Disconnect**' to shut down the connection to the DataSocket server. If you '**Close**' the configuration panel the data connection holds up until it is disconnected or the Wavefront Sensor application is shut down.

Enable basic data

Enable basic data

When this check box is marked the software will continuously send setup and result data of the Wavefront Sensor measurement to the DataSocket server. See [Available Data Items](#) for a description of the available data items.

Enable wavefront data

 Enable wavefront data

When this check box is marked the software will automatically send the entire wavefront data array to the DataSocket server. Because the amount of data can be considerably it can be disabled to increase transfer speed. See [Available Data Items](#) for a description of the available data items.

4.3.10.2 Available Data Items

When '**Enable basic data**' is checked on the DataSocket configuration panel the following data items from the actual Wavefront Sensor measurement are sent to the DataSocket server. As soon as a measurement is complete the data on the DataSocket server is updated.

Measurement results in 'float' format may contain the coding 'NaN' which stands for 'Not A Number'. This indicates that the parameter is not available. Data is split in two groups, Wavefront Sensor settings and measurement results.

Wavefront Sensor settings are:

Data Item	Format	Unit / example
Instrument_Name	string	e.g. "WFS150C Wavefront Sensor"
Serial_Number	string	e.g. "M00224955"
Wavefront_Unit_Um_Waves	short	0 = μm , 1 = waves
Wavefront_Data_EntireArea_Pupil	short	data relate to 0 = entire area, 1 = pupil
Wavefront_Type_Meas_Recon_Diff	short	0 = measured, 1 = reconstructed, 2 = difference
Zernike_Orders	short	number of Zernike orders
Zernike_Modes	short	number of Zernike modes

Wavefront Sensor results are:

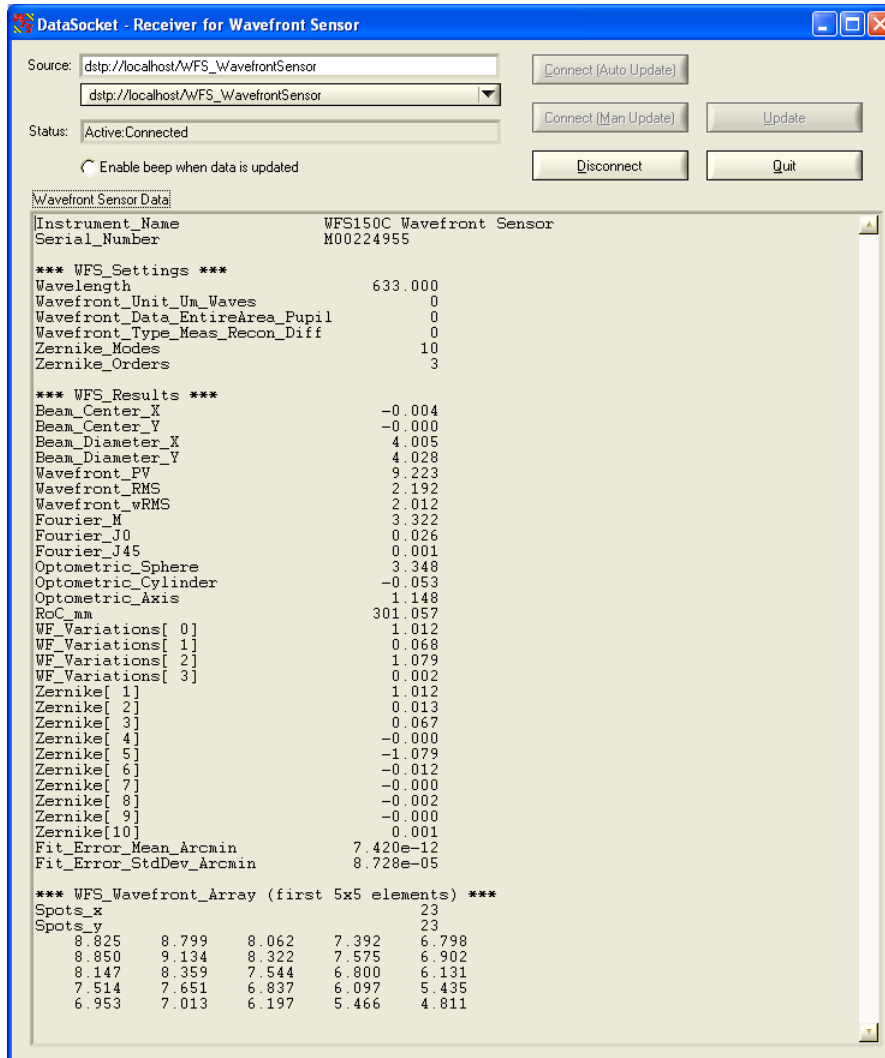
Data Item	Format	Unit / example
Beam_Center_X	float	[mm]
Beam_Center_Y	float	[mm]
Beam_Diameter_X	float	[mm]
Beam_Diameter_Y	float	[mm]
Wavefront_PV	float	(unit according to Wavefront_Unit_Um_Waves)
Wavefront_RMS	float	(unit according to Wavefront_Unit_Um_Waves)
Wavefront_wRMS	float	(unit according to Wavefront_Unit_Um_Waves)
Fourier_M	float	
Fourier_J0	float	
Fourier_J45	float	
Optometric_Sphere	float	
Optometric_Cylinder	float	
Optometric_Axis	float	[deg]
RoC_mm	float	[mm]
Wavefront_Variations	float array	(unit according to Wavefront_Unit_Um_Waves)
Zernike	float array	(unit according to Wavefront_Unit_Um_Waves)
Fit_Error_Mean_Arcmin	float	arcmin
Fit_Error_StdDev_Arcmin	float	arcmin

When '**Enable wavefront data**' is checked on the DataSocket configuration panel the following data items from the actual Wavefront Sensor measurement are sent to the DataSocket server.

Data Item	Format	Unit / example
Wavefront_Spots_X	short	
Wavefront_Spots_Y	short	
Wavefront	float array	(unit according to Wavefront_Unit_Um_Waves)

4.3.10.3 WFS Receiver Application sample

The Wavefront Sensor software package contains the sample application **WFS_Receiver.exe** for demonstrating the data transfer using DataSocket. The following is a screen shot of this program panel.



