THORLABS

Optical Wavefront Sensors
(Shack-Hartmann)

WFS Series
Operation Manual

2015

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Contents

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

Thorlabs GmbH

Warning

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

Attention

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

Note

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

Please read these advices carefully!

1 General Information

A Thorlabs wavefront (Shack-Hartmann) sensor is comprised oif a camera with a microlens array (MLA) mounted in front of the camera sensor.

Two types of wavefront sensors are available with different camera sensors and performance:

- WFS150/300 Series, based on a CCD camera
- WFS20 Series, based on a high resolution CMOS camera head with external control box that allows a remarkably higher measurement speed at an improved measurement accuracy.

For all sensor types, three different types of microlens arrays are available.

As a special feature, the WFS Series is equipped with an interchangeable microlens array mounted into a precision patent pending magnetic holder. The exchange of the microlens arrays allows economical switching to different applications requiring different WFS specifications in terms of spatial resolution (lenslet pitch), focal length, wavefront sensitivity and dynamic range. See chapter Microlens Data 108 for a table of available MLAs and Ordering Codes 6 for available kits of a WFS with two microlens array.

1.1 Safety

Attention

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

Prior to applying power to the WFS Series, make sure that the protective conductor of the 3 conductor mains power cord is correctly connected to the protective earth ground contact of the socket outlet! Improper grounding can cause electric shock with damages to your health or even death!

Be careful when working with open laser beams. Follow the relevant laser safety regulations, avoid skin irradiation and use laser protection glasses to protect your eyes!

The WFS Series must not be operated in explosion endangered environments!

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

Do not cover the Wavefront Sensor in order to prevent heating the instrument.

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

Do not open the cabinet, there are no parts serviceable by the operator inside!

Refer servicing to qualified personnel!

This precision device is only serviceable if properly packed into the complete original packaging including the plastic foam sleeves. If necessary, ask for a replacement package.

Attention

Mobile telephones, cellular phones or other radio transmitters are not to be used within the range of three meters of this unit since the electromagnetic field intensity may then exceed the maximum allowed disturbance values according to IEC 61326-1.

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).

1.2 Ordering Codes and Accessories

Available wavefront sensor types (Order Codes)

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

WFS20-5C	Fast Wavefront Sensor, Chrome Apertures 300-1100 nm, pitch=150 µm
WFS20-7AR	Fast Wavefront Sensor, AR Coated 400-900 nm, pitch=150µm
WFS20-14AR	Fast Wavefront Sensor, AR Coated 400-900 nm, pitch=300 µm

All Thorlabs Wavefront Sensors are equipped with an easily exchangeable lenslet array and available in both imperial and metric (/M) versions.

Available WFS kits with 2 MLA

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

Type	Used camera	Included microlens arrays
WFS-K1	WFS150 (CCD)	MLA150-5C - Chrome Mask 300-1100 nm, pitch=150 µm MLA150-7AR - AR Coated 400-900 nm, pitch=300 µm
WFS-K2	WFS150 (CCD)	MLA150-7AR - AR Coated 400-900 nm, pitch=150µm MLA300-14AR - AR Coated 400-900 nm, pitch=300 µm
WFS20-K1	WFS20 (CMOS)	MLA150-5C - Chrome Mask 300-1100 nm, pitch=150 µm MLA300-14AR - AR Coated 400-900 nm, pitch=300 µm
WFS20-K2	WFS20 (CMOS)	MLA150-7AR - AR Coated 400-900 nm, pitch=150µm MLA300-14AR - AR Coated 400-900 nm, pitch=300 µm

Wavefront Sensor types and kits as stated above are factory calibrated. For other than above mentioned combinations, please contact your local Thorlabs office 137.

Three Wavefront Sensor Models

There are three different versions available which differ in the type of implemented microlens array (MLA, see data here Microlens Data 108) and its distance to the CCD camera sensor.

- **WFS150-5C / WFS20-5C** uses a MLA with a **chrome mask** on it that prevents the light from passing through the spaces between microlenses directly to the sensor. This increases the image contrast of the detected spotfield and improves the instrument accuracy, especially in the case of strong wavefront deformations. The wavelength range is not restricted (no AR coating) and covers the full sensitivity range of the Silicon CCD/ CMOS detector of **300 - 1100 nm** (with largely reduced sensitivity at the edges). Take into account that such a chrome mask cannot be anti-reflection coated, and may **reflect up to 25%** of the input light back into your measurement setup. It can be helpful to tilt the sensor a bit or insert an attenuator in order to reduce the amount of light reflected back into your measurement setup.

- **WFS150-7AR / WFS20-7AR** uses an anti-reflection (AR) coated MLA that reduces the reflection from the array to **below 1% within the wavelength range of 400 - 900 nm**. Note that the total reflection from the entire instrument can be higher due to reflection from the sensor cover glass and chip itself.

  This model is well suited **for applications that do not tolerate back-reflections** into the measurement setup, e.g., an experiment that contains a laser without an isolator that has a parallel beam and long coherence length. Use this model if other ways of preventing back-reflection like tilting the Wavefront Sensor with respect to the input beam are not feasible.

- **WFS300-14AR / WFS20-14AR** uses an anti-reflection (AR) coated MLA that reduces the reflection from the array to **below 1% within the wavelength range of 400 - 900 nm**. Note that the total reflection from the entire instrument can be higher due to reflection from the sensor cover glass and chip itself.

  Due to the increased focal length of the MLA, this sensor features increased sensitivity and accuracy (λ/50 instead of λ/15 for WFS300). On the other hand, this advantage comes along with reduced spatial resolution (300 µm pitch instead of 150 µm) and dynamic range.

Note

The specified reflectivity of the AR coated MLA is valid only within the stated wavelength range. Outside of this wavelength range, the reflectivity may increase significantly. Please see also Microlens Data 108.

How to order additional microlens arrays

Due to the fact, that each MLA shows individual optical characteristics (geometry, lens pitch and lens allocation accuracy), it is necessary to calibrate each individual MLA with the appropriate camera. This calibration is carried out at the factory, where the calibration data are saved to the camera's internal memory (EEPROM).

So if you have purchased a WFS with a single MLA and want to order an additional MLA, your existing WFS must be returned to Thorlabs. In our factory, your sensor will be calibrated with the additional MLA, calibration data will be added to the sensor's memory, and the WFS will be returned to you with both MLAs.

Adding an additional microlens array is an upgrade of the existing WFS with a single MLA to one of the above mentioned WFS kits with 2 MLAs.

Please contact Thorlabs 137 for return instructions.

Note

If the desired MLA combination is not stated in the above list, please contact Thorlabs 137 for support.

The WFS software accepts only one set of calibration data for each MLA type. In other words, it is impossible to calibrate the same sensor for two microlens arrays of the same type.

Example:

You have an WFS20-14AR and would like to add an additional microlens array with chrome mask and 150 µm lens pitch.

➔ *Contact Thorlabs for return instructions of your **WFS20-14AR** in order to convert it to **WFS20-K1** (WFS20 with two MLA)*

➔ *Upon receipt of your **WFS20-14AR**, your sensor will be calibrated with the additional MLA.*

➔ *Thorlabs will return a **WFS20-K1** (WFS20 with 2 MLA) to you.*

Exchange Program for Old-Style Wavefront Sensors

Our Wavefront Sensor Exchange Program allows to customers who purchased either a WFS150 or WFS150C wavefront sensor (with fixed MLA) to upgrade to a WFS150/WFS300 wavefront sensor (or to a WFS-K1 / WFS-K2 kit) with exchangeable lenslet array. Please contact Thorlabs 137 for more details.

1.3 Requirements

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

1.3.1 Hardware Requirements

CPU:	1 GHz or higher
RAM:	256 MB
Graphic card	Min. 128 MB memory, min. resolution 1024 x 768, 24 bit True Color, Indexed color
Hard disc	Min 240 MB free storage space
Interface	free USB2.0 port, USB cable according the USB 2.0 specification (a **USB 1.1** full speed port is **not usable**!)

1.3.2 Software Requirements

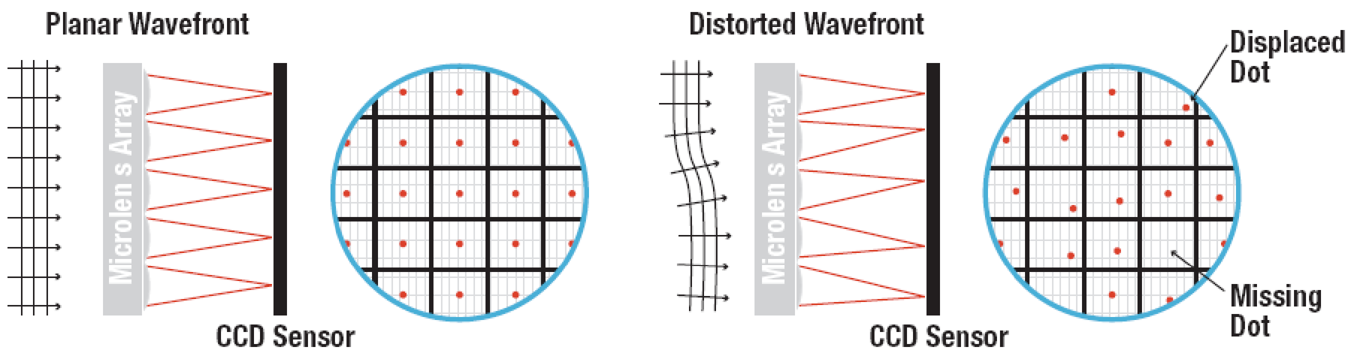
The WFS Series software is compatible with the following operating systems:

- Windows® Vista (32-bit, 64-bit)
- Windows® 7 (32-bit, 64-bit)
- Windows® 8.1 (32-bit, 64-bit)

For operation of the WFS Series, an NI-VISA (version 5.1.1 or higher) is also required. A NI-VISA engine comes with the Thorlabs GmbH WFS Series Installation Package, but can also be downloaded from National Instruments' website www.ni.com.

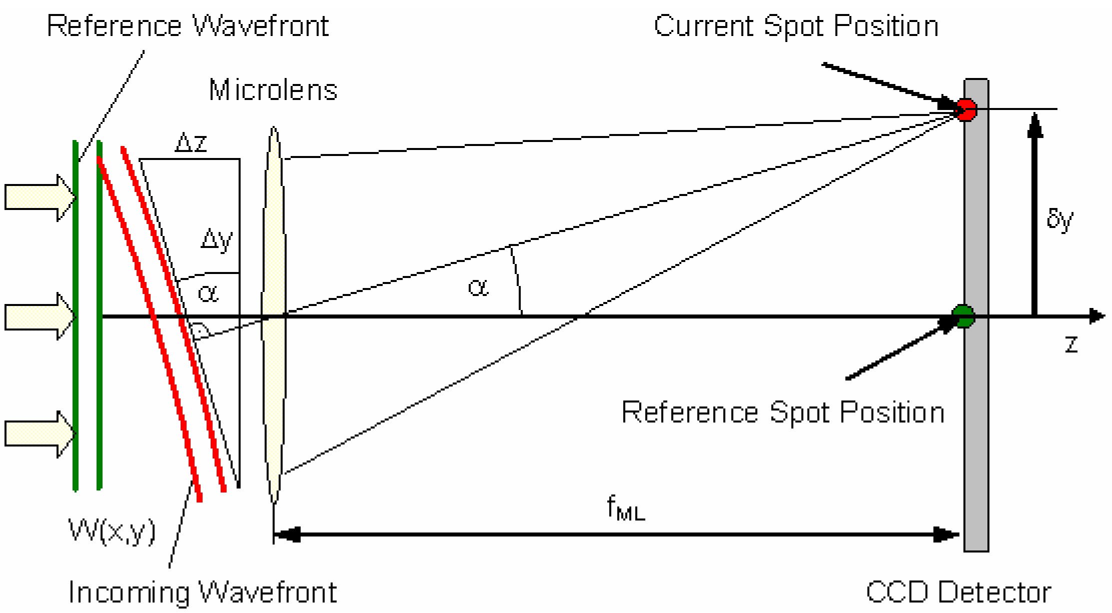
2 Operating Principle

The WFS Series instruments comprise a CCD/CMOS camera and a microlens array that is mounted at a defined distance in front of the camera sensor chip. Each microlens generates a spot on the sensor surface. The spot centroid position depends on the wavefront gradient in front of the lens area.



Each microlens of the lenslet array collects the light incident to its aperture and generates a single spot on the detector plane (CCD/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 **Reference Spotfield**.

Depending on the distortion of the wavefront incident on the sensor, the current spot positions will be shifted in the X and Y directions away from the optical axis Z of its associated microlens. The displacement is described by the angle α.



From the above sketch it can be seen that this deviation is caused by the deviation of the wavefront incident on the microlens from the reference wavefront, or in geometrical terms:

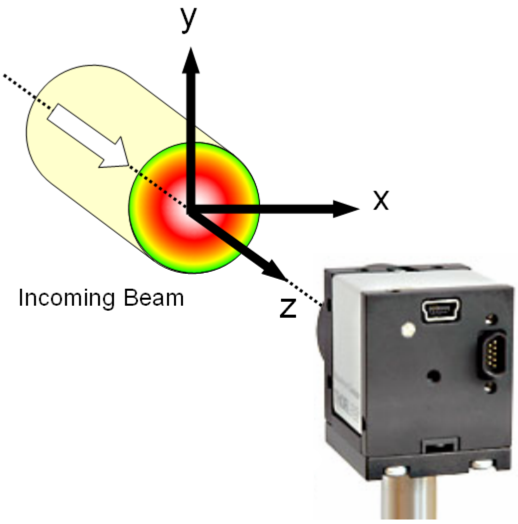
$$tan\ \alpha = \frac{\Delta z}{\Delta y} = \frac{\delta y}{f_{ML}}$$

If $W(x,y)$ describes the shape of the wavefront, then its partial derivations 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}:

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

Spot deviations δx and δy are determined by calculating the centroid coordinates of all detectable spots and 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.

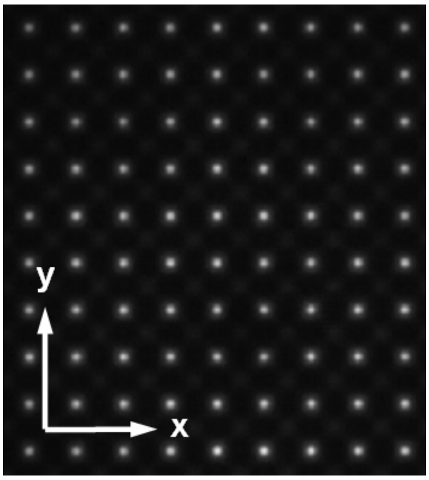
3 Coordinate Definitions



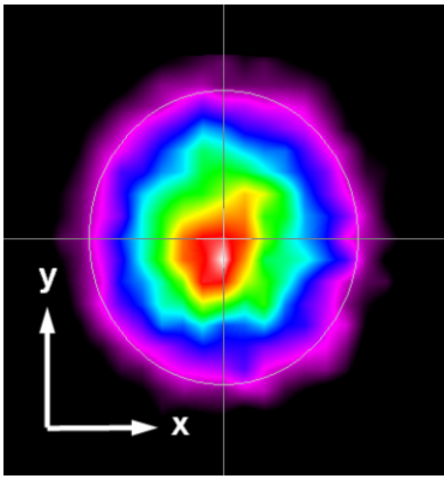
The WFS Series Wavefront Sensors use an orthogonal right-hand coordinate system (x,y,z) as shown to the left.

Imagine that you are looking towards the light source. Then the x-direction points towards right, the y-direction points up, and the optical beam to be analyzed is propagating in 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.

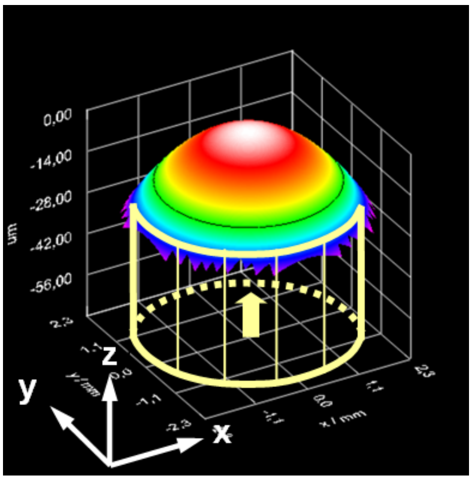


Spotfield Graph



Beam View Graph

In the 3D wavefront graph the beam's cross section in the X-Y plane is drawn at the bottom, and the Z axis points upwards. If the beam is coming from the bottom up, then the displayed 3D curve will represent the wavefront at the top of the beam.



Wavefront Graph

4 Getting Started

4.1 Parts List

Inspect the shipping container for damage.

If the shipping container seems to be damaged, keep it until you have inspected the contents and you have inspected the WFS Series mechanically and electrically.

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

WFS150/300:

1. Wavefront Sensor head with dust cover
2. USB2.0 high-speed cable, USB A to Mini USB B, 2.0 m
3. Mounting adapter plate and 4 mounting screws M3x6 (WFS)
4. SM1A9 C-Mount to SM1 Adapter
5. Wavefront Sensor Quick Start manual.

WFS20:

1. Wavefront Sensor head with dust cover
2. WFS20 Control Box with mounting accessories
3. 12 V / 1.5 A DC Power supply (wide range) with power cord
4. PoCL cable for connection of the WFS20 sensor head to the Control Box (angled to straight)
5. USB2.0 high-speed cable, USB A to Mini USB B, 2.0 m
6. SM1A9 C-Mount to SM1 Adapter
7. Wavefront Sensor Quick Start manual

Mounting Adapter Plate

A mounting adapter is added to the camera housing of the WFS150/WFS300 in order to supply standard M4 and UNC8-32 threads that are compatible with many of Thorlabs' mounts and posts holders.

If you want to use one of the M4 or UNC8-32 mounting threads, this adapter plate can be mounted on the bottom side of the WFS150/WFS300 using the four M3x6 screws. Otherwise, this adapter can be omitted. See Appendix Mounting Adapter 121 for a drawing of this adapter plate.

C-Mount Adapter

The C-Mount thread on the face of the Wavefront Sensor is compatible with Thorlabs' SM1A9 adapter. This 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.

Optional Accessories

Exchangeable Microlens Arrays

As a special feature, the WFS Series of Wavefront Sensors are equipped with an interchangeable microlens array mounted into a patented precision magnetic holder (US Patent No. 8,289,504).

The ability to exchange microlens arrays allows a single wavefront sensor to be used for different applications requiring different WFS specifications in terms of spatial resolution (lenslet pitch), focal length, wavefront sensitivity and dynamic range. See chapter Microlens Data 108 for a table of available MLAs.

Trigger Cable

An optional trigger cable (CAB-DCU-T2 for WFS150/300 and CAB-WFS20-T1 for WFS20 series instruments) can be ordered separately for supplying an electrical trigger signal to the WFS series instruments. See chapter Trigger Input 112 for details.

4.2 Installing Software

Note

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

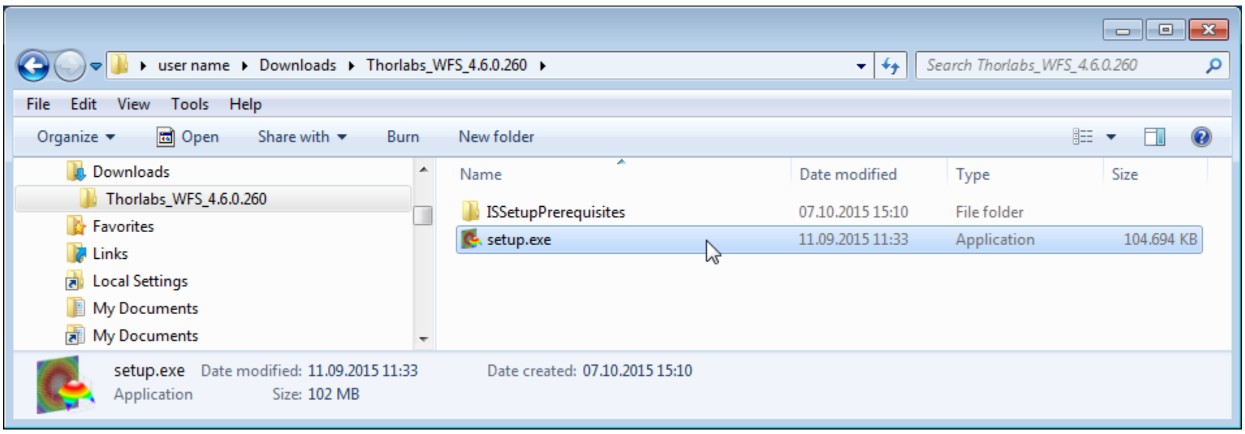
Attention

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

Thorlabs is breaking new ground in saving our environment. We decided to refrain from shipping an installation CD ROM 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 Series software package can be found easily on the website: Go to www.thorlabs.com, enter the item name (e.g., WFS150-5C) into the search bar, and click on the link to open the product page. Open the software tab:

Click the **Software** button to download the WFS Software ZIP archive, unpack it and open the installation folder:

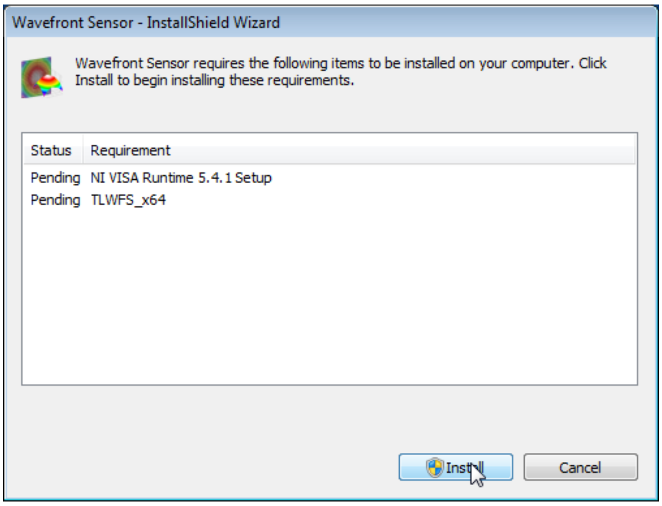


Then start the installation by double clicking the setup.exe file. The software installation on a Windows 7 64 bit operation system will be described below in detail.

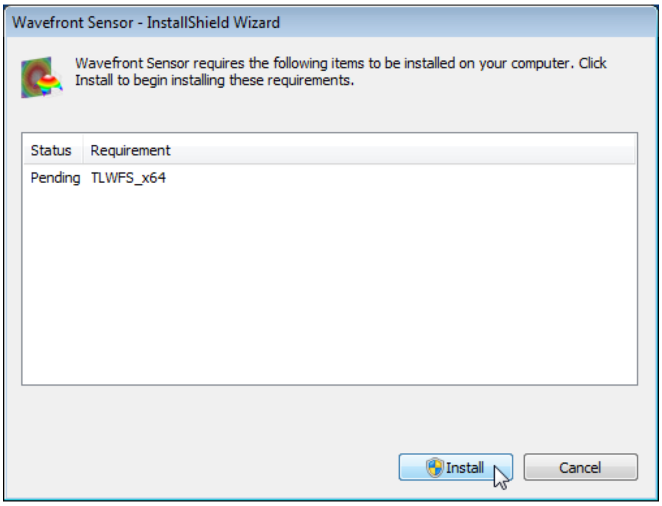
The installation includes three main components:

- Installation of NI VISA Runtime (if required)
- Installation of WFS software 64 bit components (only in case of a 64 bit operating system)
- Installation of the 32 bit WFS software and device drivers

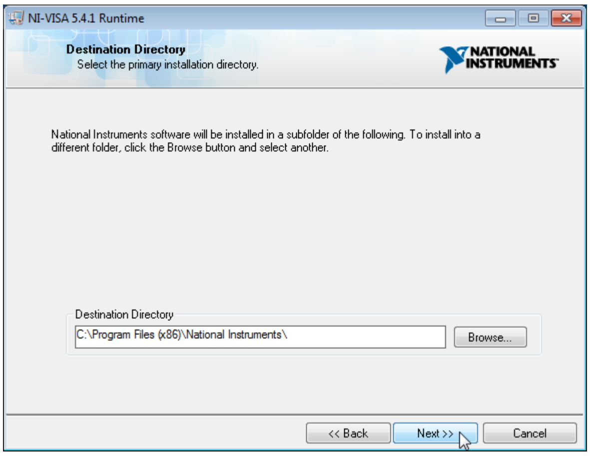
The installer will perform a check for an installed NI-VISA Runtime Version. If there is no NI-VISA installed on the PC or the installed version is before 5.1.1, the installer recognizes that and requests the installation of NI software:

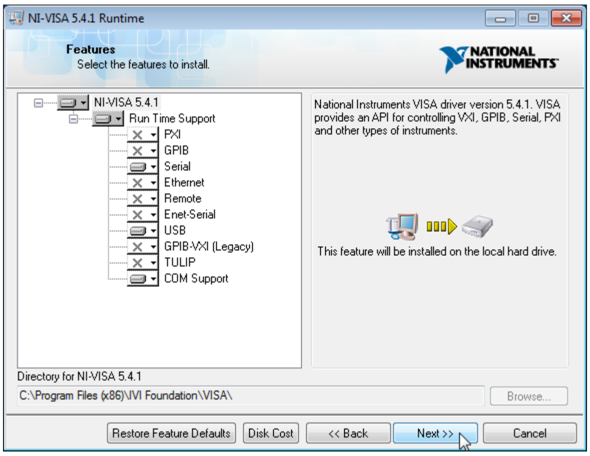


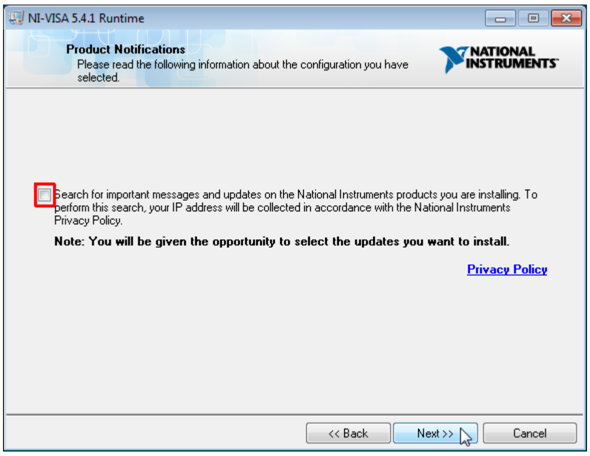
Click **Install** and allow in the following dialog to perform installation:

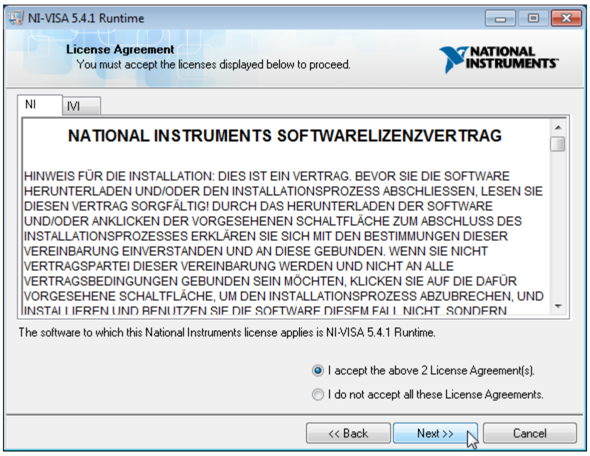


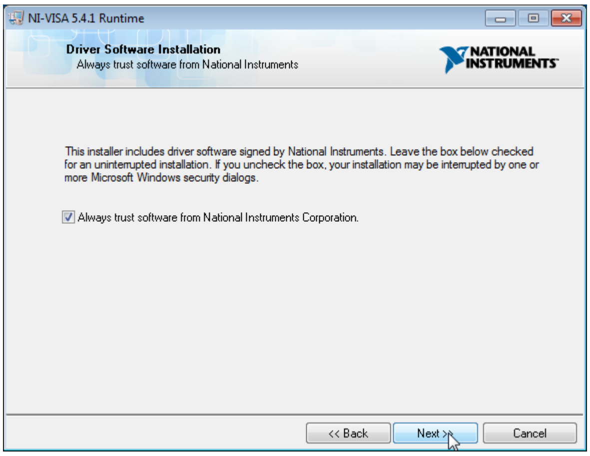
In the subsequent dialogs, follow the highlighted actions to continue the installation:

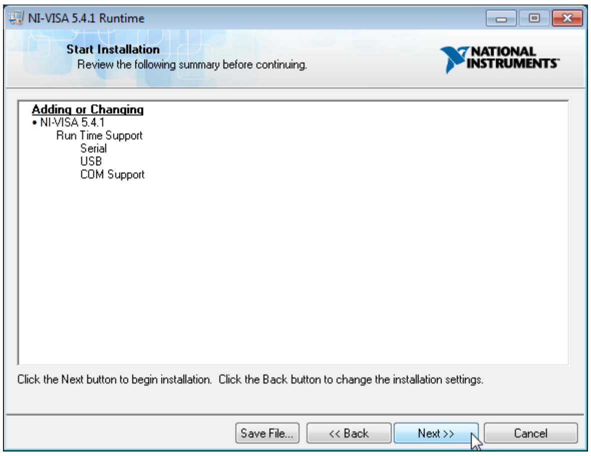


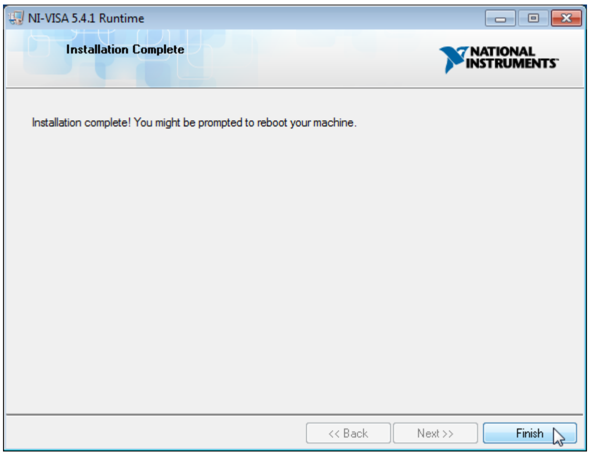




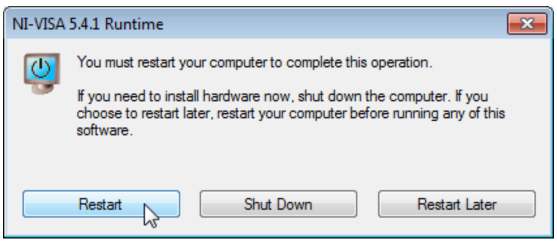








When you are prompted for a restart, please do so. This is important to continue the proper software installation procedure:

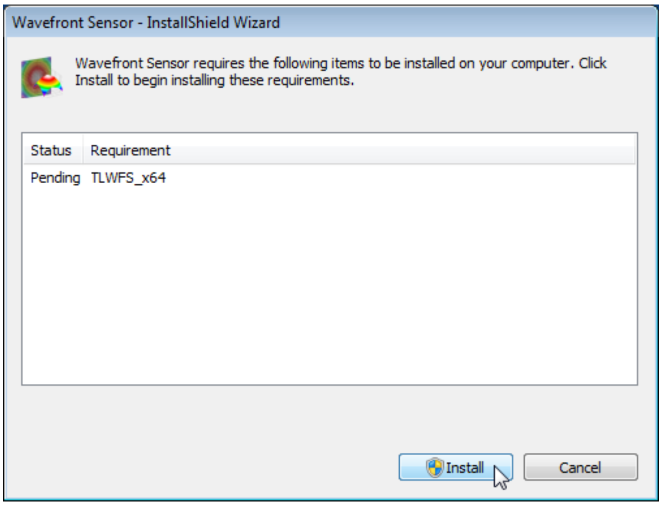


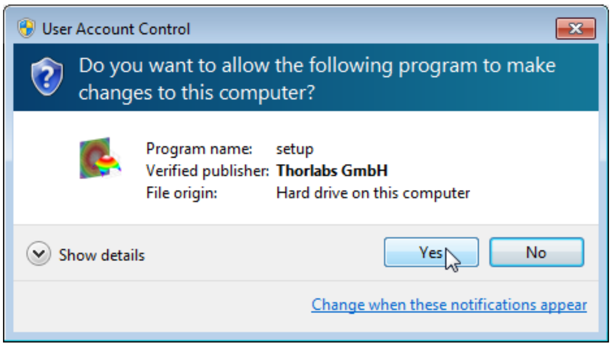
After the restart, the installer might not automatically continue to install 64 bit WFS software components to the PC - in this case start the **setup.exe** once again.

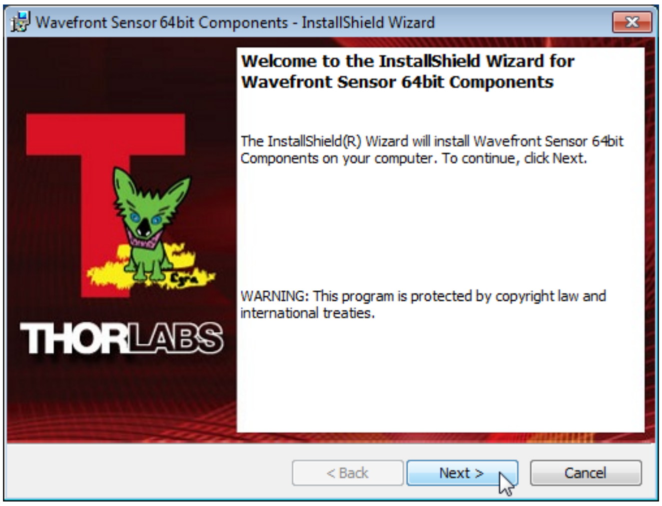
Note

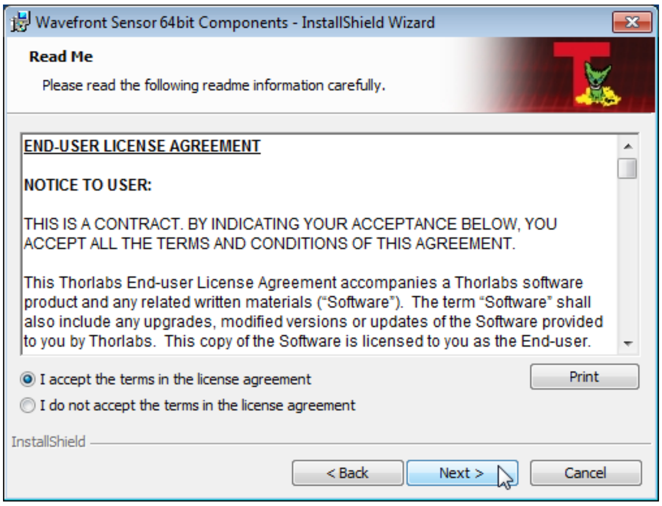
If a 32 bit operating system is recognized, the installer skips the following steps and continues with WFS Software installation 19.

