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THORLABS

Optical Wavefront Sensors (Shack-Hartmann Sensors)

WFS Series

Operation Manual



2012

Version: 3.5
Date: March 27, 2012

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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 WFS series Wavefront Sensors.

WARNING

Sections marked with this heading explain dangers that might result in personal injury or death. Always read the associated information carefully before performing the indicated procedure.

ATTENTION

Paragraphs preceeded by this symbol in the manual explain hazards that could damage the instrument and connected equipment or may cause loss of data.

NOTE

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

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1 General Information

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 as it was designed for.
All modules must only be operated with proper shielded connection cables.
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 serviceable if properly packed into the complete original packaging including the plastic foam sleeves. If necessary, ask for a replacement package.

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1.2 Preconditions

Please install Wavefront Sensor application software and USB drivers (all in one package) on your PC prior to connect the WFS series Wavefront Sensor 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.

1.3 System requirements

Hardware Requirements:

- CPU: Pentium III, 900 MHz or higher
- RAM: 256 MB
- Graphic card with at least 128 MB memory, min. resolution 1024 x 768, 24 bit True Color, Indexed color
- Hard disc with at least 240 MB free storage space
- free USB2.0 high speed port (a **USB 1.1** full speed port is **not usable**!)
- USB high speed cable according the USB 2.0 specification

Software compatibility:

- Microsoft Windows XP® (32-bit),
- Microsoft Windows Vista® (32-bit, 64-bit),
- Microsoft Windows Windows 7® (32-bit, 64-bit)

2 Installation

2.1 General

Thorlabs wavefront (Shack-Hartmann) sensors consists of a camera with a mounted in front of the camera sensor microlens array (MLA).

There are 2 types of sensors differing in the type and performance of the camera.

- WFS150/300 series, based on a CCD camera (higher resolution, but slower performance)
- WFS10 series, based on a lower resolution CMOS camera enabling remarkably higher measurement speed at a somewhat reduced measurement accuracy.

Both sensor types are available with three different types of microlens arrays.

As a special feature the WFS Wavefront Sensor series is equipped with an interchangeable microlens array mounted into a precision patent pending magnetic holder. The exchange of the microlens arrays allows economic switching to different

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applications requiring different WFS specifications in terms of spatial resolution (lenslet pitch), focal length, wavefront sensitivity and dynamic range. See chapter Microlens Data 125 for a table of available MLAs.

Available wavefront sensor types (Order Codes)

WFS150-5C	Wavefront Sensor, Chrome Apertures 300-1100 nm, pitch=150 µm
WFS150-7AR	Wavefront Sensor, AR Coated 400-900 nm, pitch=150µm
WFS300-14AR	Wavefront Sensor, AR Coated 400-900 nm, pitch=300 µm
WFS10-5C	Fast Wavefront Sensor, Chrome Apertures 300-1100 nm, pitch=150 µm
WFS10-7AR	Fast Wavefront Sensor, AR Coated 400-900 nm, pitch=150µm
WFS10-14AR	Fast Wavefront Sensor, AR Coated 400-900 nm, pitch=300 µm

All Thorlabs Wavefront Sensors are equipped with an easily exchangeable lenslet array.

Available WFS kits with 2 MLA

You may order also a WFS Wavefront Sensor calibrated with two included microlens arrays:

Type	Used camera	Included micro lens arrays
WFS-K1	WFS150 (CCD)	Chrome Mask 300-1100 nm, pitch=150 µm AR Coated 400-900 nm, pitch=300 µm
WFS-K2	WFS150 (CCD)	AR Coated 400-900 nm, pitch=150µm AR Coated 400-900 nm, pitch=300 µm
WFS10-K1	WFS10 (CMOS)	Chrome Mask 300-1100 nm, pitch=150 µm AR Coated 400-900 nm, pitch=300 µm
WFS10-K2	WFS10 (CMOS)	AR Coated 400-900 nm, pitch=150µm AR Coated 400-900 nm, pitch=300 µm

Wavefront Sensor types and kits as stated above are factory calibrated. For other than above mentioned combinations, please contact your local Thorlabs office (see Addresses 148)

Three Wavefront Sensor Models

There are three different versions available which differ in the type of implemented microlens array (MLA, see data here Microlens Data 125) and its distance to the CCD camera sensor.

- **WFS150-5C / WFS10-5C** 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 **300 - 1100 nm** (with largely reduced sensitivity at the edges). Take into account that such a chrome mask

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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.

- **WFS150-7AR / WFS10-7AR** 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.

- **WFS300-14AR / WFS10-14AR** 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. Due to the increased focal length this sensor features an increased sensitivity and accuracy ($\lambda/50$ instead of $\lambda/15$). On the other side, this advantage comes along with reduced spatial resolution (300 µm pitch instead of 150 µm) and dynamic range.

NOTE

The specified reflectivity of the AR coated MLA is valid only within the stated wavelength range. Outside of this wavelength range, the reflectivity may increase remarkably. Please see also Microlens Data 125.

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How to order additional microlens arrays

Due to the fact, that each MLA shows individual optical characteristics (geometry, lens pitch and lens allocation accuracy), it is necessary to calibrate each individual MLA with the appropriate camera. This calibration is carried out at factory, calibration data are saved to the camera's internal memory (EEPROM).
So if you have purchased a WFS with a single MLA and want to order an additional MLA, your existing WFS must be returned to Thorlabs. In our factory, your sensor will be calibrated with the additional MLA, calibration data will be added to the sensor's memory and the WFS will be returned to you with both MLA.

Adding an additional microlens array is an upgrade of the existing WFS with a single MLA to one of the a.m. WFS kits with 2 MLA.
Please contact your local Thorlabs office 148 for return instructions.

NOTE

If the desired MLA combination is not stated in above list, please contact your local Thorlabs office 148 for support.
The WFS software accepts only different MLA types. By other words, it is impossible to calibrate the same sensor for two microlens arrays of the same type.

Example:
To an existing WFS10-14AR should be added an additional microlens array with chrome mask and 150µm lens pitch.

- ➔ *Contact your local Thorlabs office for a return of your **WFS10-14AR** in order to convert it to **WFS10-K1** (WFS10 with two MLA)*
- ➔ *Upon receipt of your **WFS10-14AR**, the additional MLA will be calibrated with your sensor.*
- ➔ *Thorlabs will return to you a **WFS10-K1** (WFS10 with 2 MLA)*

Exchange Program for Old Style Wavefront Sensors

Our Wavefront Sensor Exchange Program offers to customers who purchased either a WFS150 or WFS150C wavefront sensor (with fixed MLA) an upgrade to a WFS150/WFS300 wavefront sensor (or to a WFS-K1 / WFS-K2 kit) with exchangeable lenslet array. **Please contact your local Thorlabs office** 148 for more details.

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2.2 Parts List

A complete wavefront analyzing system consist of a WFS series 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 (WFS)
- Mounting adapter plate and 2 mounting screws M3x6 plus 1 screw M2x6 (WFS10)
- USB2.0 high speed cable USB A to Mini USB B, 2,0 m
- CD-ROM with the required driver and application software included
- Wavefront Sensor operating manual

Exchangeable Microlens Arrays

As a special feature the WFS series Wavefront Sensors are equipped with an interchangeable microlens array mounted into a precision patent pending magnetic holder.
The exchange of the microlens arrays allows economic switching to different applications requiring different WFS specifications in terms of spatial resolution (lenslet pitch), focal length, wavefront sensitivity and dynamic range. See chapter Microlens Data 125 for a table of available MLAs.

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 (WFS) and 2x M3x6 + 1x M2x6 (WFS10) if you want to use one of the mounting threads M4 or UNC8-32. Otherwise, this adapter can be omitted. See Appendix Mounting Adapter 135 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.

Trigger Cable (optional)

An optional trigger cable CAB-DCU-T2 for WFS and CAB-WFS10-T1 for WFS10 series instruments can be ordered separately for supplying an electrical trigger signal to the WFS series instruments. See chapter Trigger Input 130 for details.

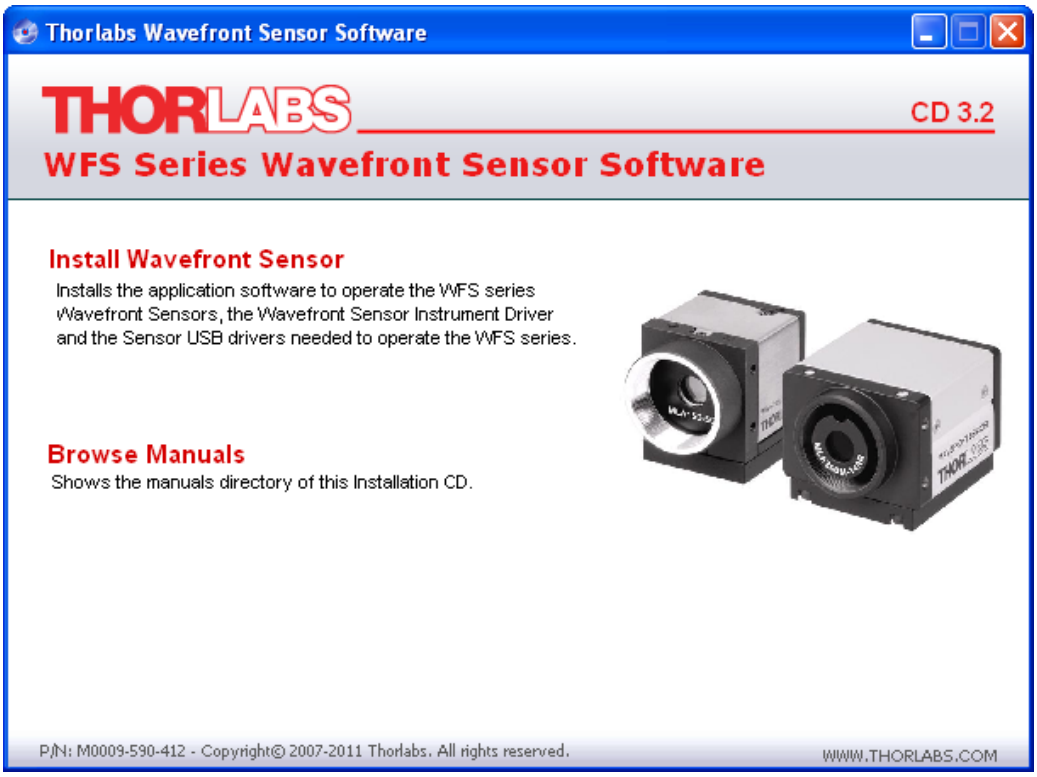
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2.3 Getting Started

Don't connect the wavefront sensor prior to install the software.
For description of software installation, please see next section in this manual.

2.4 Installing Software

Insert the "Thorlabs Wavefront Sensor CD 3.5" (or higher) CD-ROM, included with your WFS Series 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 is only one software components selectable.

Install Wavefront Sensor	Installs the application software to operate a WFS series Wavefront Sensors as well as the required camera USB drivers. In addition, this software installs the Wavefront Sensor instrument drivers for usage with C, LabView or other compilers.
Browse Manuals	Opens an explorer window and shows the provided Wavefront Sensor manual. Note: An Adobe Acrobat® viewer is required to view the PDF file.

NOTE
It is recommended to close all other programs on your computer prior to start the

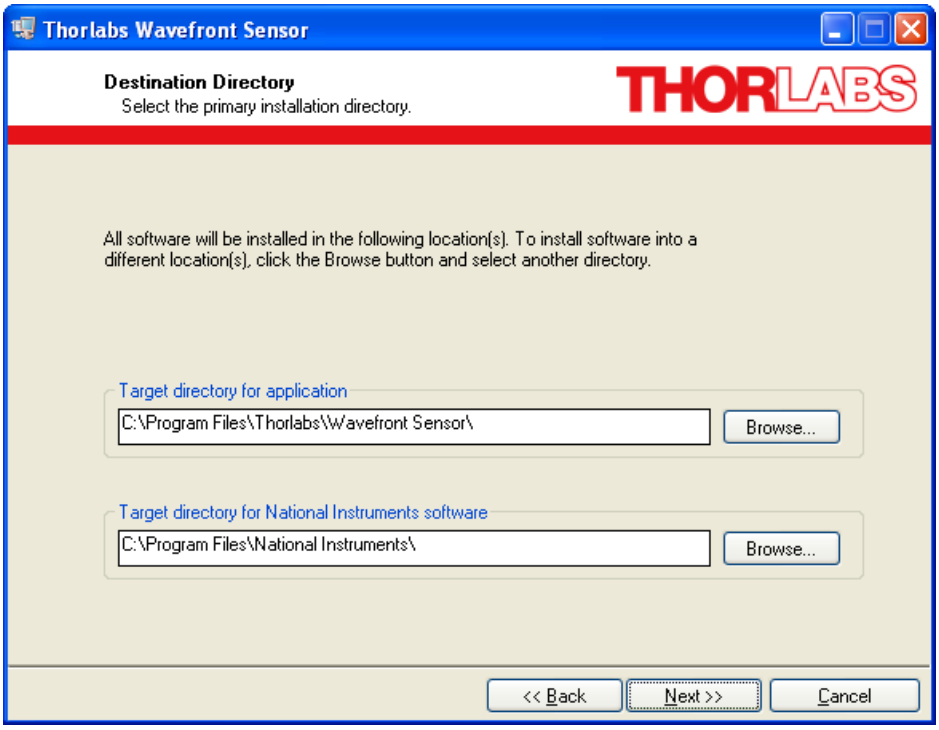
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installation process.

Installing the Wavefront Sensor Application Software

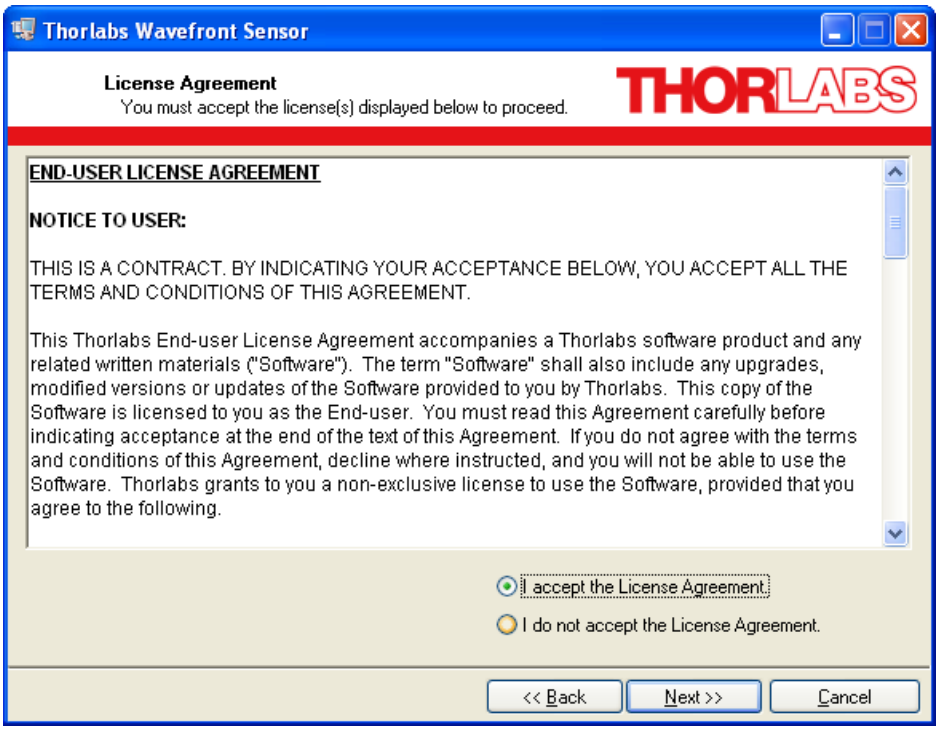
Click on '**Install Wavefront Sensor Application Software**' to start the installation procedure. First of all, an update of the Windows© installer may be required. Follow the instructions on the screen.
The Wavefront Sensor software installation starts with the following opening screen:



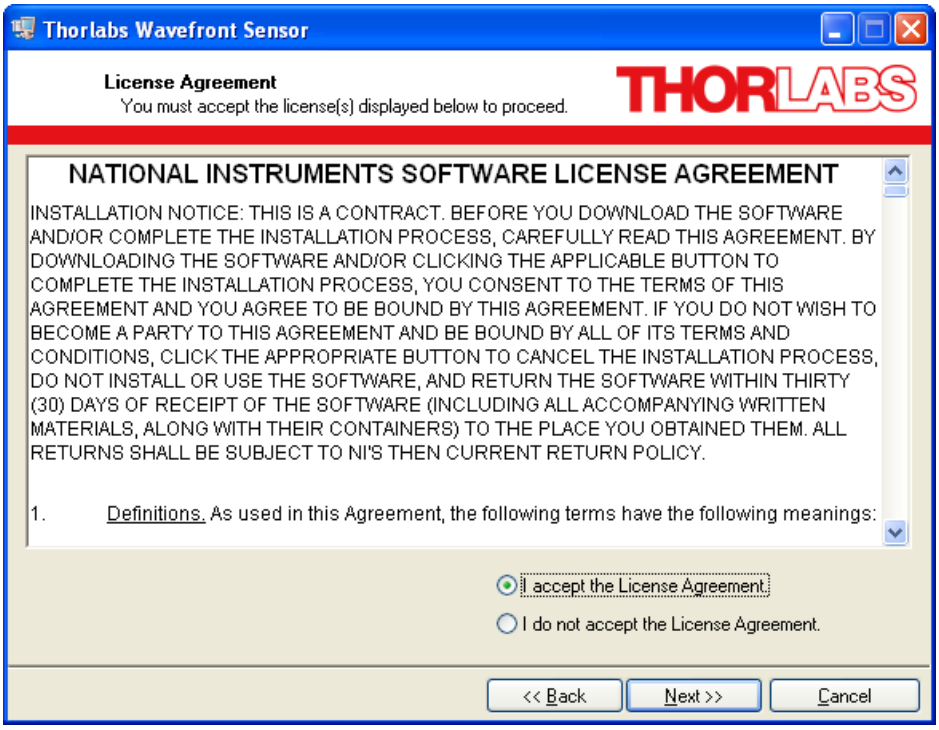


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You may change the target installation folders but it is recommended to leave the default path names.
Click 'Next' to proceed.

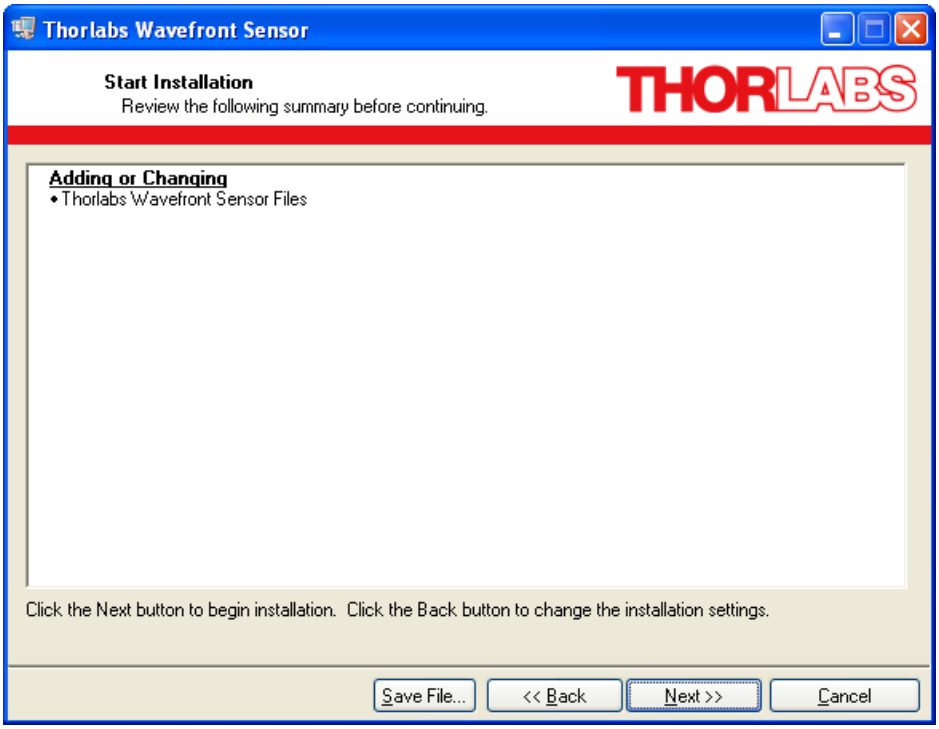


Read the License Agreement carefully. Mark 'I accept the License Agreement' and click 'Next' to proceed.

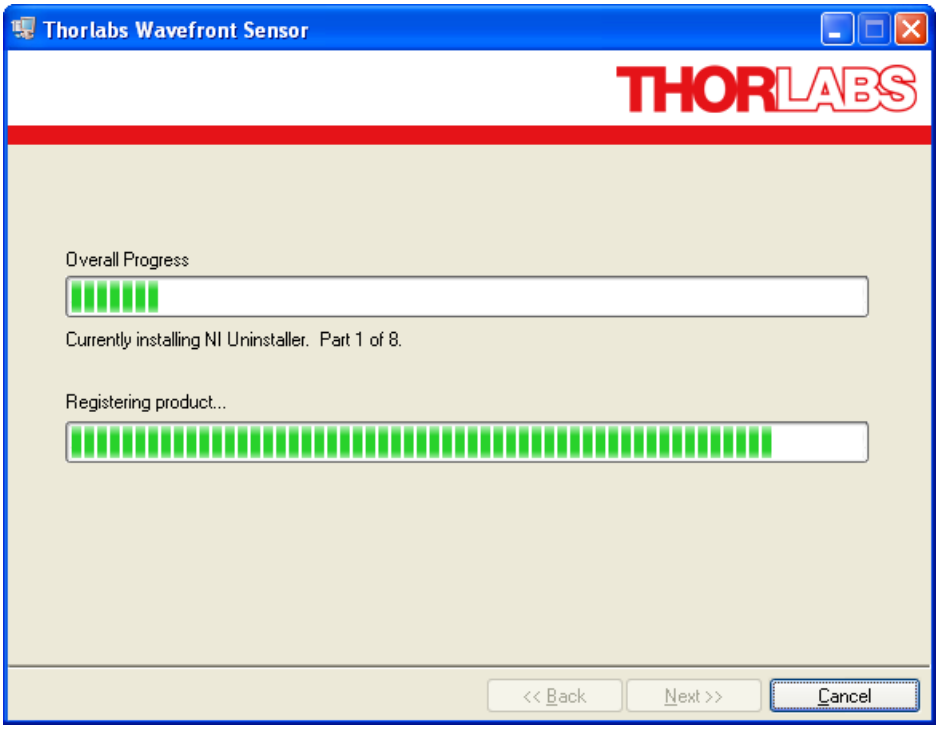


Read also this NI License Agreement carefully. Mark 'I accept the License Agreement' and click 'Next' to proceed.

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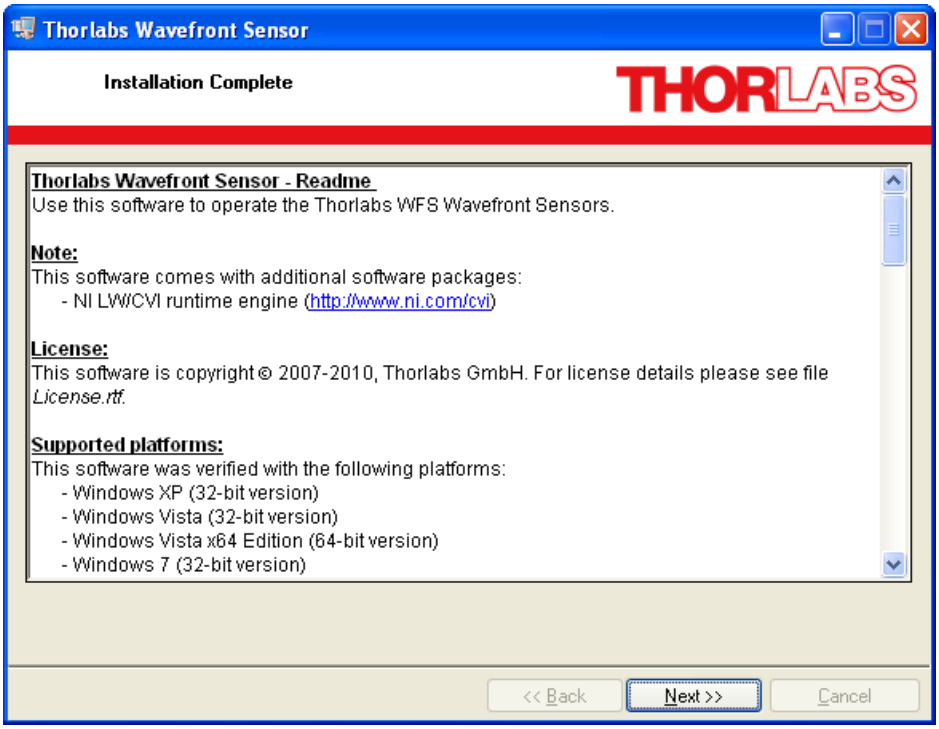


You will be informed about items that are going to be installed. Click 'Next' to proceed.

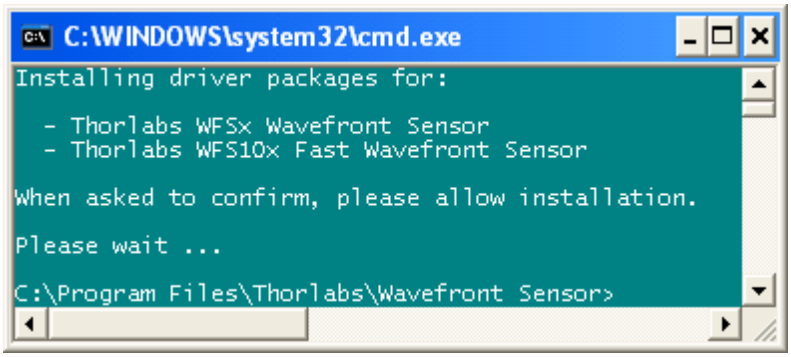


The installation process will take a minute.
After completion of this installation process the Readme.rtf file coming with each software release appears. It informs you about newly added features or removed bugs.

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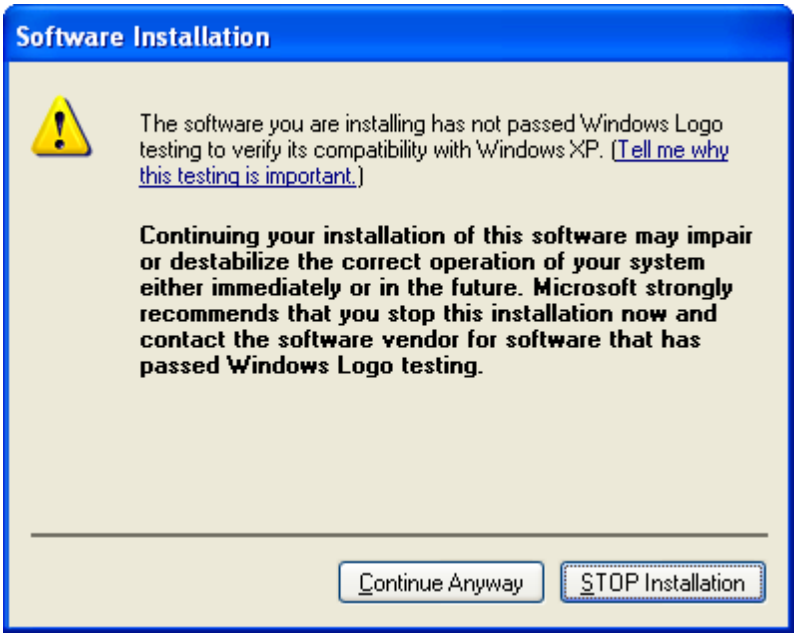


Click 'Next' to proceed.
Now, a command prompt window opens temporarily which is required to install the camera USB drivers on the operating system.

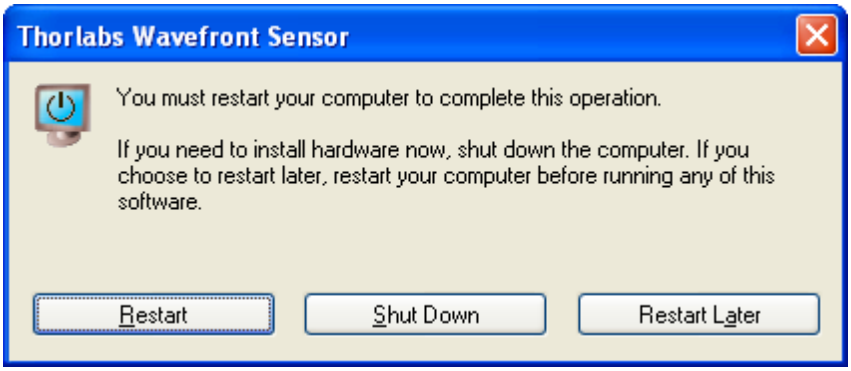


The following warning may appear:

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



Depending on your operating system it may be required to restart your computer. Click 'Restart' to reboot your system.

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2.4.1 Included Wavefront Sensor Instrument Drivers

When installing software from CD, at the same time the Wavefront Sensor Instrument Driver was installed to your computer. This Instrument Driver package contains the following files for operating the WFS series instrument under control of LabView, C or DotNet.

[Program Files]\Microsoft.NET\Primary Interop Assemblies
Thorlabs.WFS.dll - ***DotNet** DLL*
Thorlabs.WFS.XML - *DotNet help file*

[System]
WFS_Drv.dll - *driver dynamic link library*

[LabVIEW]\user.lib\WFS_Drv
WFS.llb - ***LabVIEW WFS Library and Example file***
dir.mnu - *LabVIEW menu file*
dir - Action Status Functions.mnu - *LabVIEW menu file*
dir - Calibration Functions.mnu - *LabVIEW menu file*
dir - ConfigFunctions.mnu - *LabVIEW menu file*
dir - Data Functions.mnu - *LabVIEW menu file*
dir - Utility Functions.mnu - *LabVIEW menu file*

[VXI PnP OS]\bin
WFS_Drv.dll - *driver dynamic link library*

[VXI PnP OS]\include
WFS_Drv.h - *driver include file*

[VXI PnP OS]\lib\msc
WFS_Drv.lib - *library import file for **Microsoft compiler***

[VXI PnP OS]\Thorlabs WFS
Readme.rtf - *this file*
WFS_Drv.fp - ***LabWindows/CVI function panel** file*
WFS_Drv.lib - *library import file*

[VXI PnP OS]\Thorlabs WFS\Examples\C
sample.exe - *Command line **sample application***
sample.c - *Source code of sample application*

[VXI PnP OS]\Thorlabs WFS\License
License.rtf - *License file*

[VXI PnP OS]\Thorlabs WFS\Manual
WFS_Drv.txt - ***programmers reference file***
WFS_Drv.html - ***driver online help***

[VXI PnP OS]\Thorlabs WFS\Typelib
WFS_Drv.def - *Export definition file*
WFS_Drv.odl - *Interface definition language file*

NOTE
LabView driver files are copied to a location which is pre-defined by previous

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installations of National Instruments LabView software, for instance:
C:\Program Files\National Instruments\LabVIEW\user.lib\WFS_Drv.
Other compiler support and help files can be found here:
C:\Program Files\IVI Foundation\VISA\WinNT\Thorlabs WFS

Please note that there are **short sample application files with supplied source code for C and LabView** which should help you to understand the driver usage. For a full documentation of the driver functions open **WFS_Drv.html** file or see text file WFS_Drv.txt.

2.5 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.

Models WFS150* and WFS300*

For models WFS150* and WFS300*, the Wavefront Sensor represents a modified Thorlabs DCU camera, the driver software is basically the same for both instruments. Below are some comments and screenshots if the connected wavefront sensor is of WFS150-5C, WFS150-7AR or WFS300-7AR type.

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 WFS150-5C, WFS150-7AR and WFS300-14AR devices for operation.

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

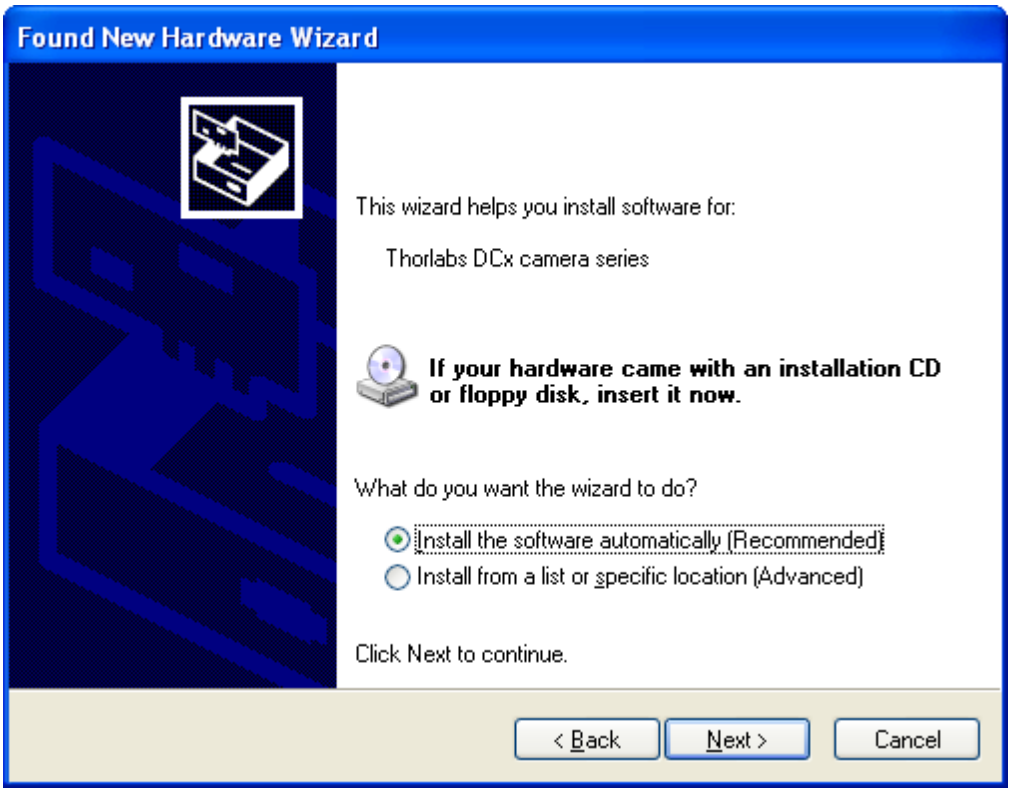
NOTE

You may also be prompted to confirm the driver installation.

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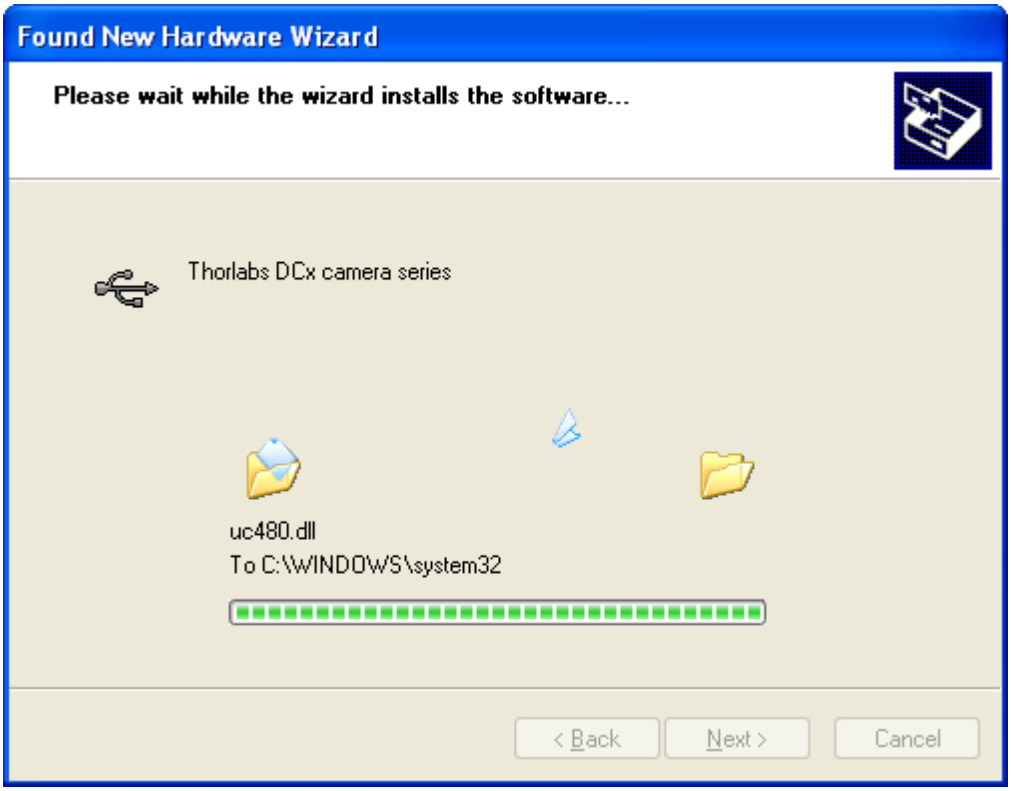


Mark 'No, not at this time' and proceed with 'Next'.

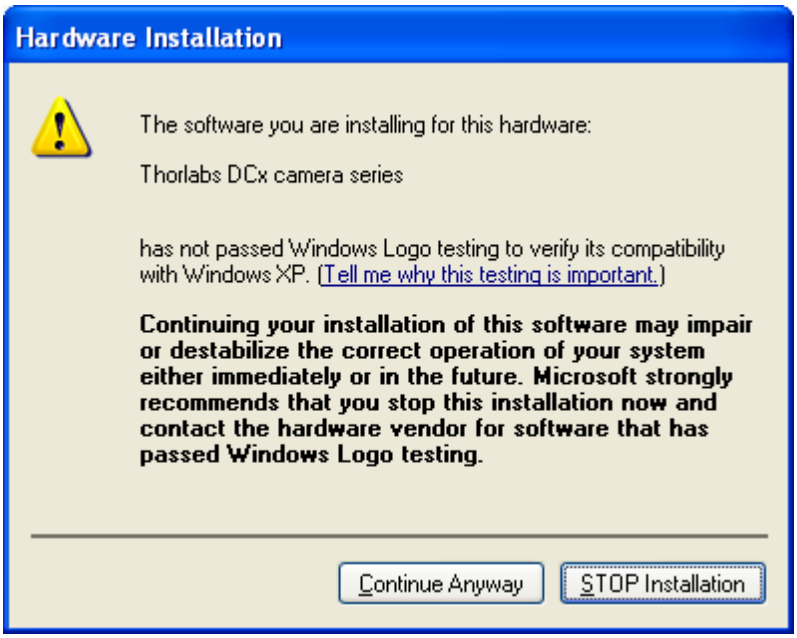


Mark 'Install the software automatically (Recommended)' option and click 'Next'.

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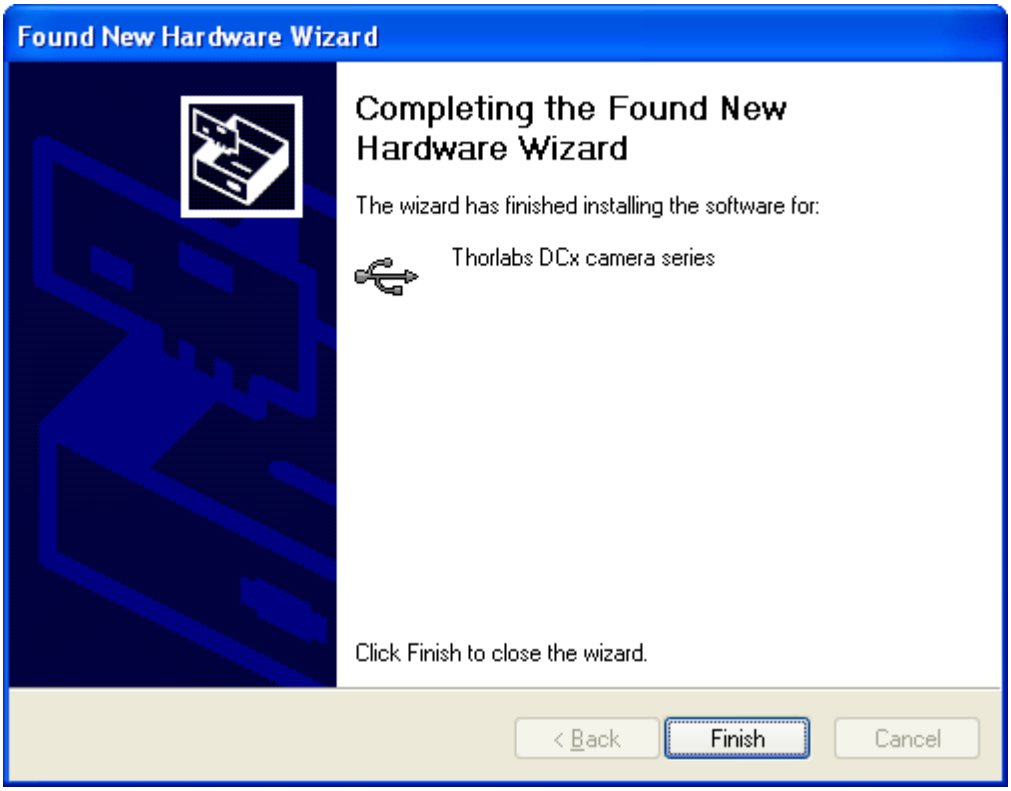


Files are being copied and a warning will appear:



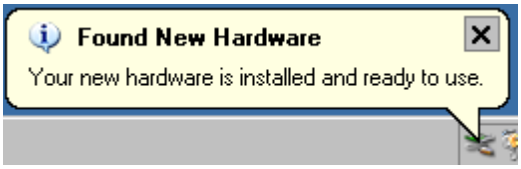
Please ignore this warning '…has not passed Windows Logo testing…' and click on 'Continue Anyway'.