First you have to connect to the same DataSocket server where the Wavefront Sensor application sends the data to. Click '**Connect (Auto Update)**' for connecting and automatically updating the data items as soon as they are modified on the DataSocket server. Mark the '**Enable beep when data is updated**' switch for an acoustic signal on each data update.

An update is carried out automatically by the callback routine 'DSCallback (...)' which is fired whenever data or status on the DataSocket is changed. When '**Connect (Man Update)**' was used an update is only done by a click on '**Update**'.

See the sample source code WFS_Receiver.c on the Wavefront Sensor installed in the 'Thorlabs Wavefront Sensor \ WFS_Receiver' directory for detailed information of how programming is done.


4.3.11 Printing

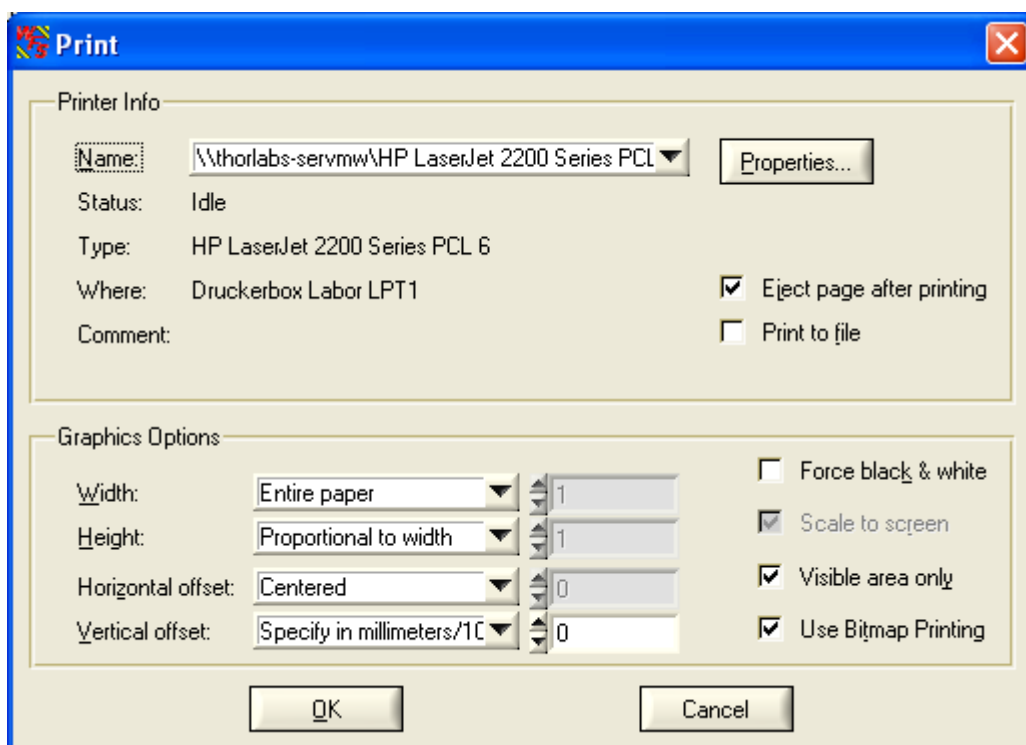
The Wavefront Sensor software enables the user to print out a screen shot of whether

- the entire panel or
- the graph only (the right hand panel with changing content)

on a printer installed under Microsoft Windows®.

Select '**File → Print Window**' or '**File → Print Graph Only**' from the menu to start printing.

Clicking on the printer symbol  in the tool bar or using the short cut (Ctrl + P) triggers the software to print out the entire window. Beforehand a panel will be displayed to set some printing options.



Select the printer connected to your PC or network. Just click '**OK**' for immediate printing.

It is recommended however to keep an eye on some printing options. First of all, select the desired printer, go to its '**Properties**' button and set the desired paper format (portrait or landscape) there.

There are some predefined options already set which force the entire panel or just the graph panel to be printed on **top of portrait paper**.

The graphics options that ensure usage of whole paper width for that are:

Width	entire paper
Height	Proportional to width
Hor. offset	Centered
Vert. offset	Specify in mm/10

If you like to use **max. height in landscape format** please change it to:

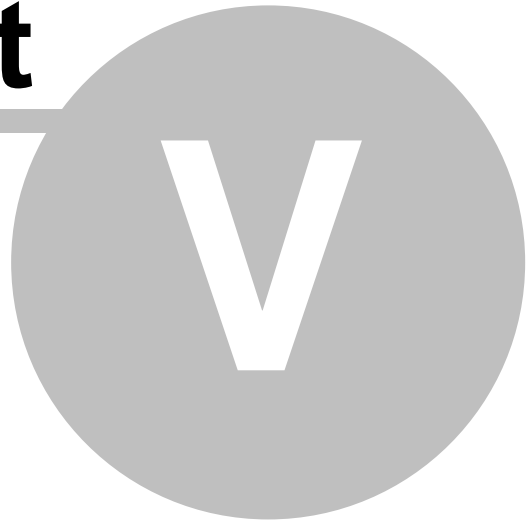
Width	Proportional to height
Height	entire paper
Horn. offset	Centered
Vert. offset	Centered

The option '**Use Bitmap Printing**' is enabled by default which results in a printout which is pixel by pixel a copy of the screen. To increase printing resolution and readability you might switch it off. In this configuration the printout may differ from the original screen image.

Service and Maintenance

WFS150 / WFS150C Manual

Part



5 Service and Maintenance

5.1 Service

In normal operation the WFS150 / WFS150C does not need any service. It is recommended to screw on the dust cover when the Wavefront sensor is not used.

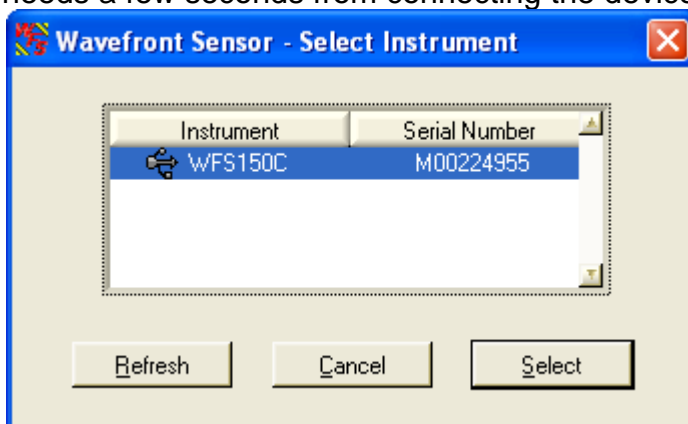
Remove dust in the instruments entrance aperture with oil-free compressed air.