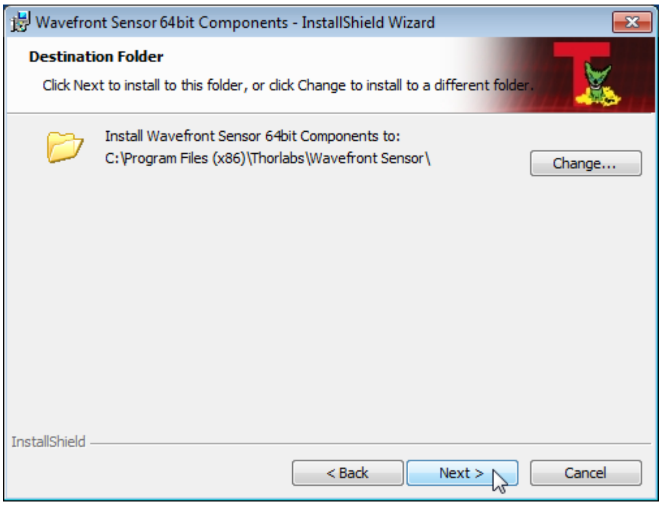
Follow the highlighted actions to proceed with the installation:

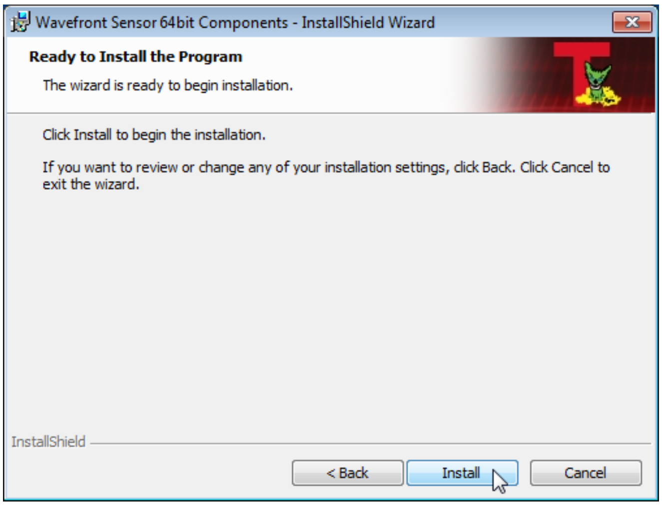


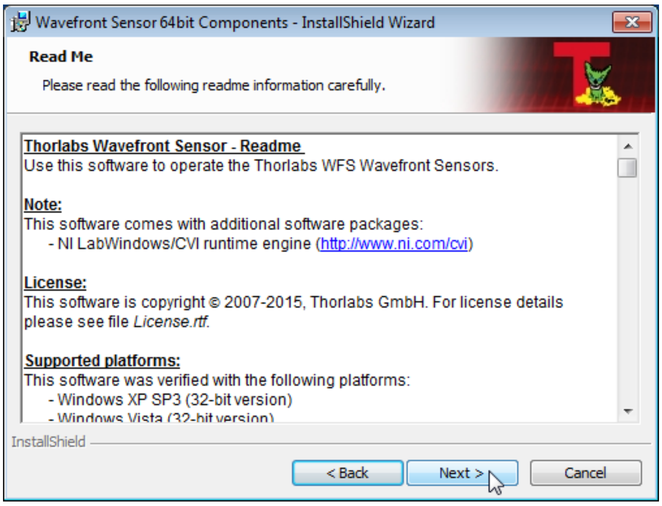


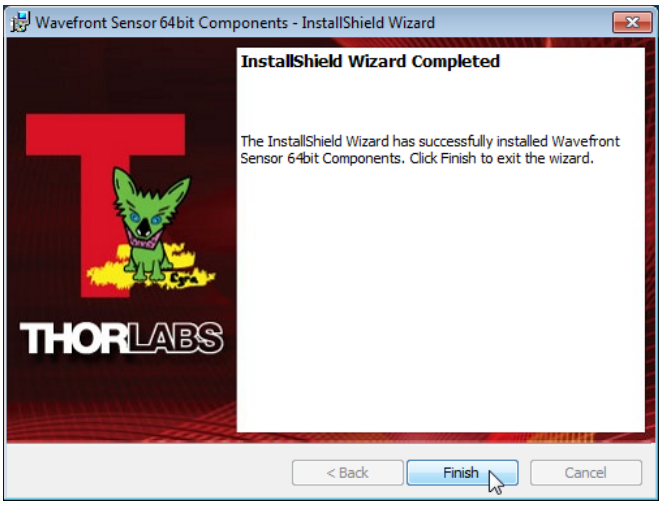




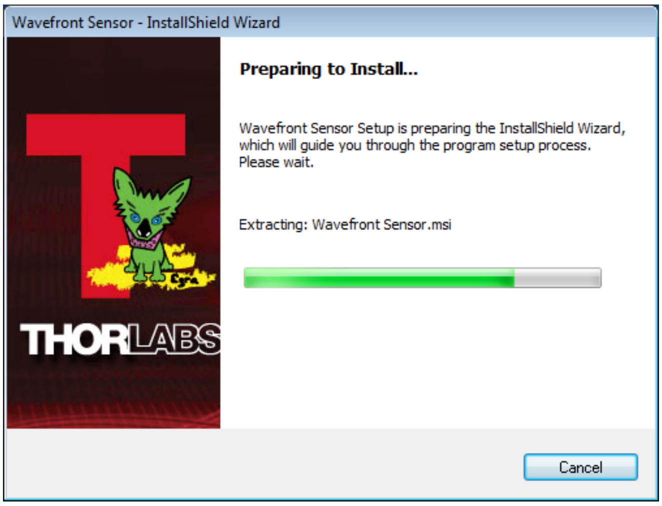


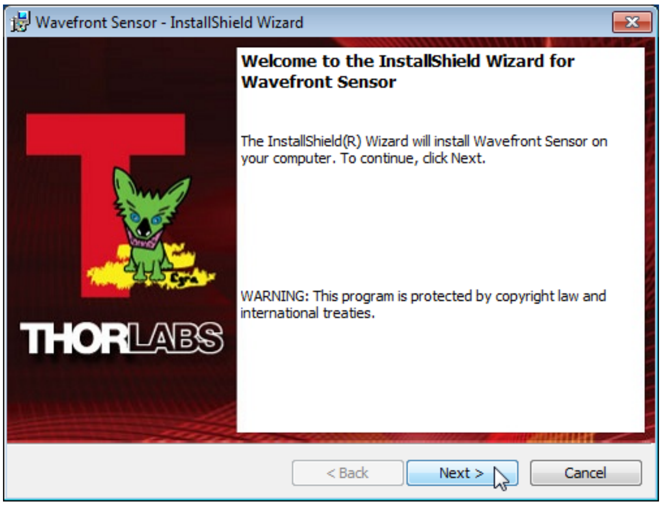


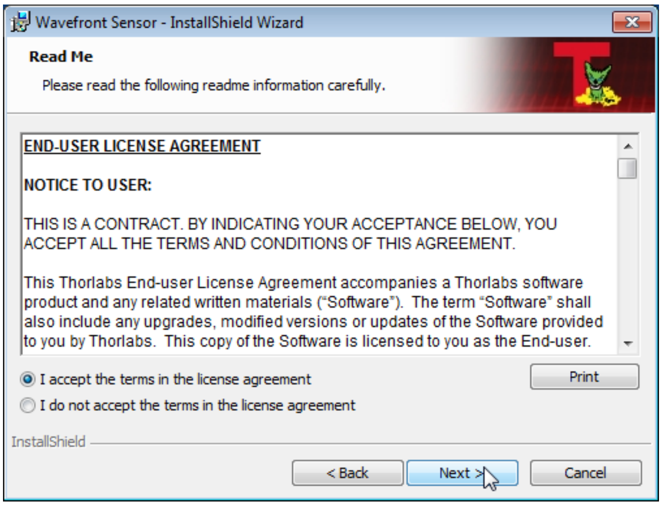


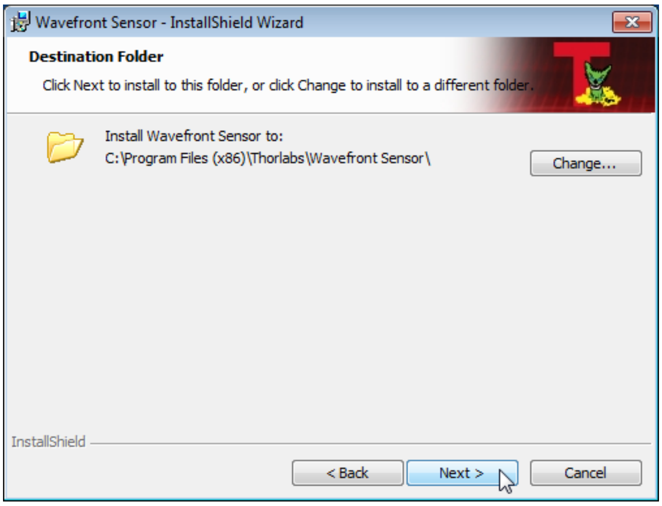


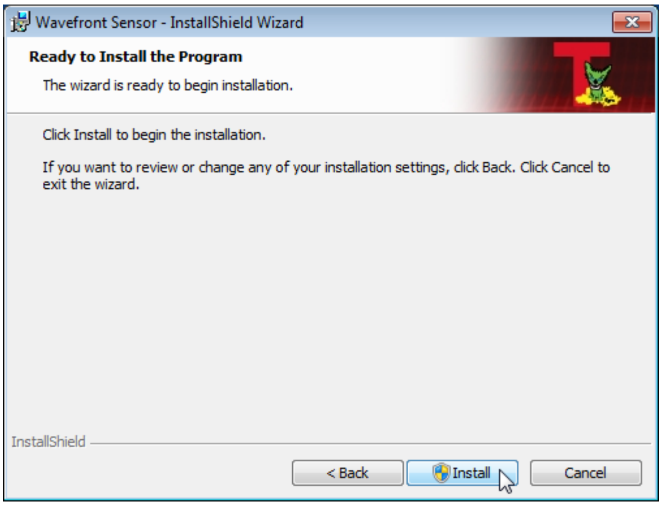
After finishing the installation of the 64 bit software components, the main WFS software (32 bit) will be installed. The appropriate dialog boxes are shown on the following pages:

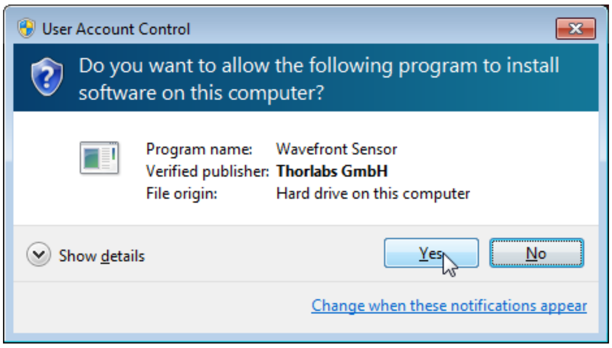

Wavefront Sensor - InstallShield Wizard
Preparing to Install...
Wavefront Sensor Setup is preparing the InstallShield Wizard, which will guide you through the program setup process. Please wait.
Extracting: Wavefront Sensor.msi
THORLABS
Cancel

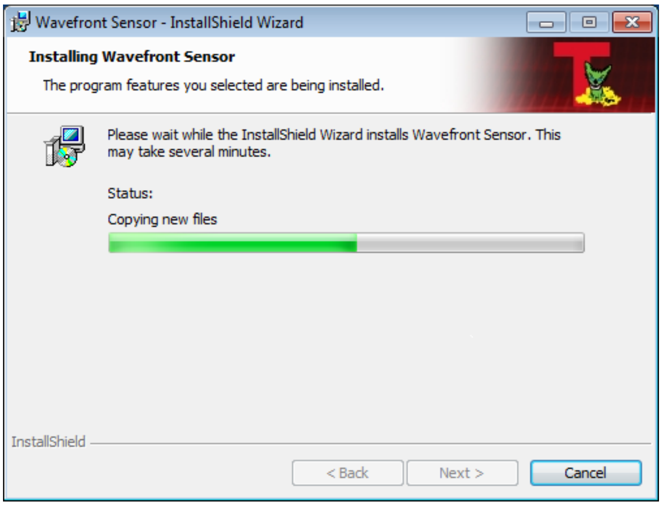

Wavefront Sensor - InstallShield Wizard
Welcome to the InstallShield Wizard for Wavefront Sensor
The InstallShield(R) Wizard will install Wavefront Sensor on your computer. To continue, click Next.
WARNING: This program is protected by copyright law and international treaties.
THORLABS
< Back
Next >
Cancel

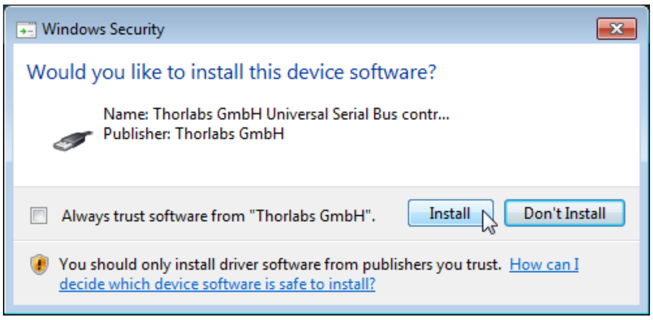

Wavefront Sensor - InstallShield Wizard
Read Me
Please read the following readme information carefully.
END-USER LICENSE AGREEMENT
NOTICE TO USER:
THIS IS A CONTRACT. BY INDICATING YOUR ACCEPTANCE BELOW, YOU ACCEPT ALL THE TERMS AND CONDITIONS OF THIS AGREEMENT.
This Thorlabs End-user License Agreement accompanies a Thorlabs software product and any related written materials ("Software"). The term "Software" shall also include any upgrades, modified versions or updates of the Software provided to you by Thorlabs. This copy of the Software is licensed to you as the End-user.
I accept the terms in the license agreement
I do not accept the terms in the license agreement
Print
InstallShield
< Back
Next >
Cancel


Wavefront Sensor - InstallShield Wizard
Destination Folder
Click Next to install to this folder, or click Change to install to a different folder.
Install Wavefront Sensor to:
C:\Program Files (x86)\Thorlabs\Wavefront Sensor\
Change...
InstallShield
< Back
Next >
Cancel

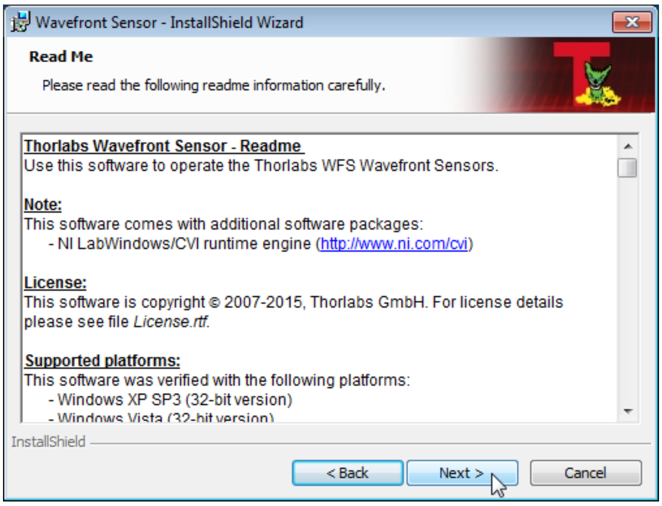

Wavefront Sensor - InstallShield Wizard
Ready to Install the Program
The wizard is ready to begin installation.
Click Install to begin the installation.
If you want to review or change any of your installation settings, click Back. Click Cancel to exit the wizard.
InstallShield
< Back
Install
Cancel

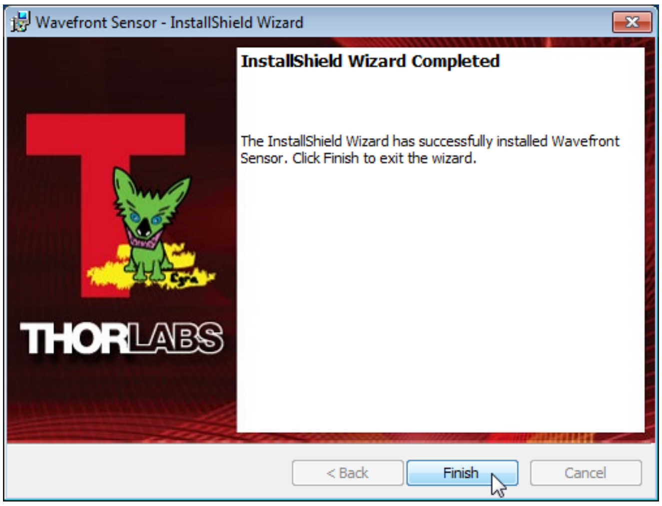

User Account Control
Do you want to allow the following program to install software on this computer?
Program name: Wavefront Sensor
Verified publisher: Thorlabs GmbH
File origin: Hard drive on this computer
Show details
Yes
No
Change when these notifications appear





The above dialog box will appear twice. Please allow installation.

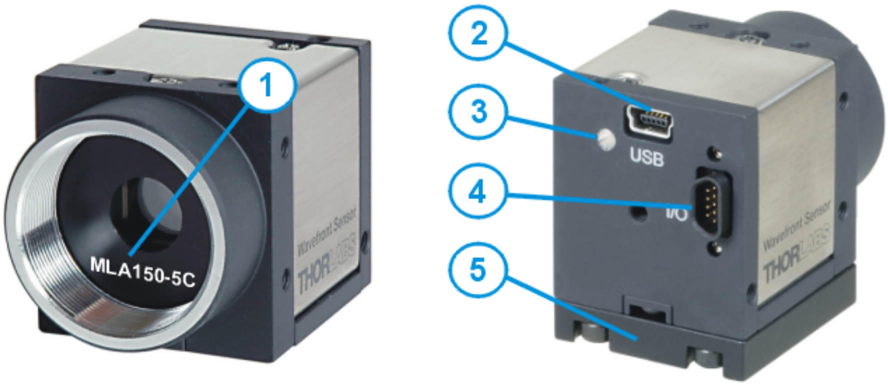




Now, the WFS Series Software package is installed properly on your computer.

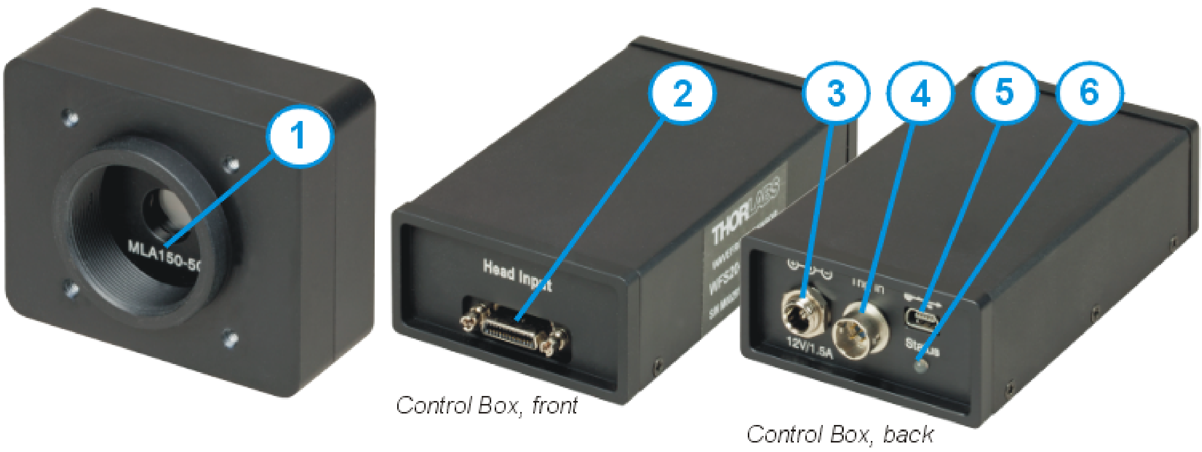
4.3 Operating Elements

Operating Elements WFS150-x / WFS300-x Series



1 Exchangeable Micro Lens Array (MLA)
2 USB Connector
3 Status LED:
Red: USB connected, driver not (yet) installed
Green: Ready
4 Combined USB / Digital I/O (Trigger Input 112)
5 Mounting Adapter 121

Operating Elements WFS20-x Series



1 Optical Head with Micro Lens Array (MLA), exchangeable
2 Connector Control Box to Optical Head
3 Control Box Power Supply Input
4 Trigger Input 114
5 USB Connector
6 Status LED:
Red: USB connected, driver not (yet) installed
Green: Ready

4.4 Mounting

WFS150

A mounting adapter (see Mounting Adapter 121) is delivered with the WFS150/300 models in order to provide standard M4 and UNC8-32 threads that are compatible with Thorlabs' posts. This adapter plate is fixed to the bottom side of the Wavefront Sensor using the four included M3x6 screws.

The C-Mount thread of the camera 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 conveniently mount ND filters, lens tubes (to prevent stray light from entering the input aperture) or additional optomechanical components.

WFS20

The WFS20 has four 4-40 threaded taps (1) for use with ER rods. In this way, the WFS20 can easily be mounted to 30 mm cage system assemblies. Additionally, three taps (2) with M4x0.7 (metric WFS with item # ending in /M) or UNC8-32 (imperial WFS) threads are located on the bottom of the sensor head, depending on the WFS20 version - metric or imperial.

Like the WFS150 models, the WFS20 camera opening is C-mount threaded.

4.5 First Steps

Note

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

Please install the WFS Series application software and USB drivers (all in one package) on your PC prior to connecting the Wavefront Sensor to your PC. For a detailed description of software installation, please see Installing Software 14.

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

Attention

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

Connecting a WFS20

Follow the order described below:

1. Connect the WFS20 sensor head to the WFS20 control box using the included PoCL cable.
2. Connect the power supply to the mains supply.
3. Connect the power supply to the WFS20 control box.
4. Connect the USB port of the WFS20 control box to computer using the included USB2.0 cable.

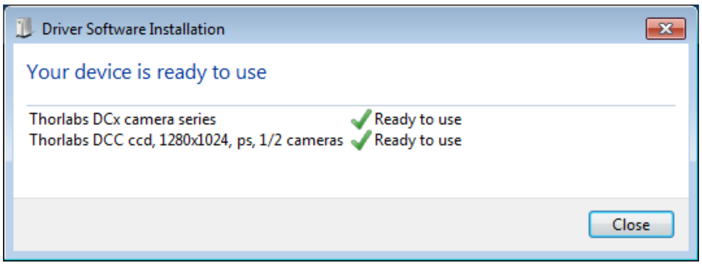
To disconnect the WFS20, follow the above steps in the reverse order!

Do not connect or disconnect the PoCL cable while power is supplied to the WFS20 control box! This will damage the electronics!

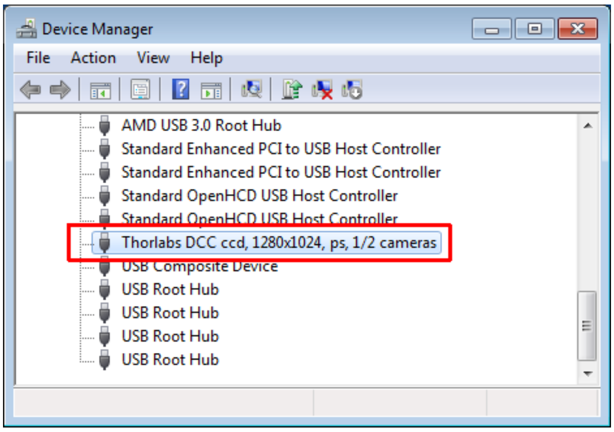
After connecting the instrument, the operating system recognizes the connected instrument, installs the appropriate driver software, and identifies the connected hardware.

WFS150-x and WFS300-x

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



In the Windows Device Manager, these types of Wavefront Sensors are recognized as a Thorlabs DCC camera:



Attention

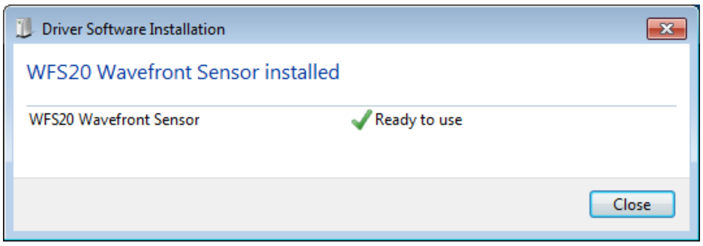
Don't worry that a 'Thorlabs DCC camera' is displayed in the device manager. This is because the Thorlabs WFS150/WFS300 are based on a Thorlabs CCD camera which is also available separately from Thorlabs.

Since the CCD camera and the wavefront sensor both use the same driver software, they are not distinguishable in the device manager. Both instruments are displayed as 'Thorlabs DCC camera'.

A differentiation takes place within the Wavefront Sensor application program wfs.exe that accepts only WFS150-5C, WFS150-7AR and WFS300-14AR devices for operation; it does not accept DCC cameras that do not have a microlens array.

WFS20-x

After connection and driver installation, it shows up as



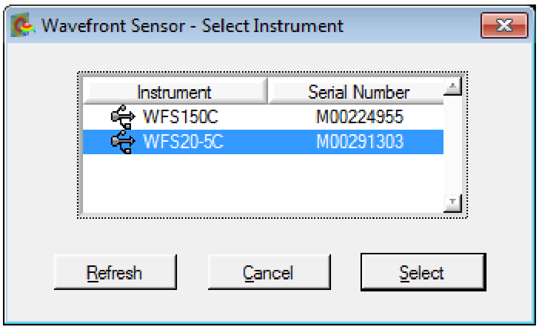
The green LED at the back of the Wavefront Sensor (WFS150/WFS300) or beside the USB connector of the Control Box (WFS20) indicates that the instrument is ready for operation and the application software can be started.

Note

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

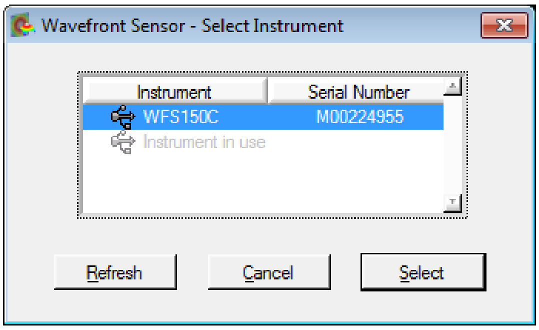
Run the WFS Series software, either from the Start Menu -> All Programs ->Thorlabs -> Wavefront Sensor or from the appropriate desktop icon.

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

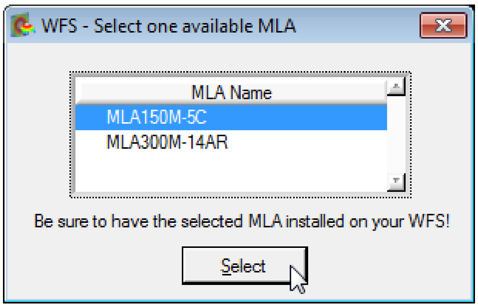


If no entry can be seen, click on 'Refresh' to update the list of available Wavefront Sensor instruments. If there is still no instrument displayed please refer to the Troubleshooting 92 chapter.

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



In the case that your WFS instrument was calibrated for more than one Microlens Array (MLA) you need to select the one that is mechanically installed:



Attention

Make sure that the MLA that you have selected in the software is the same as the MLA physically installed in your Wavefront Sensor. Otherwise, the measurement data will be incorrect because software is using calibration data for the wrong MLA.

The WFS Series GUI 26 comes up and displays the beam spotfield taken from the camera. In the header the connected wavefront sensor type and the selected MLA are displayed.

Attention

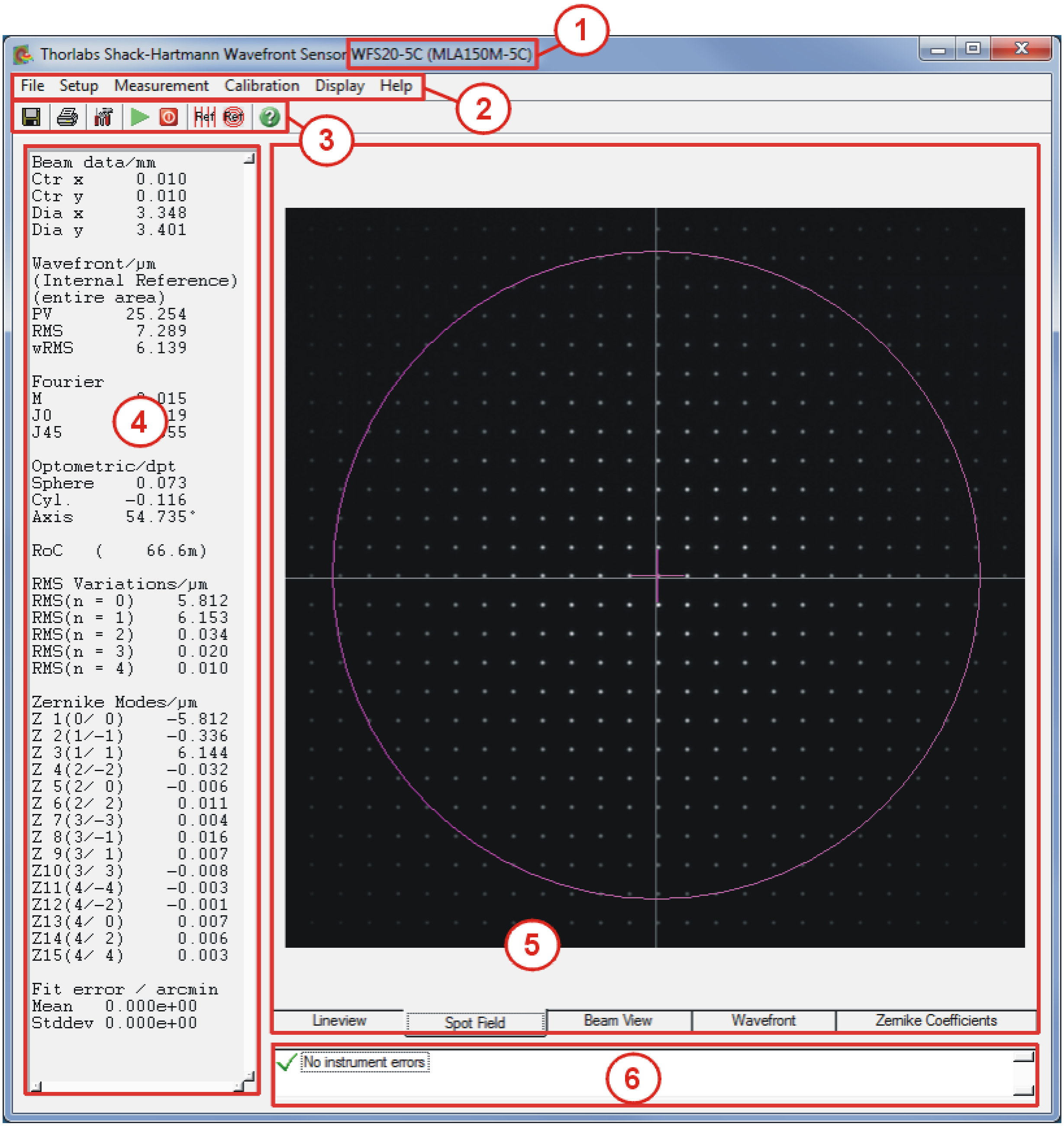
Do not stick anything into the Wavefront Sensor's aperture! This may damage the microlens array as there is no protective glass in front of it.

Be very careful when handling high power optical beams, particularly focused beams! Avoid skin irradiation and use laser protection glasses to protect your eyes!

In order to achieve reliable wavefront measurement results, it is necessary to understand the measurement technique as well as the influence of instrument and software settings. These settings are described in the following sections; please read them carefully.

5 Operating Instruction

5.1 Graphical User Interface (GUI)



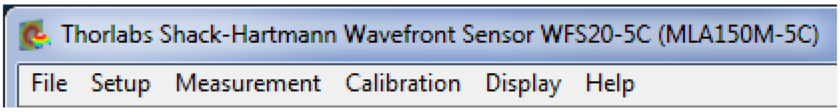
GUI Areas

1 Recognized instrument and selected *MLA*
2 Menu bar 27
3 Tool bar 31
4 Numerical measurement results 31
5 Graphical display 31 consisting of 5 tabs
6 Status bar

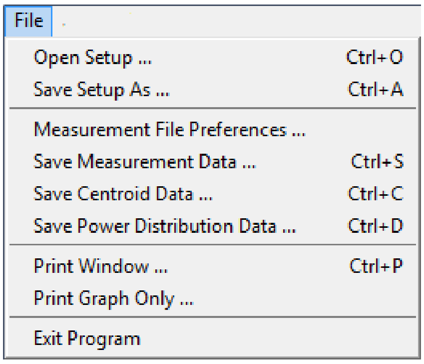
The GUI size can be adjusted according to your preferences. When exiting the application, the actual settings are saved and will be applied when starting the application software again.

At the first program start, all Wavefront Sensor settings and GUI configurations are set to default values. Please see section Wavefront Sensor Setup Panel 50 for individual configurations.

5.1.1 Menu Bar



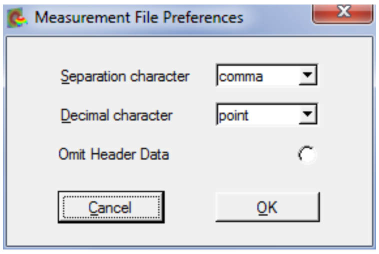
5.1.1.1 File Menu

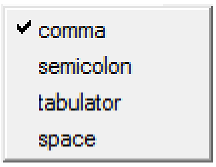


Setup: The actual settings of the WFS GUI including configurations of the graphical displays and the instrument setup are automatically saved when you leave the program. When you start the Wavefront Sensor GUI again your last settings are automatically loaded and you are able to go on with your work as if there never was a break.

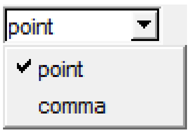
In addition, you might store the complete instrument settings in a *.cfg file. These files contain different wavefront sensor configurations and can be reloaded to the application software in order to restore previous measurement conditions.