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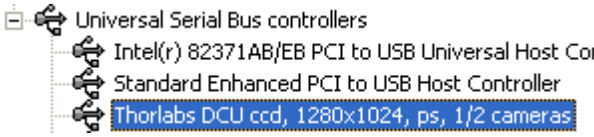


This above procedure repeats for a second time, please answer the questions the same way.

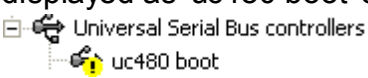
The USB driver for the Wavefront Sensor hardware is now properly assigned. Click 'Finish' to complete this process.
Windows will inform you that the hardware is correctly installed and ready to use:

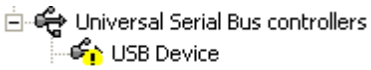


For verification purposes you might check the existence of this instrument in the Device Manager of your computer.
From the Start button select Control Panel → System → Hardware → Device Manager. The following entry under the USB Serial Bus controllers group indicates that the Wavefront Sensor device 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'.





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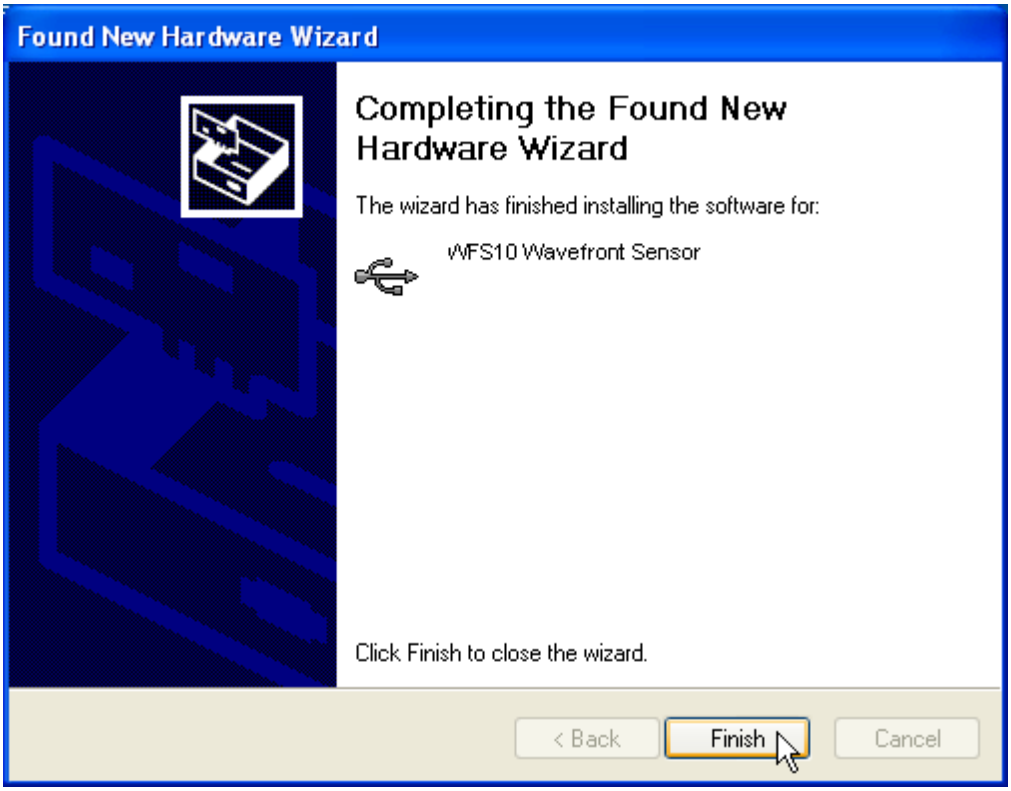
Wait a few seconds to let the driver communicate with the instrument. If you still cannot see the entry 'Thorlabs DCU camera' please check the troubleshooting 117 chapter.

WFS10* models

In case that the connected wavefront sensor was the highspeed capable version WFS10*, the Found New Hardware Wizard recognizes a WFS10 Wavefront Sensor:



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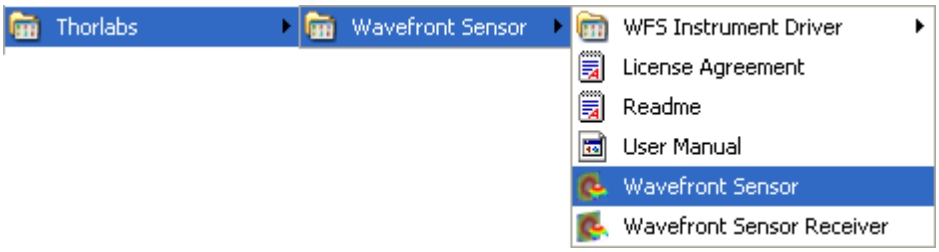


This above procedure repeats for a second time, please answer the questions the same way, and the WFS10* now is ready for use.

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 initialization process and the instrument becomes ready to use by the application program.

2.6 Start the Application

Access the Application Programs from the START button. Find the "Programs" → "Thorlabs" → "Wavefront Sensor" → "Wavefront Sensor" entry, or simply click on the icon on your desktop.



Do not forget to remove the dust cover from the Wavefront Sensor.
Refer for Start the GUI 40 chapter for detailed description.

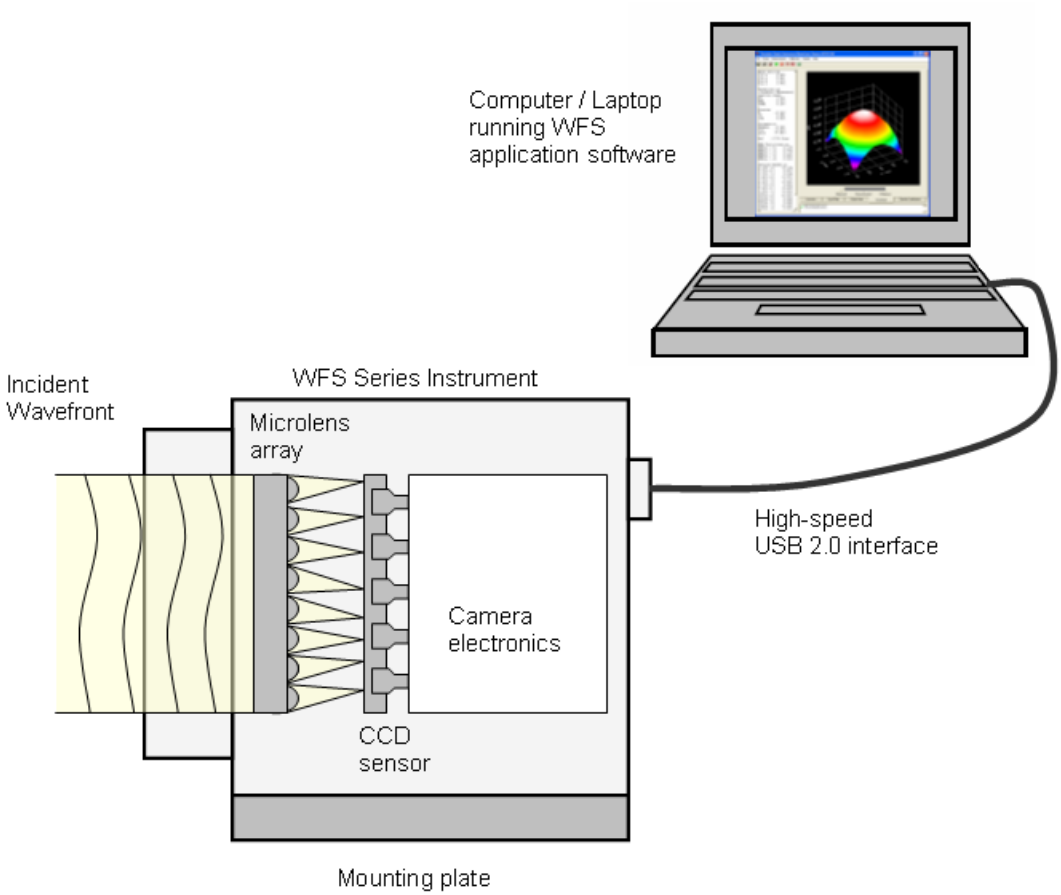
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3 Description

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 WFS 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/CMOS 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.

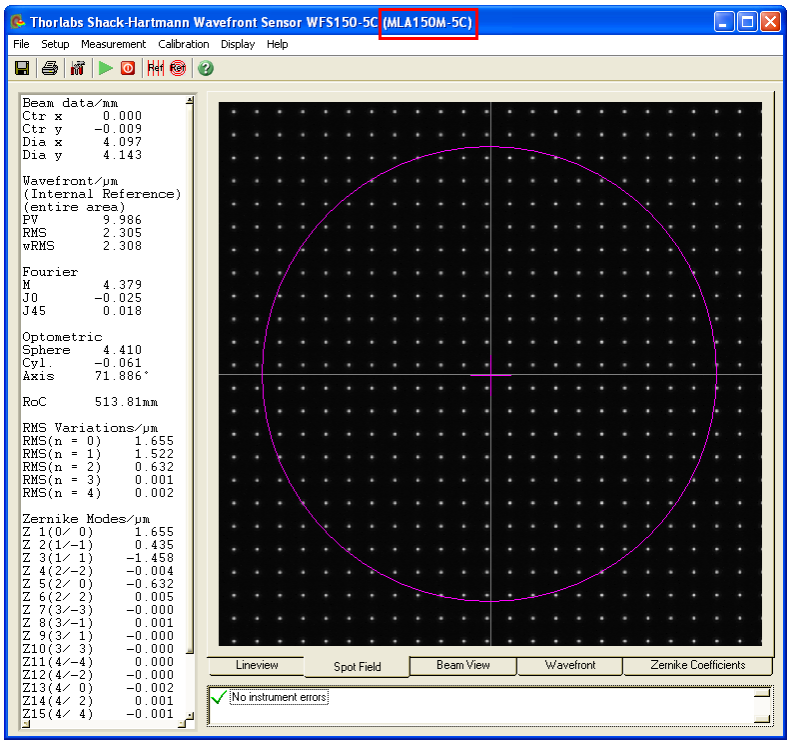


The sensor operation confirms to **International Standard ISO 15367:**
"Laser and laser-related equipment - Test methods
for determination of the shape of a laser beam wavefront"
Part 2: "Shack-Hartmann sensors"

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

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Megapixels) USB 2.0 CCD camera (WFS) or a lower resolution but faster CMOS camera (WFS10) 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 camera allows with the help of an adapter (Thorlabs SM1A9) for the convenient mounting of ND filters, to help prevent the saturation of camera pixels, 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

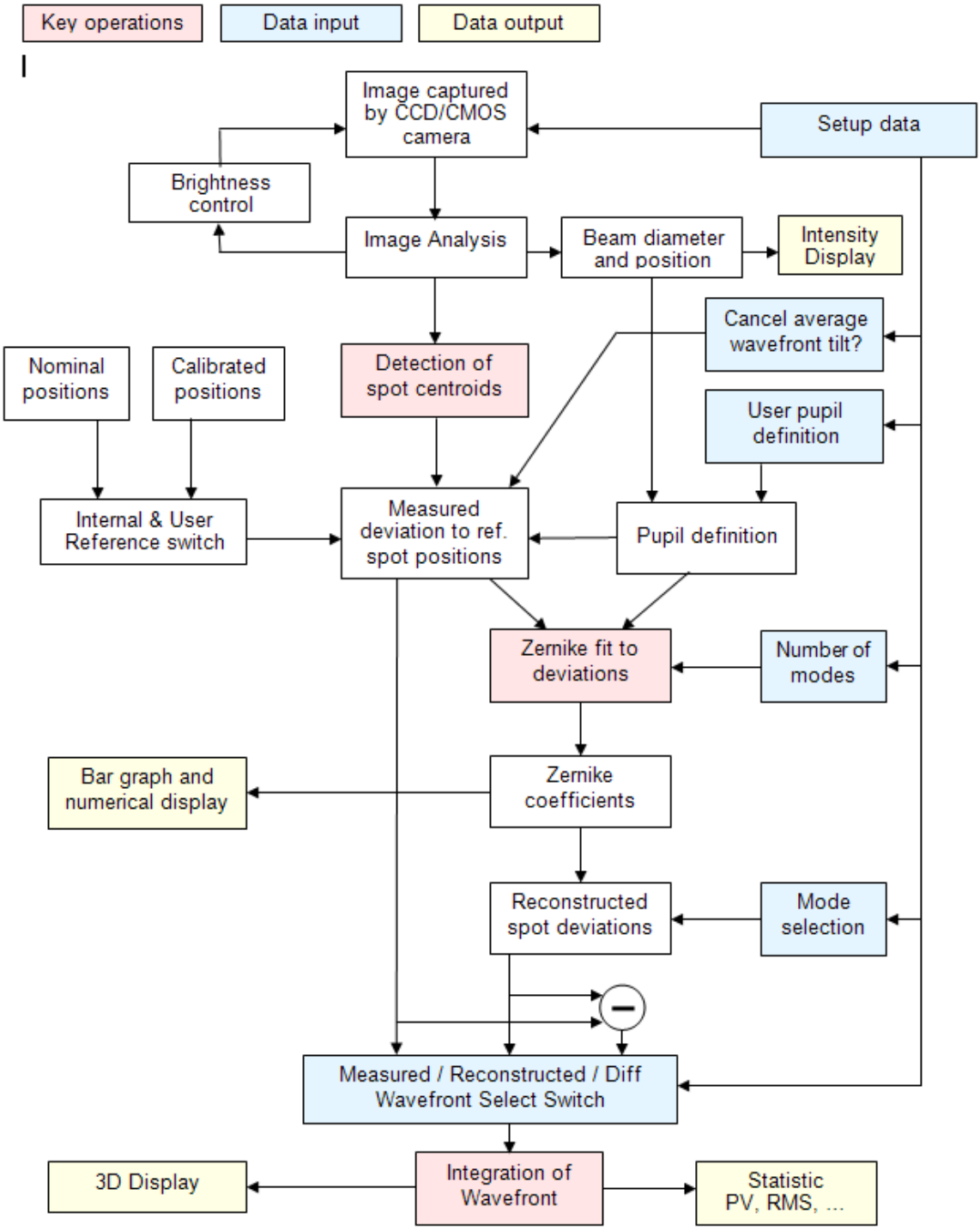
The camera image is transferred via USB 2.0 interface to a computer or laptop that is running the Thorlabs Wavefront Sensor application software. Special algorithms within the software calculate the centroid positions of all detectable spots and the corresponding deviations compared to the appropriate 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 visualization 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.

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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.



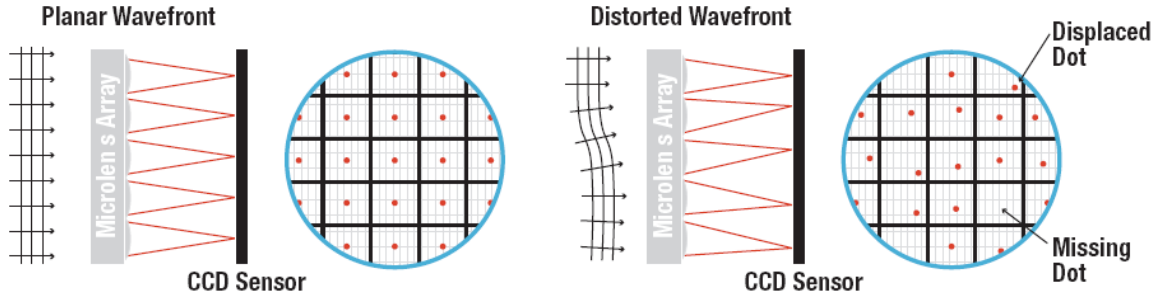
The brightness of the camera image is controlled within a loop to ensure an optimal saturation level. Diameter and position of the beam is detected and these data are used optionally for defining the instruments pupil area. Otherwise pupil data can be defined by the user.

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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

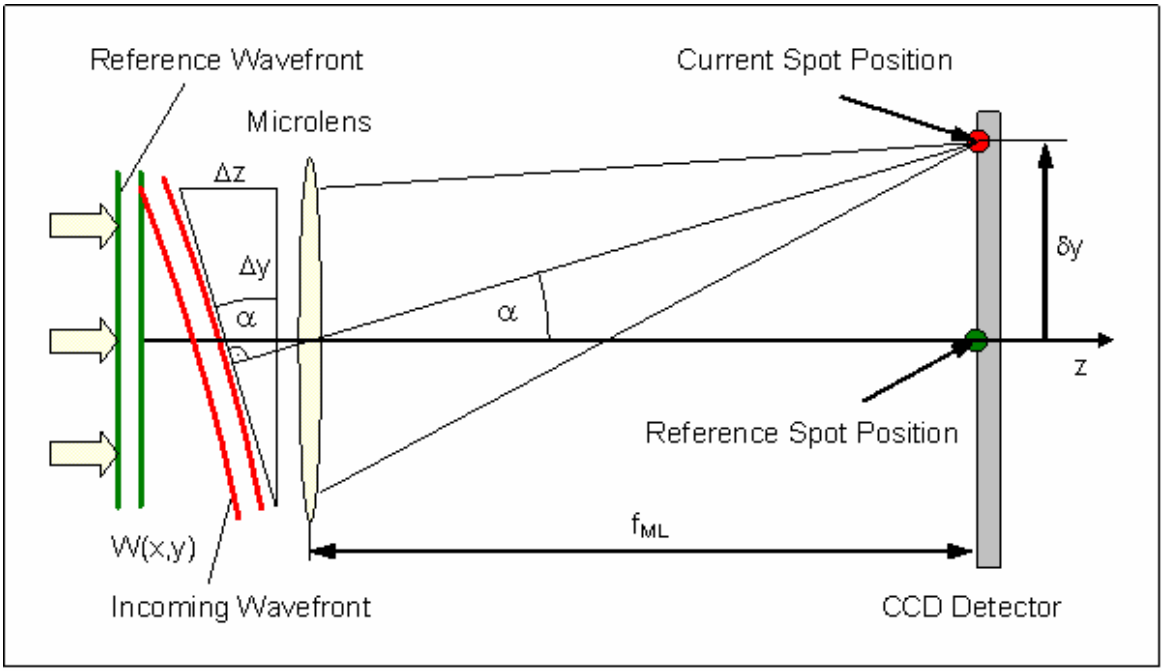
The WFS series Wavefront Sensor consists basically of a CCD/CMOS camera with a microlens array mounted in a defined distance in front of its sensor chip. Each microlens generates a spot onto the sensor whereas the spot centroid position depends on the wavefront gradient in front of the lens area.



Each microlens of the lenslet array collects the light falling onto its aperture and generates a single spot on the detector plane (CCD/CMOS 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.

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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 end detector which is usually the focal length of the microlens f_{ML}.

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

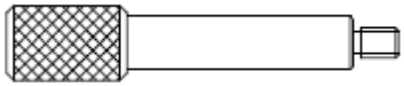
Spot deviations δx and δy are determined by calculating the centroid coordinates of all detectable spots and subtracting the corresponding reference coordinates afterwards. These spot deviations are integrated within a 2-dimensional integration process that gives the wavefront W(x,y).

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3.2 Exchanging the Microlens Arrays

Thorlabs Wavefront Sensors WFS150-5C, WFS150-7AR, WFS300-14AR and WFS10-5C, WFS10-7AR, WFS10-14AR are equipped with exchangeable microlens arrays MLA150M-5C, MLA150M-7AR and MLA300M-14AR, respectively. Due to its precision patent pending magnetic holder it is very easy to switch between different mounted MLAs. See chapter Parts List 9 for details.

This **Pickup-Tool** is automatically supplied with your WFS instrument when you have ordered it with more than one calibrated MLA or when you returned your WFS instrument for adding calibration data for a second MLA.



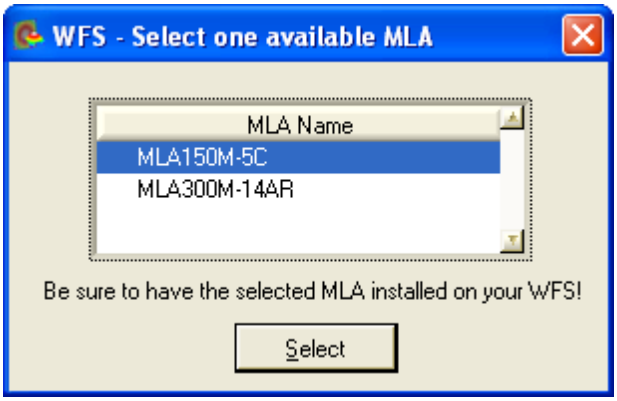
Follow these steps to exchange an installed MLA1 with MLA2:

- Screw the Pickup-tool into the MLA1 currently mounted within the WFS instrument
- Pull MLA1 out of the instrument along its optical axis
- Unscrew and remove the pickup-tool from MLA1
- Pack MLA1 into a dust-proof storage box
- Unpack MLA2 and screw the pickup-tool into it
- Clean MLA2 using **compressed air, keep a safety distance of at least 4 inches (10 cm)!**
- Insert MLA2 along the optical axis into the WFS instrument, whereas the pickup-whole is up
- Tell the WFS software that the MLA was changed

NOTE

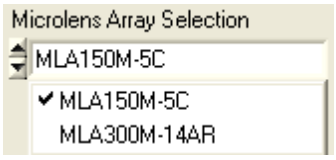
It is essential for the wavefront measurement to set the name of the currently installed MLA within the WFS software!

On startup of the WFS software use this dialog to define one of the selected MLA your WFS instrument is calibrated for. See Start the GUI 40 for details.



During WFS operation, go to the Wavefront Setup 79 and select the actual mounted MLA from the pull down list.

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Attention

Be sure to have the selected MLA physically installed in front of your Wavefront Sensor!
Otherwise, all measurement data become invalid because wrong calibration data!

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4 Operating Instruction

This section gives a more detailed description for operating the WFS series Wavefront Sensors.

4.1 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 26 as well as the setup options (see Wavefront Sensor Setup Panel 65) in order to perform reliable wavefront measurements.

Mounting options

A mounting adapter (see Mounting Adapter 135) 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 (WFS) and 2x M3x6 + 1x M2x6 (WFS10) 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 or CMOS 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

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and to allow for the mounting of additional optical components.

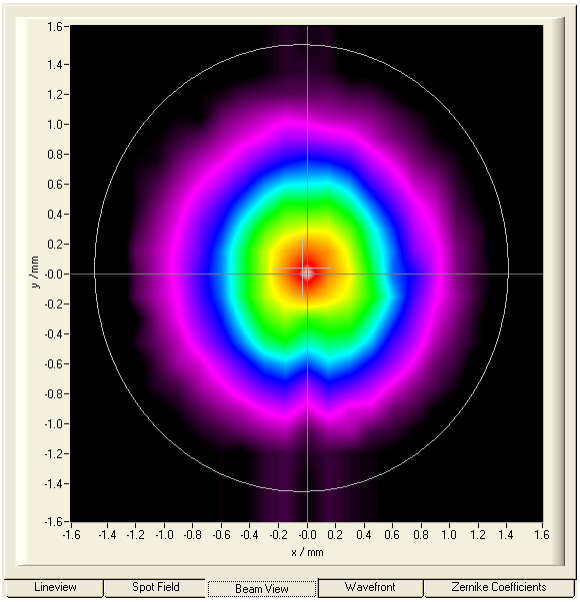
Beam Size

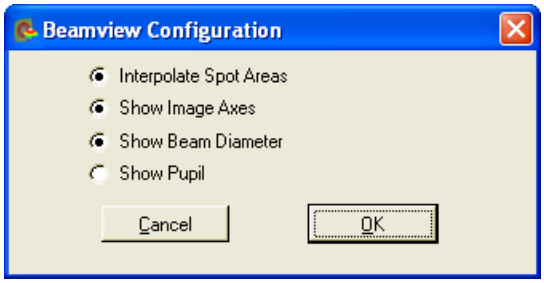
The active area on the CCD / CMOS camera chip can be selected (see Camera Settings Setup 67) in order to adapt it to the actual beam size. Otherwise, a beam much smaller than the sensor area will illuminate only the microlenses at the center and no wavefront data can be retrieved from the ambient area. 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 for WFS and 6,33 x 4,75 mm for WFS10) 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.

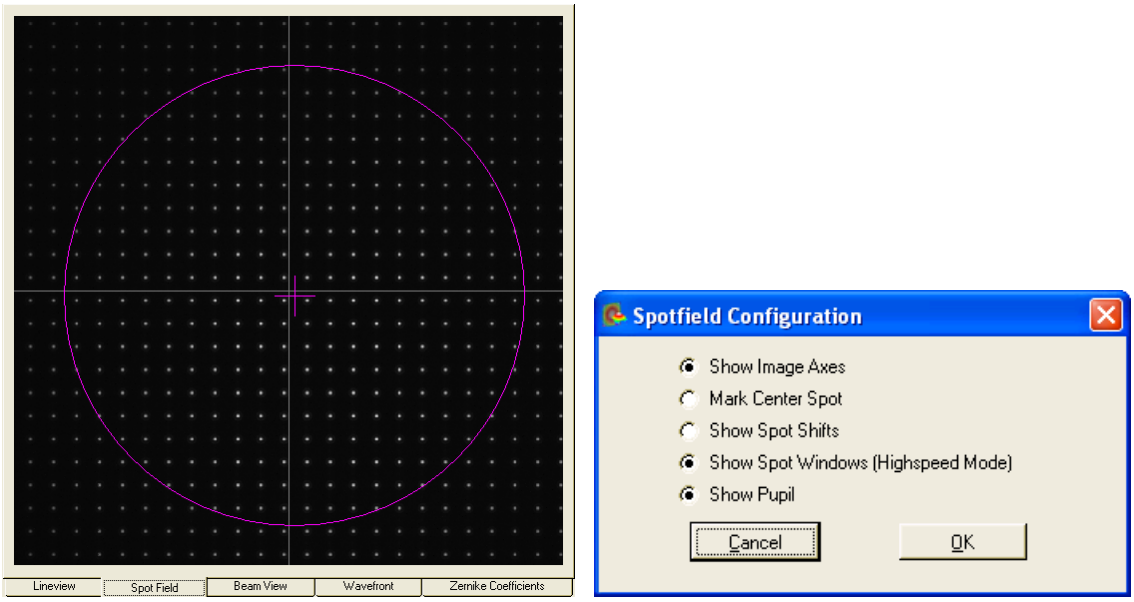
Direct the beam to be analyzed into the center of the entrance aperture of the Wavefront Sensor. Although an off-center beam can also be measured as long as it is not truncated by the active sensor area it is recommended to adjust the beam to be measured so that it hits the center of the Wavefront Sensor. Verify this adjustment by checking the power density distribution displayed within the **Beam View Panel** 56. 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.



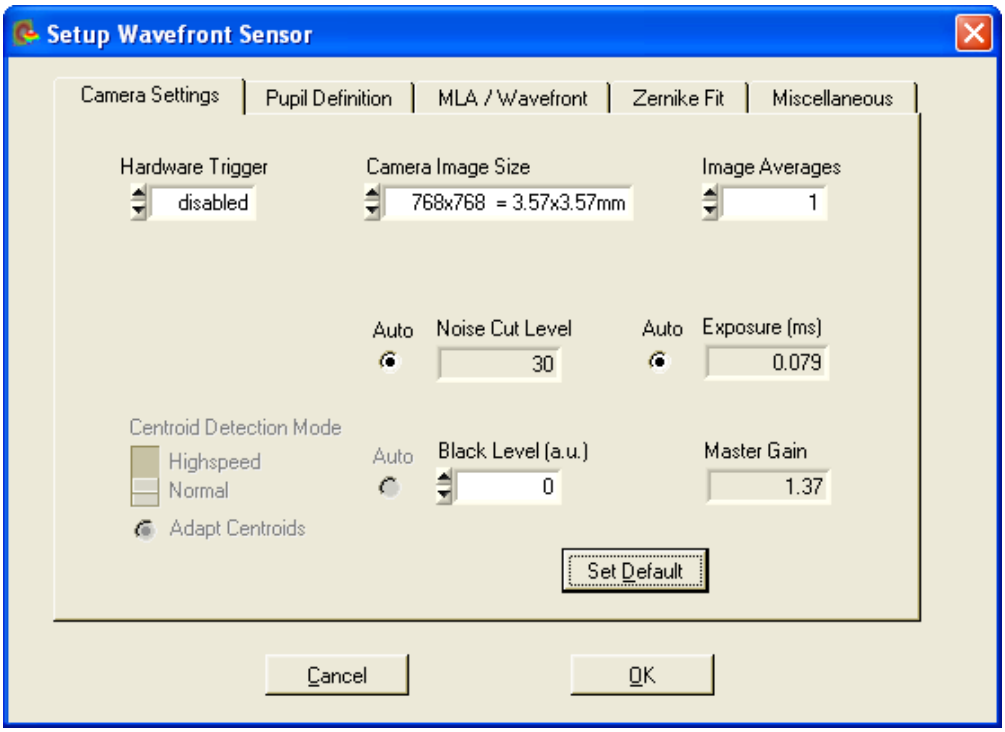


Alternatively, you can check the correct beam position also using the **Spotfield Panel** 52. Enable the diagram options '**Show Image Axes**' and '**Show Pupil**'.

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Be sure you have enabled the '**Use Beam Centroid**' option within the Pupil Definitions Setup 76 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 128. Especially at the edges of the sensitive wavelength range (300 - 1100 nm for WFS150-5C and WFS10-5C) there is a drastically reduced sensitivity which allows measurement of higher power sources directly. On the other hand, the Wavefront Sensor can get

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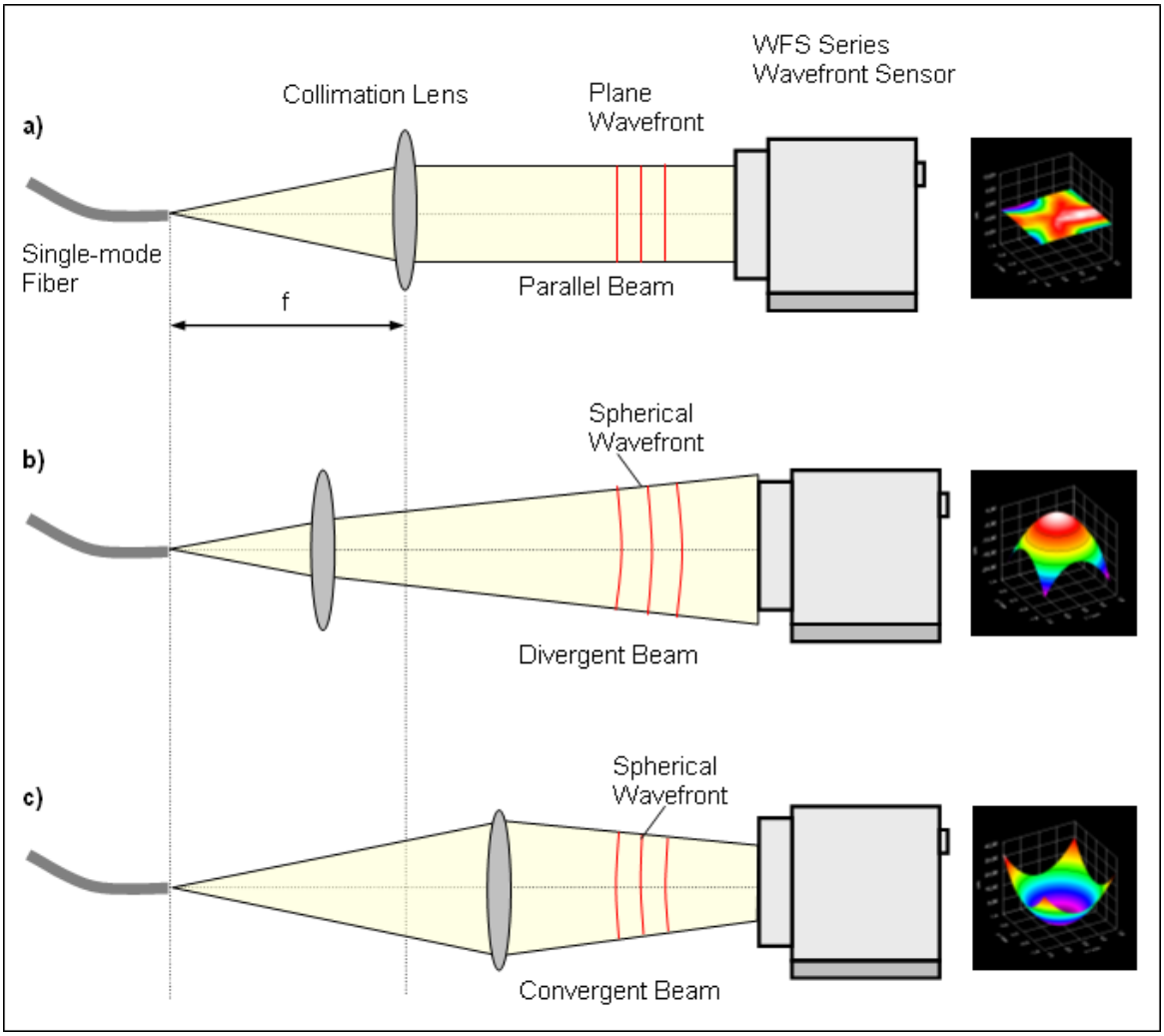
saturated for small beams at the lower mW levels. Use an external attenuator in that case.

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 91 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 single-mode 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'

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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.

4.1.1 WFS10 Highspeed Mode

Fast Wavefront Sensor instruments (WFS10) are based on a much faster CMOS camera compared to the WFS instruments which are based on a CCD camera. Besides the higher achievable frame rate in Normal Mode an even higher measurement speed is available in Highspeed Mode.
Please note, that a CMOS sensor may have more "hot pixels" (pixels showing a certain intensity even with camera darkened) than CCD sensors. See chapter Hot Pixel 120 for details.

What is Highspeed Mode?
Normally, the complete spotfield image is transmitted from the camera to the computer and interrogated there. This method is speed limited because of the available USB 2.0 bandwith and the calculation speed of the PC.

Compared to Normal Mode there are a number of **differences in Highspeed Mode**:

- The spotfield image is captured inside the camera but not transmitted via USB.
- Instead, the camera's DSP is calculating the spot centroid coordinates. Due to this internal calculations, the pupil center may shift slightly, when switching from normal to high speed mode.
- Only the calculated centroid positions are transmitted via USB.
- Much lower volume of transmitted data increases maximum measurement rate.
- On the other side, the PC is freed from time-consuming centroid calculations so that further calculations (wavefront, Zernike fit) speed up.

That is, entering Highspeed Mode enables one important **advantage:**

- higher measurement speed, especially at large camera resolutions

but also brings along some **restrictions and disadvantages**:

- Centroid calculation windows are no more dynamically positioned but are placed on a semi-rigid grid.
- This calculation grid will be configured each time you enter Highspeed Mode and is fixed afterwards.

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- The max. wavefront dynamic range is considerably lower because spot shifts are limited to the fixed calculation windows.
- Therefore, there is an increased risk of mismeasurement due to camera saturation!
- Besides that, centroid position results become extremely sensitive to the cameras black level and ambient light because all pixel intensities within the entire spot window (width x height pixels) contribute to the final centroid result. Also low black level intensities will shift the result towards the window center.

In order to assure correct measurements in Highspeed Mode you need to take care especially for the following setup parameters:

- **Exposure Time** and **Master Gain**
- **Black level** of the camera
- **Noise cut level** for centroid interrogation

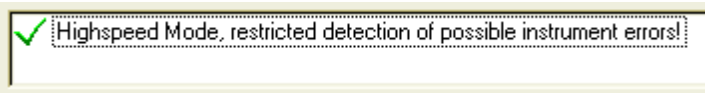
Please refer to chapter Camera Settings Setup 67 for a detailed explanation of these settings.

NOTE

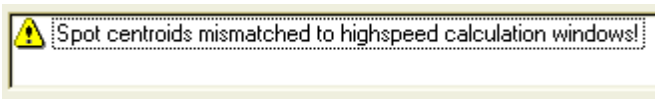
Measurement speed is limited by the camera's exposure time. You need to apply a sufficient high power level so that exposure time can be set much shorter than 1 / required speed in fps!

Keep an eye on the status window!

Because the camera saturation remains unknown in Highseed Mode in case the auto exposure option is disabled the camera image may suffer from over- or under exposure which is leading to wavefront mismeasurement.



In order to reach the highest possible measurement speed, all 'power too high' or 'power too low' warnings are disabled in Highspeed Mode when the auto exposure feature is also disabled. As a consequence, Highspeed Mode with disabled auto exposure feature is only applicable when working at a quite constant power level. But, a measurement error due to violation of the spot windows by the detected centroids can be displayed.



NOTE

If this warning occurs, the wavefront measurement is most likely disturbed by spots which are truncated by its detection window.

Achivable Speed

The following table shows the speed enhancement in Highspeed Mode for a typical

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PC (Intel® Xenon© Dual Core, 2.5 GHz).

WFS10-5C, WFS10-7AR (150µm pitch)			Speed in fps		Enhancement
Resolution	Spots	Spot count	Normal	Highspeed	%
640 x 480	41 x 29	1189	57	175	207
480 x 480	29 x 29	841	73	175	140
360 x 360	21 x 21	441	113	233	106
260 x 260	15 x 15	225	189	320	69
180 x 180	9 x 9	81	450	458	2

WFS10-14AR (300µm pitch)			Speed in fps		Enhancement
Resolution	Spots	Spot count	Normal	Highspeed	%
640 x 480	19 x 13	247	73	175	140
480 x 480	13 x 13	169	105	175	67
360 x 360	9 x 9	81	189	233	23
260 x 260	7 x 7	49	332	320	-4
180 x 180	3 x 3	9	487	458	-6

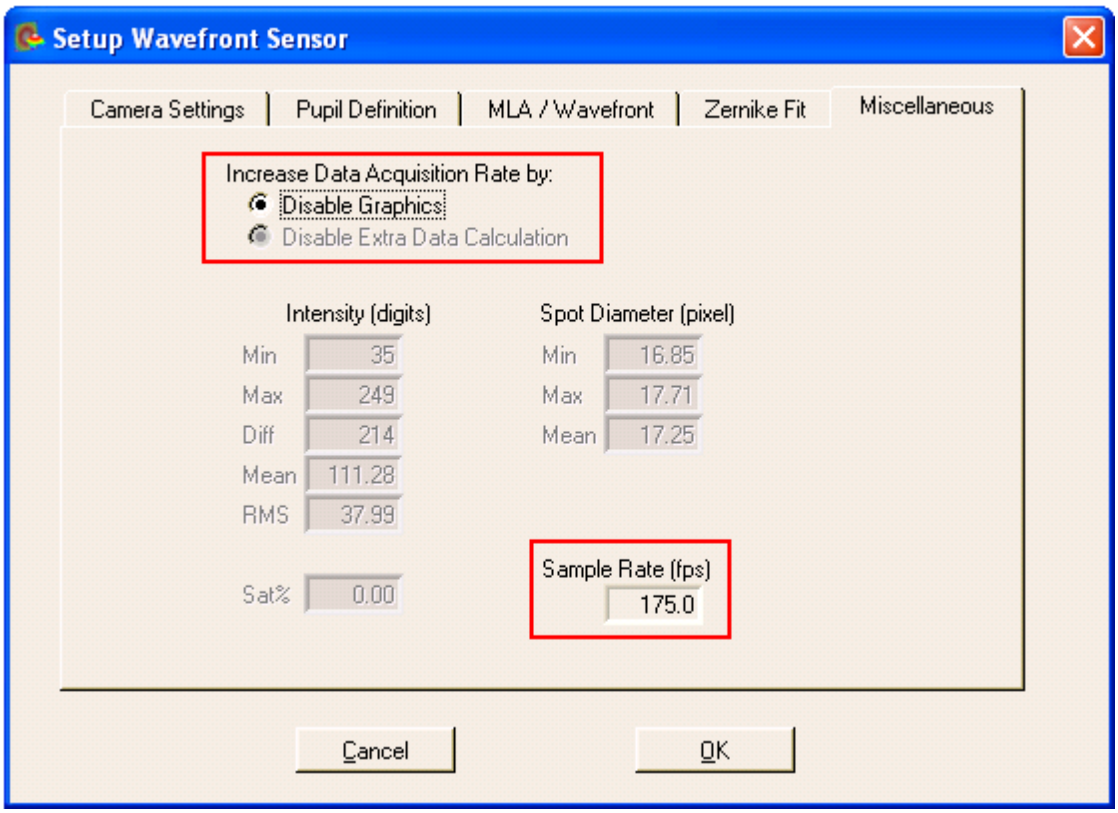
Measurement Conditions: 33 µs exposure time, 5th order Zernike fit (21 modes), auto exposure off, disabled graphics and DataSocket

Because the number of spots to be calculated is different for WFS10 instruments with 150 or 300 micron lenslet pitch, the resulting speed in Normal Mode is be different. As seen, the speed enhancement is especially distinct for large camera resolutions and high spot count.