There is no need to recalibrate the WFS150 / WFS150C Wavefront Sensors after a period of time.

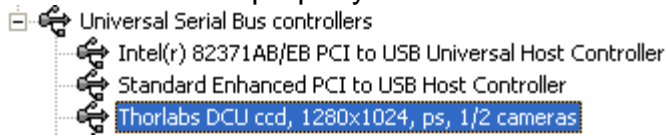
5.2 Troubleshooting

1. No Wavefront Sensor found after start of wfs.exe

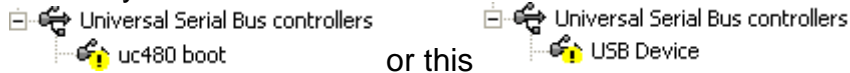
- Look if the Wavefront Sensor is connected to the USB 2.0 port of the PC by the delivered USB 2.0 cable. The LED at the back of the Wavefront Sensor will indicate the instrument state:
 - LED = off USB cable or USB port is defect
 - LED = red Sensor not recognized by the Windows system, install the Wavefront Sensor drivers (see [Software Installation](#))
 - LED = green Wavefront Sensor is properly installed and can be used by the application program
- Did you complete installation from the Wavefront Sensor Installation CD?
Note: If you connected the Wavefront Sensor to another USB port of the PC as you did during installation process you have to enable this USB port for Wavefront Sensor, too. If so, wait a few seconds until the new hardware (for this port) was found and the popup window occurs and look at [Connection to the PC](#).
- Be sure to have administrative rights on your computer which enables you to install software at all. Ask your system administrator to give you such rights or to do the installation himself.
- Click 'Refresh' button on the 'Select Instrument' popup window. The system needs a few seconds from connecting the device to make it ready to use.



For verification purposes you might check the existence of this instrument in the device manager of your computer. From the Start button select **Settings** → **System Control** → **System** → **Hardware** → **Device Manager**. The following entry under 'USB Devices' group indicates that the Wavefront Sensor device is properly installed.



In case you see entries like this

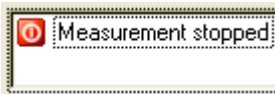



the installation process did not come to an end. Click right on this entry, select 'Update driver' and follow the guidance of your system. If required lead the system to this directory. c:\Windows\Inf containing all installed drivers.

2. No measurement values are updated

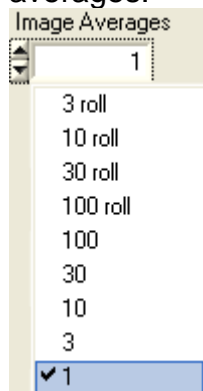
Displayed power values (and graphs) seems to be not updated.

- Perhaps the measurement has been stopped. Look at the message window of the Wavefront Sensor GUI (right down). If there is a message like this



you only have to start the measurement again by clicking on the menu **'Measurement** → **Start**' or click on the  symbol of the toolbar or simply press 'F2'.

- If the measurement isn't stopped it may take only a long time for getting the first or next result because average control is set to a high number of averages.



Go to the [Camera Settings Setup](#) panel and select a small number of averages.

- 3. The menu items, toolbar buttons and setting values in the main panel are not reacting on your clicks**
- There is a Wavefront Sensor popup window open like 'Wavefront Sensor Message'. The input focus lies only on this open popup window. Close the open popup window to get the input focus back to the main panel.

Listings

WFS150 / WFS150C Manual

Part



VI

6 Listings

6.1 List of Acronyms

The following acronyms and abbreviations are used in this manual:

3D	<u>3</u> <u>D</u> imensional
CW	<u>C</u> ontinuous <u>W</u> ave
DFB	<u>D</u> istributed <u>F</u> eedback
EC	<u>E</u> uropean <u>C</u> ommunity
EU	<u>E</u> uropean <u>U</u> nion
FPS	<u>F</u> rames <u>p</u> er <u>S</u> econd
FWHM	<u>F</u> ull <u>W</u> idth <u>H</u> alf <u>M</u> aximum
GUI	<u>G</u> raphical <u>U</u> ser <u>I</u> nterface
MLA	<u>M</u> icro <u>l</u> ens <u>A</u> rray
NI	<u>N</u> ational <u>I</u> nstruments
OEM	<u>O</u> riginal <u>E</u> quipment <u>M</u> anufacturer
PC	<u>P</u> ersonal <u>C</u> omputer
PCB	<u>P</u> rinted <u>C</u> ircuit <u>B</u> oard
RoC	<u>R</u> adius <u>o</u> f <u>C</u> urvature
RoHS	<u>R</u> estriction <u>o</u> f the Use of Certain <u>H</u> azardous <u>S</u> ubstances in Electrical and Electronic Equipment
VISA®	<u>V</u> irtual <u>I</u> nstrument <u>S</u> oftware <u>A</u> rchitecture
USB	<u>U</u> niversal <u>S</u> erial <u>B</u> us
WFS	<u>W</u> ave <u>f</u> ront <u>S</u> ensor

6.2 Addresses

Our company is represented by several distributors and sales offices throughout the world.

Europe

Thorlabs GmbH
Hans-Boeckler-Strasse 6
D-85221 Dachau
Germany

Sales and Support
Phone: +49 (0) 8131-5956-0
Fax: +49 (0) 8131-5956-99
Email: europe@thorlabs.com

USA

Thorlabs, Inc.
435 Route 206 North
Newton, NJ 07860

Sales and support
Phone: 1-973-579-7227
Fax: 1-973-300-3600
Email: sales@thorlabs.com
Email: techsupport@thorlabs.com

Japan

Thorlabs, Inc.
6th Floor, Fujimizaka Building
5-17-1, Ohtsuka
Bunkyo-ku, Tokyo 112-0012

Sales and support
Phone: +81-3-5977-8401
Fax: +81-3-5977-8402
Email: sales@thorlabs.jp

Please call our hotlines, send an Email to ask for your nearest distributor or just visit our homepage

<http://www.thorlabs.com>

Appendix

WFS150 / WFS150C Manual

Part



VII

7 Appendix

7.1 Zernike Fit and Zernike Modes

The wavefront can be expressed in terms of a set of Zernike functions, also called Zernike modes.

$$W(x,y) = \sum_0^{\infty} c_n Z_n(x,y)$$

The wavefront $W(x,y)$ is derived from a summation of orthonormal Zernike functions $Z_n(x,y)$ weighted by its amplitudes or Zernike coefficients c_n . Generally a least square Zernike fit is done in order to determine the Zernike coefficients c_n .