- **Open Setup ...** opens a Wavefront Sensor configurations file (*.cfg) stored with this application (see below). This configuration file contains instrument settings (camera, pupil, wavefront) as well as display and graphical settings. You can easily switch between different configurations by loading alternative files.
- **Save Setup As ...** stores a Wavefront Sensor configurations file (*.cfg) containing all instrument settings (camera, pupil, wavefront) as well as display and graphical settings. You may save different configurations to files with different names.
- **Measurement File Preferences** The following pop up window allows the attributes of the measurement data file to be set.





Separation character: select the separator between two subsequent data values within a line. Default: "Comma"



Decimal character: This choice is important to match with the **Region and Langauge** settings of the computer where the saved measurement data shall be processed. 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 for yourself using programs like Microsoft Excel®.

- **Save Measurement Data (Ctrl + S)**

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

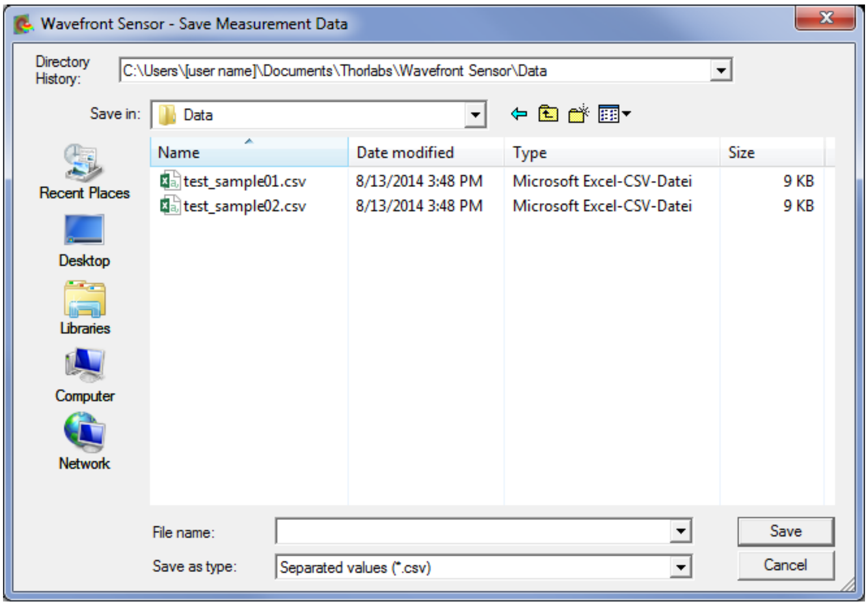
- **Save Centroid Data (Ctrl + C)**

  The measured centroid positions of the spots visible in the Spotfield Panel 36 can be saved to a text file. The preferred file extension is .csv (comma separated values). This file type can be loaded directly into Microsoft Excel®.

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

  The measured intensities in arbitrary units of the spots visible in the Spotfield Panel 36 can be saved to a text file. The preferred file extension is .csv (comma separated values). This file type can be loaded directly into Microsoft Excel®.

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 is defined in the 'Measurement File Preferences' panel, see above.

- **Print Window (Ctrl + P)**
- **Print Graph Only**

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

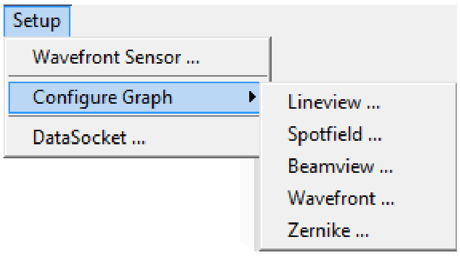
- the entire panel or
- the graphical display panel only

to a printer.

- **Exit Program**

You will be asked to confirm this action.

5.1.1.2 Setup Menu

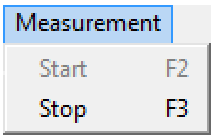


This menu allows settings to be defined for

- the wavefront sensor: a separate configuration panel 50 opens. Alternatively, click the icon in the tool bar or right click to the graph area.
- the graphic displays and
- the DataSocket Interface 70.

For each graphic display, an individual configuration panel opens. These panels can be accessed directly by double clicking to the appropriate display area. Details can be found in chapters Line View Panel 34, Spotfield Panel 36, Beam View Panel 40, Wavefront Panel 42, and Zernike Coefficients Panel 46.

5.1.1.3 Measurement Menu



In this menu, the measurement can be stopped and restarted:

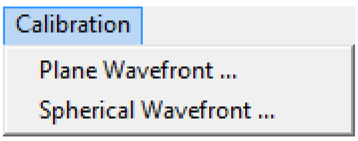
Stop: F3 key or in the tool bar. Stops the current measurement immediately and terminates screen updates to keep the actual displayed graphical plots and numerical values so that the data can be examined or saved.

(Re-)Start: F2 key or in the tool bar. Starts / restarts the continuous measurements and displays the results on the screen.

Note

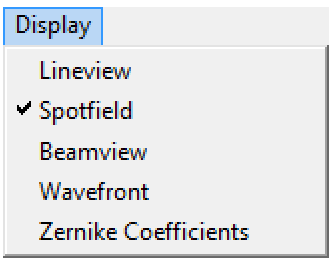
The continuous measurement will stop automatically if severe measurement errors occur. You will be asked to check settings and to re-start the continuous measurement again.

5.1.1.4 Calibration Menu



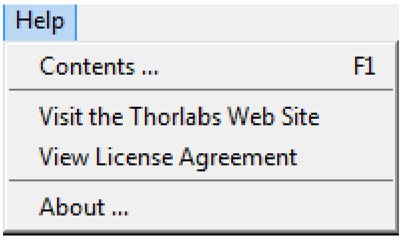
Start a user calibration of the wavefront incident on the sensor. Details please see in section User Calibration 73. The calibration can be done to a planar (toolbar:) or spherical (toolbar:) wavefront.

5.1.1.5 Display Menu



Select the graph you want to be displayed. The same selection can be made just by clicking to the appropriate tab of the graphic display. The displays are explained in section Graphical Display Panels 31.

5.1.1.6 Help Menu



- **Contents (F1)**

This opens the Wavefront Sensor help file. It contains the same information as the manual.

- **Visit the Thorlabs Website**

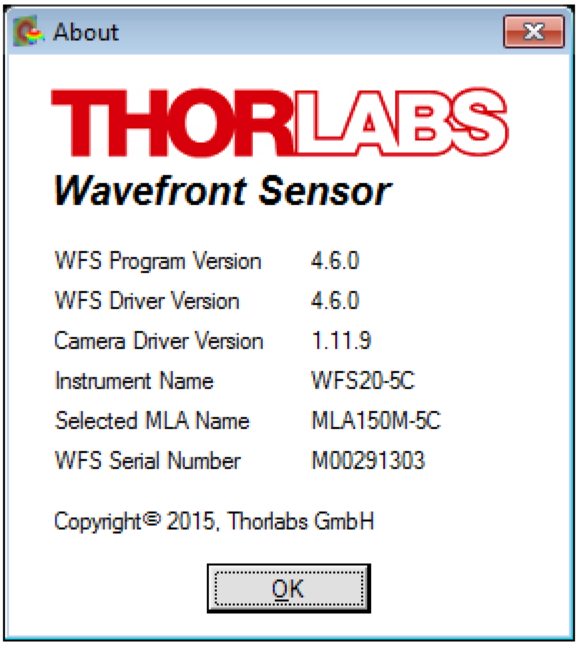
You were directed to the Thorlabs website at **www.thorlabs.com** that contains information about new software releases or related products.

- **View License Agreement**

The Thorlabs End User License Agreement (agreed to when the software was installed) is displayed.

- **About**

Shows you the actual software and driver version, the Instrument Name, the selected MLA and serial number of the used device. Please have this information ready when contacting Thorlabs 137 for technical support.



5.1.2 Tool Bar

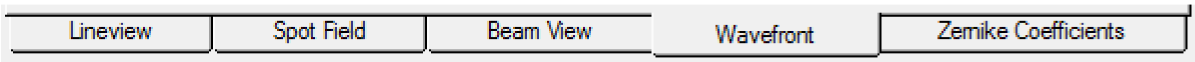
The tool bar gives access to the most common menu functions by simply clicking on the appropriate symbol.

The **Tool Bar** symbols stand for:

- Save Measurement Data 28
- Print Window 28
- Setup Wavefront Sensor 50
- Start Measurement 29
- Stop Measurement 29
- Calibrate with Planar Wavefront 73
- Calibrate with Spherical Wavefront 73
- Show Help File

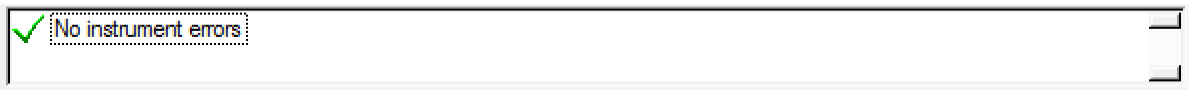
5.1.3 Graphical Display Panels

The panels can be selected either from the menu **File -> Display** or by clicking to the appropriate tab below the graph area:



5.1.3.1 Measurement Results

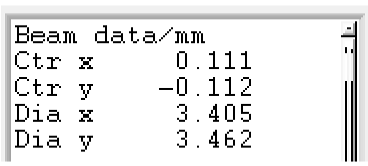
Numerical measurement results are displayed on the left side of the of the main panel. Be sure that no error occurred during image capture and its subsequent analysis.



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 84 for a listing of possibly occurring errors.

Beam Data



Calculated from the centroid and the second moment of the entire camera image, the beam center coordinates **Ctr x** and **Ctr y** and the beam diameter **Dia x** and **Dia y** direction are displayed in mm. In the case of a Gaussian beam shape, the second moment coincides with the beam width at the standard 1/e^2 clip level.

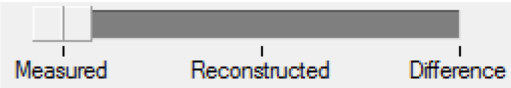
Please take into account that these data cannot give an exact measure of the beam because the lenslet array in front of the camera and wavefront distortions change the intensity distribution between the real beam and the camera image. Furthermore, high ambient light level and improper setting of the camera 'Black Level' (see Camera Settings 51) may distort the beam data results.

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 selection made by the user (Wavefront Sensor Setup Panel) 50. Calculated data are related either to the entire wavefront or to the pupil interior only, according to the settings entered in the Pupil Definitions Setup 58 panel.

The calculated wavefront statistics refer to the selection of wavefront display (Measured, Reconstructed or Difference) that can be made using the switch in the Wavefront Panel 42:



PV The total Peak-to-Valley value, i.e., the maximum variance of the wavefront in the observed area.

RMS The Root Mean Squared average value.

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

Fourier Constants

```
Fourier
M          1.741
J0        -0.046
J45        0.034
```

Fourier constants are M, J0 and J45 and are derived from the Zernike coefficients. Depending on setting in the Zernike Fit Setup 66 panel, Zernike orders up to 2, 4 or 6 enter into the calculation of these constants.

Optometric Constants

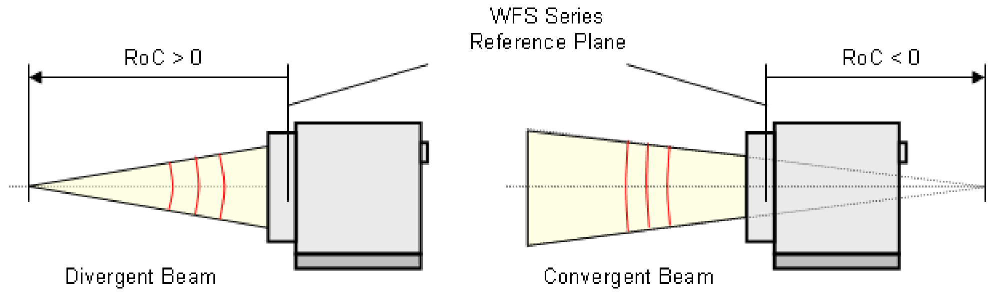
```
Optometric/dpt
Sphere     1.798
Cyl.      -0.115
Axis      71.626°
```

Optometric constants are Sphere, Cylinder (in diopters) and the axis angle of the cylinder in degrees. Depending on setting in the Zernike Fit Setup 66 panel, Zernike orders up to 2, 4 or 6 enter into the calculation of 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 identical to the distance from a point source which is emitting a 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 is 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 RoC - infinite. As a result, the wavefront sensor will not be able to measure large RoC values accurately. In order to draw attention to the reduced accuracy 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 summarized and expressed as total RMS variation of this Zernike order. The number of Zernike orders, defined in the Zernike Fit Setup 66 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 that 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.