NOTE
Reduce the camera resolution as much as possible in order to get the highest measurement speed.

How to get the highest speed?
Besides the limitation due to the Wavefront Sensor and the interrogation software there is another speed limit by the GUI software, because displaying the results numerical and graphical requires more time than available. Therefore, the GUI cannot display results at the max. speed.
For checking the speed performance of the WFS10 sensor and the WFS instrument driver go to Setup Wavefront Sensor → Miscellaneous and mark options 'Disable Graphics' and 'Disable Extra Data Calculation'.

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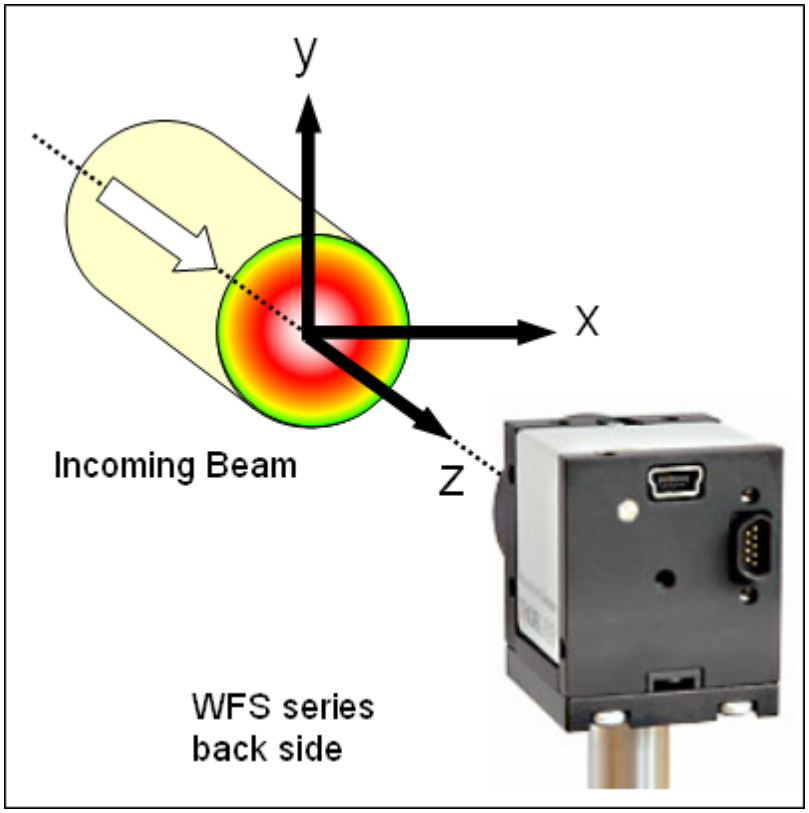
When the auto exposure feature is enabled in Highspeed Mode the max. achievable speed will drop from 175 to about 150 fps because the camera needs to calculate the actual saturation level for each frame.

The displayed 'Sample Rate' is the max. available measurement speed with the current settings but without graphical display. This speed is available to you when writing your own application in C or LabView using the WFS instrument driver functions.

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4.1.2 Coordinate Definitions

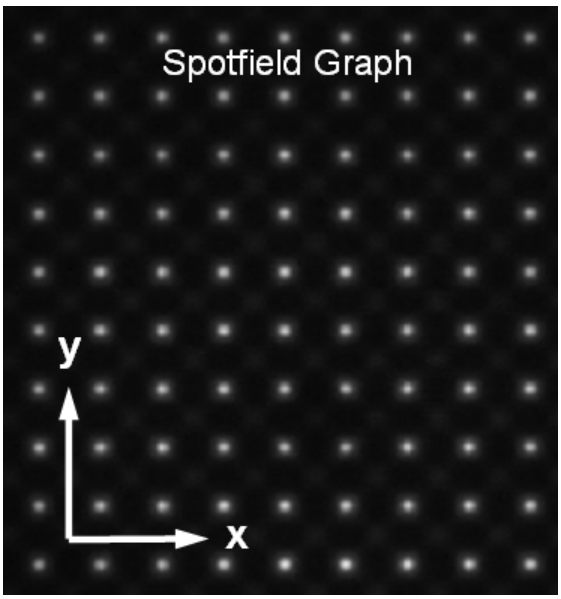
The WFS series Wavefront Sensors is using a orthogonal right-hand coordinate system (x,y,z) that is defined as follows:

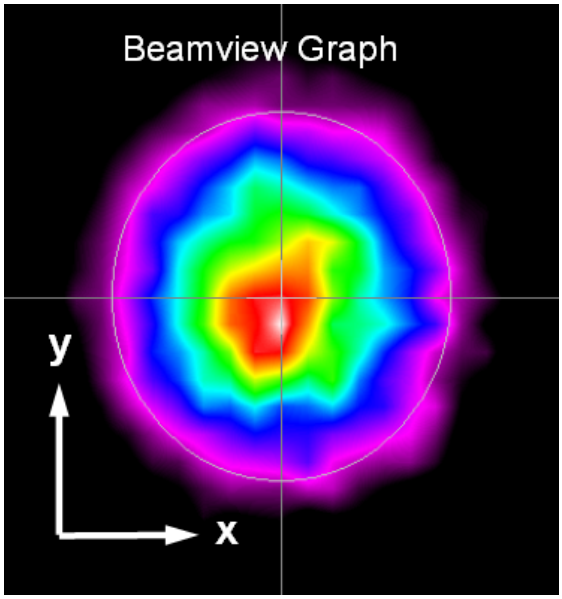


Imagine you are within the Wavefront Sensor and are looking towards the light source. Then the x-direction points towards right and the y-direction points up whereas the optical beam to be analyzed is propagating in z direction towards the entrance aperture of the Wavefront Sensor.

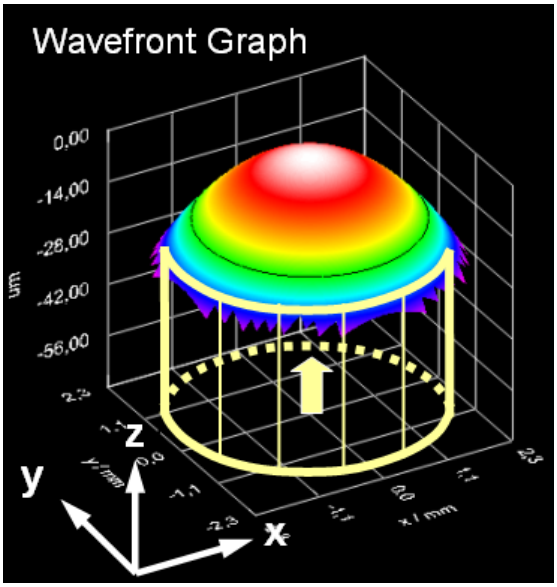
The graphs within the Wavefront Sensor GUI (Spotfield, Beamview) are defined the same way, that is the positive x axis points rightwards and the y axis points upwards.

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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.



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4.2 The Graphics User Interface (GUI)

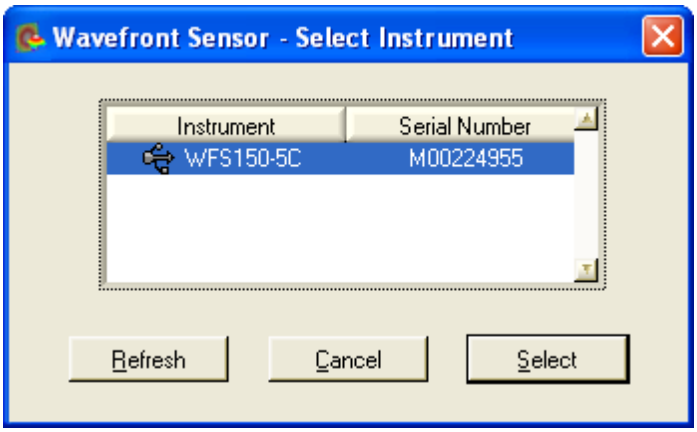
4.2.1 Start the GUI

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.

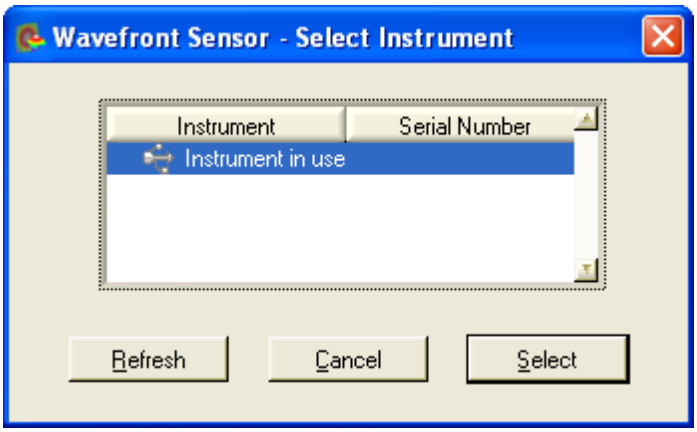


If there is no entry to be seen, click on 'Refresh' to update the list of available Wavefront Sensor instruments. If there is still no instrument displayed please refer to the Troubleshooting 117 chapter.

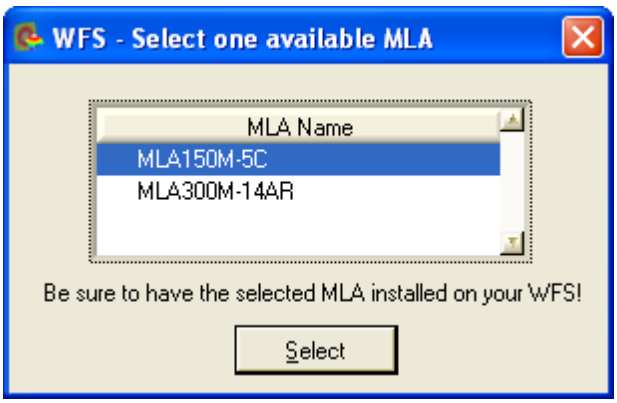
You can also operate two or more Thorlabs Wavefront Sensors at the same time on the same computer by starting the application software again. In this case, mark the desired instrument in the list and press 'Select' or just double-click the entry.

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

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In case your WFS instrument contains calibration data for more than one Microlens Array (MLA) you need to select one of the available MLAs.
Mark the MLA entry you want to work with and click 'Select' or just double-click on the MLA entry.

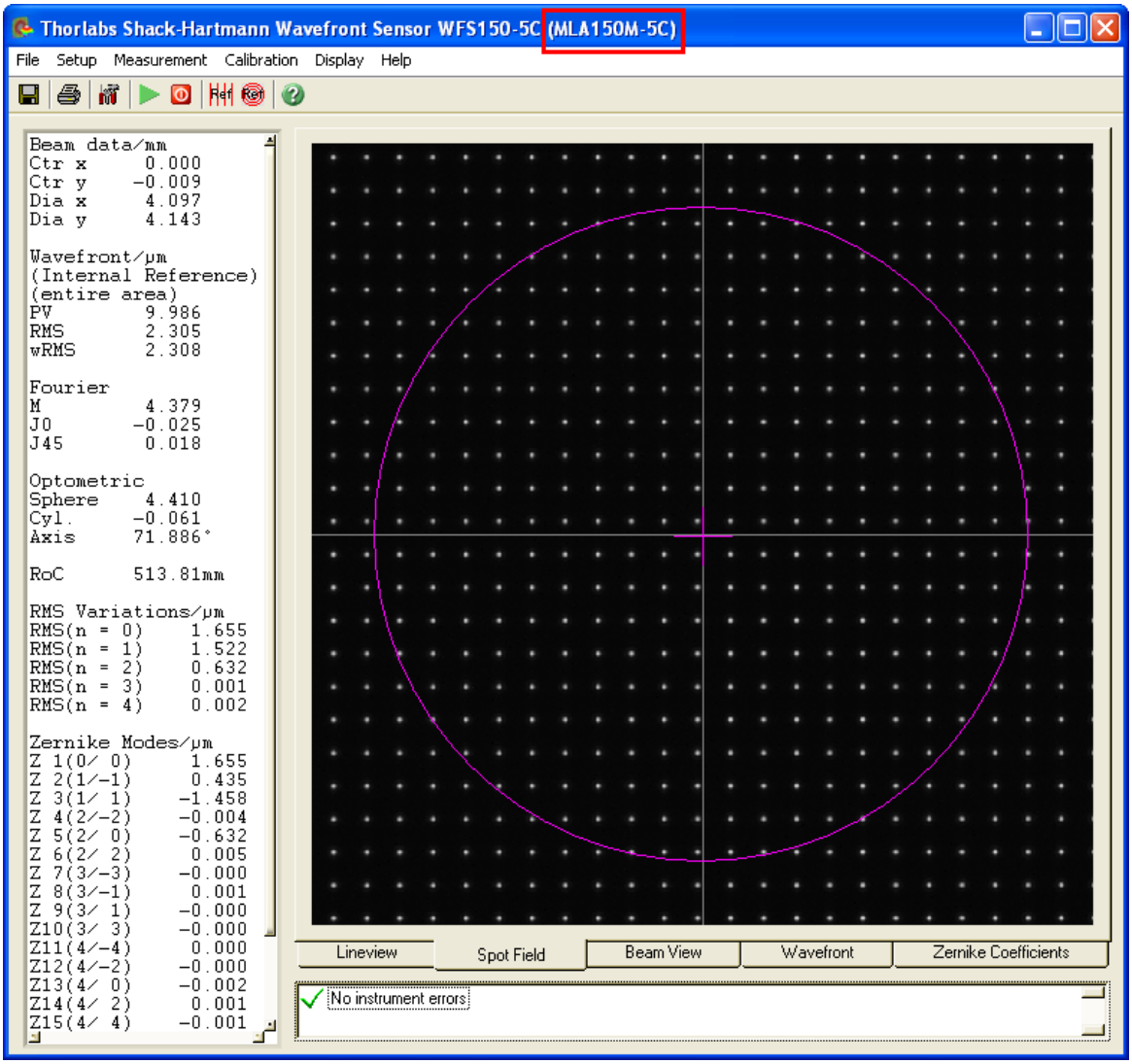


Attention

Be sure to have the selected MLA physically installed in front of your Wavefront Sensor!
Otherwise, all measurement data become invalid because wrong calibration data!

The selected Wavefront Sensor starts to work and the Graphical User Interface (GUI) displays the measured data. You need to verify that the correct MLA name appears in the title bar of the application window (see red rectangle).
The GUI looks like this:

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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 65 chapter carefully and configure the Wavefront Sensor software according to the beam properties and your specifications.

4.2.2 Operating the Wavefront Sensor Software

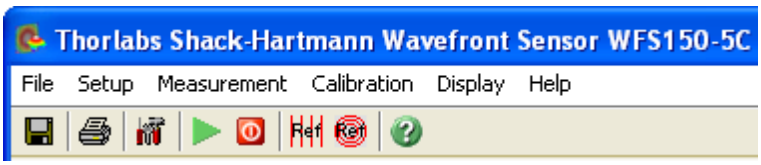
Now let's get familiar with the Wavefront Sensor GUI.

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

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4.2.2.1 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

Open Setup ... (Ctrl + O)
Save Setup As ... (Ctrl + A)

Measurement File Preferences ...
Save Measurement Data ... (Ctrl + S)
Save Centroid Data ... (Ctrl + C)
Save Power Distribution Data ... (Ctrl + D)

Print Window ... (Ctrl + P)
Print Graph Only ...

Exit Program

Setup

Wavefront Sensor ...

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

DataSocket ...

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Measurement

Start Measurement F2 
Stop Measurement F3 

Calibration

Plane Wavefront ... 
Spherical Wavefront ... 

Save Spotfield Reference
Load Spotfield Reference

Display

Lineview
Spotfield
Beamview
Wavefront
Zernike Coefficients

Help

Contents ... F1 

Visit the Thorlabs Website
View License Agreement

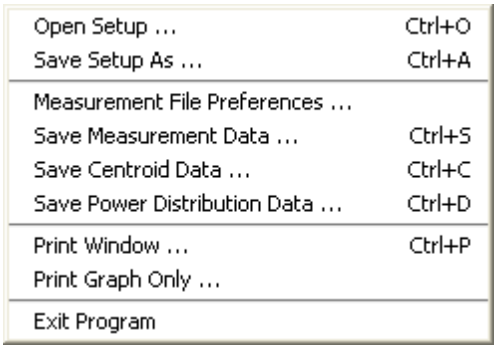
About ...

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Explanation of the menu items

1. File

The following pull down menu occurs:



- **Open Setup ...**

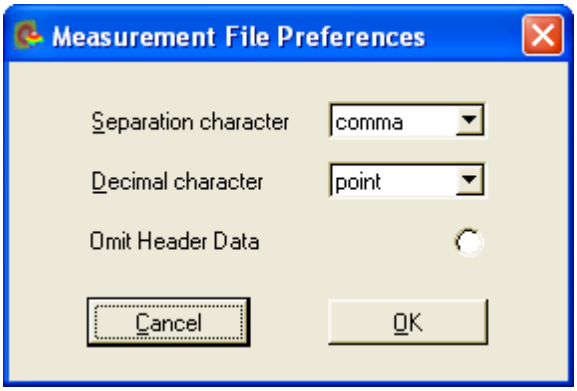
Opens a Wavefront Sensor configurations file (*.cfg) stored with this application (see below). This configuration file contains instrument settings (camera, pupil, wavefront) as well as display and graphical settings. You can easily switch between different configurations by loading alternative files.

- **Save Setup As ...**

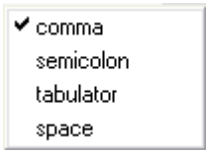
Stores a Wavefront Sensor configurations file (*.cfg) containing all instrument settings (camera, pupil, wavefront) as well as display and graphical settings. You may save different configurations into files with different names.

- **Measurement File Preferences**

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

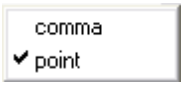


You can choose a 'Separation character' that separates two successive data values within a text line out of the following:



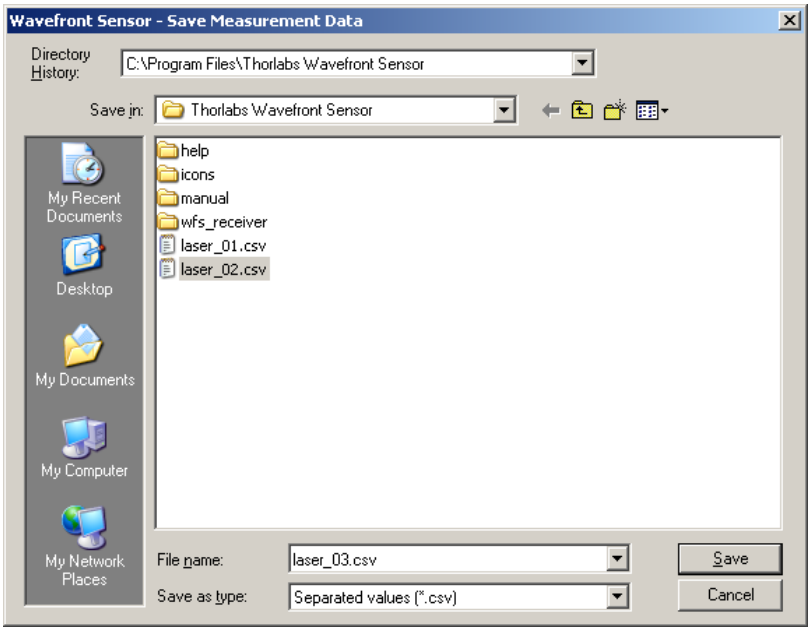
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For 'Decimal character' which is whether decimal point or comma you have the choice between the following:



If the option **'Omit Header Data'** is enabled the entire header including the listing of single wavefront and Zernike fit results is omitted and only the pure data array is saved. 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.

- **Save Centroid Data (Ctrl + C)**

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

- **Save Power Distribution Data (Ctrl + D)**

Choose drive and path for storing data within and type in a name for your Power Distribution 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

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- 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 116 chapter for a detailed description of the available features.

- **Exit Program**

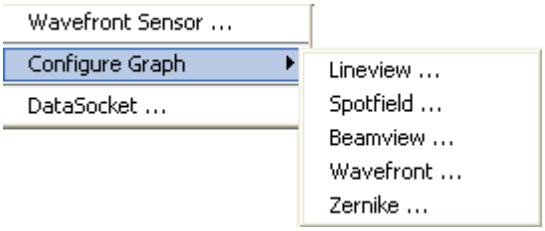
You will be asked if you are sure.



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

2. Setup

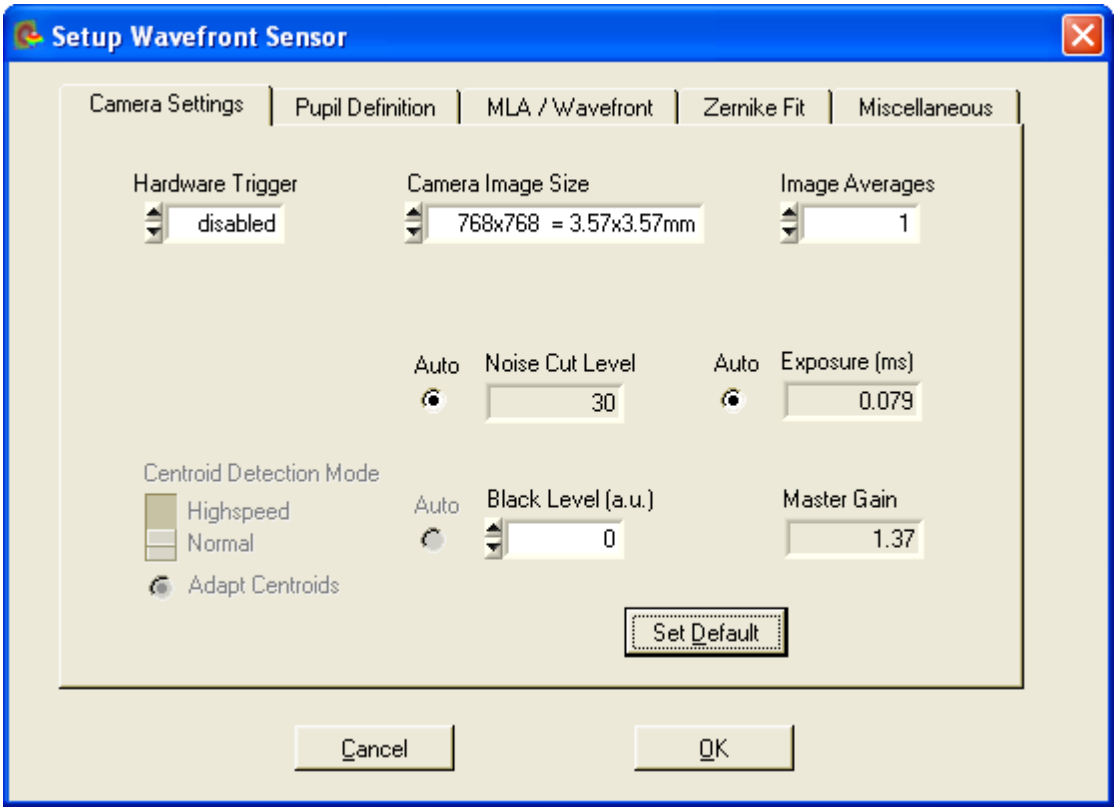
The following pull down menu occurs:



- **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.

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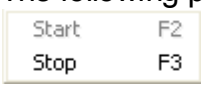
See the Wavefront Sensor Setup Panel 65 chapter for a detailed description of all setup controls.

• **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 109 for details.

3. Measurement

The following pull down menu occurs:



• **Measurement Start**
Starts continuous Wavefront Sensor measurements and displays the results on the screen.

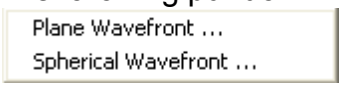
• **Measurement Stop**
Stops the Wavefront Sensor measurement immediately and terminates the screen updates to keep the actual displayed graphical plots and numerical values to survey and/or save these data.

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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.

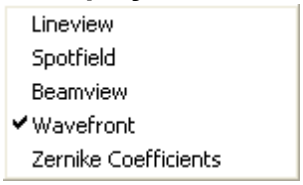
4. Calibration

The following pull down menu occurs:



There are two different ways to perform a User Calibration of the Wavefront Sensor. See chapter User Calibration 95 for a detailed description.

5. Display

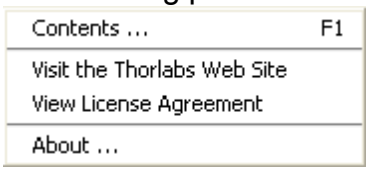


See the following chapters for a detailed description of the interchangeable graphical displays. Alternatively click on the tabs below the graphics to see the desired one.



6. Help

The following pull down menu occurs:



- **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.

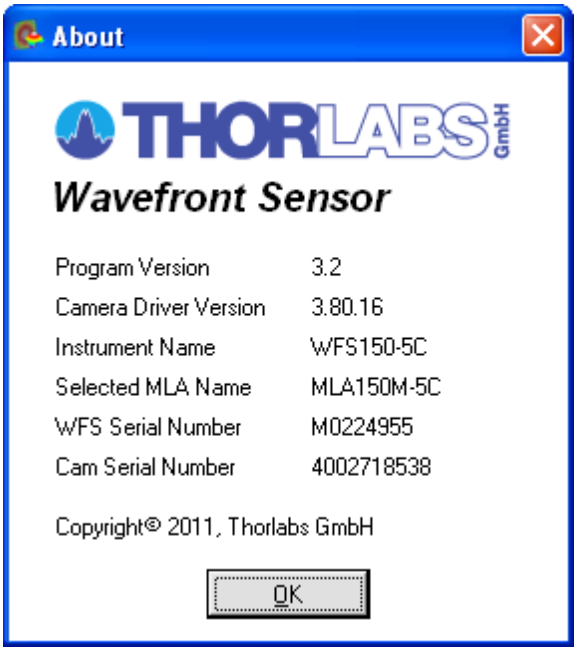
- **View License Agreement**

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

- **About**

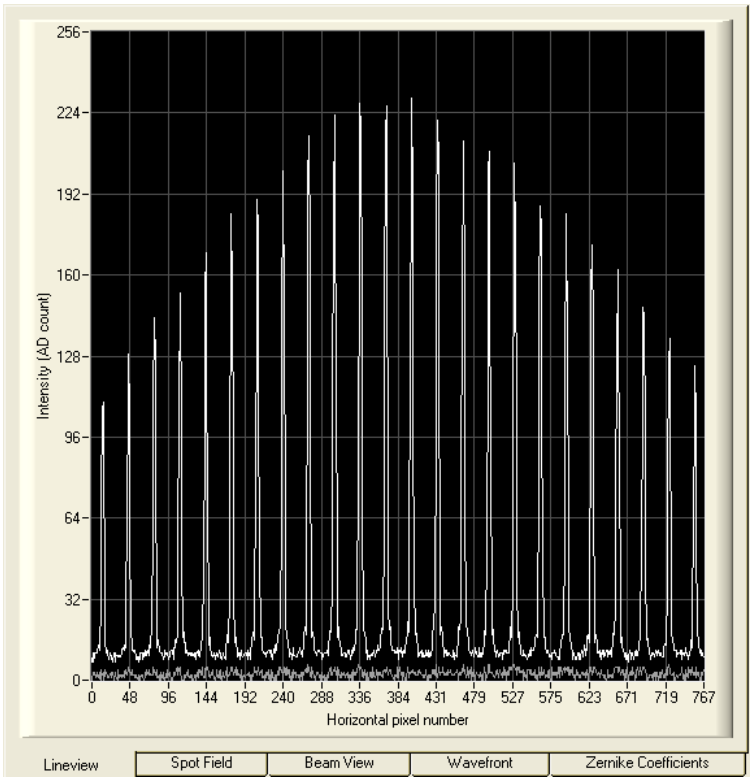
Shows you the actual software release versions, the Instrument Name and Serial Number of the used device.

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4.2.2.2 Lineview Panel

This graph displays the horizontal intensity distribution of the CCD/CMOS camera. Each point on the horizontal axis of the diagram correspond to one column of the CCD/CMOS 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.

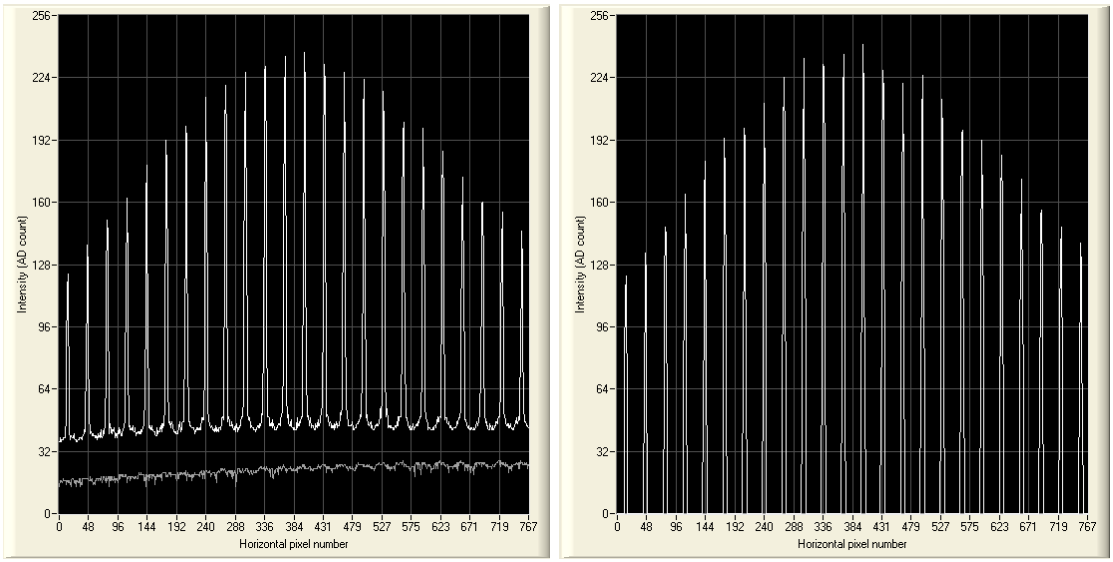


This graph is useful to check the power level of the analysed beam, especially when

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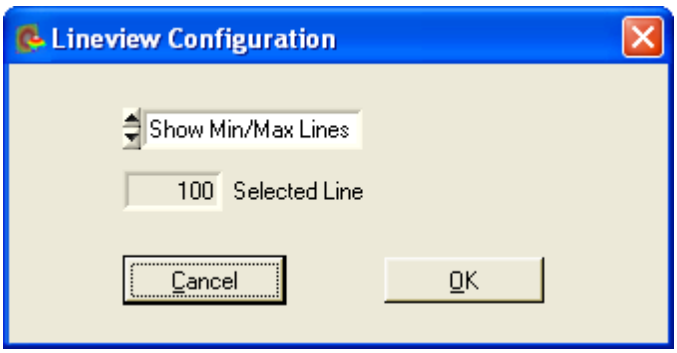
the automatic brightness control is disabled. Improperly manual camera settings will lead to low or saturated peak intensities or saturation. Prevent both by proper adjustments of the exposure time and master gain (see chapter Camera Settings 67).
Also the 'Black Level' camera setting adjusts an offset 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 67 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

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each point of the lower curve (gray) displays the minimum intensity of the appropriate CCD column.



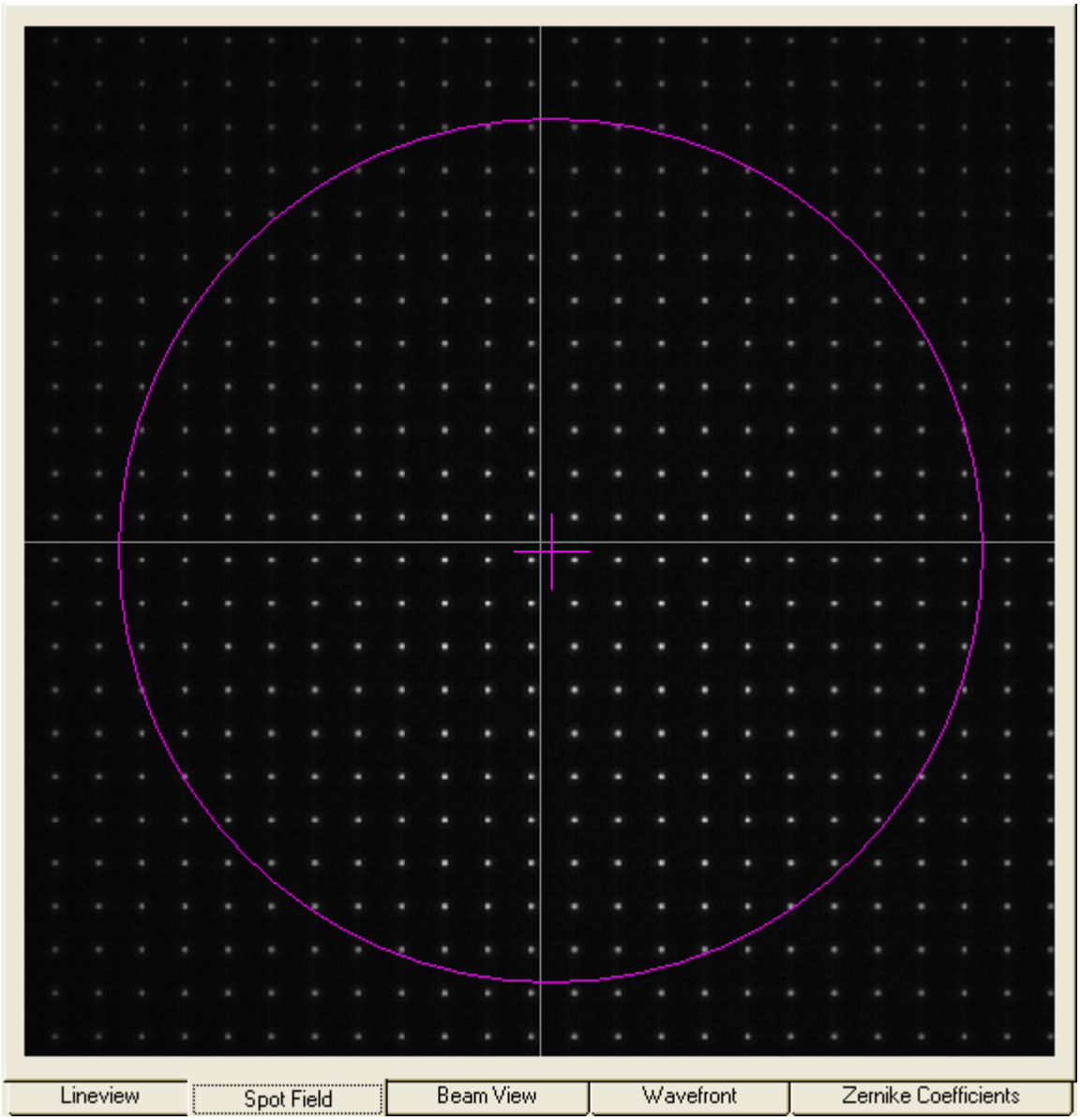
Switch to '**Show Single Line**' in order to enable selection of a single line out of the CCD array. Enter the line number into the control '**Selected Line**' to see the intensity distribution of the appropriate CCD row. The line number ranges from 0 (bottom) to the number of vertical pixels - 1. The selected line is marked within the Spotfield Panel 52.

NOTE
This panel display is not available for WFS10 instruments in Highspeed Mode.

4.2.2.3 Spotfield Panel

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

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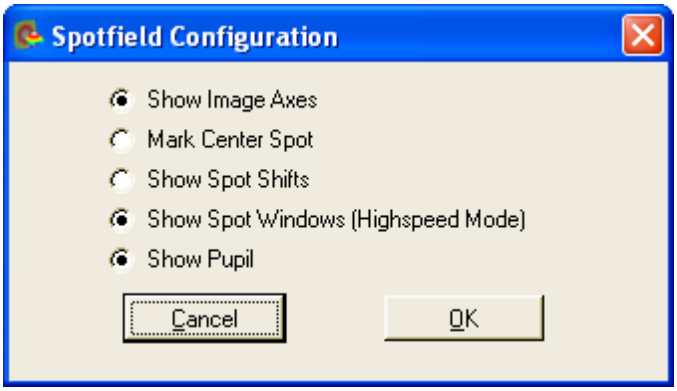


Select the camera resolution and therewith the number of spots in horizontal and vertical direction using the Camera Settings 67 panel. It is recommended to select the camera resolution and therewith the active sensor area to be a bit larger than the analyzed beam. A too large area will contain lots 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.

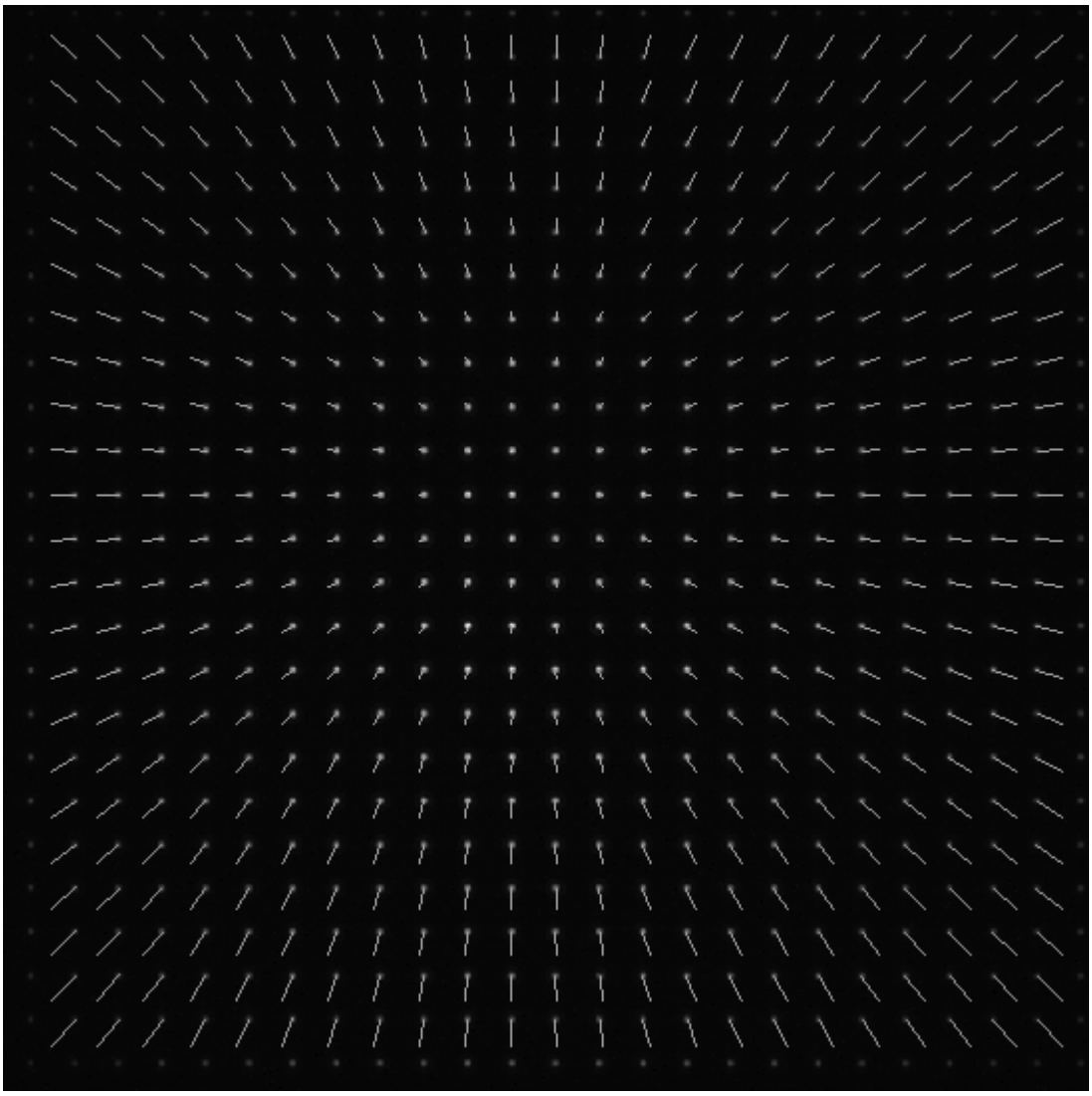
Double click on the graph to see the '**Spotfield Configuration**' panel.

