Optical Wavefront Sensors (Shack-Hartmann)

WFS31-5C(/M), WFS31-7AR(/M), WFS31-14AR(/M), WFS31-K1(/M), WFS31-K2(/M)

User Guide



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Chapter 1 Safety

Attention

The safety of any system incorporating the equipment is the responsibility of the assembler of the system.

All statements regarding safety of operation and specifications in this instruction manual will only apply when the unit is operated correctly as it was designed for.

The WFS31 must not be operated in explosion endangered environments!

Do not remove covers! Do not open the cabinet. There are no user-serviceable parts inside!

This precision device is only serviceable if returned and properly packed into the complete original packaging including the cardboard inserts. If necessary, ask for replacement packaging.

Refer servicing to qualified personnel! Changes to this device cannot be made nor may components not supplied by Thorlabs be used without written consent from Thorlabs.

Attention

The following statement applies to the products covered in this manual, unless otherwise specified herein. The statement for other products will appear in the respective accompanying documentation.

Note

This equipment has been tested and found to comply with the limits for a Class B digital device, pursuant to Part 15 of the FCC Rules and meets all requirements of the Canadian Interference-Causing Equipment Standard ICES-003 for digital apparatus. These limits are designed to provide reasonable protection against harmful interference in a residential installation. This equipment generates, uses, and can radiate radio frequency energy and, if not installed and used in accordance with the instructions, may cause harmful interference to radio communications. However, there is no guarantee that interference will not occur in a particular installation. If this equipment does cause harmful interference to radio or television reception, which can be determined by turning the equipment off and on, the user is encouraged to try to correct the interference by one or more of the following measures:

- Reorient or relocate the receiving antenna.
- Increase the separation between the equipment and receiver.
- Connect the equipment into an outlet on a circuit different from that to which the receiver is connected.
- Consult the dealer or an experienced radio/T.V. technician for help.

Users that change or modify the product described in this manual in a way not expressly approved by Thorlabs (party responsible for compliance) could void the user's authority to operate the equipment.

Thorlabs is not responsible for any radio television interference caused by modifications of this equipment or the substitution or attachment of connecting cables and equipment other than those specified by Thorlabs. The correction of interference caused by such unauthorized modification, substitution or attachment will be the responsibility of the user.

The use of shielded I/O cables is required when connecting this equipment to any and all optional peripheral or host devices. Failure to do so may violate FCC and ICES rules.

This product has been tested and found to comply with the limits according to IEC 61326-1 for using connection cables shorter than 3 meters (9.8 feet).

The instrument must only be operated with a duly shielded and low resistance USB cable delivered by Thorlabs.

Chapter 2 Intended Use

The WFS31(/M) Thorlabs' Shack-Hartmann Wavefront Sensors provide accurate measurements of the wavefront shape, its Zernike fit representation, and the intensity distribution of optical beams. The WFS31(/M) wavefront sensors are used in photonics research and development applications such as adaptive optics, beam characterization, quality control, and optical alignment.

The WFS31 Wavefront Sensor is designed for laboratory use only. This product may not be used or integrated into equipment that is applied in pharmaceutical, medical or military applications.

Thorlabs, Inc. Life Support and Military Use Application Policy is stated below:

THORLABS' PRODUCTS ARE NOT AUTHORIZED FOR USE AS CRITICAL COMPONENTS IN LIFE SUPPORT DEVICES OR SYSTEMS OR IN ANY MILITARY APPLICATION WITHOUT THE EXPRESS WRITTEN APPROVAL OF THE PRESIDENT OF THORLABS, INC. As used herein:

1. Life support devices or systems are devices or systems which, (a) are intended for surgical implant into the body, or (b) support or sustain life, and whose failure to perform, when properly used in accordance with instructions for use provided in the labeling, can be reasonably expected to result in a significant injury to the user.
2. A critical component is any component in a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system or to affect its safety or effectiveness.
3. The Thorlabs products described in this document are not intended nor warranted for usage in Military Applications.

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Chapter 3 Introduction

Thorlabs' WFS31x Shack-Hartmann Wavefront Sensors (WFSs) provide accurate measurements of the wavefront shape and the intensity distribution of optical beams. During operation, light is incident on a microlens array (MLA), which creates a matrix of focal spots on a CMOS camera sensor. The Thorlabs WFS application software analyzes the centroid locations of the focal spots and provides wavefront measurements. The WFS appciation software is available for download via the WFS31 website. The WFS31x wavefront sensor modules feature a 1920 x 1200 pixel CMOS camera with a rectangular 11.25 mm x 7.03 mm active area. The sensor head connects directly to the PC via USB 3.0.

The WFS31 models are available in both imperial and metric (/M) versions. For the purpose of this manual, the ending (/M) refers to both metric and imperial versions.

All Thorlabs Wavefront Sensors can be equipped with any one of three different mounted microlens arrays of the types MLA150-5C, MLA150-7AR, or MLA300-14AR listed in the chapter Ordering Codes and Accessories. Each MLA is permanently mounted in a holder which fits in a socket on the front of the sensor head. These holders are easily exchanged, which eases switching to the most suitable MLA for the application. WFS31 wavefront sensors can be purchased with one single MLA or in a kit with two MLAs. Please see the chapter Ordering Codes and Accessories for more purchase information.

Additional mounted MLAs can be purchased for an existing WFS31. For other requests, please contact Thorlabs.

Note

Each MLA used with a WFS31 must be calibrated at the Thorlabs factory and mounted in the custom holder for use with the sensor head.

To ease integration into custom made setups, Thorlabs provides all required information to generate custom-made software. Please see the chapter Custom Software for more information.

C-Mount Adapter

The C-Mount thread on the front side of the Wavefront Sensor is compatible with the included Thorlabs' SM1A9 adapter. This SM1A9 adapter allows the Wavefront Sensor to be integrated with Thorlabs' line of SM1-threaded components including neutral density (ND) filters, to prevent device saturation, and lens tubes, to reduce scattered light.

Attention

Please find all safety information and warnings concerning this product in the chapter Safety.

3.1 Ordering Codes and Accessories

Wavefront Sensor and MLA Combinations

Note

All Thorlabs Wavefront Sensors are equipped with one mounted microlens array and are available in both imperial and metric (/M) versions.

Item #	Wavefront Sensor Head	Included mounted Microlens Array
WFS31-5C(/M)	WFS31(/M) 1920 x 1200 Pixel CMOS Camera, 11.25 mm x 7.03 mm Active Area	Chrome Mask 300-1100 nm, Pitch 150 µm (MLA150-5C)[1)]
WFS31-7AR(/M)	WFS31(/M) 1920 x 1200 Pixel CMOS Camera, 11.25 mm x 7.03 mm Active Area	AR-Coated 400-900 nm, Pitch 150 µm (MLA150-7AR)[1)]
WFS31-14AR(/M)	WFS31(/M) 1920 x 1200 Pixel CMOS Camera, 11.25 mm x 7.03 mm Active Area	AR-Coated 400-900 nm, Pitch 300 µm (MLA300-14AR)[1)]

[1)] The specifications for the included mounted microlens array are equivalent to those of this item number.

For the parts included in the respective products, please see the section Parts List.

For the optical data of the microlens arrays, please see the section MLA Microlens Arrays.

WFS31 Kits with Two MLAs

The WFS31x wavefront sensors are also available as kits with a WFS31 that is calibrated with two included mounted MLAs.

Item #	Wavefront Sensor Head	Included mounted Microlens Arrays
WFS31-K1	WFS31(/M) 1920 x 1200 Pixel CMOS Camera, 11.25 mm x 7.03 mm Active Area	Chrome Mask 300-1100 nm, Pitch 150 µm (MLA150-5C)[1)] AR-Coated 400-900 nm, Pitch 300 µm (MLA300-14AR)[1)]
WFS31-K2	WFS31(/M) 1920 x 1200 Pixel CMOS Camera, 11.25 mm x 7.03 mm Active Area	AR-Coated 400-900 nm, Pitch 150 µm (MLA150-7AR)[1)] AR-Coated 400-900 nm, Pitch 300 µm (MLA300-14AR)[1)]

[1)] The specifications for the supplied microlens array correspond to the specified part number.

To purchase Wavefront Sensor / Microlens combinations not listed above, please contact Thorlabs for support.

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Optional Accessories

Additional Mounted Microlens Arrays

Additional Mounted Microlens Arrays can be purchased for an existing wavefront sensor head. Adding a mounted microlens array to a WFS is always an upgrade.

Please contact Thorlabs for pricing of the upgrade.

Available Mounted Microlens Arrays for WFS31

W30150-5C
- Based on Thorlabs MLA150-5C
- Chrome Mask with no Anti-Reflection Coating
- Wavelength Range: 300 nm to 1100 nm
- Round Microlenses, Pitch 150 µm, Effective Focal Length 4.1 mm

W30150-7AR
- Based on Thorlabs MLA150-7AR
- Anti-Reflection Coating
- Wavelength Range: 400 nm to 900 nm
- Round Microlenses, Pitch 150 µm, Effective Focal Length 5.2 mm

W30300-14AR
- Based on Thorlabs MLA300-14AR
- Anti-Reflection Coating
- Wavelength Range: 400 nm to 900 nm
- Square Microlenses, Pitch: 300 µm, Effective Focal Length 14.6 mm

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 significantly. Please see also section MLA Microlens Arrays.

Attention

Each specific combination of a WFS31 head and an MLA needs to be calibrated as a set by Thorlabs at the factory. This is because each MLA has individual optical characteristics. When purchasing an additional MLA for your wavefront sensor head, please follow these steps:

1. Contact Thorlabs for pricing of the upgrade and return instructions (Example: Upgrade of your WFS31-14AR to WFS31-K1 by adding a mounted MLA150-5C microlens array).
2. Send the complete WFS31 sensor (including existing mounted MLA) for the upgrade to the Thorlabs factory. (Example: Send the WFS31-14AR to Thorlabs).
3. Upon receipt of the WFS31, the sensor head will be additionally calibrated with the newly purchased MLA in a holder. The calibration data will be saved to the internal non-volatile memory (EEPROM) of the camera. (Example: WFS31 sensor head is calibrated with the mounted MLA150-5C array).
4. Thorlabs will return the newly calibrated sensor head as you sent it to Thorlabs, along with the new MLA (Example: WFS31 sensor head, now calibrated for the mounted MLA300-14AR MLA150-5C arrays, and the two mounted MLAs).

Note

The WFS software accepts only one set of calibration data for each mounted MLA type. It is not possible to calibrate the same sensor head for two mounted microlens arrays of the same type.

Trigger Cable

An optional trigger cable can be ordered separately to supply an electrical trigger signal to the Wavefront Sensor. See for details.

CAB-DCU-T3 Trigger Cable for WFS31 Wavefront Sensor Head

3.2 Requirements

These are the requirements for the PC intended to be used for remote operation of the WFS31.

Hardware Requirements

Processor:	2 GHz or Higher
Memory:	1 GB RAM
Graphic Card:	Min. 256 MB Memory (Shared)
Graphics Card Resolution:	1024 x 768 (Minimum), Recommended: 1280 x 1024 Pixels
Hard Drive:	500 MB (Minimum) of Available Disk Space (32-Bit)
Interface:	Free USB 3.0 Port, USB Cable According the USB 3.0 Specifications as Supplied

Running multiple Wavefront Sensors in parallel using one PC requires an increase in RAM size and CPU power. The number of processor cores should be at least equal to the number of connected Wavefront Sensors.

Software Requirements

When used with the WFS31, the Wavefront Sensor Software is compatible with the following operating systems:

- Windows® 10 (32-Bit, 64-Bit)
- Windows® 11

For operation of the WFS31, also the NI-VISA Runtime Engine (V 17.0 or later) is required. This NI-VISA software is included with the Thorlabs WFS31 installation package, but can be downloaded also from National Instruments' website.

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Chapter 4 Getting Started

4.1 Parts List

Please inspect the shipping container for damage. Please do not cut through the cardboard, as the box might be needed for storage or returns.

If the shipping container appears to be damaged, keep it until you have inspected the contents for completeness and tested the WFS31 mechanically and electrically.

Verify that you have received the following items within the package:

WFS31-5C, WFS31-7AR, WFS31-14AR, WFS31-K1, and WFS31-K2

1. Wavefront Sensor Head with Dust Cover and Adapter Plate:
   Metric Adapter Plate: M4 and M6 Threads; Imperial Adapter Plate: 8-32 and 1/4"-20 Threads
2. USB 3.0 High-Speed Cable, A to Micro B, 3.0 m
3. SM1A9 C-Mount to SM1 Adapter for Mounting to Optical Accessories
4. Printed Quick Reference
5. Mounted Microlens Array(s)

Note

If a single MLA was ordered it will be mounted on the sensor head at the factory. If multiple MLAs are ordered, as for example in the kits WFS31-K1 or WFS31-K2, one mounted MLA of choice will be placed on the sensor head and the other(s) will be packaged separately. A tool for removing and replacing the mounted MLA will also be included.

4.2 Installing Software

Download the Thorlabs' Shackman-Hartmann Wavefront Snesor Software package ZIP archive from the website, unpack it and open the installation folder to start the installation by double-clicking the setup.exe file.

Note

Do not connect the WFS31 to the PC prior to software installation!

Attention

Exit all running applications on your PC as the installer may require a reboot of your PC during installation!

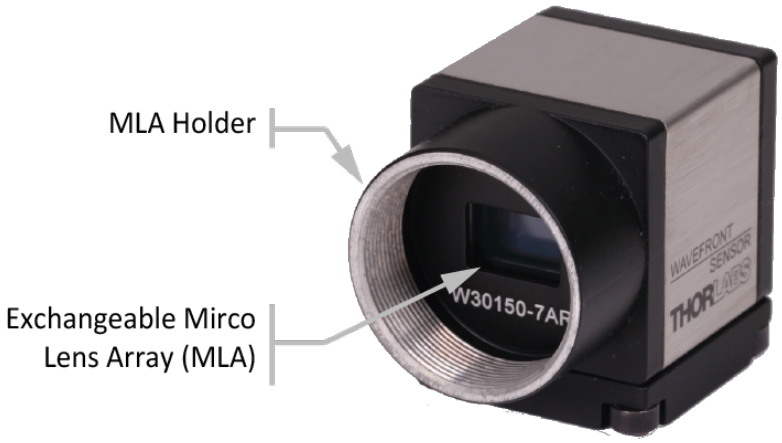
Thorlabs decided to refrain from shipping an installation CD ROM to save our environment and to offer a download of the software from our website instead. As an additional advantage to this distribution method, the most recent version of the software will always be available online.

The WFS software package can be found easily on the software tab of the WFS31x website.

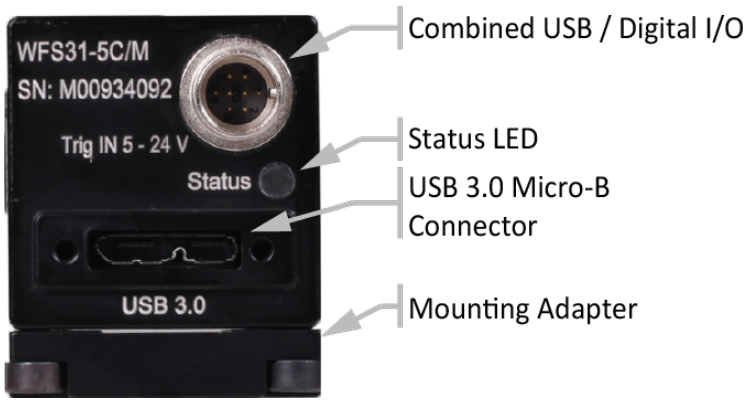
4.3 Operating Elements

The outer dimensions of all WFS31 models in combination with any mounted MLA are identical. The WFS31 wavefront sensor with the W30-150-7AR mounted MLA is shown.

Front View



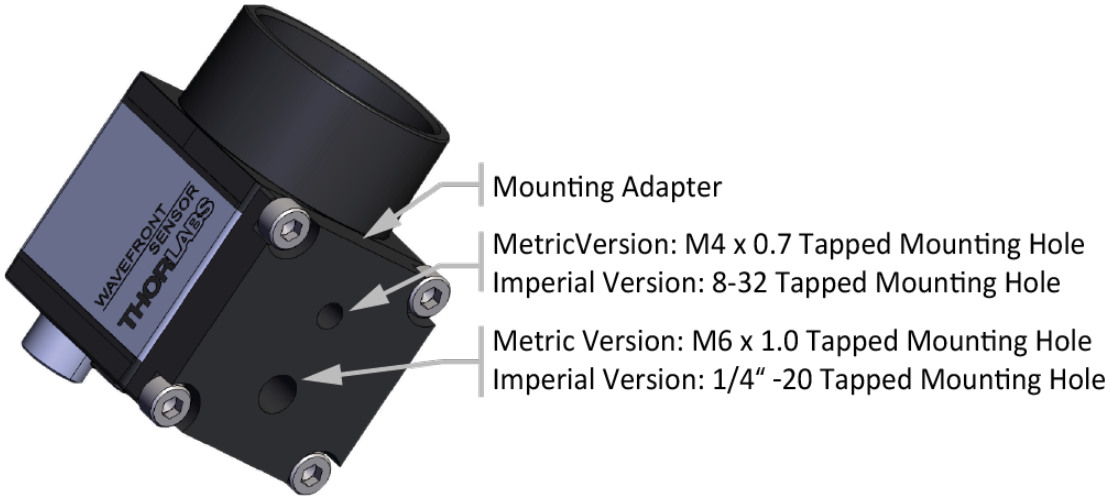
Rear View



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4.4 Mounting

An adapter plate with standard metric (M4 and M6) or imperial threads (8-32 and 1/2"-20) is included with the shipment and already mounted to the WFS31 model. This allows the instrument to be mounted on standard Thorlabs posts.



The C-Mount thread of the camera aperture allows other optical components to be mounted directly to the WFS. Use the included Thorlabs' SM1A9 adapter (external C-mount thread to internal SM1) to mount ND filters, lens tubes (to prevent stray light from entering the input aperture), or additional opto-mechanical components.

4.5 Setup

Connecting the WFS to the PC

Note

Do not connect the Wavefront Sensor to the PC prior to software installation!

Attention

Do not use cables other than the supplied USB cable because other cables may not support the high-speed USB transfer rate and high-power requirements of the WFS. Cables with insufficient performance may cause transmission errors and improper instrument operation!

Be sure to connect the supplied USB cable to a high speed USB 3.0 port. Connecting the WFS31 heads to a USB 2.0 port leads to a degradation of performance (slower data transfer). The Wavefront Sensor will not work when connected to a USB 1.1 port!

1. Install the wavefront sensor software package and USB drivers (all in one package) on your PC prior to connecting the Wavefront Sensor to your PC.
2. Connect the WFS to a USB 3.0 port of the used PC. Use only the cable included with the WFS shipment. The software will automatically recognize the WFS.

After connecting the instrument to the PC, the operating system recognizes the connected instrument, installs the appropriate driver software, and identifies the connected hardware.

Chapter 5 Operating Instructions

All Thorlabs WFS31 models are operated using the Thorlabs WFS31 software. The software can be downloaded from the Thorlabs website. Please see the section Installing Software for installation instructions.

The WFS31 software offers the following functions:

- Instrument Setup
- Instrument Calibration
- Measurement Setup
- Graphical Display Options for the Measurement
- Numerical Data Viewing

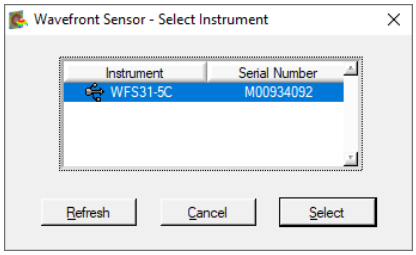
5.1 Status LED

The status LEDs indicates the power status.

Color Status LED	Control Status
(Off)	No Power Supplied, WFS Not Connected
Green	Ready
Red	USB Connected, Driver Not (Yet) Installed

5.2 Instrument Setup in the Software

After starting the application, the connected hardware is recognized; click "Select" to choose the desired device:



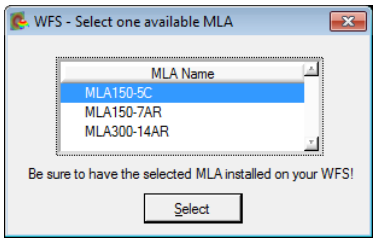
If no entry can be seen, click Refresh to update the list of available Wavefront Sensor instruments. If there is still no instrument displayed please refer to the chapter Troubleshooting.

The recognized wavefront sensor will always be named for the sensor head and the MLA that the sensor head was first calibrated with (i.e. 5C for MLA150-5C). The currently installed MLA will be selected in a next step.

The WFS software can be run in several instances. An already connected wavefront sensor is not selectable and displayed as "Instrument in use".

In case your WFS31 instrument was calibrated for more than one Microlens Array (MLA) you need to select the one that is mechanically installed. Identify the installed MLA by the label on the front of the Wavefront Sensor.

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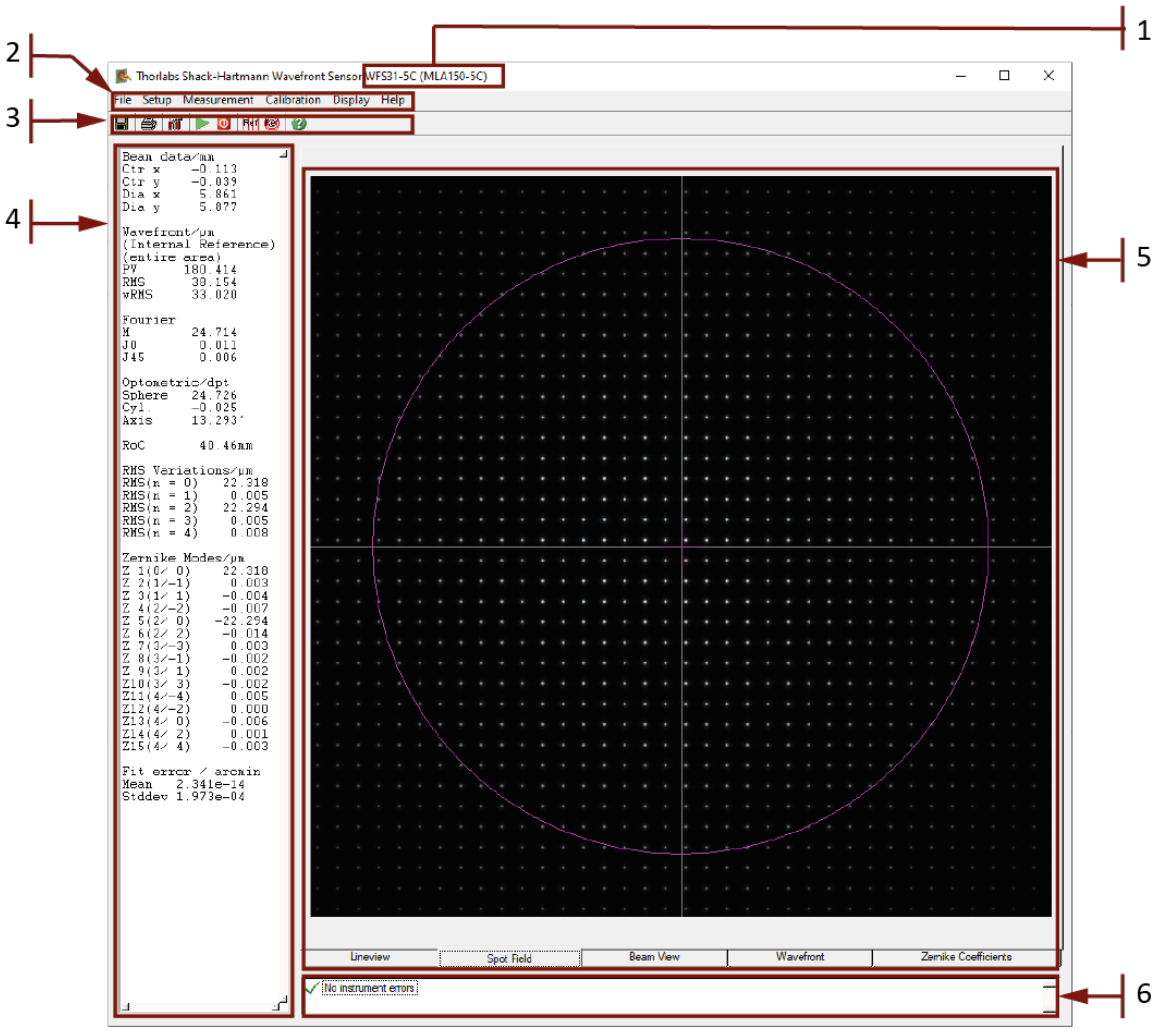
Attention

When the MLA selected in the software is not the MLA physically installed on your Wavefront Sensor, the measurement data will be incorrect because the software will use calibration data for the wrong MLA.

5.3 Graphical User Interface - Startscreen

After the instrument is selected, the GUI opens and displays the beam spotfield taken from the camera. The connected wavefront sensor type and the selected MLA are displayed in the header.

The Graphical User Interface starts with the following screen.



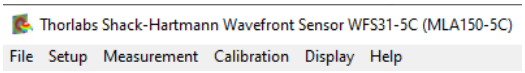
GUI Areas

1 Recognized Instrument and Selected MLA
2 Menu Bar
3 Tool Bar
4 Numerical Measurement Results
5 Graphical Display (Consisting of 5 Tabs)
6 Status Bar

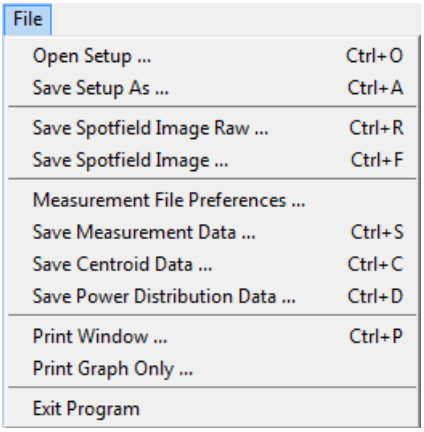
The GUI attributes can be adjusted according to your preferences. When exiting the application, the actual settings are saved and will be applied when starting the application software again.

At the first program start, all Wavefront Sensor settings and GUI configurations are set to default values. Please see section Setup Menu for individual configurations.

5.4 Menu Bar



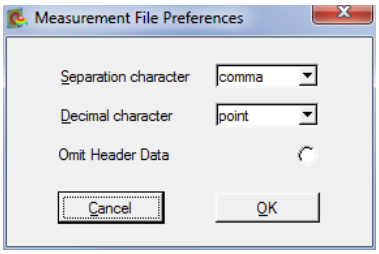
5.4.1 File Menu



The actual settings of the WFS GUI including configurations of the graphical displays and the instrument setup are automatically saved when exiting the program. The next time the Wavefront Sensor software is run, the most recent settings are automatically loaded.

Additionally, the complete instrument and GUI settings can be saved to a configuration file. The application software can load this file to restore previous measurement conditions.

- **Open Setup**... opens a Wavefront Sensor configuration file (*.cfg) stored with this application (see below). This configuration file contains instrument settings (camera, pupil, wavefront) as well as display and graphical settings.
- **Save Setup As**... stores a Wavefront Sensor configuration file (*.cfg) containing all instrument settings (camera, pupil, wavefront) as well as display and graphical settings. Assign a meaningful individual name to the configuration file.
- **Save Spotfield Image Raw...** saves the Spotfield Display as a *.bmp image with the size of the selected camera resolution.
- **Save Spotfield Image...** saves the Spotfield Display as a *.bmp image with the size as displayed in the software.
- **Measurement File Preferences...** opens a dialog to set the attributes of the measurement data file:



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Separation Character: select the separator between two subsequent data values within a line. Options: comma, semicolon, tabulator, or space. Default: "Comma".

Decimal Character: This choice is important to ensure compatibility with the Region and **Language settings** of the computer where the saved measurement data shall be processed. Options: point or camera. Default: "Point".

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, e.g. in Microsoft® Excel.

- **Save Measurement Data**

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

- **Save Centroid Data**

  The measured centroid positions of the spots visible in the Spotfield Panel can be saved to a text file. The default file extension is .csv (comma separated values). This file type can be loaded directly into Microsoft Excel®.

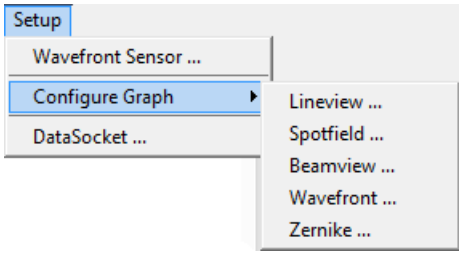
- **Save Power Distribution Data**

  The measured intensities in arbitrary units of the spots visible in the Spotfield Panel can be saved to a text file. The default file extension is .csv (comma separated values). This file type can be loaded directly into Microsoft Excel®.

When saving data, a dialog window comes up.

Select the location for the saved data file, select a file name, and click 'Save'. The content and format of the saved data is defined in the 'Measurement File Preferences' panel, see previous page.

5.4.2 Setup Menu



You can configure the following settings in this menu:

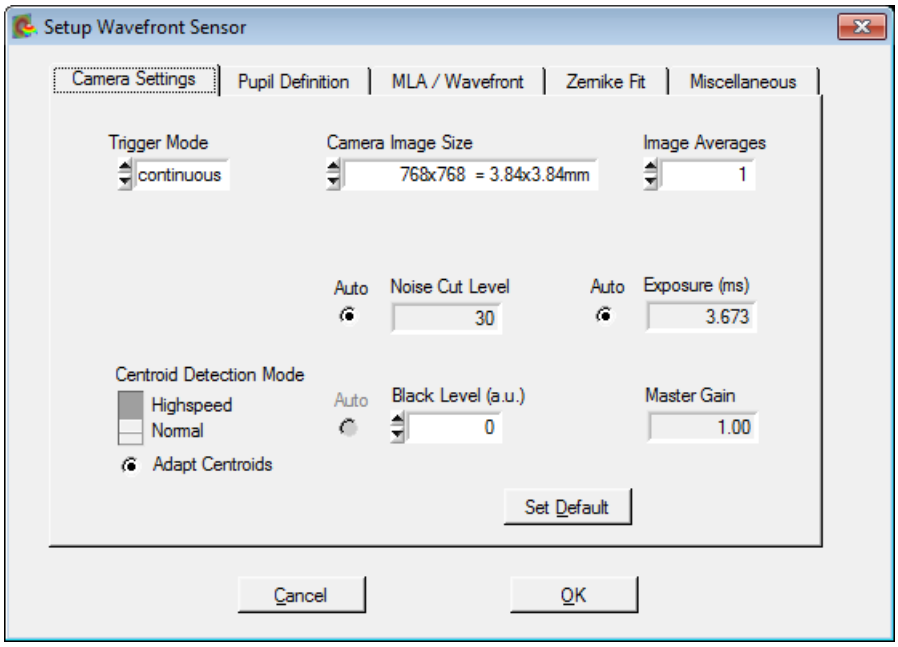
- Wavefront Sensor: A separate configuration panel opens.
  Alternatively, click the icon in the tool bar or right click to the graph area.
- Graphical Display
- DataSocket Interface

The Graphical display includes five different panels, and each can be configured individually. These panels can be accessed directly by double clicking to the appropriate display area. Details can be found in chapters Line View Panel, Spotfield Panel, Beam View Panel, Wavefront Panel, and Zernike Coefficients Panel.