There exist various definitions about these Zernike functions. The Thorlabs Wavefront Sensor software and this manual follows the convention according to **Malacara**, see literature.

The Zernike polynomials are recommended for describing wave aberration functions over circular pupils with unit radius. Individual terms or modes of a Zernike polynomial are mutually orthogonal over the unit circle and are easily normalized to form an orthonormal basis. Zernike modes are conveniently expressed in either **polar or rectangular coordinate** reference frames.

Polar coordinates (r, θ) are radius r and radial angle θ , whereas $r = \rho/a$ with ρ as polar radial dimension and a as the pupil radius. Rectangular coordinates are x and y both normalized to unit radius 1.

$$R_n^m(r) \cos m\theta, \dots f \leq 0, |m| \leq 1$$

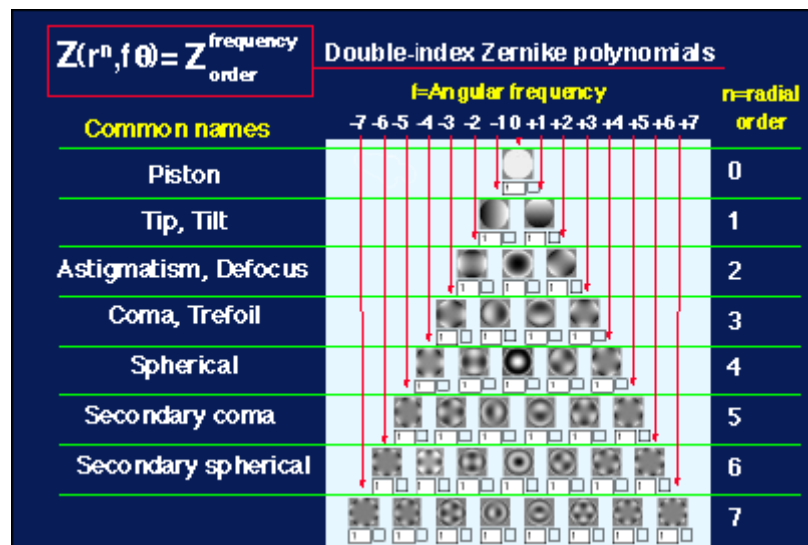
$$R_n^m(r) \sin m\theta, \dots f > 0, |m| \leq 1$$

The natural scheme for ordering of the Zernike modes is to use a double index corresponding to the **radial order** and **angular frequency** as shown above in the above equation. However, for numerical purposes it is useful to have a single-index scheme which allows the Zernike coefficients to be written as a vector for use in linear algebra calculations. Numerous schemes for ordering the Zernike modes have been proposed in the optics literature, each with its own advantages and disadvantages.

The following table gives the Zernike polynomials in radial coordinates of order 0 - 4 according to the Malacara index scheme.

Mode	Orde r	Freq	Norm	Zernike polynomial
1	0	0	1	1
2	1	1	2	$r \cdot \sin(\theta)$
3	1	-1	2	$r \cdot \cos(\theta)$
4	2	2	$\sqrt{6}$	$r^2 \cdot \sin(2\theta)$
5	2	0	$\sqrt{3}$	$2r^2 - 1$
6	2	-2	$\sqrt{6}$	$r^2 \cdot \cos(2\theta)$
7	3	3	$2\sqrt{2}$	$r^3 \cdot \sin(3\theta)$
8	3	1	$2\sqrt{2}$	$3r^3 \cdot \sin(\theta) - 2r \cdot \sin(\theta)$
9	3	-1	$2\sqrt{2}$	$3r^3 \cdot \cos(\theta) - 2r \cdot \cos(\theta)$
10	3	-3	$2\sqrt{2}$	$r^3 \cdot \cos(3\theta)$
11	4	4	$\sqrt{10}$	$r^4 \cdot \sin(4\theta)$
12	4	2	$\sqrt{10}$	$4r^4 \cdot \sin(2\theta) - 3r^2 \cdot \sin(2\theta)$
13	4	0	$\sqrt{5}$	$6r^4 - 6r^2 + 1$
14	4	-2	$\sqrt{10}$	$4r^4 \cdot \cos(2\theta) - 3r^2 \cdot \cos(2\theta)$
15	4	-4	$\sqrt{10}$	$r^4 \cdot \cos(4\theta)$

The next table illustrates the wavefront aberrations for Zernike functions of order 0 - 7 for all angular frequencies.



Literature: D. Malacara, Optical Shop Testing, 2nd ed., (John Wiley & Sons, Inc., New York, 1992).

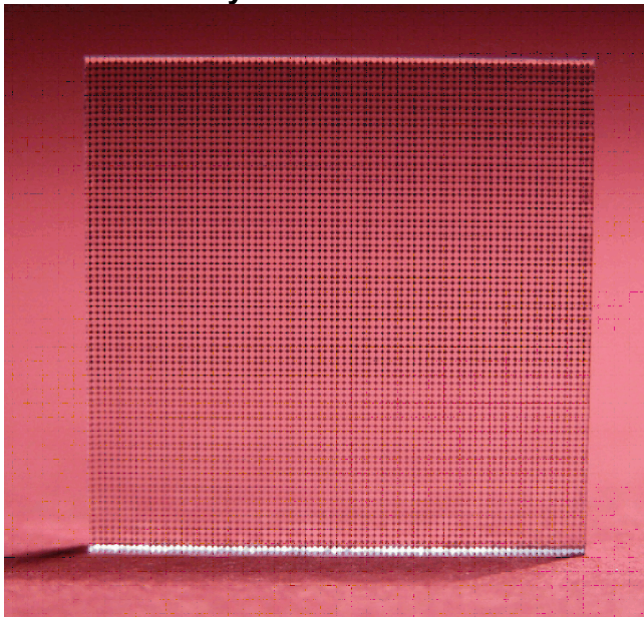
7.2 Microlens Data

The Thorlabs uses high-quality microlens arrays for its Wavefront Sensors WFS150 / WFS150C which are best suited for Shack-Hartmann Wavefront Sensor applications. Both lenslets are made from fused silica for excellent transmission characteristics from the deep UV to IR and have a plano-convex shape that allows nearly refraction limited spots.