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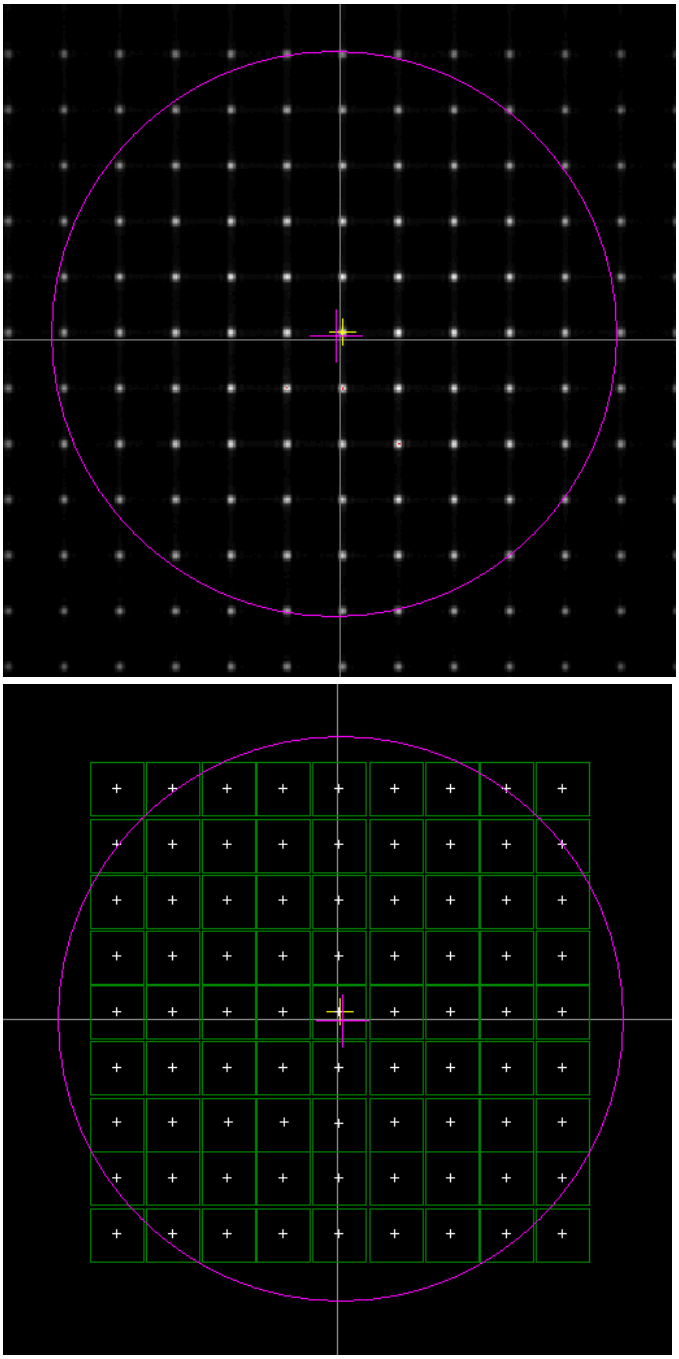
Enable the appropriate option to visualize the graphical items:

'**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.



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'Show Spot Windows' is an option only available for WFS10 instruments in Highspeed Mode (see WFS10 Highspeed Mode 34).



In contrast to Normal Mode in which the spots are visible within the real camera image (left), each detected spot is displayed by a white cross in High Speed Mode. The user is able to check if the detected spots are well within the detection windows (green).

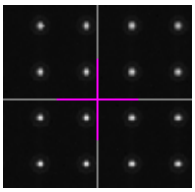
'**Show Pupil**' displays a circle or an ellipse (magenta) that illustrates the actual pupil

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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 76 panel to show the actual beam centroid.

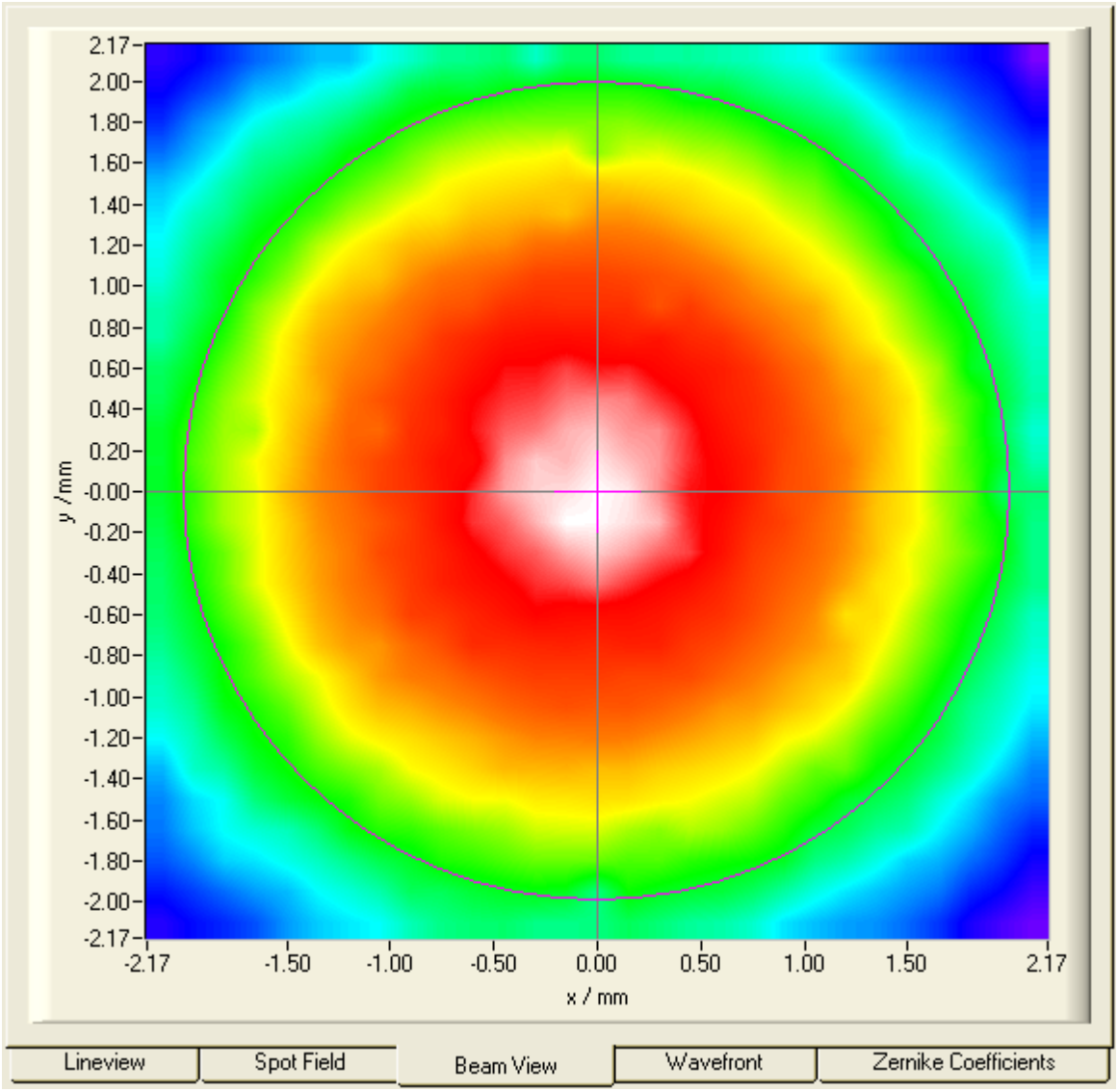
Align the beam so that the center cross of the pupil coincides with the center image axis.



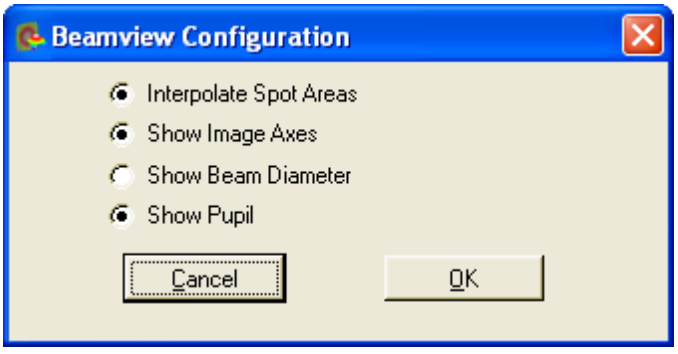
4.2.2.4 Beam View Panel

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.

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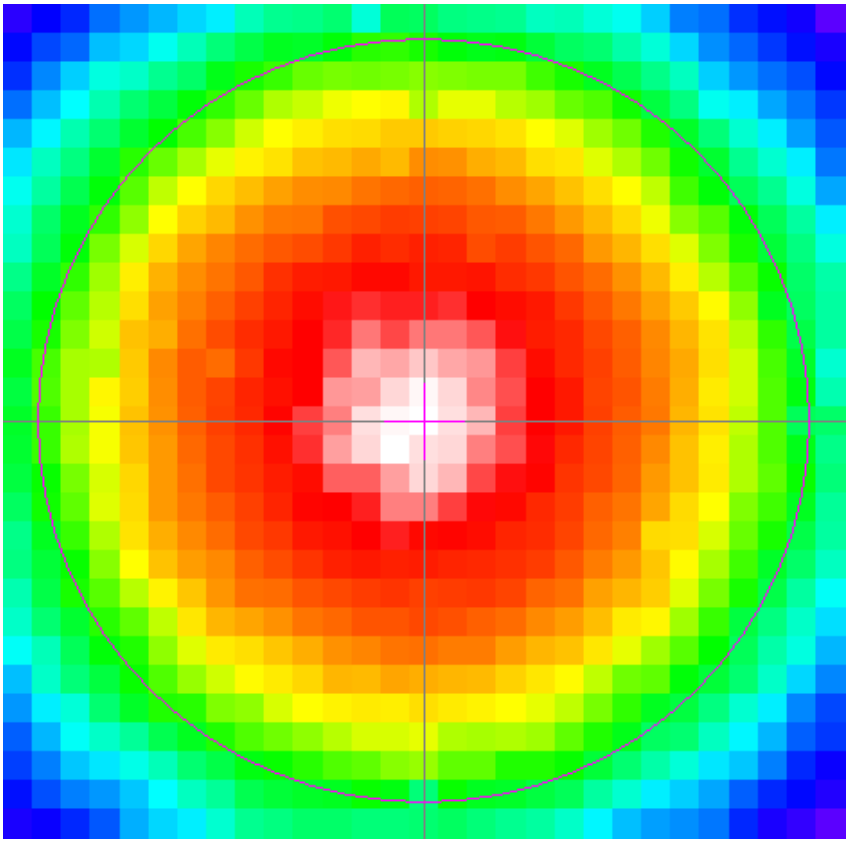


Double click on the graph to see the '**Beamview Configuration**' panel.



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

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'**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.

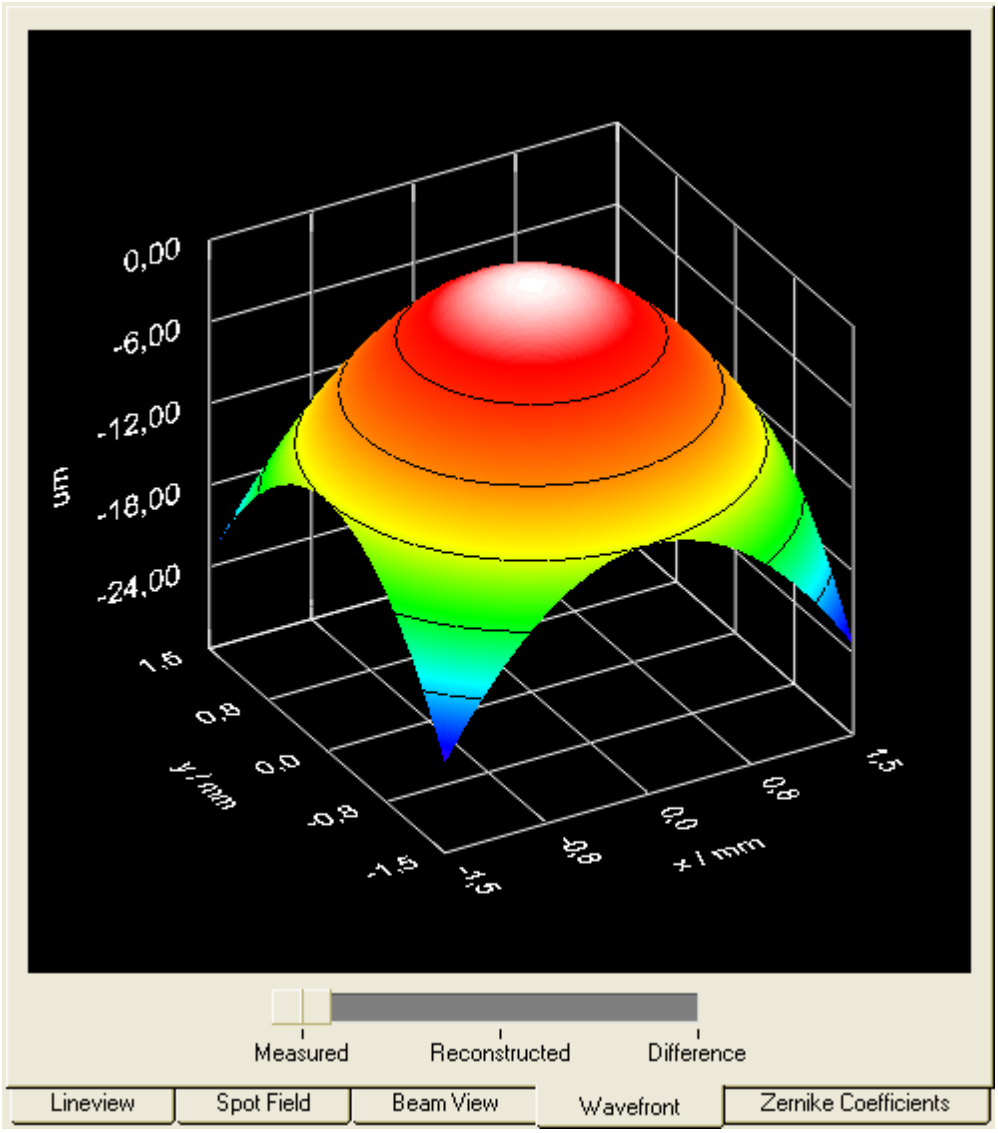
NOTE
Usually, there is a difference between the actual beam size and position and the actual pupil size and position. Only in case you marked '**Use Beam Width**' and '**Use Beam Centroid**' options within the Pupil Definitions Setup 76 panel both parameters coincide.

This display is also available for WFS10 instruments in Highspeed Mode with the only difference, that the appropriate intensities are calculated within the camera's DSP.

4.2.2.5 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.

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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 65.

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

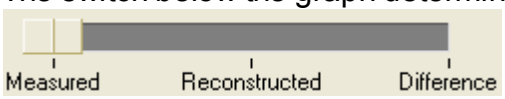
black, magenta	lowest wavefront parts
green	medium
red, white	highest wavefront parts

When the option '**Limit wavefront calculation and display to pupil interior**' is enabled within the Pupil Definitions Setup 76, 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.

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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 canceled 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 canceled in order to see only the higher order modes of interest.
- Only particular Zernike modes that are enabled within the Zernike Fit Setup 83 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

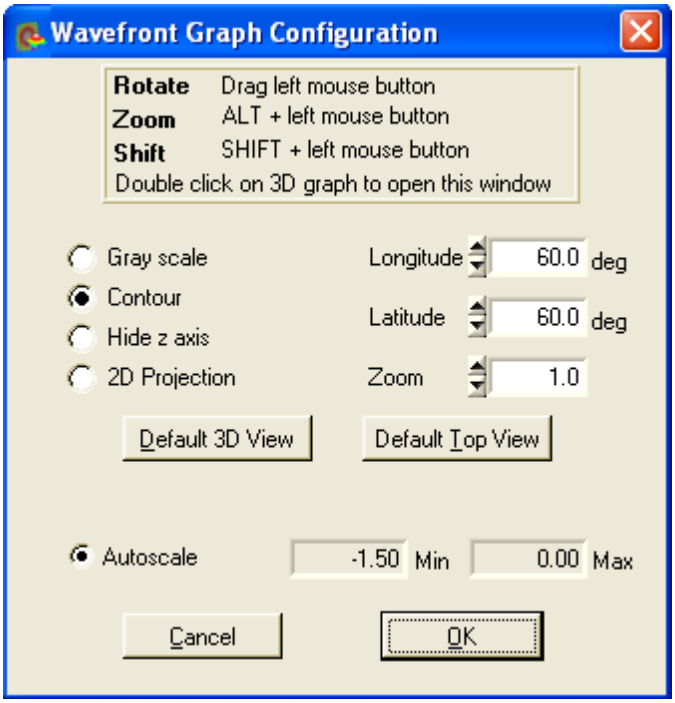
The actual switch setting is also important to the calculated wavefront statistics **PV, RMS** and **wRMS** (see Measurement Results 88) because the displayed values refer to the selected wavefront (Measured, Reconstructed or Difference).

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.

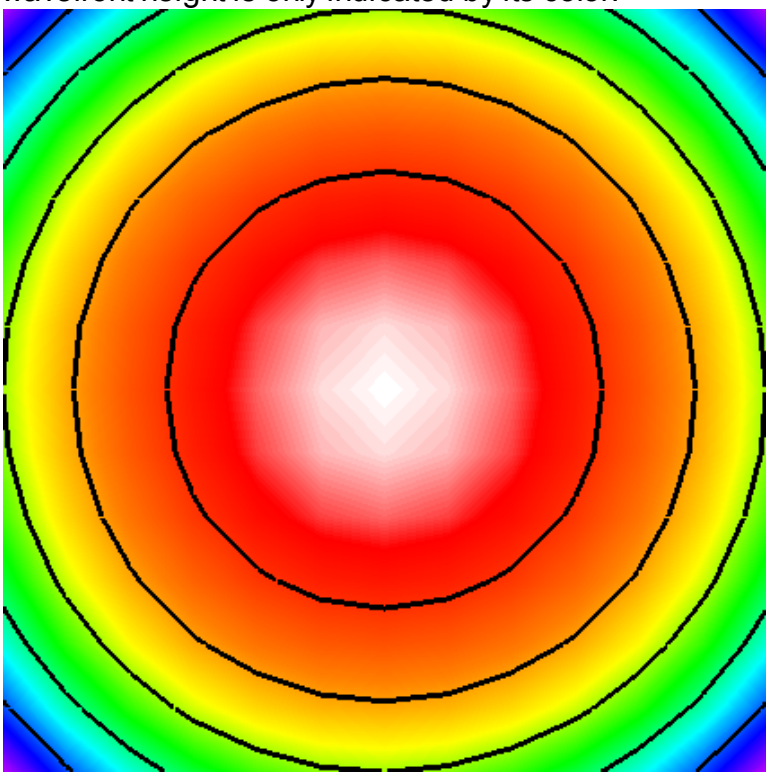
Double click on the graph to see the '**Wavefront Graph Configuration**' panel.

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

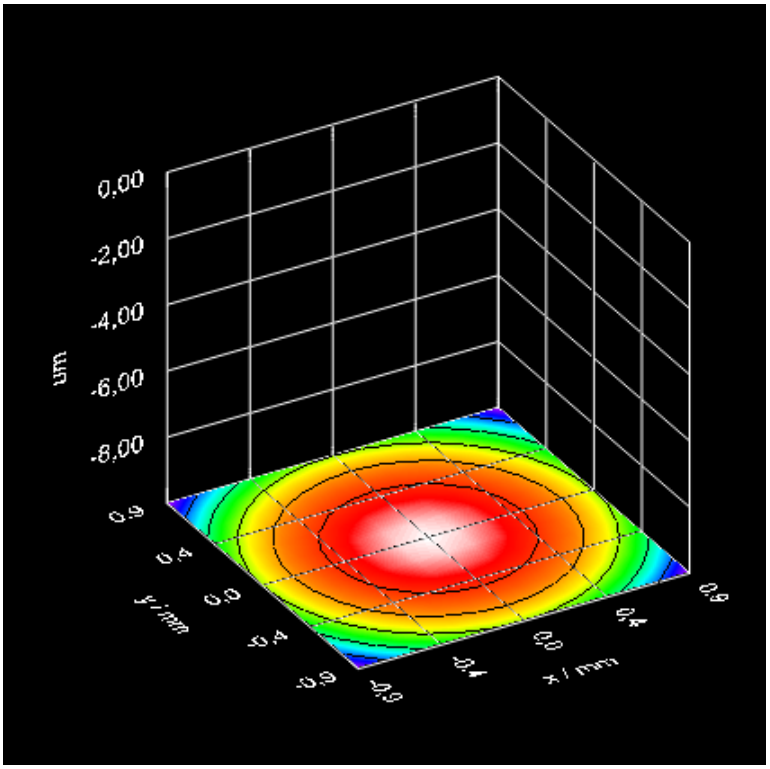
'**Default 3D view**' arranged the view angles so that all three axis are to be seen and the wavefront can be viewed as a 3D curve.
'**Default top view**' sets the 'Latitude' view angle to zero and allows a view parallel to the z-axis towards the x-y plane. The x-y-plane becomes rectangular and the wavefront height is only indicated by its color.



The following options define the look of the 3D graph

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'Gray scale'	switched between a color spectrum and a graduated gray color palette
'Contour'	inserts contour lines into the graph indicating lines of equal wavefront height
'Hide z axis'	hides the z-axis and the corresponding grid and caption
'2D Projection'	let the 3D graph collapse to the base x-y plane



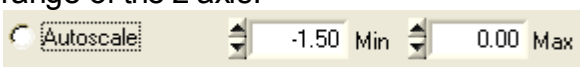
The following items define the view of the 3D graph

'Longitude'	determines the rotation angle about the z axis
'Latitude'	determines the view angle to the graph
'Zoom'	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

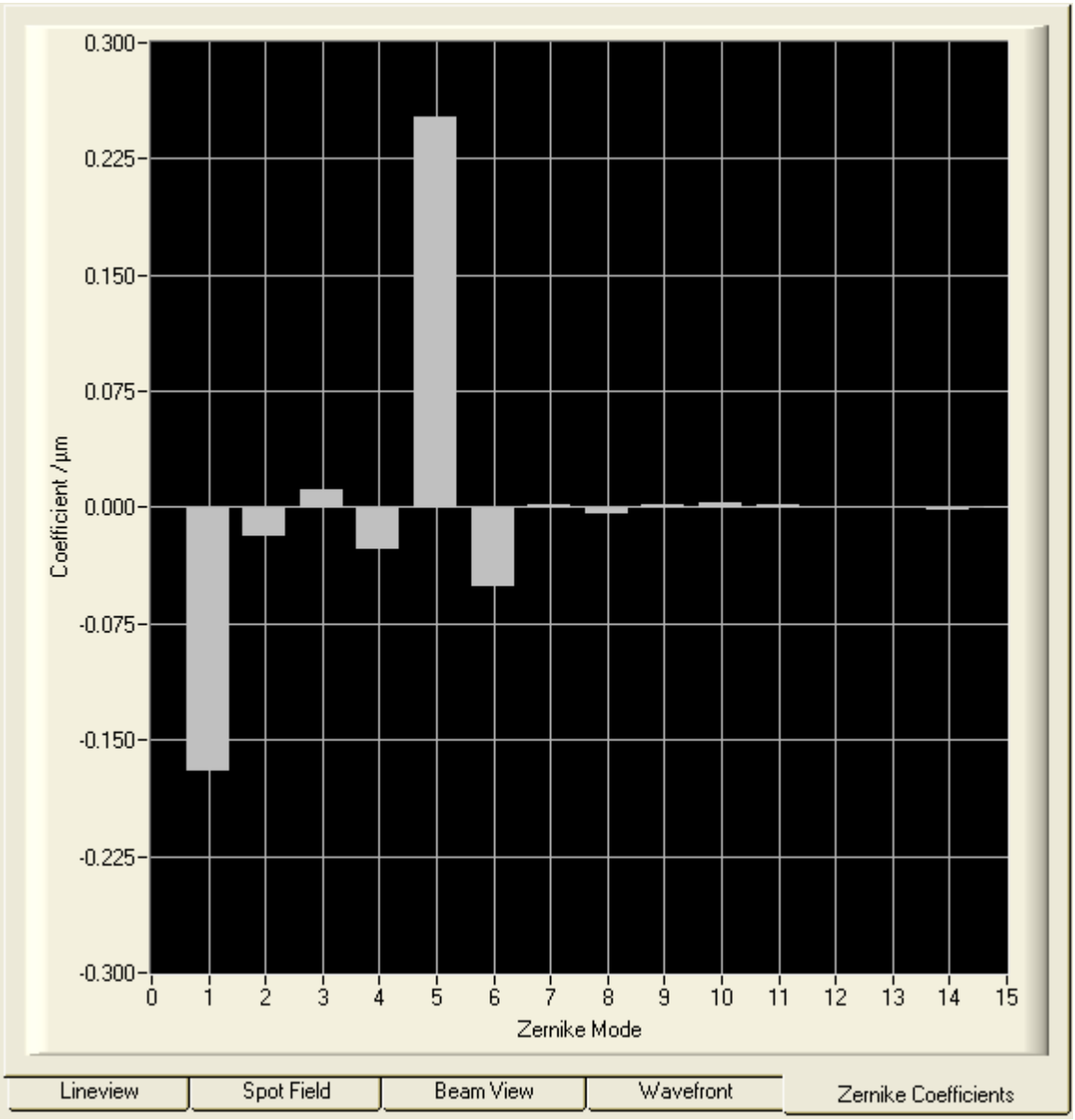
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determined by the wavefront center that is always set to zero.
Wavefront areas that are not defined because the appropriate spot was not detectable will not be displayed at all.

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

4.2.2.6 Zernike Coefficients Panel

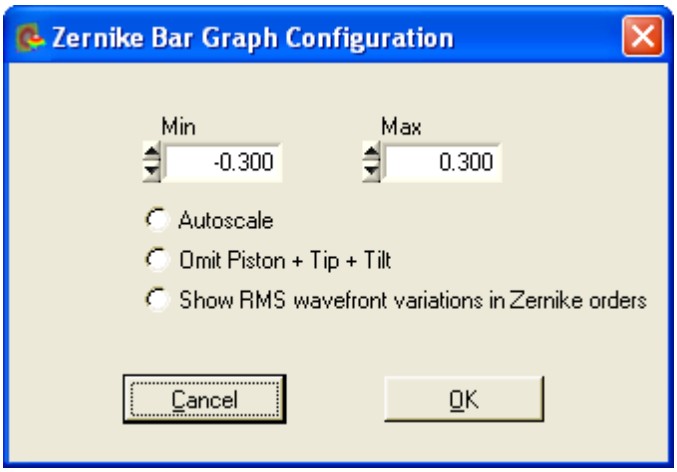
This panel displays a bar graph whereas the vertical bars indicate the Zernike coefficients which are the results of the Zernike fit.



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.

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

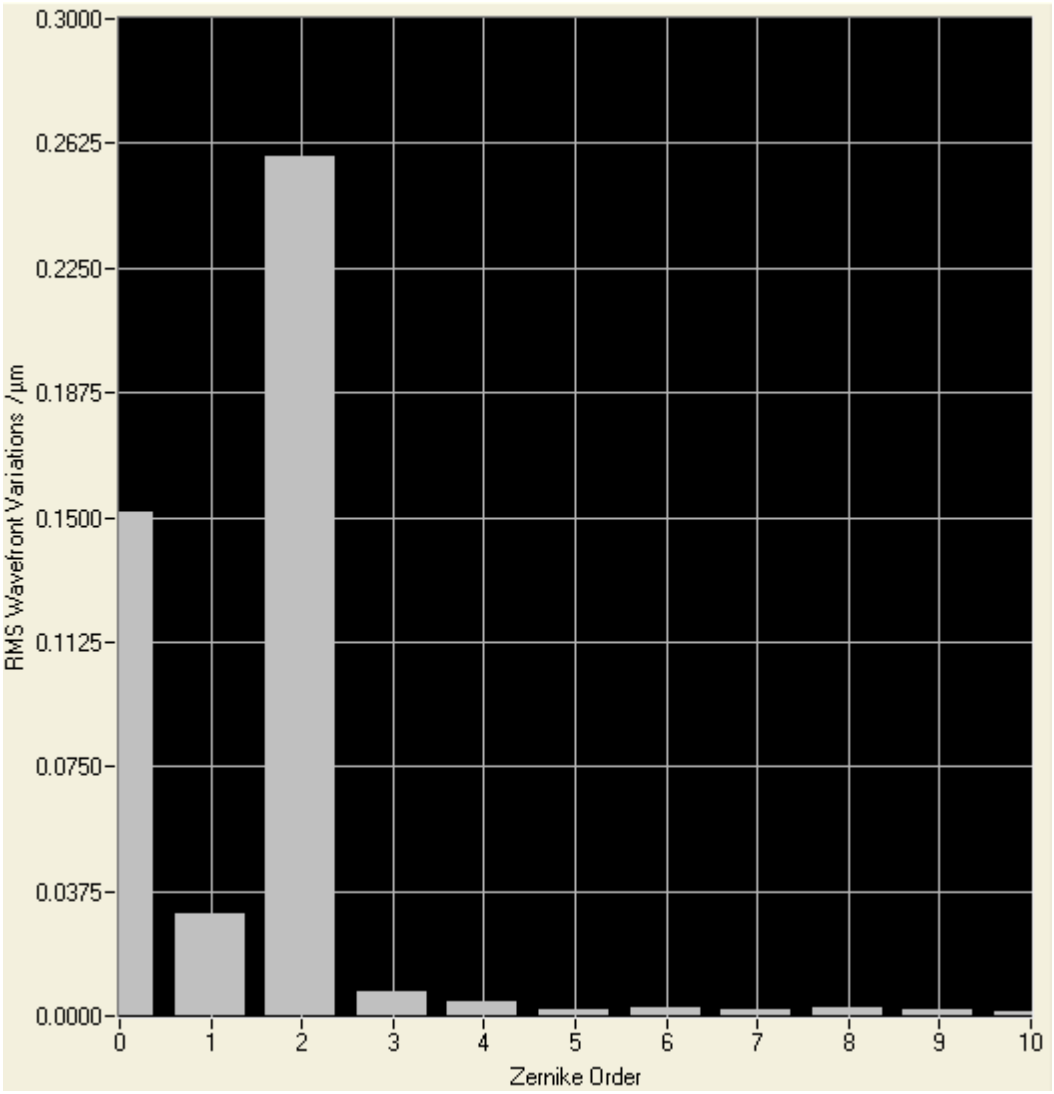


By default, the graph's vertical axis is scaled automatically. In case some of the displayed Zernike coefficients are huge compared to other distortions you like to focus on it is advantageous to switch '**Autoscale**' off. Also in case of fluctuating Zernike coefficients that cause a permanently changing 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.

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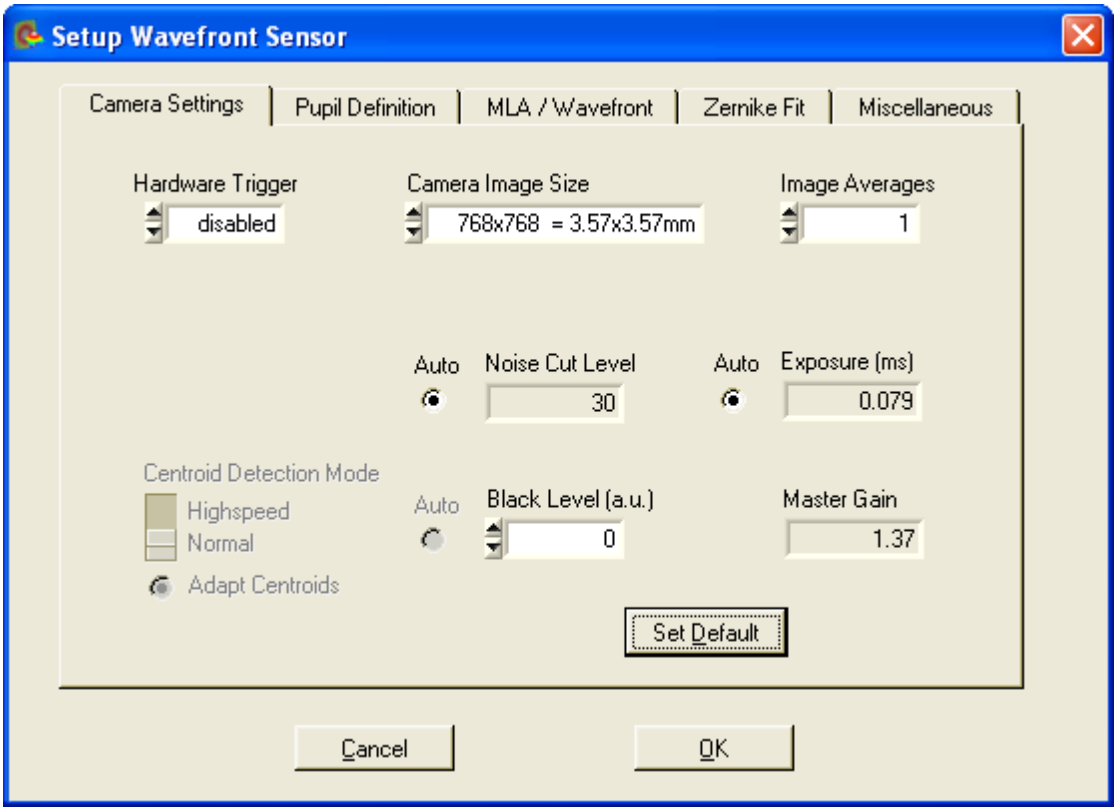
Use the **'Omit Piston + Tip + Tilt'** option to suppress the display of Zernike orders 1 and 2 if they are of less interest.

4.2.3 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 → Setup → Wavefront Sensor** entry or simply **click right** on one of the graphs on the right hand side of the main panel.

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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

Important Note

Please be aware of the fact, that settings for Camera Image Size, Pupil Definition and Zernike Fit (Zernike order number) depend each on the other and further, impact on measurement speed.

- With a large image size, you can choose a large pupil diameter, and it is possible to allow a high Zernike resolution (Zernike order). The downside is an increase of the transferred data volume and this way the measurement speed decreases.
- The smaller the image size, the less spots can be used for calculation and thus, the maximal achievable Zernike order decreases. On the other hand,

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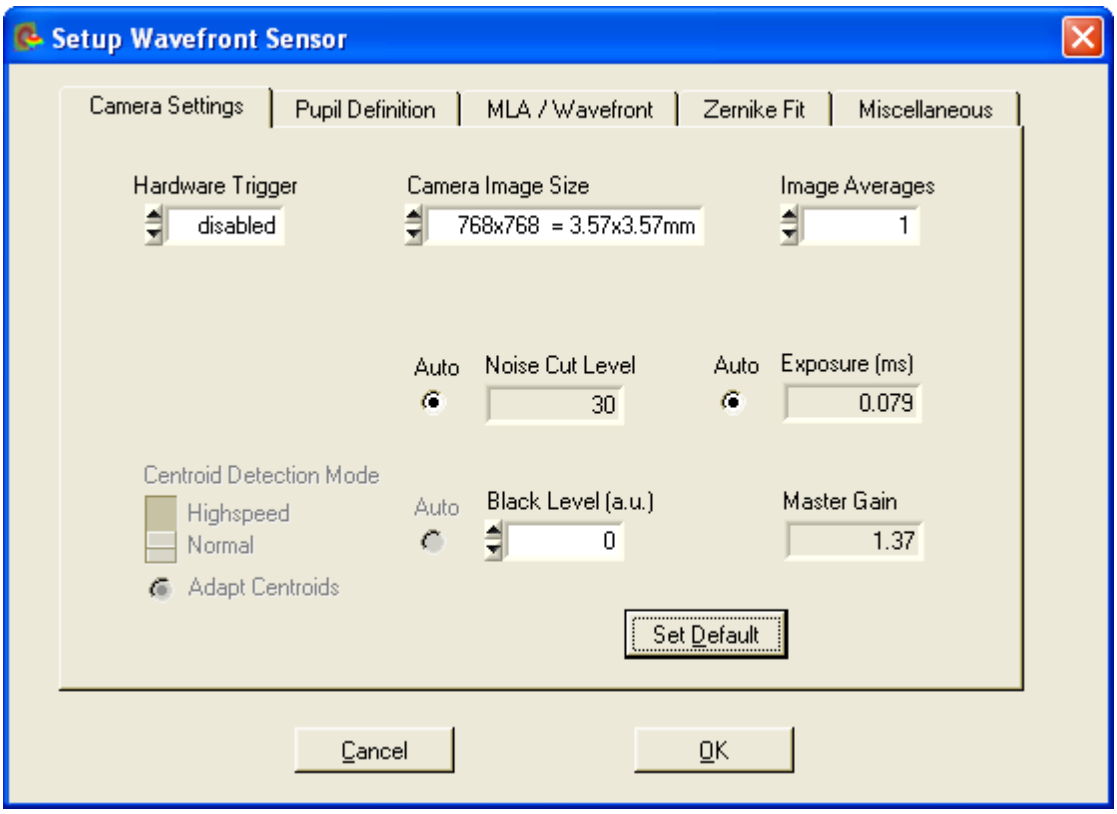
measurement speed increases.

If these setting are made critically or contradictory, warnings or error messages will appear in the instrument status box, see section Measurement Warnings and Errors 91 and Minimal Beam and Pupil Diameter 127.

4.2.3.1 Camera Settings Setup

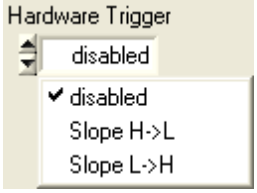
'Camera Settings' handle adjustments concerning the image capturing of the CCD camera.

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**'.



Hardware Trigger enables synchronization to an external trigger signal which may be a pulsed laser source or an electrical function generator. See chapter Trigger Input 130 for a detailed specification of this input.

The following trigger options can be selected:



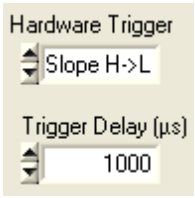
As soon as a trigger slope is selected, the WFS waits for the trigger event at the

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electrical input and no wavefront measurement and screen update take place. This state is indicated by the 'Awaiting hardware trigger...' message within the Status/ Error window at the bottom.



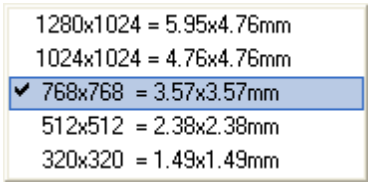
In addition, a trigger delay can be programmed in the range 15 µs to 4 s.

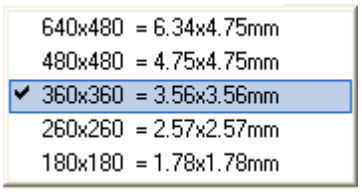


After the trigger edge was detected by the WFS camera it waits the specified time interval until it starts exposure of the next image.