5.4.2.1 Setup Wavefront Sensor

The Wavefront Sensor GUI automatically starts measuring the applied wavefront using default parameters. Using these default settings, the instrument is able to make initial measurements. Nevertheless, it is highly recommended that all settings be reviewed and adjusted to suit the application.

The setup panel can be accessed via the Menu bar (Menu → Setup → Wavefront Sensor...) or simply by right clicking on the graphical display:



Changes in instrument operation and data display parameters take immediate effect.

Click '**OK**' or close the panel to save the actual settings.

Click '**Cancel**' to discard all changes that were made after opening the panel; the settings will be reverted to the state before opening the panel.

The Setup Panel is divided into five tabs:

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

Note

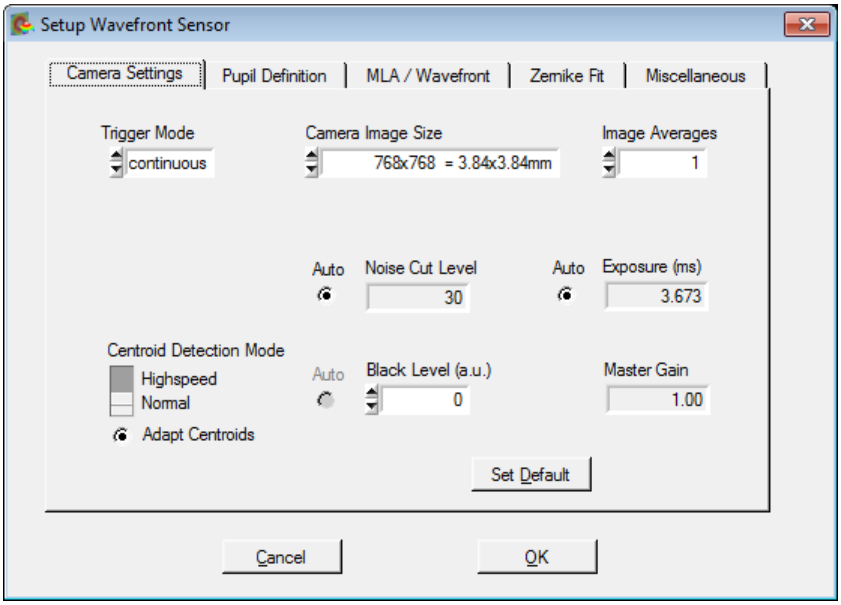
Please be aware that settings for Camera Image Size, Pupil Definition and Zernike Fit (Zernike order number) are interdependent and also impact the measurement speed.

If these settings are critical or contradictory, warnings or error messages will appear in the instrument status bar, see the chapters Measurement Warnings and Errors and Minimal Beam and Pupil Diameter.

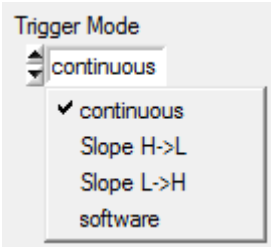
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5.4.2.1.1 Camera Settings Tab

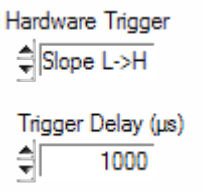
Camera Settings Tab

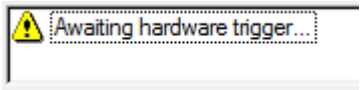


Trigger Mode allows the synchronization mode to be selected. Three modes are available:



- **Continuous** - this is the default mode. The images are acquired automatically and continuously by the camera - the camera operates in free running mode, and the software displays the last available image, which might be buffered in the camera or in the driver. This mode provides the fastest measurement speed, but the internal buffering causes a delay of several frames between the exposure and the appropriate wavefront result.
- **Slope H->L (L->H)** - this mode enables image acquisition to be synchronized to an external trigger signal, which may be a pulsed laser source or an electrical function generator. See chapter Trigger Input for a detailed specification of this input. The trigger slope can be selected. In addition, a trigger delay can be programmed. The possible delay range depends on the connected instrument. As soon as a trigger slope is selected, the WFS waits for the trigger event at the electrical input. Until the trigger is received, no wavefront measurement or screen update take place. This state is indicated by the 'Awaiting hardware trigger...' message in the status bar at the bottom.



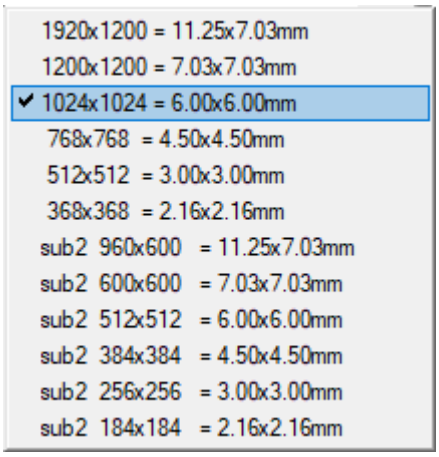


Software: The WFS application controls the image acquisition. All buffered images are deleted at the start of each new exposure, and new images acquired by the camera are transferred to the PC. This operating mode is somewhat slower than Continuous mode, but it is advantageous if a fixed correlation between exposure start and retrieved image is required, e.g., in control loops.

Camera Image Size defines the active area of the camera that is used for wavefront measurement. This setting should be adapted to the beam size that is applied to the instrument. Limiting the active image size will reduce the unused sensor area, resulting in an increase of measurement speed by saving the time that is required to transfer data from the sensor head and evaluate the spotfield images.

- Large image sizes allow the chosen pupil diameter to be large, which supports a high Zernike resolution (Zernike order).
- The smaller the image size, the fewer spots are used for calculation and thus, maximum achievable Zernike order decreases. On the other hand, measurement speed increases.

The following image sizes are selectable, depending on the connected WFS instrument:



Camera Image Sizes - WFS31

The highlighted values are start-up defaults. The camera in the Wavefront Sensor instrument determines the resolution (pixel density) and maximum available sensor area:

Item #	Sensor Size	Max. Sensor Area	
WFS31	2.3 MP	1920 x 1200	11.25 mm x 7.03 mm

In the case that the beam diameter is larger than the maximum sensor area, only the fraction of the beam cross section incident on the active sensor area can be analyzed by the instrument. When the input aperture is overfilled, the Wavefront Sensor can still provide correct results. However, the pupil parameters must be selected carefully (see Pupil Definition tab).

The selectable image sizes for the WFS31 models can be found in the Specifications as well.

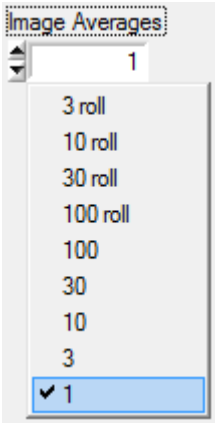
The WFS31 offers a "sub2" mode, in which subsampling selects a single pixel out of a 2x2 grid to use for measurement. The measurement speed increases, with the disadvantage of a lower spatial wavefront resolution and accuracy.

Note

Changing the camera resolution will also change the number of detectable spots. If the instrument is operated with a User Calibrated Wavefront Reference, a new User Calibration may be required!

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Image Averages

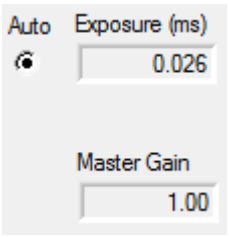


Averaging will reduce measurement noise. This can be advantageous when analyzing a low-light-level source. Setting the number of averages higher than 1 will take multiple images from the camera, average the pixel intensity pixel by pixel, and output an averaged image to the subsequent evaluating routines. Due to reduced intensity noise, the accuracy of detected spot centroids is increased.

3, 10, 30, 100 indicate normal averages. The instrument acquires the selected number of images, performs the average, and then executes data evaluation and displays the results. As the display is not refreshed until after each set of images is acquired, this type of averaging reduces the update rate. of numerical and graphical data on the main panel. This may be a beneficial effect as it can improve the readability of the numeric results.

Settings 3 roll, 10 roll, 30 roll, 100 roll indicate pseudo rolling averages. Here, the average of subsequently captured camera images is calculated every time a new image is retrieved. A new image is added to a buffer that already contains the previous averaged image. The previous averaged image is weighted (for 100 roll by 99), the new image added and the summarized image divided by the number of averages (ie 100). 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 that the **'Auto'** setting be selected. In this case, the WFS software automatically analyzes the maximum image intensity and correspondingly adapts the control parameters 'Exposure time (ms)' and 'Master Gain' in order to reach a maximum image intensity close to the 255 digits maximum.

In some cases, e.g. if the intensity of the light source is fluctuating, it may be helpful to deactivate the 'Auto' feature and allow manual adjustments.

The exposure time range depends on the instrument, please see the Specifications.

The Master Gain indicates the analogue amplification factor of the CMOS sensor signal.

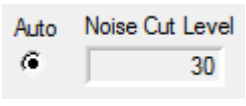
To change these values manually, we recommend adjusting the brightness primarily by changing the exposure time. Increase the Master Gain only if the exposure control does not give the desired result, as the image noise increases with gain.

Check the actual saturation degree of the camera's AD converter in the Lineview panel.

Attention

Manual settings of 'Exposure time' and 'Master gain' must not lead to image saturation (pixel intensity = 255 digits) or to a low image brightness (maximum intensity < 128 digits), otherwise measurement errors occur and noise increases.

Noise Cut Level



The Noise Cut Level defines a brightness level (in digits), which a spot intensity must exceed to be included in the data analysis. This level can be set to exclude contributions of ambient light and noise terms. This parameter is set in the

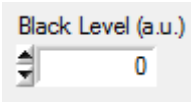
Lineview panel. Since defining such a fixed level is problematic when beam intensities and ambient light are changing, the **Auto** setting is highly recommended, as it enables dynamic adaption to the different intensity levels for each spot area and yields the best results for centroid calculation.

The noise cut level values can also be set manually between 0 and 255 digits.

Attention

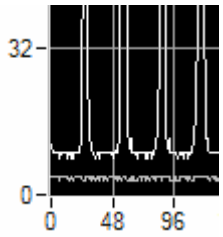
Improper manual settings for 'Noise Cut Level' may lead to increased measurement errors.

Black Level

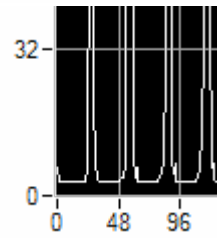


Black Level is a camera setting that adjusts the brightness level offset for all illuminated pixels. It should be adjusted so that the entire minimum line in the Lineview panel is below zero and the entire maximum line is above zero. In the case of very high noise level, reduce the setting. "Arbitrary Unit" (a.u.) values range from 0 to 255.

Examples:



Black Level set to 255 - this is too high: the lowest intensity pixels (lower gray curve) show high offset.



Black Level set to 0 is acceptable, as the entire minimum line is below zero, and the entire maximum intensity line is above zero. The maximum intensity line includes the low-intensity pixels between the spots, which preserves the measurement sensitivity.

An automatic adjustment is currently not supported by any of the Thorlabs WFS cameras. Therefore, it is suggested to check the correct setting.

Set Default

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

- Noise Cut Level = Auto
- Exposure Time and Master Gain = Auto
- Black Level = 0
- Disable Hardware Trigger

Settings for Camera Image Size and Averaging remain unchanged.

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5.4.2.1.2 Pupil Definition Tab

Pupil Definintion Tab

The pupil defines a circular area within the spot field and wavefront display. It is the physical representation of a mathematical unit circle (radius = 1).

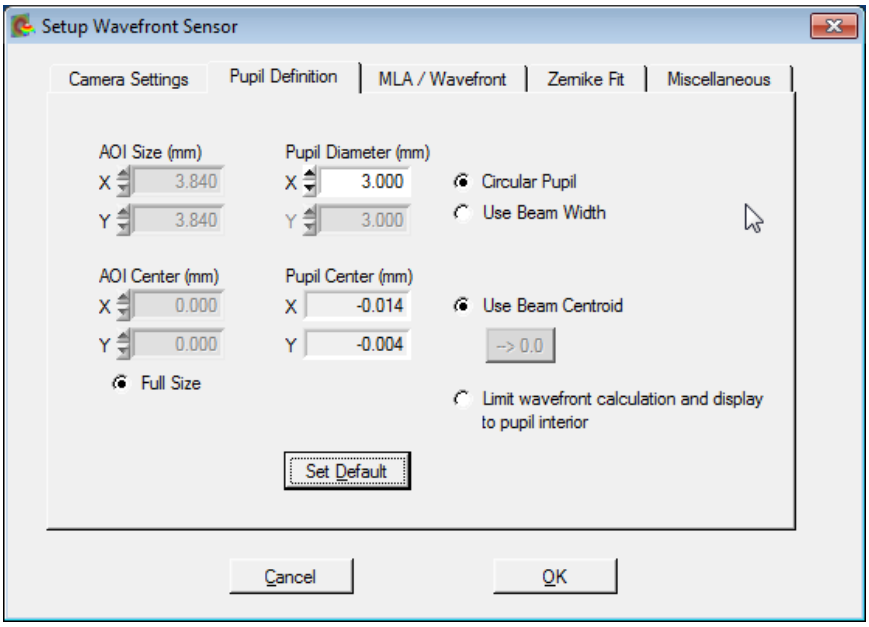
Since all Zernike functions are defined within this unit circle ($r \leq 1$), only the sports that are located within the pupil are used for fitting the measured wavefront distortions to Zernike functions. This is accomplished by normalizing the physical centroid positions (in mm or camera pixels) to the dimensionless positions within the unit circle.

Consequently, a wavefront reconstructed from selected Zernike functions can be calculated and displayed only within the pupil area.

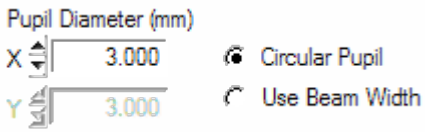
The Zernike calculations, which require a circular pupil, can also be adapted to elliptical beams. Set the pupil to an elliptical shape, and the software scales the x and y axes to fit a unit circle. After completing the calculations, the software scales the results back to the elliptical pupil.

For a measurement, the pupil size and shape are selected to match the diameter of the beam that is tested. The measured Zernike coefficients are related to this selected area only. For a Gaussian beam shape the pupil diameter is often set to its $1/e^2$ diameter.

To define the pupil, Select the Pupil Definition tab in the Setup Wavefront Sensor panel:



Pupil Diameter (mm)



The Pupil Diameter as set here 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/e2 diameter in case of a Gaussian beam shape.

Note

The second moment method will calculate accurate beam widths only in the case that ambient light is shielded from the Wavefront Sensor and the **Black Level** of the camera is aligned properly (see chapter

Camera Settings). A positive offset to the beam intensity distribution will lead to beam diameters larger than real. A manually defined **Noise Cut Level** in the chapter Camera Settings is helpful to compensate an increased dark level.

Disable Use Beam Width if the pupil size should be set manually. An elliptical pupil can be set up by entering different values for X and Y diameter. In this case, the geometric mean of the ellipse dimensions defines the diameter of the Zernike circle, and for Zernike calculations the elliptical beam is scaled to fit and fill the dimensions of that circle.

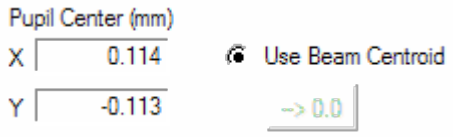
Note

The pupil diameter must be smaller than the active camera area as defined by Camera Image Size setting (see chapter Camera Settings), otherwise the warning "Pupil is larger than selected camera area" will occur (see chapter Measurement Warnings and Errors). This requirement prevents Zernike calculation errors that would occur if the pupil included regions with no measurement data points (lenslet focal spots).

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

It is recommended that the Circular Pupil be used with the appropriate diameter and center position. In this case, only the X diameter needs to be entered and the Y diameter is set to the same value.

Pupil Center (mm)



The pupil center coordinates (in mm) can be set manually or automatically.
Enabling **Use Beam Centroid** is recommended 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 moving spot. If switching to manual input, use the 

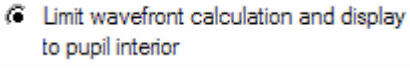
button to set the pupil centroid to the center of the Wavefront Sensor.

Note

Manual definition of the pupil center requires a careful and stable beam adjustment, otherwise the measurement accuracy drops.

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

Limit Wavefront Calculation and Display to Pupil Interior



By default, the wavefront parameters are calculated over the entire selected sensor area, while the Zernike functions are calculated only for the area of the pupil interior. Enabling this option will limit the wavefront calculation and display to the pupil interior as well - the 3D wavefront display on the Wavefront Panel will show only the wavefront data within the pupil.

Note

Selecting this option influences the total measured wavefront distortions (PV, RMS). Distortions within the defined pupil area are usually lower that the total measured distortions outside the pupil.

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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

5.4.2.1.2.1 Area of Interest (AOI)

Area of Interest (AOI)

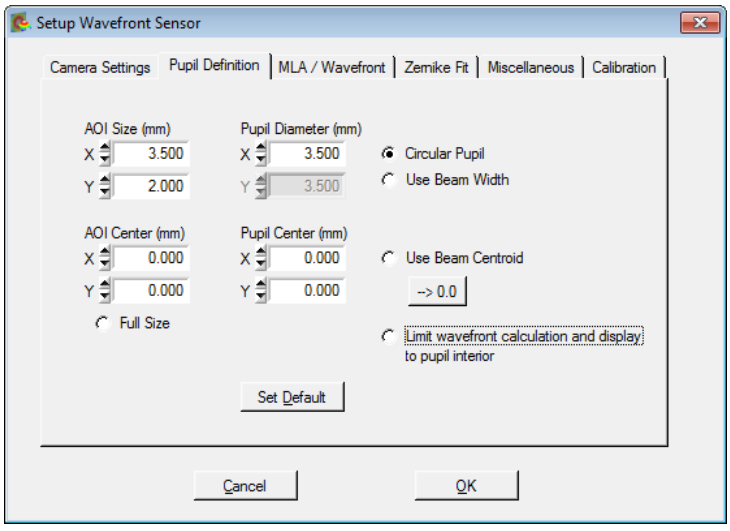
The AOI functionality allows the measurement area to be limited to a rectangular region called the Area of Interest (AOI). Similar to the option “Limit wavefront calculation and display to pupil interior” that limits the wavefront display and the appropriate numerical parameters to the pupil area, the AOI limits measurements to the selected rectangular area. The boundary of this region is indicated by a yellow rectangle in the Spot Field panel.

This feature was customer inspired.

This is helpful particularly when rectangular objects are measured using the WFS. For instance, when components of a HD display are measured with respect to wavefront deformations, the results should only reflect the properties of the active display area, but not of the surrounding frames and holders. This way, measurement errors due to uncertainties in detecting spot centroids at the border of the target area can be prevented.

Setting Up the AOI

Set the AOI in the ‘Pupil Definition’ tab.



When the ‘Full Size’ option is enabled (default), the AOI is equal to the actual camera image size that is selected. In this case the yellow rectangle is not displayed in the Spot Field panel.

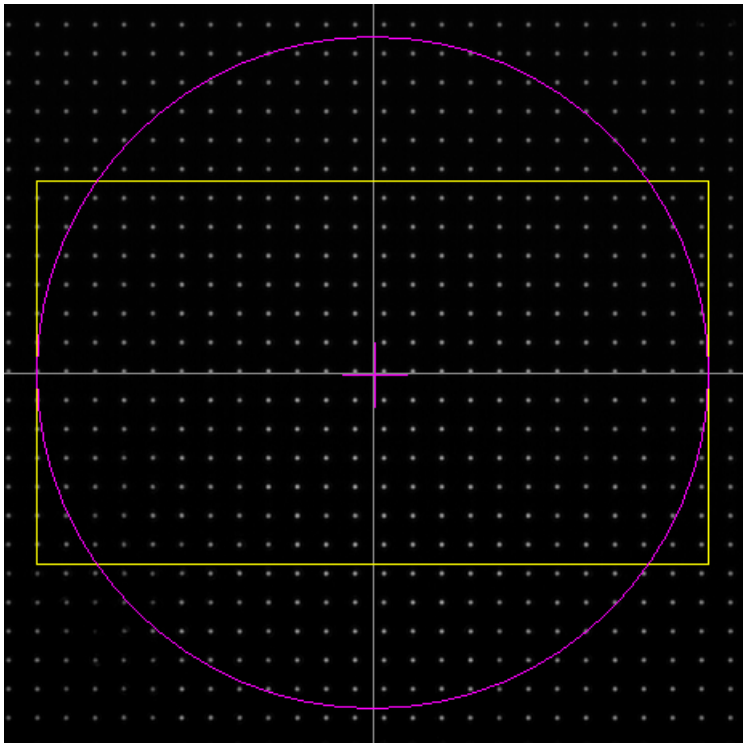
To set smaller AOI dimensions, enter the size and center coordinates of the desired AOI and uncheck the ‘Full Size’ button.

How the AOI Works

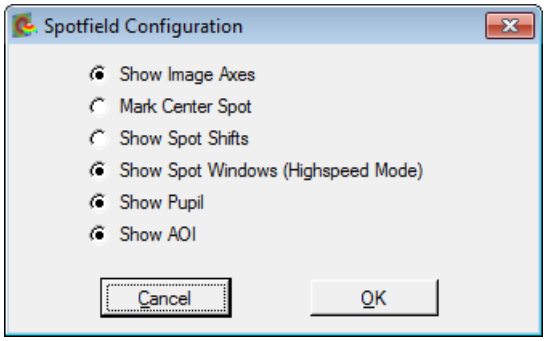
Limiting the AOI is related to the reference centroid positions; in other words, a detected spot is masked if its appropriate reference position is outside the AOI.

AOI Display

Spot Field panel Display:

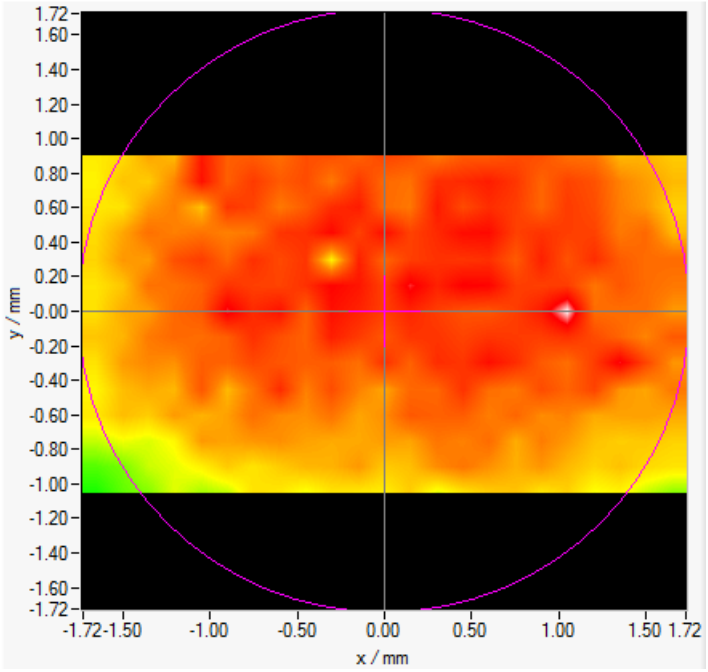


Double-click onto the Spot Field image to open its configuration. Option 'Show AOI' determines if a user-defined AOI is displayed or not.

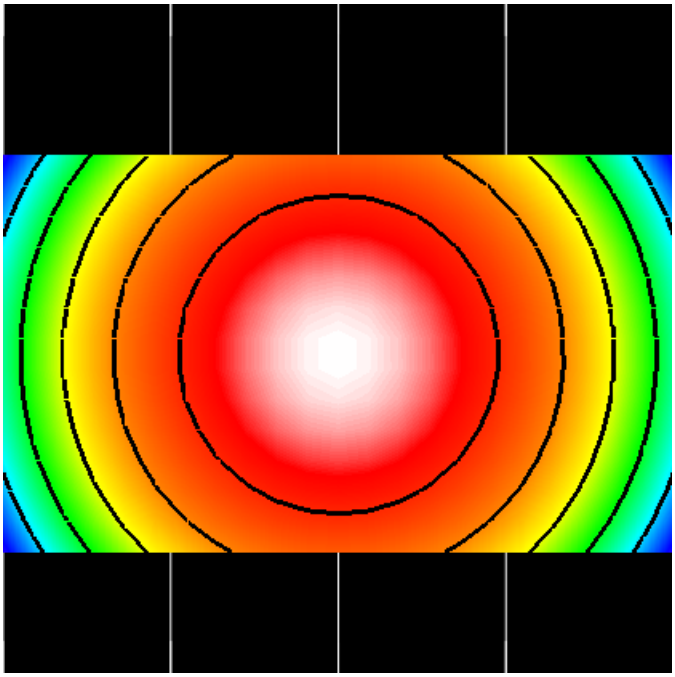


In the **Beam View** panel there is no special visualization of the AOI, except that the power distribution outside the AOI is suppressed.

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The **Wavefront Panel** is limited by the AOI as well and wavefront points outside are not displayed:



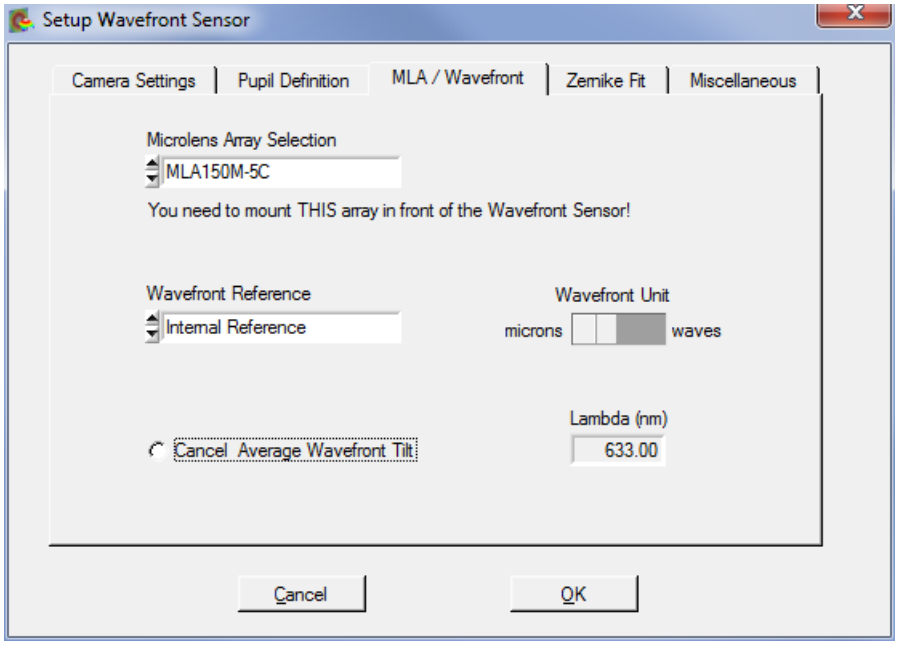
Numerical calculations like the Wavefront Peak-to-Valley or RMS and the entire Zernike calculation are also reduced to the area within the AOI.

Note

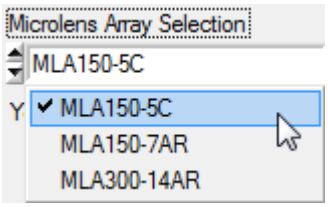
For a valid Zernike calculation, it is required that the pupil is well filled with valid spots. An AOI smaller than the pupil area may cause errors in the Zernike calculation.

5.4.2.1.3 MLA / Wavefront Tab

MLA / Wavefront Tab

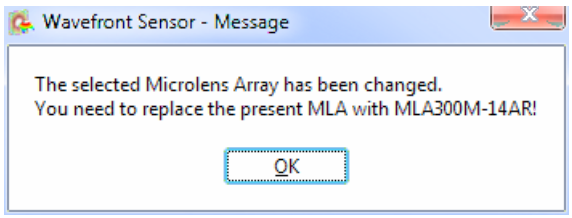


Microlens Array Selection



The mounted holder with a Microlens Array (MLA), installed on a Thorlabs Wavefront Sensor can be exchanged,, see Parts List section. Each MLA is factory calibrated with the individual Wavefront Sensor. The calibration data are saved to the WFS internal non-volatile memory. 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.

Selecting a different MLA than was recently used opens an alert message stating that the physically installed WFS MLA must match the software selection:



Attention

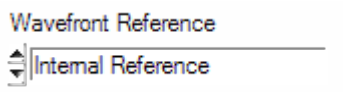
Make sure that the MLA selected in the software is the same as the MLA physically installed in your Wavefront Sensor. Otherwise, the software will use the wrong calibration data, which will result in incorrect measurement data.

Wavefront Reference

As a part of Thorlabs' factory calibration of the Wavefront Sensors, the centroid positions of all lenslet spots on the sensor surface are accurately determined for an incident planar wavefront. The Internal Reference calibration data file contains these centroid positions. To use the this factory-calibrated

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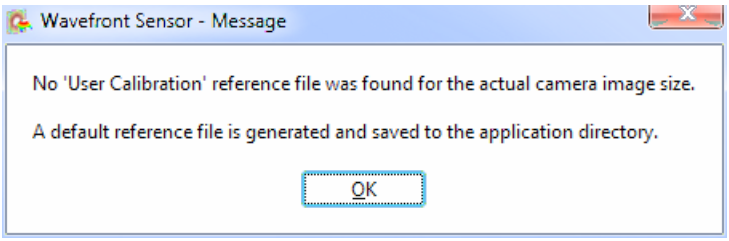
internal reference file for the analysis of the measured spot field centroids, select the Internal Reference option as shown below.



This internal reference is based on the well known and highly accurate parameters:

- Pixel Grid of the CMOS Sensor WFS31: 5.86 µm
- 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 Rotation between the Sensor Chip and the Lenslet Array
- Correction Parameters for Lenslet Astigmatism

This internal planar wavefront reference should be used unless the application requires a different calibration reference, such as a spherical wavefront reference. In this case, it is possible to perform User Calibration. There is no default **user calibration** delivered with the instrument. Therefore, if '**User Calibrated Reference**' id selected, a default reference is created and saved to the application directory.



This default user reference file is the internal reference. To create and use a different reference file, perform a User Calibration using the planar or spherical wavefront user-calibration options. It is necessary to provide the optical input reference when performing a user calibration. The planar wavefront user-calibration option can be used to record a reference of an arbitrary wavefront profile; however, the instrument will ensure that the wavefront meets certain specifications, detailed below, when the spherical wavefront user-calibration option is selected.