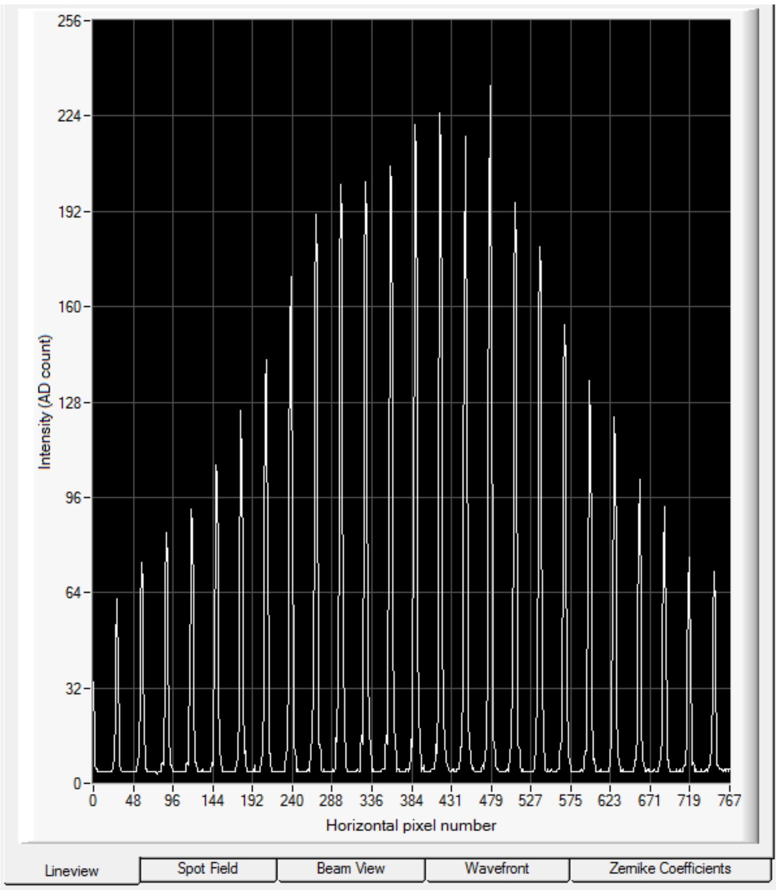
Fit Error

```
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.

5.1.3.2 Lineview Panel

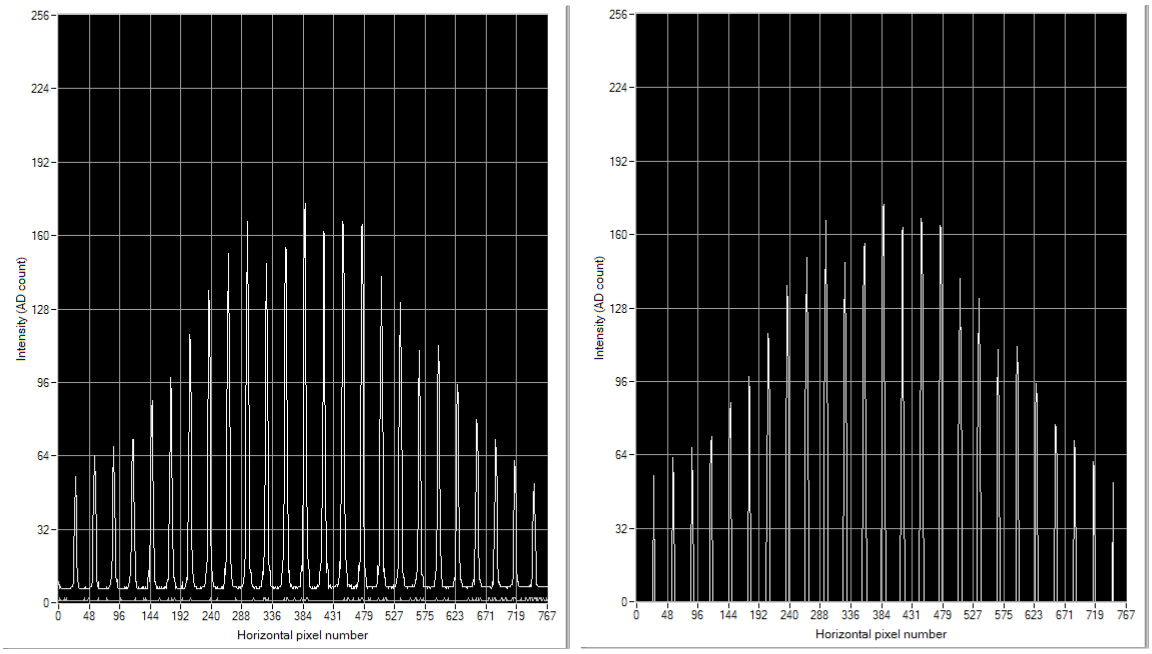
In this graph the horizontal intensity distribution of the CCD (CMOS) camera is displayed. Each point on the horizontal axis of the diagram corresponds to one column of the CCD/CMOS array and displays both the minimum (gray, at the bottom) and the maximum intensity level (white) of the entire pixel column. The peaks are due to the focusing ability of the lenslet array that 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 51).

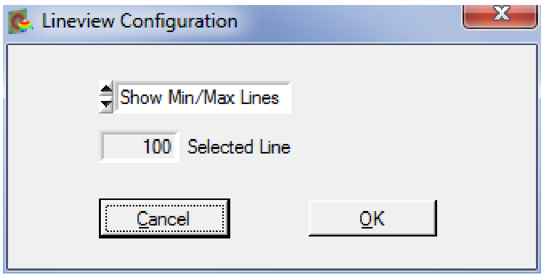
The **Black Level** setting of the camera introduces an offset to the brightness level for all illuminated pixels and should be adjusted in such way that the minimum (noise) line is visible. See section Camera Settings 51 for a detailed description.

In the Line View panel the influence of the **Noise cut level** setting can be observed easily. The Noise Cut Level defines a brightness level in digits which needs to be exceeded by the spots in order to be recognized; its effect can be observed in the Lineview panel shown below. For instance, an increased ambient light level that will influence the determination of spot centroids can be rejected by setting the 'Noise cut level' to a value higher than the valleys in the diagram.

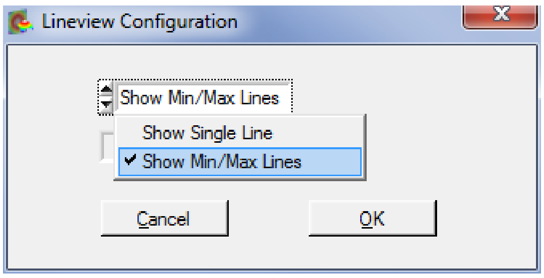


The example illustrates the effect when the 'Noise cut level' is changed from 0 (left) to 50 (right).

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.



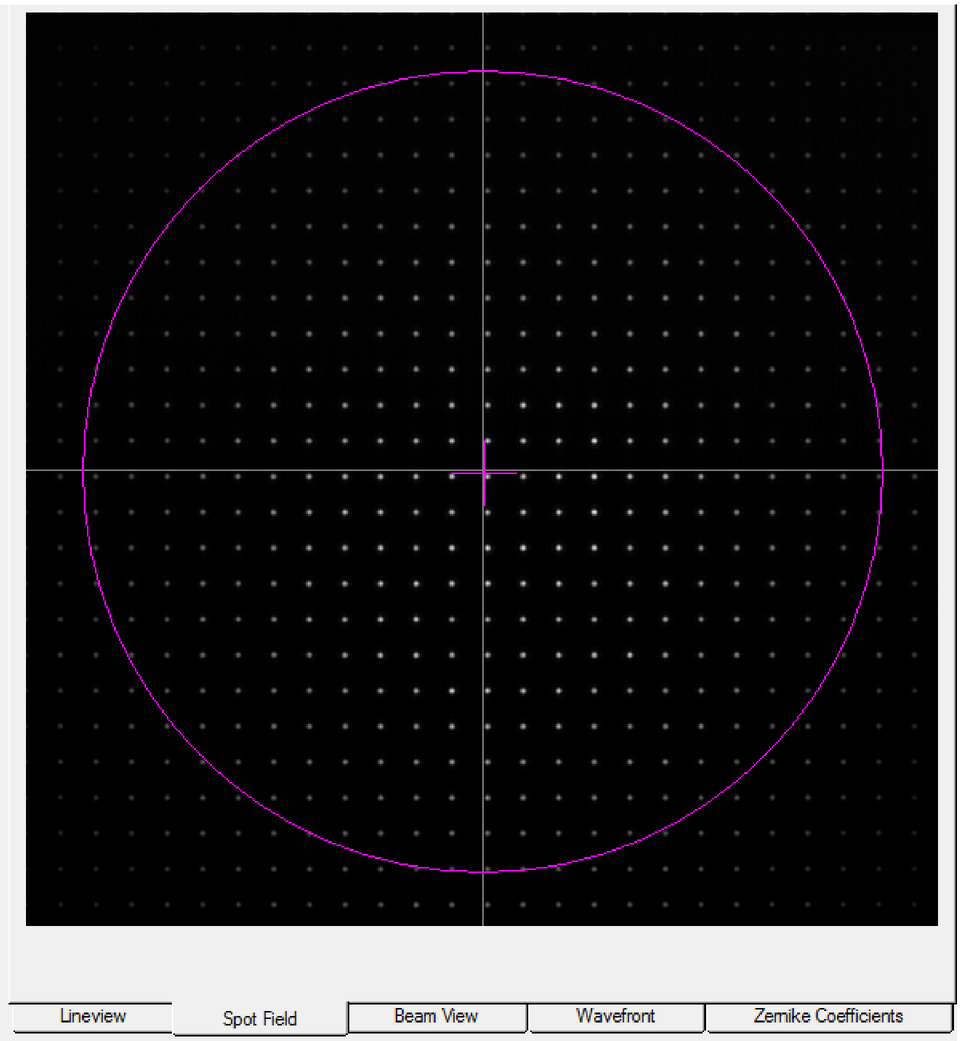
Switch to '**Show Single Line**' in order to enable selection of a single line out of the sensor array. Enter the line number into the '**Selected Line**' control to see the intensity distribution of the appropriate CCD row. The line number ranges from 0 (bottom) to the number of vertical pixels - 1. The selected line is marked within the Spotfield Panel 36.

Note

This panel display is not available for WFS20 (WFS10) instruments in Highspeed Mode.

5.1.3.3 Spotfield Panel

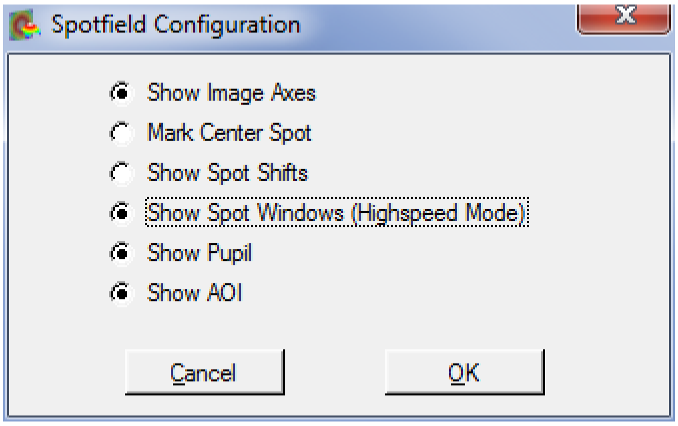
The Spotfield panel allows a direct view of the image taken by the CCD/CMOS camera. Intensity levels are displayed as gray scale from 0 (black) to 254 digits (white), while saturated pixels are displayed red.



The camera resolution and the number of spots in the horizontal and vertical direction can be selected in the Camera Settings 51 panel. The camera resolution (equal to the active sensor area) should be selected in such way that the entire analyzed beam is displayed. If the area is too large, there will be undetectable spots that cannot be converted into wavefront data, which leads also to a decrease of measurement speed.

In addition, some more additional graphical elements can be overlayed on the image.

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

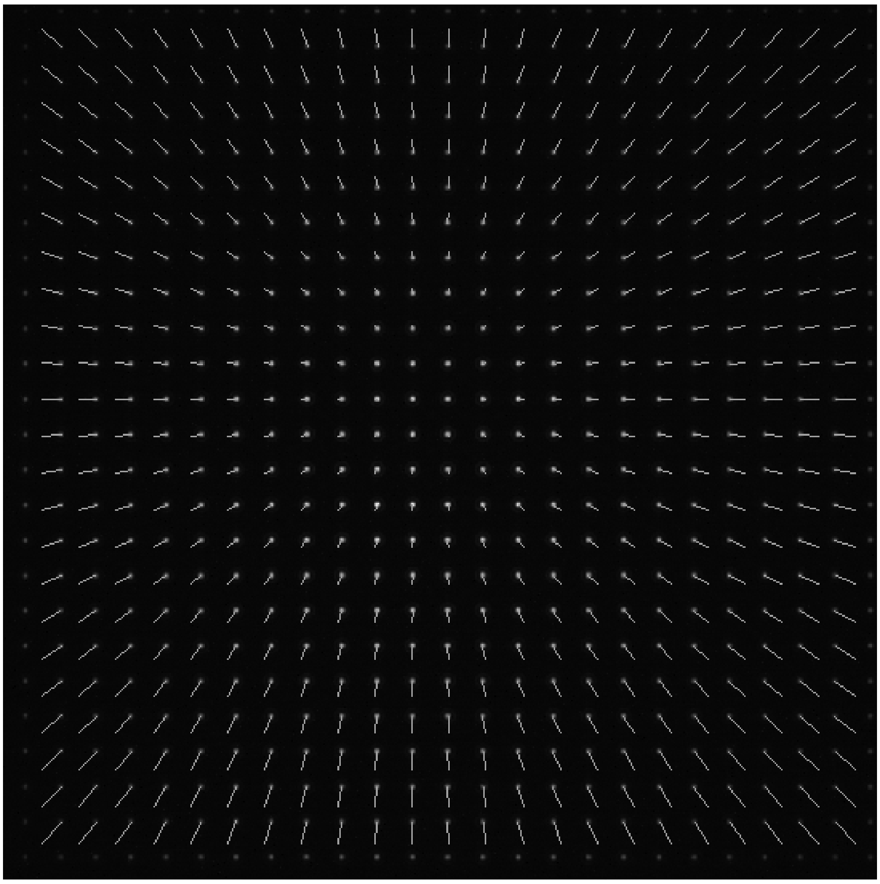


Enable the appropriate option to visualize the graphical items:

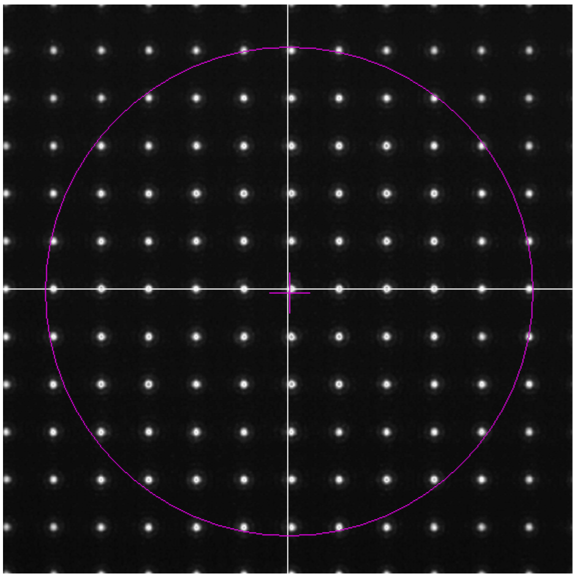
'Show Image Axes' displays the center axis in horizontal and vertical direction.

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

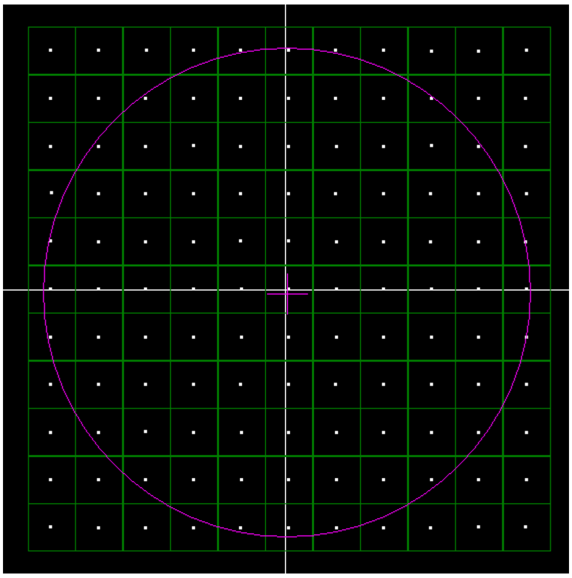
'Show Spot Shifts' displays the shift between the actual spot position and its corresponding reference position as a gray line.



'Show Spot Windows' is an option that is available only for WFS20 (WFS10) instruments in high speed mode (see WFS20 Highspeed Mode 77):



WFS20 (WFS10) in Normal Mode



WFS20 (WFS) in High Speed Mode

In contrast to the normal mode, where the spots are visible within the real camera image (left), in high speed mode each detected spot is displayed within its spot window (green lines) that is used internally in the instrument for spot calculation. This allows the user to observe if the spots are within their calculation window.

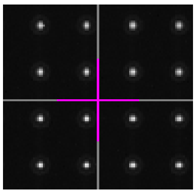
'**Show Pupil**' displays a purple circle or ellipse that represents the actual pupil size and position.

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

Note

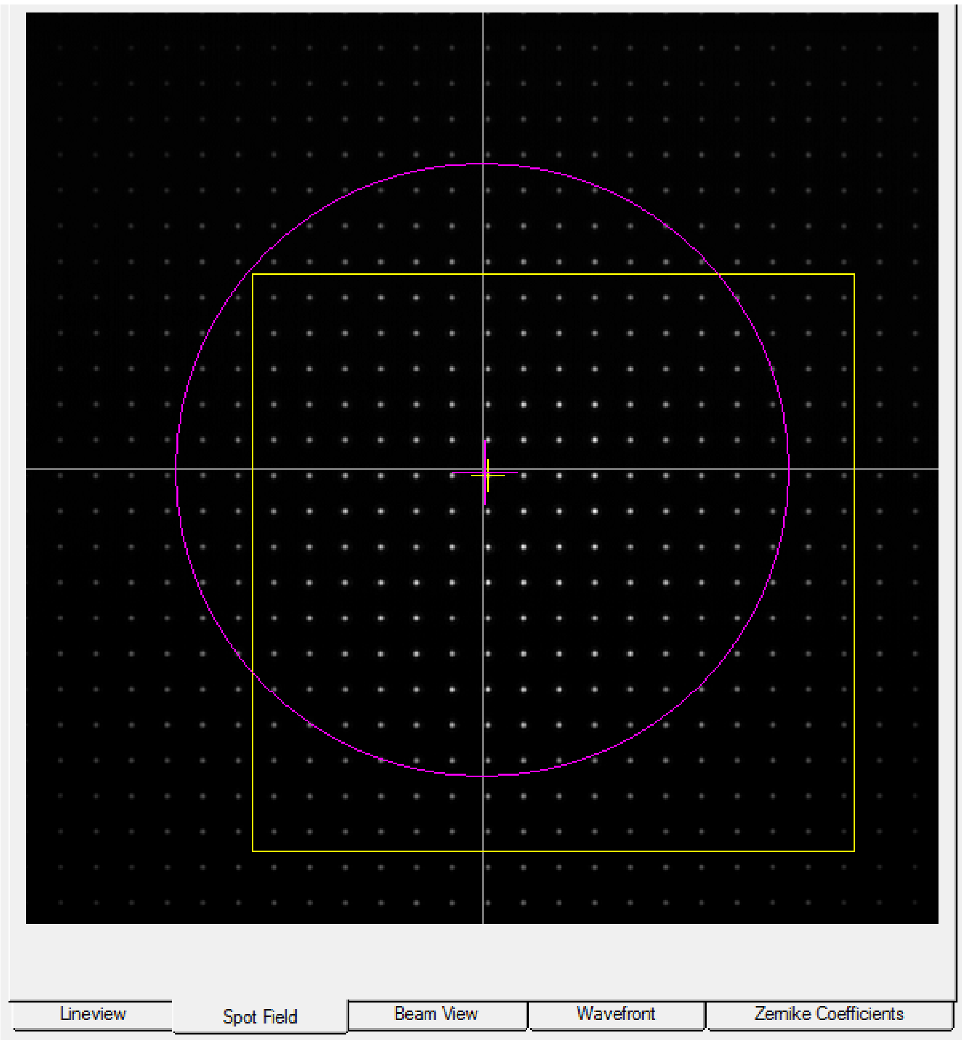
The '**Use Beam Centroid**' option must be activated in the Pupil Definitions Setup 58 panel to show the actual beam centroid.

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



Show AOI

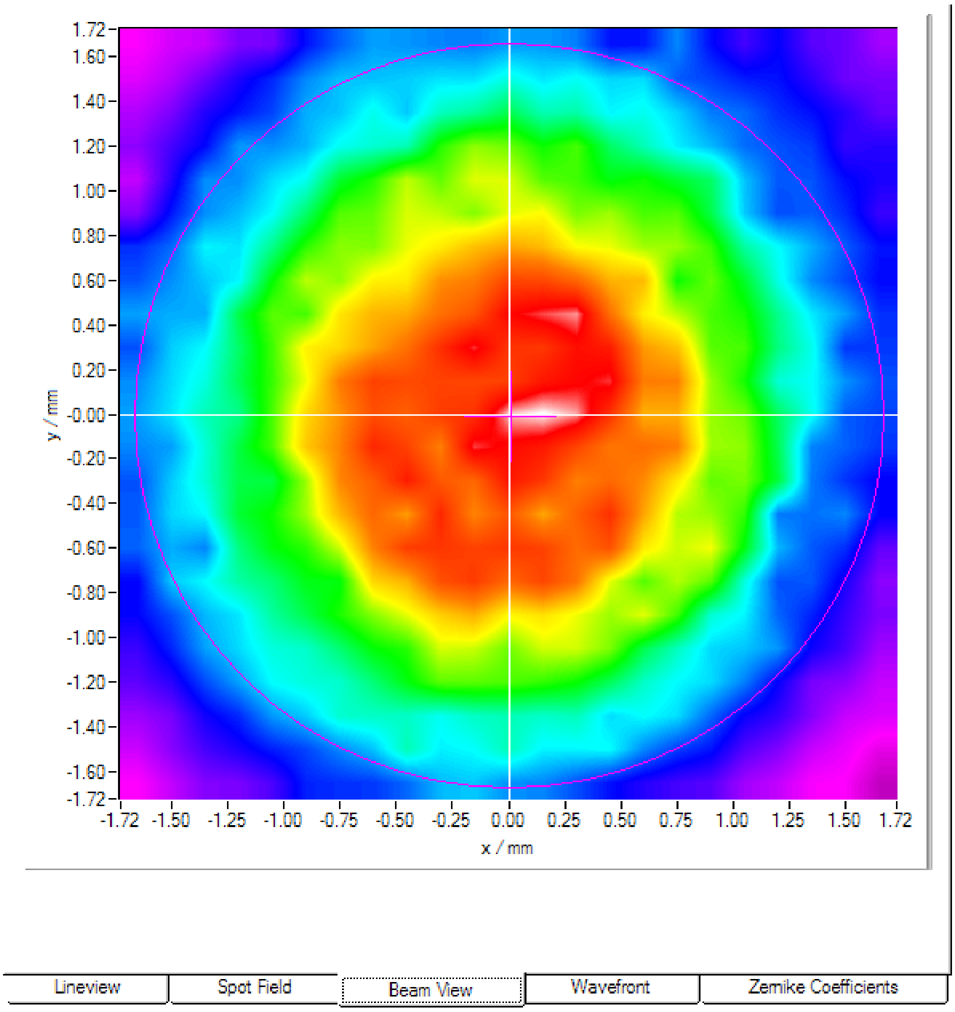
The WFS software allows an area of interest to be defined (see section Settings 60). When this function is enabled, the position and size of the AOI is shown in yellow:



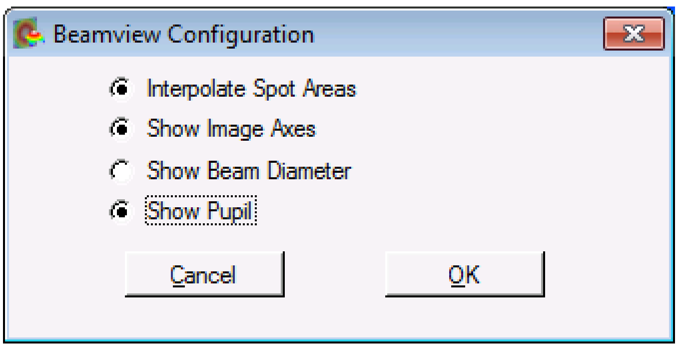
5.1.3.4 Beam View Panel

The Beam View panel gives you 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 very poor resolution.

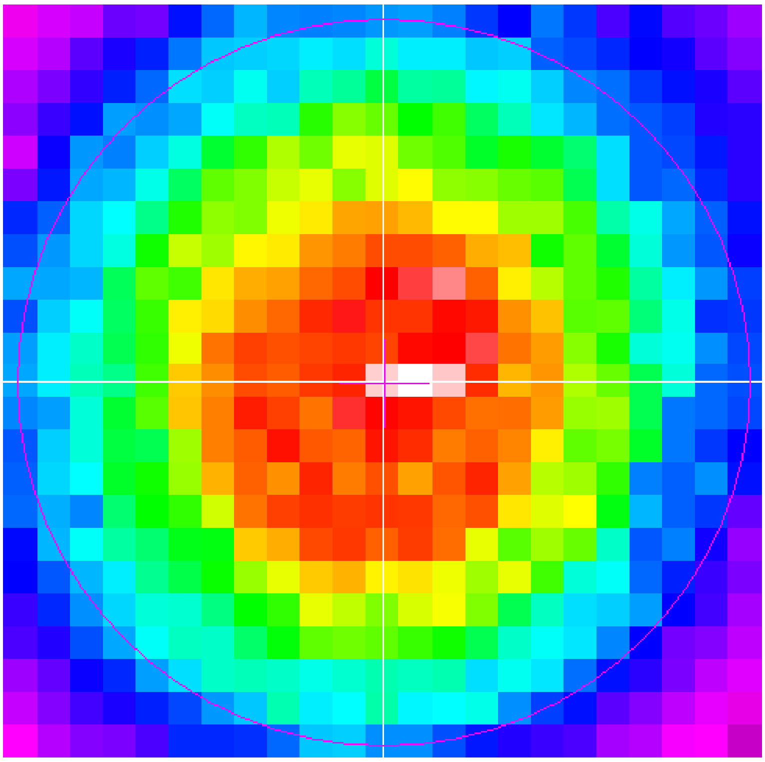
The lateral resolution is not determined by the camera pixel size as in the case of a real Beam Profiler, but rather given by the pitch of the lenslet array. One point of the displayed intensity array is derived from the calculated mean intensity of the corresponding spot.



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 direction.
'**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.

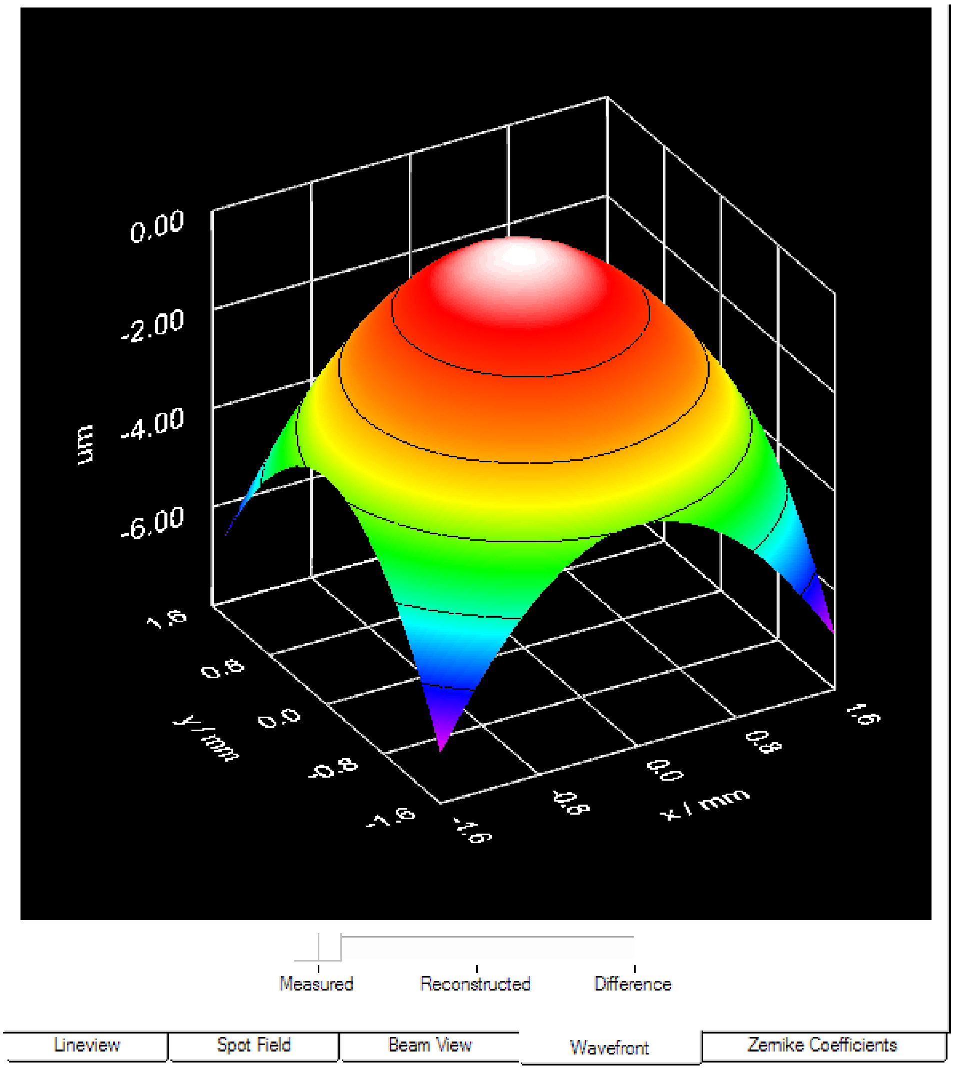
Note

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 Pupil Definitions Setup 58 panel).

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).

5.1.3.5 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 50).

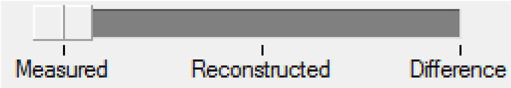
The surface is displayed as a color spectrum. The assignment between color and curve height is always the same:

- black, purple: lowest wavefront parts
- green: medium
- red, white: highest wavefront parts

With the option **'Limit wavefront calculation and display to pupil interior'** (Pupil Definitions Setup 58) 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**' will display the wavefront that is reconstructed using the selected set of the determined Zernike coefficients (Zernike Fit Setup 66). The advantages of this display are:

- Selecting only a few Zernike modes of lower order for reconstruction smooths the wavefront surface (noise cancelling).
- Lowest order Zernike terms (for instance piston, tip, tilt) that are always present but are of less interest can be omitted 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 31) because the statistic values refer to the selected wavefront (Measured, Reconstructed or Difference).

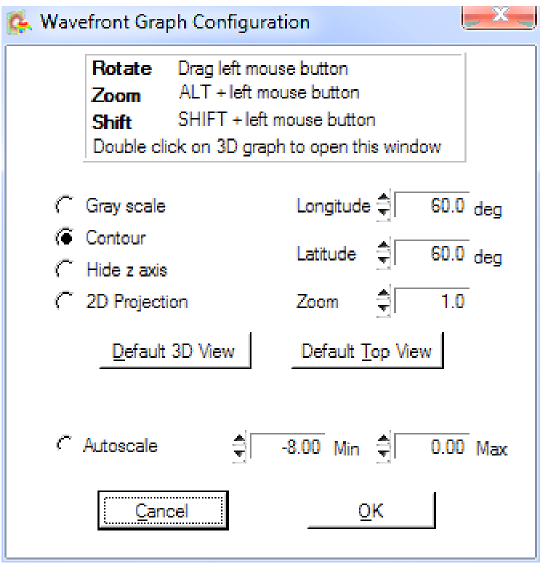
Direct rotation, zoom and shifting of the 3D graph

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.

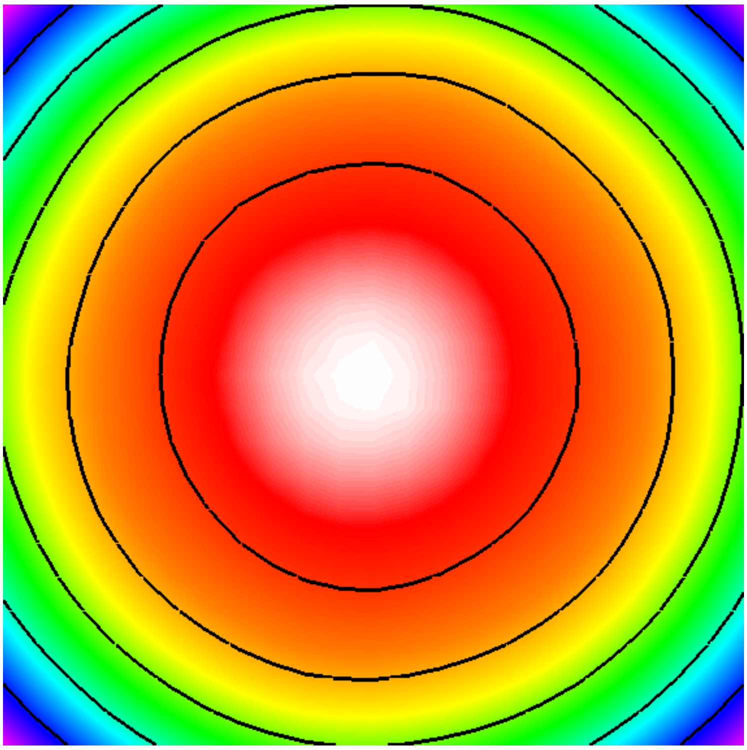
Double click to the graph area to access the **Wavefront Graph Configuration** panel:



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

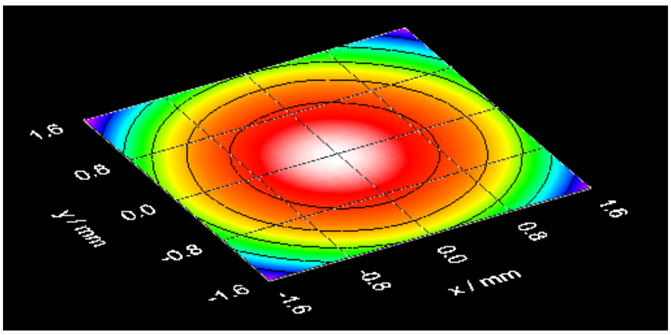
'Default 3D view' arranged the view angles so that all three axis are to be seen and the wavefront can be viewed as a 3D curve.

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



The following options define the look of the 3D graph

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



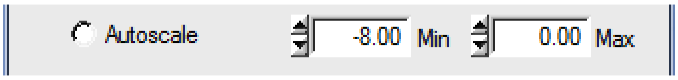
The following items define the view of the 3D graph

'Longitude' determines the rotation angle about the z axis
'Latitude' determines the view angle to the graph
'Zoom' changes the graph size (range 1...10)

Clicking 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

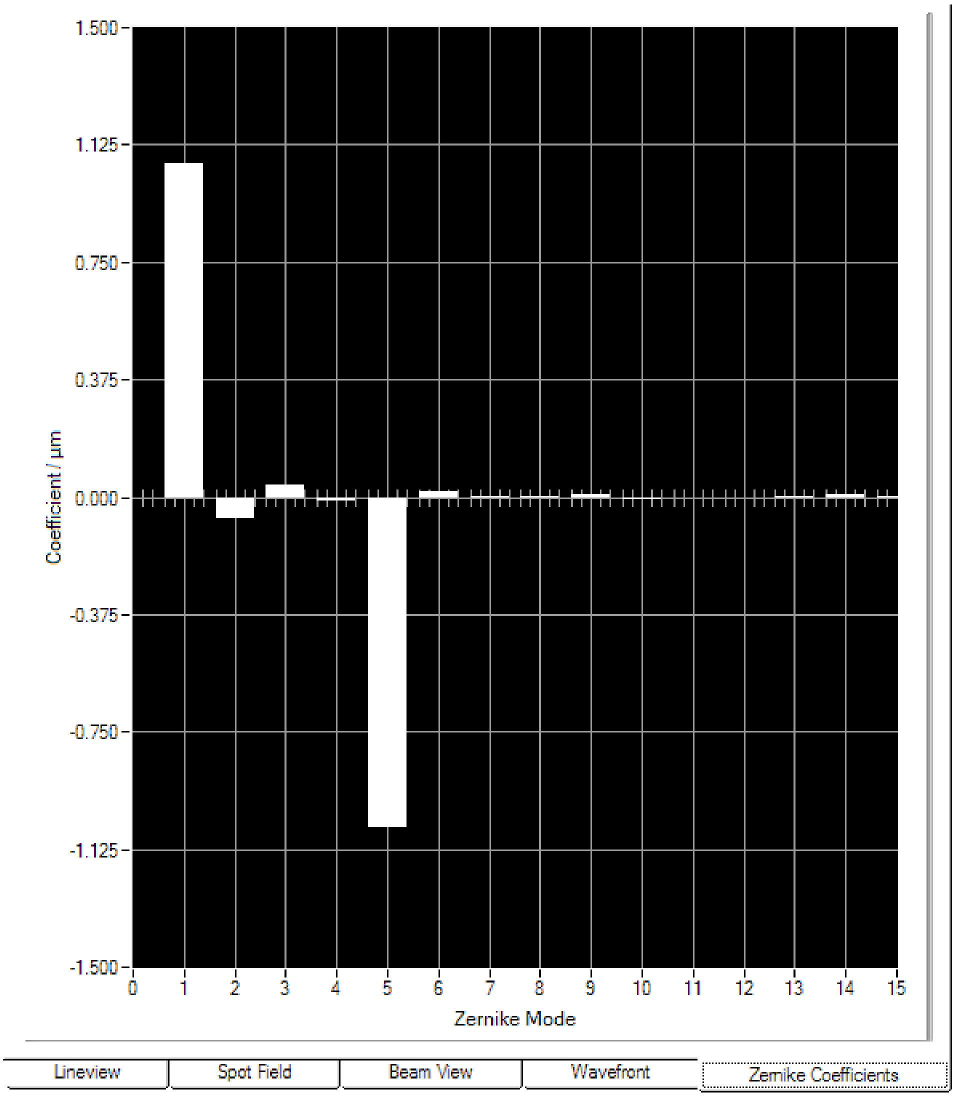
The absolute position of the wavefront surface with respect to the z-axis is determined by the wavefront center that is always set to zero.

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.

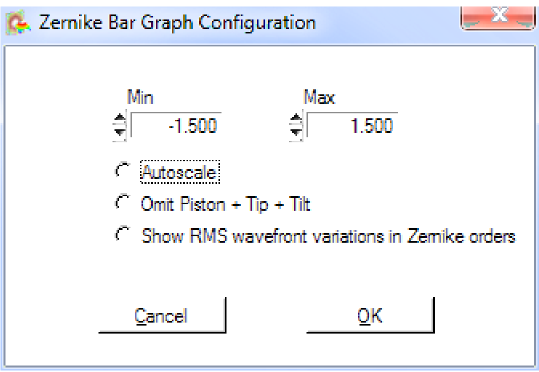
5.1.3.6 Zernike Coefficients Panel

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.

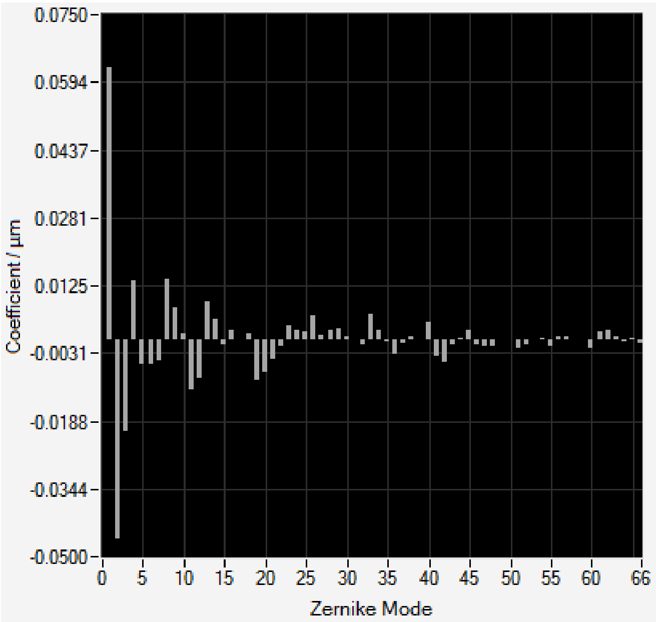
The **Zernike Bar Graph Configuration** panel opens by double clicking to the graph area:



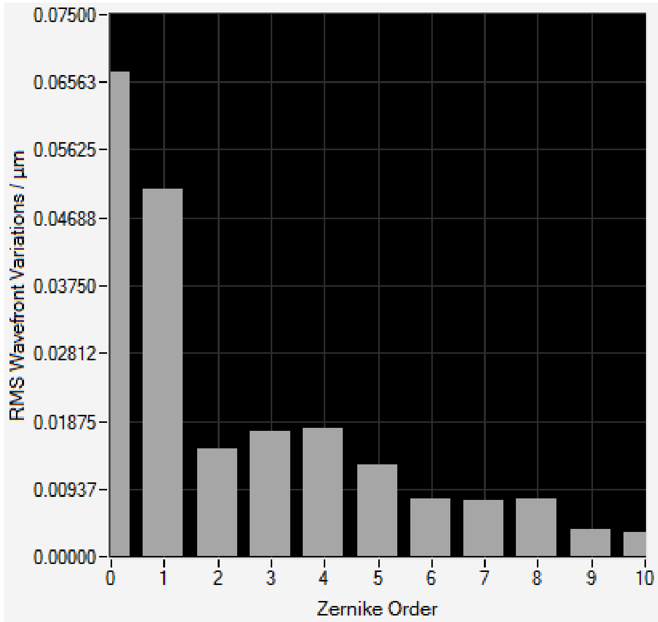
By default, the graph's vertical axis is scaled automatically. Disabling **Autoscale** can be advantageous, if some Zernike coefficients are much larger than the Zernike of interest, or if the wavefront is fluctuating. When **Autoscale** is disabled, the minimum and maximum scale values must be entered 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. Since these lowest order modes may have a considerably higher amplitude than the higher order modes, they can be omitted so that they do not set the Y-axis scale to a larger value than is useful.

'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

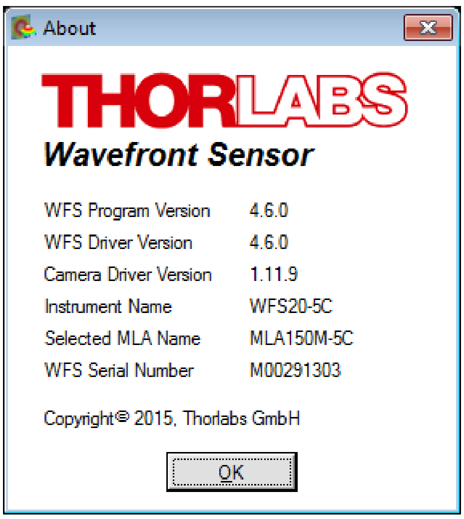


RMS Wavefront Variations in Zernike Orders

Use the **'Omit Piston + Tip + Tilt'** option to suppress the display of Zernike Orders 1 and 2.

5.1.4 Version and other Program Information

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



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

5.2 Settings

5.2.1 Beam Size and Alignment

Beam Size

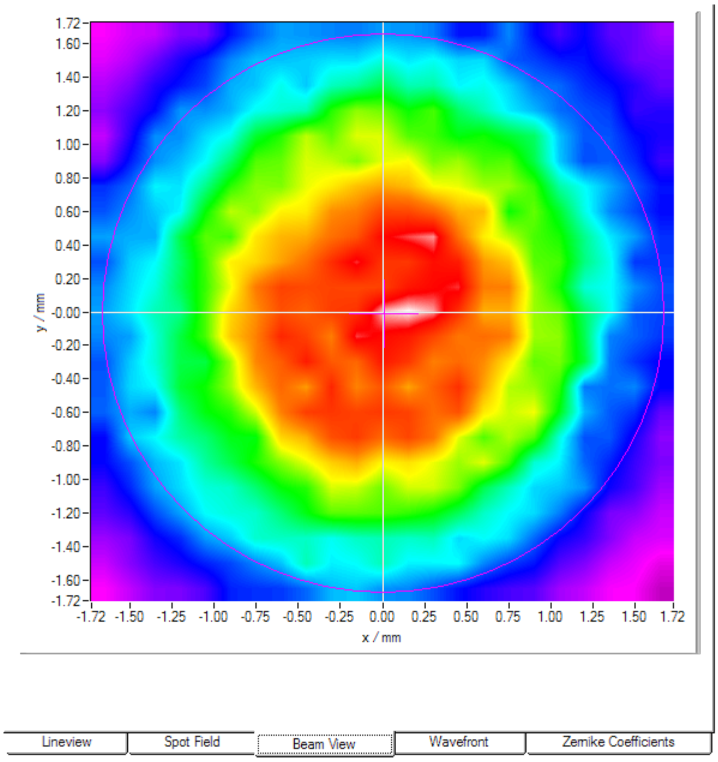
The active area on the CCD / CMOS camera chip needs to be adapted (see Camera Settings Setup 51) to the actual beam size. Otherwise a beam that is much smaller than the sensor area will illuminate only the microlenses at the center and no wavefront data is retrieved from the surrounding area. As a side effect, the measurement speed increases with reduced camera image size.

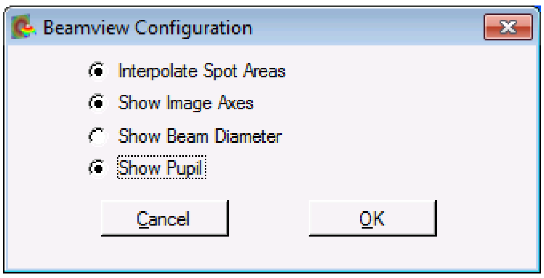
Beam sizes larger than the available aperture (5.95 x 4.76 mm for WFS150/300 and 7.20 x 5.40 mm for WFS20) can be adapted by using a reversed beam expander (Thorlabs GBE02 through GBE20 series).

Alignment

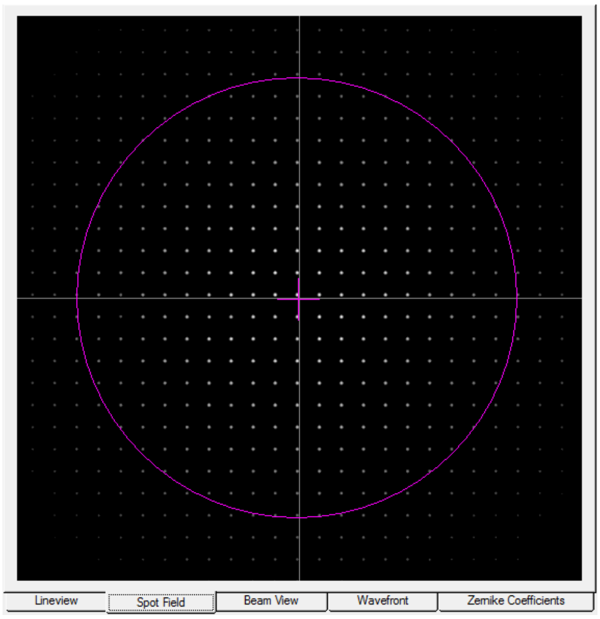
Align the Wavefront Sensor in such way that the beam propagates towards the instrument perpendicular to the front face of the housing. In some cases, a small tilt angle out of that position can be helpful to prevent unwanted reflections from re-entering the measurement setup.

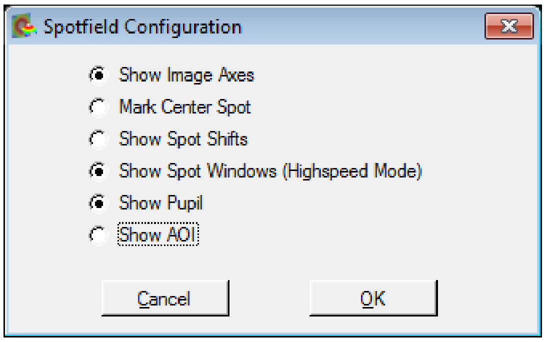
Align the incident beam to the center of the entrance aperture of the Wavefront Sensor. An off-center beam can be measured as well, as long as it won't exceed active sensor area; however, aligning the beam to the center of the sensor area is recommended. Verify this alignment by checking the power density distribution displayed in the Beam View Panel 40. Enable the Beam 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.



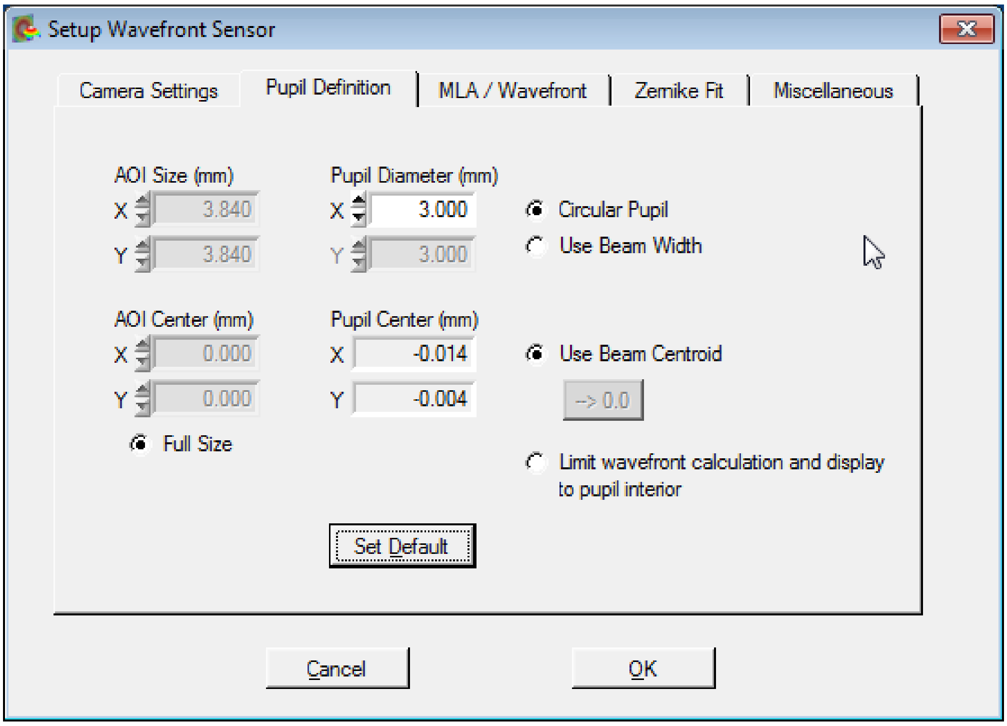


Alternatively, you can check the correct beam position using the Spotfield Panel 36. Enable the diagram options '**Show Image Axes**' and '**Show Pupil**'.





Make sure, that the '**Use Beam Centroid**' option is enabled (Pupil Definitions Setup 58) in order to couple the displayed pupil position to the measured beam centroid position.



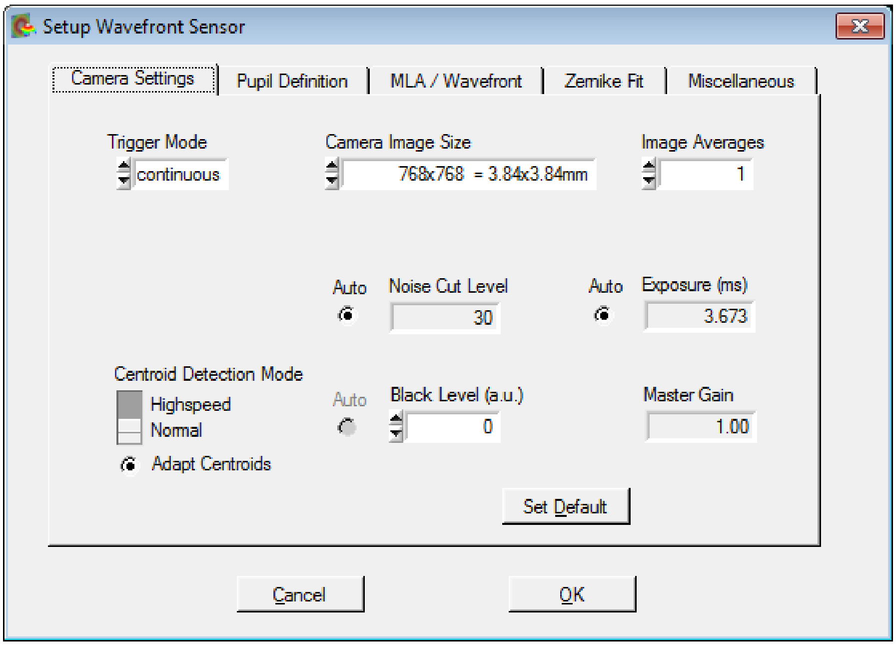
5.2.2 Optical Power

Due to the implemented automatic shutter control of the Wavefront Sensor camera, it can handle optical input power spanning 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 (300 - 1100 nm for WFS150-5C 101 and WFS20-5C 107), which allows higher power sources to be measured directly. On the other hand, the Wavefront Sensor can enter saturation even at lower power levels if the beam is focused (small diameter). In such case, an external attenuator is recommended.

During operation, observe the status bar the bottom of the GUI. Take note of any 'Power too low', 'Power too high' and 'High Ambient light level' errors and find a way to correct the power level accordingly. See Measurement Warnings and Errors 84 chapter for details.

5.2.3 Wavefront Sensor Setup Panel

The Wavefront Sensor GUI automatically starts measuring the applied wavefront using favorable default parameters. Using these default settings, the instrument is able to do first measurements. Nevertheless, it is highly recommended to verify all the applied settings.
The setup panel can be accessed via the Menu bar (Menu -> Setup -> Wavefront Sensor...) or simply by right clicking on the graphical display:



Changing a setup control has immediate influence on the instrument operation or data display.

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

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

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

- Camera Settings 51
- Pupil Definition 58
- Wavefront 63
- Zernike Fit 66
- Miscellaneous 68

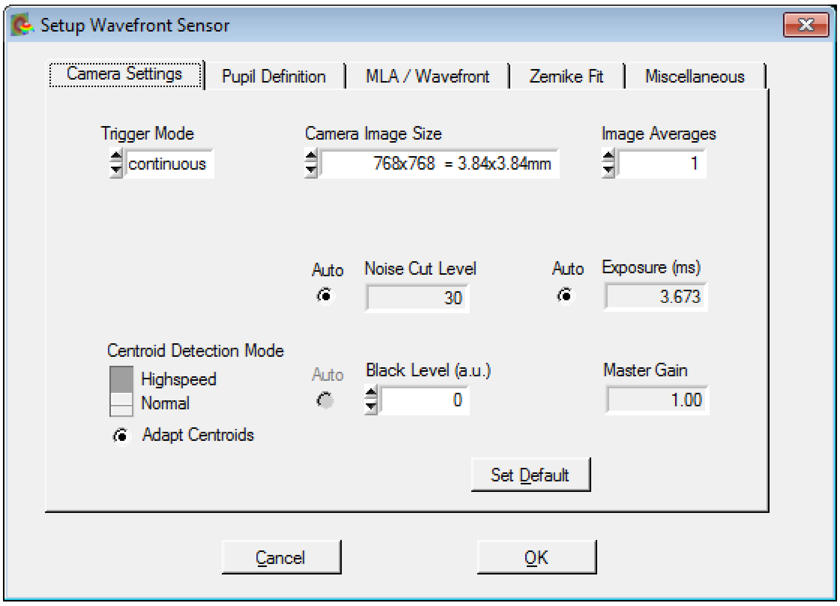
Note

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

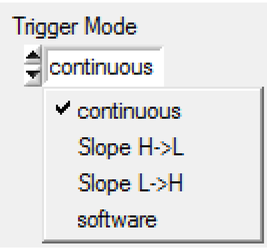
If these settings are critical or contradictory, warnings or error messages will appear in the instrument status bar, see section Measurement Warnings and Errors 84 and Minimal Beam and Pupil Diameter 111.

5.2.3.1 Camera Settings Tab

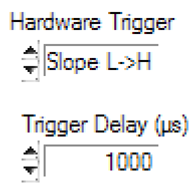
Select in the WFS Setup panel the tab **Camera Settings**:

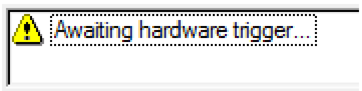


Trigger Mode allows a synchronization mode to be selected for WFS. There are 3 modes available:



- **Continuous** - this is the default mode. The images are being acquired automatically and continuously by the camera - the camera is in free running mode, and the software reproduces the last available image, which might be buffered in the camera or in the driver. This mode allows the fastest measurement speed but the internal buffering causes a delay of several frames between exposure and appropriate wavefront result.
- **Slope H→L (L→H)** - this mode enables synchronization to an external trigger signal which may be a pulsed laser source or an electrical function generator. See chapter Trigger Input 112 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 and no wavefront measurement and screen update take place. This state is indicated by the 'Awaiting hardware trigger...' message in the status bar at the bottom.





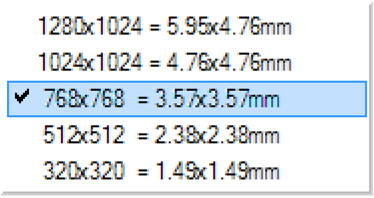
- **Software** The WFS application controls the image acquisition in the camera by starting a new exposure. In this case, all buffered images are deleted and with the start of the exposure, a new image is acquired by the camera and transferred to the PC. This operating mode is somewhat slower than Continuous 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 used for measuring the wavefront. This setting should be adapted to the beam size that is applied to the instrument. Limiting the used image size will reduce the unused sensor area and increases measurement speed by saving time required to evaluate the spotfield images.

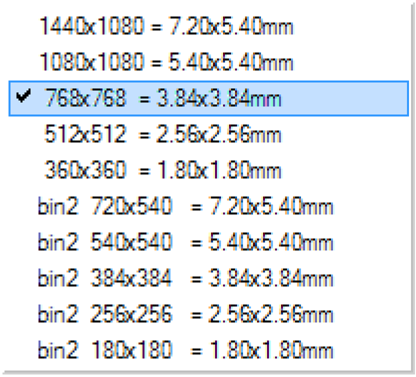
- With a large image size, you can choose a large pupil diameter, and it is possible to allow a high Zernike resolution (Zernike order). The downside is an increased volume of transferred data and subsequently, a decrease of the measurement speed.

- The smaller the image size, the fewer spots can be used for calculation and thus, the maximal achievable Zernike order decreases. On the other hand, measurement speed increases.

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



Camera Image Sizes - WFS150 / 300



Camera Image Sizes - WFS20

The highlighted values are start-up defaults. The WFS Series instruments offer different resolution and maximum available sensor areas:

Item	Sensor Type	Sensor Size	Max. Sensor Area	
WFS150 / WFS300	CCD	1.3 MP	1280 x 1024	5.95 x 4.76 mm
WFS20	CMOS	1.5 MP	1440 x 1080	7.20 x 5.40 mm

In the case that the beam diameter is larger than the maximum sensor area, only a fraction of the beam cross section can be analyzed by the instrument. The input aperture of the Wavefront Sensor is overfilled but can still yield correct results. In this case, the pupil parameters must be selected carefully (see Pupil Definitions Setup 58).

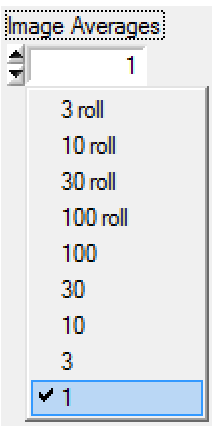
The selectable image sizes for the existing WFS Series instruments can be found in the appropriate Technical Data sections (see Appendix 98) as well.

The WFS20 instrument offers a binning mode ("bin2"). In this mode, 2x2 pixels are combined and averaged. The result is an increased frame rate with the trade-off of reduced spatial wavefront resolution.

Note

Changing the camera resolution will also change the number of detectable spots. If the instrument is operated with a User Calibrated Wavefront Reference 63, a new User Calibration 73 may be required!

Image Averages

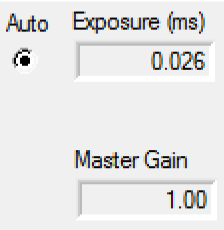


Averages will reduce measurement noise. This can be advantageous when analyzing a low-light-level source. An average setting higher than 1 will take multiple images from the camera, average the pixel intensity pixel by pixel, and output an averaged image to the subsequent evaluating routines. Due to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