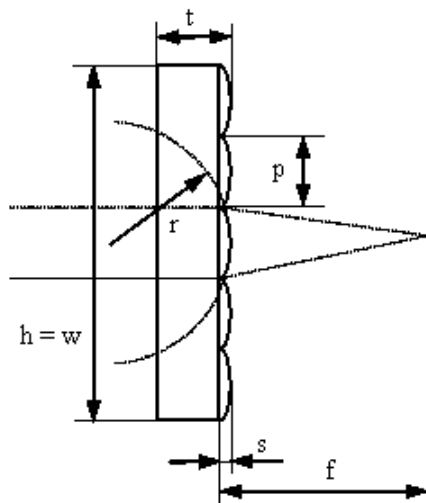
The lenses are formed using photolithographic techniques based on semiconductor processing technology, which allows for excellent uniformity in the shape and position of each microlens, unlike some microlens arrays produced from molded epoxy.

The two Wavefront Sensor models WFS150 and WFS150C utilize the microlens arrays MLA150-7AR and MLA150-5C, respectively. The MLA150-5C has a chrome mask that blocks light from being transmitted unless it goes through a microlens and therefore increases image contrast. The MLA150-7AR has a broadband AR coating to reduce surface reflections in the 400-900nm spectral region to below 1%.

Microlens Array MLA150-5C



Geometric Parameters of the MLA150 Series



Parameter	MLA150-7AR	MLA150-5C
h, w	10 mm	10 mm
t	1,19 mm	1,24 mm
p	150 μm	150 μm
s	0,87 μm	1,12 μm
r	3,063 mm	2,380 mm
f	6,7 mm	5,2 mm

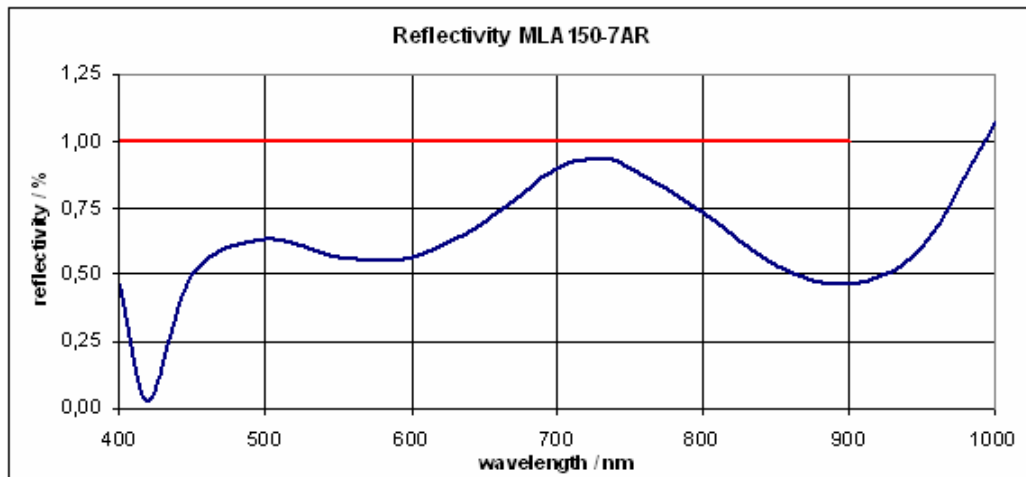
Specifications of the MLA150 Series

Parameter	MLA150-7AR	MLA150-5C
Substrate Material	Fused Silica (Quartz)	
Wavelength Range	From DUV to IR	
Array Size and Type	10 x 10 mm, Square Grid	
Lens Type	Round, Refractive, Plano-Convex	
Lens Pitch / Diameter	150 μm / 146 μm	
Focal Length	6,7 mm	5,2 mm
AR-Coating	Yes, Reflectivity < 1% Within 400 ... 900 nm	no
Chrome Apertures	no	Yes, Around Microlenses

7.3 Typical Wavelength Curves

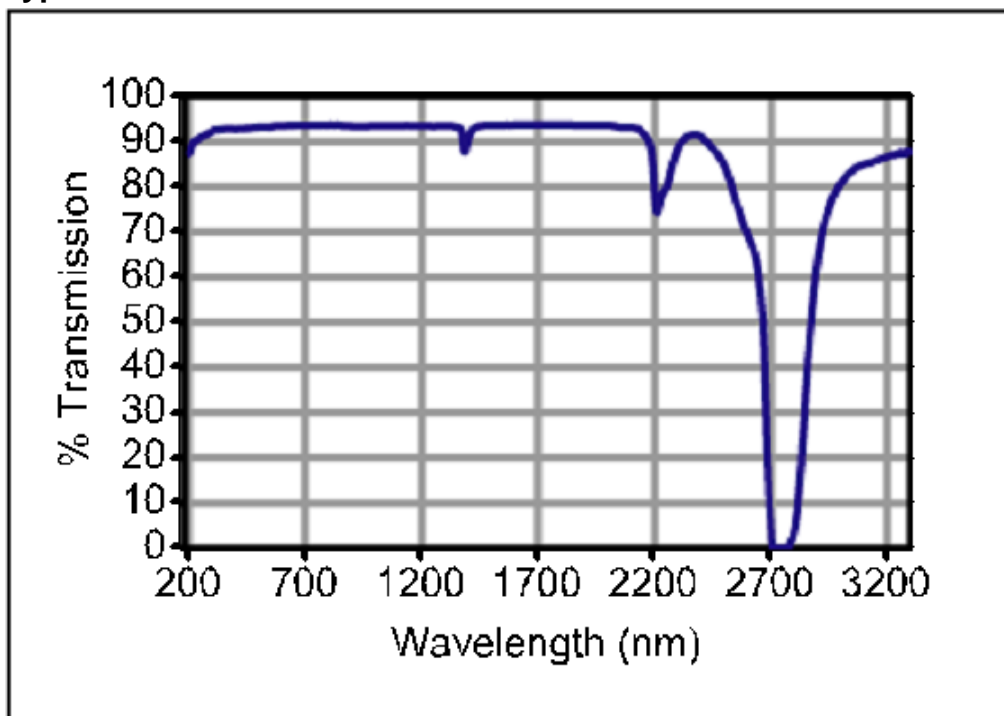
Wavefront Sensor WFS150 contains an anti reflection coated (AR) lenslet array. The following diagram shows the typical reflectivity of the lenslet array. Its guaranteed reflectivity in the wavelength range 400 to 900 nm is below 1%.