The **user reference file name** is automatically composed of the following data:

- WFS Serial Number
- MLA Name
- Camera Resolution Index

For instance: *WFS_M00224955_MLA150M-5C_2.ref*

The file saved to the following folder:

`My Documents\Thorlabs\Wavefront Sensor\Reference`

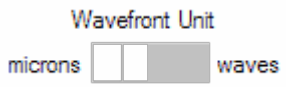
Note

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

Note

There can be only one User Calibration file defined for each combination of wavefront sensor head, MLA, and resolution.

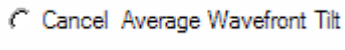
Wavefront Unit and Wavelength



Select the desired wavefront measurement units. Units of **microns** (µm) are absolute units. Provide the operating wavelength in nm to use units of **waves**.

Switch to the '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 the WFS31.

Cancel Average Wavefront Tilt



In real experiments, the direction of the input beam is not aligned perfectly perpendicularly to the sensor area. This means that the measured wavefront is determined for the most part by tip and tilt; the wavefront deformations are typically much smaller and cannot be seen in the wavefront panel. Since wavefront tip and tilt is mostly of less interest, this option allows to omit the average tip and tilt prior to wavefront and Zernike calculations.

Note

The average wavefront tip and tilt will not be removed completely. Small relics are still visible in terms of Zernike coefficients Z1 and Z2.

With the option **Cancel Average Wavefront Tilt** enabled, the displayed Zernike terms Z1 and Z2 are not related to the original wavefront, but to the tilt-corrected wavefront.

Default Settings

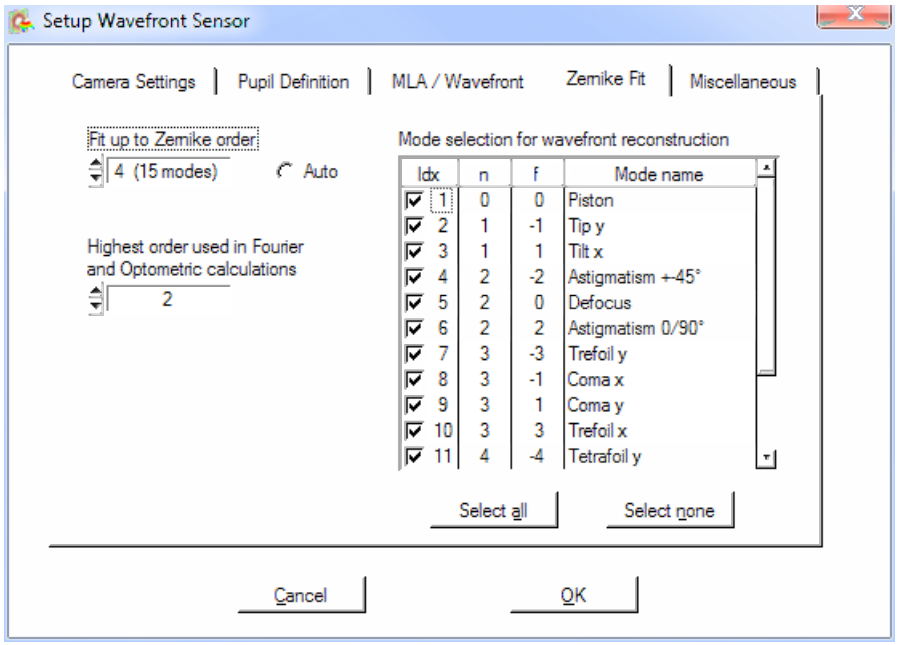
At the first start of the software, the following default settings are in use:

- Wavefront Reference: Internal Reference
- Wavefront Unit: µm
- Operating Wavelength: 633 nm
- Cancel Average Wavefront Tilt: Off

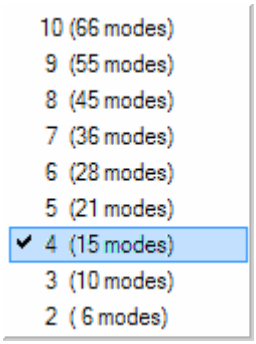
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5.4.2.1.4 Zernike Fit Tab

Zernike Fit Tab



Fit up to Zernike Order



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

According to the well known set of Zernike polynomials, ($\mathbf{r}^n$), the highest radial order, n, determines the number of Zernike modes that contain n or lower potencies of the pupil radius ***r***.

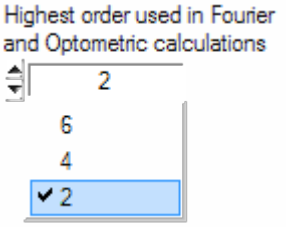
By default, the highest Zernike order is set to n = 4 which implies a total number of 15 Zernike modes. The resulting coefficients are displayed as a bar graph chart on the Zernike Coefficients panel.

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 that 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

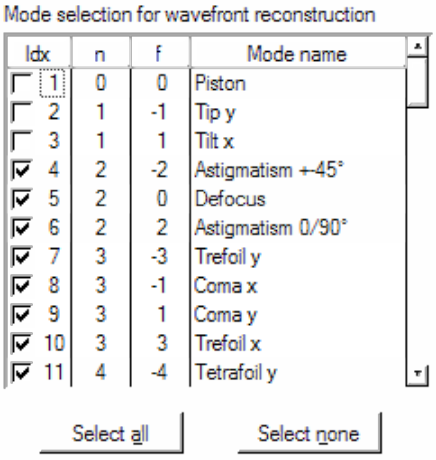


This control specifies that Zernike terms up to the selected number of 2, 4, 6 be used to calculate the numerical calculation of the Fourier coefficients M, J0 and J45 as well as the Optometric parameters Sphere, Cylinder and Axis.

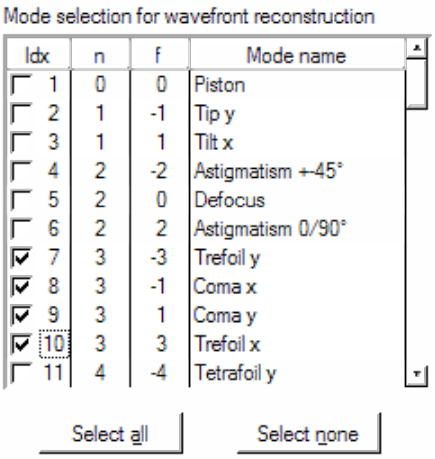
Mode Selection for Wavefront Reconstruction

This table provides a list of all calculated Zernike coefficients listed in rows. The total 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 a wavefront reconstruction 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:



Another example: In order to focus on modes that describe third order (n = 3), do the following selection:



Note

When 'Reconstructed' wavefront is selected, only the selected Zernike Modes will be displayed in the Wavefront panel. The numerical value Peak to Valley (PV) and RMS wavefront distortions depend on this mode selection as well.

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```
Wavefront/µm
(Internal Reference)
(entire area)
PV        39.159
RMS        9.484
wRMS       8.308
```

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

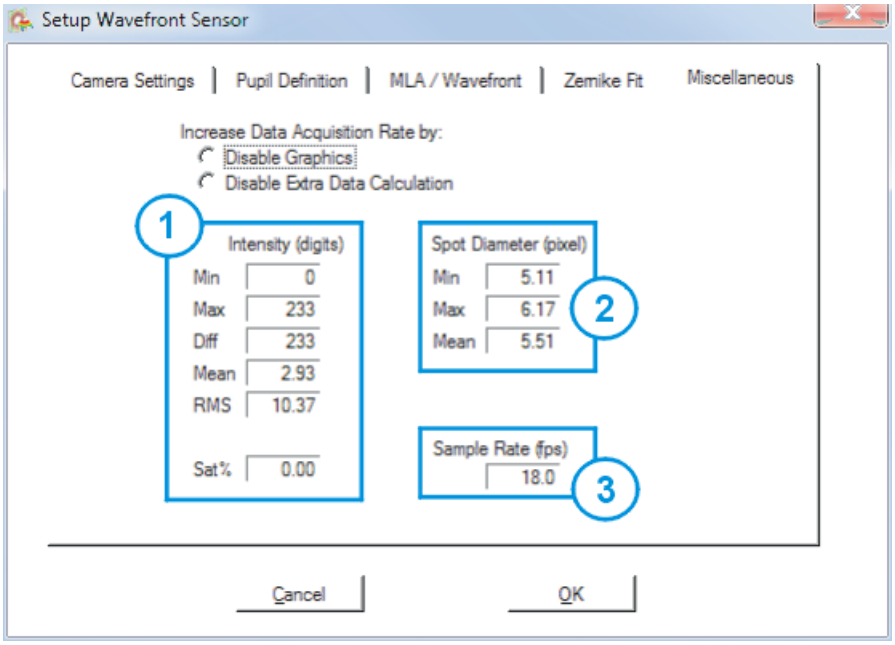
Default Settings

At the first start of the software, the following default settings are in use:

- Fit up to Zernike Order = 4 (Manual Setting)
- Highest Order in Fourier and Optometric Calculations = 2
- All Zernike Modes Selected for Wavefront Reconstruction

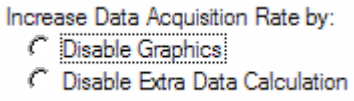
5.4.2.1.5 Miscellaneous

Miscellaneous



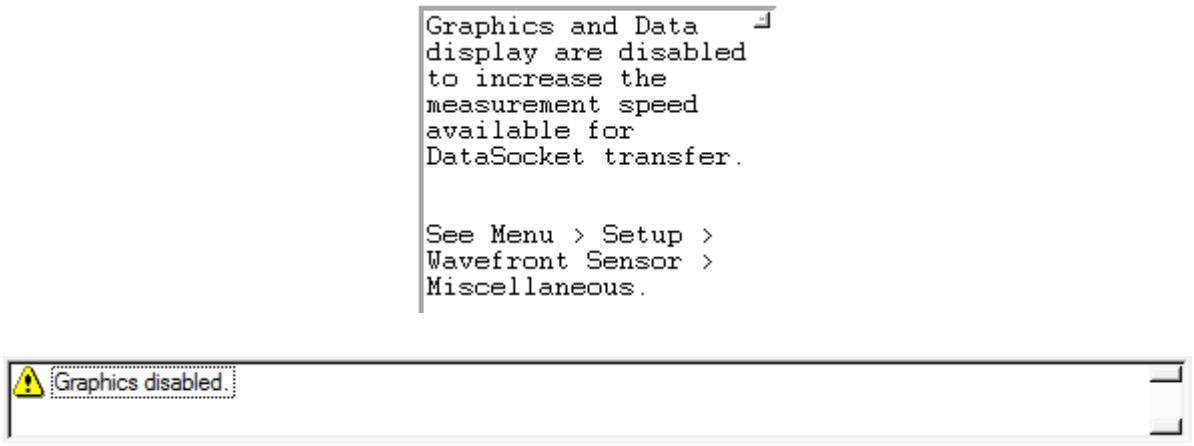
1. Intensity (digits): The maximum pixel intensity (Max) must not reach 255 digits to prevent sensor saturation Below Mean and RootMeanSquare (RMS), Sat% indicates how many pixels are in saturation.
2. The calculated values of Spot Diameter are used to verify the optical quality during assembly.
3. The Sample Rate in frames per second (fps) is an indication of the measurement speed.

Speed Up the Measurement



- If the WFS software is connected to the DataSocket interface, the software is used as a data source for a user application that is connected via the interface. In this case the graphical displays become redundant and the 'Disable Graphics' option can be used to disable GUI display updates. This saves calculation time and increases measurement speed. All graphs including the output

panel for numerical parameters are cleared. A corresponding message in the parameter box and in the status bar will appear:



- If the image statistics and the spot diameter calculations are of less interest, these calculations can be omitted. This speeds up the measurements as well. Check the option Disable Extra Calculation.
- The measurement speed can be increased by selecting a lower camera resolution (Camera Settings), resulting fewer spots used for the calculation.

Default Settings

At the first start of the software, the following default settings are in use:

- Disable Graphics = Off
- Disable Extra Data Calculation = Off

5.4.2.2 DataSocket Configuration

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

For more information, please see the chapter Data Socket for Live Data Transfer.

Note

Since the DataSocket interface of the Wavefront Sensor software is **not** capable of controlling the measurement parameters of the Wavefront Sensor, it is only possible to transmit the measurement data to a DataSocket receiver.

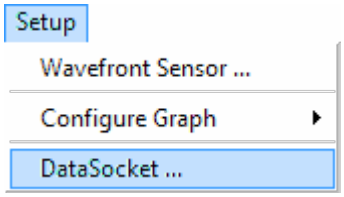
The following possible scenarios are imaginable:

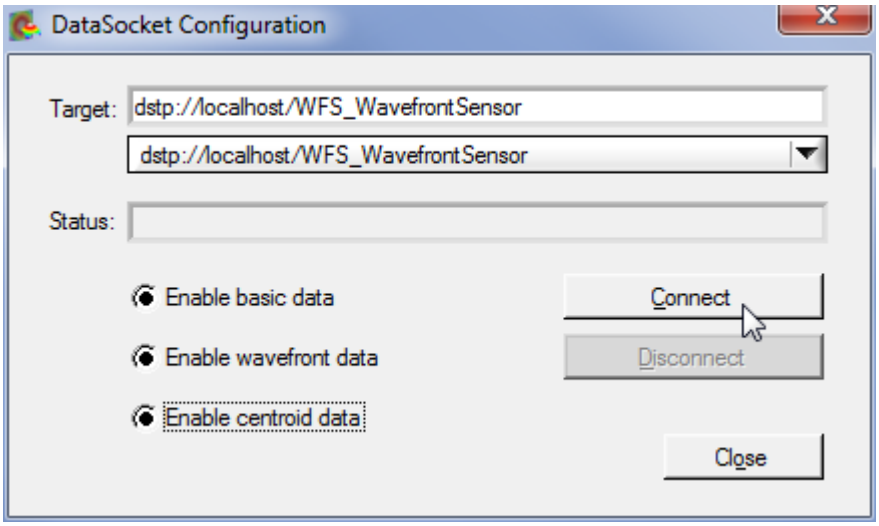
1. PC "A" runs the Wavefront Sensor application that sends the measurement data to the local DataSocket server running on the same computer. Another application on the same PC "A" retrieves the data.
2. PC "A" runs the Wavefront Sensor application that sends the measurement data to the local DataSocket server running on the same computer. An application on a PC "B" retrieves the data. PCs "A" and "B" are connected via a network.

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3. PC "A" runs the Wavefront Sensor application that sends the measurement data to the remote DataSocket server that is running on PC "B". An application on PC "B" retrieves the data.
4. PC "A" runs the Wavefront Sensor application that sends the measurement data to a DataSocket server which is running on PC "B". An application on a third PC "C" retrieves the data from the DataSocket server on PC "B". All PCs are connected via a TCP/IP network.

Select the DataSocket Configuration from the Setup Menu:





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 network computer, **first** start the DataSocket server on the network computer and configure it according to the description in the chapter DataSocket for Live Data Transfer. Then type in the correct network name of the target network computer hosting the DataSocket server.
For instance: *dstp://[pc_name].[domain_name]/WFS_WavefrontSensor*

The name of this computer is displayed in the appropriate DataSocket server panel. Then click '**Connect**'. In case of failure, look for firewall settings - these may block the data transfer (DataSocket for live data transfer).

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

Enable Basic Data

Check this box to have the software continuously send setup and result data from the WFS measurement to the DataSocket server. See the chapter Available Data Items for a detailed description of the submitted data items.

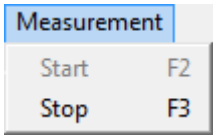
Enable Wavefront Data

Check this box to transfer the entire wavefront data array to the DataSocket server. As the data volume increases considerably in comparison with basic data transfer, the transfer speed will decrease. See the chapter Available Data Items for a detailed description of the submitted data items.

Enable Centroid Data

Check this box to send entire centroid data arrays (for X and Y coordinates separately) to the DataSocket server. The transfer speed will decrease due to the transmitted data volume. See the chapter Available Data Items for a detailed description of the submitted data items.

5.4.3 Measurement Menu



This menu includes controls for starting, stopping, and re-starting the measurement.

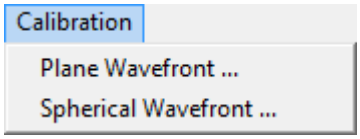
Stop: **F3** or in the tool bar. Stops the current measurement immediately and terminates screen updates. The numerical values and data displayed in the plots are preserved, so that the data can be examined and/or saved.

Start: **F2** or in the tool bar. Starts / restarts the continuous measurements and displays the results on the screen.

Note

The continuous measurement will stop automatically if severe measurement errors occur. You will be asked to check settings and to re-start the continuous measurement again.

5.4.4 Calibration Menu



Start a user calibration of the incident to the sensor wavefront. The Wavefront Sensor can be calibrated for a spherical wavefront (toolbar:) as well as a planar or arbitrary wavefront (toolbar:).

A user calibrated reference can increase the measurement accuracy when the desired wavefront includes small distortions. To perform a user calibration, the desired wavefront is used as an optical input. The resulting User Calibrated reference can then be used in place of the default internal calibration reference. The user calibrated reference is then used as the reference against which all subsequent measurements are evaluated, and it will allow accurate measurement of wavefront distortions introduced by optical elements in the light path.

The **user reference file name** is automatically composed of

- the WFS serial number,
- the MLA name,
- and the camera resolution index.

For instance: *WFS_M00224955_MLA150M-5C_2.ref*

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The file saved to the following folder:

`My Documents\Thorlabs\Wavefront Sensor\Reference`

Note

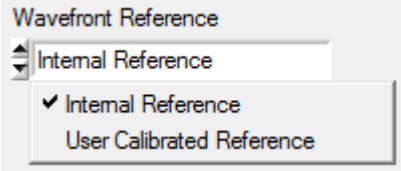
Do not change the content of these reference files, they might become unusable!

Note

There can be only one User Calibration file defined for each combination of wavefront sensor head, MLA, and resolution.

After successful user calibration and saving the reference file, the user reference is activated automatically.

Use the 'Wavefront Reference' in the Wavefront Sensor Setup Panel to switch between internal and user calibration.



Note

The accuracy of the calibration increases if image averaging is set to > 1, see the Camera Settings panel.

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

If the 'User Calibration' option is enabled, the stored file for a particular camera, MLA, and resolution is automatically loaded at program start and every time the camera resolution or MLA is changed.

5.4.4.1 Spherical Wavefront

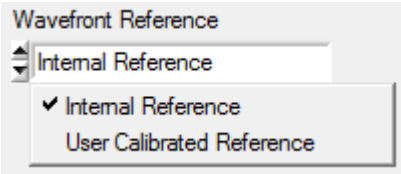
User Calibration Using a Spherical Wavefront

In order to perform a spherical wavefront user calibration you need to apply a high-quality divergent beam that originates from a point source with 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 insufficiently illuminated regions of the camera sensor. Although no error occurs, the corresponding area will be excluded from further wavefront measurements.

1. Select the **Internal Reference** in the Wavefront Sensor Setup panel:

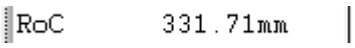


2. Adjust the point source so that it is centered in front of the Wavefront Sensor at a distance in the range 100 mm to a maximum of 5 m.

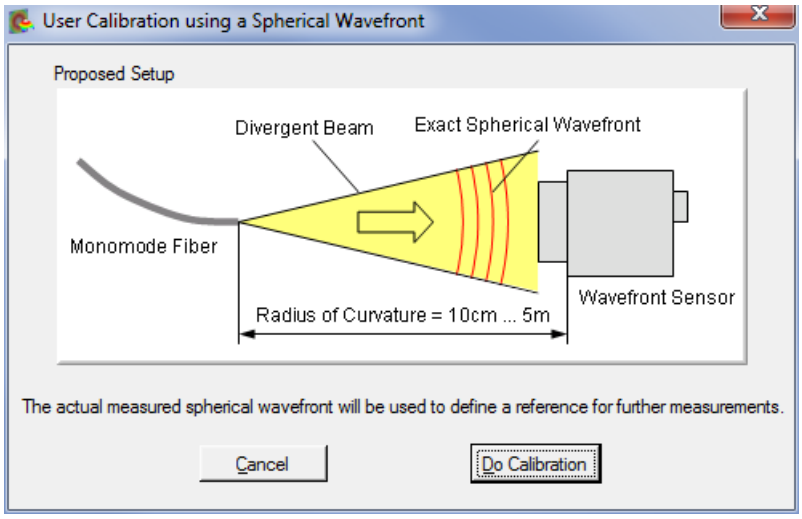
Note

The geater the distance between the point source and the WFS, the lower the curvature of the wavefront. In other words, the spot displacements decrease and the measurement of the wavefront curvature becomes more sensitive to noise and ambient light. In addition, the power density on the CMOS sensors drops with the square of distance, which also increases the impact of noise sensitivity on the measurement. For these reasons, it is recommended that the distance to the source not exceed 500 mm.

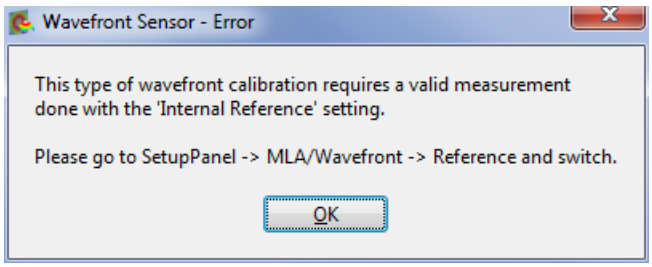
The Radius of Curvature (RoC) is calculated and displayed by the WFS software. Assuming a point source and propagation in air, the RoC is equivalent to the distance between the camera sensor and the light source.



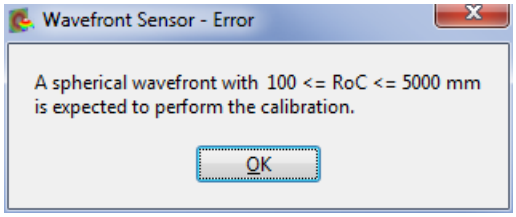
3. Start the calibration procedure using **Menu Calibration Spherical Wavefront** or simply click on the appropriate symbol in the toolbar. The dialog window illustrates the required calibration setup:



4. Click '**Do Calibration**' to perform the user calibration. In the case that a user reference is enabled, an error message will come up

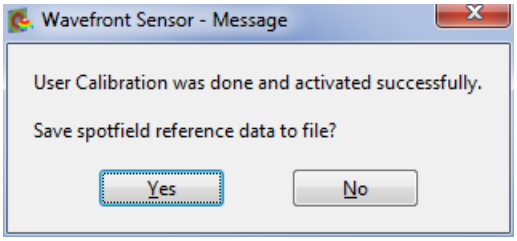


5. If the RoC is too large (point source too close to the WFS) or too small (point source too far from the WFS), the following error occurs.



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6. Change the setup accordingly and repeat the calibration. Go back to Step 4, Click '**Do Calibration**' to perform the user calibration and the following message verifies successful operation:



7. You are asked to save the reference data to a file. Click '**Yes**' to store this user calibration to a predefined file within your **My Documents** directory to keep it for future WFS software sessions. Otherwise, if you click '**No**' the calibration remains in memory and active, but will be lost as soon as the software is exited or when the sensor resolution (see Camera Settings) or the MLA selection (see the chapter Wavefront Setup) is changed.

5.4.4.2 Planar Wavefront

User Calibration Using a Planar Wavefront

In order to perform a planar wavefront user calibration you need to apply a high-quality beam that has a perfectly planar wavefront. Be sure the beam is properly aligned to the Wavefront Sensor and fills the selected active camera area completely.

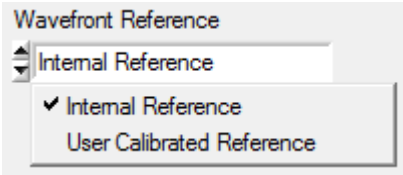
Note

This calibration option can also be used to create a calibration reference of an wavefront with an arbitrary profile.

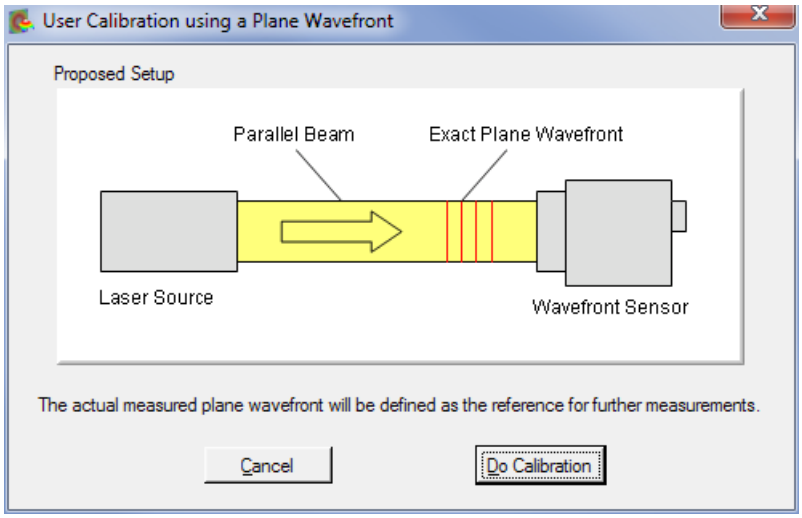
Note

The calibration fails for insufficiently illuminated regions of the camera sensor. Although no error occurs, the corresponding area will be excluded from further wavefront measurements.

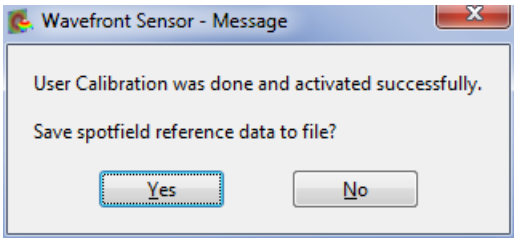
1. Select the **Internal Reference** in the Wavefront Sensor Setup panel:



2. Adjust the light source, start the calibration procedure using **Menu → Calibration → Plane Wavefront** or simply click on the appropriate symbol in the toolbar. The dialog illustrates the required calibration setup:

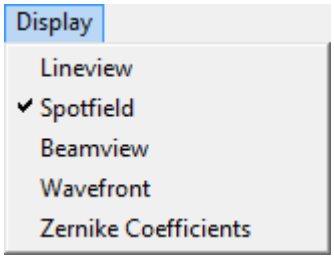


3. Click '**Do Calibration**' to perform the user calibration.



4. You are asked to save the reference data to a file. Click '**Yes**' to store this user calibration to a predefined file within your **My Documents** directory to keep it for future WFS software sessions. Otherwise, if you click '**No**' the calibration remains in memory and active, but will be lost as soon as the software is exited or when the sensor resolution (see Camera Settings) or the MLA selection (see chapter Wavefront Setup) is changed.

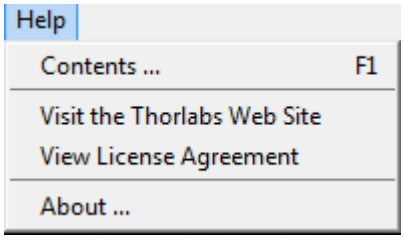
5.4.5 Display Menu



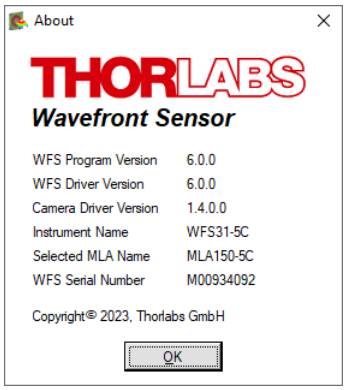
Select the graphical display panel to be shown in the GUI. The same selection can be made just by clicking to the appropriate tab of the graphical display. The displays are explained in the chapter Graphical Display Panels.

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5.4.6 Help Menu



- **Contents (F1)**
  This opens the Wavefront Sensor software help file.
- **Visit the Thorlabs Website**
  Open the Thorlabs website.
- **View License Agreement**
  Display the Thorlabs End User License Agreement.
- **About**
  This displays information about the installed software, driver versions, and the connected hardware (WFS type, selected MLA and serial number). Please have this information ready when contacting Thorlabs for technical support.



5.5 Tool Bar



The most common menu functions can be quickly accessed via the tool bar:

- Save Measurement Data
- Print Window
- Setup Wavefront Sensor
- Start Measurement
- Stop Measurement
- Calibrate with Planar Wavefront
- Calibrate with Spherical Wavefront
- Open the WFS Software Online Help

5.6 Numerical Measurement Results

Numerical measurement results are displayed on the left side of the main panel.

Note

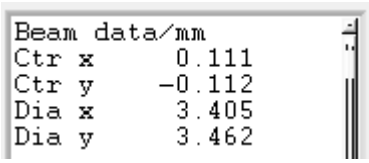
These data are valid when no error occurs during image capture and the subsequent data analysis. To ensure no errors occurred, check the error messages, such as the one shown below, displayed in the status bar at the bottom of the GUI.



Note

If **'No instrument errors'** does **not** appear in the status window you **cannot** rely on the measurement results! Please refer to Measurement Warnings and Errors for a listing of possible errors.

Beam Data



Calculated from the centroid and the second moment of the entire camera image, the beam data include the beam center coordinates **Ctr x** and **Ctr y** and the beam diameter **Dia x** and **Dia y** in X and Y direction, displayed in mm. In the case of a Gaussian beam shape, the second moment coincides with the beam width at the standard 1/e2 clip level.

Please take into account that these data cannot give an exact measure of the beam because the lenslet array in front of the camera and wavefront distortions change the intensity distribution between the real beam and the camera image. Furthermore, high ambient light levels and an improper 'Black Level' camera setting (see Camera Settings) may distort the beam data results.

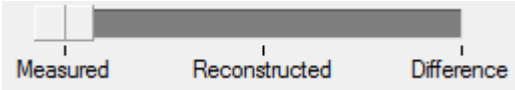
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Wavefront Data

Wavefront/µm	
(Internal Reference)	
(entire area)	
PV	39.159
RMS	9.484
wRMS	8.308

These wavefront statistics are displayed in microns or waves, depending on the user selection (Wavefront Sensor Setup panel). Calculated data are related either to the entire wavefront image or to the pupil interior only. The pupil area defines the area of interest of the beam and can be defined by the user. Please see the section Pupil Definition Tab for information on entering the pupil parameters.

The calculated wavefront statistics refer to the wavefront display (Measured, Reconstructed or Difference), selected in the Wavefront Panel:



PV Total Peak-to-Valley Value, i.e., the Maximum Variance of the Wavefront in the Observed Area

RMS Root Mean Squared Average Value

wRMS Intensity Weighted Root Mean Square Average Value Higher Intensity Spots in the Pupil Center have more Weight than Lower Intensity Spots away from the Center.

Fourier Constants

Fourier	
M	1.741
J0	−0.046
J45	0.034

The Fourier Constants M, J0 and J45 are derived from the Zernike coefficients. Depending on the setting in the Zernike Fit Tab of the Wavefront Sensor Setup panel, Zernike orders up to 2, 4 or 6 are used to calculate these constants.

Optometric Constants

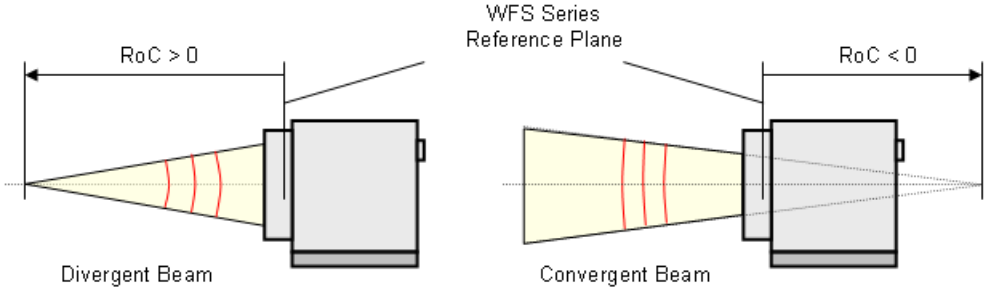
Optometric/dpt	
Sphere	1.798
Cyl.	−0.115
Axis	71.626°

Optometric Constants are Sphere, Cylinder (in diopters) and the Axis Angle of the cylinder in degrees. Depending on settings in the Zernike Fit Setup panel, Zernike orders up to 2, 4 or 6 are used to calculate these constants.

Radius of Curvature RoC

RoC	574.42mm

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 equal to the distance (in air) between the reference plane of the WFS and the point source of the spherical wavefront.



Positive RoC distances represent divergent spherical wavefronts where the point source is located in front of the Wavefront Sensor reference plane, whereas negative values indicate a convergent spherical wavefront with a virtual focal point that lies behind the Wavefront Sensor reference plane. The higher the absolute RoC value, the flatter the corresponding wavefront and the higher the parallelism of the beam.

In the case of a planar wave front, the Z5 term theoretically should be 0, and the RoC infinite. As a result, the wavefront sensor will not be able to measure large RoC values accurately. In order .to indicate the reduced accuracy of of RoC values ≥ 10.000mm, the result will be displayed in the following format:

```
RoC    (     22.6m)
```

RMS Variations

```
RMS Variations/µm
RMS(n = 0)     4.047
RMS(n = 1)     9.818
RMS(n = 2)     0.044
RMS(n = 3)     0.029
RMS(n = 4)     0.016
```

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

Zernike Modes

```
Zernike Modes/µm
Z 1(0/ 0)      4.047
Z 2(1/-1)     -8.677
Z 3(1/ 1)      4.594
Z 4(2/-2)     -0.019
Z 5(2/ 0)     -0.018
```

The coefficients of the Zernike modes which are determined by a least square fit to the measured wavefront are displayed either 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    6.219e-10
Stddev 1.722e-04
```

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

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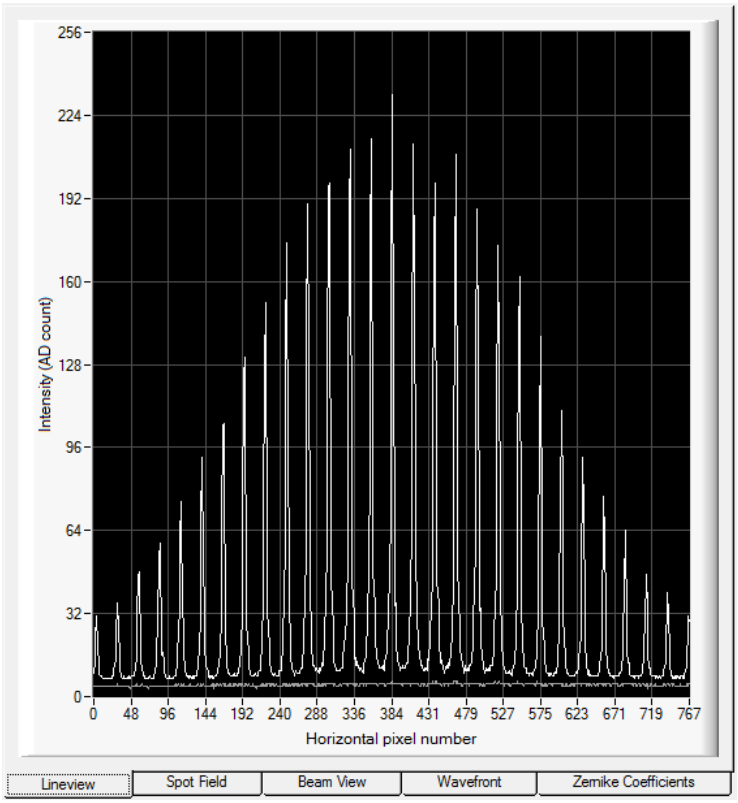
5.7 Graphical Display Panels

The graphical display can be selected either from the menu **File → Display** or by clicking to the appropriate tab below the graph area:



5.7.1 Lineview Panel

In this graph, the horizontal intensity distribution of the CMOS camera is displayed. Each point on the horizontal axis of the diagram corresponds to one column of the 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 concentrates the intensity within small spots.

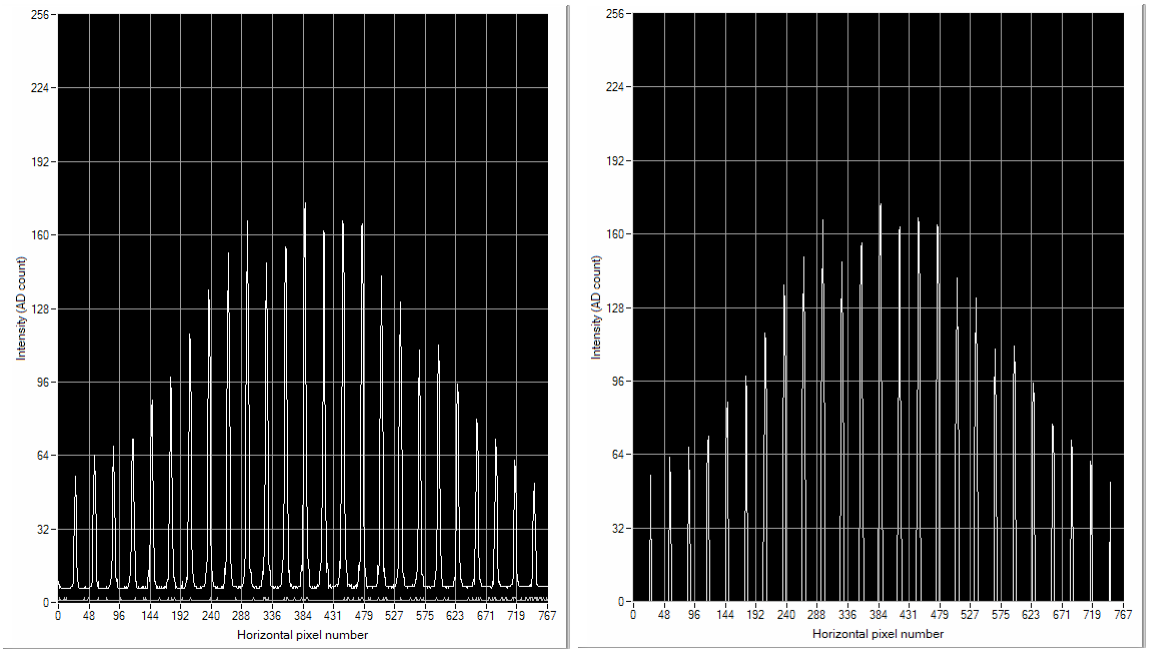


This graph is useful for checking the power level of the analyzed beam, particularly with the auto exposure control disabled. Improper manual settings of the camera will lead to low or saturated peak intensities or to saturation. Avoid this by a proper adjustment of the **Exposure Time** and **Master Gain** (see section Camera Settings).

The **Black Level** setting of the camera introduces an offset to the brightness level for all illuminated pixels and should be adjusted in such way that the minimum (noise) line is visible. See section Camera Settings for a detailed description.

In the Lineview panel the influence of the **Noise Cut Level** setting can be observed easily. The Noise Cut Level defines a minimum threshold brightness level. Only measurements from pixels that exceed this threshold are used during subsequent data analysis. The effect of the Noise Cut Level on the Lineview panel is shown in the images below. One use of this function is to mitigate the effect of a

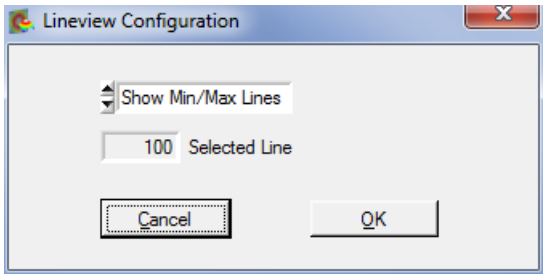
significant ambient light level on the determination of spot centroids. The ambient light background can be rejected by setting the 'Noise cut level' to a value higher than the valleys in the diagram.



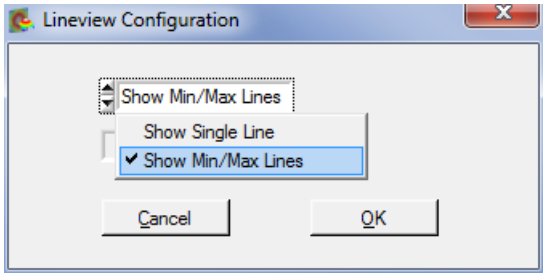
Noise Cut Level = 0 ***Noise Cut Level = 50***

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

The **Lineview Configuration** panel opens by double clicking to the graph area:



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

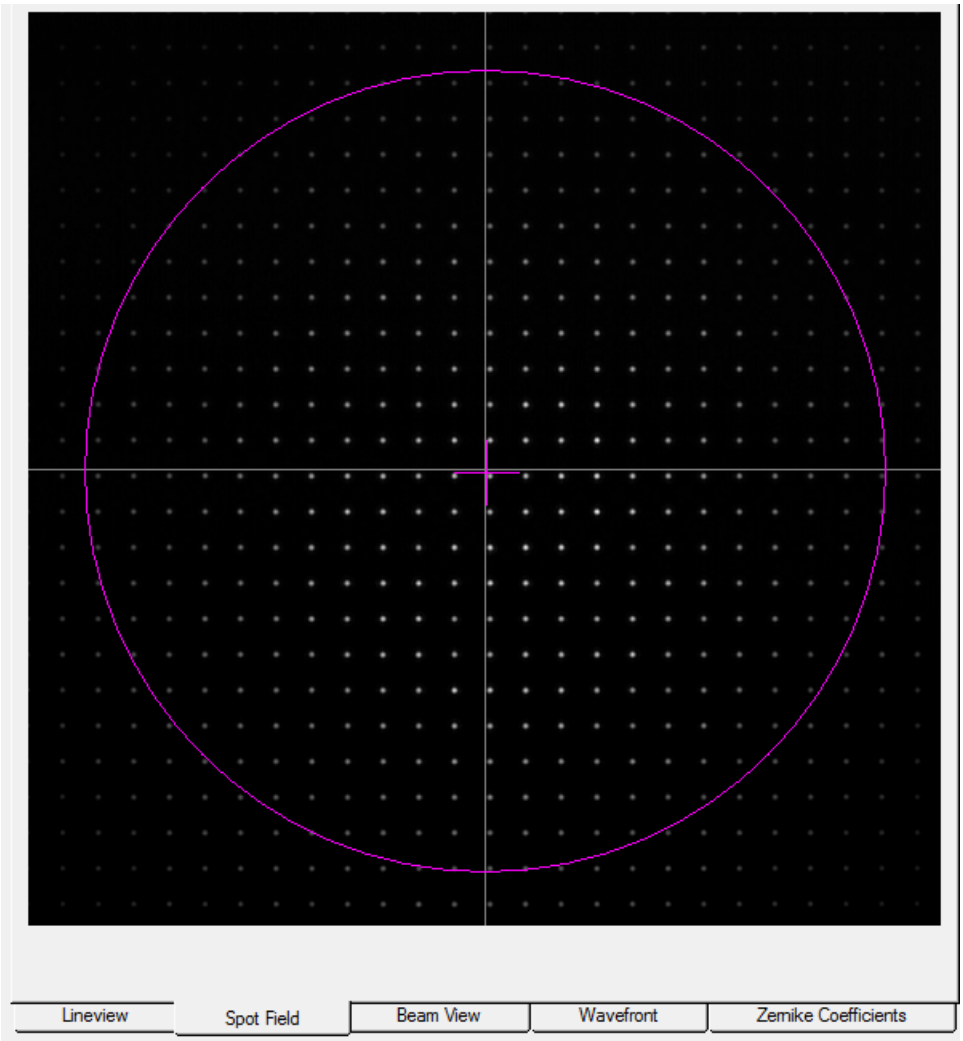


Switch to '**Show Single Line**' in order to enable selection of a single line out of the sensor array. Enter the line number into the '**Selected Line**' control to see the intensity distribution of the appropriate CMOS row. The line number ranges from 0 (bottom) to the number of vertical pixels - 1.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

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5.7.2 Spot Field Panel

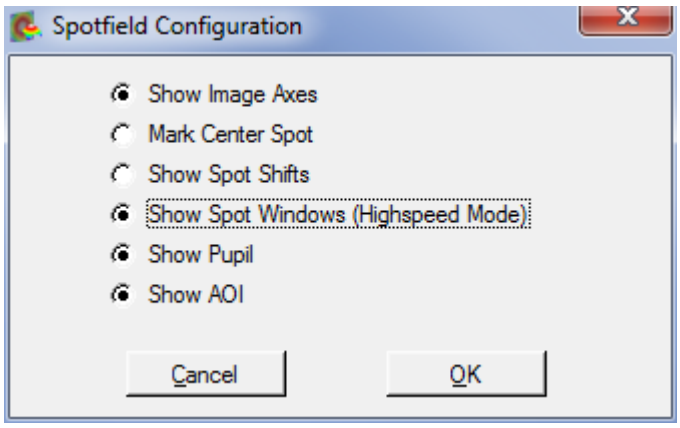
The Spot Field panel shows the direct view of the image taken by the CMOS camera. Intensity levels are displayed as gray scale levels from 0 (black) to 254 digits (white), while saturated pixels are displayed in red.



The camera resolution and the number of spots in the horizontal and vertical direction can be selected in the Camera Settings panel. The Camera Image Size should be chosen slightly larger than is required to display the entire beam. This ensures that the entire beam is analyzed as well as minimizing the unused area of the camera sensor. Pixels that are not illuminated by the beam can contribute to measurement error, and including them in the data analysis also decreases the measurement speed. Note that the camera image size affects the camera resolution, which is the pixel dimensions of the active sensor area.

Additional graphical elements described in the following can be displayed as overlays on the image.

The **Spot Field Configuration** panel opens by double clicking on the graph area:

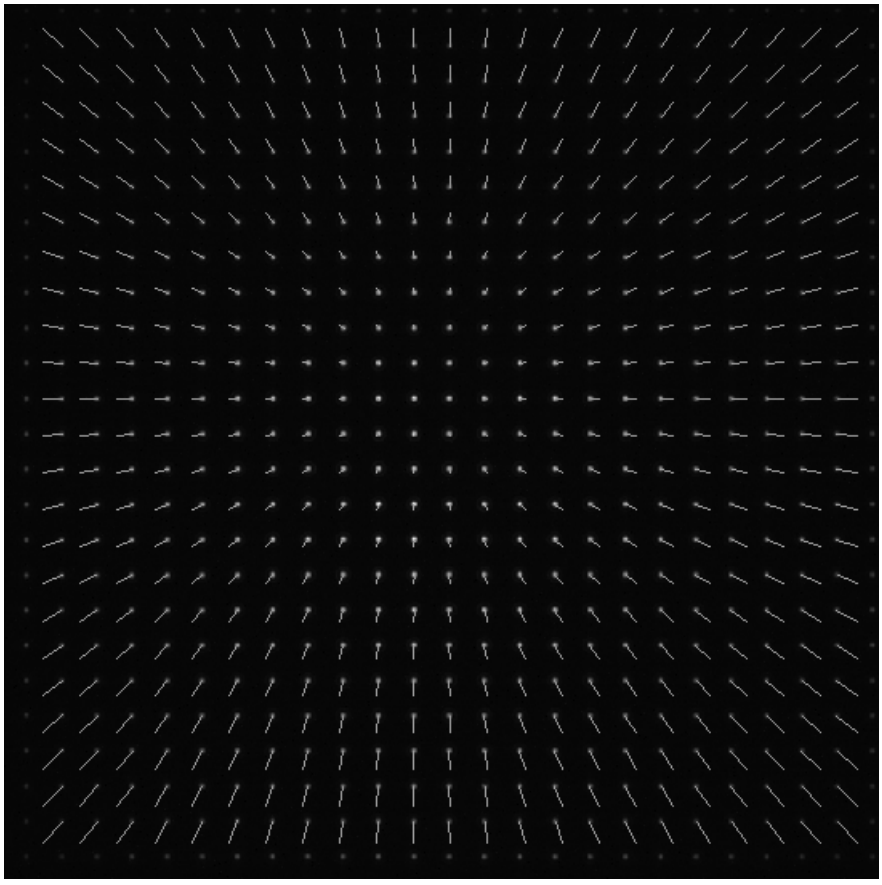


Enable the appropriate option to visualize the graphical items:

Show Image Axes Displays the Center Axis in Horizontal and Vertical Directions

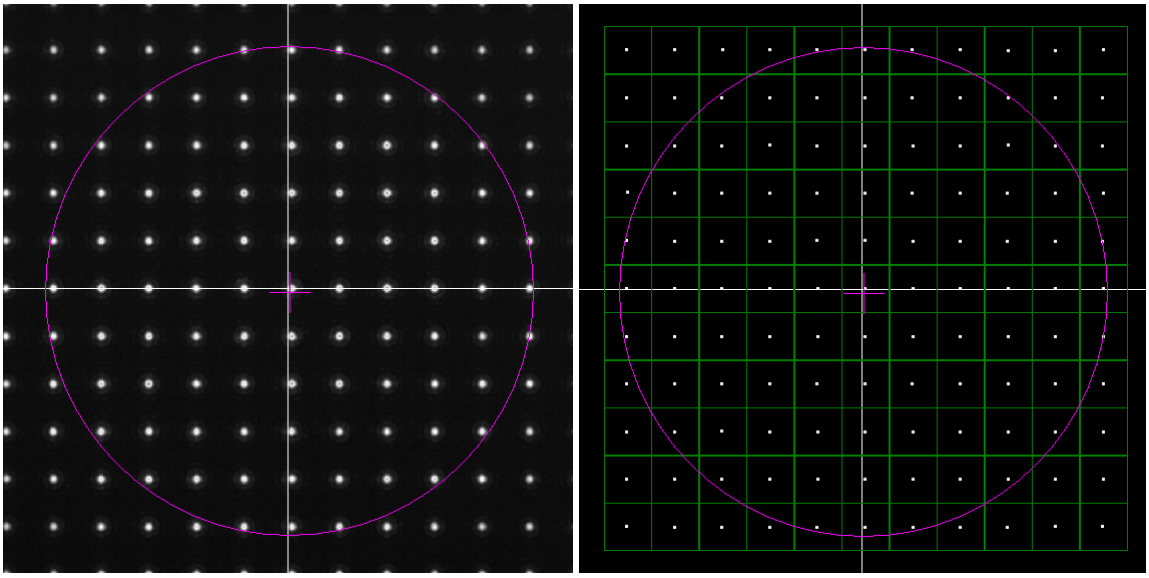
Mark Center Spot Marks the Spot at the Image Center that Acts as the Starting Point for the Centroid Determination Algorithm

Show Spot Shifts Displays the Shift Between the Actual Spot Position and its Corresponding Reference Position as a Gray Line (Shown in the Image Below)



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Show Spot Windows is an option that is available only for WFS20 instruments in high speed mode (see chapter "WFS20 Highspeed Mode" in the WFS20 Operation Manual):



WFS20 in Normal Mode ***WFS20 in High Speed Mode***

In normal mode, the software receives the complete image data file measured by the camera. The Spot Field panel display (left) shows the real camera image and measured spots. In contrast, when WFS20 instruments operate in High-Speed Mode, only the calculated centroid locations of the spots are sent from the control box to the software. The Spot Field panel display in High-Speed Mode (right) consequently depicts the centroid location of each spot within the defined spot window (green lines). This display allows the user to observe whether the spots are within their calculation windows.

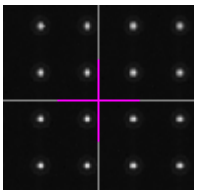
Show Pupil displays a purple circle or ellipse that represents the actual pupil size and position.

Use this panel with the 'Show Pupil' option activated to interactively align the beam 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 must be activated in the Pupil Definitions Setup panel to show the actual beam centroid.

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

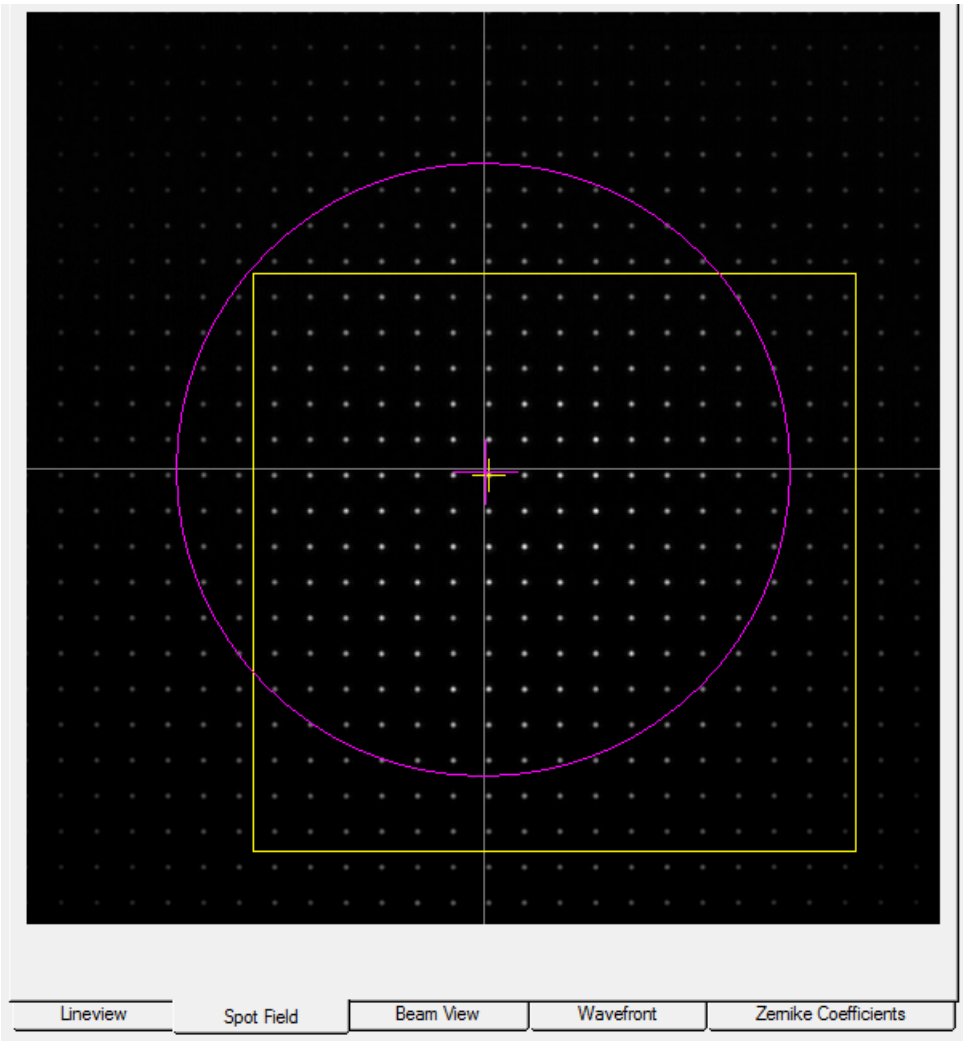


Show AOI

The WFS software allows an area of interest to be defined (see section Settings). When this function is enabled, the position and size of the AOI is shown in yellow and the Zernicke calculations are based on the data from the AOI only.

Note

For a valid Zernike calculation, it is required that the pupil is well filled with valid spots. An AOI smaller than the pupil area may cause errors in the Zernike calculation.

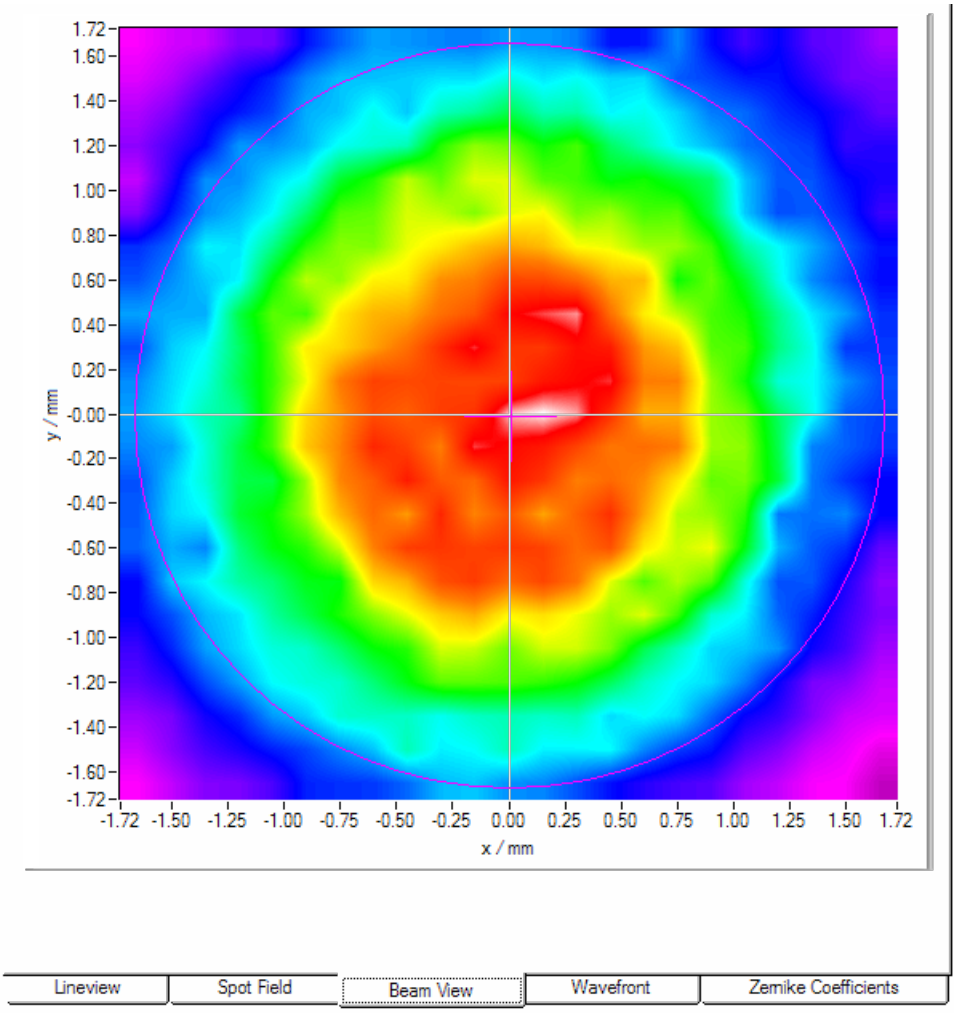


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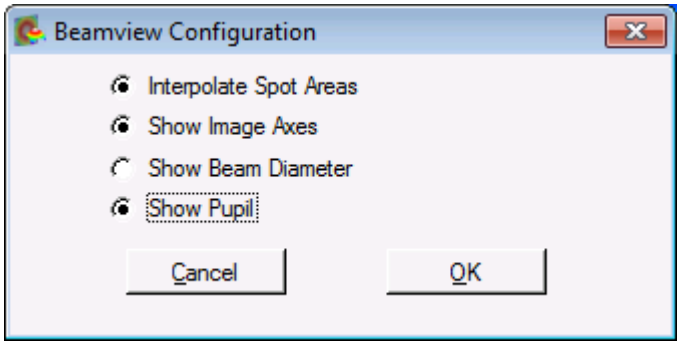
5.7.3 Beam View Panel

The Beam View panel provides an overview of 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 a lower resolution.

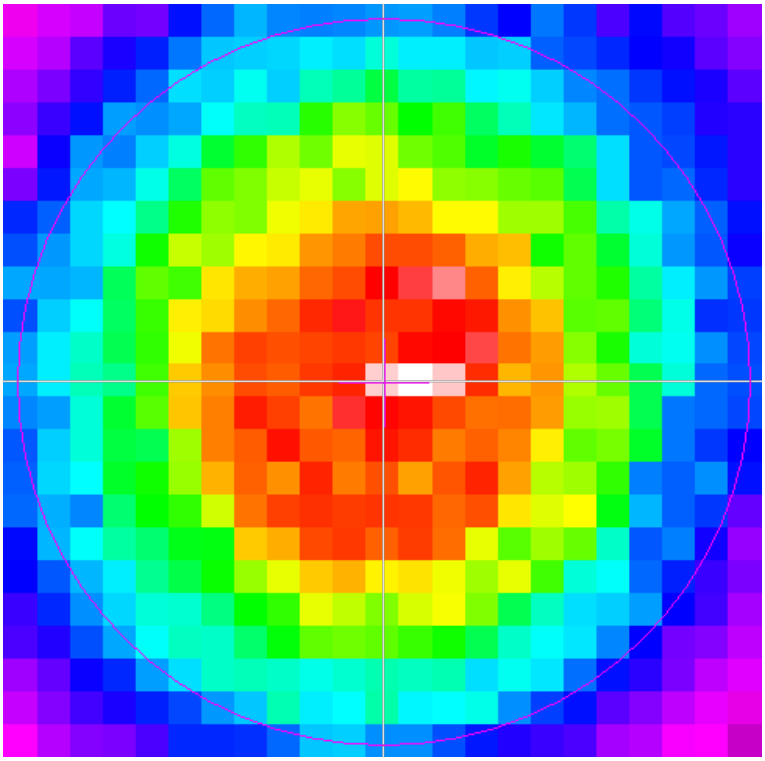
The lateral resolution is not determined by the camera pixel size as in the case of a real Beam Profiler, but rather delete by the pitch of the lenslet array. Each point of the displayed intensity array is derived from the calculated mean intensity of the corresponding spot.



The **Beamview Configuration** panel opens by double clicking to the graph area:



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



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

'Show Beam Diameter' displays a gray circle or ellipse that represents the actual beam diameter and position.

'Show Pupil' displays a purple circle or ellipse that represents the actual pupil size and position.