3, 10, 30, 100 indicate **normal averages** where the average is taken in the background. The instrument will continue operation and start data evaluation and display only after reaching the selected number of averaged images. This type of averaging also 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 averaged image and the summarized image is divided by the number of averages. This way a pseudo rolling average across the last 3, 10, 30 or 100 images is retrieved. This type of averaging does not slow down the update rate on the screen.

Exposure Time and Gain



For normal operation it is highly recommended to select the **'Auto'** setting. In this case, the 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.

Note

For WFS20 instruments, the Master Gain is fixed to 1.0.

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, see Technical Data.

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

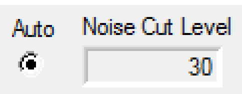
When setting these values manually, we recommend adjusting the brightness by changing the exposure time and increasing the Master Gain only if the exposure control does not give the desired result, otherwise the image noise will be increased without need.

We recommend to check the actual saturation degree of the camera's AD converter in the LineView 34 panel.

Attention

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

Noise Cut Level



The Noise Cut Level defines a brightness level (in digits) which needs to be exceeded by the spots. Ambient light and noise terms below this limit will be canceled. This can be seen in the Lineview 34 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.

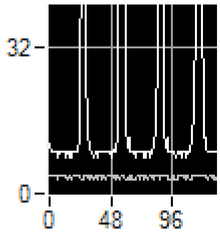
Attention

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

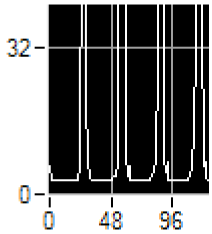
Black Level

Black Level is a camera setting that adjusts the offset brightness level for all illuminated pixels and should be adjusted so that the minimum line in the Lineview 34 panel 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 curve) show high offset.



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

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

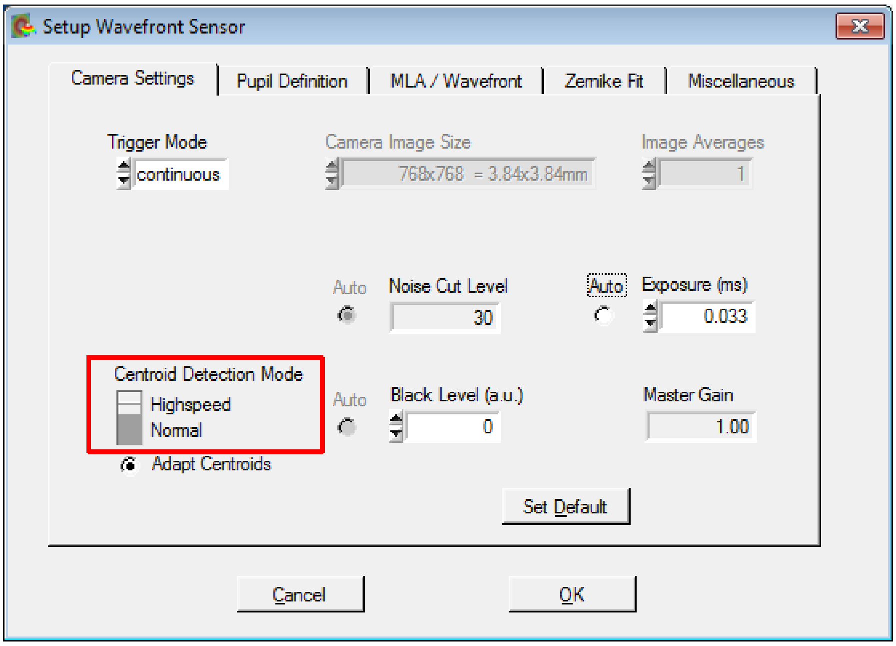
Set Default

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

- Noise Cut Level = Auto
- Exposure Time and Master Gain = Auto
- Black Level = 0 (WFS150, WFS300, WFS20 instruments) or 100 (WFS10)
- Disable Hardware Trigger

Settings for Camera Image Size and Averaging remain unchanged.

Highspeed Mode (WFS20 only)



Settings details are described in the next section High Speed Mode 55. For a detailed description of the differences between Normal and Highspeed Mode please refer to section WFS20 Highspeed Mode 77.

5.2.3.1.1 High Speed Mode

Prior to entering the Highspeed Mode, pay attention to the following setup parameters:

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

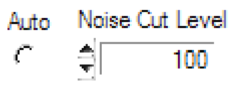
Note

In Highspeed Mode, the detected spot centroid positions become extremely sensitive to the camera black level!

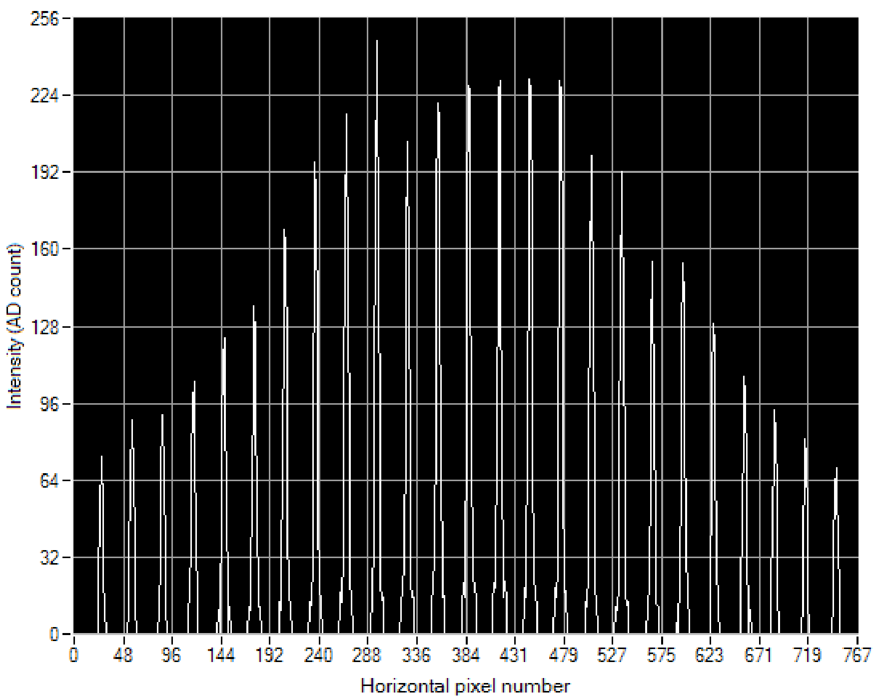
That's why all pixel intensities within the entire spot window (width x height pixels) contribute to the final centroid result. Further, small black level intensities will shift the result towards the window's center. To get rid of increased black level you have two options:

a) Change the camera analogue black level: It can be lowered so that the pixels between the spots become zero.

b) An adjustable ‘Noise cut level’ similar to the one in normal mode can be set when the camera is in Highspeed Mode. Disable the 'Auto' option since it isn't available in Highspeed Mode, anyway. The camera will subtract this level from each pixel before it starts the centroid calculation.

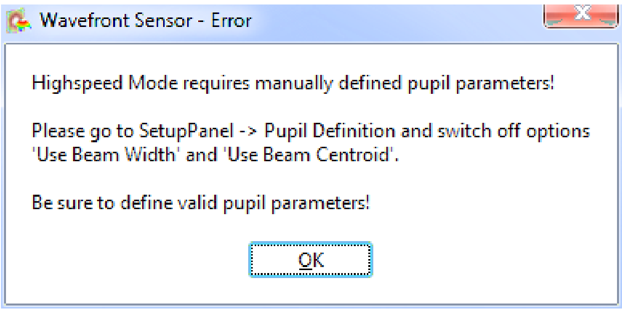


For both options, please check the Lineview panel, it should look like this:



Entering the Highspeed Mode (WFS20 only)

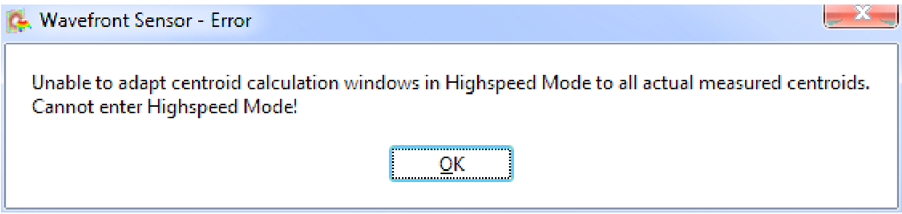
The wavefront sensor is always initialized in Normal Mode. As the detection of beam centroid and diameter with sufficient accuracy is impossible in Highspeed Mode, you will be asked to define these parameters manually:



Please go to the Wavefront Sensor Setup → Pupil Definition, switch off both options and define the pupil diameter and position manually. Please consider hints given in chapter Pupil Definitions Setup 58.

Adaption to previously measured spot centroids

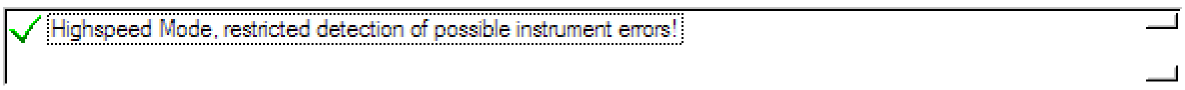
If centroid adaption is off (Adapt Centroids) the software defines a rigid grid of spot interrogation windows based on the spot reference positions. Since the actual detected spot centroids match their reference positions only in case of exactly orthogonal incidence of a pure plane wavefront, it is likely that some spots of an arbitrary measured wavefront will not fall into the reference grid. The following error occurs:



Therefore, it is highly recommended to enable option 'Adapt Centroids' (Adapt Centroids). In this case, the software checks if the spot centroid positions measured in Normal Mode are suitable to use for defining a grid of calculation windows that are sufficient to capture all spots. The grid is flexible with respect to window size and offset position in both x and y direction. This flexibility allows adaption of tilted and spherical wavefronts of moderate amplitude.

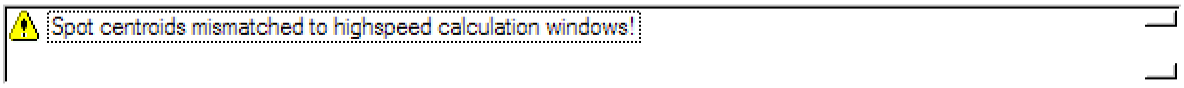
If the above error message occurs, the input wavefront is excessively deformed so that it cannot be measured in Highspeed Mode.

In Highspeed mode, the status window will display a warning that there is a risk of incorrect measurement results due to restricted error detection capabilities:



It is recommended to have the Auto Exposure enabled in high speed mode as well. This allows sensor saturation to be avoided. Overexposure or underexposure (Warnings "Power too high" or "Power too low" in the status window) lead to wavefront measurement errors. Disabling the auto exposure feature in high speed mode is possible only in the case that the incident power level is sufficient and nearly constant.

Another detectable error in high speed mode occurs when the detected centroids cross the boundaries of the spot windows.



Note

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

5.2.3.2 Pupil Definition Tab

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

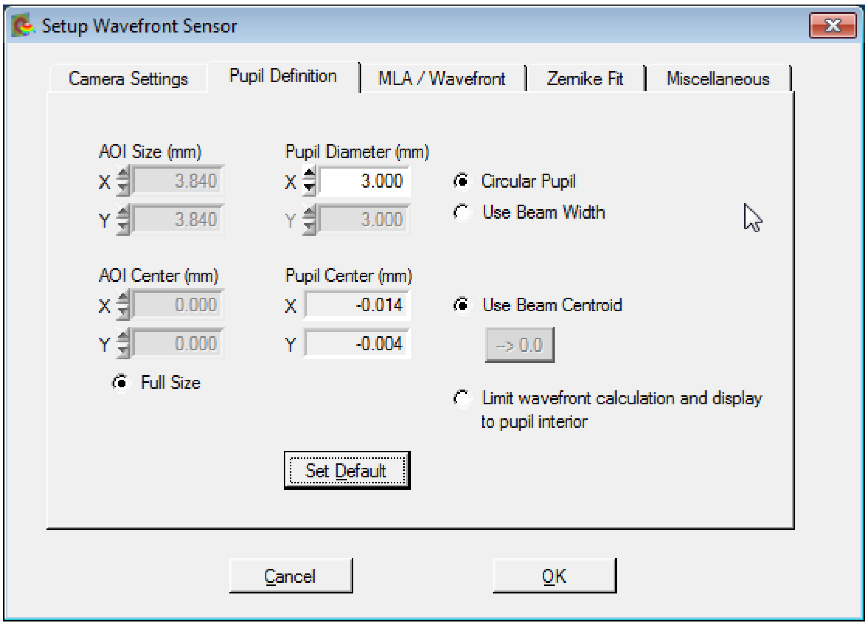
Since all Zernike functions are defined within a unit circle ($r \le 1$), only the measured spots within the pupil can be used for fitting the Zernike functions to the measured wavefront distortions. This is accomplished by normalizing the physical centroid positions (in mm or camera pixels) to the dimensionless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

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

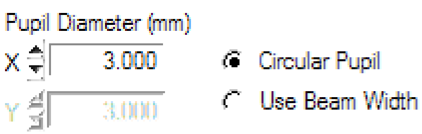
In order to adapt the measurement to elliptical beams, the pupil can also be set to an elliptical shape. The different physical radii are normalized by using separate x and y scaling factors in order to achieve a round unit circle again, which is required for the following Zernike calculations.

For practical measurements the pupil size is chosen to match the beam diameter that will be analyzed. 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.

Select in the WFS Setup panel the tab **Pupil Definition**:



Pupil Diameter (mm)



The Pupil Diameter as it is 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 $1/e^2$ 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 Camera Settings 51). A positive offset to the beam intensity distribution will lead to beam diameters larger than real. A manually defined **Noise Cut Level** in the Camera Settings 51 will help to reject an increased dark level.

Disable **Use Beam Width** in order to define the pupil size manually. An elliptical pupil can be set up by entering different values for X and Y diameter. In this case, the mean ellipse diameter defines the Zernike circle.

Note

The option **Use Beam Width** must be switched off when entering Highspeed Mode of WFS20 instruments because the beam width cannot be measured with a sufficient accuracy in Highspeed Mode.

Note

The pupil diameter must be less than the active camera area as defined by **Camera Image Size** setting (see Camera Settings 51), otherwise the warning "Pupil is larger than selected camera area" (see section Measurement Warnings and Errors 84) will occur. This limitation prevents the increase of Zernike calculation uncertainty due to fact that the measurement points (spots of the lenslets) are no longer equally distributed across the pupil area.

See section Minimal Beam and Pupil Diameter 111 for the minimal pupil diameter that is required for calculation of Zernike modes up to a desired order.

Using **Circular Pupil** with the appropriate options is recommended. Then only the diameter in X needs to be entered and the Y diameter is set to the same value.

Pupil Center (mm)

The pupil center 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 --> 0.0 button to set the pupil centroid to the center of the Wavefront Sensor.

Note

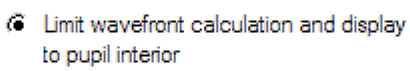
Manual definition of the pupil center requires a careful and stable beam adjustment, otherwise the measurement results will suffer from increasing errors.

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

Note

Disable the option **Use Beam Centroid** when entering high speed mode of WFS20 (WFS10) instruments because the beam centroid cannot be measured with a sufficient accuracy in high speed mode.

Limit to Pupil Interior



Enabling this option will limit the wavefront calculation and display it over the pupil interior. Points outside the pupil that do not enter into the Zernike calculation anyway will not be recognized for statistical wavefront analysis.

The 3D wavefront display on the Wavefront Panel 42 will show only the wavefront data within the pupil when this option is enabled.

Note

Selecting 'Measured Wavefront' for display 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.

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

5.2.3.2.1 Area Of Interest (AOI)

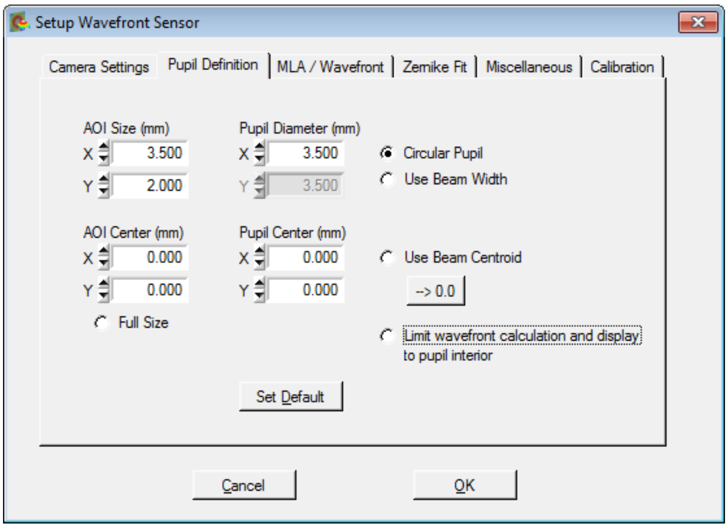
The AOI functionality allows the measurement area to be limited to a rectangular region called the Area of Interest (AOI). Similar to the option “Limit wavefront calculation and display to pupil interior” that limits the wavefront display and the appropriate numerical parameters to the pupil area, the AOI allows measurement results to be limited to the selected rectangular area.

This feature was customer inspired.

This is especially helpful 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

The AOI can be set in the ‘Pupil Definition’ tab.



When the ‘Full Size’ option is enabled (default), the AOI is equal to the actual camera image size 51 that is selected. In this case the yellow rectangle is not displayed in the Spotfield panel.

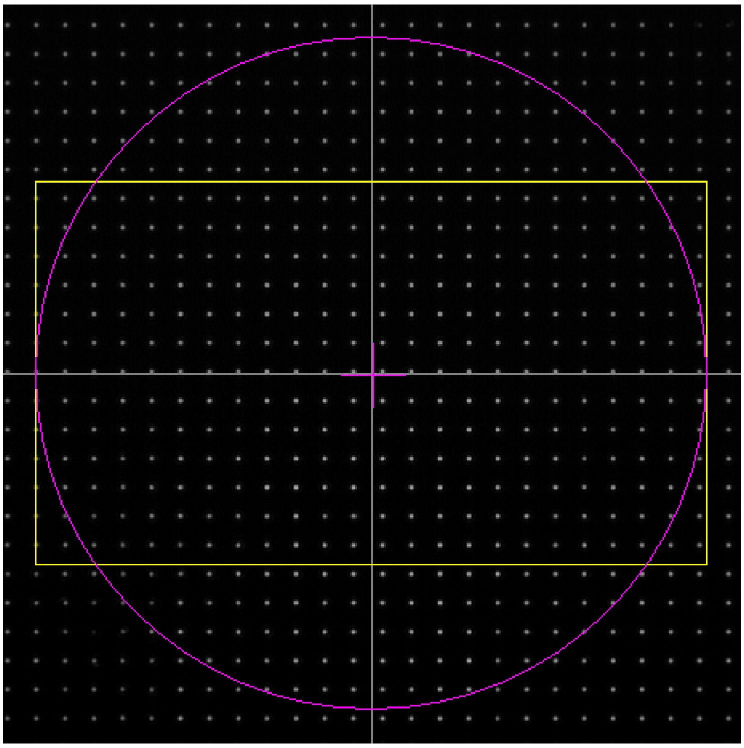
To enter smaller AOI dimensions, uncheck the ‘Full Size’ button, and enter the size and center coordinates of the desired AOI.

How the AOI works

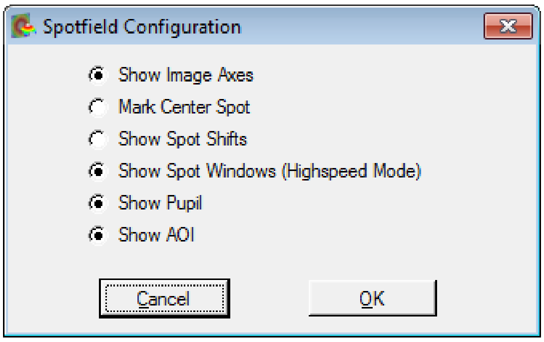
Limiting the AOI is related to the reference centroid positions; in other words, a detected spot is masked if its appropriate reference position is outside the AOI.

AOI Display

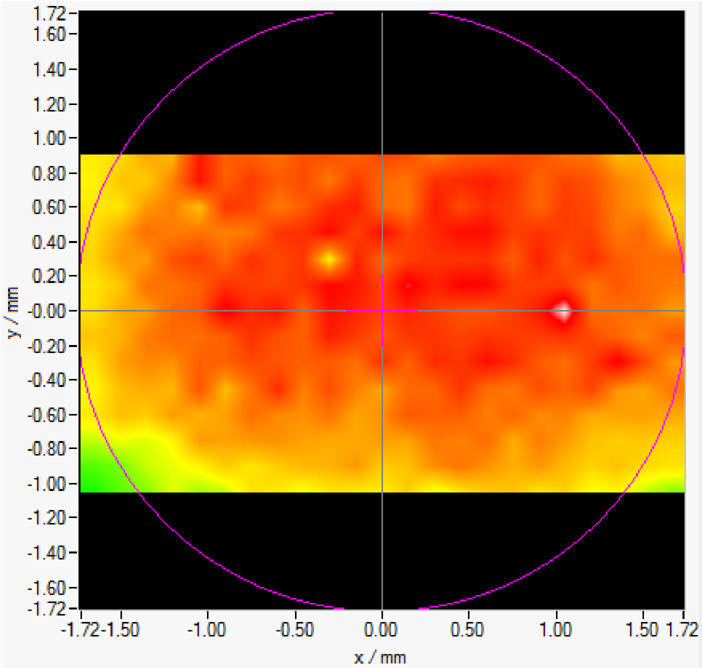
Display in Spotfield:



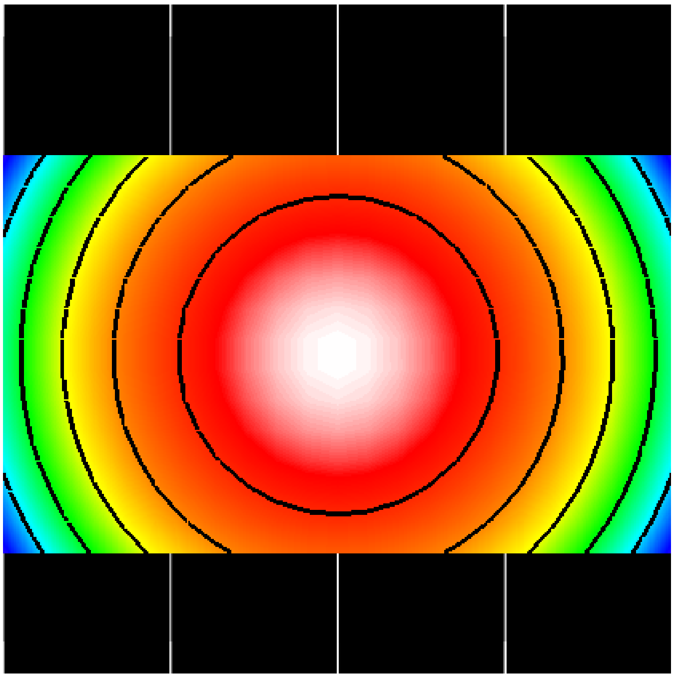
Double-click onto the Spotfield image to open its configuration. Option ‘Show AOI’ determines if a user-defined AOI is displayed or not.



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



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



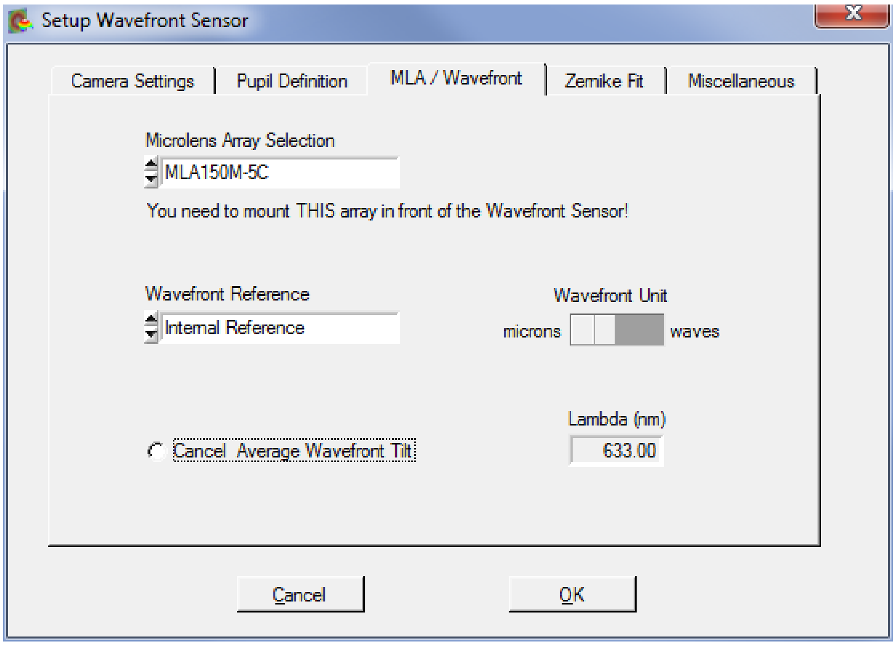
Numerical calculations like the Wavefront PV or RMS and the entire Zernike calculation are also related to the area within the AOI.

Note

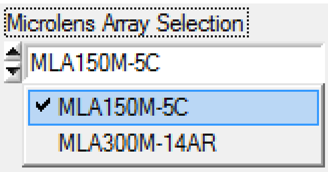
For valid Zernike calculation, it is required that the pupil is well filled with valid spots. An AOI smaller than the pupil area may cause errors in the Zernike calculation.

5.2.3.3 MLA / Wavefront Tab

Select in the WFS Setup panel the tab **MLA / Wavefront**:

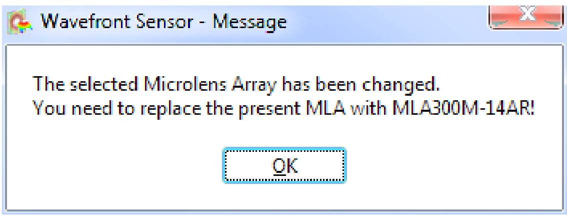


Microlens Array Selection



A Thorlabs WFS Wavefront Sensor can be operated with different Microlens Arrays (MLAs), see Parts List 12 section. Each available MLA is factory calibrated. In order to supply the correct calibration data to the WFS software you need to select the physically installed MLA from the pull down list.

When you select a different MLA than was previously entered into the program, the message below is displayed as a reminder to switch the physically installed MLA.



Attention

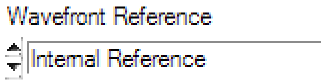
Make sure that the MLA that you have selected in the software is the same as the MLA physically installed in your Wavefront Sensor. Otherwise, the measurement data will be incorrect because software is using calibration data for the wrong MLA.

Wavefront Reference

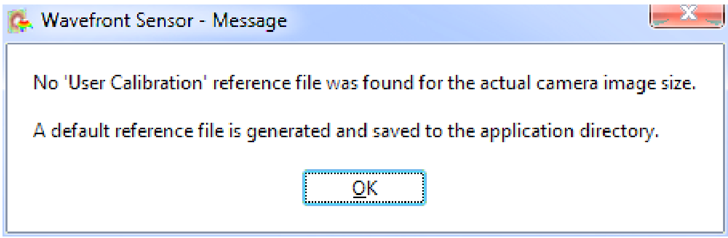
The Thorlabs WFS series Wavefront Sensors are factory calibrated and provide an internal reference for the measured spotfield centroids. This internal reference is based on the well known and highly accurate parameters

- pixel distance of the CCD sensor = 4.65 µm (WFS150/300)
- pixel distance of the CMOS sensor = 5.0 µm (WFS20)
- lenslet pitch of the microlens array = 150 or 300 µm, respectively
- calibrated out-of-center shifts in for a plane wavefront under vertical incidence
- negligible torsion between sensor chip end lenslet array
- correction parameters for lenslet astigmatism

This means that the centroid positions for all spots created by the lenslet array are accurately known for a plane wavefront at vertical incidence and acts as an **Internal reference**.



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



This default user reference file is identical to the internal reference. Perform a User Calibration 73 using a planar or spherical wavefront to fill the default file with reference data measured by the user.

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

- WFS serial number
- MLA name
- Camera resolution index

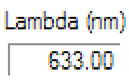
for instance WFS_M00224955_MLA150M-5C_2.ref. The file saved to

Note

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

Wavefront Unit and Wavelength

Select the desired wavefront measurement unit absolute units in **microns** (µm) or relate the wavefront deformations to the operating wavelength to yield the unit **waves**. In the latter case, the input of the operating wavelength in nm is required.



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 WFS Series.

Cancel Average Wavefront Tilt

In practice, 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 much smaller and cannot be seen in the wavefront panel. Since wavefront tip and tilt is mostly of less interest, this option allows the average tip and tilt contribution to be canceled prior to wavefront and Zernike calculation.

Note

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

Also note that 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.

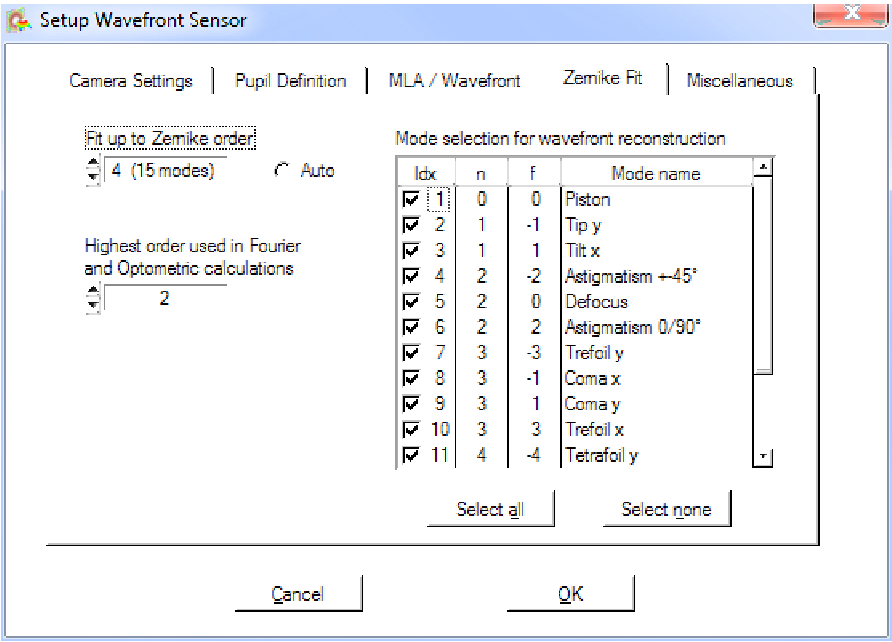
Default Settings

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

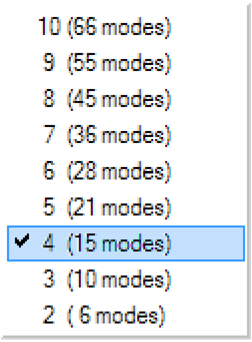
- Wavefront Reference: Internal Reference
- Wavefront Unit: µm
- Operating wavelength: 633 nm
- Cancel Average Wavefront Tilt: Off

5.2.3.4 Zernike Fit Tab

Select in the WFS Setup panel the tab **Zernike Fit**:



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

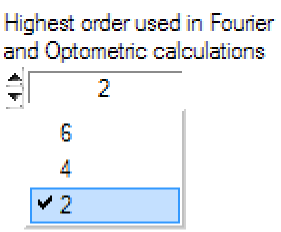
By default, the highest Zernike order is set to n = 4 which implies a total number of 15 Zernike modes. The resulting coefficients are displayed as a bar graph chart on the Zernike Coefficients panel.

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

Mode selection for wavefront reconstruction

This table provides a list of all calculated Zernike coefficients 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 the reconstruction of the wavefront or not. For instance, to see the reconstructed wavefront without primitive modes piston, tip and tilt (which often dominate the 3D graphic) use the following setting:

Mode selection for wavefront reconstruction

	Idx	n	f	Mode name
☐	1	0	0	Piston
☐	2	1	-1	Tip y
☐	3	1	1	Tilt x
☑	4	2	-2	Astigmatism +-45°
☑	5	2	0	Defocus
☑	6	2	2	Astigmatism 0/90°
☑	7	3	-3	Trefoil y
☑	8	3	-1	Coma x
☑	9	3	1	Coma y
☑	10	3	3	Trefoil x
☑	11	4	-4	Tetrafoil y

Select all | Select none

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

Mode selection for wavefront reconstruction

	Idx	n	f	Mode name
☐	1	0	0	Piston
☐	2	1	-1	Tip y
☐	3	1	1	Tilt x
☐	4	2	-2	Astigmatism +-45°
☐	5	2	0	Defocus
☐	6	2	2	Astigmatism 0/90°
☑	7	3	-3	Trefoil y
☑	8	3	-1	Coma x
☑	9	3	1	Coma y
☑	10	3	3	Trefoil x
☐	11	4	-4	Tetrafoil y

Select all | Select none

Note

In the Wavefront graphical display with '**Reconstructed**' wavefront selected, only the selected Zernike Modes will be displayed. The numerical value **Peak to Valley (PV)** and **RMS wavefront distortions** depend on this mode selection as well.