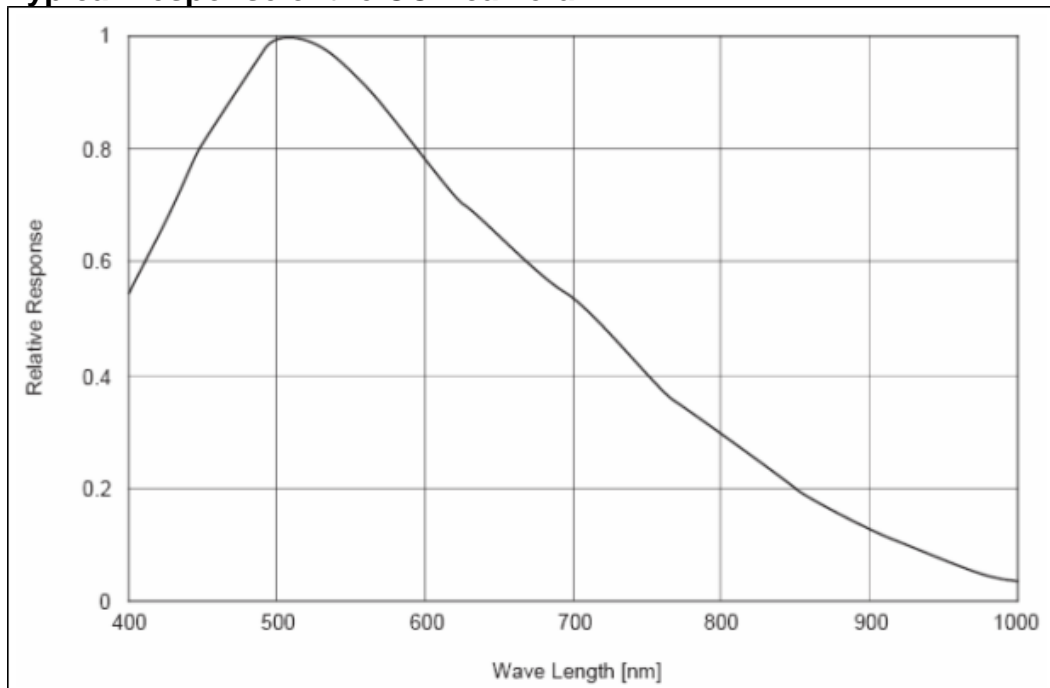
Reflectivity of MLA150-7AR including AR - Coating



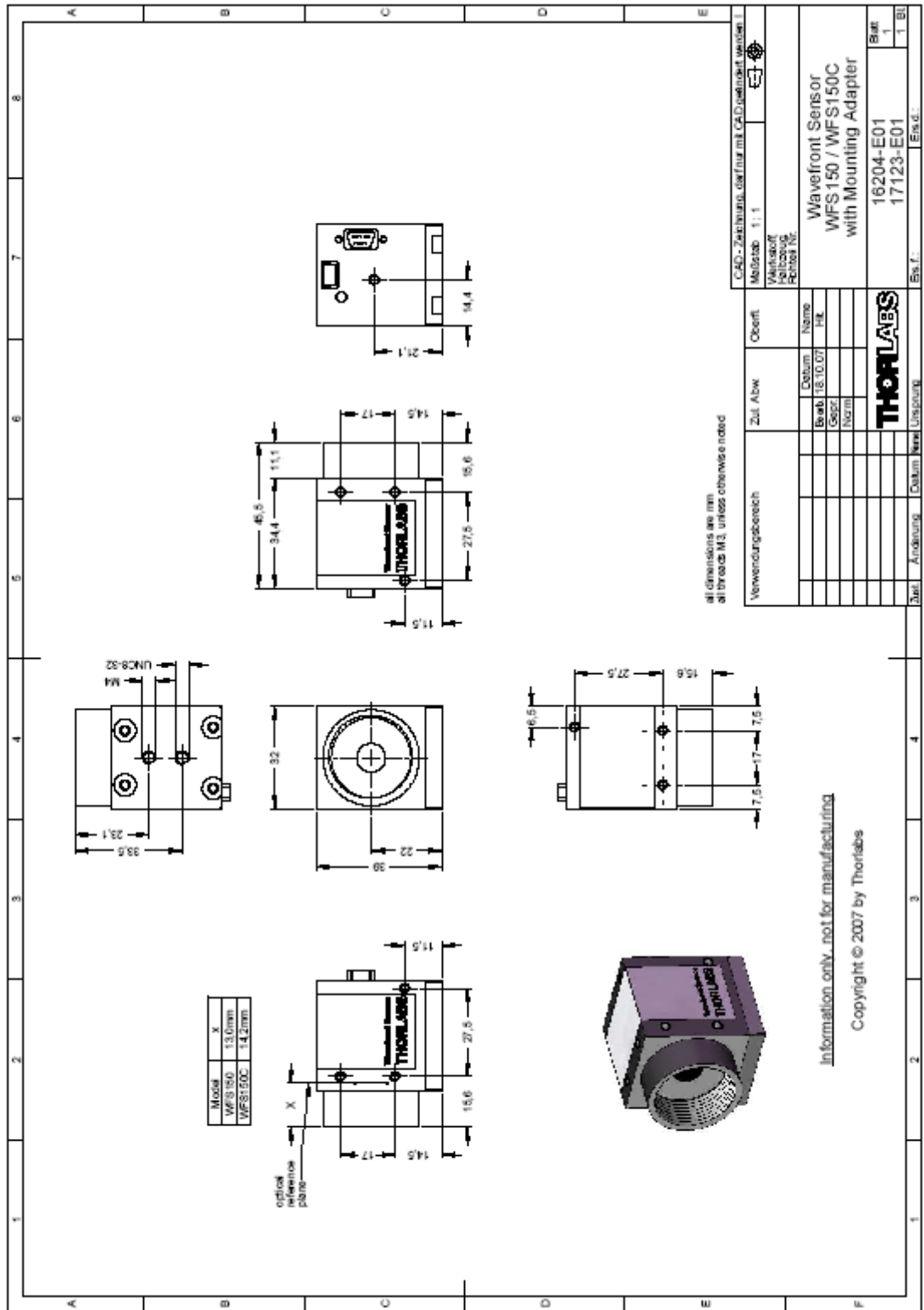
Note: The total reflectivity of the WFS150 instrument may be higher due to reflections from the CCD camera chip and its covering window.