Note

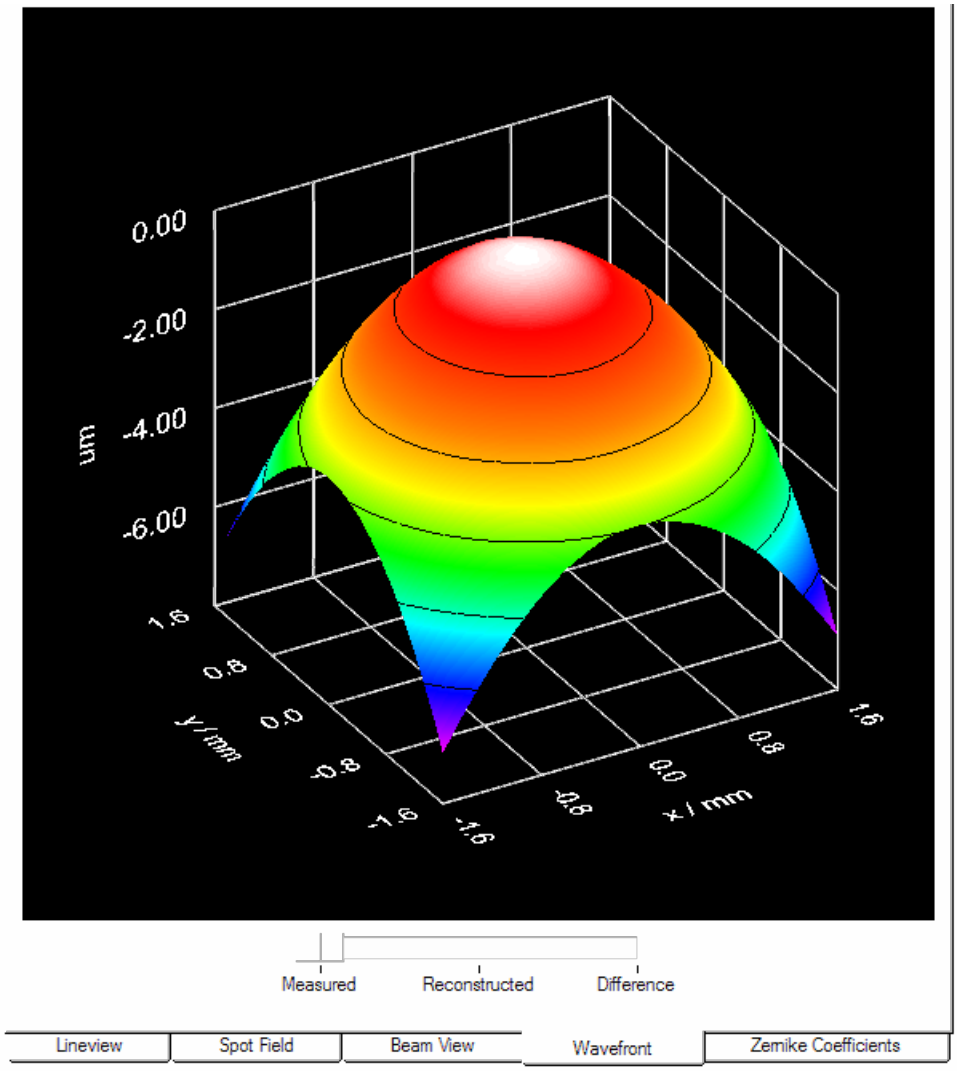
Usually, there is a difference between the actual size and position of the beam and the pupil. Both parameters will coincide only if the options **'Use Beam Width'** and **'Use Beam Centroid'** are enabled (see chapter Pupil Definition Setup).

This display is also available for WFS20 instruments in High-Speed Mode with the only difference being that the appropriate intensities are calculated within the camera's FPGA (control box).

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5.7.4 Wavefront Panel

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



The wavefront deformation is displayed in the direction of the Z axis, while the base surface, defined by the x and y axes, is parallel to the cross section of the beam. The wavefront units can be selected to microns (µm) or waves (see Wavefront Sensor Setup panel).

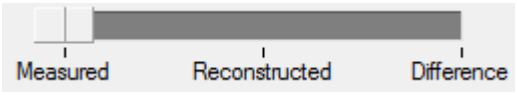
The surface is displayed as a color spectrum. The assignment between color and curve height is always the same:

- Black, Purple: Lowest Wavefront Parts
- Green: Medium
- Red, White: Highest Wavefront Parts

With the option '**Limit wavefront calculation and display to pupil interior**' (Pupil Definition Setup) enabled, only the wavefront data that are measured within the defined pupil will be displayed. This can be advantageous in the case that the wavefront measurement outside the pupil is affected by noise due to low light intensity.

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**' displays the wavefront that is reconstructed using the selected set of the determined Zernike coefficients (Zernike Fit Setup). The advantages of this display are:

- Selecting only a few Zernike modes of lower order for reconstruction smooths the wavefront surface (noise canceling).
- The lowest order Zernike modes (for instance Z1 piston, Z2 tip and Z3 tilt) are always present but they are of less interest. Using an appropriate reconstruction (e.g., starting from Z4) can omit the Z1, Z2 and Z3 Zernike modes in order to see only the higher order modes.
- If selecting particular Zernike modes, they 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 impacts the calculated wavefront statistics PV, RMS and wRMS (see Measurement Results) because the statistic values refer to the selected wavefront (Measured, Reconstructed or Difference).

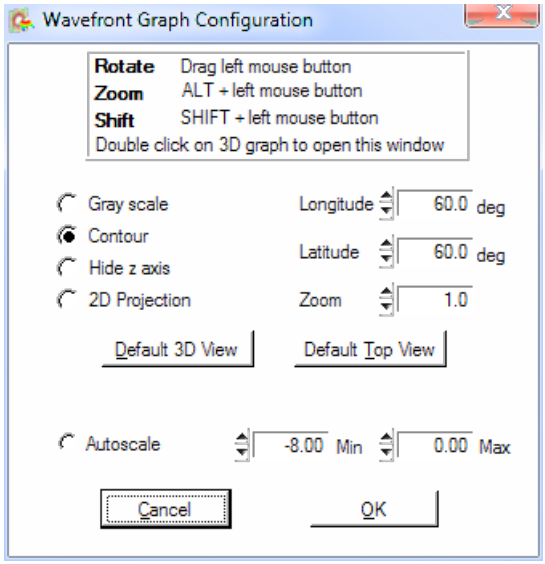
Direct rotation, Zoom and Shifting of the 3D Graph

Rotate the graph: Click and hold the left mouse button on the graph, then drag the mouse.

Zoom the graph: Use the mouse wheel.

Shift the graph: Press the Shift key, click and hold the left mouse button while dragging the mouse.

Double click on the graph area to access the **Wavefront Graph Configuration** panel:

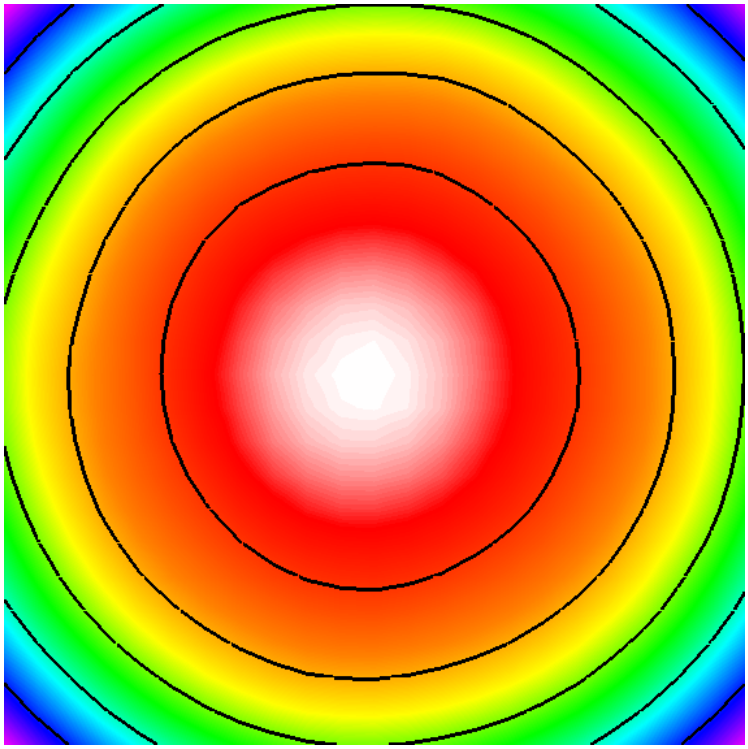


There are two predefined view adjustments, 'Default 3D view' and 'Default top view'.

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'**Default 3D View**' arranges the view angles so that all three axes can be seen and the wavefront can be viewed as a 3D object.

'**Default Top View**' sets the 'Latitude' view angle to zero and allows a view parallel to the Z axis towards the X-Y plane. The X-Y plane becomes rectangular and the wavefront height is only indicated by its color.



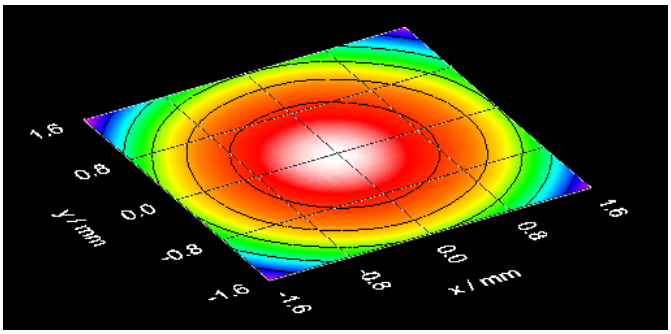
The following options define the look of the 3D graph.

'Gray scale' switches 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' collapses the 3D graph to the base X-Y plane



The following items define the view of the 3D graph.

'Longitude' determines the rotation angle around the Z axis.

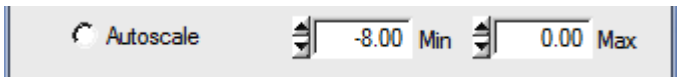
'Latitude' determines the view angle to the graph.

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

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

Autoscale

By default, the graph's Z axis is auto-scaled to utilize the full diagram heights, independent of the wavefront dynamic. Switch the **'Autoscale'** option off to enter manually defined values for the displayed range of the Z axis.



Note

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

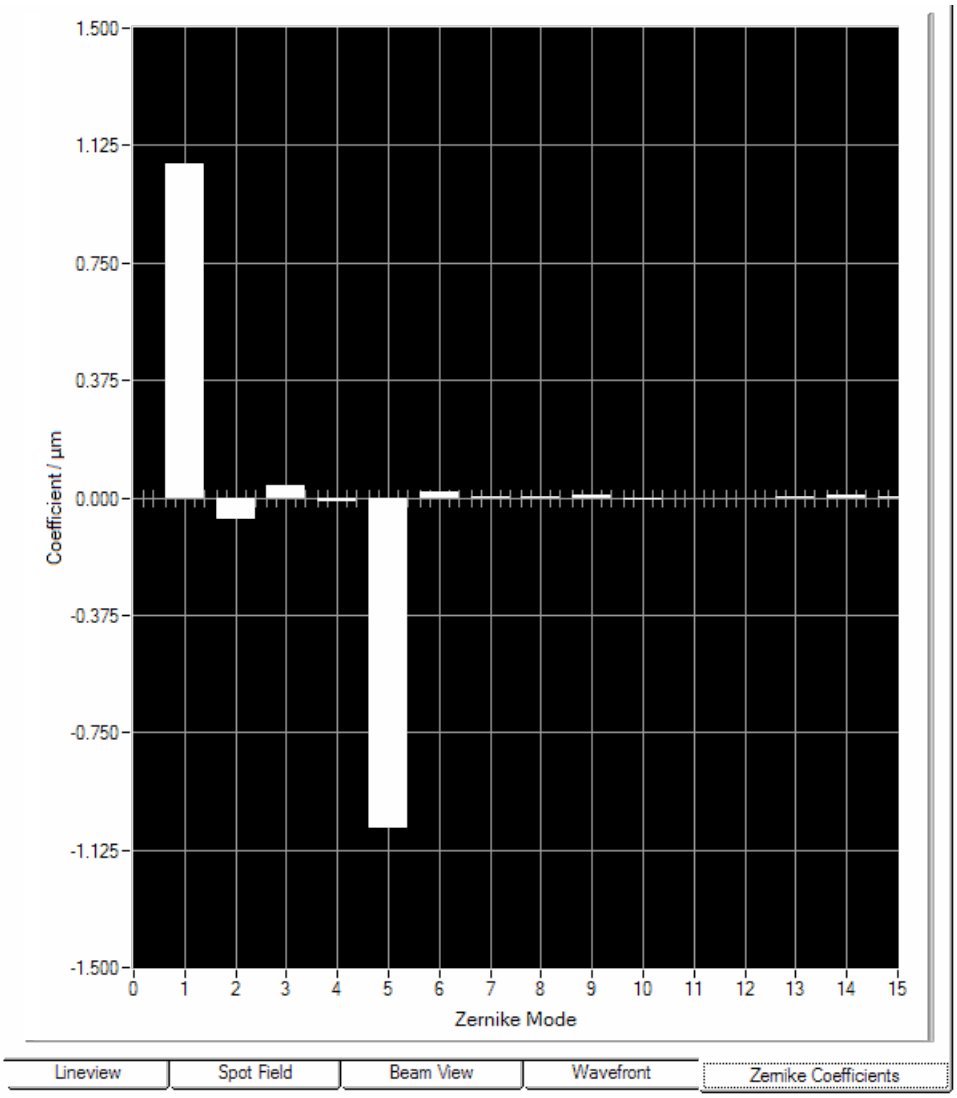
Wavefront areas that are not defined because the appropriate spot was not detectable will not be displayed at all.

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

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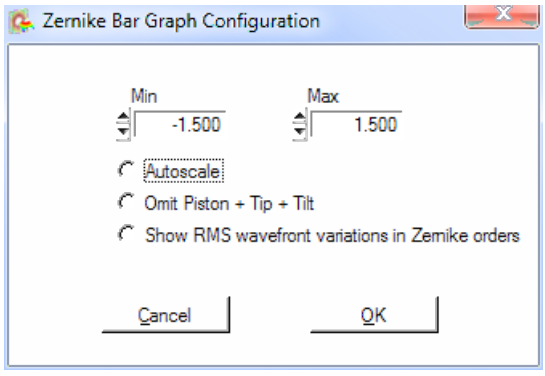
5.7.5 Zernike Coefficients Panel

This panel displays the individual Zernike coefficients, which are the results of the Zernike fit, as a bar graph.



The Zernike coefficients can be positive or negative. They indicate that the measured wavefront contains particular Zernike modes; the coefficient stands for the amplitude.

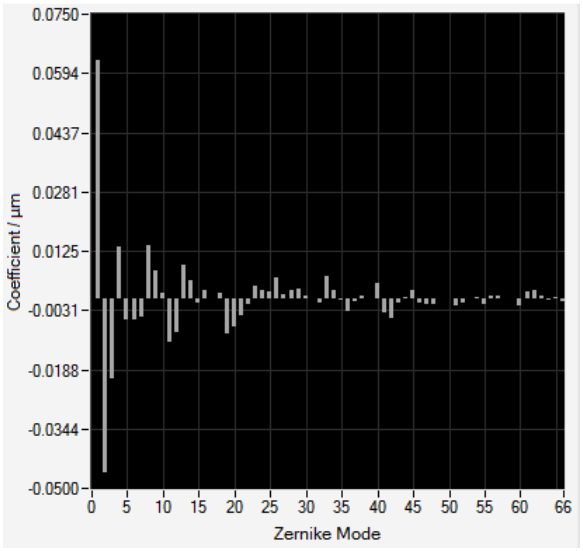
The **Zernike Bar Graph Configuration** panel opens by double clicking to the graph area:



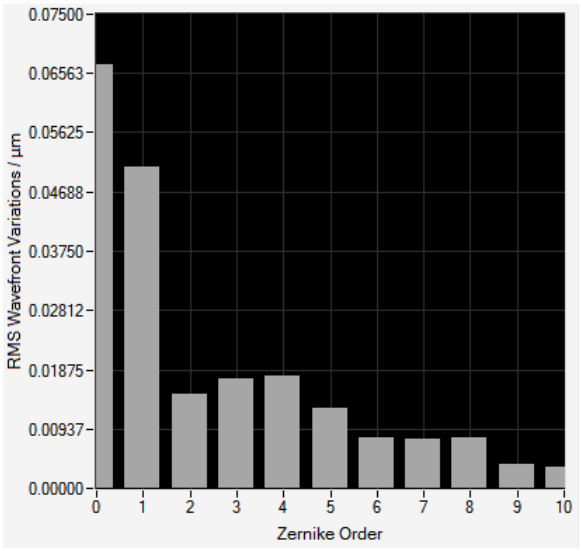
By default, the vertical axis is scaled automatically. Disabling **Autoscale** can be advantageous, if some Zernike coefficients are much larger than the Zernike coefficient of interest, or if the wavefront is fluctuating. When **Autoscale** is disabled, the minimum and maximum scale values must be entered manually.

'**Omit Piston + Tip + Tilt**': Enable this option to exclude Z1, Z2, and Z3 from bar graph display. By default, this option is disabled and all calculated Zernike Modes are displayed. However, in general the lowest order modes (Piston and the wavefront's Tip and Tilt) are of less interest. They may also have a considerably higher amplitude than the higher order modes of interest, and enabling this option can reduce the Y axis scale to a more useful range.

'**Show RMS wavefront variations in Zernike orders**': Enabling this option will change the display: Instead of the Zernike coefficients, the Zernike orders will be displayed. The value of a Zernike order is the summation of all Zernike modes of the particular order.



Display of Zernike Coefficients



RMS Wavefront Variations in Zernike Orders

Use the '**Omit Piston + Tip + Tilt**' option to suppress the display of Zernike Orders 0 and 1.

5.8 Status Bar

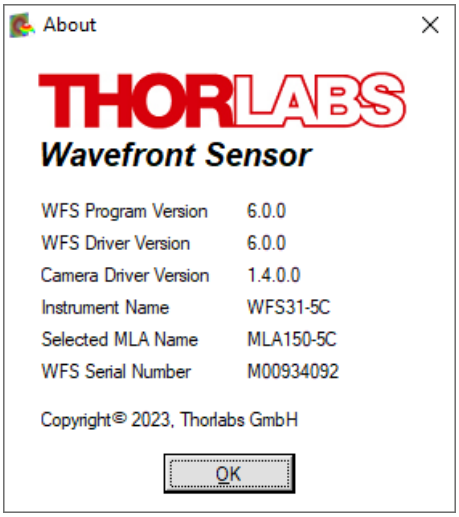
The Status bar on the bottom of the GUI shows the current status or warns the user in case of questionable settings.



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5.9 Version and other Program Information

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



Visit the Thorlabs website for downloading available updates.

Chapter 6 Beam Setup Using the Software

Prior to making measurements, several aspects of the input beam and a few related Wavefront Sensor settings should be reviewed and adjusted as necessary. The following sections provide guidance on aligning the input beam, as well as configuring the system for different beam sizes and power levels.

6.1 Beam Size and Alignment

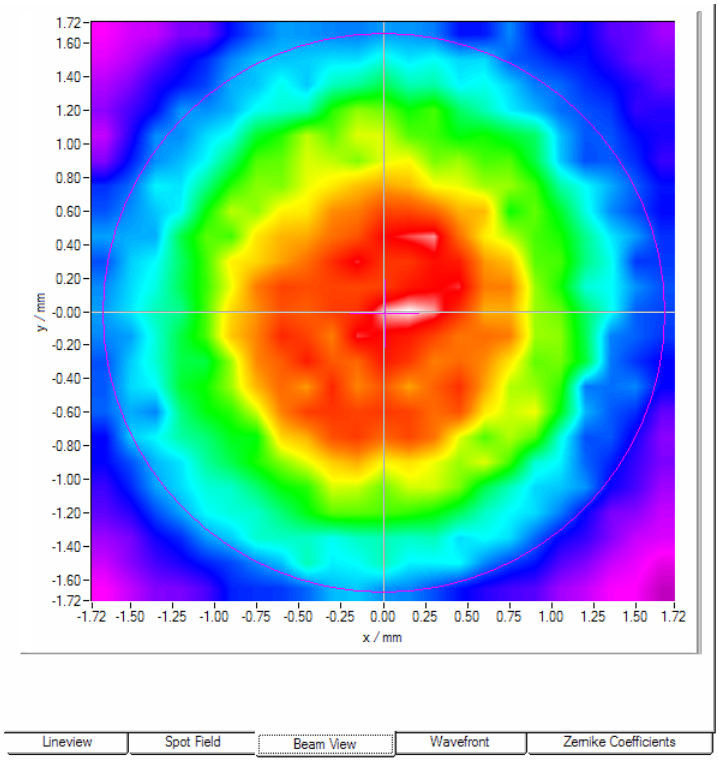
Beam Size

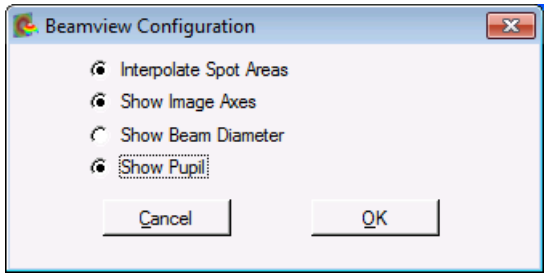
Use the software to set the active area of the CMOS camera chip to include the full beam while excluding as much of the unilluminated sensor area as possible (see Camera Settings Setup). The unilluminated region of the sensor provides no information about the beam's wavefront. Measurement speed will increase by excluding this region from the active area, as speed increases with reduced image size.
Beam sizes larger than the available aperture (11.25 mm x 7.03 mm for WFS31) can compensate for by using a beam expander (Thorlabs GBE02 through GBE20 series) used in reverse.

Alignment

Position the Wavefront Sensor so that the beam is normally incident on the sensor. To reduce unwanted reflections back into the source, rotate (tilt) the Wavefront Sensor slightly from this alignment.

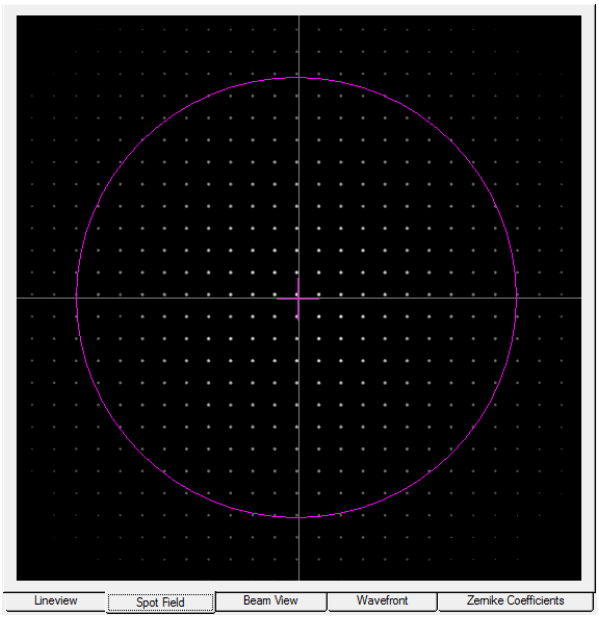
Align the incident beam to the center of the entrance aperture of the Wavefront Sensor. An off-center beam can be measured as well, provided the full beam is contained within the active sensor area. However, aligning the beam to the center of the sensor area is recommended. Verify this alignment by checking the power density distribution displayed in the Beam View Panel. Enable options 'Show Image Axes' and 'Show Beam Diameter' in order to visualize the beam position and size with respect to the analyzed sensor area.

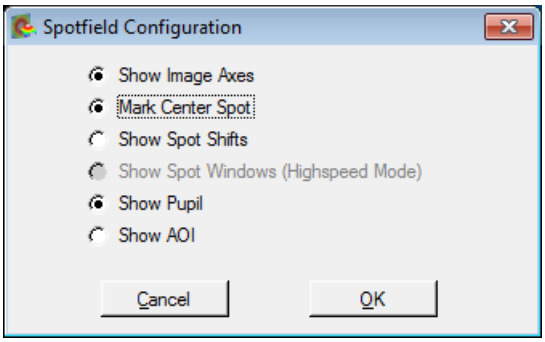




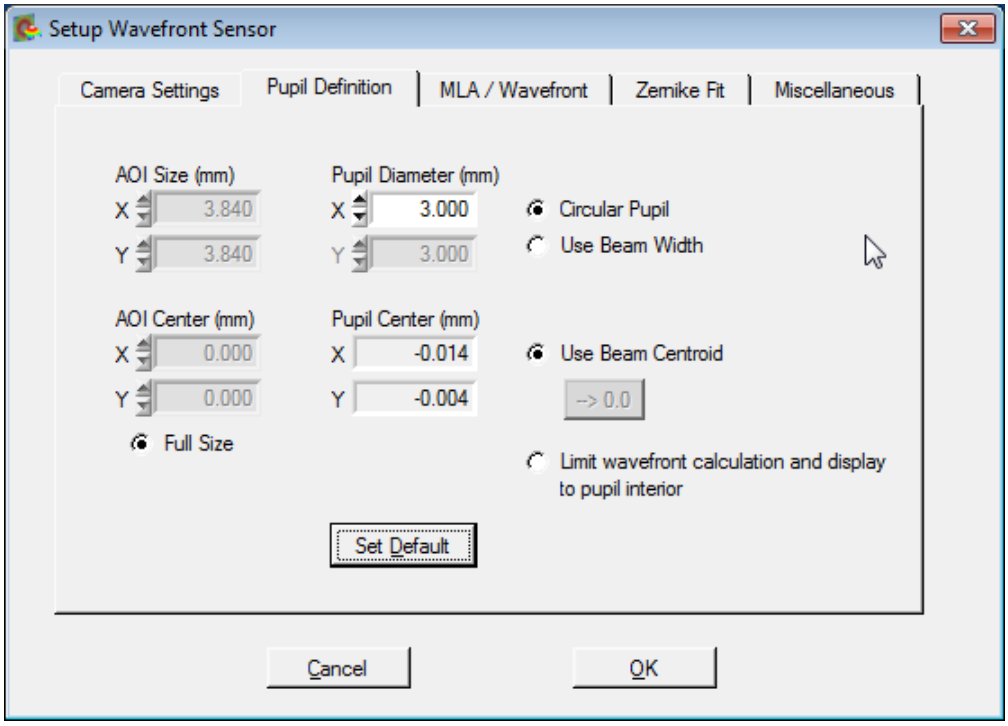
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Alternatively, you can check the correct beam position using the Spotfield Panel. Enable the diagram options '**Show Image Axes**' and '**Show Pupil**'.





Make sure that the '**Use Beam Centroid**' option is enabled (Pupil Definition Setup) in order to couple the displayed pupil position to the measured beam centroid position.



6.2 Optical Power

Due to the implemented automatic shutter control of the Wavefront Sensor cameras, they can handle optical input power values over a wide dynamic range. Note that the sensitivity is strongly wavelength dependent. In particular, the sensitivity drops drastically at the edges of the wavelength range, which can allow higher power beams with wavelengths overlapping these lower sensitivity ranges to be

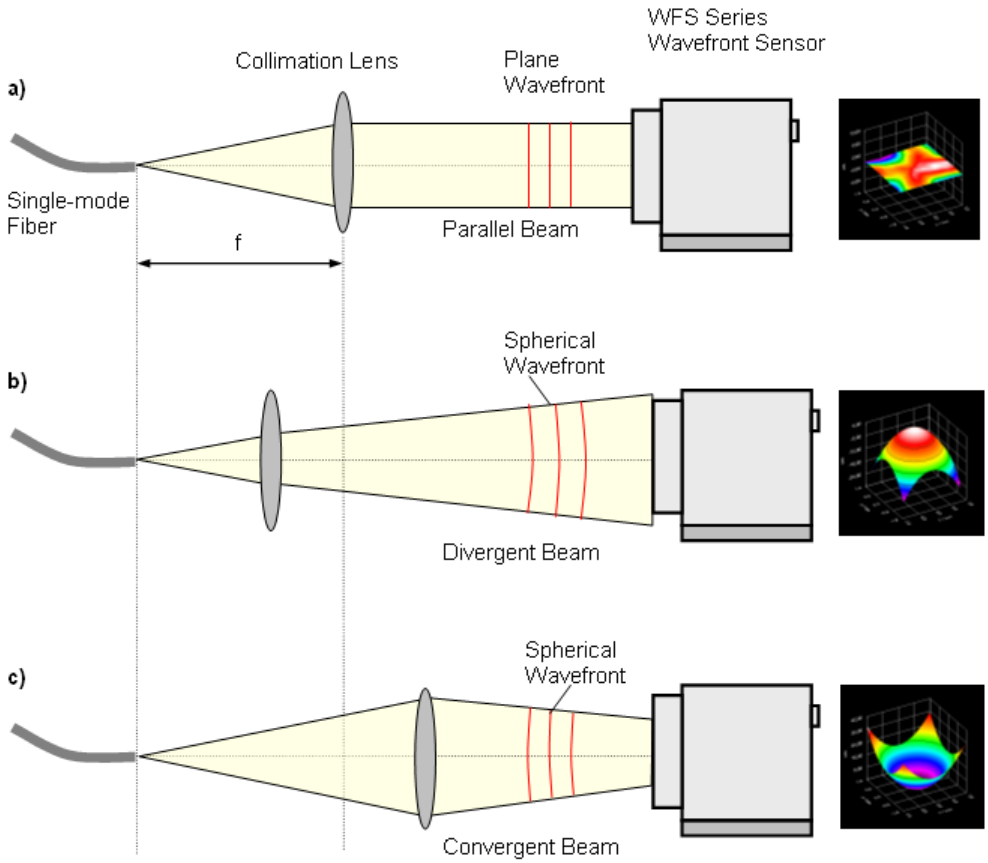
measured directly. Be aware that a lower-power beam that is focused or small in diameter beam can saturate the Wavefront Sensor. If the input beam saturates the Wavefront Sensor, an external attenuator should be used

During operation, observe the status bar at the bottom of the GUI. Take note of any 'Power too low', 'Power too high' and 'High Ambient light level' errors and correct the power level accordingly. See Measurement Warnings and Errors chapter for details.

Chapter 7 Measurement Examples

The following picture illustrates a very simple measurement example to explain what a wavefront is and how the lens position can affect it.

a) A collimation lens (e.g. bi-convex) is positioned at a distance equal to the focal length **f** of the lens from a single-mode fiber tip. In this case, the lens collimates the beam into an exactly parallel beam with a planar wavefront.



b) Moving the lens towards the fiber end leads to a 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 lags behind the center rays. The wavefront is spherical convex, and a spherical wavefront is indicated by a nonzero Zernike 'Defocus' term, Z5.

c) Moving the lens towards the Wavefront Sensor lets the beam converge - the beam diameter decreases on the way to the Wavefront Sensor and the (virtual) focal point is located behind the sensor position. The wavefront also has a spherical shape, but it is spherical concave.

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Application

Such a 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 Z5 ('Defocus') becomes close to zero. 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.

Chapter 8 Measurement Warnings and Errors



Status Bar

During image capture and analysis by the camera, some errors may occur that need to be recognized and addressed. Read the error message carefully and find a way to remove the cause of the error.