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 for WFS (left) and WFS10 (right), respectively:

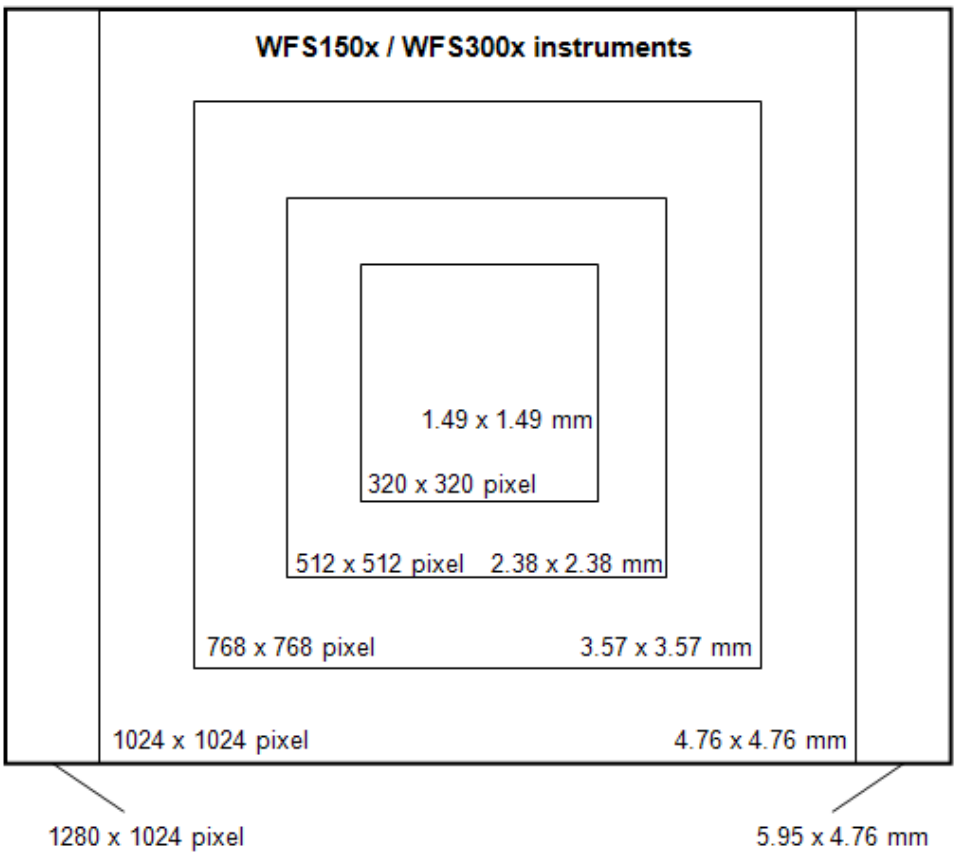


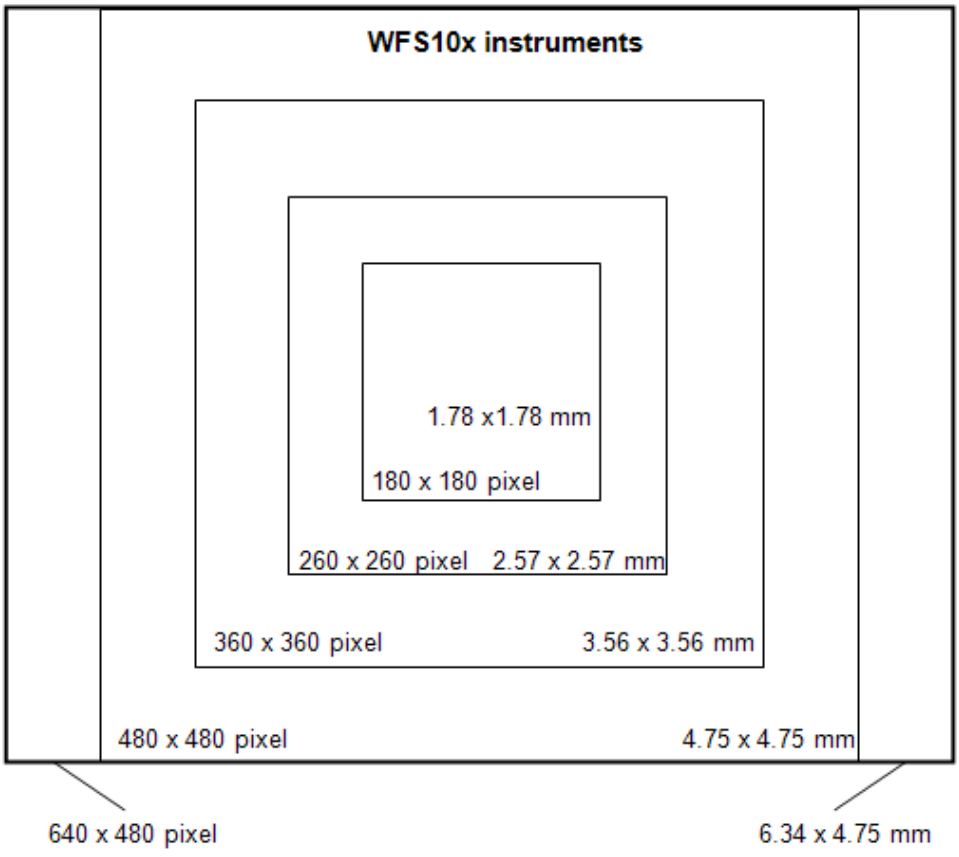


The WFS CCD camera offers a maximum of 1280 x 1024 pixel = 1.3 MegaPixel on a rectangular area 5.95 x 4.76 mm while the WFS10 CMOS camera offers a maximum of 640 x 480 pixel = 0.3 MegaPixel on a rectangular area 6.34 x 4.75 mm. For beams that have a larger diameter than 4.7 mm, only a fraction of the 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 76).

The following graph illustrates the selectable image sizes for WFS and WFS10 instruments.

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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 95 may be required.

Depending on the selected camera resolution in pixels 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 are as follows:

WFS Camera resolution in pixel	Wavefront resolution		Wavefront points	
	WFS150x	WFS300x	WFS150x	WFS300x
320 x 320	7 x 7	3 x 3	49	9
512 x 512	13 x 13	5 x 5	169	25
768 x 768	21 x 21	9 x 9	441	81
1024 x 1024	29 x 29	13 x 13	841	169
1280 x 1024	37 x 29	17 x 13	1073	221

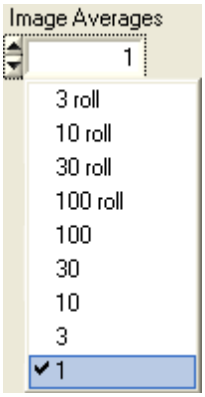
WFS10 Camera resolution in pixel	Wavefront resolution		Wavefront points	
	WFS10-5C WFS10-7AR (150 µm pitch)	WFS10-14AR (300 µm pitch)	WFS10-5C WFS10-7AR (150 µm pitch)	WFS10-14AR (300 µm pitch)
180 x 180	9 x 9	3 x 3	81	9
260 x 260	15 x 15	7 x 7	225	49
360 x 360	21 x 21	9 x 9	441	81
480 x 480	29 x 29	13 x 13	841	169
640 x 480	41 x 29	19 x 13	1189	247

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 (WFS150x). For WFS10 instruments with 150 µm lenslet pitch only about 15x15 CMOS pixels are mapped to one 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

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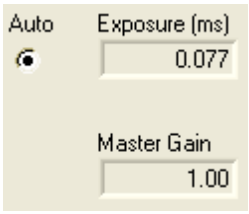


whereas 3, 10, 30, 100 indicate **normal averages** where the average is taken in the background and only after reaching the selected number of averaged images the instrument will continue operation and start data evaluation and display. This type of averaging also reduces the update rate of numerical 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.
For WFS instruments the **'Exposure'** time can be set to values between 0,077 ms and 66.501 ms in steps of 0.055 ms while for WFS10 instruments the values are between 0,033 ms and 500 ms in steps of 0.011 ms.
'Master Gain' indicates the analogue amplification factor of the CCD/CMOS sensor signal, it can be set to values between 1.0 and 5.0 (WFS) and 1.5 to 5.0 (WFS10, Gain = 1 is disabled because of insufficient image saturation in some cases).
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.

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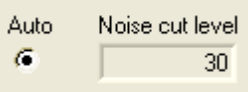
It is recommended to check the actual saturation degree of the camera's AD converter by verification on the **LineView panel**.

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.

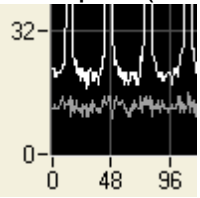
Black Level

'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.



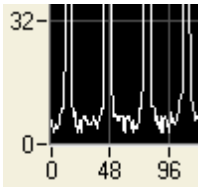
"Arbitrary Unit" (a.u.) values range from 0 to 255.

Examples (WFS):



Black Level = 255 is too high, lowest intensity pixels (lower curve) showing high offset.

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Black Level = 0 is OK because lowest intensity pixels are below zero but the highest intensity pixels between the spots are still above zero.

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

Set Default

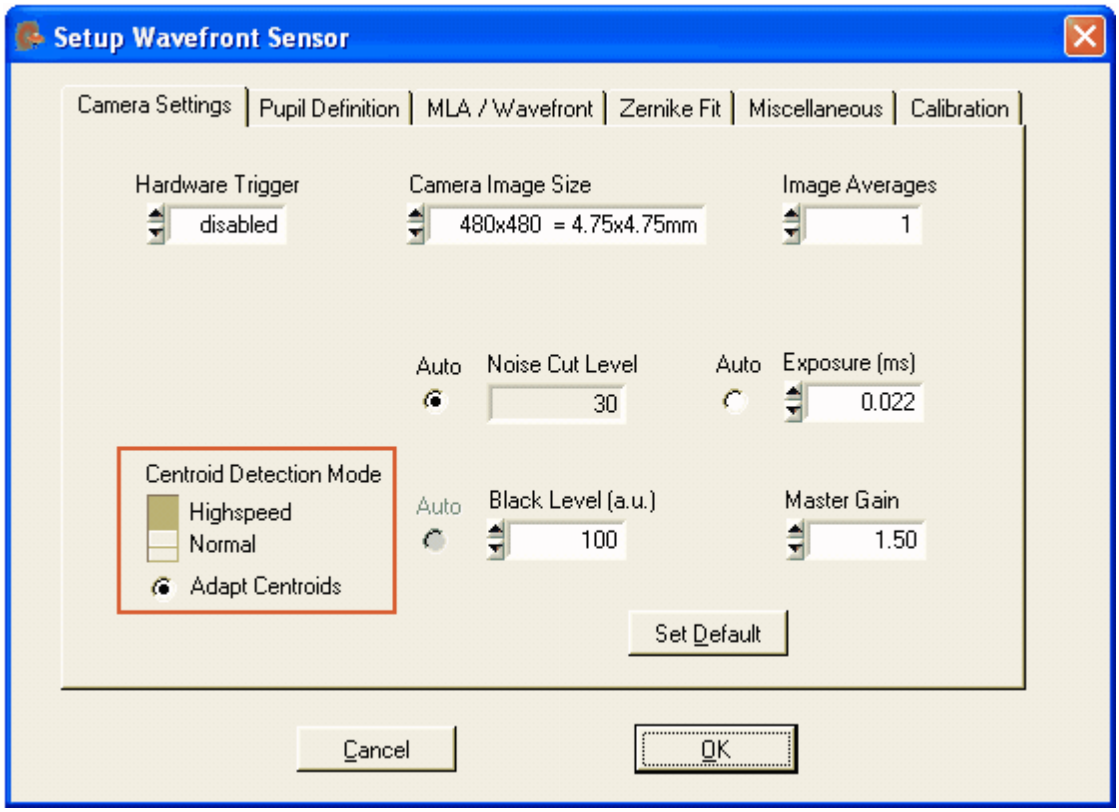
Click on 'Set Default' to activate the factory default values:

- Cam Noise Level = Auto
- Exposure time and Master Gain = Auto
- Black Level = 0 (WFS instruments)
- Black Level = 100 (WFS10 instruments)
- Disable Hardware Trigger

Settings for Camera Image Size and Averaging remain unchanged.

Highspeed Mode - For WFS10 instruments only

In case of a WFS10 Wavefront Sensor instrument, there is another switch for defining the Centroid Detection Mode.



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Please refer to chapter WFS10 Highspeed Mode 34 for a detailed description of differences between Normal and Highspeed Mode.

Before entering Highspeed Mode, you need to take care the following setup parameters:

- **Exposure Time** and **Master Gain**
  Adjust both parameters to have sufficient image saturation but no over-saturation. You may switch 'Auto' exposure option on for that.
- **Black level** of the camera
  Adjust this analogue black level so that the lower visible line (indicating the lowest intensity within a pixel column) within the Lineview Panel is close or below zero level.
- **Noise cut level** for centroid interrogation
  In Highspeed Mode this level describes the amount of digits which will be subtracted from each pixel of the detected camera image before spot interrogation starts.

NOTE

The spot centroid positions detected in Highspeed Mode become extremely sensitive to the camera's black level.

That's why all pixel intensities within the entire spot window (width x height pixels) contribute to the final centroid result. Also small black level intensities will shift the result towards the windows center. To get rid of any increased black level you will have two options a) or b):

a) Control the cameras analogue black level – it can be lowered so that the pixels between the spots become zero.



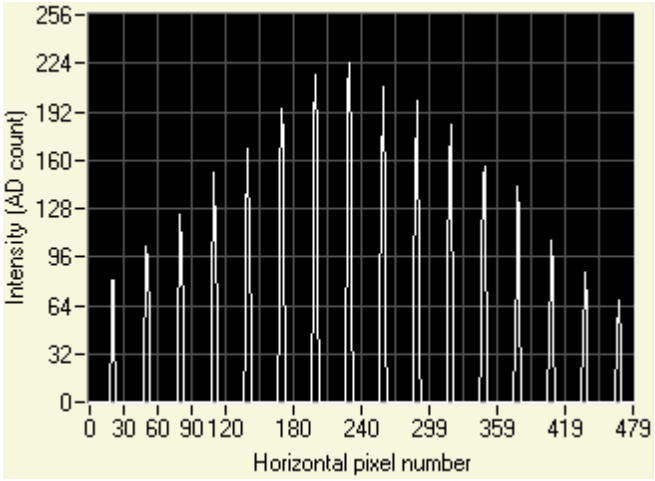
b) An adjustable ‘Noise cut level ’ similar to the one in normal mode can be set to the camera in Highspeed Mode.



Disable the 'Auto' option, it isn't available in Highspeed Mode, anyway. The camera will subtract this level from each pixel before it starts the centroid calculation.

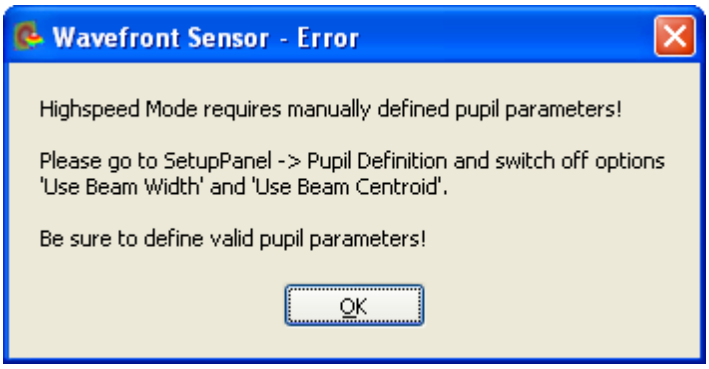
For both options, please check the Lineview panel, it should look like this:

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Entering Highspeed Mode (WFS10)

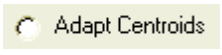
The WFS10 instruments are always initialized in Normal Mode.
Because detection of beam centroid and diameter with sufficient accuracy isn't feasible in Highspeed Mode you will be asked to define these parameters manually.



Please go to the Wavefront Sensor Setup → Pupil Definition, switch off both options and define the pupil diameter and position manually. Please consider hints given in chapter Pupil Definitions Setup 76.

Adaption to previously measured spot centroids

If centroid adaption is off



then the software defines a rigid grid of spot interrogation windows based on the spot reference positions. Since the actual detected spot centroids are identical with its reference positions only in case of exactly orthogonal incidence of a pure plane wavefront, it is likely that some spots of an arbitrary measured wavefront doesn't fall into the reference grid.
The following error occurs:

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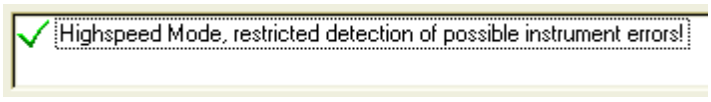


Therefore, it is highly recommended to **enable option 'Adapt Centroids'**:

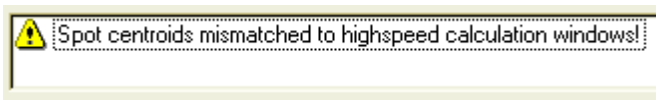


Here, the software checks if the spot centroid positions measured in Normal Mode are suited to define a grid of calculation windows which is suited to capture all spots. The grid is flexible with respect to window size and offset position in both x and y direction.
This flexibility allows adaption of tilted and spherical wavefronts of moderate amplitude.
In case the above error message occurs the input wavefront is excessively deformed so that it cannot be measured in Highspeed Mode.

As soon as Highspeed Mode was entered it is displayed within the status window.



Because the camera saturation remains unknown in Highspeed Mode if the auto exposure option is disabled the camera image may suffer from over- or under exposure which is leading to wavefront mismeasurement. As a consequence, Highspeed Mode with disabled auto exposure feature is only applicable when working at a quite constant power level.
But, a measurement error due to violation of the spot windows by the detected centroids can be displayed.



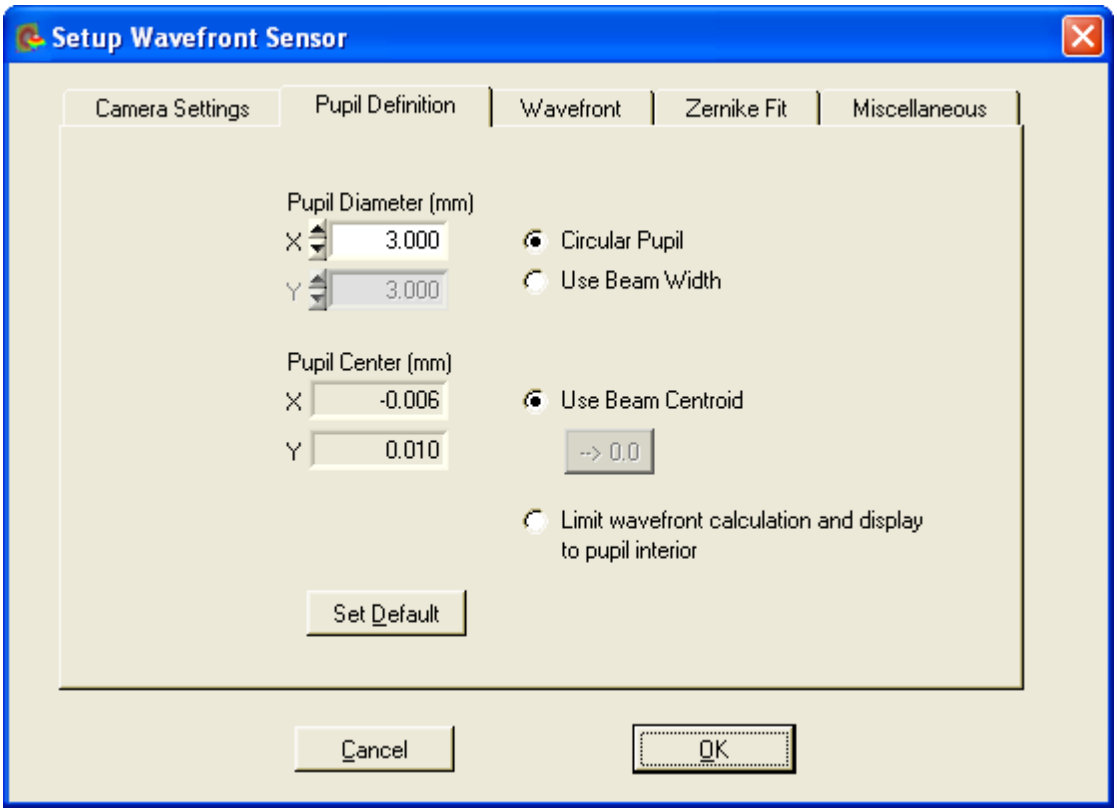
NOTE
If this warning occurs, the wavefront measurement is most likely disturbed by spots which are truncated by its detection window.

4.2.3.2 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.

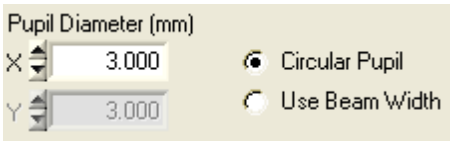
To open the setup panel you can use the **Menu → Setup → Wavefront Sensor** entry or simply **click right** on one of the graphs on the right hand side of the main panel. Select the tab '**Pupil Definitions**'.

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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 83).

Pupil Diameter (mm)
The here defined Pupil Diameter is twice the 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 67). 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 67 will help to reject an increased dark level.

Let '**Use Beam Width**' unchecked to define the pupil size manually. You may define

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an elliptical pupil by entering different values for X and Y diameter. Here, the mean diameter defines the Zernike circle.

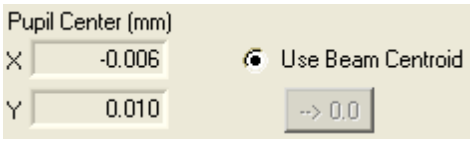
NOTE
This option 'Use Beam Width' must be switched off when entering Highspeed Mode of WFS10 instruments because the beam width cannot be measured with a sufficient accuracy in Highspeed Mode.

NOTE
The pupil diameter cannot be defined larger than the active camera area defined with **Camera Image Size** in the Camera Settings 67. In this case the warning "Pupil is larger than selected camera area" (see chapter Measurement Warnings and Errors 91) will occur. This limitation prevents Zernike calculations with increased uncertainties because the measurement points (spots of the lenslets) are no more equally distributed across the pupil area.

See chapter Minimal Beam and Pupil Diameter 127 for the minimal pupil diameter required for calculation of Zernike modes up to a desired order.

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.

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.

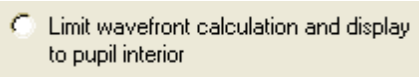
NOTE
Manual definition of the pupil center requires a careful and stable beam adjustment, otherwise the measurement results will suffer from increasing errors.

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.

NOTE
This option 'Use Beam Centroid' must be switched off when entering Highspeed Mode of WFS10 instruments because the beam centroid cannot be measured with a sufficient accuracy in Highspeed Mode.

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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 58 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 that the total measured distortions outside the pupil.

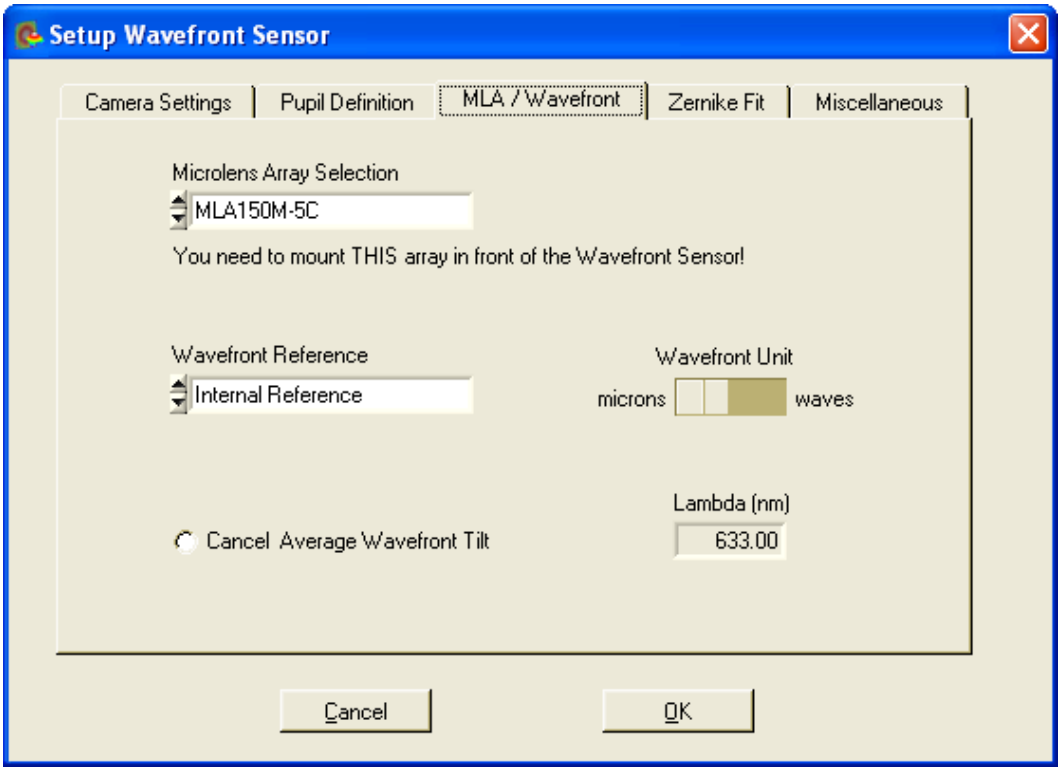
Set Default
Click on 'Set Default' to activate the factory default values:
- Circular pupil
- Use Beam Width = disabled
- Manual Pupil Diameter = 3 mm
- Use Beam Centroid = enabled
- Limit to Pupil Interior = disabled

4.2.3.3 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**'.

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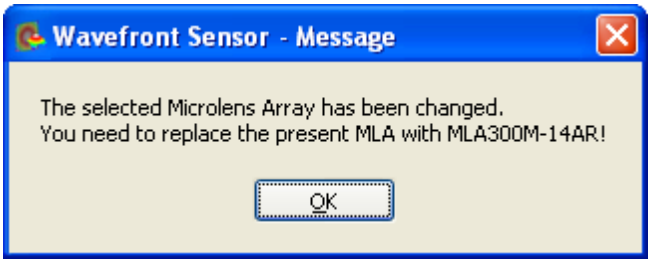


Microlens Array Selection

A Thorlabs WFS Wavefront Sensor can be operated with different Microlens Arrays (MLAs), see Parts List 9 chapter. Each available MLA is factory calibrated. In order to supply the correct calibration data to the WFS software you need to select the physically installed MLA from the pull down list.



You are reminded by the message below to switch the physically installed MLA if a different MLA than before was chosen.



Attention

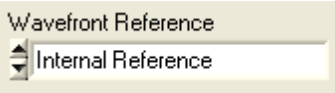
Be sure to have the selected MLA physically installed in front of your Wavefront Sensor!
Otherwise, all measurement data become invalid because wrong calibration data!

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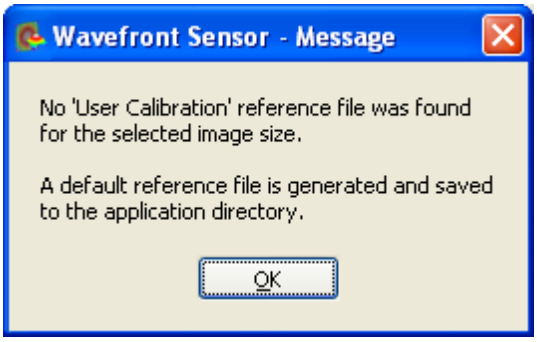
Wavefront Reference
The Thorlabs WFS series Wavefront Sensors are factory calibrated and provide an internal reference for the measured spotfield centroids. This internal reference is based on the well known and highly accurate parameters

- pixel distance of the CCD sensor = 4.65 µm (WFS)
- pixel distance of the CMOS sensor = 9.9 µm (WFS10)
- lenslet pitch of the microlens array = 150 or 300 µm, respectively
- calibrated out-of-center shifts in for a plane wavefront under vertical incidence
- negligible torsion between CCD chip end lenslet array
- correction parameters for lenslet astigmatism

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 t he 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 95 using a plane or spherical wavefront to fill the default file with reference data measured by the user.

In order to be distinctively the **user reference file name** is automatically composed of the

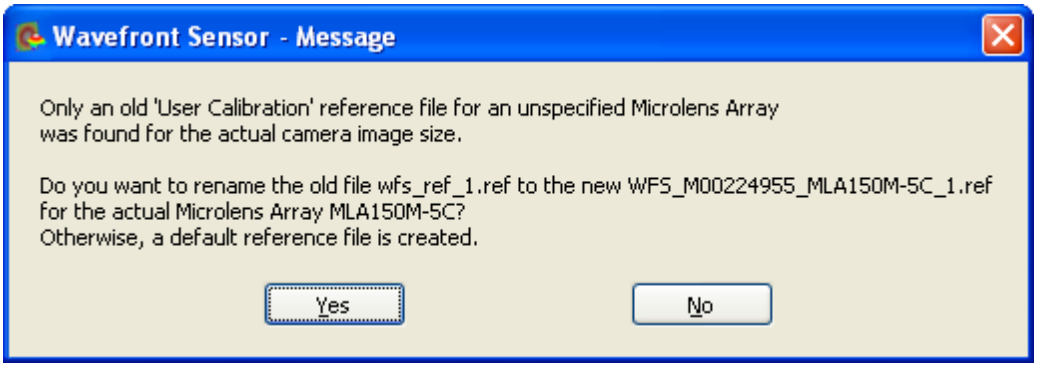
- WFS serial number
- MLA name
- Camera resolution index

for instance WFS_M00224955_MLA150M-5C_2.ref. The file itself is stored into the application directory.

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

In case only an old file name with unspecified SN and MLA name saved by older program versions < 2.0 can be found you will be asked how to proceed.



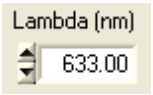
Only click 'Yes' to rename this old file if you are sure that it was generated using the same WFS instrument and MLA name.

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 300 to 1100 nm and corresponds to the wavelength range of models WFS150-5C and WFS10-5C.

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

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The average wavefront tip and tilt will not be removed completely. Small relicts 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

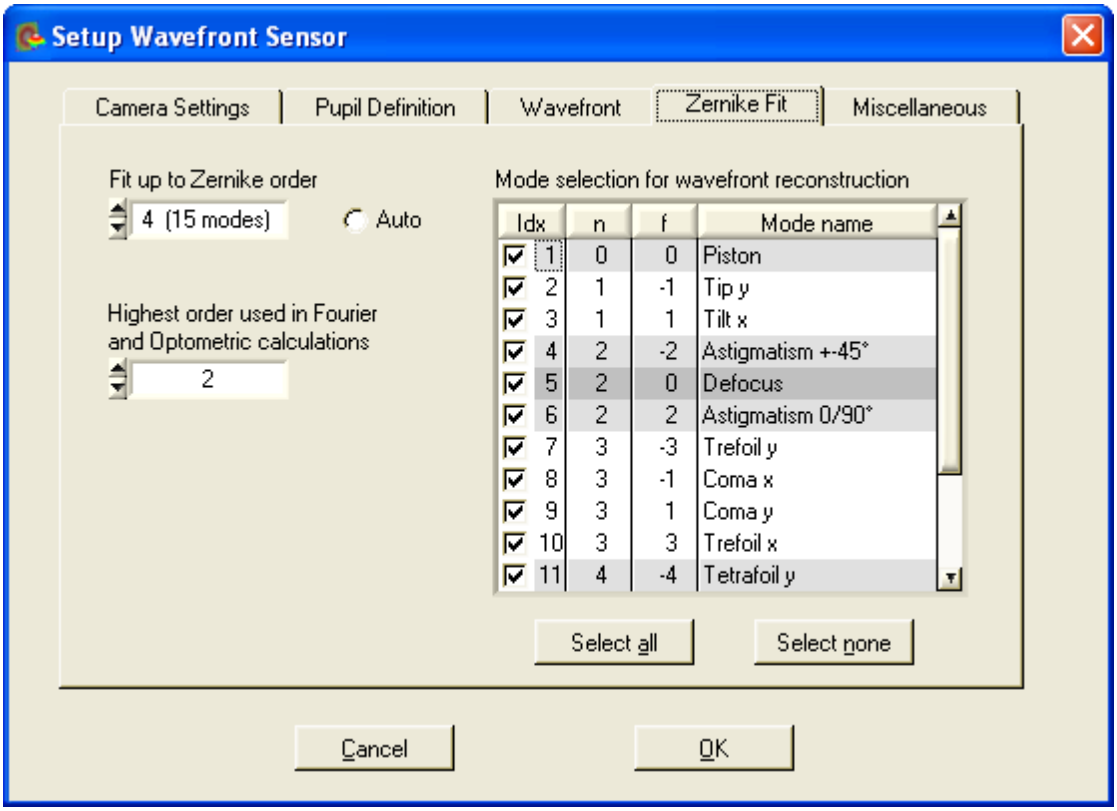
At first program start, the following default settings become active:

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

4.2.3.4 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**'.

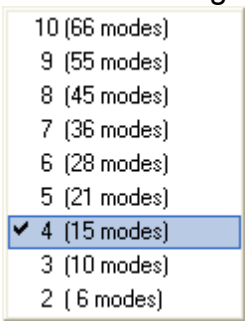


Fit up to Zernike Order

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

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Available settings are:



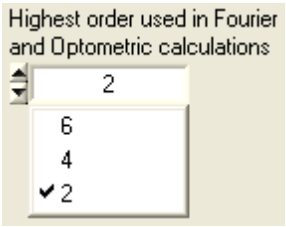
According to the well known set of Zernike polynoms, the highest radial order (r^n) determines the number of Zernike modes that contain this or lower potencies n of the pupil radius r.

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.

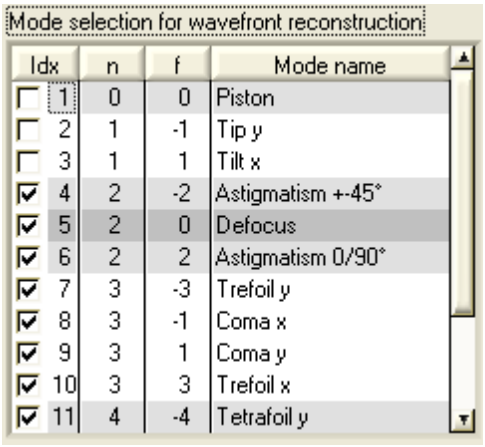
Auto
If 'Auto' is enabled, the Zernike order is set to the highest possible value which is feasible. The highest number of Zernike modes must not exceed the amount of detected spots within the pupil.

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.

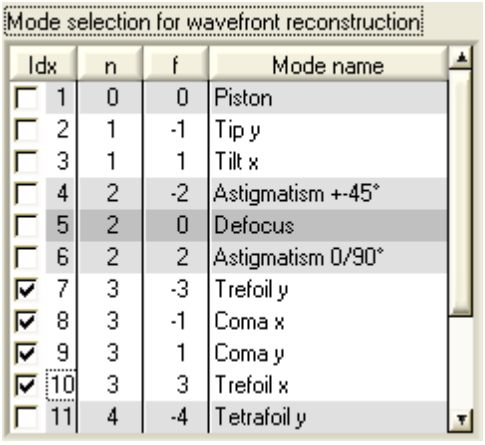


Mode selection for wavefront reconstruction
This table provides a list of all calculated Zernike coefficients each listed in a row. The number of rows is determined by the '**Fit up to Zernike Order**' control.
The check box at the left side determines whether this mode should be used for the reconstruction 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:

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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 than mark the modes of interest. To focus on third order (n = 3) aberrations, do the following selection:



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:

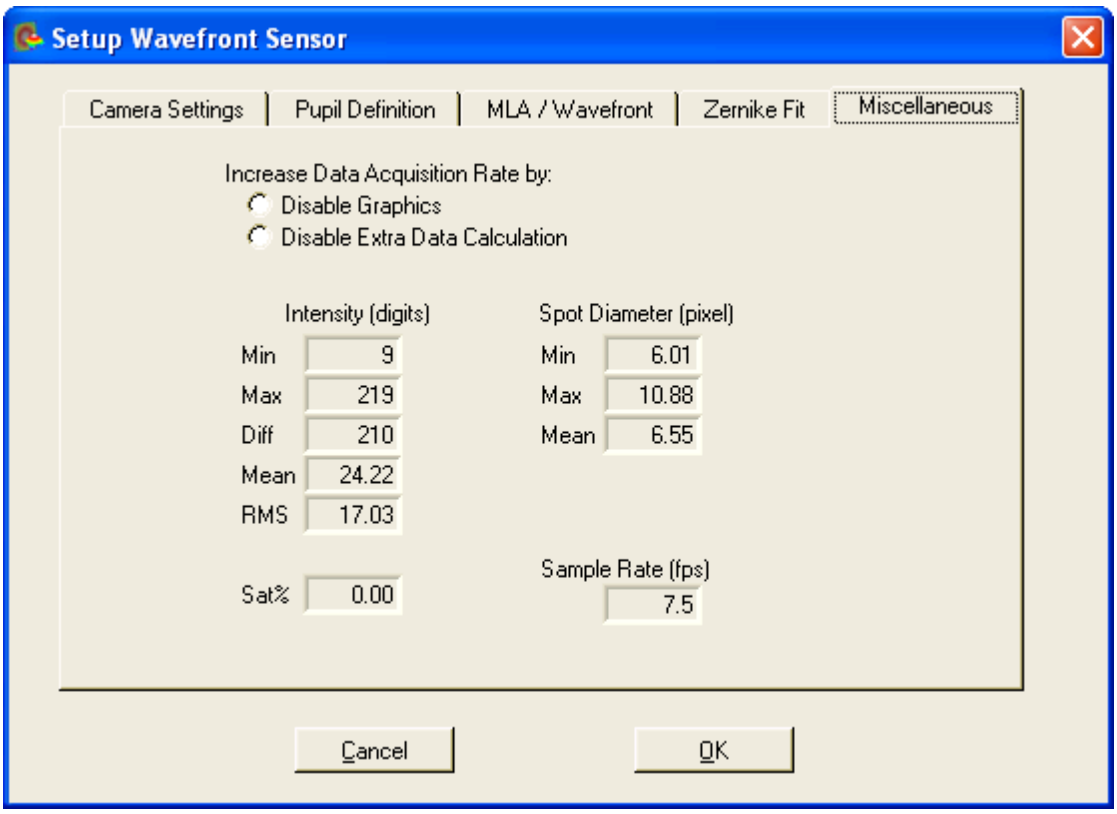
- Fit up to Zernike Order = 4 (manual setting)
- Highest order in Fourier and Optometric calculations = 2
- All Zernike modes selected for wavefront reconstruction

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4.2.3.5 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 109 interface. In this case the graphical displays of the Wavefront Sensor GUI become redundant and its updating and can be disabled.

NOTE

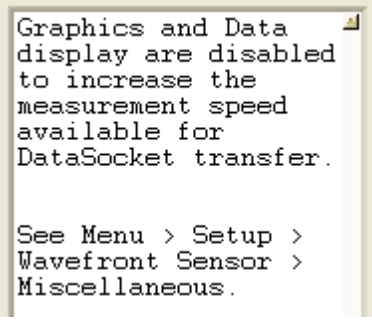
Selecting a lower camera resolution on panel Camera Settings 67 will result in less spots to be calculated and will increase overall measurement speed.

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

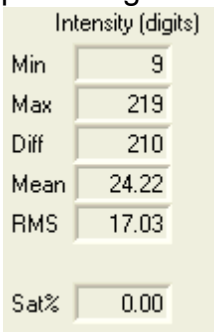
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will remind you of this active option and shows the way to deactivation.

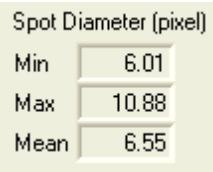


Disable Extra Data Calculation
Extra data are the parameters displayed in this tab of the setup panel. Enable this control to prevent time-consuming calculation (e.g. spot diameters) of all these parameters. The last remaining control is the speed indicator 'Sample Rate'.

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.



The calculated values for all spot diameters



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

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4.2.4 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.

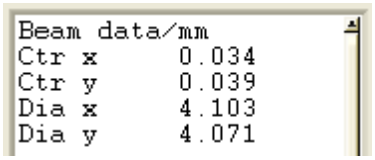


NOTE

If '**No instrument errors**' does not appear in the status window you cannot relay on the measurement results!

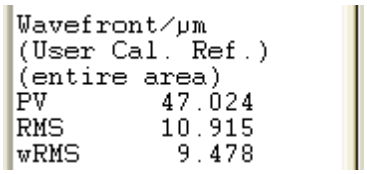
Refer to Measurement Warnings and Errors 91 for a listing of possibly occurring errors.

Beam Data

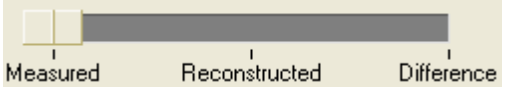


Calculated from the centroid and the second moment of the entire camera image, the beam's center coordinates **Ctr x** and **Ctr y** and beam diameter **Dia x** and **Dia y** in X and Y direction are displayed in mm. In case of a Gaussian beam shape the second moment coincides with beam width at the 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 67) will distort the beam data results.

Wavefront Data



These wavefront statistics are either displayed in microns or waves, as selected in the Wavefront Sensor Setup Panel 65. Calculated data is either related to the entire wavefront or to the pupil interior only, according to the settings within Pupil Definitions Setup 76 panel.
Depending on the actual wavefront switch setting below the wavefront graph



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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 83 panel, Zernike orders up to 2, 4 or 6 go into these constants.