Typical Transmission of Fused Silica Material



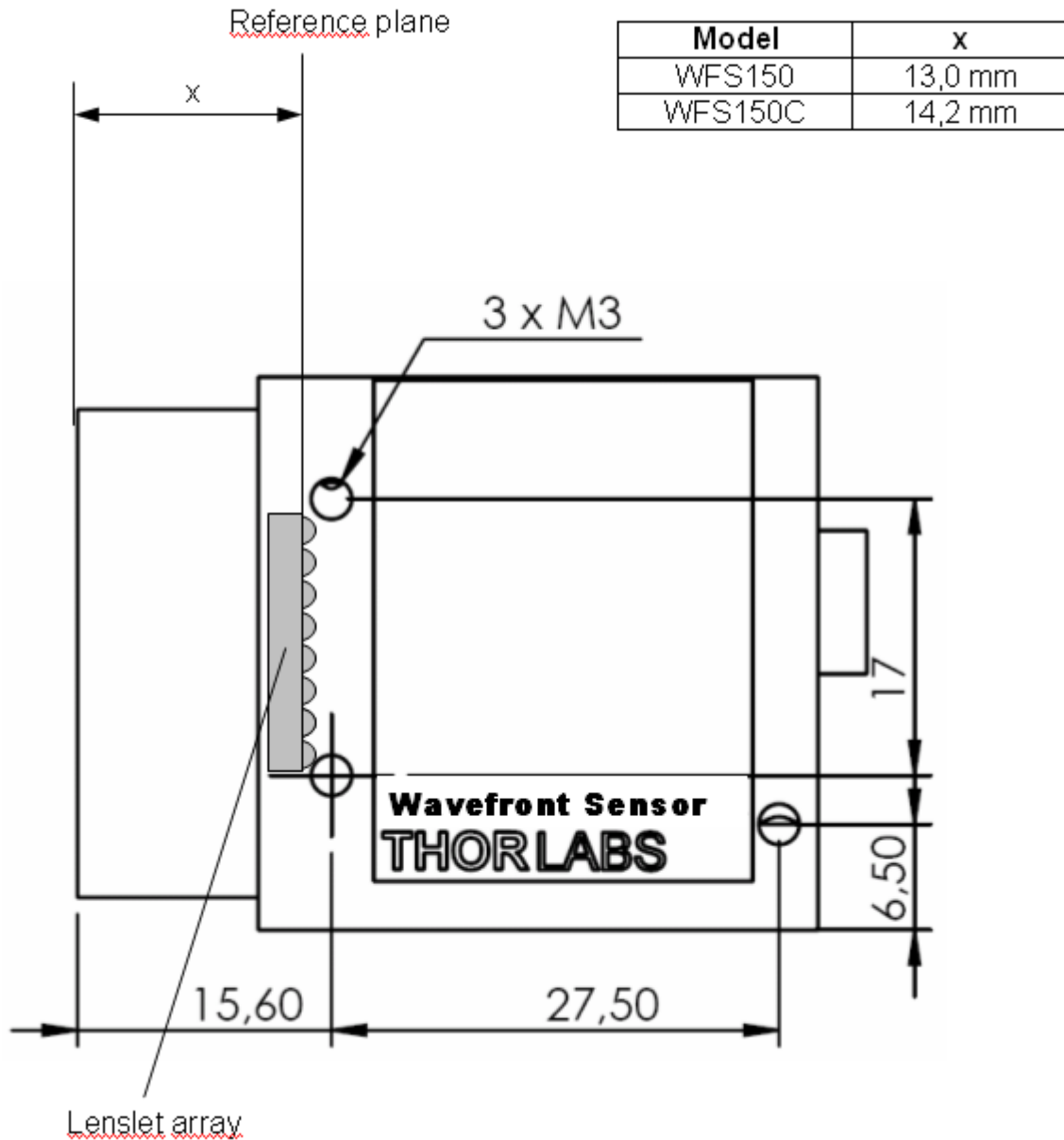
Typical Response of the CCD camera

7.4 Wavefront Sensor Drawing



7.5 WFS Reference Position

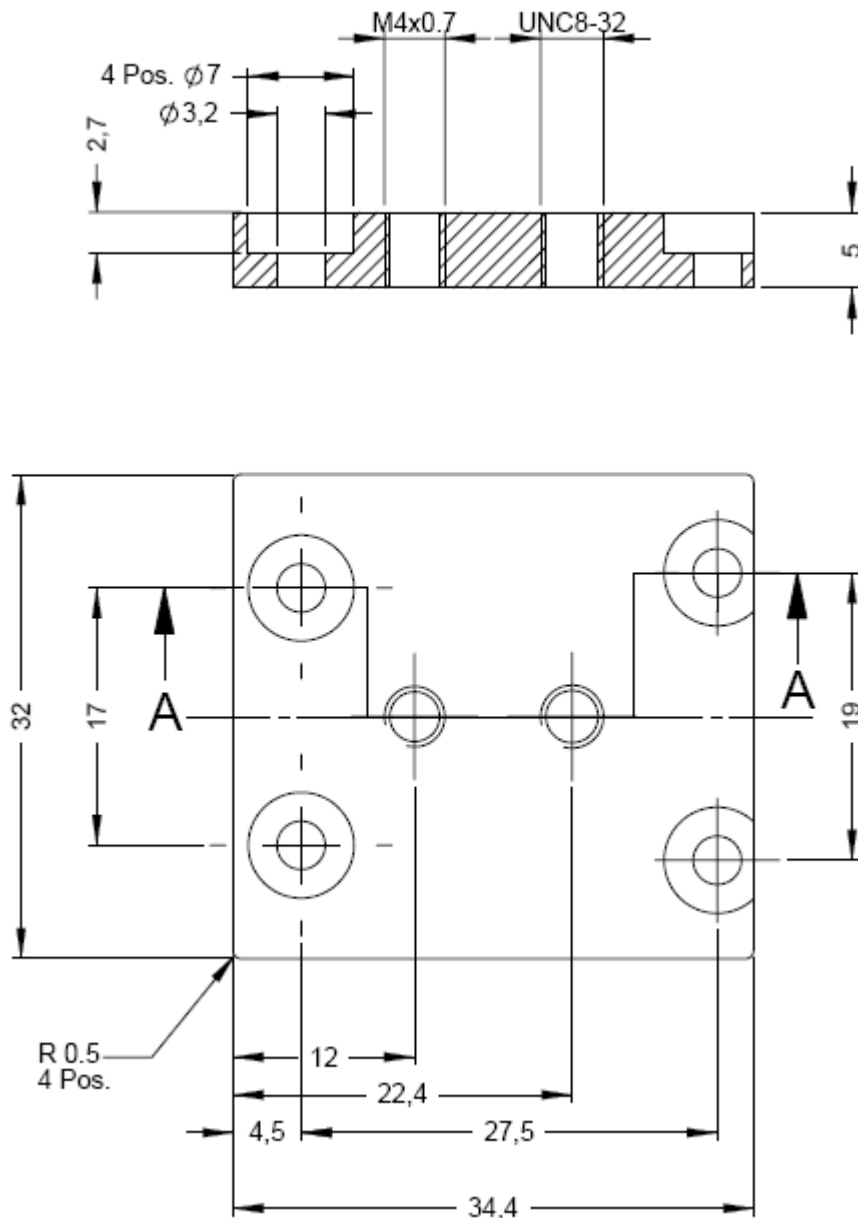
Wavefront data calculated by the Thorlabs Wavefront Sensors WFS150 / WFS150C are related to the reference position of the sensor. This position is identical to the location of the microlenses on the back face of the microlens array. Since this location is different for both models also the reference position is model specific.