Note

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

Zernike Fit failed! Insufficient spots detected.

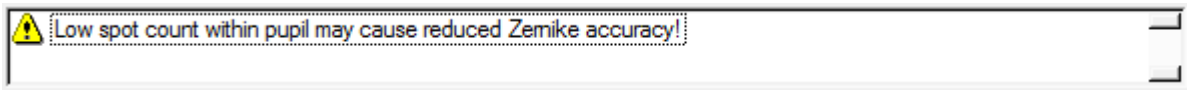


This error occurs if the number of detected spots within the pupil is lower than the number of Zernike modes to be calculated in the least square Zernike fit.

To prevent this error

- Check the analyzed beam for proper alignment and make sure that its intensity dominates the ambient light level and/or
- Increase the pupil diameter Pupil Definitions panel and/or
- Reduce the number of Zernike orders in the Zernike Fit panel.
- Increase the camera resolution (Camera Settings) in case the pupil diameter is close to the image size

Low Spot Count within pupil may cause reduced Zernike accuracy!



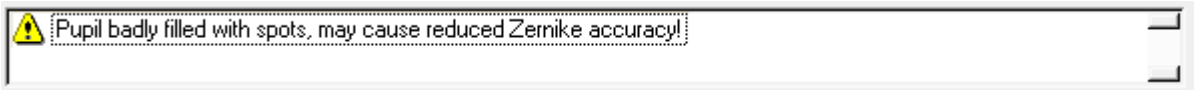
Even if the number of detected spots within the pupil exceeds the minimum required number, increased calculation errors may still occur during the Zernike Fit, especially in case of high orders. For this reason, to fit higher order Zernikes (up to order 7-10), an extra spot count of about 30% is required.

To prevent this warning

- Check the beam that is being analyzed for proper alignment and make sure that its intensity dominates the ambient light level and/or
- Increase the pupil diameter (Pupil Definitions panel) and/or
- Reduce the number of Zernike orders in the Zernike Fit panel.

- Increase the camera resolution (Camera Settings) in case the pupil diameter is close to the image size

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, some visible spots at the border of each camera image remain undetected. The pupil dimension must not be larger than the detected spot area. Otherwise, increased calculation errors may still occur during the Zernike Fit, especially in case of high orders.

To prevent this warning

- Reduce the pupil diameter Pupil Definitions panel and/or
- Increase the camera resolution (Camera Settings)

Pupil is larger than selected camera area!



The pupil diameter exceeds the camera's active area so that parts of the pupil overlap the inactive sensor area not used to detect spots and therefore not providing wavefront measurement data.

To prevent this warning

- Reduce the pupil diameter Pupil Definitions panel and/or
- Increase the camera resolution (Camera Settings) in case the pupil diameter is close to the image size.

Power too low!



The detected spot intensity is too low, resulting in an incorrect analysis of the centroid positions. Check 'Exposure Time' and 'Gain' settings (Camera Settings). Change the manual setting or enable automatic control of these camera parameters.

If this error occurs even with the highest 'Exposure Time' and 'Gain' setting or if 'Auto Exposure' is already enabled, the optical input power of the Wavefront Sensor is too low. 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, resulting in an incorrect analysis of the centroid positions. Check 'Exposure Time' and 'Gain' settings (Camera Settings). Change the manual setting or enable automatic control of these camera parameters.

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If this error occurs even with the lowest 'Exposure Time' and 'Gain' setting or if 'Auto Exposure' is already enabled, the optical input power of the Wavefront Sensor is too high. Decrease the power of your light source or insert an attenuator (e.g., neutral density filter) in front of the Wavefront Sensor.

Spot contrast too low!



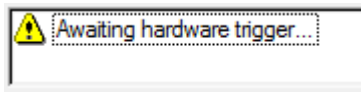
The camera image suffers from low contrast, i.e., the brightness difference between the spots and the ambient area is too low. This can be caused by manually entering an inappropriate exposure time (Camera Settings) or unwanted stray light entering the input aperture of the Wavefront Sensor. Shield the measurement beam path and the WFS input from stray light or increase the optical power of your light source.

High ambient light level!



There is a high ambient light level entering the camera that decreases the contrast between the spot peaks and the dark areas in between. Shield the WFS input from ambient light or increase the optical power of your light source.

Awaiting hardware trigger...



This status message indicates that no update of numerical and graphical measurement data is visible because the WFS trigger function was activated and no trigger event has occurred yet. Apply a trigger signal using the trigger cable (see Trigger Input for details) or disable the hardware trigger in the Camera Settings.

Measurement stopped.



This status message indicates that the continuous measurement has been stopped either by the user or due to occurrence of another error. The displayed data and graphs do not show actual wavefront data.

Graphics disabled.



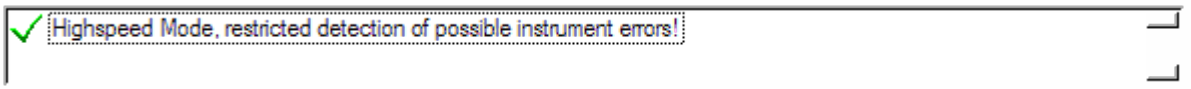
This status message notifies that all graphics and the numerical results have been disabled in order to speed up the sampling rate. See the setup menu Miscellaneous.

Connection to instrument lost.



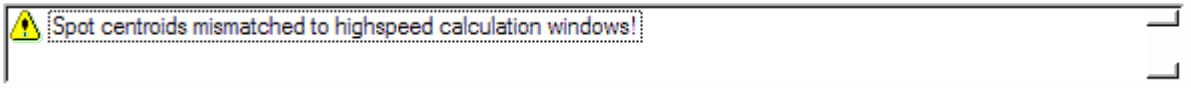
This status message indicates that a USB interface error occurred. Check the USB connection, then restart the Wavefront Sensor application again.

Additional errors in Highspeed Mode!



This status message warns of the risk of incorrect measurement results in High-Speed Mode due to restricted error detection capabilities. For instance, the image saturation level is not detected.

Spot centroids mismatched!



After entering the High-Speed mode, the detected spot centroid positions did not match the calculation windows for High-Speed mode. In other words, the spots were shifted too far and can no longer be detected with the required accuracy.

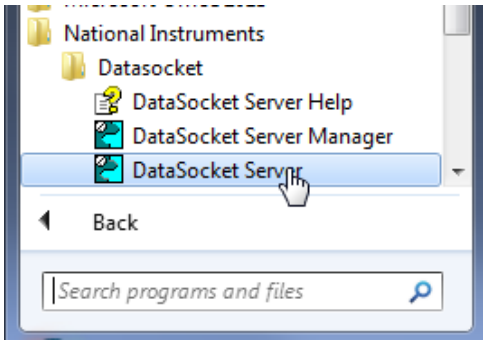
Enable the option "Adapt centroids" (see chapter "WFS20 Highspeed Mode" in the WFS20 Operation Manual) prior to entering High-Speed Mode to overcome this situation.

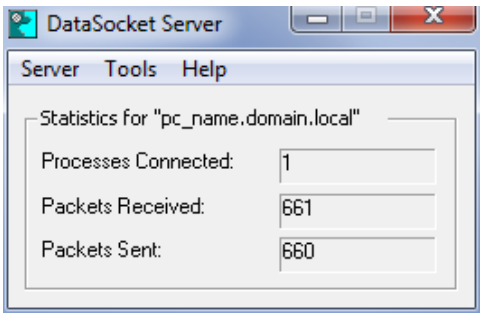
Chapter 9 DataSocket for Live Data Transfer

The following explanations are related to the National Instruments® DataSocket server. It comes with the WFS31 installation package.

Starting the DataSocket Server

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







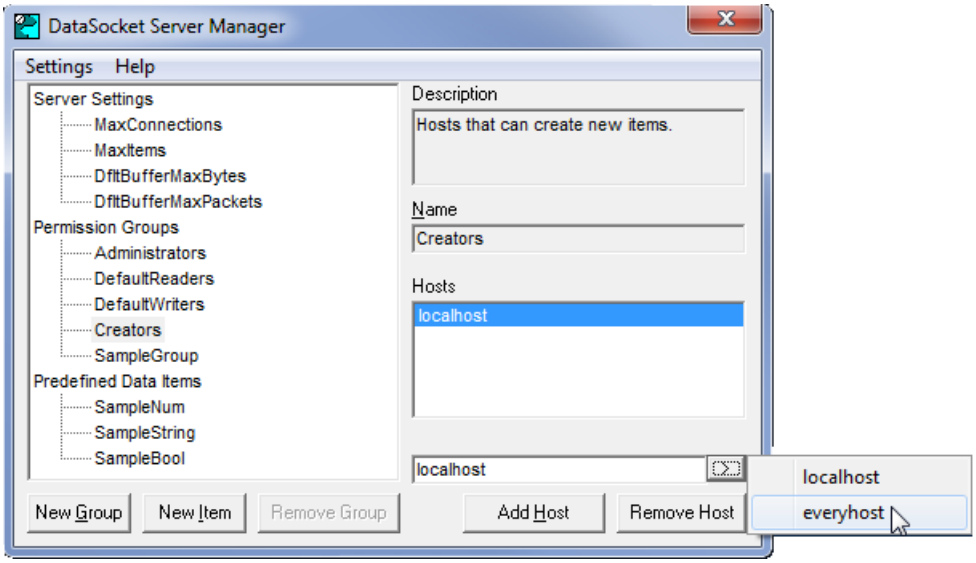
Even when the panel is closed, the server will remain active and is visible in the task bar.

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DataSocket Server Configuration

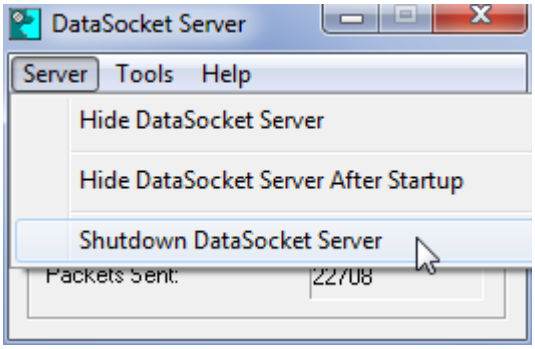
The DataSocket server needs to be configured for Wavefront Sensor data transfer to permit Read and Write access by the connected computers. In addition, the writer application, that is the PC operating the Wavefront Sensor, requires permissions as a creator of new data items.

Open the 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.

The DataSocket server must be restarted in order to update these settings. Shut it down using the appropriate menu entry and start it again:



Note

Closing the server panel is not sufficient to update the setting. The DataSocket server needs to be relaunched to start with the new configuration!

Firewall Configuration

The firewall software integrated in Windows® operating systems might be configured to block access to the DataSocket server. Make sure that the firewall is switched off or - in the case that your IT policies require an activated firewall - that the 'National Instruments DataSocket Server' is marked as an Allowed Program.

9.1 Available Data Items

With the activated '**Enable basic data**' option in 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 completed, the data on the DataSocket server are 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 are split in two groups: Wavefront Sensor settings and measurement results.

Wavefront Sensor Settings

Data Item	Format	Unit / example
Instrument_Name	string	e.g. "WFS31-5C Wavefront Sensor"
Serial_Number	string	e.g. "M00934092"
Wavelength	float	e.g. "633.000"
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

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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With the activated '**Enable wavefront data**' option in 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)

With the activated '**Enable centroid data**' option in 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 in units of pixels. Lowest indices are related to the upper left corner of the selected camera image size.

Note

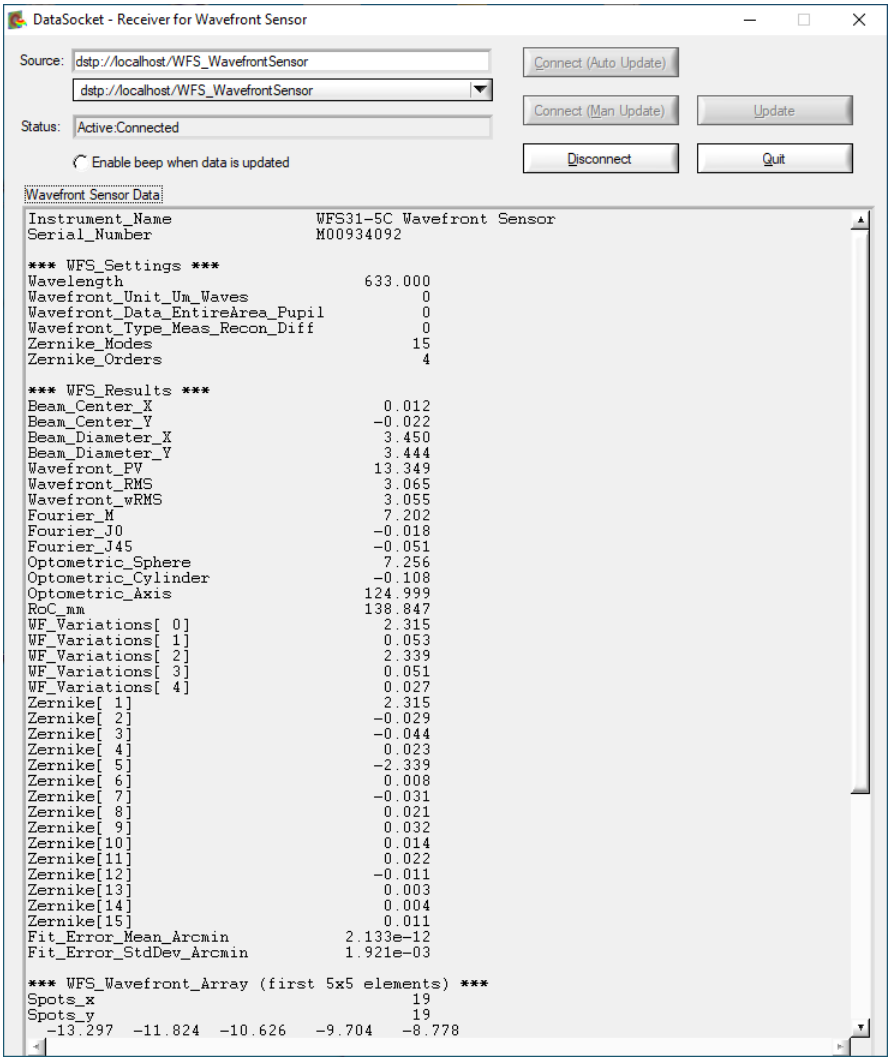
Format of Centroid_Pos_X and Centroid_Pos_Y data arrays were changed in software release 2.0 from double to float!

9.2 WFS Receiver Application Sample

The Wavefront Sensor software package contains the sample application **WFS_Receiver.exe** for demonstrating the data transfer using DataSocket. The sample application can be started from the desktop icon, from the Windows **Start** button (All Programs - Thorlabs-Wavefront Sensor - WFS_Receiver) or directly from it's location:

C:\Program Files (x86)\Thorlabs\Wavefront Sensor\WFS_Receiver\WFS_Receiver.exe

Below is a screen shot of this panel.



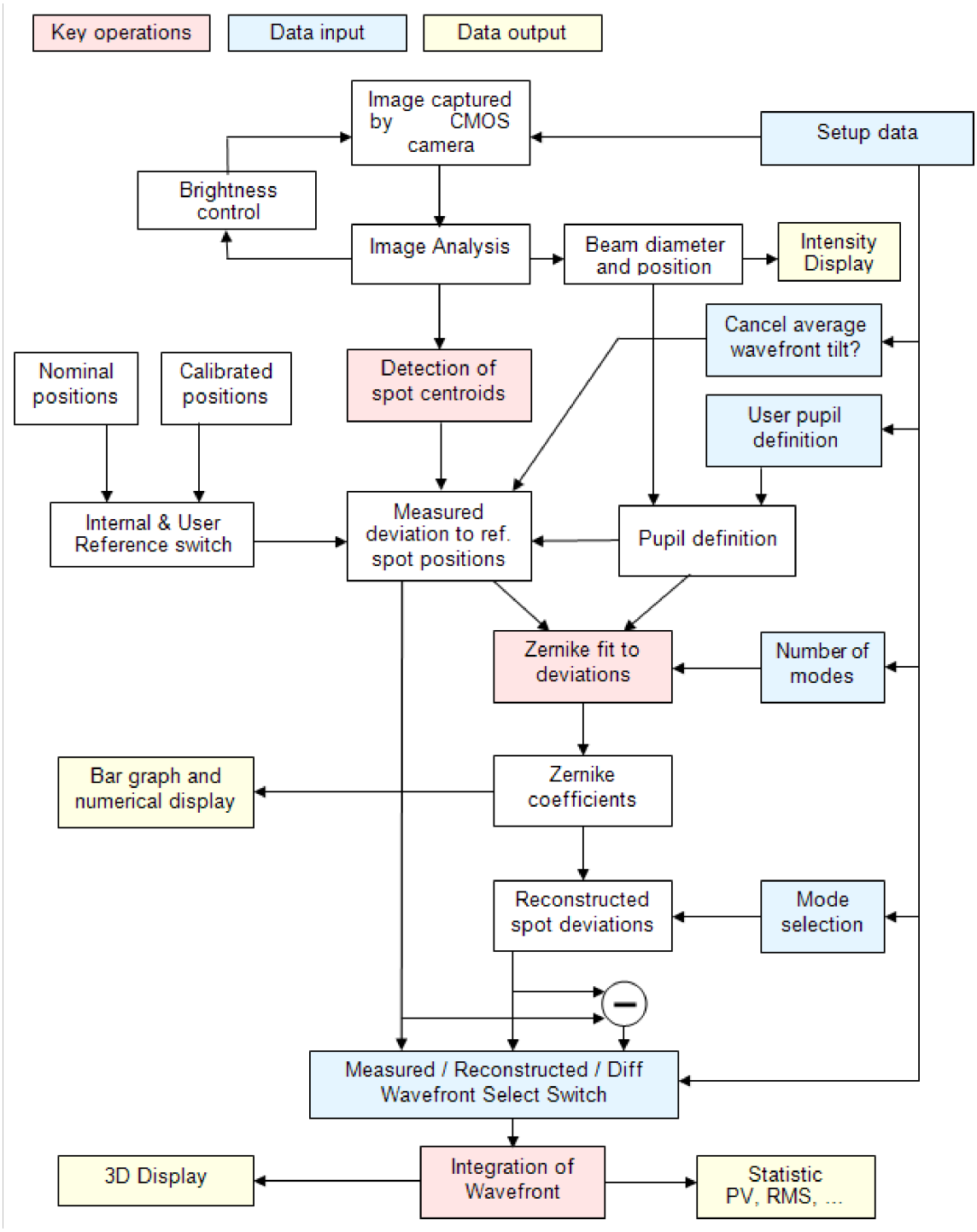
1. Connect to the same DataSocket server where the Wavefront Sensor application is sending the data to.
2. Click 'Connect (Auto Update)' for connecting and automatically updating the data items as soon as they are modified on the DataSocket server.
3. Mark the 'Enable beep when data is updated' switch for an acoustic signal on each data update.
4. An update is carried out automatically by the callback routine 'DSCallback (...)' which is fired whenever data or status on the DataSocket is changed.
5. When 'Connect (Man Update)' was used, an update is only done by a click on 'Update'.

See the sample source code WFS_Receiver.c (it is installed to the same directory as the WFS_Receiver.exe) for detailed information of how programming is done.

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Chapter 10 Data Flow Chart

The following chart shows the data flow within the Wavefront Sensor software and the user defined inputs and data outputs.



The brightness of the camera image is loop-controlled to ensure an optimal saturation level.

The beam diameter and position are detected and are optionally used to define the instruments pupil area. Alternatively, the pupil data can be set by the operator.

The image is scanned for detectable spots that are generated by the microlenses and their positions are compared to reference positions. The user can 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 is used to fit the measured wavefront by using well-known Zernike functions.

Output data are Zernike coefficients that are displayed numerically as well as in a bar graph panel.

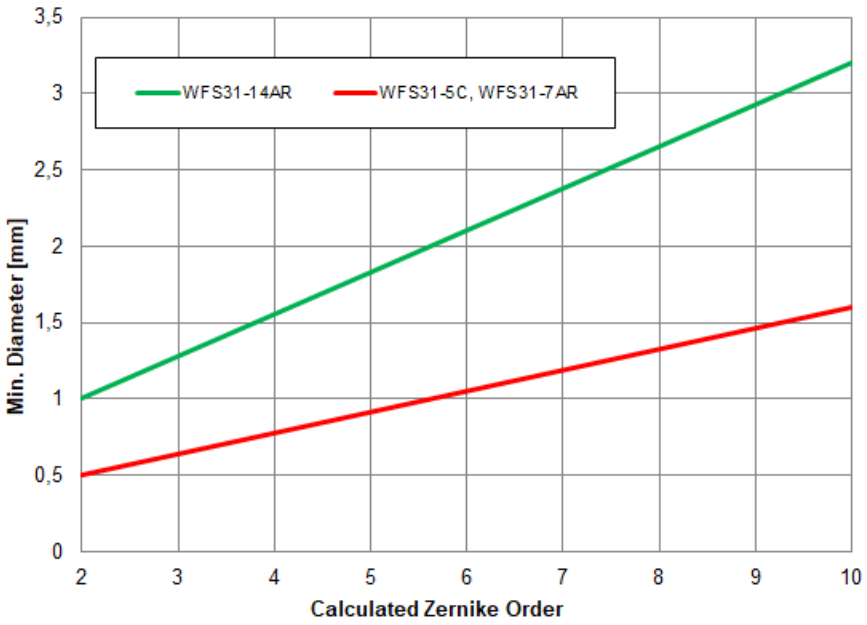
The wavefront reconstruction is performed using all or a user-selected subset of the Zernike modes.

The difference between measured and fitted wavefront data is available as well.

Chapter 11 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.

Consequently, this minimum number of spots requires a beam and pupil diameter of at least a certain minimum size. The following graph shows the dependency for both available microlens arrays of 150 and 300 µm pitch.



Minimum Beam and Pupil Diameter

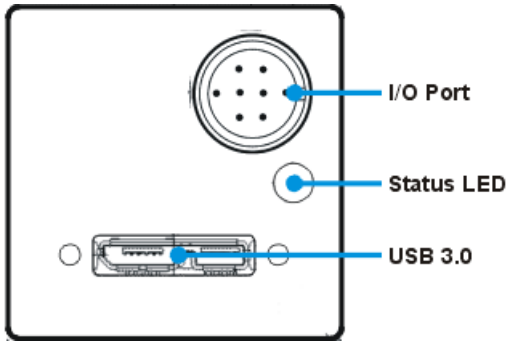
For a desired Zernike order, you need to set the pupil to the required diameter within the Pupil Definitions setup. Also, your physical beam diameter needs to illuminate at least the same camera area so that the required number of spots can be detected.

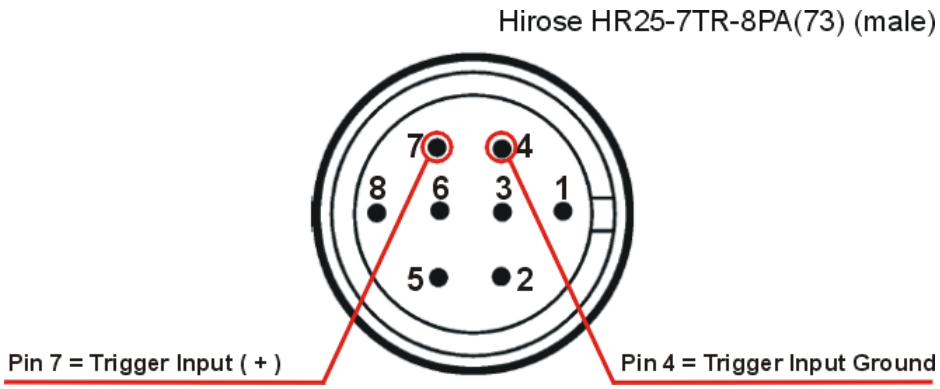
In case of unfavorable pupil settings, warnings or errors may occur. See the chapter Measurement Warnings and Errors for a detailed description and suited arrangements for its prevention.

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Chapter 12 Trigger Input

Besides the USB3.0 connector, the WFS31 models have a combined I/O and trigger interface at the rear side of the camera housing. The WFS software supports only the trigger functionality.



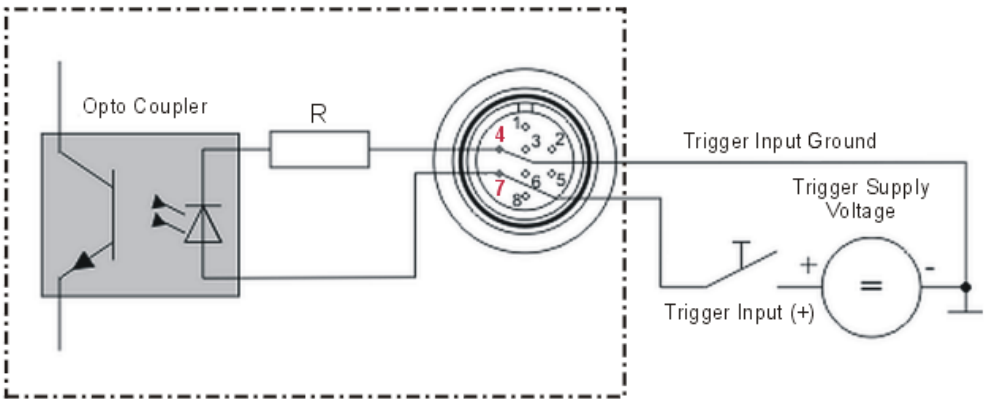


To use the trigger, connect your trigger source to the WFS instrument using the trigger cable **CAB-DCU-T3** (available separately). This cable is designed for the camera on which the WFS31 are based.

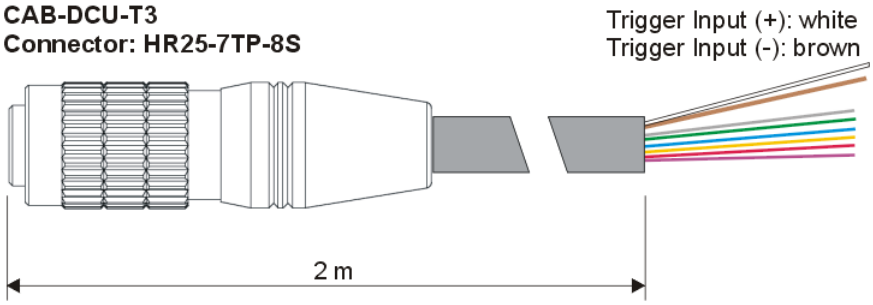
Attention

Please see the chapter Specifications for the allowed voltage level in order to avoid damage!

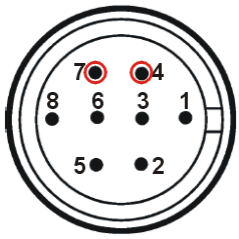
Apply the external trigger signal using the trigger cable CAB-DCU-T3 as shown in the following sketch:



Details on the CAB-DCU-T3 Trigger Cable



Pin	Description	Wire Color
1	GND	grey
2	Flash OUT (+)	green
3	GPIO 1	blue
4	Trigger IN (-)	brown
5	Flash OUT (+)	yellow
6	GPIO 2	red
7	Trigger IN (+)	white
8	VCC OUT	pink



Hirose HR25-7TR-8PA(73)
male socket, camera rear view

This cable can be ordered from Thorlabs (https://www.thorlabs.com/thorproduct.cfm?partnumber=CAB-DCU-T3).

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Chapter 13 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 their amplitudes or Zernike coefficients c_n. Generally a least square Zernike fit is done in order to determine the Zernike coefficients c_n.

A variety of definitions exist for these Zernike functions. The Thorlabs Wavefront Sensor software and this manual follows the *ANSI Standard Z80.28-210*.

The Zernike polynomials are recommended for describing wave aberration functions over circular pupils with a 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.

Rectangular coordinates are x any y both normalized to unit radius 1.

Polar coordinates (ρ,θ) are normalized radius coordinate ρ and angular coordinate θ, where ρ= r/a with r as physical radial coordinate and a as the pupil radius.

The natural scheme for ordering of the Zernike modes is to use a double index corresponding to the **radial order** n and **angular frequency** *m* as following equation.

$$Z_n^m(\rho,\theta)$$

$n \geq 0$	Radial Order
$\|m\| \leq n$	Angular frequency
$\rho \leq 1$	normalized radial coordinate
$\theta (0 .. 2\pi)$	angular coordinate
r	physical radial coordinate
a	physical pupil radius

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 tables give the Zernike polynomials in Polar (Radial) and Cartesian coordinates of order 0 to 4 according to the *ANSI Standard Z80.28-210*.

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

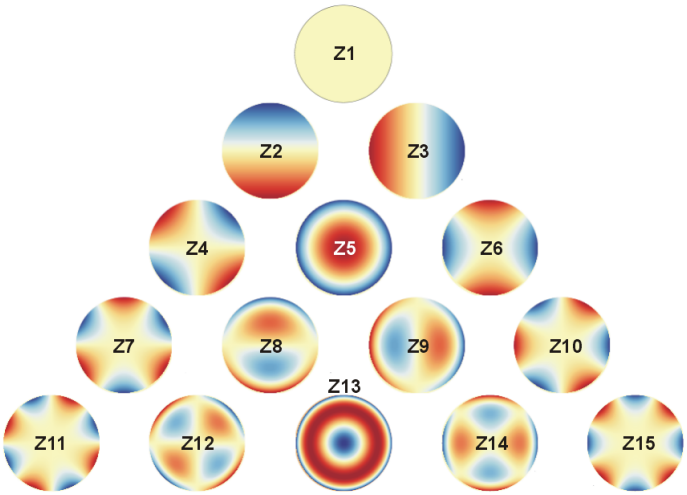
Normalization Factor

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 across the pupil for a particular mode is: WFS_Coefficient * Norm_Factor * Zernike function, where the Zernike function variable is the normalized pupil dimension with origin at the center (i.e. x = distance from the origin in x direction / pupil radius).

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Zernikes and Optical Abberations

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



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Zernike Term	Shortcut	Description
Z 1	-	Piston
Z 2	-	Tip Y
Z 3	-	Tilt X
Z 4	Ast45	Astigmatism 45°
Z 5	Def	Defocus
Z 6	Ast0	Astigmatism 0°
Z 7	TreY	Trefoil Y
Z 8	ComY	Coma Y
Z 9	ComX	Coma X
Z 10	TreX	Trefoil X
Z 11	TetY	Tetrafoil Y
Z 12	SAstY	Secondary Astigmatism Y
Z 13	SAb3	3rd Order Spherical Abberation
Z 14	SAstX	Secondary Astigmatism X
Z 15	TetX	Tetrafoil X

Chapter 14 Example Zernike Calculations

Example Tilt

Q: How can the linear wavefront tilt in x direction be derived from a measured Zernike coefficient of Z3 = 0.1 µm at a pupil diameter of 4 mm?