Optometric Constants

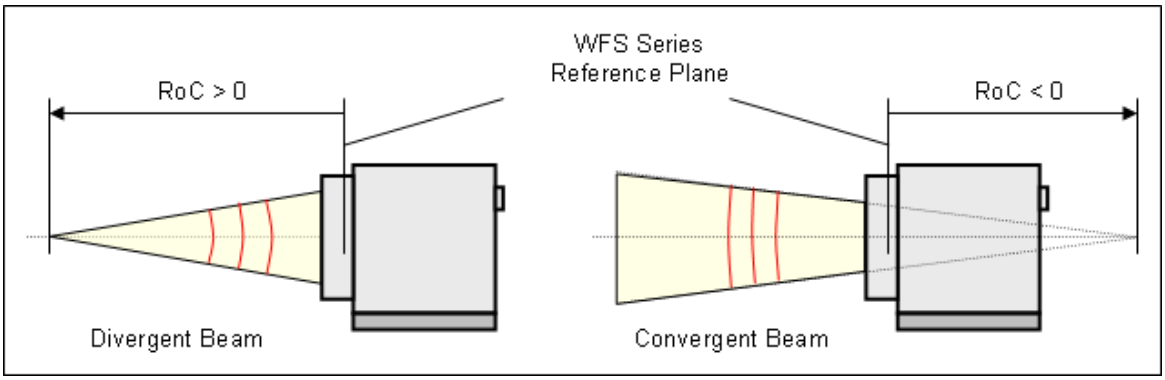
Optometric/dpt	
Sphere	18.099
Cyl.	−3.653
Axis	62.148°

Optometric constants are Sphere, Cylinder (in diopters) and the axis angle of the cylinder in degrees. Depending on setting in the Zernike Fit Setup 83 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

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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.
In case of a plane wave front, the Z5 term theoretically should be 0, and RoC - infinite. It's obvious, that the wave front sensor will not be able to measure accurately large RoC values. In order to point attention to reduced accuracy at RoC values ≥ 10.000mm, the result will be displayed like

```
RoC    (    -37.8m)
```

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 83 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 wavefont 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.

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4.2.5 Measurement Warnings and Errors

During capturing of the camera image and its subsequent analysis some errors may arise which needs to be recognized. Read the error message carefully and find a way to remove the reason of it.

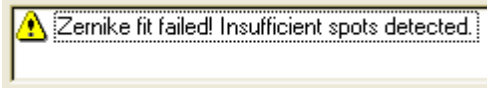


NOTE

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

Error List

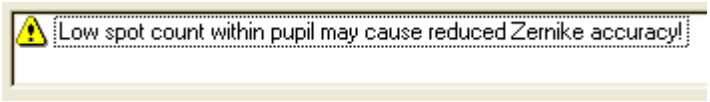
Zernike Fit failed! Insufficient spots detected.



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 76 panel and/or
- reduce the number of Zernike orders in the Zernike Fit Setup 83 panel
- increase the camera resolution within the Camera Settings Setup 67 in case the pupil diameter is close to the image dimensions

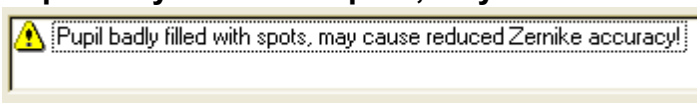
Low Spot Count within pupil may cause reduced Zernike accuracy!



Even if the number of detected spots within the pupil exceeds the minimum required number, there may occur an increased calculation error during the Zernike Fit, especially in case of high orders. Therefore, higher order fits (up to order 7-10) require an extra spot count of about 30%.
To prevent this warning

- 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 76 panel and/or
- reduce the number of Zernike orders in the Zernike Fit Setup 83 panel
- increase the camera resolution within the Camera Settings Setup 67 in case the pupil diameter is close to the image dimensions

Pupil badly filled with spots, may cause reduced Zernike accuracy!



The pupil area is not properly filled with detected spots up to its full diameter. Because the number of detected spots is defined by the selected camera resolution,

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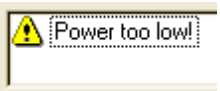
some visible spots at the border of each camera image remain undetected. But the pupil dimension must not be larger than the detected spot area. Otherwise, there may occur an increased calculation error during the Zernike Fit, especially in case of high orders.
To prevent this warning
- reduce the pupil diameter within the Pupil Definitions Setup 76 panel and/or
- increase the camera resolution within the Camera Settings Setup 67

Pupil is larger than selected camera area!



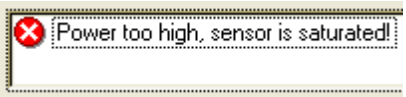
The pupil diameter exceeds the camera image dimensions so that parts of the pupil remain uncovered with detected spots.
To prevent this warning
- reduce the pupil diameter within the Pupil Definitions Setup 76 panel and/or
- increase the camera resolution within the Camera Settings Setup 67 in case the pupil diameter is close to the image dimensions

Power too low!



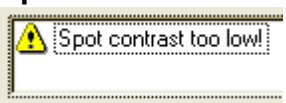
The detected spot intensity is too low so that the analysis of its centroid positions becomes incorrect. Check if 'Exposure Time' and 'Gain' settings within the Camera Settings Setup 67 of the camera are fixed to a manual entered level. Change the manual setting or enable automatic control of these camera 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 67 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.

Spot contrast too low!



The camera image suffers from low contrast, that is the brightness difference

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between the spots and the ambient area is too low. This may be a result from an imperfect manually adjusted exposure time in Camera Settings Setup 67. Reduce the stray light by shielding its incident from the Wavefront Sensor or increase the power of the analyzed beam.

High ambient light level!



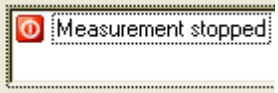
The captured camera image is overlayed a high amount of ambient light that decreases the contrast between the spot peaks and the dark areas between. Reduce the stray light by shielding its incident from the Wavefront Sensor or increase the power of the analyzed beam.

Awaiting hardware trigger...



No update of numerical and graphical measurement data is visible because the WFS trigger function was activated and no trigger event has occurred so far. Apply a trigger signal using the trigger cable (see Trigger Input 130 for details) or switch back to disabled trigger functionality in the Camera Settings Setup 67.

Measurement stopped



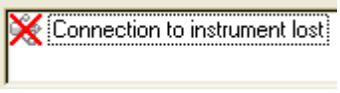
This message is not an error or warning but will notice the user that the continuous measurement has been stopped either by the user or due to occurrence of an other error so that the displayed data and graphs do not indicate actual wavefront data.

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.

Additional errors in Highspeed Mode

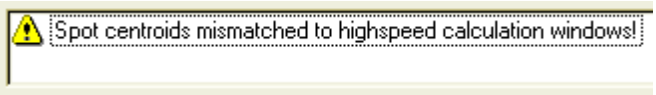
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NOTE

In Highspeed Mode there is an enhanced risk of mismeasurement because not all violations of save measurement conditions can be detected. For instance, the image saturation level remains unknown.

Spot centroids mismatched



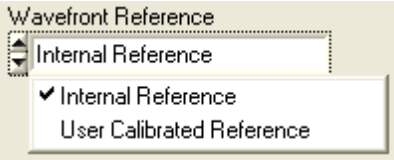
There is a violation of the spot centroid positions detected within the camera with its calculation windows defined when Highspeed Mode was entered. That is, the spot shifts went too far and cannot be detected accurately anymore.
Switch off and on Highspeed Mode with option 'Adapt centroids' enabled to overcome this situation.

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4.2.6 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 65 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 67 panel.

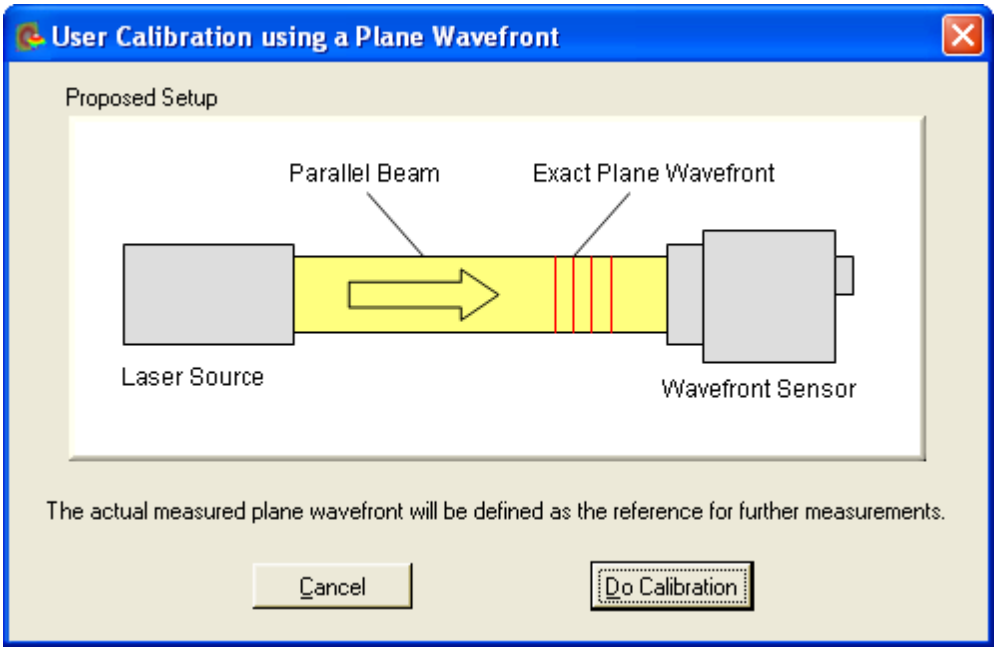
The generated user calibration data are only valid for the actual MLA and camera image size, selected in the Camera Settings Setup 67 and Wavefront Setup 79 panel. Switching to an other MLA or camera resolution will require a new calibration!

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.

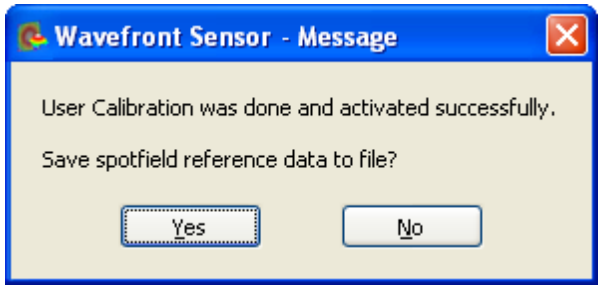
NOTE
The calibration fails for positions that are insufficient illuminated. Although no error occurs the according area will be excluded in further wavefront measurements.

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.

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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 67) and MLA (see Wavefront Setup 79) is changed and the appropriate reference file is loaded, the current reference in memory get lost.

User Calibration using a Spherical Wavefront

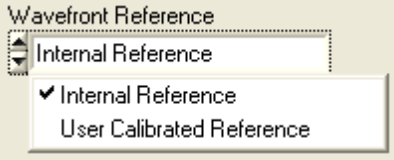
In order to perform this user calibration you need to apply a high quality divergent beam that originates from a point source having a perfect spherical wavefront. A single-mode fiber output without any collimators or lenses is ideally suited for that purpose. Be sure the beam is properly aligned to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

NOTE

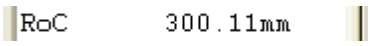
The calibration fails for positions that are insufficient illuminated. Although no error occurs the according area will be excluded in further wavefront measurements.

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Setup the Wavefront Sensor to work using the internal reference. Do the appropriate setting within the Wavefront Sensor Setup Panel 65.

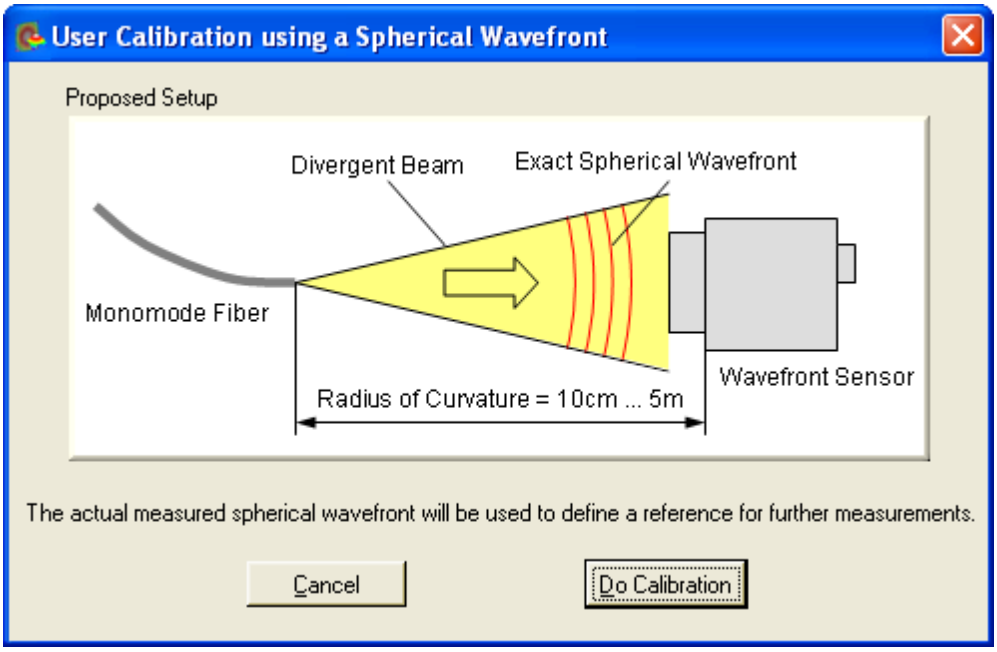


Adjust the point source straight in front of the Wavefront Sensor at a distance in the range 10 cm to 5 m. The Wavefront Sensor will measure the distance and displays it as Radius of Curvature RoC.



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

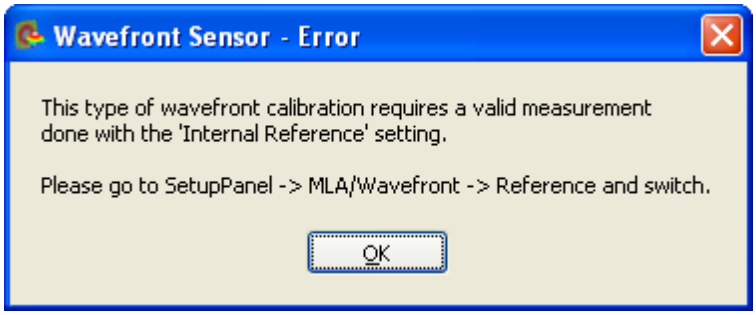
Start the calibration procedure using **Menu → Calibration → Spherical Wavefront** or simply click on the appropriate symbol in the toolbar. The following panel illustrates the required calibration setup.



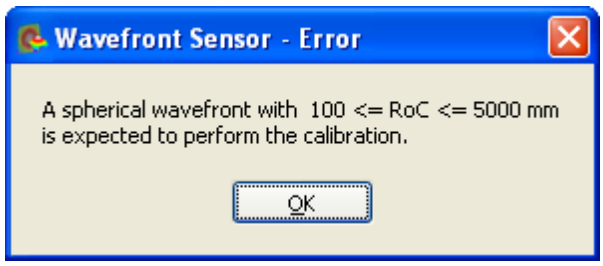
Click '**Do Calibration**' to perform the user calibration.

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

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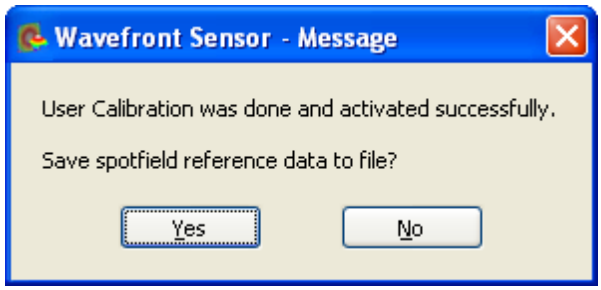


In case the distance to the point source is measured too short or too far the following error occurs.



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 67) or the MLA (see Wavefront Setup 79) is changed and the appropriate reference file is loaded, the current reference in memory gets lost.

In order to be distinctively the **user reference file name** is automatically composed of the

- WFS serial number
- MLA name
- Camera resolution index

for instance WFS_M00224955_MLA150M-5C_2.ref. The file itself is stored into the application directory.

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NOTE

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

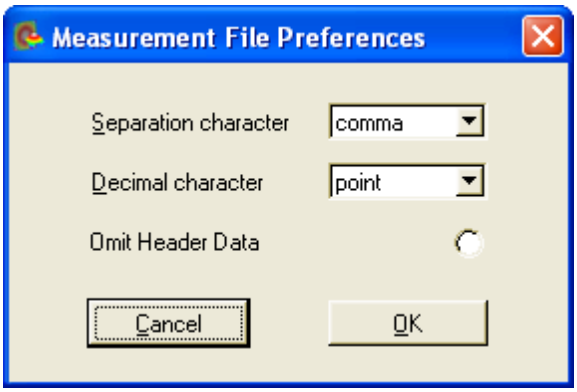
The stored file for an particular camera resolution is loaded automatically at program start and every time the camera resolution is changed but only if '**User Calibration**' option is enabled.

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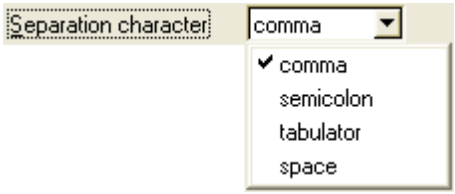
4.2.7 Save Measurement Data

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.**

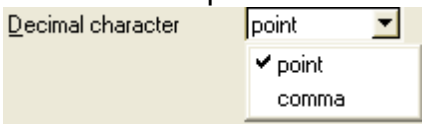


The separation character between the parameter name and the appropriate value can be set to four different characters:



'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 **'Omit Header 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
```

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```
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
```

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```
   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 [dpt],        3.358
Optometric Cyl. [dpt]  ,       -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 '**Omit Header Data**' was enabled the file content is limited to the following lines:

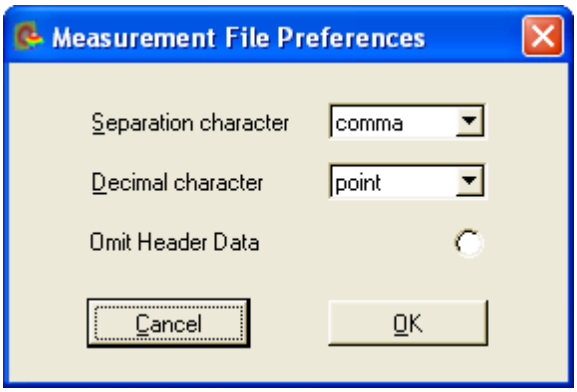
```
Spots X                ,        9
Spots Y                ,        9
y / x [mm],    -0.600,    -0.450,    -0.300,    -0.150,     0.000,     0.150,     0.300,     0.450,     0.600,
     0.600,     1.103,     1.087,     0.876,     0.740,     0.668,     0.655,     0.671,     0.739,     0.860,
     0.450,     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,
```

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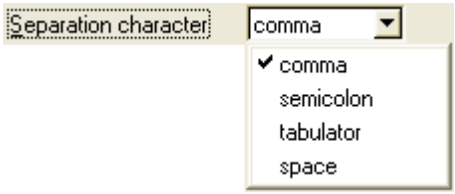
4.2.8 Save Centroid Data

The measured centroid positions of the spots visible in the Spotfield Panel[52] 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.**

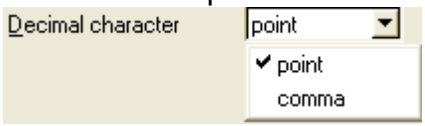


The separation character between the parameter name and the appropriate value can be set to four different characters:



'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 '**Omit Header Data**' is enabled the entire header including the listing of camera, beam and pupil data is omitted and only the centroid data array is saved.

Choose menu item **File → Save Centroid Data** or just press Ctrl + C to save the centroid 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                    ,        WFS150-5C
Serial Number            ,        M00224955

Date MM-DD-YYYY          ,        06-22-2009
Time HH:MM:SS            ,        15:01:17
```

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```
*** CAMERA ***
Camera Type             ,       Thorlabs DCU224M
Camera SN               ,       4002680294
Resolution X            ,       320
Resolution Y            ,       320
Exposure Time [ms]      ,       0.079
Master Gain             ,       1.437
Averages                ,       1
Average Type            ,       Normal


*** BEAM ***
Beam Center X [mm]      ,       0.008
Beam Center Y [mm]      ,       0.007
Beam Diameter X [mm]    ,       1.708
Beam Diameter Y [mm]    ,       1.701


*** PUPIL ***
Circular                ,       1
Use Beam Centroid       ,       1
Use Beam Dia            ,       0
Wavefront Calc In Pupil,        1
Pupil Diameter X [mm]   ,       1.200
Pupil Diameter Y [mm]   ,       1.200
Pupil Center X [mm]     ,       0.008
Pupil Center Y [mm]     ,       0.007


*** CENTROIDS [pixels] ***
Centroids X             ,       9
Centroids Y             ,       9
  20.229,  42.844,   52.574,  42.775,   84.773,  42.773,  117.051,  42.724,
149.295,  42.743,  181.650,  42.777,  213.902,  42.787,  246.146,  42.733,
278.366,  42.821,
  20.246,  75.042,   52.565,  74.955,   84.823,  75.045,  117.106,  75.022,
149.304,  75.012,  181.650,  75.046,  213.917,  74.977,  246.184,  75.009,
278.430,  75.019,
  20.242, 107.439,   52.473, 107.460,   84.777, 107.314,  117.048, 107.325,
149.359, 107.294,  181.699, 107.331,  213.876, 107.270,  246.219, 107.205,
278.445, 107.308,
  20.218, 139.755,   52.772, 139.424,   85.022, 139.721,  117.093, 139.573,
149.309, 139.615,  181.727, 139.616,  213.887, 139.590,  246.201, 139.585,
278.454, 139.498,
  20.415, 171.895,   52.737, 171.847,   84.831, 171.819,  117.084, 171.803,
149.366, 171.828,  181.724, 171.859,  213.953, 171.815,  246.173, 171.853,
278.390, 171.825,
  20.309, 204.342,   52.625, 204.186,   84.893, 204.197,  117.122, 204.171,
149.345, 204.099,  181.733, 204.063,  213.944, 204.079,  246.234, 204.045,
278.466, 204.056,
  20.327, 236.448,   52.601, 236.437,   84.789, 236.406,  117.132, 236.364,
149.395, 236.349,  181.685, 236.399,  213.999, 236.440,  246.165, 236.486,
278.482, 236.338,
  20.348, 268.788,   52.630, 268.775,   84.893, 268.695,  117.157, 268.744,
149.417, 268.760,  181.611, 268.689,  213.961, 268.685,  246.152, 268.639,
278.508, 268.645,
  20.318, 301.021,   52.625, 301.042,   84.872, 301.003,  117.127, 300.935,
149.372, 300.958,  181.709, 300.946,  213.959, 300.971,  246.212, 300.944,
278.446, 300.924,
```

Spot centroid coordinates are saved as (x, y) pairs. The unit is pixels whereas the upper left corner of the selected camera image size is the origin (point 0,0).

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In case the option '**Omit Header Data**' was enabled the file content is limited to the following lines:

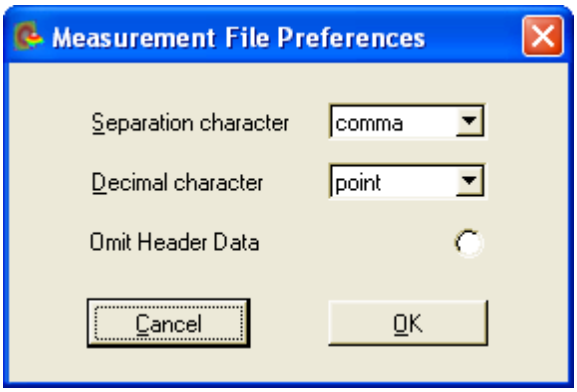
```
Centroids X            ,       9
Centroids Y            ,       9
  20.229,  42.844,   52.574,  42.775,   84.773,  42.773,  117.051,  42.724,
149.295,  42.743,  181.650,  42.777,  213.902,  42.787,  246.146,  42.733,
278.366,  42.821,
  20.246,  75.042,   52.565,  74.955,   84.823,  75.045,  117.106,  75.022,
149.304,  75.012,  181.650,  75.046,  213.917,  74.977,  246.184,  75.009,
278.430,  75.019,
  20.242, 107.439,   52.473, 107.460,   84.777, 107.314,  117.048, 107.325,
149.359, 107.294,  181.699, 107.331,  213.876, 107.270,  246.219, 107.205,
278.445, 107.308,
  20.218, 139.755,   52.772, 139.424,   85.022, 139.721,  117.093, 139.573,
149.309, 139.615,  181.727, 139.616,  213.887, 139.590,  246.201, 139.585,
278.454, 139.498,
  20.415, 171.895,   52.737, 171.847,   84.831, 171.819,  117.084, 171.803,
149.366, 171.828,  181.724, 171.859,  213.953, 171.815,  246.173, 171.853,
278.390, 171.825,
  20.309, 204.342,   52.625, 204.186,   84.893, 204.197,  117.122, 204.171,
149.345, 204.099,  181.733, 204.063,  213.944, 204.079,  246.234, 204.045,
278.466, 204.056,
  20.327, 236.448,   52.601, 236.437,   84.789, 236.406,  117.132, 236.364,
149.395, 236.349,  181.685, 236.399,  213.999, 236.440,  246.165, 236.486,
278.482, 236.338,
  20.348, 268.788,   52.630, 268.775,   84.893, 268.695,  117.157, 268.744,
149.417, 268.760,  181.611, 268.689,  213.961, 268.685,  246.152, 268.639,
278.508, 268.645,
  20.318, 301.021,   52.625, 301.042,   84.872, 301.003,  117.127, 300.935,
149.372, 300.958,  181.709, 300.946,  213.959, 300.971,  246.212, 300.944,
278.446, 300.924,
```

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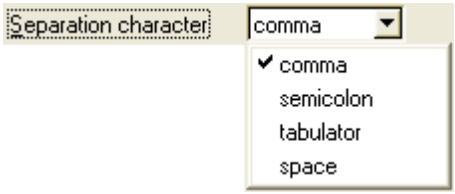
4.2.9 Save Power Distribution Data

The measured intensities in arbitrary units of the spots visible in the Spotfield Panel 52 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.**

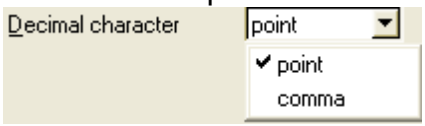


The separation character between the parameter name and the appropriate value can be set to four different characters:



'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 '**Omit Header Data**' is enabled the entire header including the listing of camera, beam and pupil data is omitted and only the power distribution data array is saved.

Choose menu item **File → Save Power Distribution Data** or just press Ctrl + D to save the power distribution 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                   ,       WFS150-5C
Serial Number           ,       M0224955

Date MM-DD-YYYY         ,       06-22-2011
Time HH:MM:SS           ,       10:17:32
```

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```
*** CAMERA ***
Camera Type             ,       Thorlabs DCU224M
Camera SN               ,       4002718538
Resolution X            ,       320
Resolution Y            ,       320
Exposure Time [ms]      ,       0.079
Master Gain             ,       1.000
Averages                ,       10
Average Type            ,       Normal


*** BEAM ***
Beam Center X [mm]      ,       0.003
Beam Center Y [mm]      ,       0.013
Beam Diameter X [mm]    ,       1.671
Beam Diameter Y [mm]    ,       1.668


*** PUPIL ***
Circular                ,       1
Use Beam Centroid       ,       1
Use Beam Dia            ,       0
Wavefront Calc In Pupil,        0
Pupil Diameter X [mm]   ,       1.400
Pupil Diameter Y [mm]   ,       1.400
Pupil Center X [mm]     ,       0.003
Pupil Center Y [mm]     ,       0.013


*** POWER DISTRIBUTION [a.u.] ***
Power points X          ,       7
Power points Y          ,       7
    6398,     7217,     7718,     8002,     7848,     7329,     6621,
    7161,     8132,     8862,     9068,     8898,     8327,     7417,
    7623,     8757,     9498,     9800,     9623,     9192,     8032,
    7911,     9085,     9696,    10105,     9870,     9378,     8261,
    7738,     8839,     9687,     9732,     9762,     9227,     8113,
    7257,     8161,     8802,     9143,     8958,     8341,     7516,
    6494,     7317,     7893,     8088,     7849,     7548,     6761,
```

Spot intensities are saved in arbitrary units and result from summing the camera pixel intensities belonging to a single spot. The upper left corner of the selected camera image size is the origin (point 0,0).

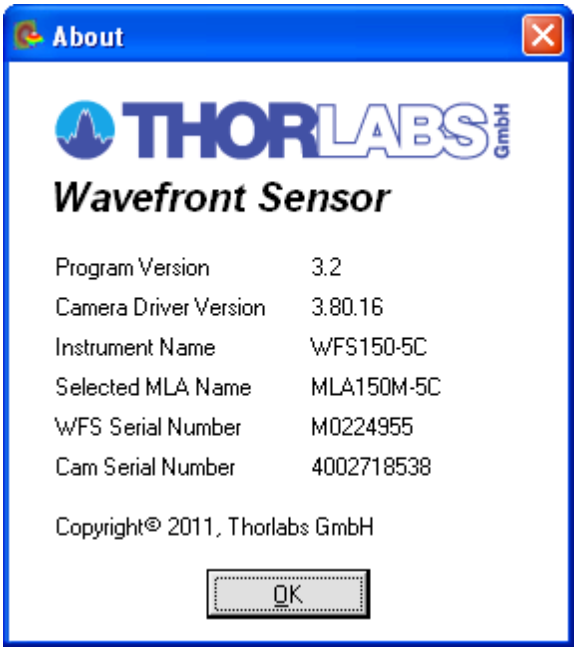
In case the option '**Omit Header Data**' was enabled the file content is limited to the following lines:

```
Power points X          ,       7
Power points Y          ,       7
    6398,     7217,     7718,     8002,     7848,     7329,     6621,
    7161,     8132,     8862,     9068,     8898,     8327,     7417,
    7623,     8757,     9498,     9800,     9623,     9192,     8032,
    7911,     9085,     9696,    10105,     9870,     9378,     8261,
    7738,     8839,     9687,     9732,     9762,     9227,     8113,
    7257,     8161,     8802,     9143,     8958,     8341,     7516,
    6494,     7317,     7893,     8088,     7849,     7548,     6761,
```

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4.2.10 Version and other Program Information

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



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

4.2.11 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.

In addition you might store the complete instrument settings into a *.cfg file. These files containing different Wavefront Sensor configurations can be reloaded to the application software in order to repeat the previously stored measurement conditions.
See chapter Menu and Toolbar 43.

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4.2.12 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.

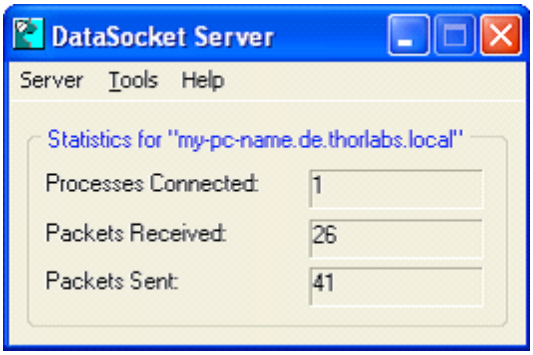
The following explanations are related to the National Instruments® DataSocket server. It comes with the LabWindows/CVI® and LabView® packages or is available from the National Instruments® download website http://digital.ni.com/public.nsf/allkb/40295802535E31B686256E91001859AB .

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

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

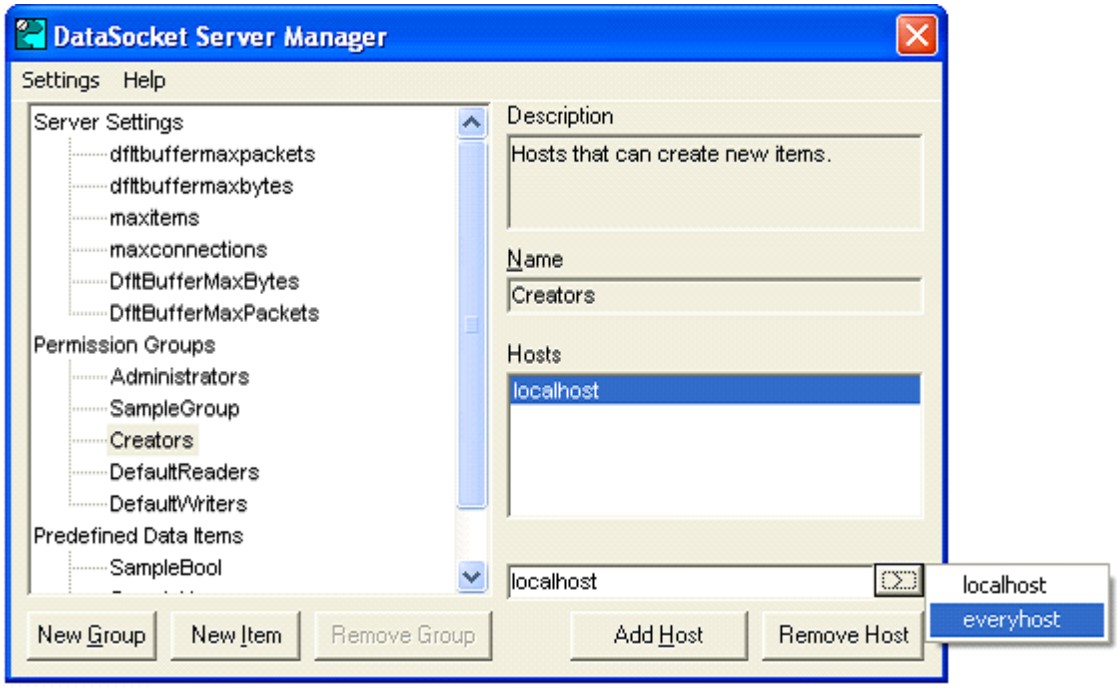


Before using the DataSocket server for Wavefront Sensor data transfer it has to be configured.

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.

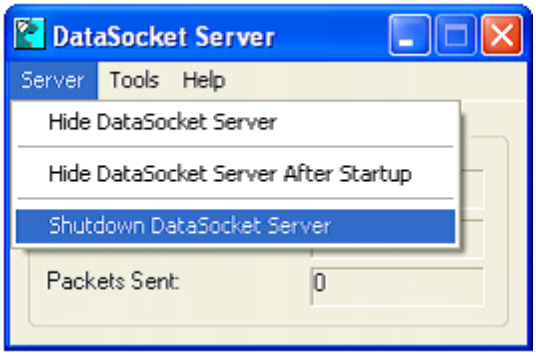
Open the DataSocket Server Manager using **Start → Program Files → National Instruments → DataSocket → DataSocket Server Manager**. Click on 'Creators' and set 'everyhost' to be allowed to create new data items. Repeat this also for the groups 'Default Readers' and 'Default Writers'.



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

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

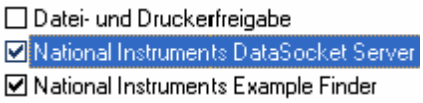


NOTE

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

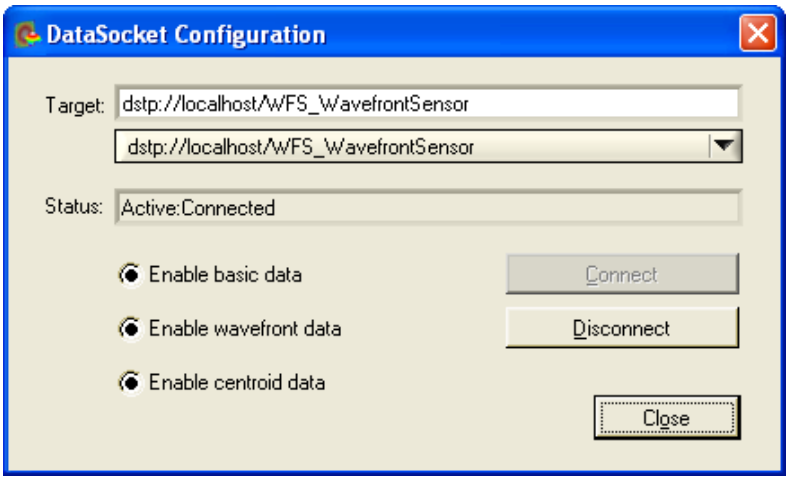
Firewall configuration

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.



4.2.12.1 Configuration Panel

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



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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

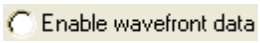
If you want to use a DataSocket server on a separate machine connected via a TCP/IP network you have to start the DataSocket server on the remote machine **first** and configure it according to the description in DataSocket for live data transfer 109. Now type in the correct network name of this computer 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 109).
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



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 112 for a description of the available data items.

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 112 for a description of the available data items.

Enable wavefront data



When this check box is marked the software will automatically send the entire centroid data arrays (for x- and y coordinates separately) to the DataSocket server. Because the amount of data can be considerably it can be disabled to increase transfer speed. See Available Data Items 112 for a description of the available data items.

4.2.12.2 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.

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Wavefront Sensor settings are:

Data Item	Format	Unit / example
Instrument_Name	string	e.g. "WFS150-5C 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

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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	required array size in x direction (2nd index)
Wavefront_Spots_Y	short	required array size in y direction (1st index)
Wavefront	float array	(unit according to Wavefront_Unit_Um_Waves)

When '**Enable centroid data**' is checked on the DataSocket configuration panel the raw spot centroid data arrays from the actual Wavefront Sensor measurement are sent to the DataSocket server.

Data Item	Format	Unit / example
Centroids_X	short	required array size in x direction (2nd index)
Centroids_Y	short	required array size in y direction (1st index)
Centroid_Pos_X	float array	centroid x-coordinates in [pixels]
Centroid_Pos_Y	float array	centroid y-coordinates in [pixels]

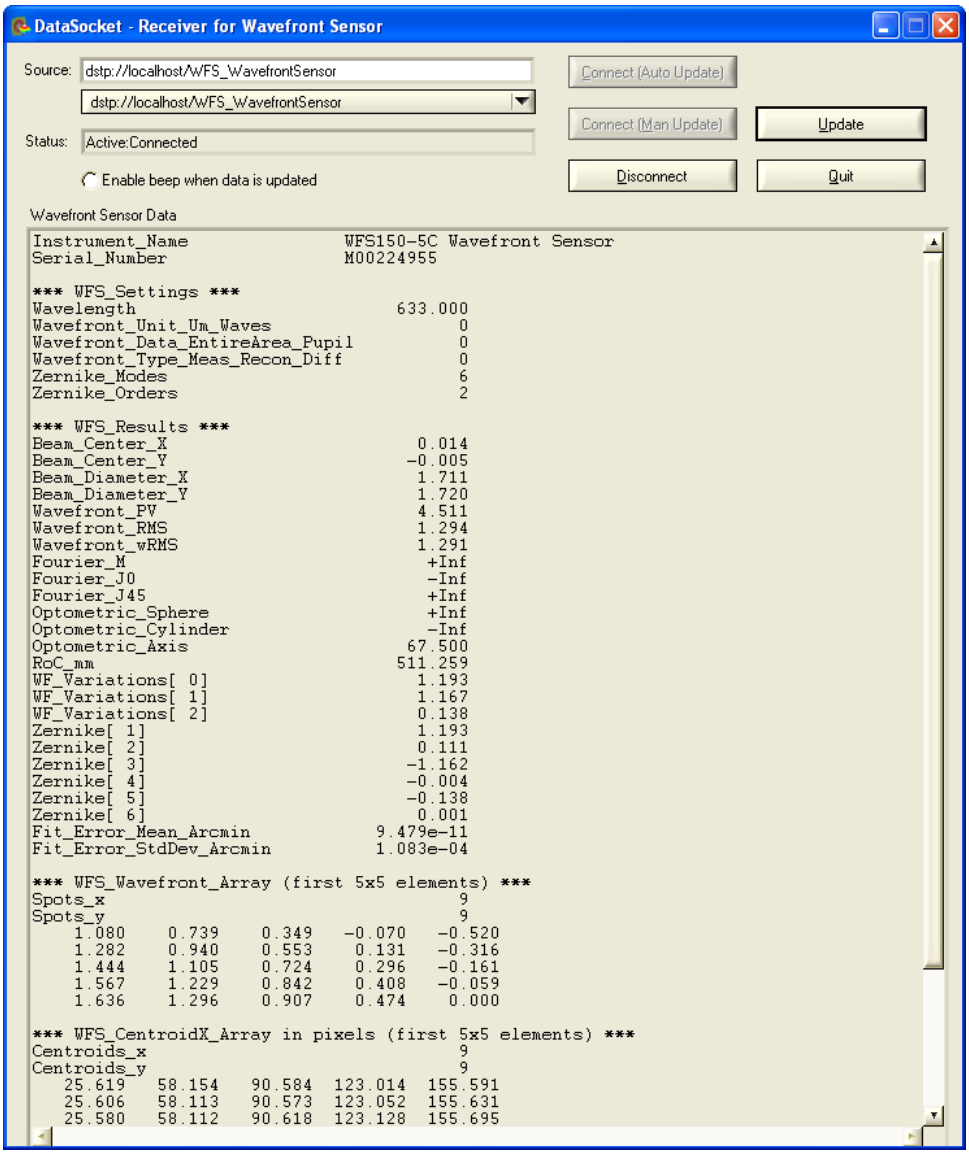
Both x and y centroid arrays contain spot coordinates, the unit is pixels. Lowest indices are related to the upper left corner of the selected camera image size.