7.6 WFS Mounting Adapter

A mounting adapter is added to the camera housing of the Wavefront Sensor in order to supply standard threads M4 and UNC8-32 which are compatible to the palette of Thorlabs' mounts and posts holders.

Mount this adapter plate on the bottom side of the Wavefront Sensor using the 4 screws M3x6 if you want to use one of the mounting threads M4 or UNC8-32. Otherwise, this adapter can be omitted.



Index

- A -

Accessories 29
 Acronyms 106
 Addresses 107
 administrative rights 102
 angular frequency 109
 Autorun 9
 Averages 64

- B -

Beam Data 80
 Beam View Panel 54
 Beamview Configuration 54
 Bitmap Printing 99
 Black Level 64

- C -

Calc extra data 77
 Calibration 43, 102
 Camera Image Size 64
 Camera Settings 64
 Cancel Wavefront Tilt 72
 CCD camera 24
 Certifications and compliances 32
 Chrome mask 111
 Circular pupil 69
 C-Mount 24
 Connection to the PC 18
 Coordinate Definitions 39
 csv 88

- D -

Data flow chart 24
 Data Items 96
 DataSocket 92
 DataSocket Configuration 95
 DataSocket server 92
 DCU 9
 Default 3D View 56
 Default Setup Parameters 63
 Default Top View 56
 Description 24

Difference 56
 Display 43
 Display Graphics (time consuming) 77
 Drawing 115
 Driver 9

- E -

EcologicalBackground 7
 Enable basic data 95, 96
 Enable wavefront data 95, 96
 Error List 83
 Errors 83
 Exposure time 64

- F -

File 43, 88
 Firewall 92
 Fit Error 80
 Fit up to Zernike Order 74
 Fourier constants 80
 Functionality 24

- G -

Gain 64
 Getting Started 9
 Graphical User Interface 41
 GUI 41

- H -

Help 43
 Highest order in Fourier and Optometric calculations 74

- I -

Internal reference 72

- L -

Limit to Pupil Interior 69
 Lineview Configuration 49
 Lineview Panel 49
 Literature 109
 Live data exchange 92
 Local DataSocket server 95
 Localhost 95

- M -

Malacara 109

Master Gain 64
Measured 56
Measurement 43
Measurement results 80
Measurement Warnings and Errors 83
Menu 43
Microlens Data 111
microns 72
Miscellaneous 77
MLA150-5C 111
MLA150-7AR 111
Mode selection for wavefront reconstruction 74
Mounting Adapter 117

- N -

Noise Cut Level 64

- O -

Omit Piston + Tip + Tilt 61
Operating Instruction 34
Operating the instrument 43
Optometric constants 80

- P -

Paper format 99
Part List 29
Photodiode 116
polar or rectangular coordinate 109
Position 116
Preconditions 34
Print Graph 99
Print Window 99
Printer 99
Pupil Center 69
Pupil Definitions 69
Pupil Diameter 69
PV 80

- Q -

Quick Start-up 9

- R -

radial order 109
Radius of Curvature 80
Reconstructed 56
Reference Position 116
Reflectivity of MLA150-7AR 113

Right-hand coordinate system (x, y, z) 39
RMS 80
RMS Variations 80
RMS wavefront variations 61
RoC 80
Rremote DataSocket server 95

- S -

Safety 5
Save Instrument Settings 92
Save Measurement Data 88
Save Only Wavefront Data 88
Separate DataSocket server 95
Serial Number 92
Service 102
Setup 43, 63
Setup Panel 63
Shack-Hartmann 24
Show RMS wavefront variations in Zernike orders 61
Slit 116
Software Installation 9
Specifications 31
Specifications of the MLA150 Series 111
Spotfield Configuration 52
Spotfield Panel 52
Start the Application 22
Start the GUI 22, 41

- T -

TCP/IP network 92
Technical Data 31
Tilt 72
Toolbar 43
Transmission of Fused Silica Material 113
Troubleshooting 102

- U -

uc480 9
USB 18
USB Device 18
Use Beam Centroid 69
User Calibrated Reference 72
User Calibration 84
User Calibration using a Plane Wavefront 84
User Calibration using a Spherical Wavefront 84

- V -

Version Information 92

- W -

Warnings 83

Warranty 5

Waste Treatment 7

Wavefront 72

Wavefront data 80

Wavefront Graph Configuration 56

Wavefront Panel 56

Wavefront Reference 72

wavefront resolution 64

Wavefront Sensor Drawing 115

Wavefront Sensor Setup 63

Wavefront Unit 72

Wavelength 72

Wavelength Curves 113

waves 72

WEEE 6

WFS_Receiver example program 98

wRMS 80

- Z -

Zernike Bar Graph Configuration 61

Zernike Coefficients Panel 61

Zernike Fit 74, 109

Zernike Modes 80, 109

Zernike Order 74