A: With a normalization factor of 2 the wavefront shape $WF(x)$ in Cartesian coordinates is:

$$WF(x) = 0.1\ \mu m*2*x$$

Since the normalized x coordinate ranges from -1 to +1 within the unit circle, the maximum wavefront deviation is therefore -0.2 µm at x = -1 and 0.2 µm at x = 1.

That is, we have a total tilt of 0.4 µm across the entire physical pupil diameter of 4 mm which gives a tilt angle of

$$arctan\ (0.4\ \mu m / 4\ mm) = 0.1\ mrad = 0.0057\ deg.$$

Example Defocus

Q1: What peak-to-valley (PV) deformation corresponds to a Defocus term of Z5 = -1 µm?

A1: As the pure mathematical defocus formula ($2r^2$ - 1) describes a concave wavefront, the negative amplitude belongs to a convex wavefront. With a normalization factor of √3 the wavefront shape $WF(\rho)$ in polar coordinates is:

$$WF(\rho) = -1\ \mu m*\sqrt{3}*(2\rho^2-1)$$

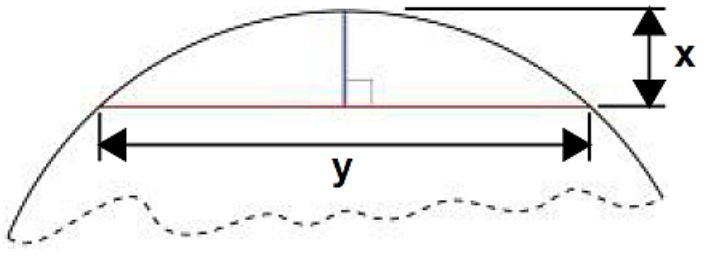
Since the normalized radial coordinate ρ ranges from 0 to 1 and the spherical shape achieves its minimum and maximum wavefront deviation at these points, the PV value is just the difference

$$PV=WF(\rho=0) - WF(\rho=1) = -1\ \mu m * \sqrt{3} * (-1\ -1) = 2*\sqrt{3}\ \mu m = 3.46\ \mu m$$

This PV result is independent of the physical pupil diameter because it just describes the wavefront deviation in z direction.

Q2: What Radius of Curvature (RoC) is related to this spherical wavefront when measured at a pupil diameter of d = 3 mm?

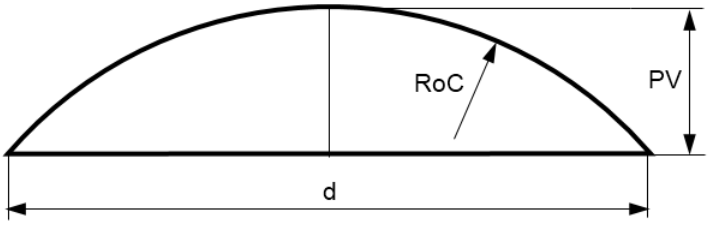
A2: To convert the PV value into a RoC result, a standard mathematimatical circle function is used. In literature [2] under 'Sagitta' the following formula is given:



$$r=\frac{y^2}{8x}+\frac{x}{2}$$

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Related to the spherical wavefront this formula is adapted to:



$$RoC = \frac{d^2}{8PV} + \frac{PV}{2}$$

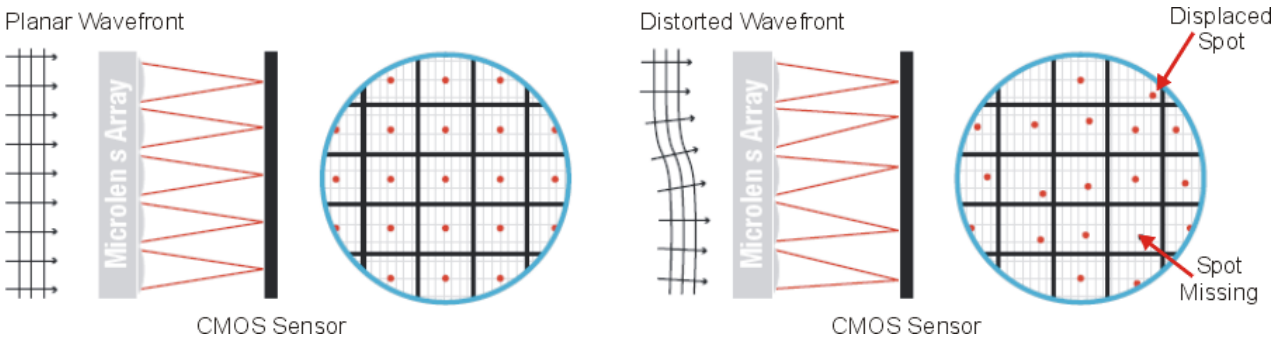
Since the second term PV/2 is much smaller than the RoC to be calculated, this term can be omitted:

$$RoC \approx \frac{d^2}{8PV}$$

The remaining formula gives an RoC of $(3\ mm)^2 / (8 * 3.46 * 10^{-3}\ mm) = 325\ mm$.

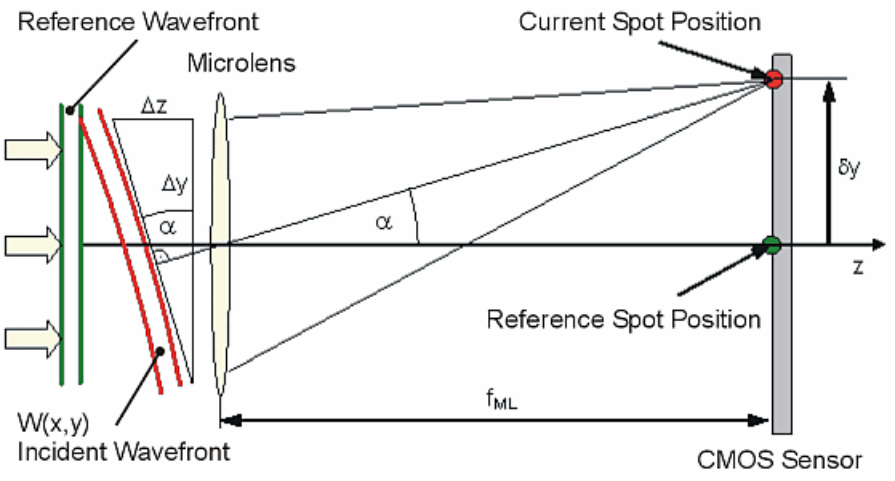
Chapter 15 Operating Principle

The WFS31 instruments comprise a CMOS camera and a microlens array that is mounted at a defined distance in front of the camera sensor chip. Each microlens of the lenslet array collects the light incident to its aperture and generates a single spot on the detector plane (CMOS camera) that is located at a distance of one focal length behind the lenslets.



Each spot is centered behind the lens that generated it, only if the incident wavefront is planar and parallel to the plane of the lenslets. These are the **Reference Spot Positions,** also known as the **Reference Spotfield**.

In case of a distorted wavefront incident on the sensor, the focal spot positions shift along the X and Y directions, away from the optical axis Z of its associated microlens and the predetermined **Reference Spot**. The displacement is described by the angle α.



The above sketch shows that this deviation from the reference spot is caused by the deviation of the wavefront incident angle on the microlens, or in geometrical terms:

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

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

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

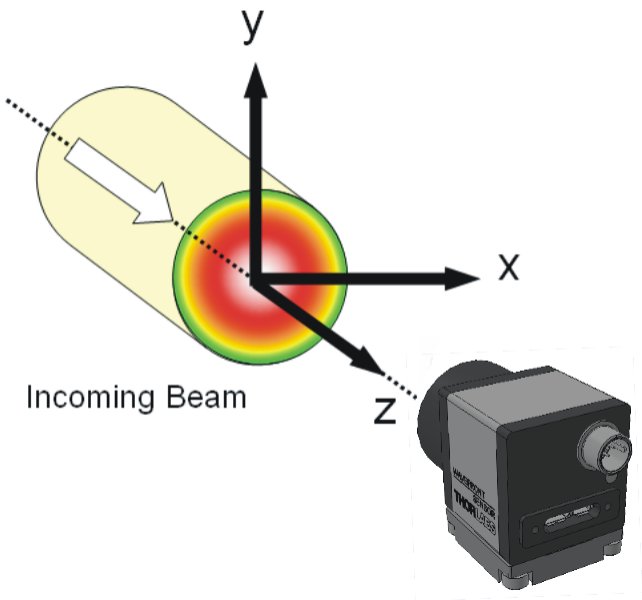
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$$\frac{\partial}{\partial y} W(x,y) = \frac{\delta y}{f_{ML}}$$

The spot deviations δx and δy are determined by calculating the centroid coordinates of all detectable spots and subsequently subtracting the corresponding reference coordinates. The wavefront shape function $W(x,y)$ is the result of a 2-dimensional integration process of these spot deviations.

Please see section Data Flow Chart for detailed explanation of the data flow in the WFS software.

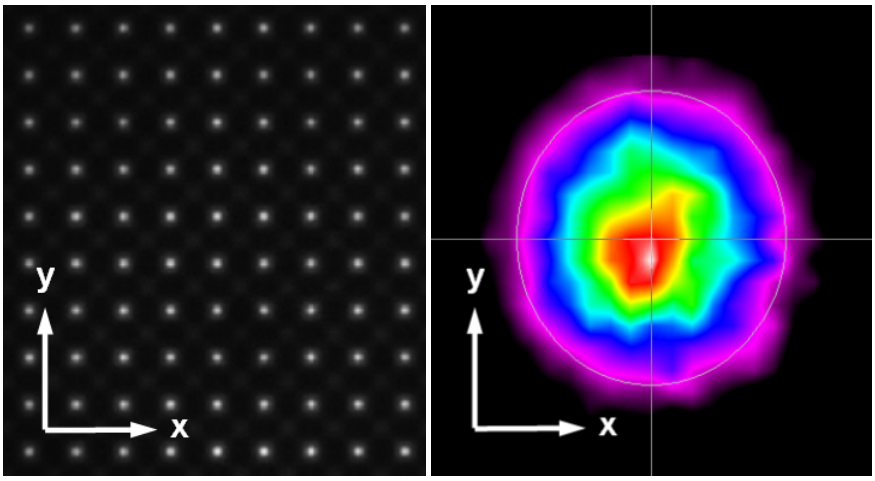
Chapter 16 Coordinate Definitions



The Wavefront Sensors use an orthogonal right-hand coordinate system (x,y,z) as shown to the left.

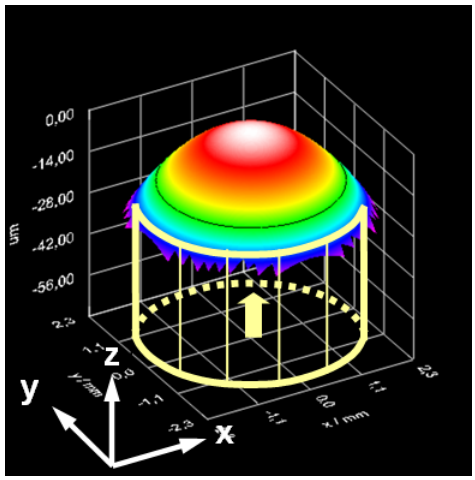
When looking towards the light source, the x-direction points towards the right, the y-direction points up, and the optical beam to be analyzed is propagating in the z direction towards the entrance aperture of the Wavefront Sensor.

The graphs in the Wavefront Sensor GUI (Spotfield, Beam View) are defined in the same way - the positive X axis points rightwards and the Y axis points upwards.



Spotfield Graph ***Beam View Graph***

In the Wavefront Graph shown in 3D, the cross section in the X/Y plane of the beam is drawn at the bottom, and the Z axis points upwards. The beam is shown to emerge up from the bottom and the displayed 3D curve will represent the wavefront at the top of the beam.



Wavefront Graph

Chapter 17 Literature

[1] ANSI Z80.28-2010 Ophthalmics - Methods of Reporting Optical Aberrations of Eyes: ANSI eStandards

[2] Wikipedia - Circle: http://en.wikipedia.org/wiki/Circle (Creative Commons Attribution - ShareAlike 3.0 Unported [CC BY-SA 3.0])

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Chapter 18 Custom Software

In order to write your own custom software to control the WFS31, you need a specific instrument driver and some tools for use in different programming environments. The driver and tools are installed to your computer during software installation and cannot be found in the installation package.

In this section the location of drivers and files, required for programming in different environments, are given for installation under Windows® VISTA, Windows® 7, Windows® 8.x and Windows® 10 (32-Bit and 64-Bit).

Note

WFS31 software and drivers contains 32-Bit and 64-Bit applications.

In 32-Bit systems, only the 32-Bit components are installed to

`C:\Program Files\`…

In 64-Bit systems the 64-Bit components are being installed to

`C:\Program Files\`…

while 32-Bit components can be found at

`C:\Program Files (x86)\`…

In the table below you will find a summary of what files you need for particular programming environments.

Programming environment	Necessary files
C, C++, CVI	*.fp (Function Panel File; CVI IDE only) *.h (Header File) *.lib (Static Library) *.dll (Dynamic Linked Library)
C#	.net wrapper dll
Visual Studio	*.h (Header File) *.lib (Static Library) or .net wrapper dll
LabView™	*.fp (Function Panel) and NI VISA™ Instrument Driver The LabVIEW™ driver VI's are provided with the *.llb container file. **Note** LabVIEW™ drivers and components are installed only if a LabVIEW™ installation was recognized.

Note

All above environments require also the NI VISA™ instrument driver dll.

During NI-VISA™ Runtime installation, a system environment variable `VXIPNPPATH` for including files is created. It contains information on the installation location of the drivers, which is usually:

`C:\Program Files\IVI Foundation\VISA\WinNT\.`

As this environment variable is required to install the instrument driver software components, it is necessary to perform a system reboot after installation of NI-VISA™ Runtime.

In the next chapters the location of above files is described in detail.

18.1 32-Bit Operating System

VXIpnp Instrument driver:

Note

According to the VPP6 (Rev6.1) Standard, the installation of the 32-Bit VXIpnp driver includes both the WINNT and GWINNT frameworks.

`C:\Program Files\IVI Foundation\VISA\WinNT\Bin\WFS_32.dll`

This instrument driver is required for all development environments!

Header File

`C:\Program Files\IVI Foundation\VISA\WinNT\include\WFS.h`

Static Library

`C:\Program Files\IVI Foundation\VISA\WinNT\lib\msc\WFS_32.lib`

Function Panel

`C:\Program Files\IVI Foundation\VISA\WinNT\WFS\WFS.fp`

Online Help for VXIpnp Instrument Driver

`C:\Program Files\IVI Foundation\VISA\WinNT\WFS\Manual\WFS.html`

NI LabVIEW™ Driver (Including an Example VI)

The LabVIEW™ Driver is a 32-Bit driver and compatible with 32-Bit NI-LabVIEW™ versions 2018 and higher only.

`C:\Program Files\National Instruments\LabVIEW xxxx\Instr.lib\…`

`…TLWFS\WFS.llb`

(LabVIEW™ container file with driver vi's - "LabVIEW™ xxxx" stands for actual LabVIEW™ installation folder.)

.net wrapper dll

`C:\Program Files\Microsoft.NET\Primary Interop Assemblies\…`
`…Thorlabs.WFS.Interop.dll`

Example for C

`C:\Program Files\IVI Foundation\VISA\WinNT\WFS\Examples\CVI C Sample\sample.c`

A C program how to use the WFS driver functions

`C:\Program Files\IVI Foundation\VISA\WinNT\WFS\Examples\CVI C Sample\…`
`…sample.exe`

Executable sample program how to use the WFS driver functions.

Example for C#

Solution file:

`C:\Program Files\IVI Foundation\VISA\WinNT\WFS\Examples\…`

`…MS VS CSharp Demo\Thorlabs.WFS.Demo.sln`

Project File

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```
C:\Program Files\IVI Foundation\VISA\WinNT\WFS\Examples\…
…MS VS CSharp Demo\Thorlabs.WFS.Demo.csproj
```

Example for LabView™

Included in driver llb container.

18.2 64-Bit Operating System

Note

According to the VPP6 (Rev6.1) Standard the installation of the 64-Bit VXIpnp driver includes the WINNT, WIN64, GWINNT and GWIN64 frameworks. That means, that the 64-Bit driver includes the 32-Bit driver as well.

In case of a 64-Bit operating system, 64-Bit drivers and applications are installed to

"C:\Program Files"

while the 32-Bit files - to

"C:\Program Files (x86)"

Below are listed both installation locations, so far applicable.

VXIpnp Instrument Driver

```
C:\Program Files (x86)\IVI Foundation\VISA\WinNT\Bin\WFS_32.dll
C:\Program Files\IVI Foundation\VISA\Win64\Bin\WFS_64.dll
```

Note

This instrument driver is required for all development environments! There is no source code provided for this driver.

Header File

```
C:\Program Files (x86)\IVI Foundation\VISA\WinNT\include\WFS.h
C:\Program Files\IVI Foundation\VISA\Win64\Include\WFS.h
```

Static Library

```
C:\Program Files (x86)\IVI Foundation\VISA\WinNT\lib\msc\WFS_32.lib
C:\Program Files\IVI Foundation\VISA\Win64\Lib_x64\msc\WFS_64.lib
```

Function Panel

```
C:\Program Files (x86)\IVI Foundation\VISA\WinNT\WFS\WFS.fp
```

Online Help for VXIpnp Instrument Driver

```
C:\Program Files (x86)\IVI Foundation\VISA\WinNT\WFS\Manual\…
…WFS.html
```

NI LabVIEW™ Driver (Including an Example VI)

The LabVIEW™ Driver is a 32-Bit and 64-Bit driver and compatible with NI-LabVIEW™ versions 2018 and higher only.