NOTE
Format of Centroid_Pos_X and Centroid_Pos_Y data arrays was changed in software release 2.0 from double to float!

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4.2.12.3 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.

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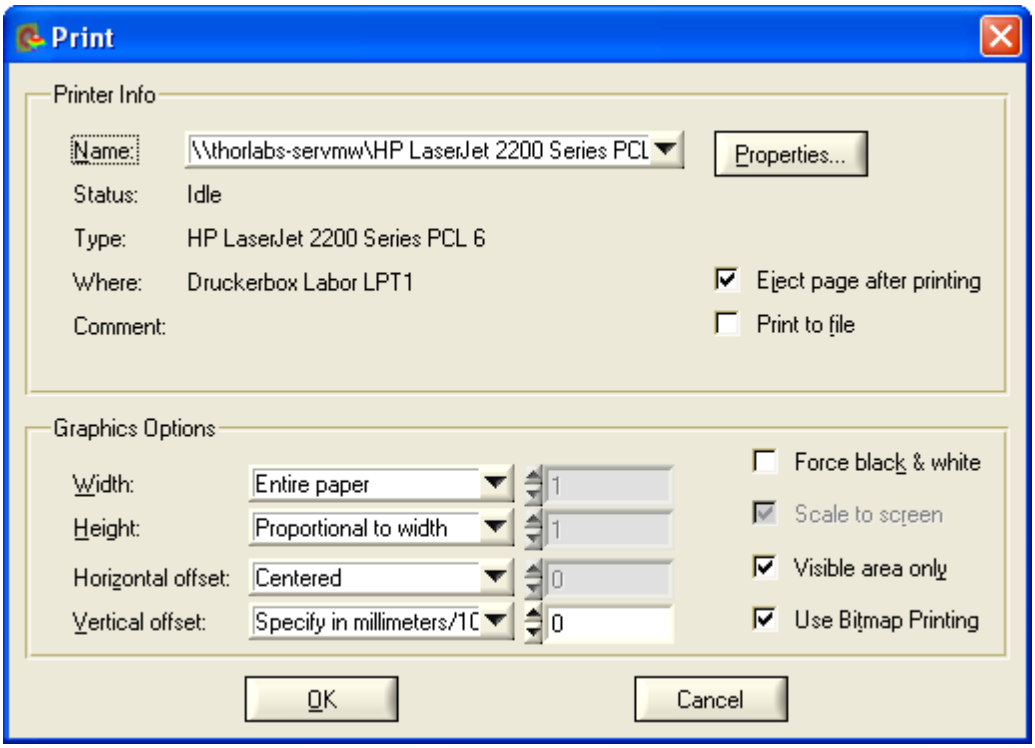
4.2.13 Printing

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

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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.

5 Service and Maintenance

5.1 Service

In normal operation the WFS series Wavefront Sensors 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 WFS series Wavefront Sensors after a period of time.

5.2 Troubleshooting

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

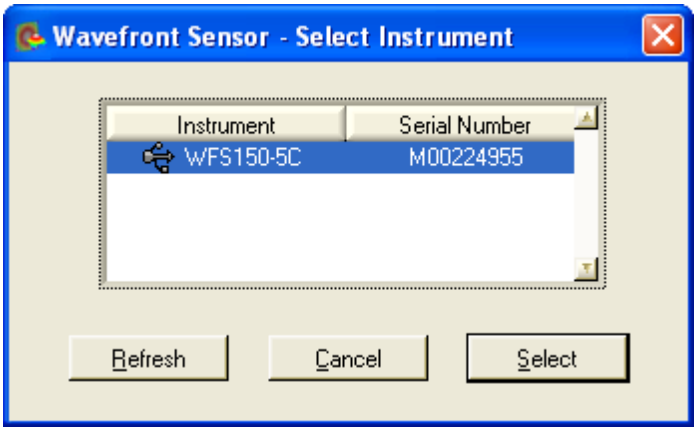
- Look if the Wavefront Sensor is connected to the USB 2.0 port of the PC by the delivered USB 2.0 cable. The LED at the back of the Wavefront Sensor will indicate the instrument state:
  - LED = off USB cable or USB port is defect
  - LED = red Sensor not recognized by the Windows system, install the Wavefront Sensor drivers (see Software Installation 10)
  - LED = green Wavefront Sensor is properly installed an 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 17.

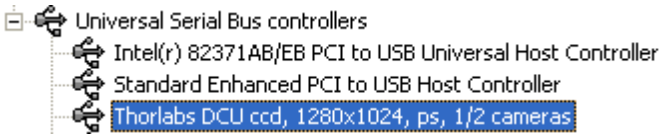
- Be sure to have administrative rights on your computer which enables you to install software at all. Ask your system administrator to give you such rights or to do the installation himself.

- 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.

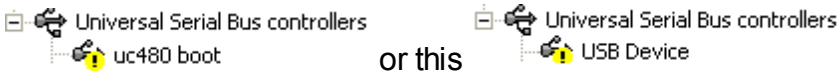
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For verification purposes you might check the existence of this instrument in the device manager of your computer. From the Start button select **Settings → System Control → System → Hardware → Device Manager**. The following entry under 'USB Devices'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

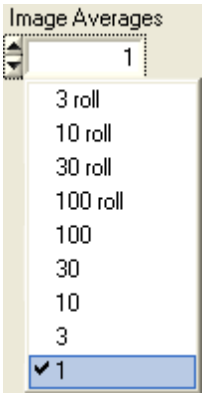
- Perhaps the measurement has been stopped. Look at the message window of the Wavefront Sensor GUI (right down). If there is a message like this



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.

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Go to the Camera Settings Setup 67 panel and select a small number of averages.

- There is probably the trigger functionality activated but no trigger signal applied. Check the 'Hardware Trigger' control within the Camera Settings Setup 67 and see the Trigger Input 130 chapter for correctly applying a trigger signal.



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.

4. **Erroneous or no measurement data**
   - Check the correct Microlens Array (MLA) selection in the Wavefront Setup 79, probably you have physically installed a different MLA than selected within the WFS software.

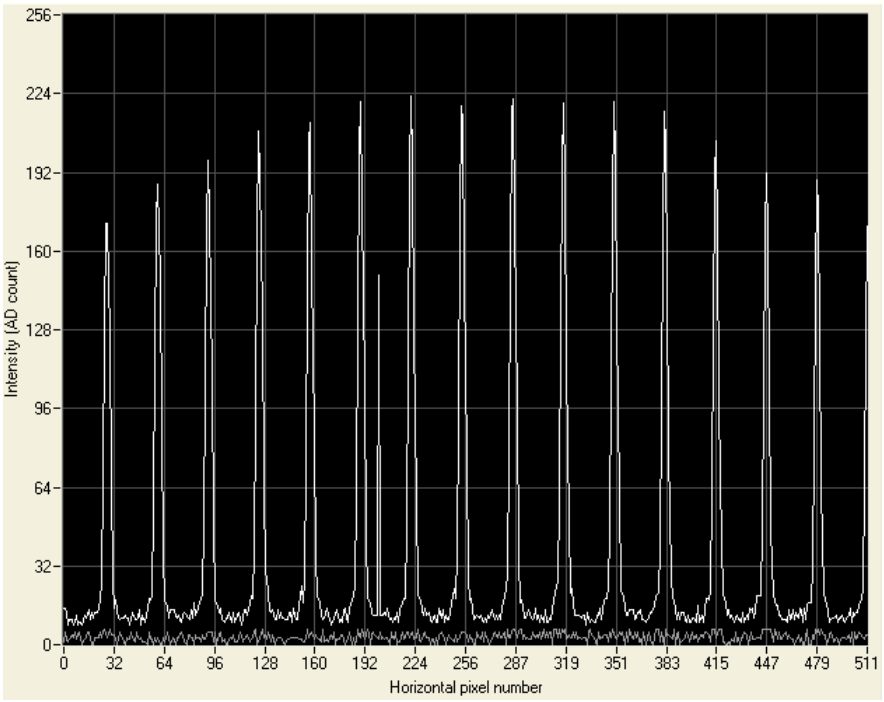
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5.3 Hot Pixel

Every digital camera can have a few ‚hot pixels' which are defective pixels showing an intensity that is not proportional to the amount of absorbed light. Often, such pixels appear brighter than ambient pixels, in rare cases also darker. Its appearance depends strongly on exposure time and ambient temperature.

All cameras used for the Thorlabs series Wavefront Sensors have a hot pixel correction already included which reduces such effects to a minimum.

Due to a long lifetime and temperature cycles the WFS cameras may show new hot pixels which didn't appear during factory calibration. Although such single pixel defects do not degrade the WFS accuracy noticeably, functions like the automatic exposure control may be influenced.



New hot pixel, visible in Lineview panel at horizontal position 200

In case a new, stable and strong hot pixel (more than 50 digits intensity deviation to ambient pixels) becomes visible whether in panels 'Lineview' or 'Spot Field', you may send your WFS instrument back to Thorlabs in order to repeat the hot pixel correction.
Please contact your local Thorlabs office 148 for return instructions.

The CMOS camera used for the WFS10 series instruments is much faster but shows a higher noise level and less image uniformity. In addition, there are sporadic hot pixels appearing rarely at a random image position. Such single pixel defects are visible only momentarily within a single camera frame and do not lead to a violation of the instrument's specification.
The appearance of such sporadic hot pixels cannot be corrected and is no reason for return the instrument.

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6 Appendix

6.1 Certifications and Compliances

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

Wavefront Sensor
WFS150-5C, WFS150-7AR, WFS300-14AR,
WFS10-5C, WFS10-7AR, WFS10-14AR

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.		

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6.2 Warranty

Thorlabs warrants material and production of the WFS series 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.

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6.3 Technical Data

All technical data are specified at 23 ± 5°C and 45 ± 15% rel. humidity

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

WFS150/300 Wavefront Sensor Specifications

Item #	WFS150-5C	WFS150-7AR	WFS300-14AR
Aperture Size	5.95 mm x 4.76 mm Max		
Camera Resolution	**1280 x 1024 Pixels Max, Selectable**		
Detector Array Type	CCD		
Pixel Size	4.65 µm x 4.65 µm		
Shutter	Global		
Number of Active Lenslets	Selectable by Software, Depending on Microlens Array		
Max Number of Active Lenslets	39 x 31		19 x 15
Wavefront Accuracy a)	λ/15 rms @ 633 nm		λ/50 rms @ 633 nm
Wavefront Sensitivity b)	λ/50 rms @ 633 nm		λ/150 rms @ 633 nm
Wavefront Dynamic Range c)	>100λ @ 633 nm		>50λ @ 633 nm
Local Wavefront Curvature d)	>7.4 mm	>10 mm	>40 mm
Exposure Range	79 µs - 65 ms		
Frame Rate	**15 Hz Max**		
Image Digitization	8 bit		
Optical Input Connector	C-Mount		
Physical Size (H x W x D)	34 mm x 32 mm x 45.5 mm		
Power Supply	<1.5 W, via USB		

a) Absolute accuracy using internal reference. Measured for spherical wavefronts of known RoC.
b) Typical relative accuracy. Achievable after, and with respect to a user calibration, 10 image averages
c) Over entire aperture of wavefront sensor
d) Radius of wavefront curvature over single lenslet aperture

See Microlens Data 125 for detailed specifications of the supplied mounted Microlens Arrays.

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WFS10 Wavefront Sensor Specifications

Item #	WFS10-5C	WFS10-7AR	WFS10-14AR
Aperture Size	6.34 mm x 4.76 mm. Max		
Camera Resolution	640 x 480 Pixels Max, Selectable		
Detector Array Type	CMOS		
Pixel Size	9.9 µm x 9.9 µm		
Shutter	Global		
Number of Active Lenslets	Selectable by Software, Depending on Microlens Array		
Max Number of Active Lenslets	41 x 29		19 x 13
Wavefront Accuracy a)	λ/10 rms @ 633 nm		λ/30 rms @ 633 nm
Wavefront Sensitivity b)	λ/30 rms @ 633 nm		λ/100 rms @ 633 nm
Wavefront Dynamic Range c)	>100λ @ 633 nm		>50λ @ 633 nm
Wavefront Slope d)	±1.0° Max	±0.8° Max	±0.5° Max
Local Wavefront Curvature e)	>7.4 mm	>10 mm	>40 mm
Exposure Range	33 µs - 500 ms		
Frame Rate at Resolution 640 x 480 in Normal Mode f)	55 Hz		70 Hz
Frame Rate at Resolution 640 x 480 in High Speed Mode f)	175 Hz		
Frame Rate at Resolution 180 x 180 f)	450 Hz		
Image Digitization	8 bit		
Optical Input Connector	C-Mount		
Physical Size (H x W x D)	32 mm x 45 mm x 51.5 mm		
Power Supply	<1.6 W, via USB		

a) Absolute accuracy using internal reference. Measured for spherical wavefronts of known RoC.
b) Typical relative accuracy. Achievable after, and with respect to a user calibration, 10 image averages.
c) Over entire aperture of wavefront sensor, normal mode.
d) max. local wavefront slope qmax in high speed mode.
e) Radius of wavefront curvature over single lenslet aperture.
f) Typical speed without graphical display, depending on PC hardware, 5th order Zernike fit at specific camera resolution, min. exposure time.

See Microlens Data 125 for detailed specifications of the supplied mounted Microlens Arrays.

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6.3.1 Microlens Data

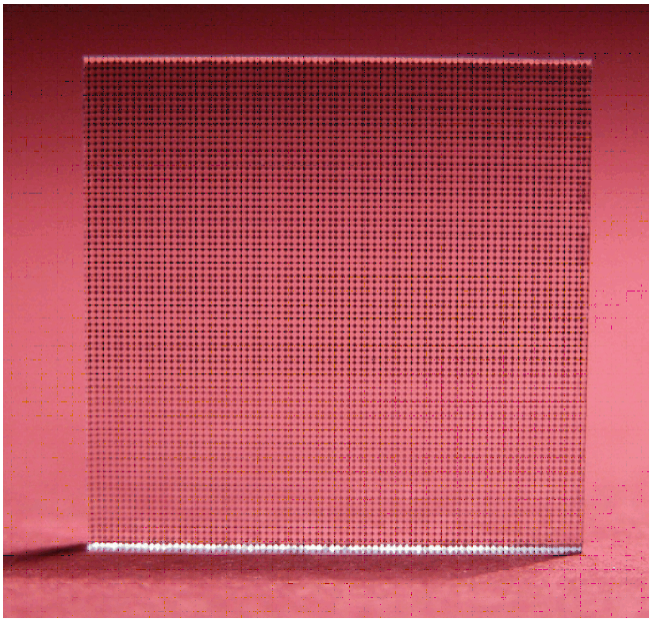
The Thorlabs uses high-quality microlens arrays for its WFS series Wavefront Sensors which are best suited for Shack-Hartmann Wavefront Sensor applications. All lenslets are made from fused silica for excellent transmission characteristics from the deep UV to IR and have a plano-convex shape that allows 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 three Wavefront Sensor models WFS150-5C, WFS150-7AR, WFS300-14AR and the corresponding fast models WFS10-5C, WFS10-7AR, WFS10-14AR utilize the mounted (M) microlens arrays MLA150M-5C, MLA150M-7AR and MLA300M-14AR, respectively.

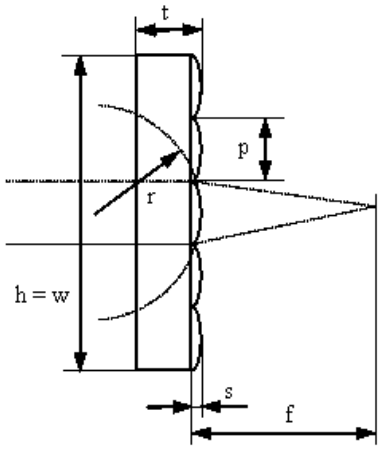
The MLA150M-5C has a chrome mask that blocks light from being transmitted unless it goes through a microlens and therefore increases image contrast. The MLA150M-7AR and MLA150M-14AR have a broadband AR coating to reduce surface reflections in the 400-900nm spectral region to below 1%.

Microlens Array MLA150-5C (without mounting)



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Geometric Parameters of the MLA Series (without mounting)



Parameter	MLA150-5C	MLA150-7AR	MLA300-14AR
h, w	10 mm	10 mm	10 mm
t	1,24 mm	1,19 mm	1,20 mm
p	150 µm	150 µm	300 µm
s	1,12 µm	0,87 µm	1,31 µm
r	2,380 mm	3,063 mm	8,6 mm
f	5,2 mm	6,7 mm	18,6 mm

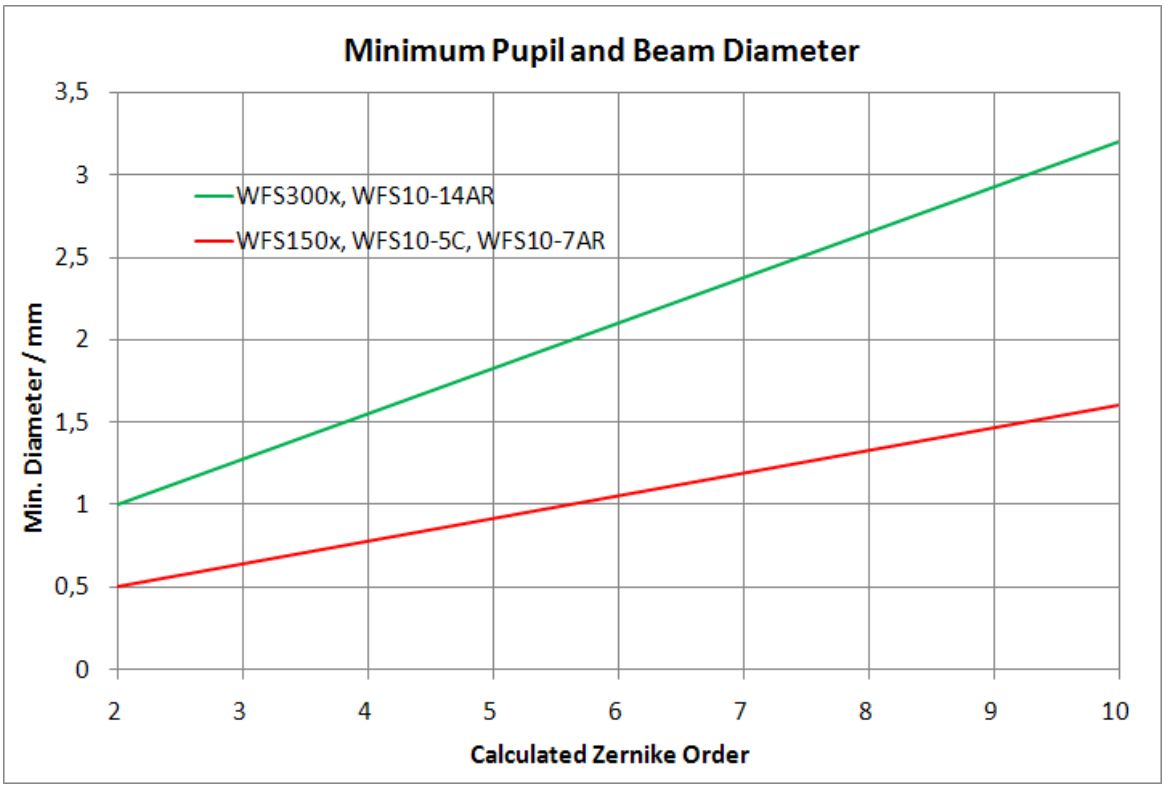
Specifications of the MLA Series

Items #	WFS150-5C/ WFS10-SC	WFS150-7AR/ WFS10-7AR	WFS300-14AR/ WFS10-14AR
Microlens Array	**MLA150M-5C**	**MLA150M-7AR**	**MLA300M-14AR**
Substrate Material	Fused Silica (Quartz)		
Wavelength Range	**300 - 1100 nm**	**400 - 900 nm**	**400 - 900 nm**
Free Aperture	Ø9 mm		
Lenslet Grid Type	Square Grid		
Lenslet Pitch	150 µm		300 µm
Lens Shape	Round, Plano Convex Spherical		Square, Plano Convex Parabolic
Lens Diameter	146 µm		300 µm
Coating	Chrome Masked	Anti Reflection	
Reflectivity	<25%	<1%	<1%
Nominal Focal Length	5.2 mm	6.7 mm	18.6 mm
Effective Focal Length	**3.7 mm**	**5.2 mm**	**14.2 mm**
Array Size	10 mm x 10 mm x 1.2 mm		

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6.3.2 Minimal Beam and Pupil Diameter

The detection of higher order wavefront terms up to a certain Zernike order requires a minimum number of detected microlens spots. The minimum number of spots must equal or exceed the number of Zernike modes to be calculated. See chapter Zernike Fit and Zernike Modes 137.
Consequently, this minimum number of spots requires a beam and pupil diameter of minimal size. The following graph shows the dependency for both available microlens arrays of 150 and 300 µm pitch.



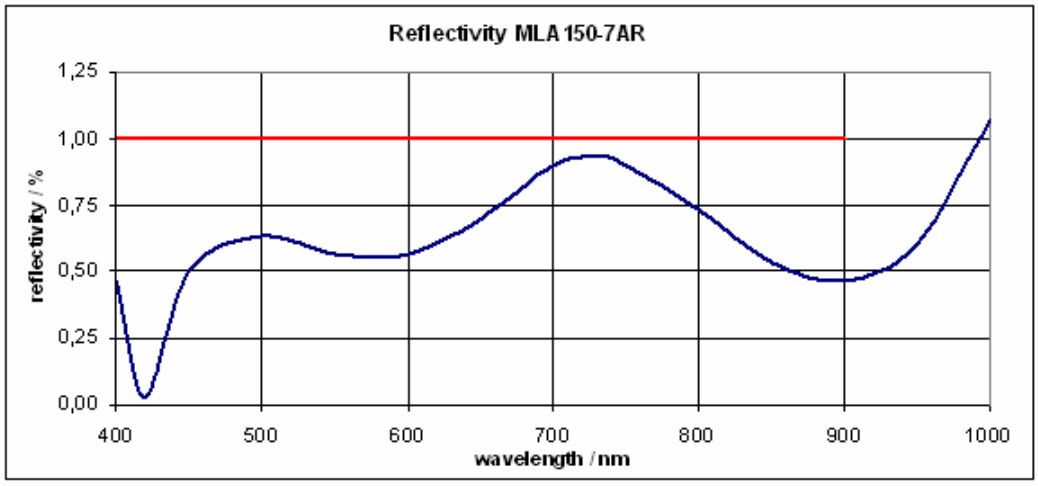
For a desired Zernike order you need to set the pupil to the required diameter within the Pupil Definitions Setup 76. Also your physical beam diameter needs to illuminate at least the same camera area so that the required number of spots can be detected.
In case of unfavorable pupil settings, warnings or errors may occur. See chapter Measurement Warnings and Errors 91 for a detailed description and suited arrangements for its prevention.

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6.3.3 Typical Wavelength Curves

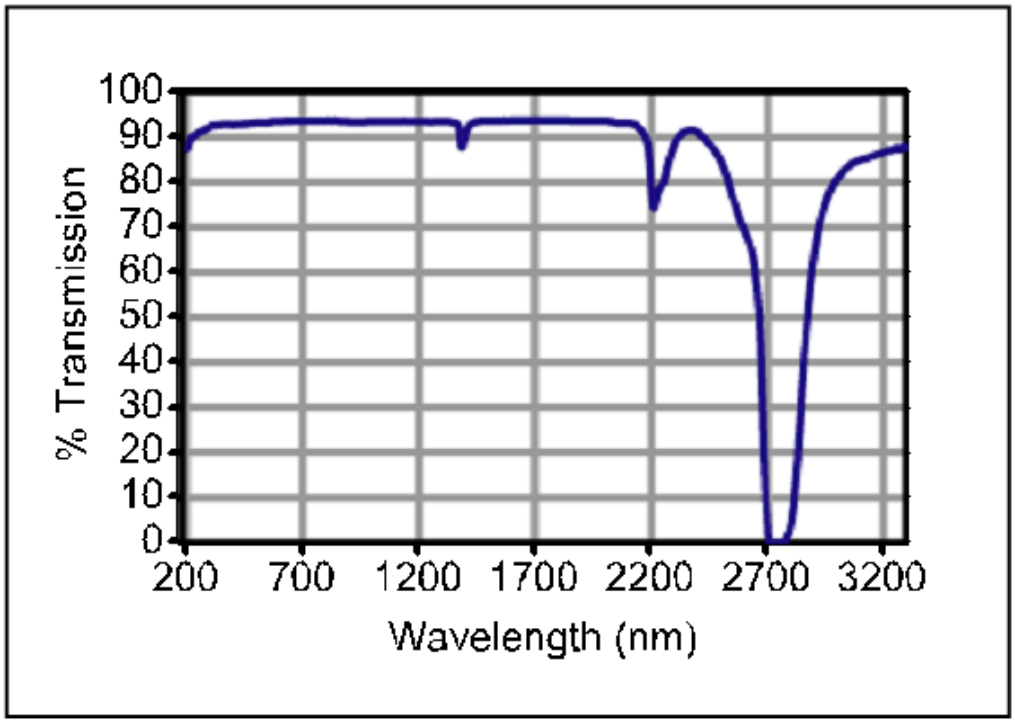
Wavefront Sensor WFS150-7AR and WFS300-14AR contains an anti reflection coated (AR) lenslet array. The following diagram shows the typical reflectivity of the lenslet array. Its guaranteed reflectivity in the wavelength range 400 to 900 nm is below 1%.

Reflectivity of MLA150-7AR and MLA300-14AR including AR - Coating



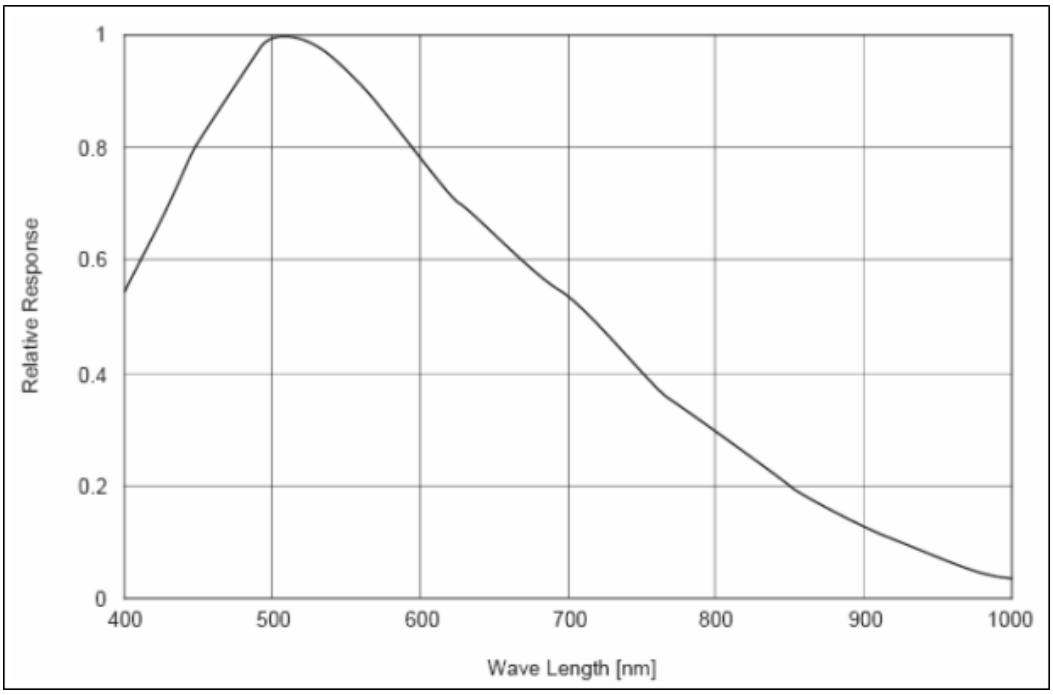
Note: The total reflectivity of the WFS series instruments may be higher due to reflections from the CCD/CMOS camera chip and its covering window.

Typical Transmission of Fused Silica Material

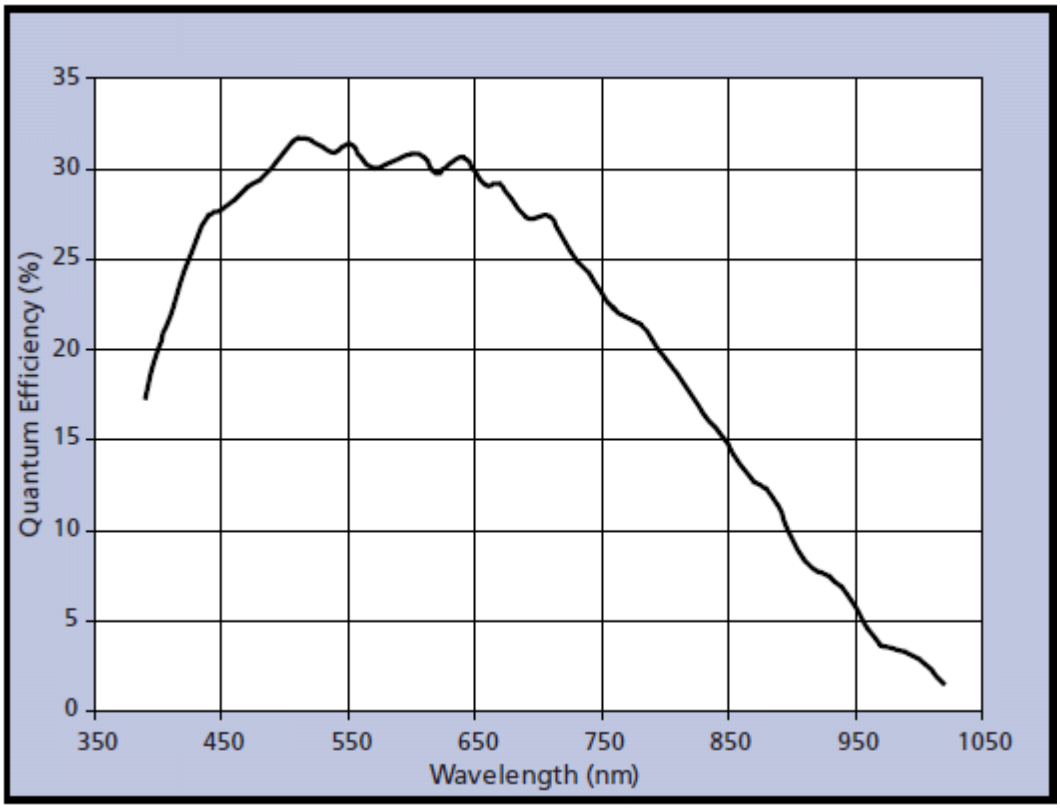


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Typical Response of the WFS CCD camera



Typical Response of the WFS10 CMOS camera



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6.3.4 Trigger Input WFS

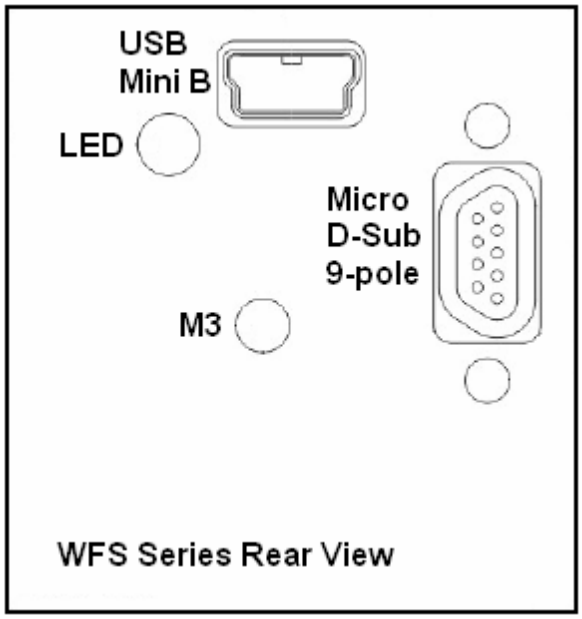
Trigger Input Specifications

Parameter	Min	Max
Low level	0 V	2 V
High level	5 V	24 V
Input voltage range	0 V	30 V
Pulse width	100 µs	
Slew rate	35 V / ms	
Input current		10 mA

AttentionAttention

Do not apply voltages exceeding the given specifications, you may damage the WFS instrument!

The trigger input of the WFS series instruments is placed at the rear side of the camera housing. Besides the standard USB Mini B connector which is normally used to connect the WFS to a PC a second 9-pole Micro D-Sub connector is available for trigger input.



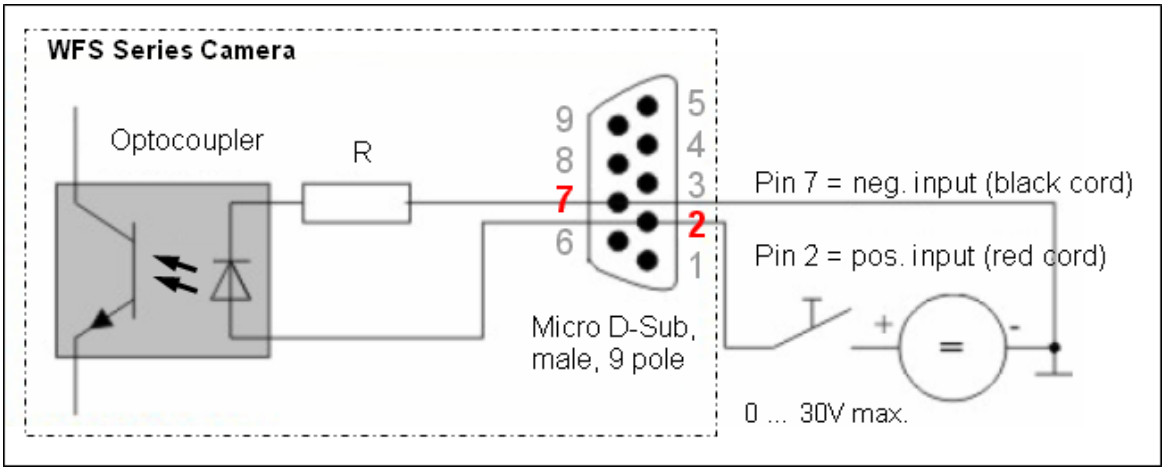
Note: For using the trigger input you need to **replace the standard USB cable** supplied with the WFS instrument with the optionally available combined **USB / Trigger Cable CAB-DCU-T2** which needs to be connected to the Micro D-Sub jack.

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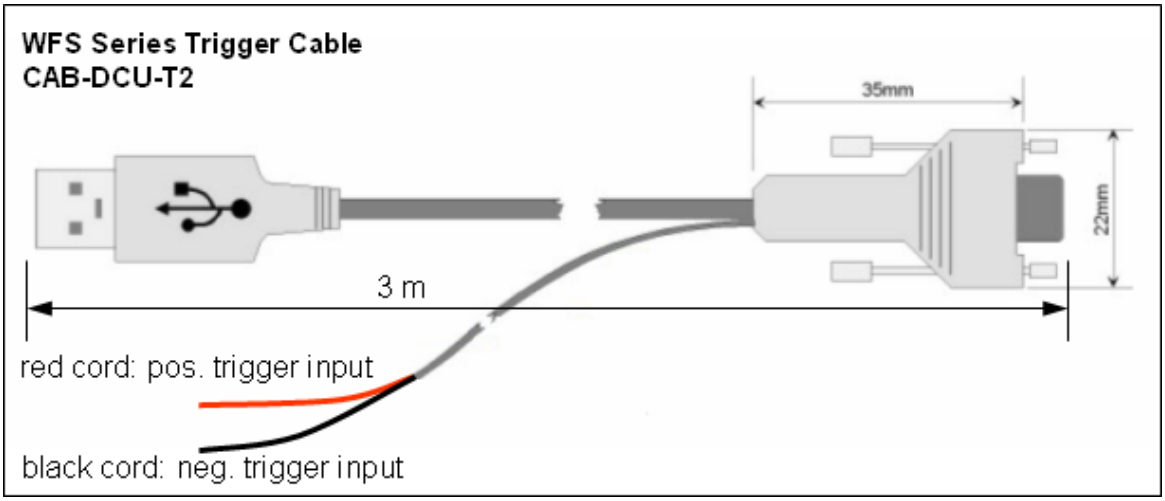
Attention

Do not operate the WFS instrument with both USB cables connected, you may damage the Wavefront Sensor and your computer!

The following drawing shows how to connect the trigger source to the Micro D-Sub jack.



Apply your trigger source to the free cords of the combined USB / Trigger Cable **CAB-DCU-T2** according to the following drawing:



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6.3.5 Trigger Input WFS10

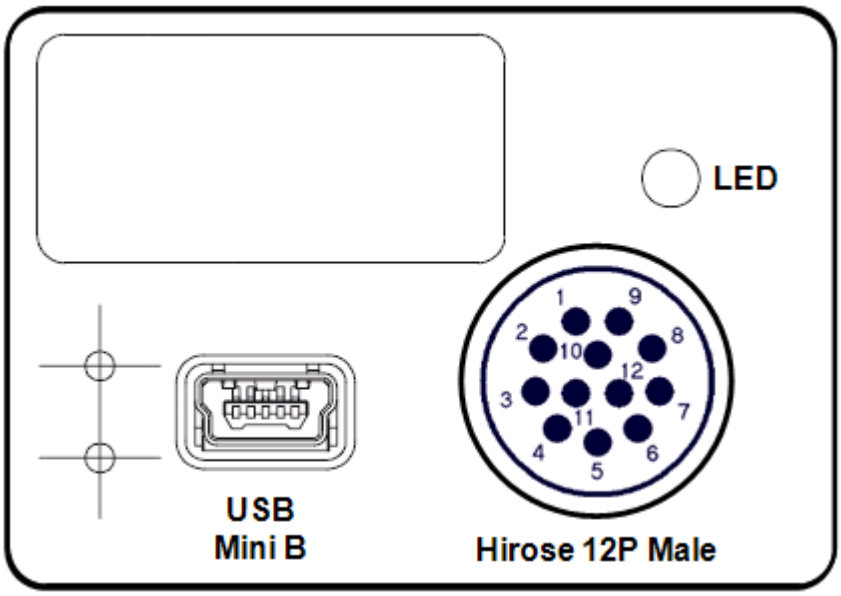
WFS10 Trigger Input Specifications

Parameter	Value
Save static voltage level	-0.5V ≤ U ≤ 6.5V
Max. low level	1.5 V
Min. high level	3.5 V
Input impedance	> 100 k
Min. pulse width	10 µs
Min. slew rate	5 ns/V
Applicable safety standards	IEC 61000-4-2 (ESD 15kV air, 8kV contact) IEC 61000-4-5 (Lightning 12A 8/20µs) IEC 61000-4-4 (EFT 40A 5/50ns)

Attention

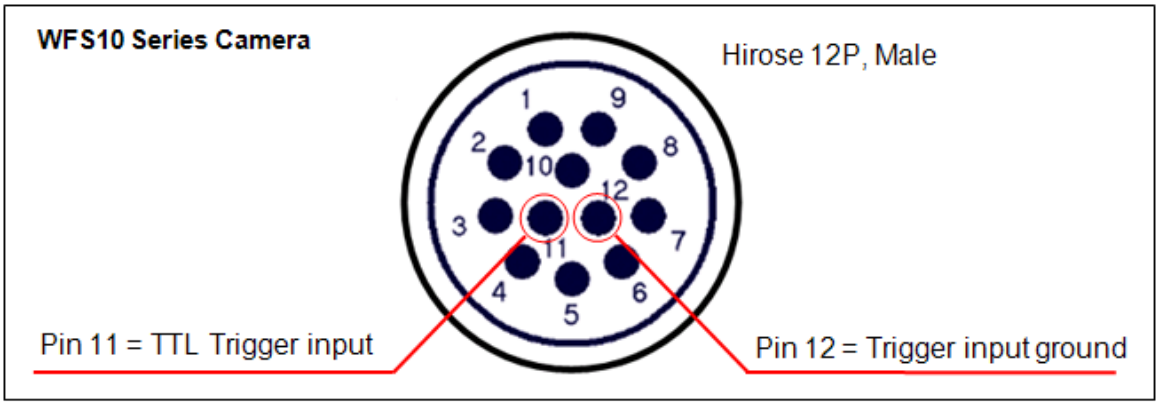
Do not apply voltages exceeding the given specifications, you may damage the WFS10 instrument!