```
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**'.

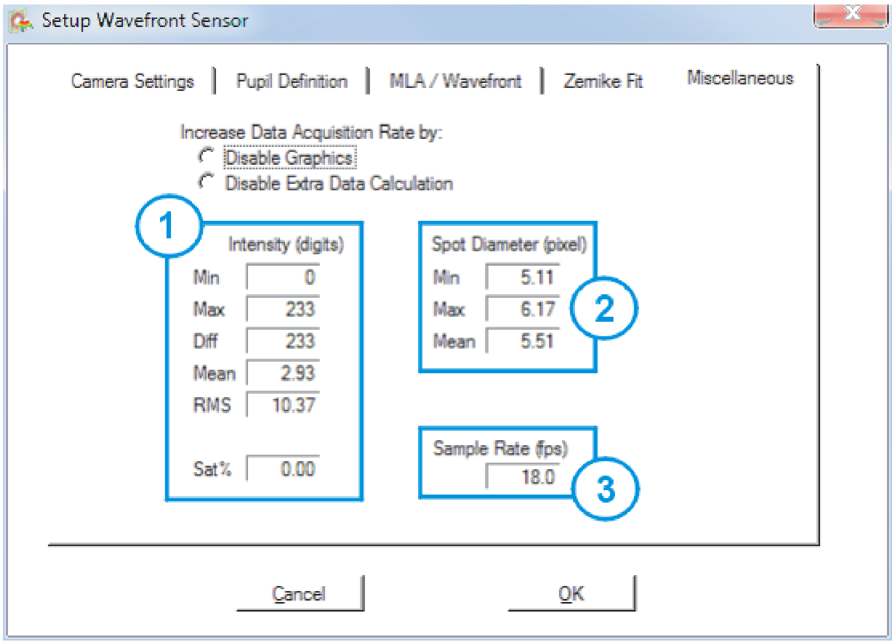
Default Settings

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

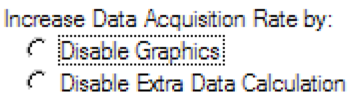
5.2.3.5 Miscellaneous

Select in the WFS Setup panel the tab '**Miscellaneous**':

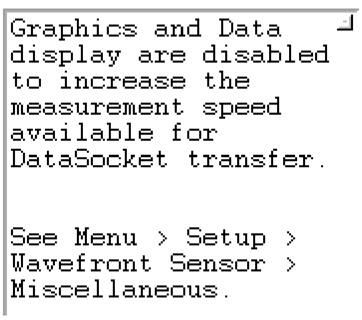


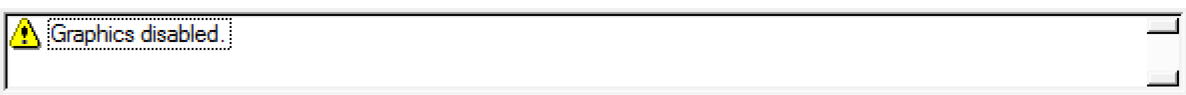
1. Image statistics. The maximum pixel intensity (**Max**) must not reach 255 digits to prevent sensor saturation. **Sat%** indicates the percentage of saturated pixels.
2. The calculated values of **Spot Diameter** are used to verify the optical quality during assembly.
3. The **Sample Rate** in frames per second (fps) is the speed indicator.

Speed up the measurement



- If the WFS software is connected to the DataSocket 79 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 their updating can be disabled - check the option **Disable Graphics**. This saves calculation time and increases measurement speed. All graphs including the output panel for numerical parameters 31 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 Exra Calculation**.

- The measurement speed can be increased by selecting a lower camera resolution (Camera Settings 51), resulting in a less number of spots to be calculated.

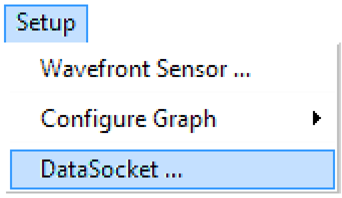
Default Settings

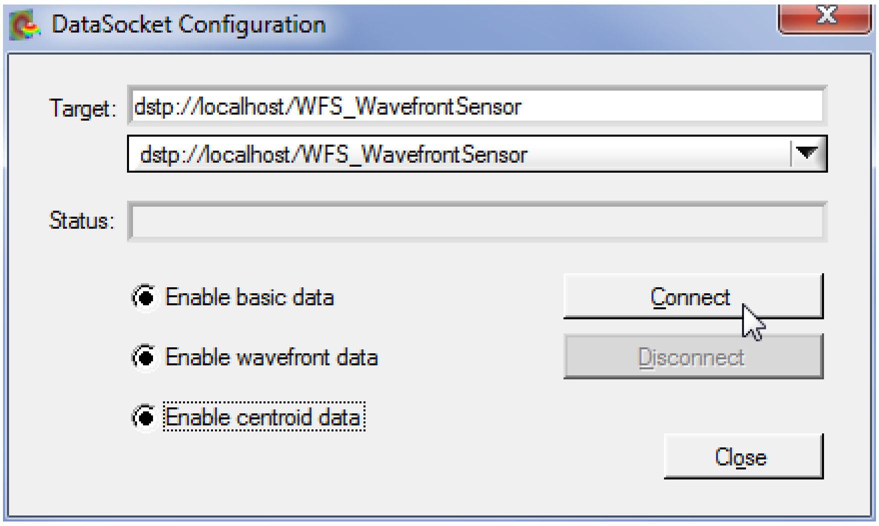
At the first start of the software, the following default settings are in use:

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

5.2.4 DataSocket Configuration

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 computer that is connected via a TCP/IP network, you must **first** start the DataSocket server on the remote machine and configure it according to the description in DataSocket for live data transfer 79. Then type in the correct network name of the computer hosting the DataSocket server. For example,

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 firewalls blocking the data transfer (DataSocket for live data transfer 79).

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 Available Data Items 81 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 Available Data Items 82 for a detailed description of the submitted data items.

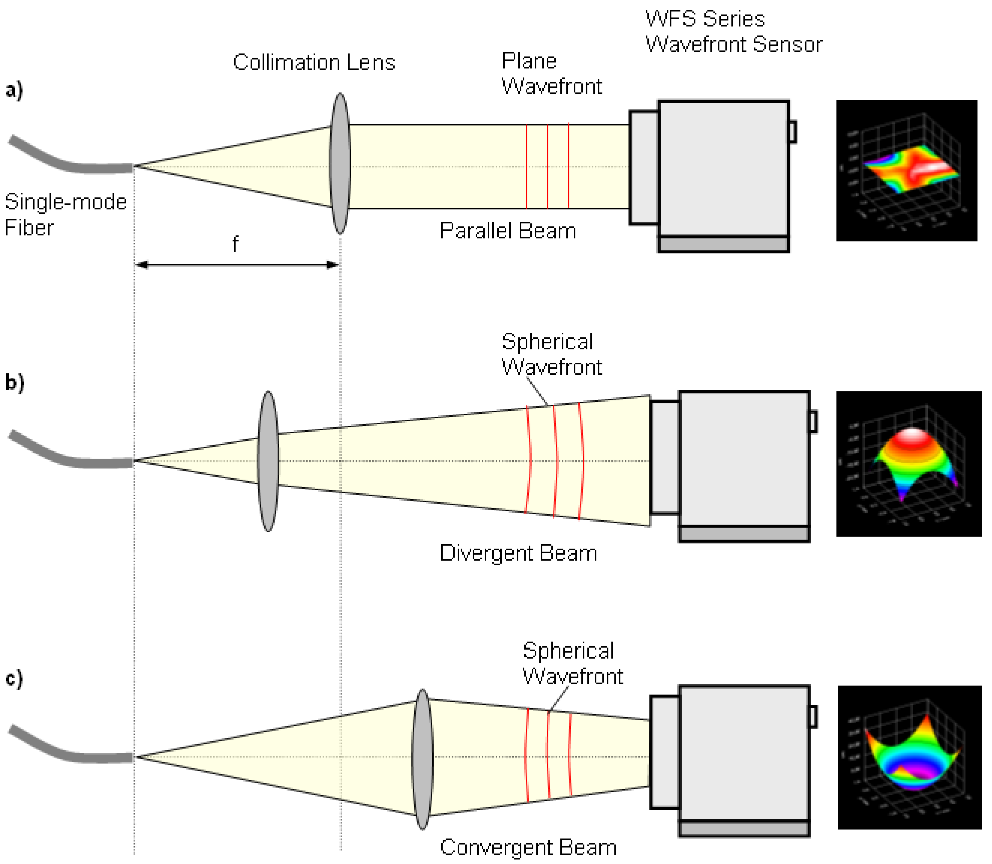
Enable centroid data

Check this box to send the 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 Available Data Items 82 for a detailed description of the submitted data items.

5.3 Measurement Examples

The following picture illustrates a very simple measurement example to explain what a wavefront is and how it can be influenced.

a) A collimation lens (e.g. bi-convex) is positioned at the distance f (focal length 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 the appropriate Zernike term 'Defocus' indicates the spherical wavefront.

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 focal point is located behind the sensor position. The wavefront is of a spherical shape as well, but now it is spherical concave.

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.

5.4 User Calibration

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

A user calibration can be advantageous in cases where a wavefront should work as a reference but already shows small distortions. In that case, execute a user wavefront calibration: the distorted wavefront acts as a reference and is displayed as ideal. All subsequent measurements will be based on this user reference and allow accurate measurements of wavefront distortions that were introduced by optical elements that have been inserted into the light path.

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

- WFS serial number
- MLA name
- Camera resolution index

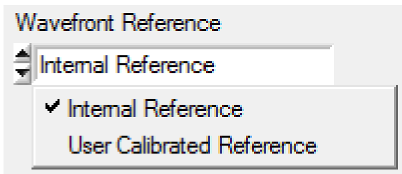
for instance WFS_M00224955_MLA150M-5C_2.ref. This ensures, that user reference files are uniquely assigned to the WFS hardware, the MLA and the camera resolution. The file saved to

Note

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

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 50 to switch between internal and user calibration.



Note

The accuracy of the calibration increases if image averaging is set to > 1, see Camera Settings Setup 51 panel.

The generated user calibration data are only valid for the actual MLA and camera image size, that are selected in the Camera Settings Setup 51 and Wavefront Setup 63 panel. Switching to an other MLA or camera resolution will require a new calibration!

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

5.4.1 Plane Wavefront

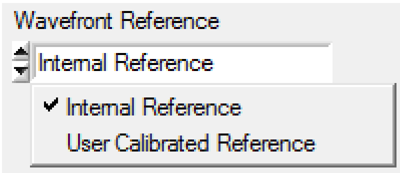
User Calibration using a Plane Wavefront

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

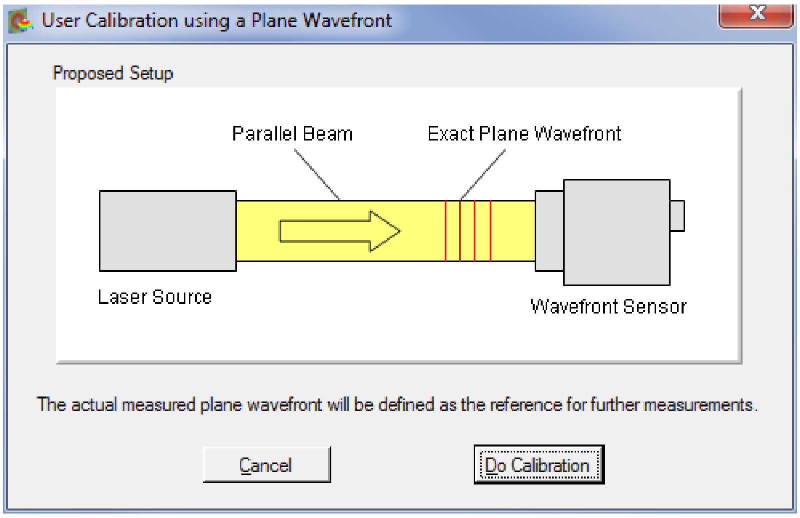
Note

The calibration fails for positions that are insufficiently illuminated. Although no error occurs, the corresponding area will be excluded from further wavefront measurements.

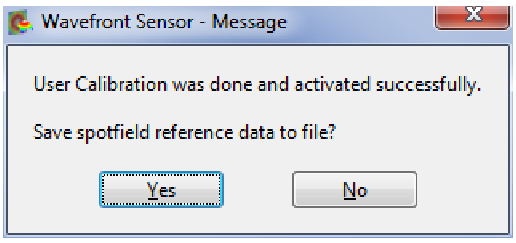
Setup the Wavefront Sensor to work using the internal reference. Do the appropriate setting within the Wavefront Sensor Setup Panel 50.



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



Click '**Do Calibration**' to perform the user calibration and the following message verifies successful operation.



You are asked to save the reference data to a file. Click '**Yes**' to store this user calibration to a predefined file within your **My Documents** directory to have it available in following Wavefront Sensor 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 51) or the MLA selection (see Wavefront Setup 63) is changed.

5.4.2 Spherical Wavefront

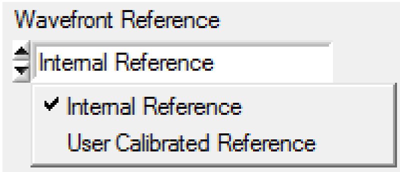
User Calibration using a Spherical Wavefront

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

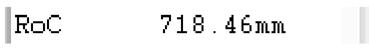
Note

The calibration fails for positions that are insufficiently illuminated. Although no error occurs, the corresponding area will be excluded from further wavefront measurements.

Setup the Wavefront Sensor to work using the internal reference. Do the appropriate setting within the Wavefront Sensor Setup Panel 50.

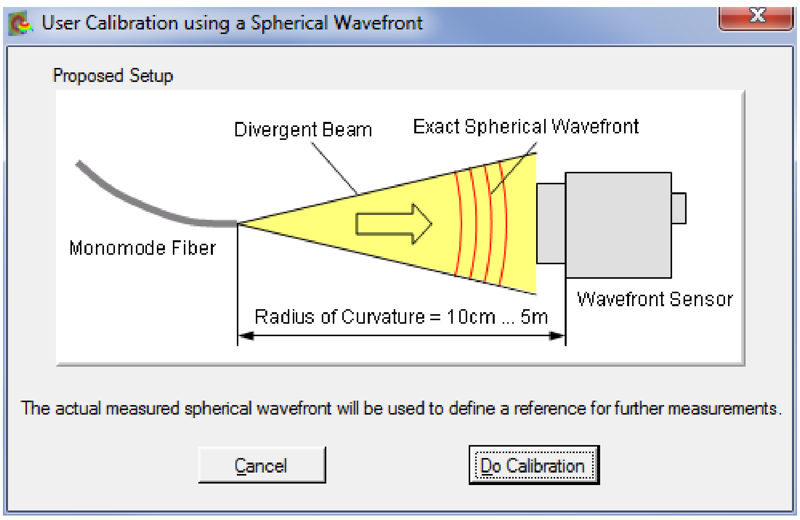


Adjust the point source so that it is centered in front of the Wavefront Sensor at a distance in the range 10 cm to 5 m. The Wavefront Sensor will measure the distance and displays it as Radius of Curvature RoC.

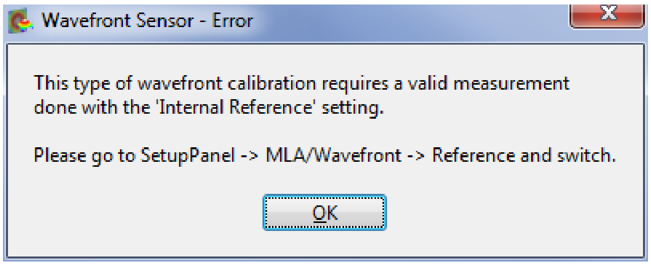


Larger distances are better suited for calibration because the wavefront curvature is lower and closer to a plane wavefront

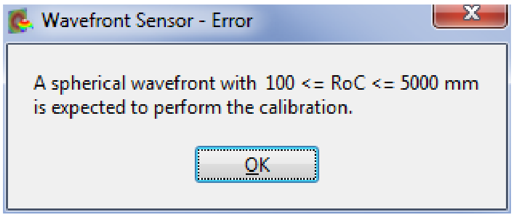
Start the calibration procedure using **Menu → Calibration → Spherical Wavefront** or simply click on the appropriate symbol in the toolbar. The dialog window illustrates the required calibration setup:



Click '**Do Calibration**' to perform the user calibration. In the case that a user reference is enabled, an error message will come up and require that the settings must be switched to internal reference first:

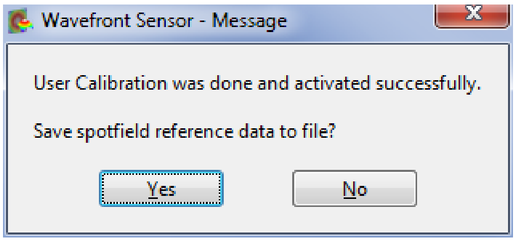


If the measured distance to the point source is too short or too far, the following error occurs.



Change the setup accordingly and repeat the calibration.

Click '**Do Calibration**' to perform the user calibration and the following message verifies successful operation:



You are asked to save the reference data to a file. Click '**Yes**' to store this user calibration to a predefined file within your **My Documents** directory to have it available in following Wavefront Sensor 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 51) or the MLA selection (see Wavefront Setup 63) is changed.

5.5 WFS20 High Speed Mode

The Fast WFS20 models are based on a much faster CMOS camera compared to the WFS150/300 instruments that are based on a CCD camera. The WFS20 offers a High Speed Mode with significantly higher measurement speed compared to the Normal Mode and to the WFS150/300 models.

Please note that a CMOS sensor may have more "hot pixels" (pixels showing a certain intensity even when not illuminated) than CCD sensors. See chapter Hot Pixel 97 for details.

What is High Speed Mode?

Normally, the complete spotfield image is transmitted from the camera to the computer and the wavefront analysis is processed in the WFS software. This method is speed-limited because of the limited USB 2.0 bandwidth and the calculation speed limitations of the PC.

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

- The spotfield image is captured inside the camera and won't be transmitted via USB.
- Instead, the camera's FPGA (control box) is calculating the spot centroid coordinates. Due to these internal calculations, the pupil center may shift slightly, when switching from normal to high speed mode.
- Only the calculated centroid positions are transmitted via USB to the GUI.
- Due to the much lower transmitted data volume, the maximum measurement rate increases.
- Shifting the time-consuming centroid calculations to the much faster FPGA reduces the CPU load and further calculations (wavefront, Zernike fit) accelerate.

The important **advantage** of the High Speed Mode is a higher measurement speed, particularly at large camera resolutions.

Along with that, some **restrictions and disadvantages** take place:

- Centroid calculation windows are no longer dynamically positioned but are placed on a semi-rigid grid.
- This calculation grid will be configured each time you enter High Speed Mode and remains fixed afterwards.
- The maximum wavefront dynamic range is considerably lower because spot shifts are limited to the fixed calculation windows.
- Therefore, there is an increased risk of incorrect measurements due to camera saturation!
- Besides that, centroid position results become extremely sensitive to the camera's black level and ambient light because all pixel intensities within the entire spot window (width x height pixels) contribute to the final centroid result. Also, low black level intensities will shift the result towards the window center.

In order to assure correct measurements in High Speed Mode, be particularly careful when choosing the following setup parameters:

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

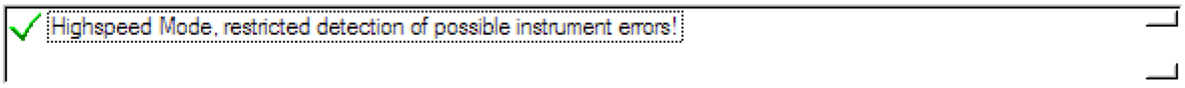
Please refer to section Camera Settings Setup 54 for a detailed explanation of these settings.

Note

The measurement speed is limited by the camera's exposure time. You need to apply a sufficiently high power level so that the exposure time can be set much shorter than the time required to acquire 1 frame:

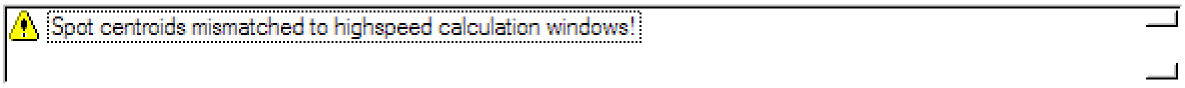
$$t_{exp} << {}^{1}/_{frame\ rate}$$

Keep an eye on the status window!



Enabling Auto Exposure in high speed mode is also recommended, as it will help with avoiding sensor saturation. Overexposure or underexposure (Warnings "Power too high" or "Power too low" in the status window) lead to wavefront measurement errors. Disabling the auto exposure feature in high speed mode is possible only in the case that the incident power level is sufficient and nearly constant.

Another detectable error in high speed mode is the violation of the spot windows by the detected centroids:



Note

If this warning occurs, the wavefront measurement is most likely affected by spots that are truncated by their detection windows.

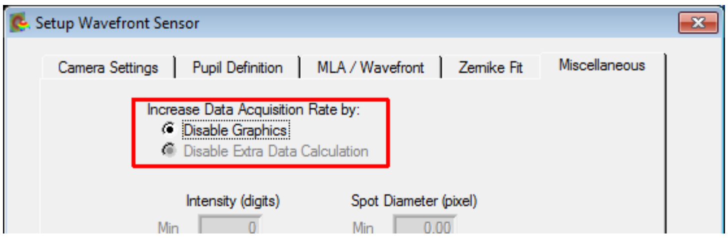
Achievable Speed

In the section Camera Resolution and Spot Count 105 the speed enhancement in High Speed Mode is represented (tables).

How to get the highest speed?

In addition to the limitations imposed by the Wavefront Sensor and the analyzing software, the speed is also limited by the calculation of data for the graphic display and image statistics, which require high system resources.

There is an easy way to check the speed performance of the WFS20 sensor and the WFS instrument driver: Go to Setup Wavefront Sensor → Miscellaneous 68 and mark options 'Disable Graphics' and 'Disable Extra Data Calculation'.



Further, with the auto exposure feature enabled in High Speed Mode, the maximum achievable speed will drop because the camera needs to calculate the actual saturation level for each frame.

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

5.6 DataSocket for live data transfer

DataSocket is a program interface 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.

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.

See http://www.ni.com/white-paper/3224/en/ for a DataSocket tutorial.

The following scenarios are imaginable:

a) PC "A" runs the Wavefront Sensor application that sends the measurement data to the local DataSocket server running on the same machine. Another application on the same PC "A" retrieves the data.

b) PC "A" runs the Wavefront Sensor application that sends the measurement data to the local DataSocket server running on the same machine. An application on another PC "B" retrieves the data. PCs "A" and "B" are connected via a network.

c) PC "A" runs the Wavefront Sensor application that sends the measurement data to the remote DataSocket server that is running on PC "B". An application on PC "B" retrieves the data.

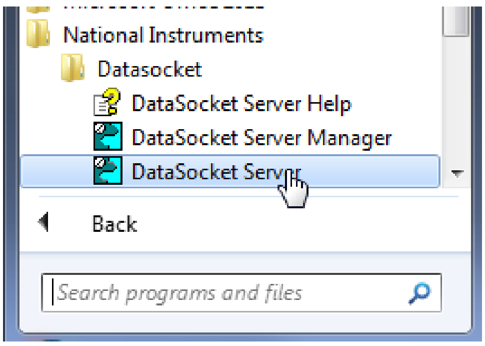
d) PC "A" runs the Wavefront Sensor application that sends the measurement data to a DataSocket server which is running on PC "B". An application on a third PC "C" retrieves the data from the DataSocket server on PC "B". All PCs are connected via a TCP/IP network.

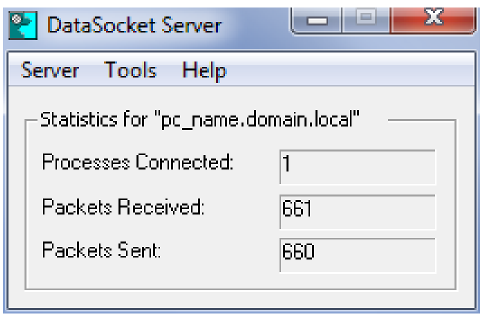
The following explanations are related to the National Instruments® DataSocket server. It comes with the WFS Series installation package. Originally, it is included in LabWindows/CVI® and LabView® packages or is available from the National Instruments® download website

http://digital.ni.com/public.nsf/allkb/40295802535E31B686256E91001859AB .

Starting the DataSocket server

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



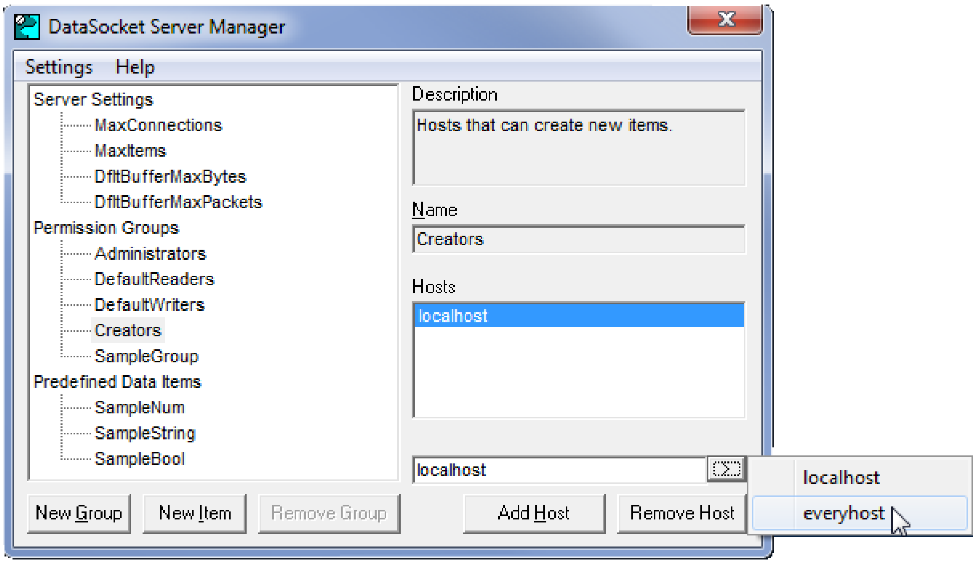


Even when the panel is closed, the server will remain active and is visible in the task bar.

DataSocket Server Configuration

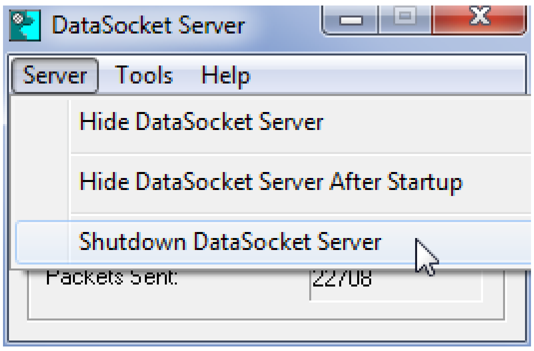
The DataSocket server needs to be configured for Wavefront Sensor data transfer to permit Read and Write access from the connected computers. In addition, the writer application, that is the PC operating the Wavefront Sensor, requires permissions as a creator of new data items.

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 then restart:



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.

5.6.1 Available Data Items

When '**Enable basic data**' is checked 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 are:

Data Item	Format	Unit / example
Instrument_Name	string	e.g. "WFS150-5C Wavefront Sensor"
Serial_Number	string	e.g. "M00224955"
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 are:

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

When '**Enable wavefront data**' is checked 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)

When '**Enable centroid data**' is checked 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

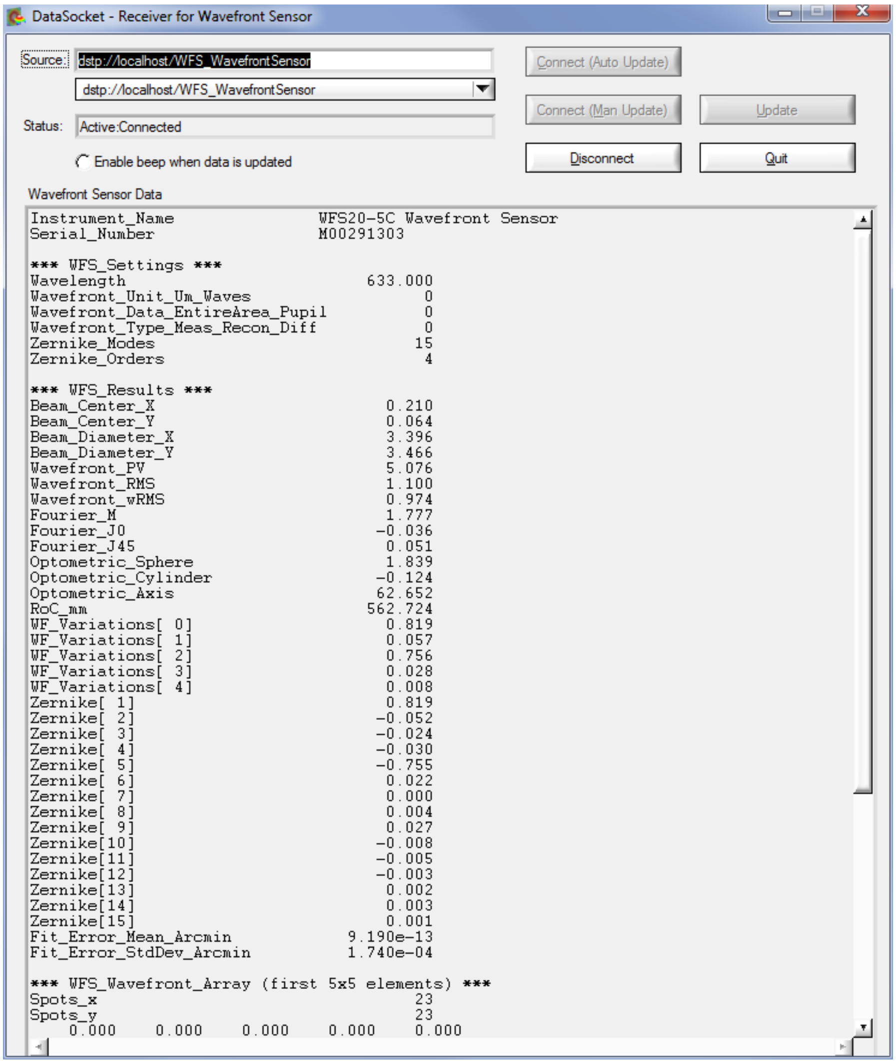
Format of Centroid_Pos_X and Centroid_Pos_Y data arrays were changed in software release 2.0 from double to float!

5.6.2 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 - Wavefrontsensor Receiver) or directly from it's location:

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

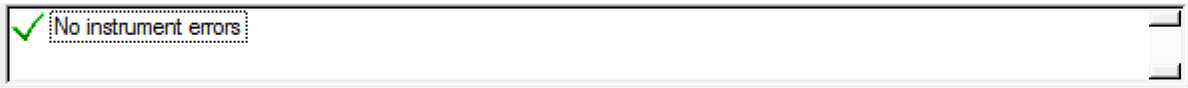
Below is a screen shot of this panel.



1. Connect to the same DataSocket server to where the Wavefront Sensor application sends the data.
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.

5.7 Measurement Warnings and Errors



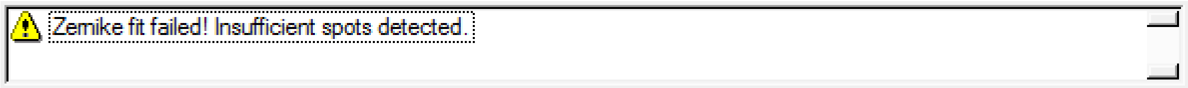
Status Bar

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.