```
C:\Program Files (x86)\National Instruments\LabVIEW xxxx\…
…Instr.lib\TLWFS\WFS.llb
```

`C:\Program Files\National Instruments\LabVIEW xxxx\…`

`…Instr.lib\TLWFS\WFS.llb`

(LabVIEW™ container file with driver vi's - "LabVIEW™ xxxx" stands for actual LabVIEW™ installation folder.)

.net wrapper dll

`C:\Program Files (x86)\Microsoft.NET\Primary Interop Assemblies\…`
`…Thorlabs.WFS.Interop.dll`

`C:\Program Files\IVI Foundation\VISA\VisaCom64\…`
`…Primary Interop Assemblies\Thorlabs.WFS.Interop64.dll`

Example for C

`C:\Program Files (x86)\IVI Foundation\VISA\WinNT\WFS\Examples\…`

`…CVI C Sample\sample.c`

C program how to use the WFS driver functions.

`C:\Program Files (x86)\IVI Foundation\VISA\WinNT\WFS\Examples\…`

`…CVI C Sample\sample.exe`

32-Bit executable C sample program how to use the WFS driver functions.

Example for C# (same for 32-Bit and 64-Bit)

Solution File

`C:\Program Files (x86)\IVI Foundation\VISA\WinNT\WFS\…`
`…Examples\MS VS CSharp Demo\Thorlabs.WFS.Demo.sln`

Project File

`C:\Program Files (x86)\IVI Foundation\VISA\WinNT\WFS\Examples\MS VS CSharp Demo\Thorlabs.WFS.Demo\…`

`…Thorlabs.WFS.Demo.csproj`

Note

To get a 64-Bit executable you can set your project options to compile for 64-Bit targets. You have to set the references for the executable to the 64-Bit DLLs (see above, Thorlabs.WFS.Interop64.dll).

Example for LabView™

Included in driver llb container.

Chapter 19 Maintenance and Service

Protect the WFS31 from adverse weather conditions. The WFS31 is not water resistant.

Attention

To avoid damage to the instrument, do not expose it to spray, liquids or solvents!

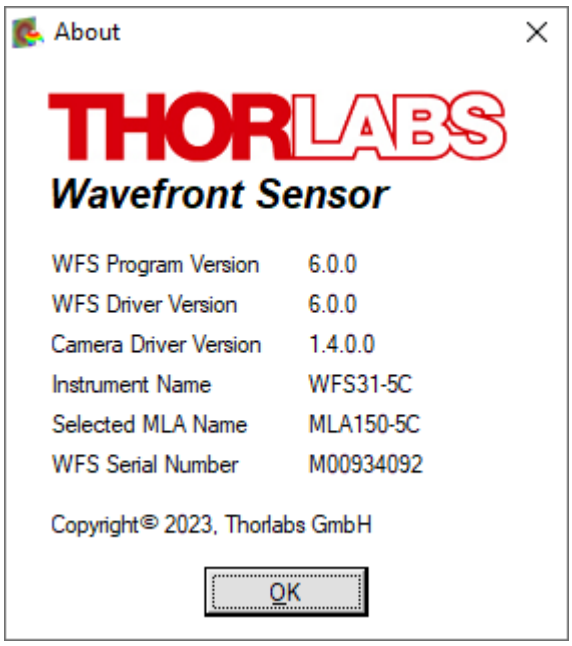
The unit does not need regular maintenance by the user. It does not contain any modules and/or components that could be repaired by the user himself. If a malfunction occurs, please see the Return of Devices section and contact Thorlabs for return instructions.

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Do not remove covers!

19.1 Version Information

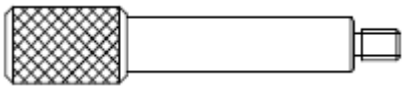
Detailed information about the WFS31 software and driver versions can be found in the about menu:



19.2 Exchanging the Microlens Arrays

Up to three exchangeable microlens arrays (MLAs) (see WFS Products and Accessories) are included with each Thorlabs WFS31. The aperture of each MLA is customized for either the respective wavefront sensors - also the WFS31. See chapter Parts List for details. Microlens arrays are permanently mounted in individual patented precision magnetic holders. One is installed on the sensor head during operation.

The mounted MLA installed on the sensor head is easily exchanged using a **Pickup Tool** (shown below). Thorlabs includes this Pickup Tool with the instrument when more than one MLA is ordered for a Wavefront Sensor, or when a Wavefront Sensor is upgraded to include an additional MLA.



Attention

Purchasing an additional MLA for an existing Wavefront Sensor requires returning the Wavefront Sensor to Thorlabs! The Wavefront Sensor must be calibrated by Thorlabs for use with the additional MLA. The calibration data are saved to the sensor's internal memory.

MLA Exchange Instruction

- Screw the pickup tool into the MLA that is currently mounted to the WFS.
- Pull out the MLA carefully from the aperture, avoid tilting!
- Unscrew the pickup tool from the extracted MLA.

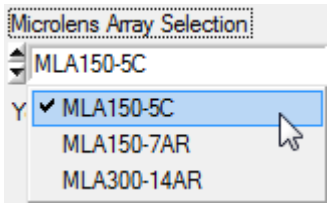
- Store the MLA away in a dust-proof box.
- Unpack the replacement MLA and screw in the pickup tool.
- Prior to installing the replacement MLA, we recommend cleaning it using duster spray. Be sure to keep a distance of at least 4 inches (10 cm) between the nozzle and the MLA to avoid damaging it!
- Insert the replacement MLA into the WFS aperture with the pickup hole up.
- Setup the new MLA in the WFS software.

Note

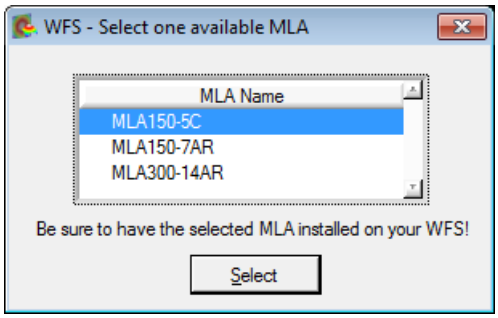
The software cannot recognize the installed MLA. The MLA-Type must be selected in the software by the user. Selecting the installed MLA is essential for correct wavefront measurements!

There are two ways to select the installed MLA in the software:

1. The MLA is exchanged during operation of the WFS: select the present MLA from the pull down list in the Wavefront/MLA Tab:



2. The MLA is exchanged while the WFS is not being operated: The correct MLA must be selected after software start in the dialog window, immediately after selecting the WFS:



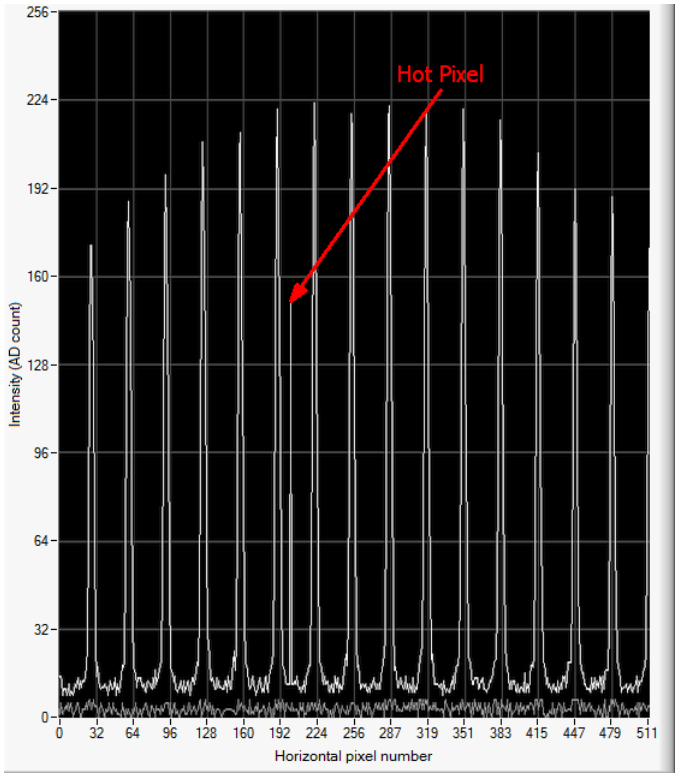
Attention

Be sure to select the correct MLA in order to avoid serious measurement errors!

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19.3 Hot Pixel

In digital imaging, defective pixels that show an intensity that is not related to the incident light are called hot pixels. Such pixels often appear brighter than ambient light pixels, although in rare cases they can appear darker. The occurrence of defective pixels is strongly dependent on exposure time and ambient temperature.



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

As a part of the factory calibration, Thorlabs identifies and implements embedded hot pixel correction for the Wavefront Sensors. After a long period of time and many temperature cycles, the WFS cameras may show new hot pixels that could not be detected during factory calibration. Although the impact of single pixel defects to the WFS accuracy is negligible, the automatic exposure control may be influenced.

If a new, stable and strong hot pixel (more than 50 digits intensity deviation from ambient pixels) appears, please return your WFS to Thorlabs for a factory hot pixel compensation.

Please contact Thorlabs for return instructions.

In rare cases hot pixels may sporadically appear at random image positions. Such single pixel defects are only visible temporarily, within a single camera frame. The appearance of such sporadic hot pixels cannot be corrected; the specifications are not violated by temporary hot pixels. So this is not a return reason.

19.4 Troubleshooting

Below are a few checks to help in troubleshooting problems that may arise. Please contact your local Thorlabs Technical Support office with any questions.

If the unit does not appear to turn on correctly, please check the following items:

- Ensure the USB cable is connected properly to an USB3 port of your PC.
- Ensure to use the USB cable provided with the WFS.

1. **No Wavefront Sensor found after software start.**

Note

If the Wavefront Sensor is connected to a different USB port of the PC than before, the Wavefront Sensor driver must be installed for this USB port, too. Wait a few seconds until the driver is installed successfully and the WFS is ready to use.

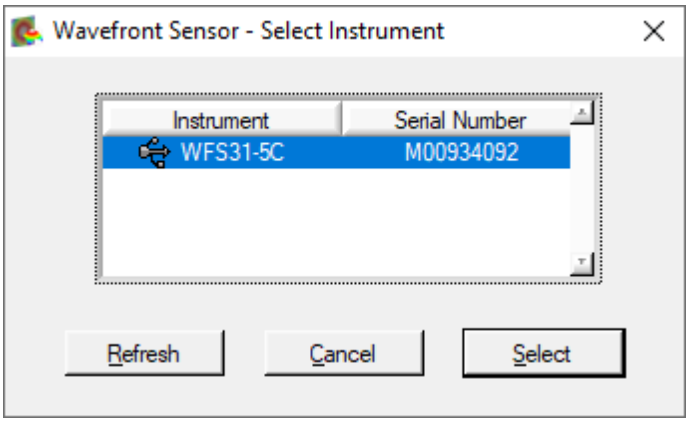
- Check if the Wavefront Sensor is connected to the USB port of the PC using the included USB cable.
- Make sure that WFS31 models are connected to a USB 3.0 port on your computer. USB3.0 ports can be recognized by their blue plastic insert. Additionally, they are marked with the USB3 SS logo.
- The LED at the back of the Wavefront Sensor indicates the instrument state:

Off USB Cable or USB Port is Defective

Red Sensor is not Recognized by the Windows System; Install the Wavefront Sensor Drivers (See Chapter Software Installation)

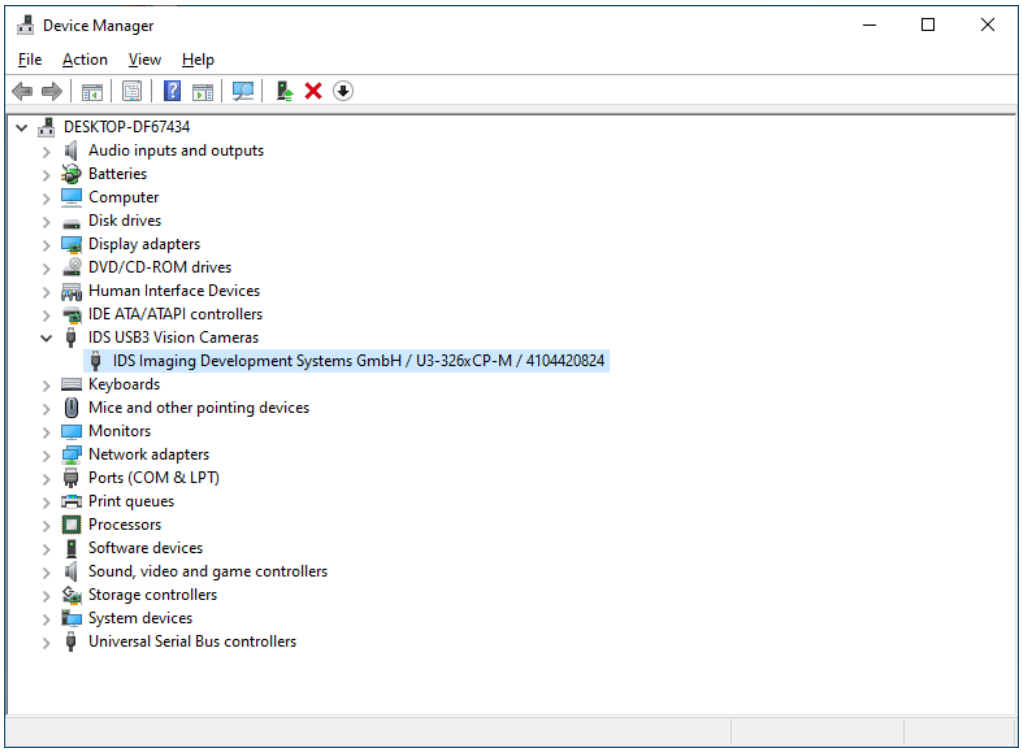
Green Wavefront Sensor is Properly Installed and Ready for Operation

- Was the WFS31 software installed completely?
- Be sure to have administrative privileges on your computer to install software. Contact your system administrator in case of trouble.
- Click the 'Refresh' button in the 'Select Instrument' dialog. It will take a few seconds to recognize the instrument.



For verification purposes, check the USB controller branch of the Device Manager in the Control Panel. If properly installed, the WFS31 hardware appears in the list as shown on the next page:

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WFS31 in Device Manager

2. **Windows Error Message: "The device driver software was not installed correctly"**
   When connecting the wavefront sensor head to the PC for the first time, Windows may show this erroneous error message.

   In most cases, this error message can be ignored and you can proceed to use the WFS. In case you can not access the WFS through the software, please see the section Troubleshooting in the full manual, downloaded from the software website.

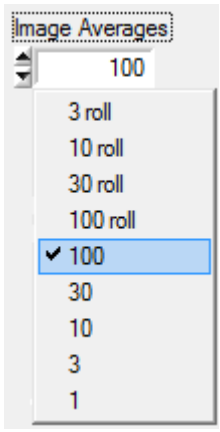
3. **Displayed Power Values and Graphs Seem to be Frozen**
   Perhaps the measurement has been stopped. Check the status window at the bottom of the Wavefront Sensor GUI. If there is a message like this



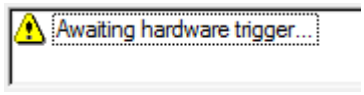
   just start the measurement again by clicking the ▶ symbol in the toolbar or simply press 'F2'.

   If the measurement isn't stopped, the reason may be that the camera is set to a high number of averages - it will take a long time to get a result in this case.

   Go to the Camera Settings panel and select a smaller number of averages.



The trigger functionality was activated but no trigger signal is applied. Check the 'Hardware Trigger' control within the Camera Settings. See the chapter Trigger Input for trigger signal input configuration.



4. **The menu items, toolbar buttons, and setting values in the main panel are not reacting to your clicks.**
   If there is a Wavefront Sensor pop-up window open, e.g. a 'Wavefront Sensor Message', the input will interact with this open pop-up window. Close any open pop-up windows to return to the main panel.
5. **Erroneous or no Measurement Data**
   Check that the correct Microlens Array (MLA) is selected in the Wavefront Setup. You may have physically installed a different MLA than you selected within the WFS software.
6. **Software: Device Driver Not Found**

   When connecting the WFS31 to the PC, Windows may show an erroneous error-message:

   "The device driver software was not installed correctly"

   In most cases, this error message can be ignored and you can proceed to use the WFS. In case you can not access the WFS through the software, try de- and reinstalling the software. If this problem can not be solved, please take screen shots of the error message and contact Thorlabs.

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Chapter 20 Specifications

20.1 WFS31 Specifications

Item #	WFS31-5C	WFS31-7AR	WFS31-14AR
Microlenses			
Microlens Array Type	MLA150-5C	MLA150-7AR	MLA300-14AR
Substrate Material	Fused Silica (Quartz)		
Wavelength Range	300 to 1100 nm	400 to 900 nm	400 to 900 nm
Lenslet Pitch	150 µm		300 µm
Lens Size	Ø140 µm (Cr Mask Hole)	Ø146 µm (Lens Diameter)	295 µm (Square)
Fill Factor (Approximate)[1)]	68.4%	74.4%	96.7%
Max. Number of Lenslets	73 x 45		35 x 21
Number of Active Lenslets	Software Selectable, Depending on the MLA		
MLA Aperture Size	11.5 mm x 7.5 mm		
Camera			
Sensor Type	CMOS		
Resolution	Max. 1920 x 1200 Pixels, Software Selectable		
Aperture Size (Max.)	11.25 mm x 7.03 mm		
Pixel Size	5.86 µm x 5.86 µm		
Shutter	Global		
Exposure Range	31 µs to 2000 ms		
Image Digitization	8 Bit		
Wavefront Measurement			
Wavefront Accuracy [2)]	λ/25 rms @ 633 nm	λ/40 rms @ 633 nm	λ/60 rms @ 633 nm
Wavefront Sensitivity [3)]	λ/80 rms @ 633 nm	λ/120 rms @ 633 nm	λ/200 rms @ 633 nm
Wavefront Dynamic Range [4)]	>500 λ @ 633 nm	>500 λ @ 633 nm	>250 λ @ 633 nm
Local Wavefront Curvature [5)]	>7.4 mm	>10.0 mm	>40.0 mm
External Trigger Input Specifications			
Safe Static Voltage level	0 to 30 V DC		
LOW Level	0.0 V to 2.0 V		
HIGH Level	5.0 V to 24 V		
Input Current, max.	10 mA		
Min Pulse Width	100 µs		
Min. Slew Rate	35 V / msec		

Item #	WFS31-5C	WFS31-7AR	WFS31-14AR
General			
Optical Input	C-Mount		
Power Supply	2.8 W (Max.), via USB 3.0		
Operating Temperature Range [6]	+5 °C to 35 °C		
Storage Temperature Range	-20 °C to 60 °C		
Warm-Up time for Rated Accuracy	15 min		
Dimensions (W x H x D)	29.8 mm x 35.4 mm x 47.9 mm (1.17" x 1.39" x 1.89")		
Weight	70 g		

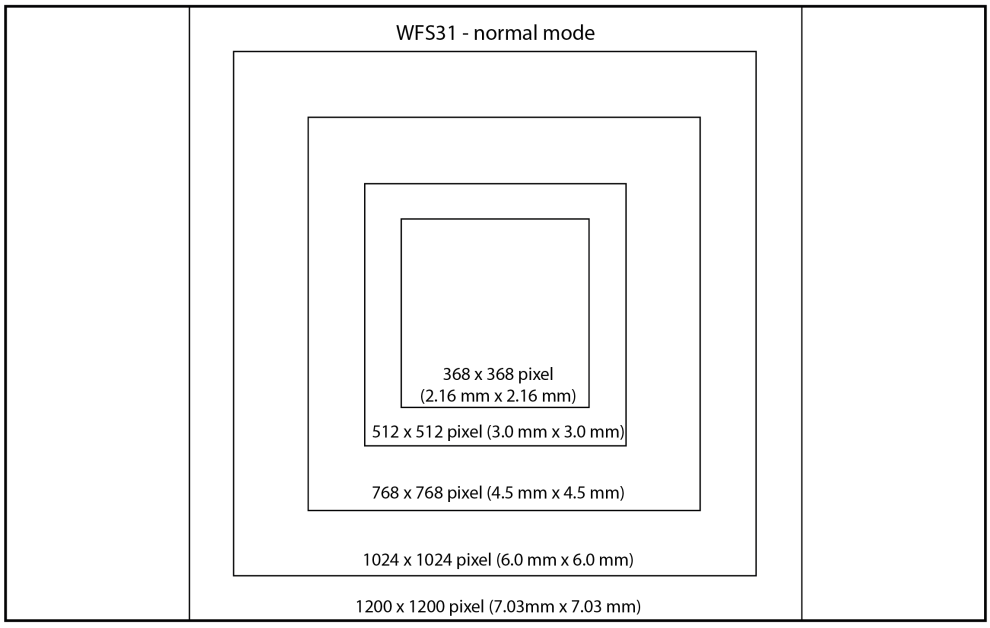
All specifications are valid at 23 ± 5°C and 45 ± 15% rel. humidity (non-condensing).

[1] The Fill Factor is a measure of the fraction of incident light on the detector. For the WFS31-5C and WFS31-7AR, the fill factor is less than 100% because the round lenses are arranged on a square grid.
[2] Absolute accuracy using internal reference. Measured for spherical wavefronts of known RoC.
[3] Typical relative accuracy. Achievable after, and with respect to a user calibration, 10 image averages.
[4] Over entire aperture of wavefront sensor
[5] Radius of wavefront curvature over single lenslet aperture
[6] Non-condensing

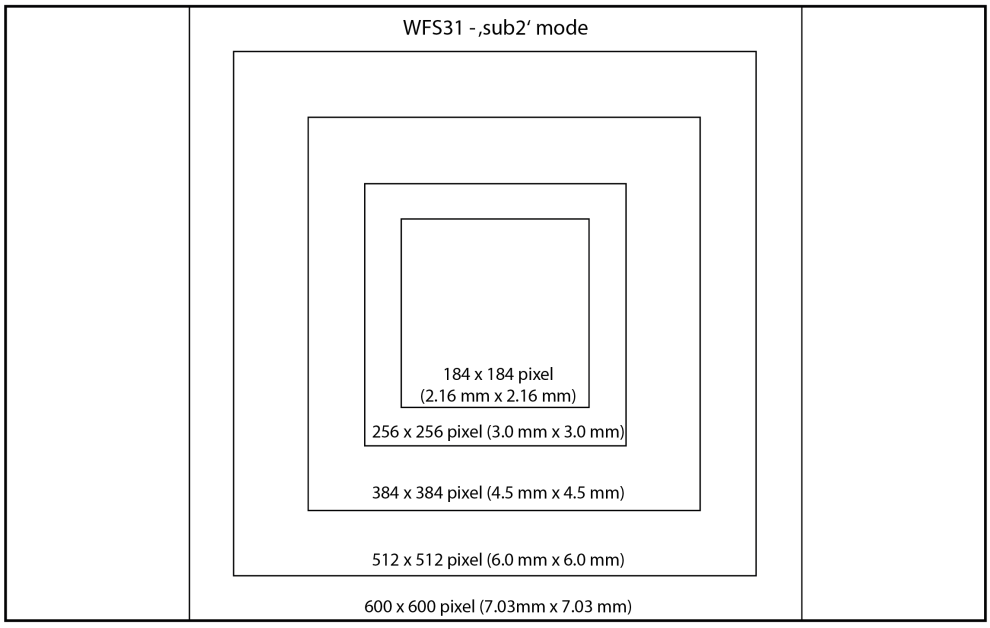
See the chapter MLA Microlens Arrays for detailed specifications of the supplied mounted Microlens Arrays.

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Selectable camera image sizes for WFS31



Full Size: 1920 x 1920 pixel (11.25 mm x 7.03 mm)



Full Size: 960 x 600 pixel (11.25 mm x 7.03 mm)

Note

The **sub2** mode allows to increase the measurement speed by subsampling - only each second pixel in rows and columns is used, in other words, from an area of 2 x 2 = 4 pixels only a single pixel is analyzed. The downside of the increased measurement speed is a decrease of measurement accuracy and spatial wavefront resolution.

Software Selectable Camera Resolution Options

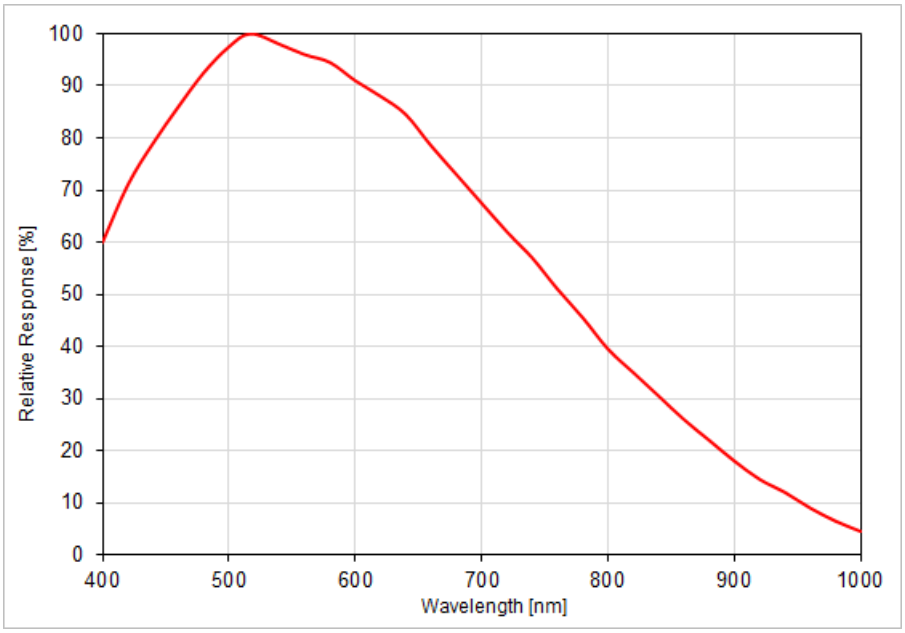
The selected camera resolution and operation mode determines the wavefront sensor resolution (the number of calculated microlens spots) and the frame rate.

Camera Resolution (Pixels)		Active Area (mm)	Microlens Spots	Spot Count	Frame Rate (fps)[2]	
Normal Mode	sub2 Mode[1]				Normal Mode	sub2 Mode
WFS31-5C, WFS31-7AR						
1920 x 1200	960 x 600	11.25 x 7.03	73 x 45	3285	13	23
1200 x 1200	600 x 600	7.03 x 7.03	45 x 45	2025	16	27
1024 x 1024	512 x 512	6.00 x 6.00	39 x 39	1521	21	32
768 x 768	384 x 384	4.50 x 4.50	29 x 29	841	30	42
512 x 512	256 x 256	3.00 x 3.00	19 x 19	361	52	59
368 x 368	184 x 184	2.16 x 2.16	13 x 13	169	70	74
WFS31-14AR						
1920 x 1200	960 x 600	11.25 x 7.03	35 x 21	735	15	25
1200 x 1200	600 x 600	7.03 x 7.03	21 x 21	441	18	29
1024 x 1024	512 x 512	6.00 x 6.00	19 x 19	361	22	32
768 x 768	384 x 384	4.50 x 4.50	13 x 13	169	34	43
512 x 512	256 x 256	3.00 x 3.00	9 x 9	81	55	61
368 x 368	184 x 184	2.16 x 2.16	5 x 5	25	76	76

[1] When in sub2 Mode subsampling is used to increase the measurement speed, subsampling analyzes a single pixel in each 2 x 2 block of 4 pixels.

[2] Typical speed without graphical display, depending on PC hardware, 4th order Zernike fit at specific camera resolution, and minimum exposure time.

Typical Wavelength Response

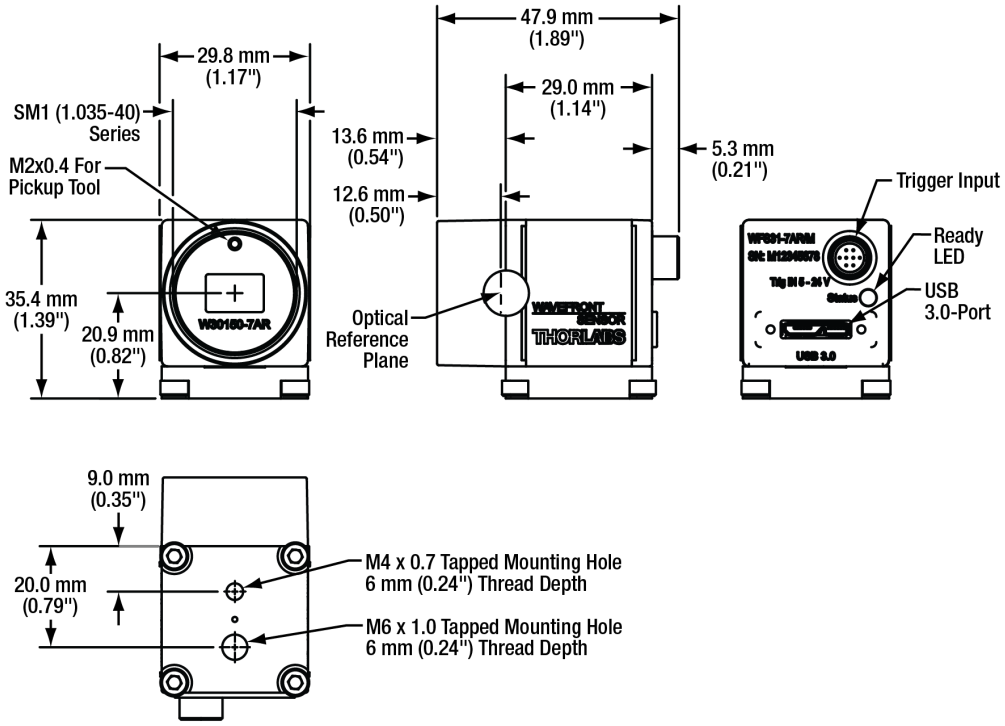


Typical Wavelength Response of the WFS31 CMOS Camera

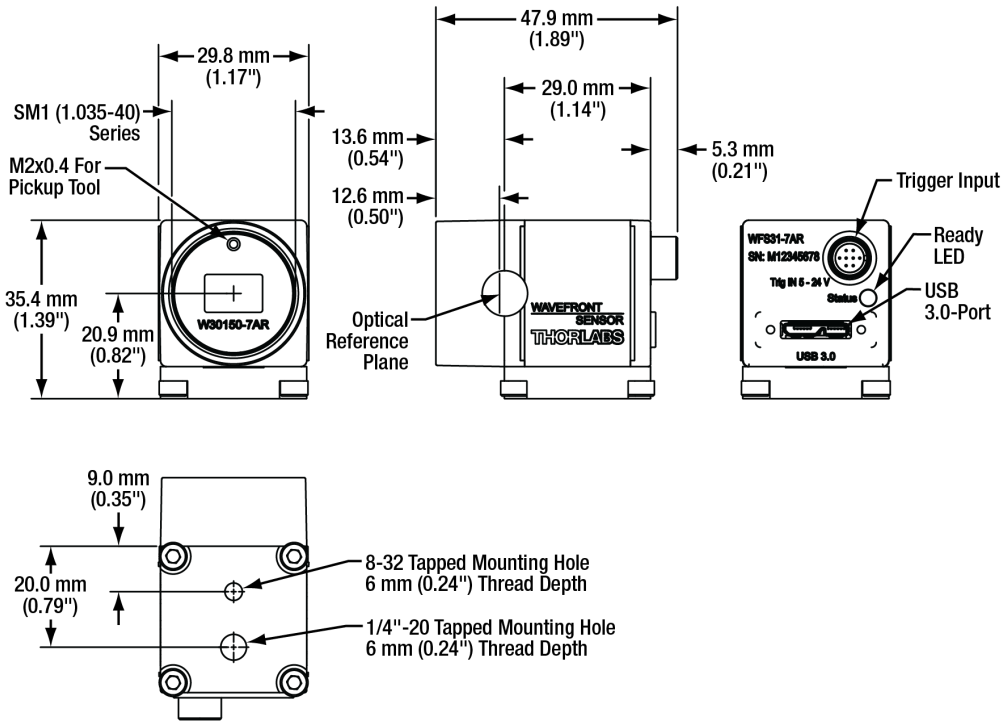
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20.2 Dimensions

Outer Dimensions of WFS31/M



Outer Dimensions of WFS31



20.3 MLA Microlens Arrays

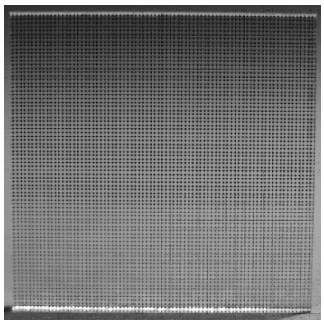
The WFS31 uses high-quality microlens arrays which are best suited for Shack-Hartmann Wavefront Sensor applications. All lenslets are made from fused silica for excellent transmission characteristics from the deep UV to IR and have a plano-convex shape that allows nearly refraction limited spots.

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.

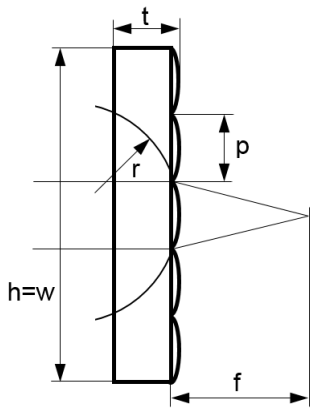
The Wavefront Sensor models WFS31-5C, WFS31-7AR and WFS31-14AR utilize the mounted microlens arrays MLA150-5C, MLA150-7AR and MLA300-14AR, respectively.

The MLA150-5C has a chrome mask grid that blocks light from being transmitted unless it passes through a microlens, which increases the image contrast. The MLA150-7AR and MLA150-14AR have a broadband AR coating that reduces surface reflections in the 400-900 nm spectral region to below 1%.

Microlens Array MLA150-5C (Without Mounting)



Geometric Parameters of the MLA Series (Without Mounting)



Parameter	MLA150-5C	MLA150-7AR	MLA300-14AR
Array Size (h=w) WFS31	12.0 mm x 12.0 mm		
t	1.2 mm		
p	150 µm		300 µm
r [1]	2.54 mm		6.5 mm
f [2]	5.6 mm		14.2 mm
f_{eff} [3]	4.1 mm	5.2 mm	14.6 mm

[1] Info value, not specified

[2] Nominal value, ±3% tolerance, Note: when built into a WFS, the effective focal length may differ!

[3] Effective (optimal) focal length when built into a WFS

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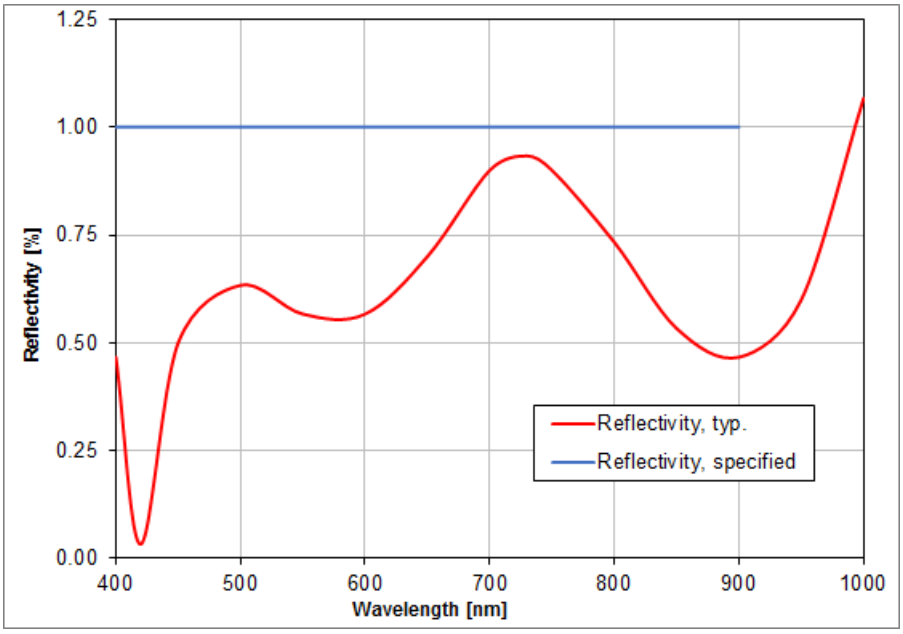
Specifications of the MLA Series

Parameter	MLA150-5C	MLA150-7AR	MLA300-14AR
Substrate Material	Fused Silica (Quartz)		
Wavelength Range	300 - 1100 nm	400 - 900 nm	
Free Aperture (W x H) WFS31	11.5 mm x 7.5 mm		
Lenslet Grid Type	Square Grid		
Lenslet Pitch	150 µm		300 µm
Lens Shape	Round, Plano Convex Spherical		Square, Plano Convex Parabolic
Lens Size	∅140 µm (CR Mask Hole)	∅146 µm (Lens Diameter)	295 µm (Square)
Fill Factor (Approximate)[1)]	68.4%	74.4%	96.7%
Coating	Chrome Mask	Anti Reflection	
Reflectivity	<25%	<1%	
Nominal Focal Length	5.6 mm		14.2 mm
Effective Focal Length (When mounted to WFS)	4.1 mm	5.2 mm	14.6 mm
Array Size for WFS31	12 mm x 12 mm x 1.2 mm		

[1)] The Fill Factor is a measure of the fraction of incident light reaching the detector. For the MLA150-5C and MLA150-7AR, the fill factor is less than the MLA300-14AR value because the round lenses are arranged on a square grid.

The WFSxx-7AR and WFSxx-14AR come with an anti-reflection coated (AR) lenslet array. The following diagram shows the typical reflectivity of the lenslet array. The guaranteed reflectivity of the coating in the wavelength range 400 to 900 nm is below 1%.

Reflectivity

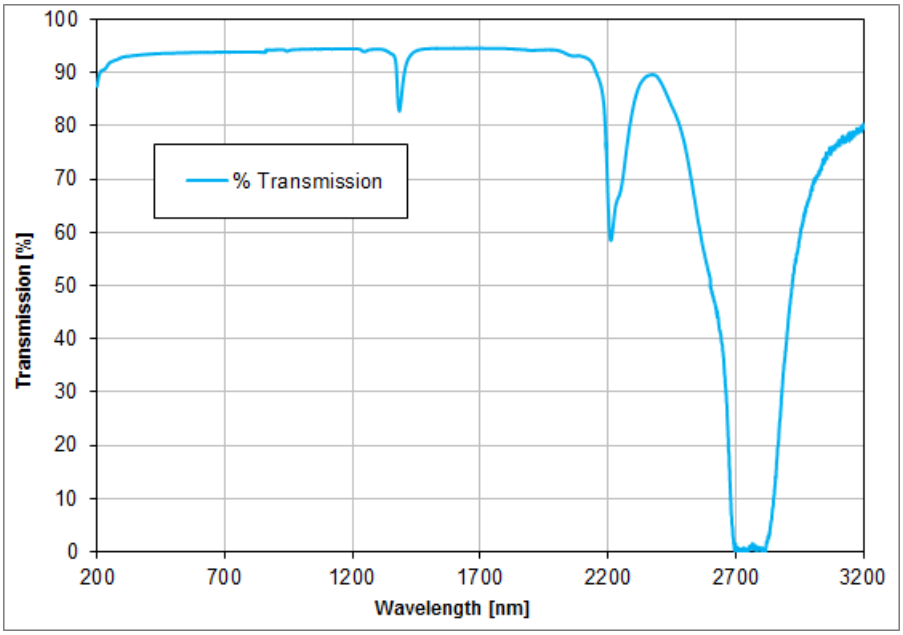


Reflectivity of MLA150-7AR and MLA300-14AR (including AR - Coating)

Note

The total reflectivity of the WFS31 instruments may be higher due to reflections from the CMOS camera chip and its protecting window.

Transmission

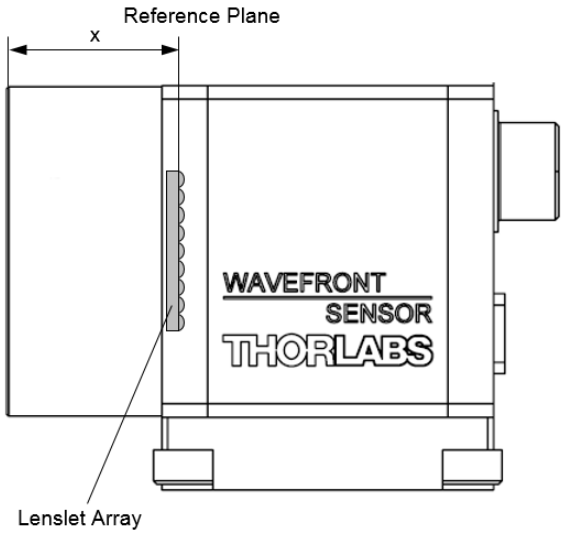


Typical Transmission of Fused Silica Material

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20.4 Reference Plane

Calculated wavefront data are related to the reference plane of the sensor. This reference plane is the location of the microlenses on the back face of the microlens array; its location "is different for each Wavefront Sensor model and depends on parameters specific the particular sensor head and installed MLA.



Model	Reference Plane - Distance "x"
WFS31-5C	13.7 mm
WFS31-7AR	12.6 mm
WFS31-14AR	3.3 mm

Chapter 21 Certifications and Compliances

EU Declaration of Conformity

Manufacturer: Thorlabs GmbH

Address: Münchner Weg 1, D-85232 Bergkirchen

We hereby declare under our sole responsibility that:

Product: **WFS31-14AR(/M), WFS31-5C(/M), WFS31-7AR(/M), WFS31-K1(/M), WFS31-K2(/M)**

Product description: **Shack-Hartmann Wavefront Sensor Family**

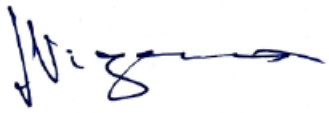
is/are in conformity with the following directive(s):

2014/30/EU	Electromagnetic Compatibility (EMC) Directive
2011/65/EU	Restriction of Use of Certain Hazardous Substances (RoHS), including 2015/863

and (harmonized) standards / technical specifications :

EN 61326-1	Electrical Equipment for Measurement, Control and Laboratory Use - EMC Requirements	2013
EN IEC 63000	Technical documentation for the assessment of electrical and electronic products with respect to the restriction of hazardous substances	2018

I hereby declare that the equipment named has been designed to comply with the relevant sections of the above referenced specifications and complies with all applicable Essential Requirements of the Directives.

Signed: 

Name: Julien Vigroux *On:* 20.07.2023

Position: General Manager

CE

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Chapter 22 Warranty and RMA Information

Thorlabs warrants material and production of the WFS31 for a period of 24 months starting with the date of shipment in accordance with and subject to the terms and conditions set forth in Thorlabs' General Terms and Conditions of Sale which can be found at:

General Terms and Conditions:

https://www.thorlabs.com/Images/PDF/LG-PO-001_Thorlabs_terms_and_%20agreements.pdf

and

https://www.thorlabs.com/images/PDF/Terms%20and%20Conditions%20of%20Sales_Thorlabs-GmbH_English.pdf

22.1 Return of Devices

This precision device is only serviceable if returned and properly packed into the complete, original packaging including the cardboard insert that holds the enclosed devices.

22.2 WEEE Policy

Thorlabs 'End of Life' Policy (WEEE)



Thorlabs verifies our compliance with the WEEE (Waste Electrical and Electronic Equipment) directive of the European Community and the corresponding national laws. Accordingly, all end users in the EC may return “end of life” Annex I category electrical and electronic equipment sold after August 13, 2005 to Thorlabs, without incurring disposal charges. Eligible units are marked with the crossed out “wheelie bin” logo (see right), were sold to and are currently owned by a company or institute within the EC, and are not dissembled or contaminated. Contact Thorlabs for more information. Waste treatment is your own responsibility. “End of life” units must be returned to Thorlabs or handed to a company specializing in waste recovery. Do not dispose of the unit in a litter bin or at a public waste disposal site. It is the user's responsibility to delete all private data stored on the device prior to disposal.

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Please refer to the general terms and conditions linked under Warranty.

Chapter 25 Thorlabs Worldwide Contacts

For technical support or sales inquiries, please visit us at www.thorlabs.com/contact for our most up-to-date contact information.



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