The trigger input of the WFS10 series instruments is placed at the rear side of the camera housing. Besides the standard USB Mini B connector there is a 12-pole Hirose connector available for trigger input.

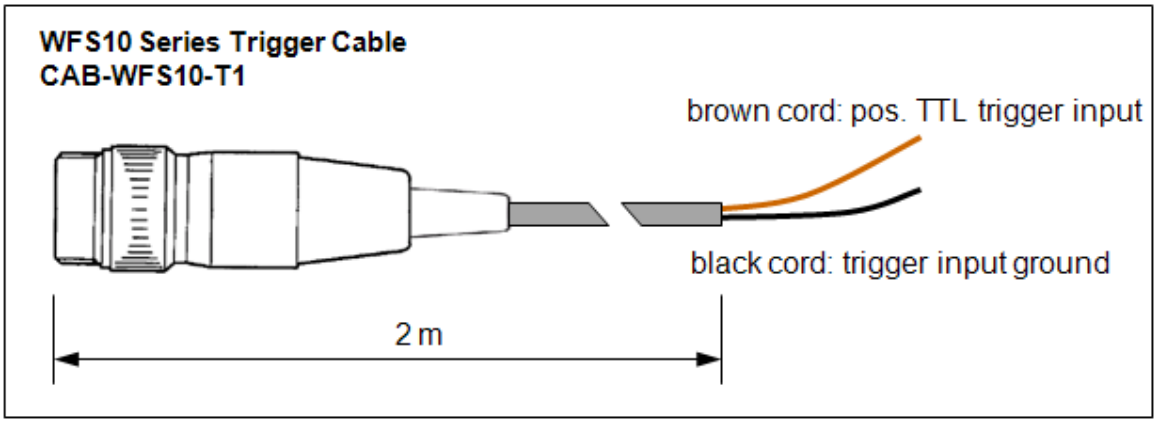


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The following drawing shows how to connect the trigger source to the Hirose jack.



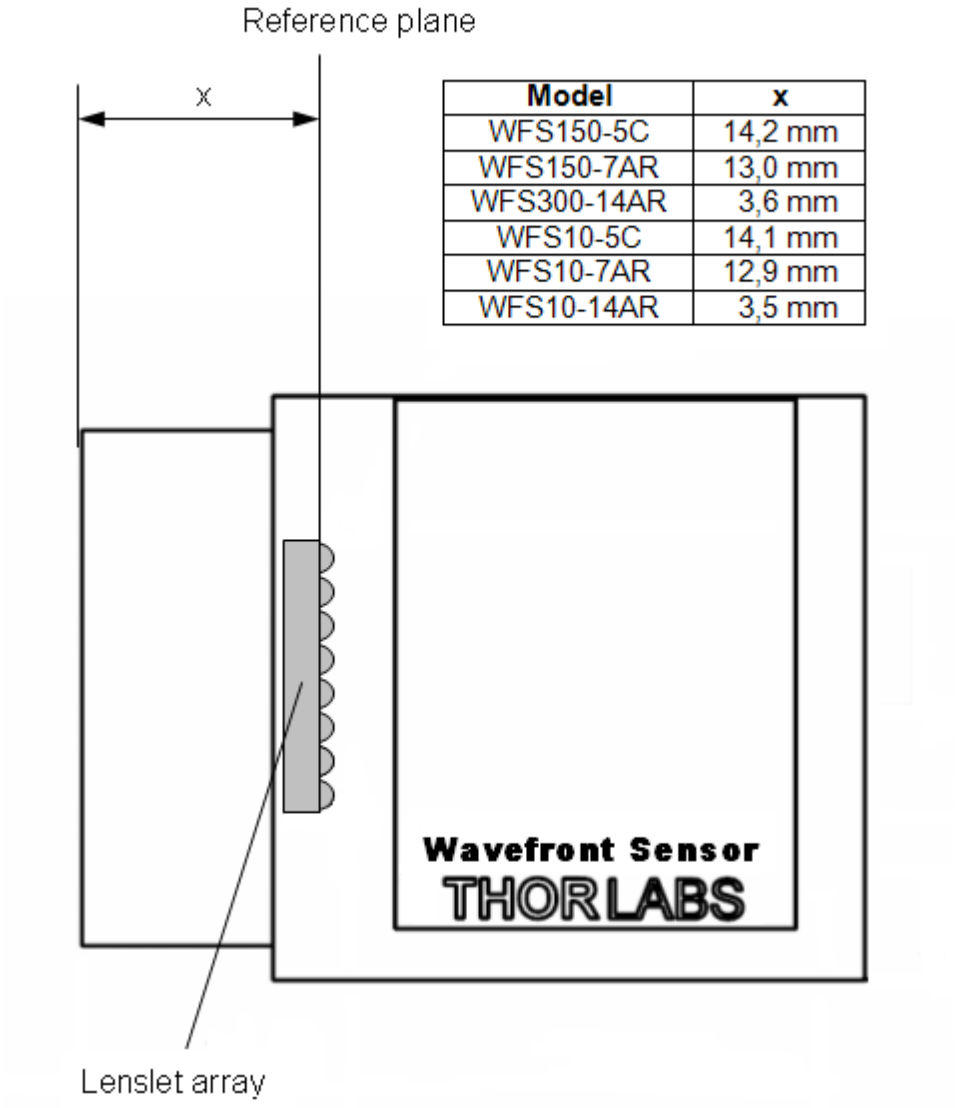
Apply your trigger source to the free cords of the Trigger Cable **CAB-WFS10-T1** according to the following drawing:



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6.3.6 Reference Position

Wavefront data calculated by the Thorlabs WFS series Wavefront Sensors 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.

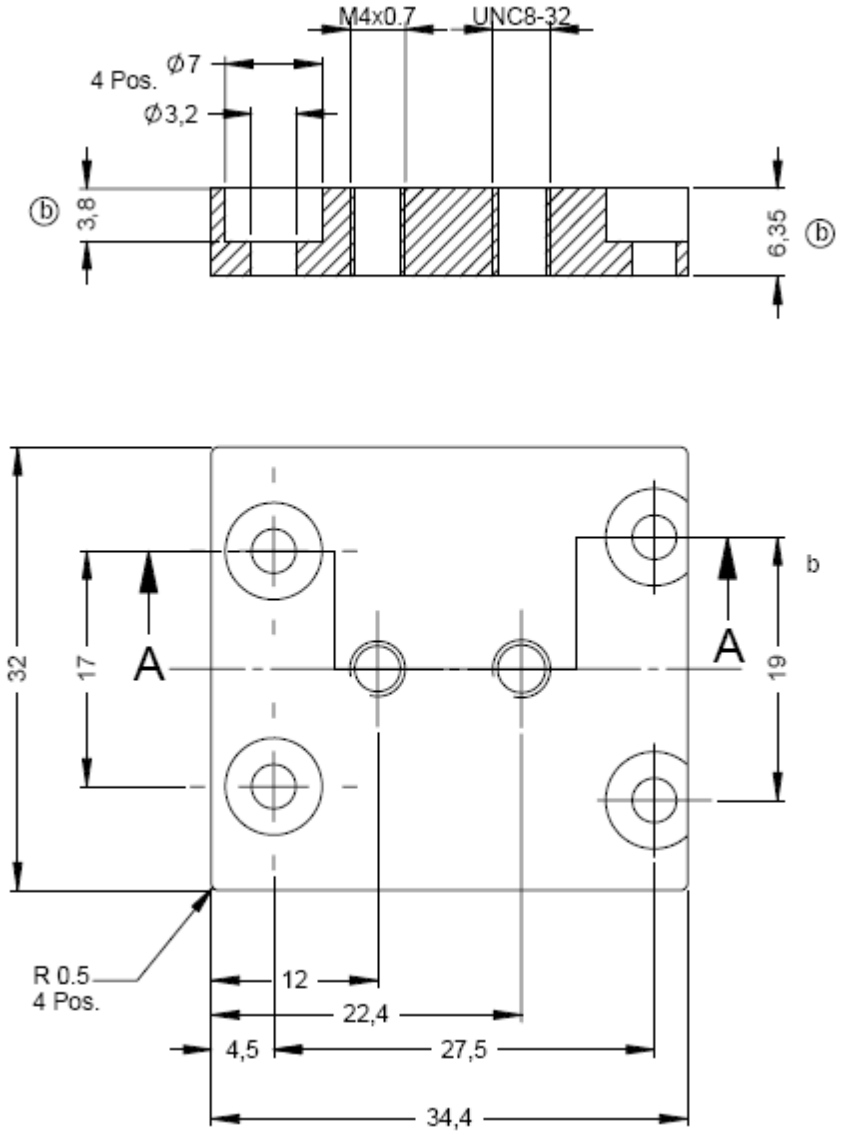


Model	x
WFS150-5C	14,2 mm
WFS150-7AR	13,0 mm
WFS300-14AR	3,6 mm
WFS10-5C	14,1 mm
WFS10-7AR	12,9 mm
WFS10-14AR	3,5 mm

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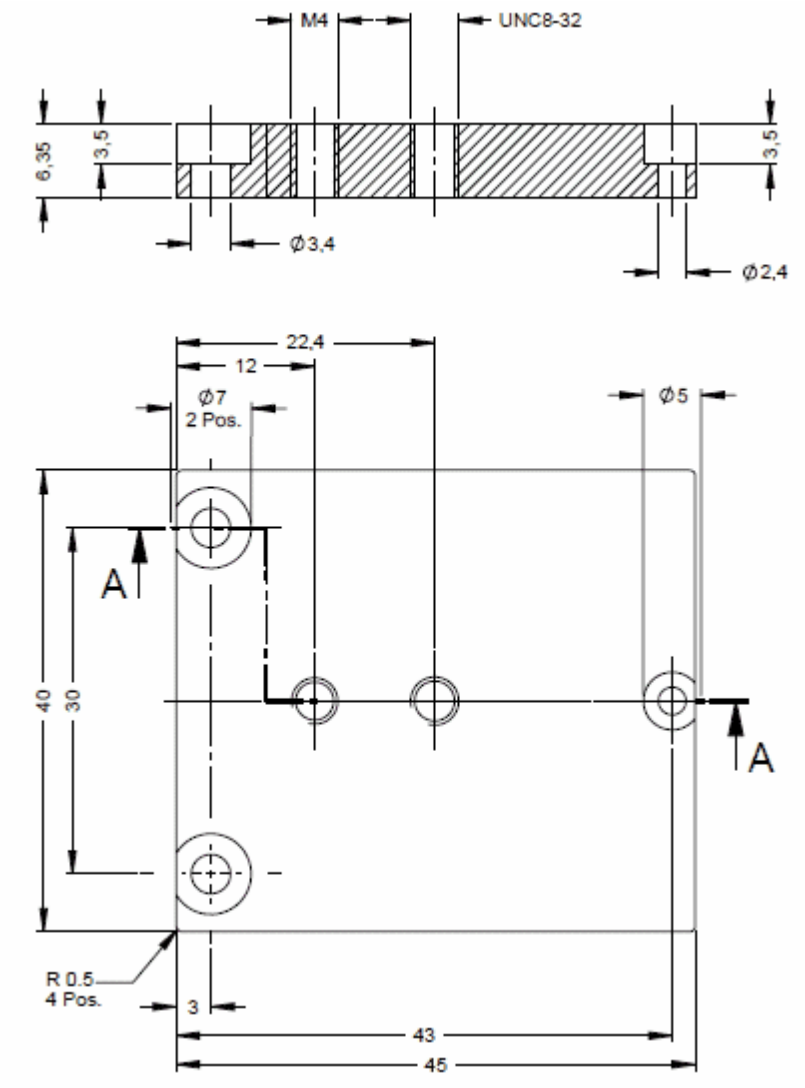
6.3.7 Mounting Adapter

A mounting adapter is added to each WFS Wavefront Sensor in order to supply standard threads M4 and UNC8-32 which are compatible to the palette of Thorlabs' mounts and posts holders.
This adapter plate is already mounted to the bottom side of the Wavefront Sensor using the 4 screws M3x6 (WFS) or 3 screws M3x6 and 1x M2x6 (WFS10). You can remove this adapter plate if it is not required.



WFS Adapter Plate

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WFS10 Adapter Plate

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6.3.8 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 = ρ/a with ρ as polar radial dimension and a as the pupil radius. Rectangular coordinates are x any y both normalized to unit radius 1.

$$R_n^m(r)\cos m\theta, \ldots r \le 0, |r| \le 1$$
$$R_n^m(r)\sin m\theta, \ldots r > 0, |r| \le 1$$

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.

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

Note: The WFS software uses a **slightly different numbering of the frequency column**. See the following table which is fully conform to the WFS software definitions:

Mode No.	Order	Freq.	Name	Norm	Zernike Polynomial, cartesian
1	0	0	Piston	1	1
2	1	-1	Tip y	2	y
3	1	1	Tilt x	2	x
4	2	-2	Astigmatism +-45°	$\sqrt{6}$	$2*x*y$
5	2	0	Defocus	$\sqrt{3}$	$2*x^2 + 2*y^2 - 1$
6	2	2	Astigmatism 0/90	$\sqrt{6}$	$x^2 - y^2$
7	3	-3	Trefoil y	$2\sqrt{2}$	$3*x^2*y - y^3$
8	3	1	Coma x	$2\sqrt{2}$	$3*x^2*y + 3*y^3 - 2*y$
9	3	1	Coma y	$2\sqrt{2}$	$3*x^3 + 3*x*y^2 - 2*x$
10	3	3	Trefoil x	$2\sqrt{2}$	$x^3 - 3*x*y^2$
11	4	-4	Tetrafoil y	$\sqrt{10}$	$4*x^3*y - 4*x*y^3$
12	4	-2	Sec. Astigmatism y	$\sqrt{10}$	$8*x^3*y + 8*x*y^3 - 6*x*y$
13	4	0	Spherical Aberr. 3	$\sqrt{5}$	$6*x^4 + 12*x^2*y^2 + 6*y^4 - 6*x^2 - 6*y^2 + 1$
14	4	2	Sec. Astigmatism x	$\sqrt{10}$	$4*x^4 + 4*x^3*y - 3*x^2 - 4*x*y^3 - 4*y^4 +3*y^2$
15	4	4	Tetrafoil x	$\sqrt{10}$	$x^4 - 6*x^2*y^2 + y^4$

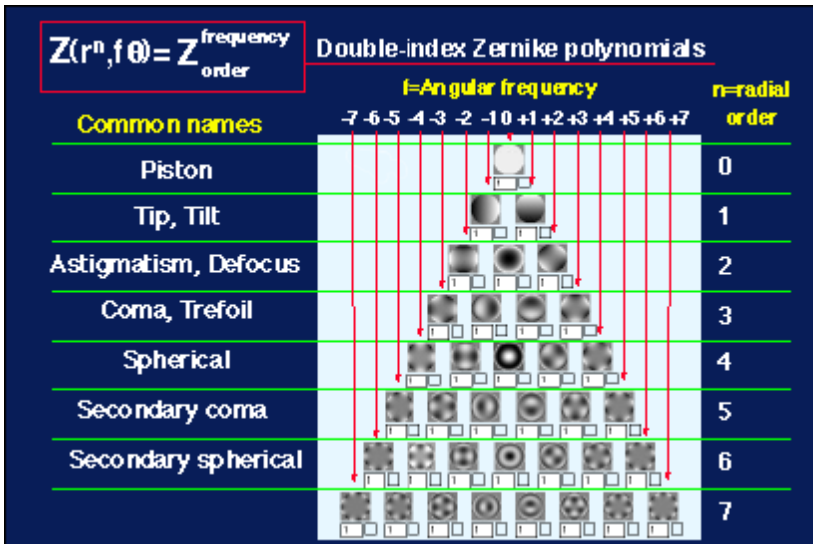
In contrast to the table from Malacara positive and negative frequencies are switched in sign to get a more natural order.

Normalization factor

A normalization factor ‘Norm’ is used to convert the orthogonal set of Zernike polynomials into a set of orthonormal functions having a 'Unity Variance' which means that each normalized function has become a RMS variation of 1.
That is, the total measured wavefront variation for a particular mode is:
WFS_Coefficient * Norm_Factor * Zernike function.

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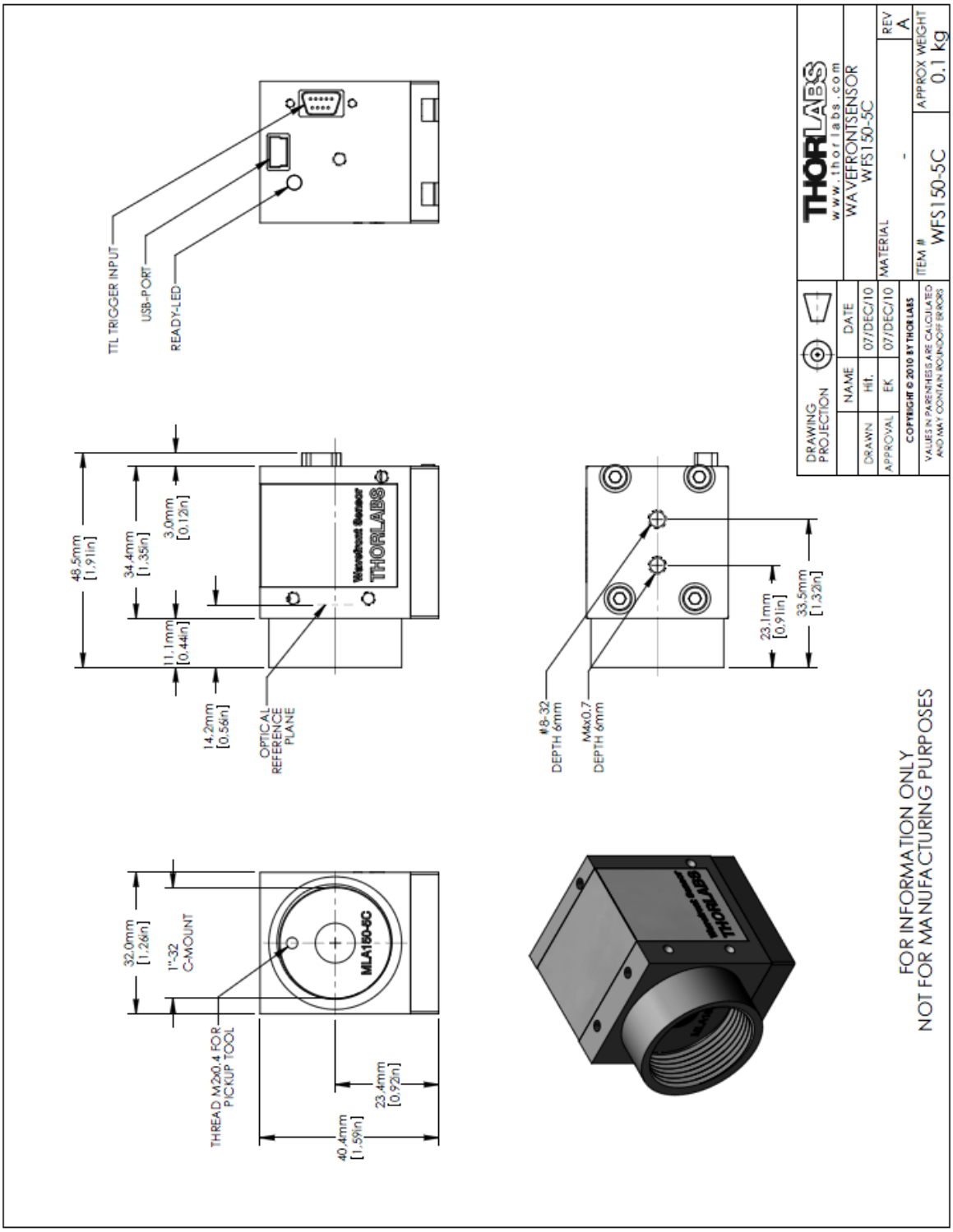
The next table illustrates the wavefront aberrations for Zernike functions of order 0 - 7 for all angular frequencies.



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

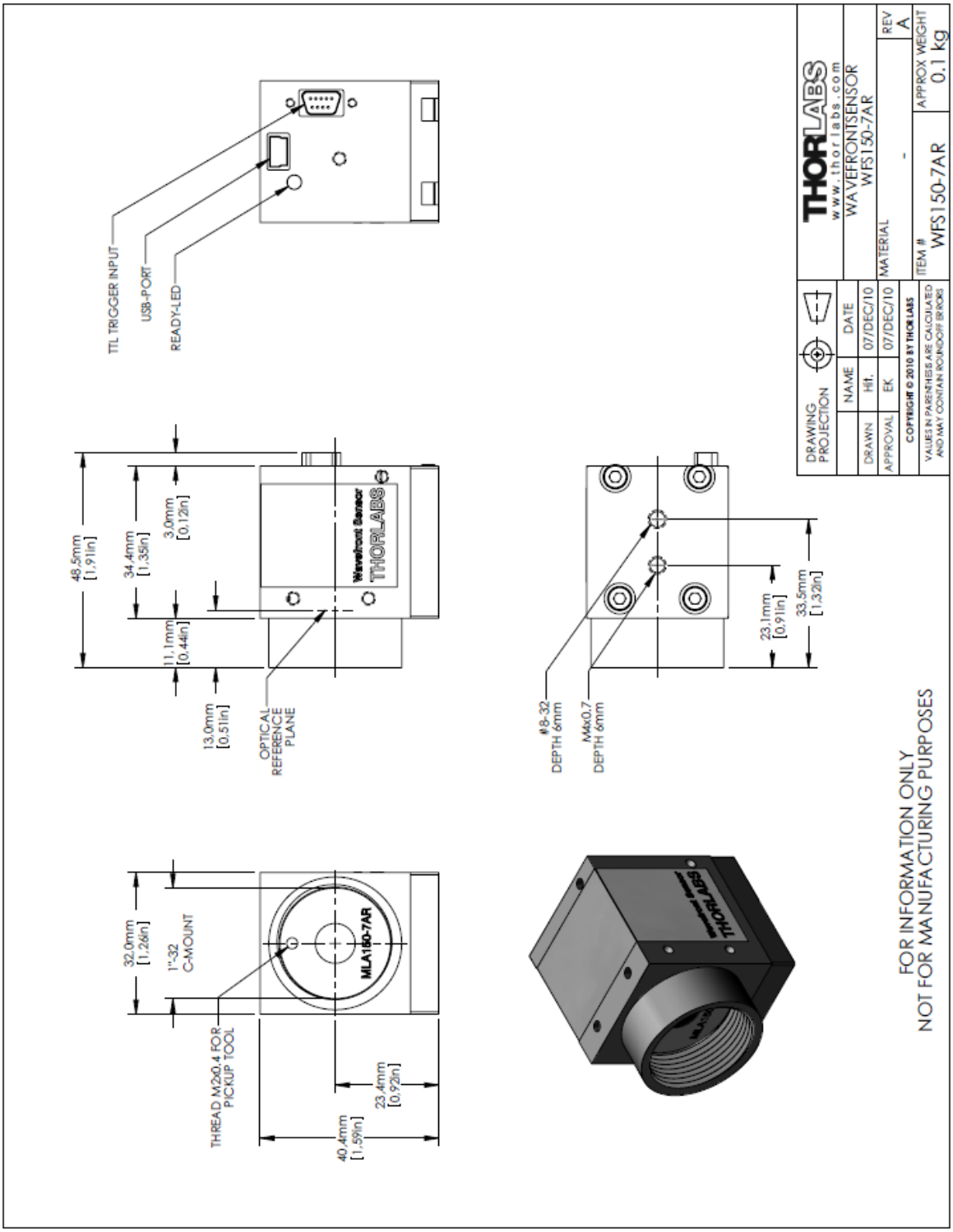
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6.3.9 Drawing WFS150-5C



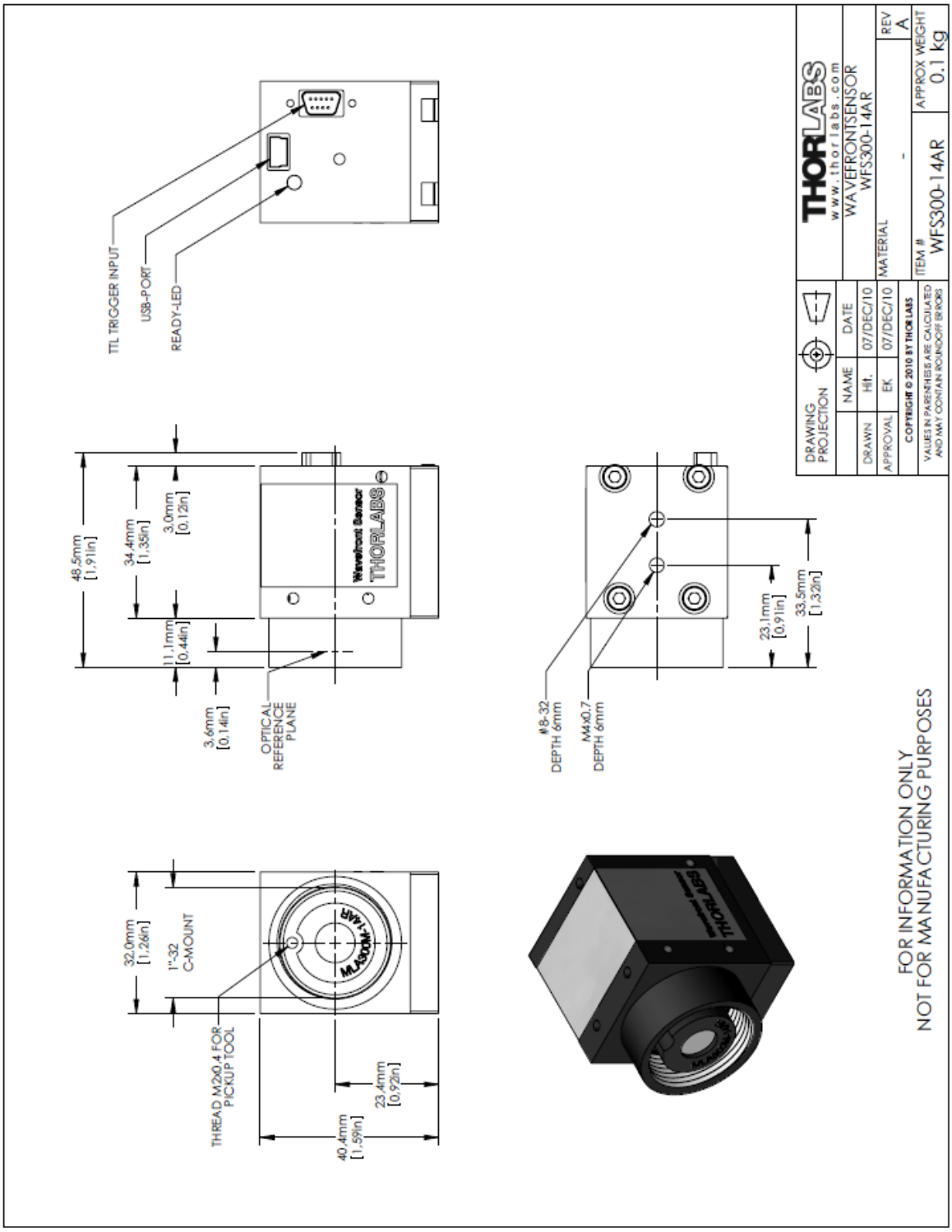
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6.3.10 Drawing WFS150-7AR



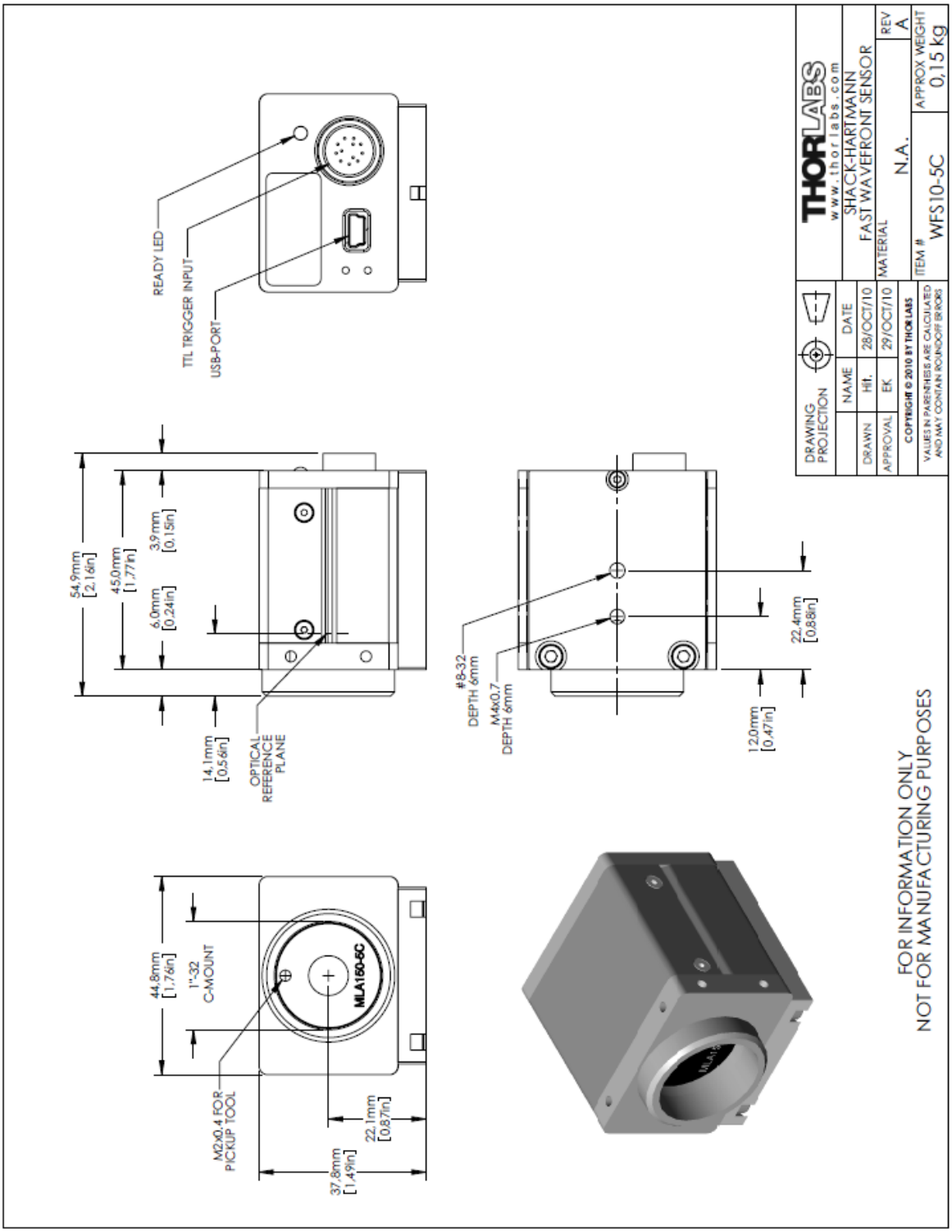
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6.3.11 Drawing WFS300-14AR



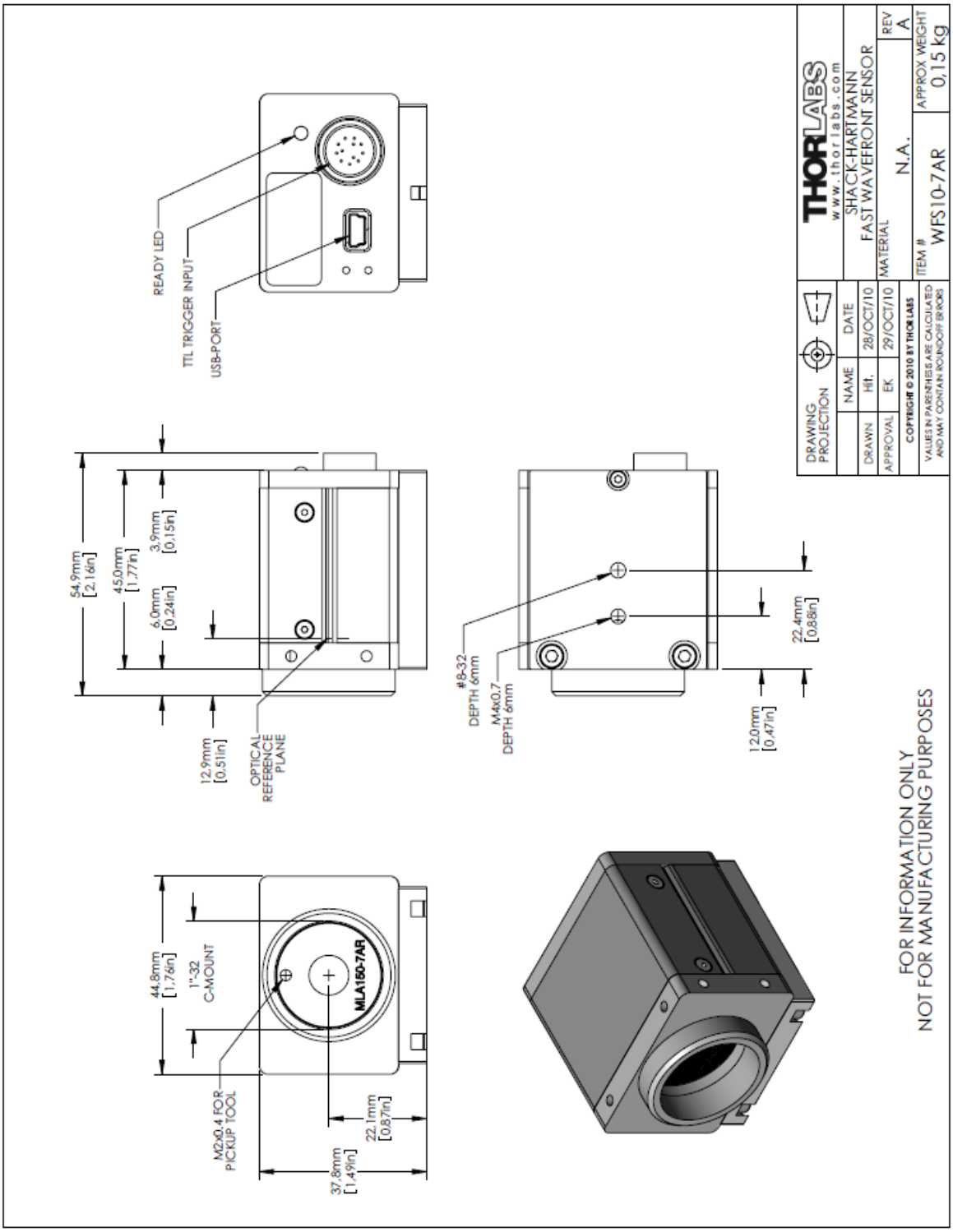
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6.3.12 Drawing WFS10-5C



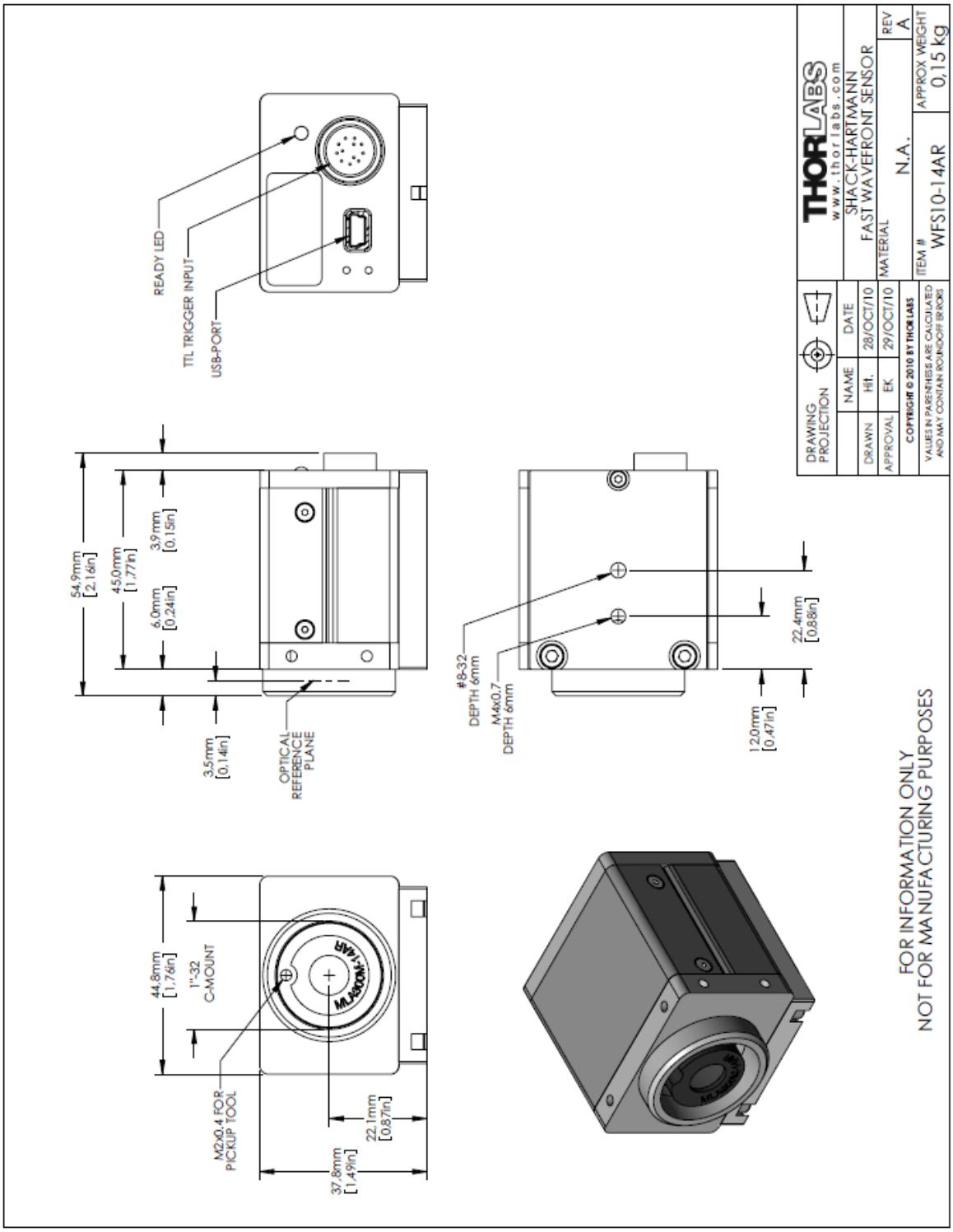
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6.3.13 Drawing WFS10-7AR



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6.3.14 Drawing WFS10-14AR



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6.4 Thorlabs 'End of Life' Policy (WEEE)

As required by the WEEE (Waste Electrical and Electronic Equipment Directive) of the European Community (EC) 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 13, 2005
- marked correspondingly with the crossed out "wheelie bin" logo
- 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 (PCBs, housings etc.)

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

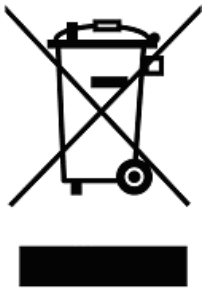
WEEE registration number (Germany): DE97581288

6.4.1 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.

6.4.2 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-life products will thereby avoid negative impacts on the environment.



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6.5 Listings

6.5.1 List of Acronyms

The following acronyms and abbreviations are used in this manual:

3D	3 Dimensional
CW	Continuous Wave
DFB	Distributed Feedback
DSP	Digital Signal Processor
EC	European Community
EU	European Union
FPS	Frames per Second
FWHM	Full Width Half Maximum
GUI	Graphical User Interface
MLA	Microlens Array
NI	National Instruments
OEM	Original Equipment Manufacturer
PC	Personal Computer
PCB	Printed Circuit Board
RoC	Radius of Curvature
RoHS	Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment
VISA®	Virtual Instrument Software Architecture
USB	Universal Serial Bus
WFS	Wavefront Sensor

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6.5.2 Addresses

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Our company is also represented by several distributors and sales offices throughout the world. Please call our hotline, send an Email to ask for your nearest distributor or just visit our homepage **http://www.thorlabs.com**

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