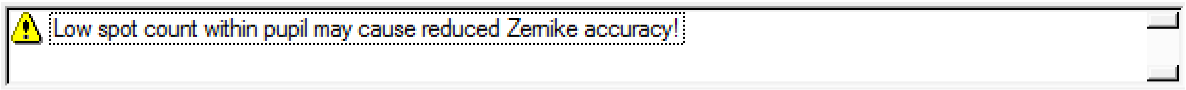


This error occurs if the number of detected spots within the pupil is lower than the number of Zernike modes to be calculated in the least square Zernike fit.

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 58 panel and/or
- Reduce the number of Zernike orders in the Zernike Fit 66 panel.
- Increase the camera resolution (Camera Settings 51) 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 58 panel) and/or
- Reduce the number of Zernike orders in the Zernike Fit 66 panel.
- Increase the camera resolution (Camera Settings 51) in case the pupil diameter is close to the image size

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

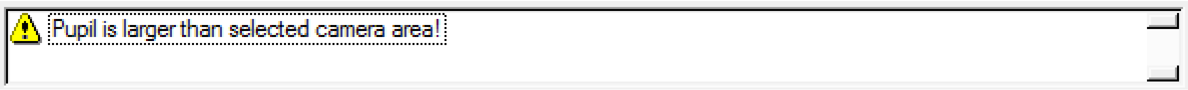
The pupil area is not properly filled with detected spots up to its full diameter. Because the number of detected spots is defined by the selected camera resolution, some visible spots at the border of each camera image remain undetected. The pupil dimension must not be larger than the detected spot 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 58 panel and/or
- Increase the camera resolution (Camera Settings 51)

Pupil is larger than selected camera area!

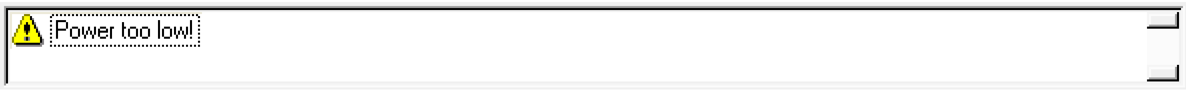


The pupil diameter exceeds the camera image dimensions so that parts of the pupil remain uncovered by detected spots.

To prevent this warning

- Reduce the pupil diameter Pupil Definitions 58 panel and/or
- Increase the camera resolution (Camera Settings 51) in case the pupil diameter is close to the image size.

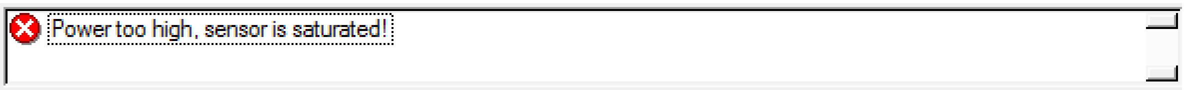
Power too low!



The detected spot intensity is too low, resulting in an incorrect analysis of the centroid positions. Check 'Exposure Time' and 'Gain' settings (Camera Settings 51). 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' 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.

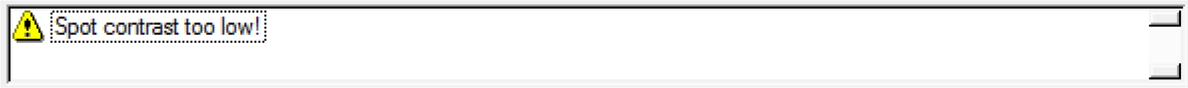
Power too high, sensor is saturated!



The detected spot intensity is too high, resulting in an incorrect analysis of the centroid positions. Check 'Exposure Time' and 'Gain' settings (Camera Settings 51). Change the manual setting or enable automatic control of these camera parameters.

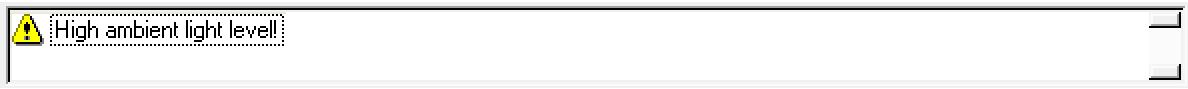
If this error occurs even with the lowest 'Exposure Time' and 'Gain' setting or if 'auto' is already enabled, the optical input power of the Wavefront Sensor is too high. Decrease the power of your light source or insert an attenuator (e.g., neutral density filter) in front of the Wavefront Sensor.

Spot contrast too low!



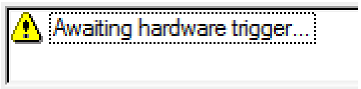
The camera image suffers from low contrast, i.e., the brightness difference between the spots and the ambient area is too low. This can be caused by manually entering an inappropriate exposure time (Camera Settings 51) or unwanted stray light entering the input aperture of the Wavefront Sensor. Shield the measurement beam path and the WFS input from stray light or increase the optical power of your light source.

High ambient light level!



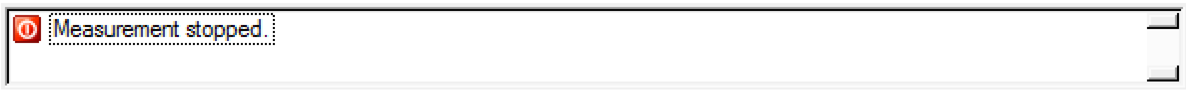
There is a high ambient light level entering the camera that decreases the contrast between the spot peaks and the dark areas in between. Shield the WFS input from ambient light or increase the optical power of your light source.

Awaiting hardware trigger...



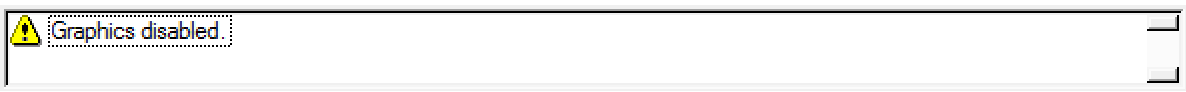
This status message indicates that no update of numerical and graphical measurement data is visible because the WFS trigger function was activated and no trigger event has occurred yet. Apply a trigger signal using the trigger cable (see Trigger Input 112 for details) or disable the hardware trigger in the Camera Settings 51.

Measurement stopped



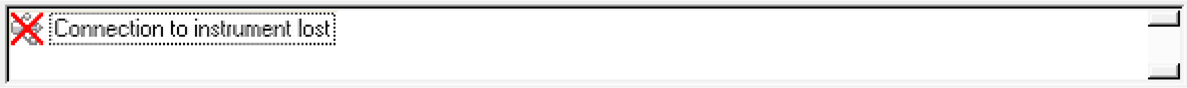
This status message indicates that the continuous measurement has been stopped either by the user or due to occurrence of another error. The displayed data and graphs do not show actual wavefront data.

Graphics disabled



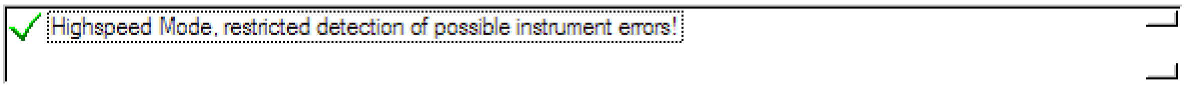
This status message notifies that all graphics and the numerical results have been disabled in order to speed up the sampling rate. See the setup menu Miscellaneous 68.

Connection to instrument lost



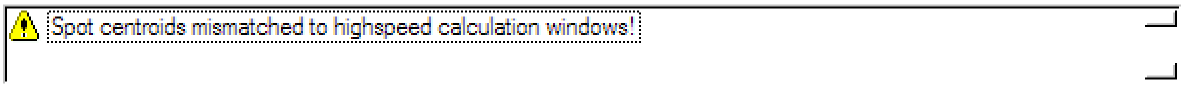
This status message indicates that a USB interface error occurred. Check the USB connection, then restart the Wavefront Sensor application again.

Additional errors in Highspeed Mode



This status message notifies about the risk of incorrect measurement results in Highspeed Mode due to restricted error detection capabilities. For instance, the image saturation level is not being 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 56' prior to entering Highspeed Mode to overcome this situation.

6 Write Your Own Application

Please note that there are **short sample application files with supplied source code for C and LabView** which should help you to understand the driver usage.

For a full documentation of the driver functions open **WFS.html** file or see text file WFS.txt.

In order to write your own application, you need a specific instrument driver and some tools for use in different programming environments. The driver and tools are included in the installer package and can be found on after installation on the PC.

In this section the location of drivers and files, required for programming in different environments, are given for installation under Windows Vista, Windows 7 and Windows 8.1 (32 and 64 bit)

Note

WFS Series 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 Beside that, 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 the information where the drivers are installed to, usually to `C:\Program Files\IVI Foundation\VISA\WinNT\`.

This is the reason, why after installation of a NI-VISA Runtime a system reboot is required: This environment variable is necessary for installation of the instrument driver software components.

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

6.1 32 bit Version

VXIpnp Instrument driver:

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

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

Online Help for NI VISA Instrument driver:

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

NI LabVIEW driver (including an example VI)

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

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

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`

.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\C`

`sample.c` - C program how to use the WFS driver functions
`sample.exe` - same, but executable

Example for C#

Solution file:

```
C:\Program Files\IVI Foundation\VISA\WinNT\WFS\...
...Examples\CSharp\ Thorlabs.WFS.Demo.sln
```

Project file

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

Executable sample demo

```
C:\Program Files\IVI Foundation\VISA\WinNT\WFS\...
...Examples\CSharp\WFS_CSharpDemo\bin\Release\WFS_CSharpDemo.exe
```

Example for LabView

Included in driver llb container.

6.2 64 bit Version

NI VISA Instrument driver 32bit on 64bit systems

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

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

Online Help for NI VISA Instrument driver:

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

NI LabVIEW driver (including an example VI)

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

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

Header file

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

Static Library

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

Function Panel

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

.net wrapper dll

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

Example for C

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

`sample.c` - C program how to use the WFS driver functions
`sample.exe` - same, but executable

Example for C#

Solution file:

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

Project file

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

Executable sample demo

```
C:\Program Files (x86)\IVI Foundation\VISA\WinNT\WFS\...
...Examples\CSharp\WFS_CSharpDemo\bin\Release\WFS_CSharpDemo.exe
```

Example for LabView

Included in driver llb container.

NI VISA Instrument driver 64bit on 64bit systems

`C:\Program Files\IVI Foundation\VISA\Win64\Bin\WFS_64.dll`

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

Online Help for NI VISA Instrument driver:

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

NI LabVIEW driver (including an example VI)

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

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

Header file

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

Static Library

`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`

.net wrapper dll

```
C:\Program Files (x86)\Microsoft.NET\Primary Interop Assemblies\...
...Thorlabs.WFS.Interop64.dll
```

Example for C

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

`sample.c` - C program how to use the WFS driver functions

`sample.exe` - 32bit executable of C sample program

Example for C#

Solution file (same as 32bit on 64bit systems):

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

Project file (same as 32bit on 64bit systems):

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

Executable sample demo (same as 32bit on 64bit systems):

```
C:\Program Files (x86)\IVI Foundation\VISA\WinNT\WFS\Examples\...
...CSharp\WFS_CSharpDemo\bin\Release\WFS_CSharpDemo.exe
```

Note

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

Example for LabView

Included in driver llb container.

7 Maintenance and Service

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

Attention

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

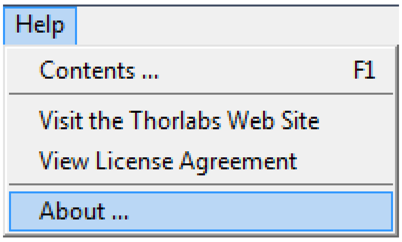
The unit does not need regular maintenance by the user. It does not contain any modules and/or components that can be repaired by the user. Remove dust only using compressed gas free of oil and water, for example Thorlabs GmbH Duster CA3 (Tetrafluoroetane). Keep the gas nozzle at least at a distance of 4 inches (10 cm) from the mirror surface, otherwise liquid gas drops may hit the surface and leave visible traces on the mirror surface.

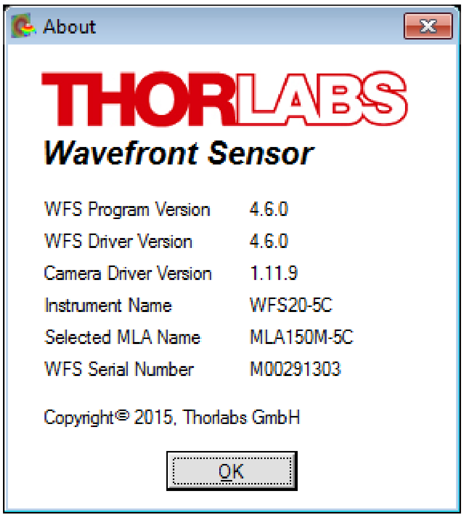
If a malfunction occurs, please contact Thorlabs GmbH 137 for return instructions.

Do not remove covers!

7.1 Version Information

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





7.2 Troubleshooting

- **No Wavefront Sensor found after start of wfs.exe**

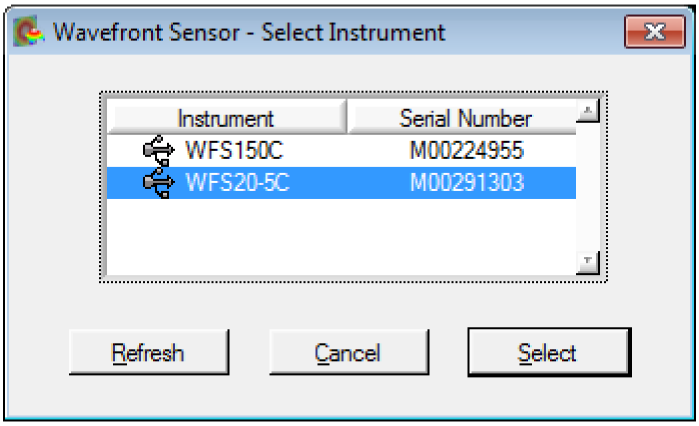
  Note

  If the Wavefront Sensor is actually 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. See also First Steps 23.

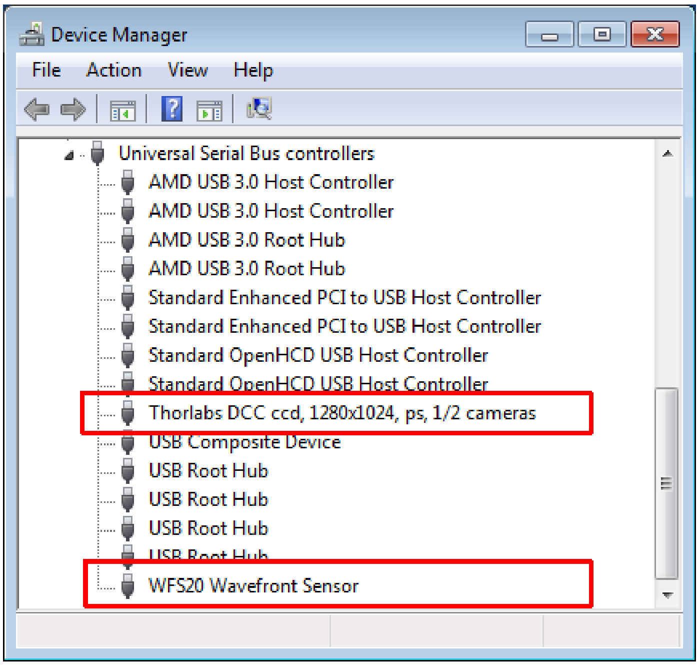
➢ Check if the Wavefront Sensor is connected to the USB 2.0 port of the PC using the included USB 2.0 cable. The LED 21 at the back of the Wavefront Sensor indicates the instrument state:

- LED = off	USB cable or USB port is defective
- LED = red	WFS150/300: Sensor is not recognized by the Windows system; install the Wavefront Sensor drivers (see Software Installation 14) WFS20: DC power supply is missing.
- LED = green	Wavefront Sensor is properly installed an can be used by the application program

- ➢ Was the WFS Series software installed completely?
- ➢ Be sure to have administrative rights on your computer that enable you to install software. Ask your system administrator to give you such rights or to do the installation himself.
- ➢ Click the 'Refresh' button on the 'Select Instrument' pop-up window. The system will take a few seconds to recognize the instrument.



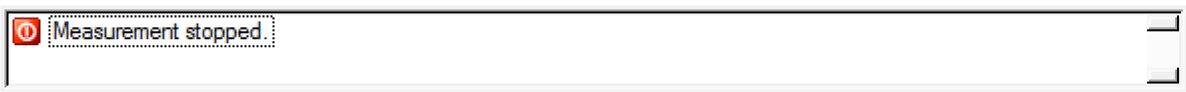
For verification purposes, check the USB controller branch of the Device Manager in the Control Panel. If properly installed, the WFS Series hardware appears in the list as shown on the next page:



The upper entry marks WFS150 / WFS 300 devices; see section First Steps 23.

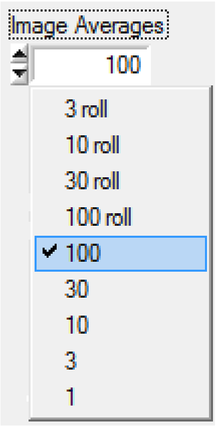
- **Displayed power values and graphs do not appear to have updated**

- ➢ 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



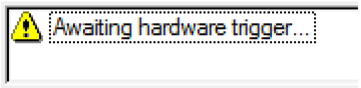
just start the measurement again by clicking on the menu 'Measurement → Start' or click the ▶ symbol in the toolbar or simply press 'F2'.

➢ 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 51 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 51 and see the Trigger Input 112 chapter for correctly applying a trigger signal.



- **The menu items, toolbar buttons, and setting values in the main panel are not reacting to your clicks**

➢ If there is a Wavefront Sensor popup window open, e.g. a 'Wavefront Sensor Message', the input will interact with this open popup window. Close any open popup windows to direct the input to the main panel.

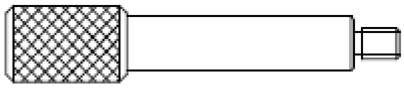
- **Erroneous or no measurement data**

➢ Check that the correct Microlens Array (MLA) is selected in the Wavefront Setup 63. You may have physically installed a different MLA than you selected within the WFS software.

7.3 Exchanging the Microlens Arrays

Thorlabs Wavefront Sensors WFS150-5C, WFS150-7AR, WFS300-14AR and WFS20-5C, WFS20-7AR, WFS20-14AR are equipped with exchangeable microlens arrays MLA150M-5C, MLA150M-7AR and MLA300M-14AR, respectively. Due to its patented precision magnetic holder, it is very easy to switch between different mounted MLAs. See chapter Parts List 12 for details.

A **Pickup Tool** is supplied with your WFS instrument if you have ordered it with more than one calibrated MLA or when you return your WFS instrument so that calibration data can be added for a second MLA.



Attention

If you wish to purchase an additional MLA, this can be done only by returning your WFS Series instrument to Thorlabs! Your wavefront sensor must be calibrated with the additional MLA; the calibration data are saved to the WFS internal memory.

MLA Exchange Instruction:

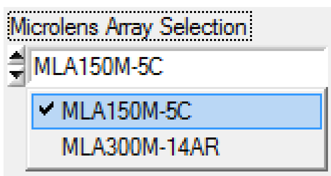
- Screw the pickup tool into the MLA that is currently mounted to the WFS.
- Pull out the MLA carefully from the aperture, avoid tilting!
- Unscrew the pickup tool from the extracted MLA.
- Stow the MLA away in a dust-proof box.
- Unpack the replacement MLA and screw in the pickup tool.
- Prior to installing 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 63.

Note

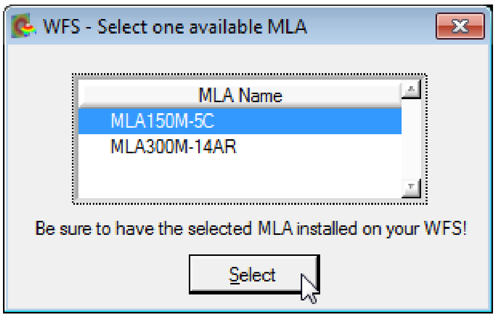
The type of the MLA that is installed in the sensor cannot be recognized by the software; it must be selected manually. Selecting the installed MLA is essential for correct wavefront measurements!

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 63:



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 :

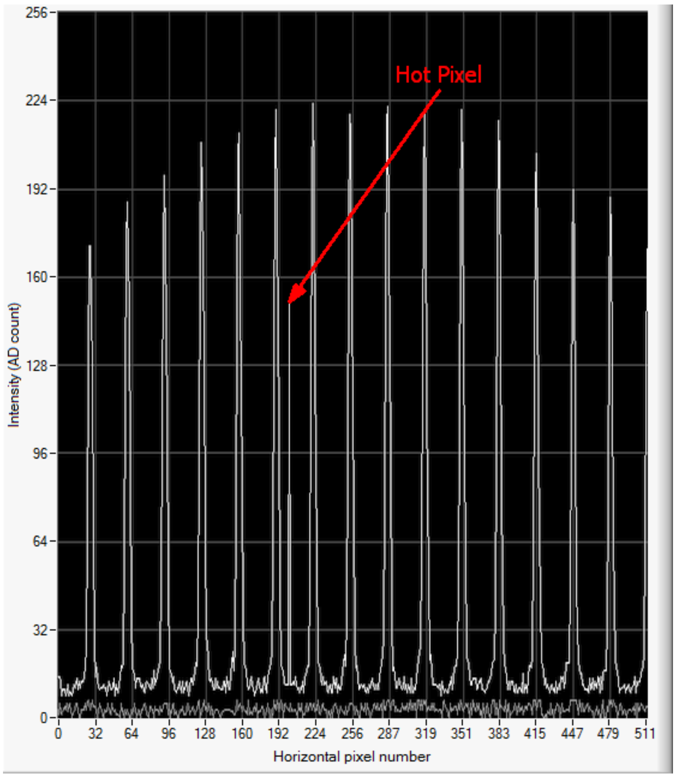


Attention

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

7.4 Hot Pixel

In digital imaging, defective pixels that show an intensity that is not proportional to the incident light, are called **hot pixels**. Such pixels appear often brighter than ambient 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

Thorlabs GmbH WFS Series are based on cameras that come with an embedded hot pixel correction. 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 137 for return instructions.

The CMOS camera used for the WFS20 series is much faster than the CCD based WFS150/300, but shows a higher noise level and less image uniformity. In addition, 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 reason for return.

8 Appendix

In this section:

8.1 Technical Data

8.1.1 WFS150/300

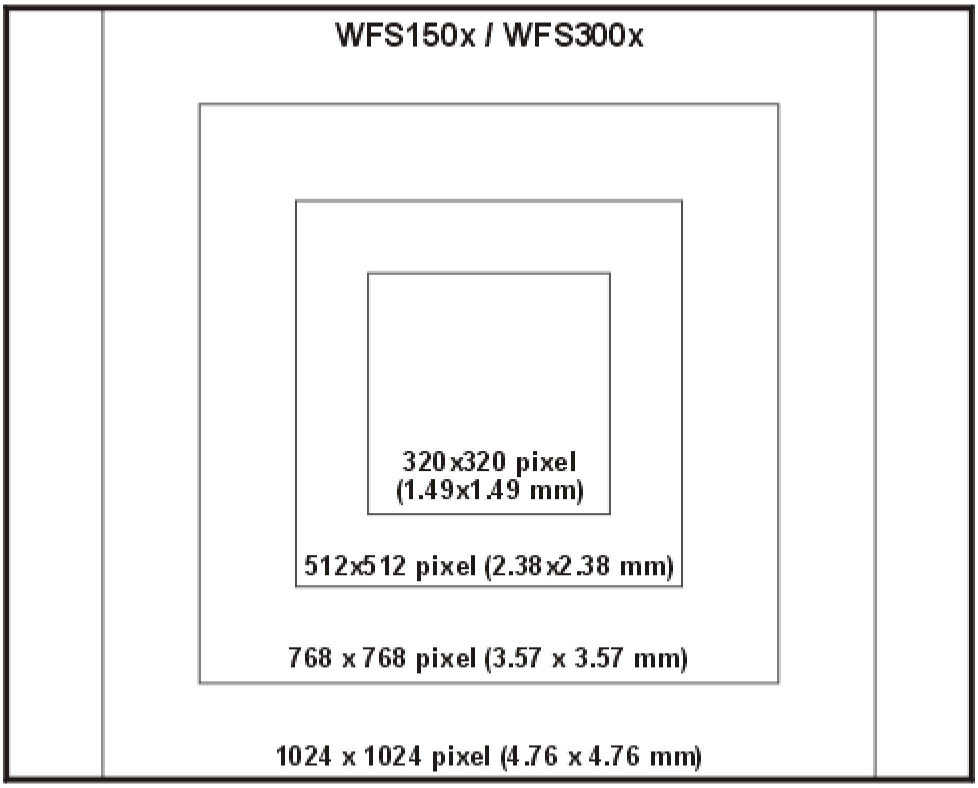
Item #	WFS150-5C	WFS150-7AR	WFS300-14AR
Microlenses			
Microlens Array	MLA150M-5C	MLA150M-7AR	MLA300M-14AR
Substrate Material	Fused Silica (Quartz)		
Number of Active Lenslets	Software Selectable		
Max. Number of Lenslets	39 x 31		19 x 15
Camera			
Sensor Type	CCD		
Resolution	max. 1280 x 1024 pixels, Software Selectable		
Aperture Size	5.95 mm x 4.76 mm		
Pixel Size	4.65 µm x 4.65 µm		
Shutter	Global		
Exposure Range	79 µs - 65 ms		
Frame Rate	max. 15 Hz		
Image Digitization	8 bit		
Wavefront Measurement			
Wavefront Accuracy [1])	λ/15 rms @ 633 nm		λ/50 rms @ 633 nm
Wavefront Sensitivity [2])	λ/50 rms @ 633 nm		λ/150 rms @ 633 nm
Wavefront Dynamic Range [3])	> 100 λ @ 633 nm		> 50 λ @ 633 nm
Local Wavefront Curvature [4])	> 7.4 mm	> 10.0 mm	> 40.0 mm
External Trigger Input			
Save 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	> 10 mA		
Min Pulse Width	100 µs		
Min. Slew Rate	35 V / msec		
Common Specifications			
Optical Input	C-Mount		
Power Supply	<1.5 W, via USB		
Operating Temperature Range [5])	+5 to +35 °C		
Storage Temperature Range	-40 to 70 °C		
Warm-Up Time for Rated Accuracy	15 min		
Dimensions (W x H x D)	32.0 mm x 40.4 mm x 45.5 mm		
Weight	0.1 kg		

[1]) Absolute accuracy using internal reference. Measured for spherical wavefronts of known RoC.
[2]) Typical relative accuracy. Achievable after, and with respect to a user calibration, 10 image averages
[3]) Over entire aperture of wavefront sensor
[4]) Radius of wavefront curvature over single lenslet aperture
[5]) non-condensing

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

See MLA Microlens Arrays 108 for detailed specifications of the supplied mounted Microlens Arrays.

Selectable camera image sizes for WFS150 / WFS 300



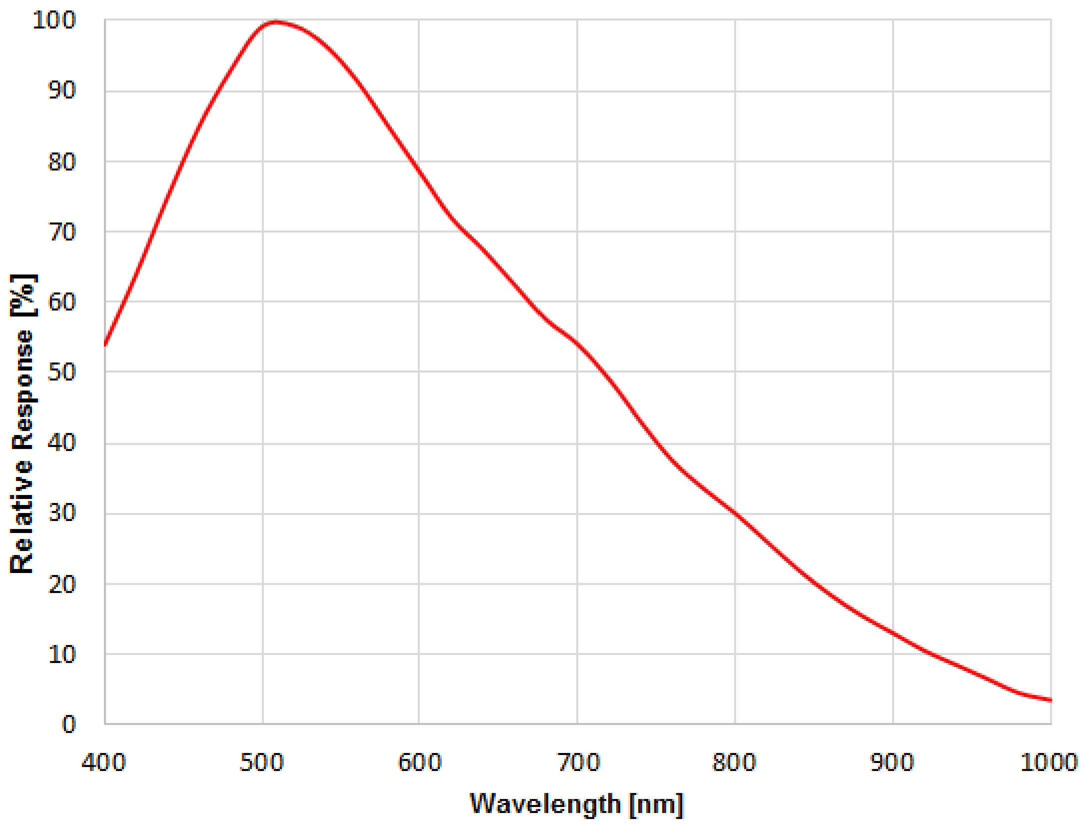
Full size: 1280 x 1024 pixel (5.95 x 4.76 mm)

Camera Resolution and Spot Count

The resolution of the Wavefront Sensor, that is the number of the calculated microlens spots, depends on the selected camera resolution. The table below shows details:

	WFS150-5C, WFS150-7AR (150 µm MLA Lens Pitch)		WFS300-14AR (300 µm MLA Lens Pitch)	
Resolution	Spots	Spot count	Spots	Spot count
1280 x 1024	37 x 29	1073	17 x 13	221
1024 x 1024	29 x 29	841	13 x13	169
768 x 768	21 x 21	441	9 x 9	81
512 x 512	13 x 13	169	5 x 5	25
320 x 320	7 x 7	49	3 x 3	9

Typical Wavelength Response



Typical Wavelength Response of the WFS150/300 CCD camera

8.1.2 WFS20

Item #	WFS20-5C	WFS20-7AR	WFS20-14AR
Microlenses			
Microlens Array	MLA150M-5C	MLA150M-7AR	MLA300M-14AR
Substrate Material	Fused Silica (Quartz)		
Number of Active Lenslets	Software Selectable		
Max. Number of Lenslets	47 x 35		23 x 17
Camera Specifications			
Sensor Type	CMOS		
Resolution	max. 1440 x 1080 pix., Software selectable		
Aperture Size	7.20 mm x 5.40 mm		
Pixel Size	5.0 µm x 5.0 µm		
Shutter	Global [1])		
Exposure Range	4 µs - 83.3 ms		
Frame Rate at 1080 x 1080, 2x Binning, Normal Mode [2]) at 1080 x 1080, High Speed Mode [2]) at 360 x 360 [2])	 69 Hz 166 Hz 880 Hz		 123 Hz 226 Hz 1120 Hz
Image Digitization	8 bit		
Wavefront Measurement			
Wavefront Accuracy [3])	λ/30 rms @ 633 nm		λ/60 rms @ 633 nm
Wavefront Sensitivity [4])	λ/100 rms @ 633 nm		λ/200 rms @ 633 nm
Wavefront Dynamic Range [5])	> 100 λ @ 633 nm		> 50 λ @ 633 nm
Wavefront Slope [6])	± 1.0 °	± 0.8 °	± 0.5 °
Local Wavefront Curvature [7])	> 7.4 mm	> 10.0 mm	> 40.0 mm
External Trigger Input Specifications			
Trigger Slope	Software Selectable; H -> L or L -> H		
Save Input Voltage Range	-0.5 to 6.5 V		
Maximum LOW Level	1.5 V		
Minimum HIGH Level	3.5 V		
Input Impedance	> 100 kΩ		
Min. Pulse Width	10 µs		
Min. Slew Rate	5 ns/V		
Common Specifications			
Optical Input	C-Mount		
Power Supply	external; 12 V DC, 1.5 A		
Operating Temperature Range [8])	+5 to +35 °C		
Storage Temperature Range	-40 to 70 °C		
Warm-Up Time for Rated Accuracy	15 min		
Dimensions (W x H x D) Camera Head Control Box	 56.0 mm x 46.0 mm x 28.3 mm 57.0 mm x 27.5 mm x 95.6 mm		

Item #	WFS20-5C	WFS20-7AR	WFS20-14AR
Weight Camera Head Control Box	 0.13 kg 0.24 kg		

[1]) A global shutter exposes the entire detector at one time.
[2]) Typical speed without graphical display, depending on PC hardware, 4th order Zernike fit at specific camera resolution, min. exposure time. Normal Mode performs image processing on the PC, while High-Speed Mode uses the internal camera processor.
[3]) Absolute accuracy using internal reference. Measured in Normal Mode for spherical wavefronts of known RoC.
[4]) Typical relative accuracy with respect to a reference wavefront (user calibration). Reference and each measurement values are averaged over 10 frames in Normal Mode.
[5]) Over entire aperture of wavefront sensor, Normal Mode.
[6]) Maximum local wavefront slope in high speed mode.
[7]) Radius of wavefront curvature over single lenslet aperture.
[8]) non-condensing

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

See MLA Microlens Arrays 108 for detailed specifications of the supplied mounted Microlens Arrays.

Selectable camera image sizes for WFS20

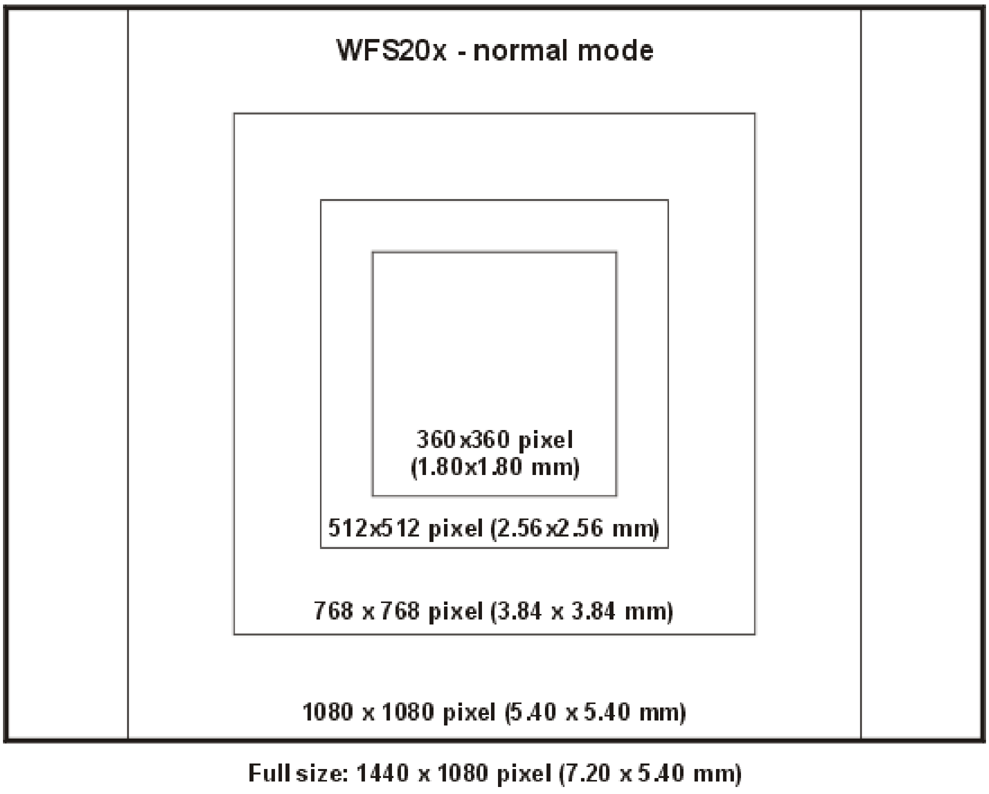


Image Sizes WFS20x (Normal Mode)

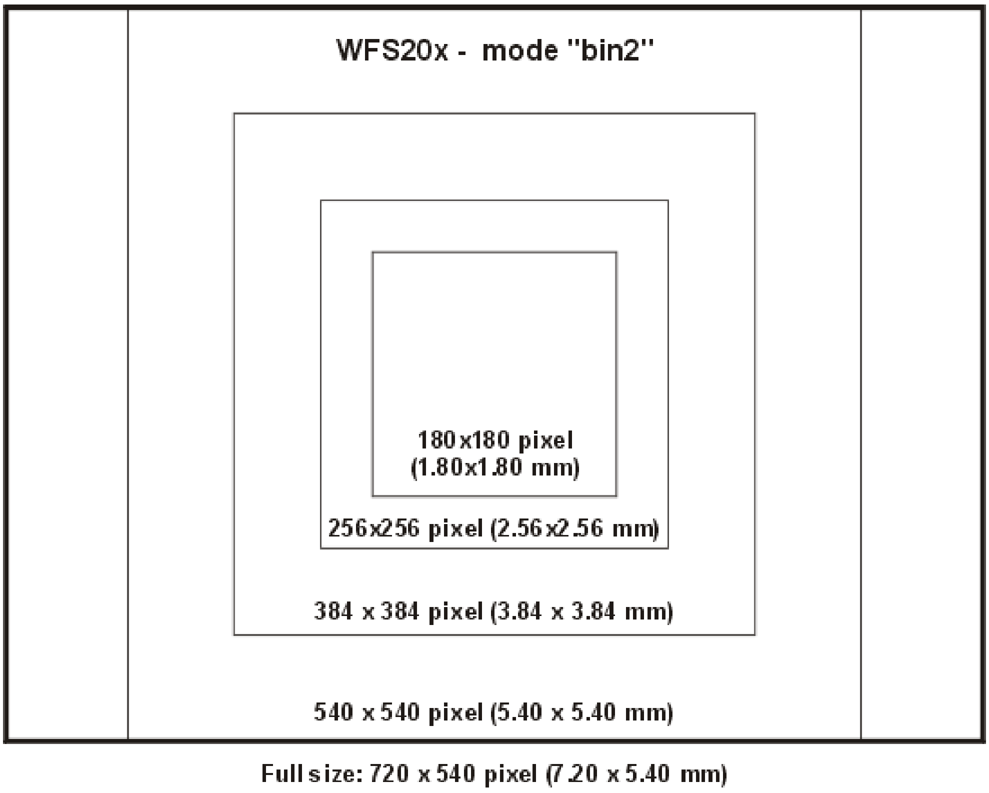
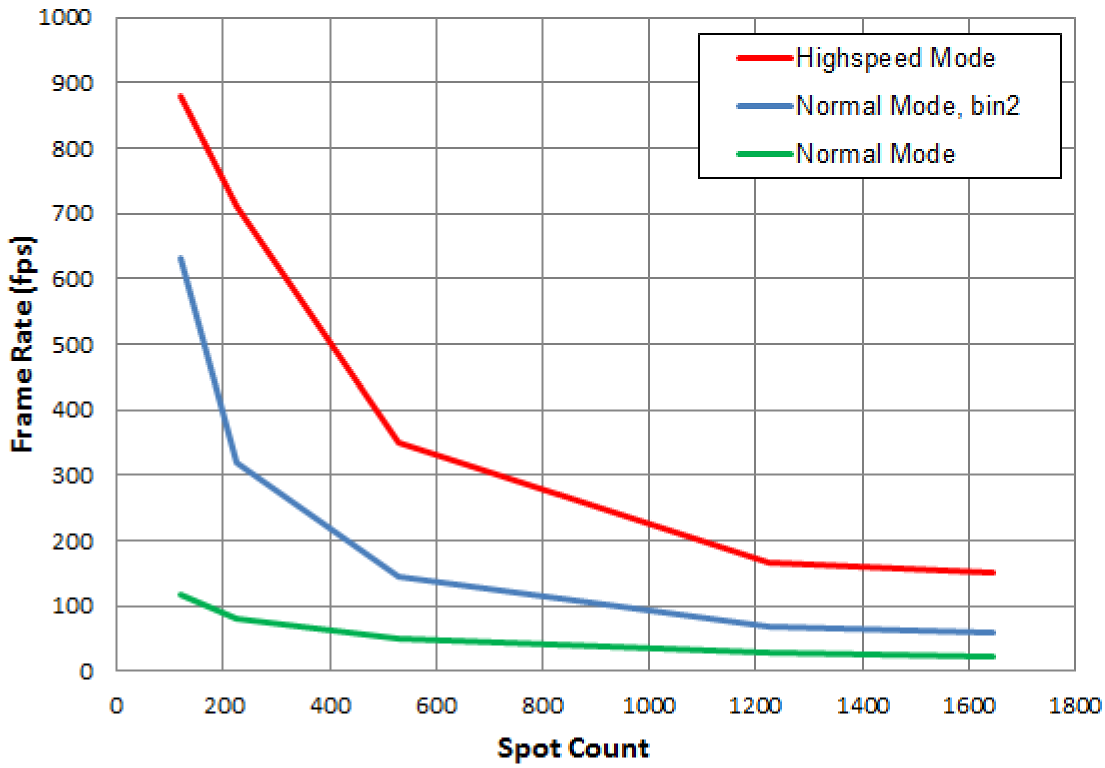


Image Sizes WFS20x (bin2 Mode)

Camera Resolution and Spot Count

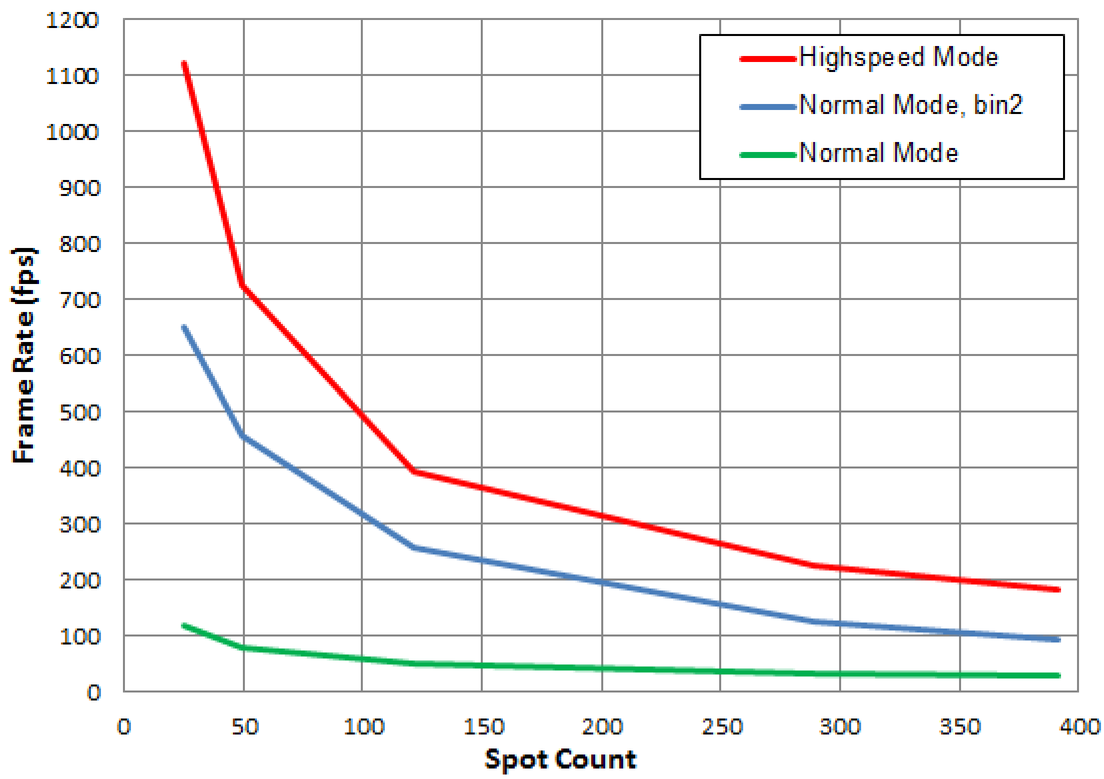
The resolution of the Wavefront Sensor, that is the number of the calculated microlens spots, depends on the selected camera resolution. Further, the WFS20 instrument offers a binning mode ("bin2"). In this mode 2x2 pixels are combined and averaged. The result is an increased frame rate with the trade-off of reduced spatial wavefront resolution. The tables below illustrates this:

WFS20-5C, WFS20-7AR (150 µm MLA Lens Pitch)					
Resolution	Spots	Spot count	Speed in fps		
			Normal Mode	Normal Mode, bin2	Highspeed Mode
1440 x 1080	47 x 35	1645	23	58	150
1080 x 1080	35 x 35	1225	29	69	166
768 x 768	23 x 23	529	50	144	350
512 x 512	15 x 15	225	79	320	710
360 x 360	11 x 11	121	116	630	880



WFS20-5C and WFS20-7AR Measurement Speed vs. Spot Count

WFS20-14AR (300 µm MLA Lens Pitch)					
Resolution	Spots	Spot count	Speed in fps		
			Normal Mode	Normal Mode, bin2	Highspeed Mode
1440 x 1080	23 x 17	391	28	92	183
1080 x 1080	17 x 17	289	33	123	226
768 x 768	11 x 11	121	50	258	394
512 x 512	7 x 7	49	79	450	725
360 x 360	5 x 5	25	116	648	1120



WFS20-14AR Measurement Speed vs. Spot Count

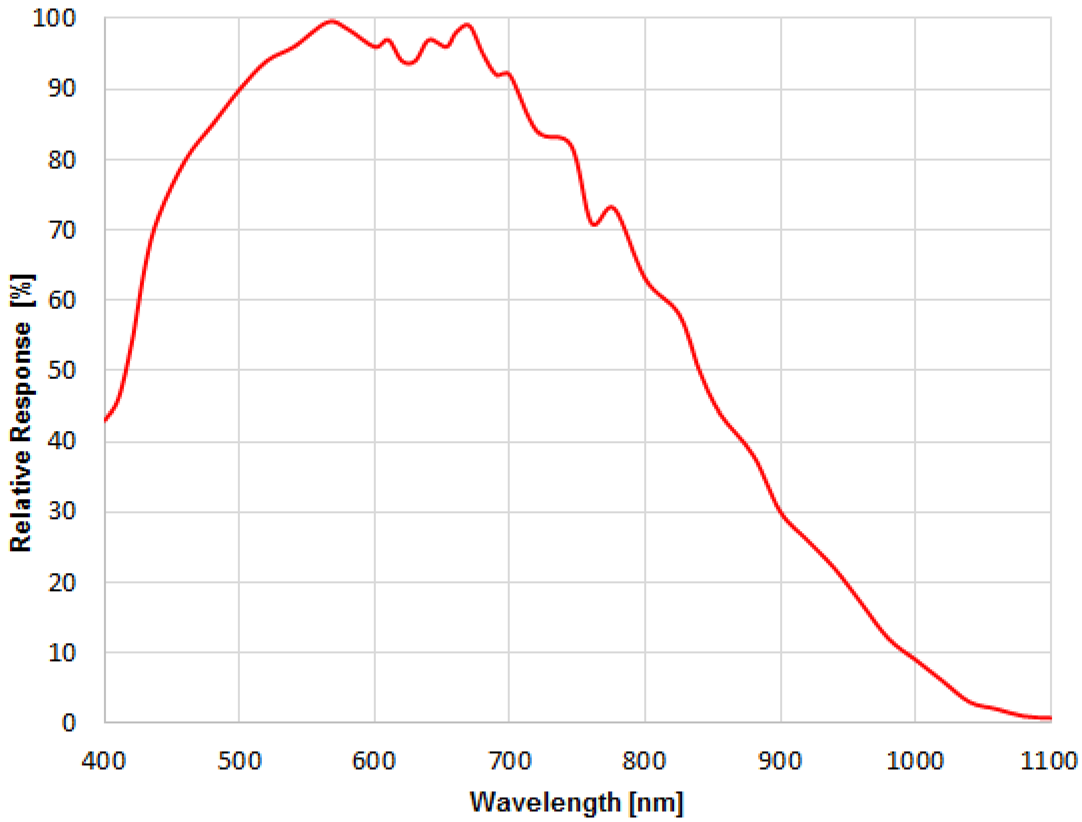
Note

Above frame rate measurements were executed on a PC with Intel Xeon 2.5 GHz, Dual Core CPU, Win 7 64 bit under the following measurement conditions:

1. Camera settings
   - in normal mode, Auto Noise Cut enabled
   - min. exposure time, set manually
2. Pupil Definition
   - pupil size close to active sensor area
3. Zernike Fit
   - 4th order Zernike fit (15 modes)
4. Miscellaneous
   - disable graphics and extra data calculation

Disable the DataSocket interface, as this slows down the measurement speed dramatically!

Typical Wavelength Response



Typical Response of the WFS20 CMOS camera

8.1.3 MLA Microlens Arrays

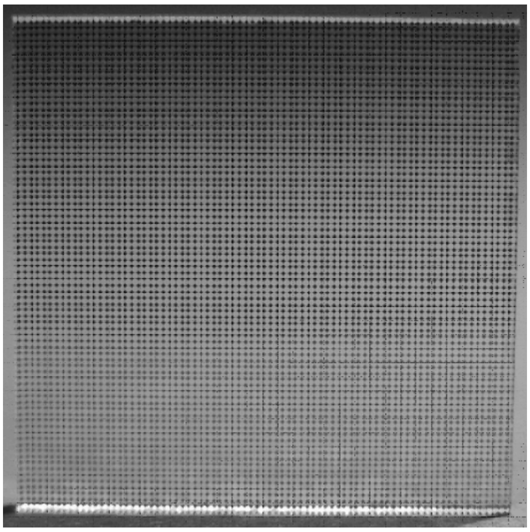
The WFS Series uses high-quality microlens arrays which are best suited for Shack-Hartmann Wavefront Sensor applications. All lenslets are made from fused silica for excellent transmission characteristics from the deep UV to IR and have a plano-convex shape that allows nearly refraction limited spots.

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.

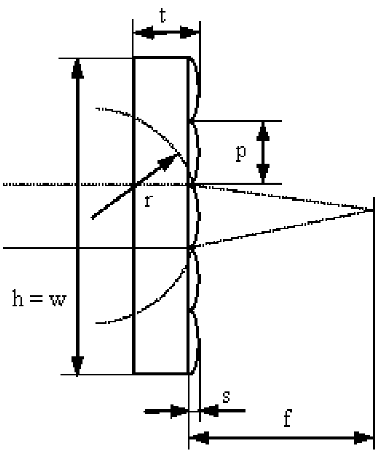
The three Wavefront Sensor models WFS150-5C, WFS150-7AR, WFS300-14AR and the corresponding fast models WFS20-5C, WFS20-7AR, WFS20-14AR utilize the mounted (M) microlens arrays MLA150M-5C, MLA150M-7AR and MLA300M-14AR, respectively.

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

Microlens Array MLA150-5C (without mounting)



Geometric Parameters of the MLA Series (without mounting)



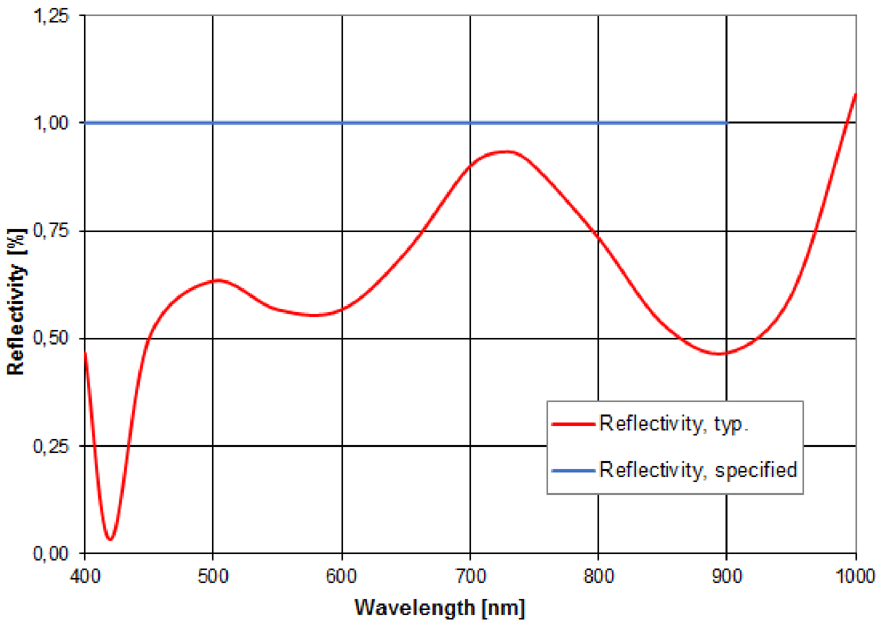
Parameter	MLA150-5C	MLA150-7AR	MLA300-14AR
h = w	10.0 mm		
t	1.24 mm	1.19 mm	1.20 mm
p	150 µm		300 µm
s	1.12 µm	0.87 µm	1.31 µm
r	2.380 mm	3.063 mm	8.600 mm
f	5.2 mm	6.7 mm	18.6 mm

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	Ø 9 mm		
Lenslet Grid Type	Square Grid		
Lenslet Pitch	150 µm		300 µm
Lens Shape	Round, Plano Convex Spherical		Square, Plano Convex Parabolic
Lens Diameter	146 µm		300 µm
Coating	Chrome Mask	Anti Reflection	
Reflectivity	< 25 %	< 1 %	
Nominal Focal Length	5.2 mm	6.7 mm	18.6mm
Effective Focal Length	3.7 mm	5.2 mm	14.2 mm
Array Size	10 mm x 10 mm x 1.2 mm		

The WFS150-7AR, WFS300-14AR, WFS20-7AR, and WFS20-14AR 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

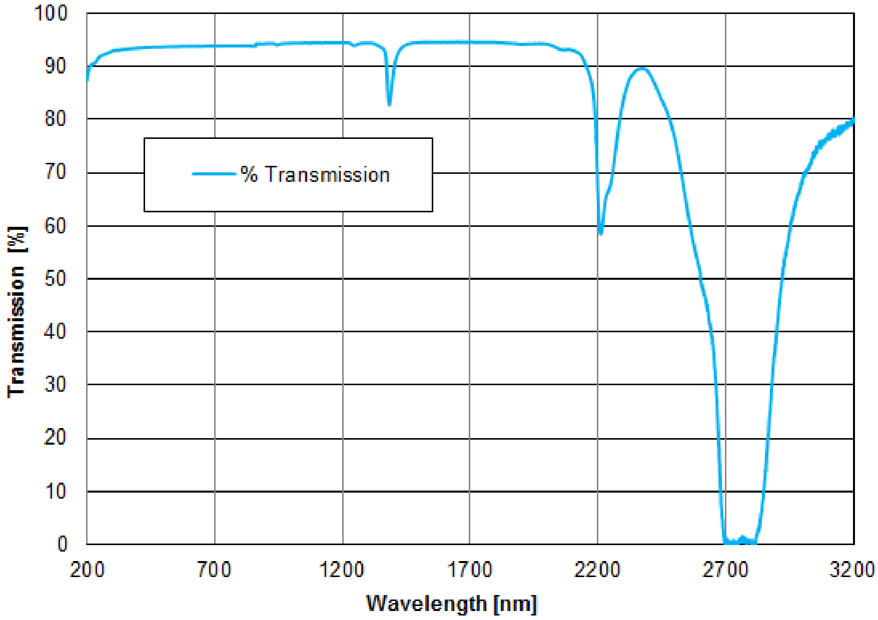


Reflectivity of MLA150-7AR and MLA300-14AR (including AR - Coating)

Note

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

Transmission

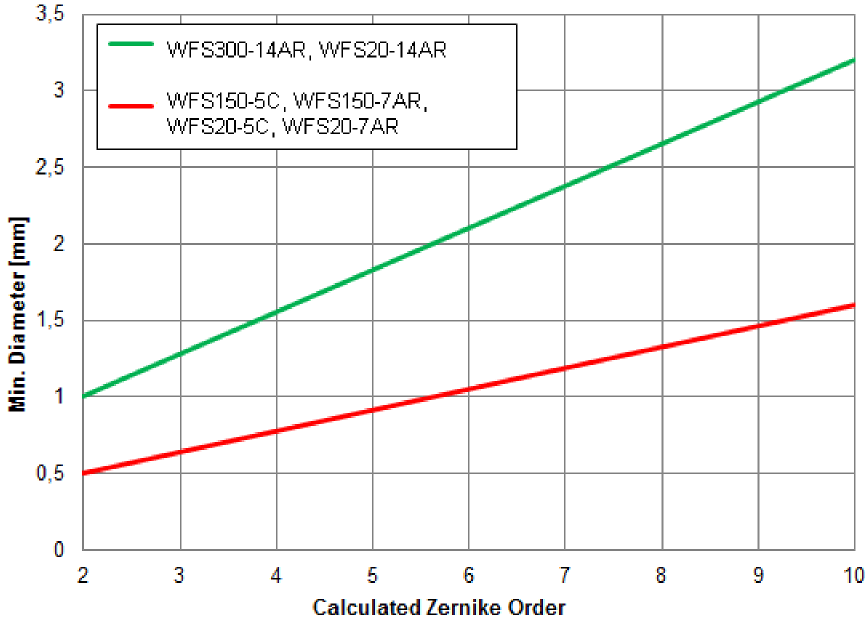


Typical Transmission of Fused Silica Material

8.2 Minimal Beam and Pupil Diameter

The detection of higher order wavefront terms up to a certain Zernike order requires a minimum number of detected microlens spots. The minimum number of spots must equal or exceed the number of Zernike modes to be calculated. See chapter Zernike Fit and Zernike Modes 115.

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

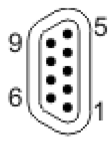
For a desired Zernike order, you need to set the pupil to the required diameter within the Pupil Definitions Setup 58. Also, your physical beam diameter needs to illuminate at least the same camera area so that the required number of spots can be detected.

In case of unfavorable pupil settings, warnings or errors may occur. See chapter Measurement Warnings and Errors 84 for a detailed description and suited arrangements for its prevention.

8.3 Trigger Input WFS150 / WFS300

The WFS150 and WFS300 model cameras come with an additional I/O input at the rear side of the camera housing that combines the USB interface with the trigger input:

Pin	Description
1	Digital output (-)
2	Digital input (+)
3	Shielding
4	USB power supply (VCC) 5 V
5	USB ground (GND)
6	Digital output (+)
7	Digital input (-)
8	USB data (+)
9	USB data (-)



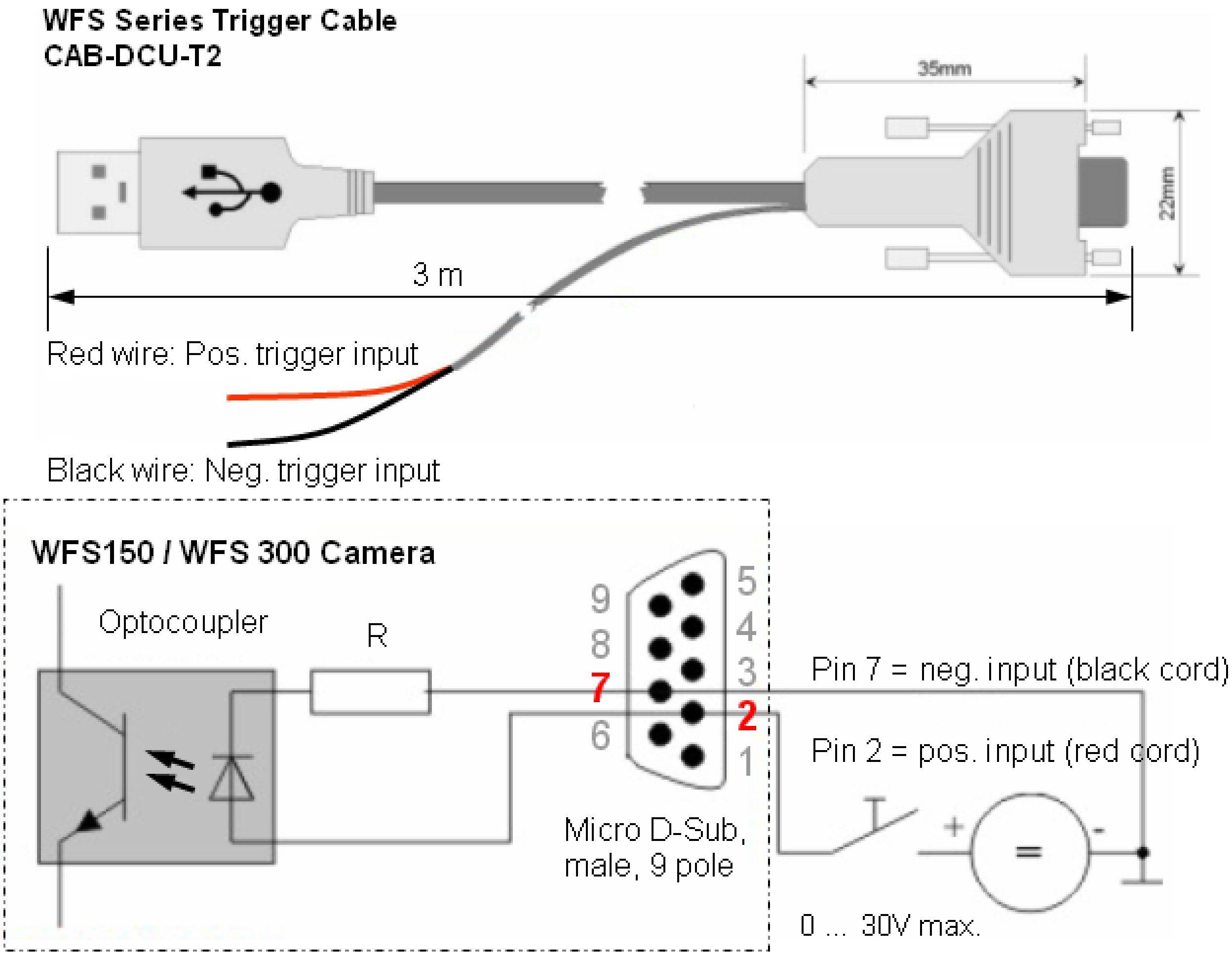
Micro D-Sub socket male, camera rear view

To use the trigger input replace the standard USB cable supplied with the WFS instrument with the optional **CAB-DCU-T2.** This cable consists of a USB connector to plug into the PC and the trigger input (open leads) and must be connected to the Micro-D-Sub jack **I/O**.

Attention

- Do not operate the WFS instrument with both USB cables connected. You may damage the Wavefront Sensor and your computer!
- Please see the External Trigger Input specifications 102 for the allowed voltage level in order to avoid damages!

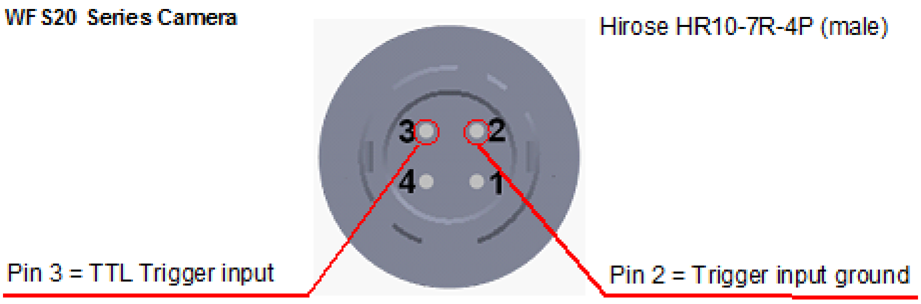
Apply the external trigger signal using the supplied trigger cable CAB-DCU-T2 as shown in the following sketch:



WFS Series Trigger Cable
CAB-DCU-T2
35mm
22mm
3 m
Red wire: Pos. trigger input
Black wire: Neg. trigger input
WFS150 / WFS 300 Camera
Optocoupler
R
9
8
7
6
5
4
3
2
1
Pin 7 = neg. input (black cord)
Pin 2 = pos. input (red cord)
Micro D-Sub,
male, 9 pole
+
=
-
0 ... 30V max.

8.4 Trigger Input WFS20

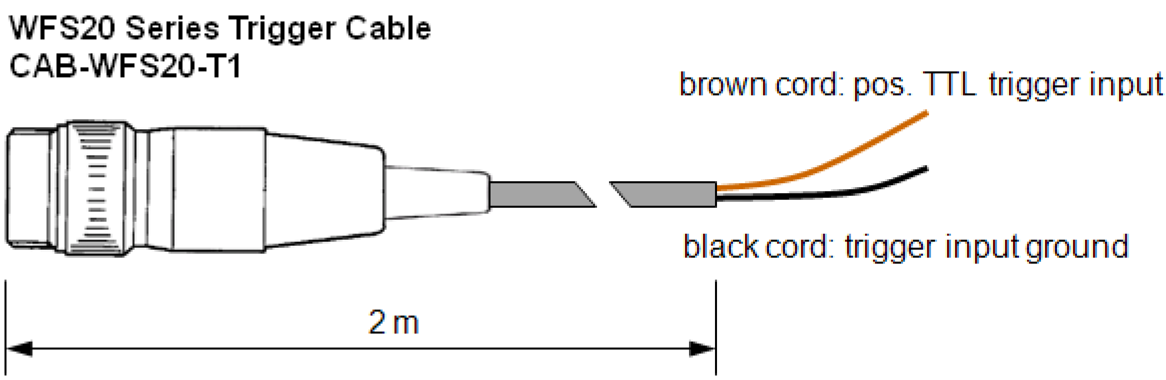
The external trigger input is located at the rear side of the control box, between the USB and power connector:



Attention

Please see the External Trigger Input specifications 102 for the allowed voltage level in order to avoid damages!

Apply the external trigger signal using the supplied trigger cable CAB-WFS20-T1 as shown below:



8.5 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*, see literature [1] 137.

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, whereas 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
$\lvert m \rvert \leq n$	Angular frequency
$\rho \leq 1$	normalized radial coordinate
θ (0 .. 2π)	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 radial and cartesian coordinates of order 0 - 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	$\sqrt{10}$	$\rho^4*\cos(4\theta)$

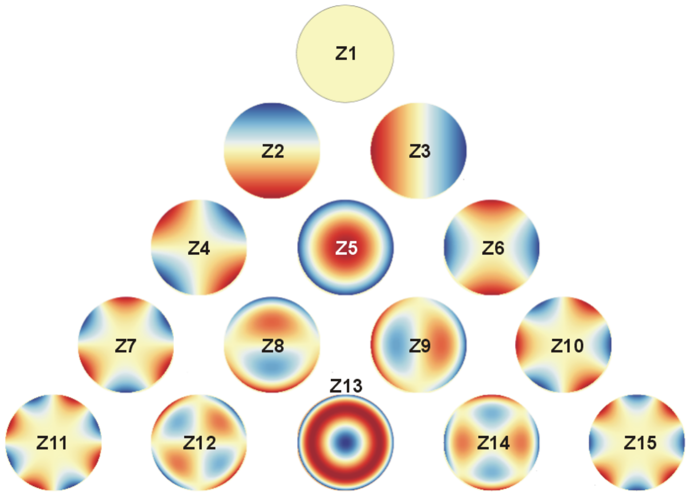
Mode	Order	Frequency	Name	Norm	Zernike Polynomial, Cartesian
1	0	0	Piston	1	1
2	1	-1	Tip Y	2	y
3	1	+1	Tilt X	2	x
4	2	-2	Astigmatism ± 45°	$\sqrt{6}$	$2xy$
5	2	0	Defocus	$\sqrt{3}$	$2x^2 + 2y^2 -1$
6	2	+2	Astigmatism 0° / 90°	$\sqrt{6}$	$x^2 - y^2$
7	3	-3	Trefoil Y	$\sqrt{8}$	$3x^2y -y^3$
8	3	-1	Coma X	$\sqrt{8}$	$3x^2y + 3y^3 - 2y$
9	3	+1	Coma Y	$\sqrt{8}$	$3x^3 + 3xy^2 - 2x$
10	3	+3	Trefoil x	$\sqrt{8}$	$x^3 - 3xy^2$
11	4	-4	Tetrafoil Y	$\sqrt{10}$	$4x^3y - 4xy^3$
12	4	-2	Sec. Astig. Y	$\sqrt{10}$	$8x^3y + 8xy^3 - 6xy$
13	4	0	Spher. Aberr. 3	$\sqrt{5}$	$6x^4 + 12x^2y^2 + 6y^4 - 6x^2 - 6y^2 +1$
14	4	+2	Sec. Astig. X	$\sqrt{10}$	$4x^4 - 4y^4 - 3x^2 + 3y^2$
15	4	+4	Tetrafoil X	$\sqrt{10}$	$x^4 - 6x^2y^2 + y^4$

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).

Zernikes and Optical Abberations

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



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	ComX	Coma X
Z 9	ComY	Coma Y
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

8.6 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:

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

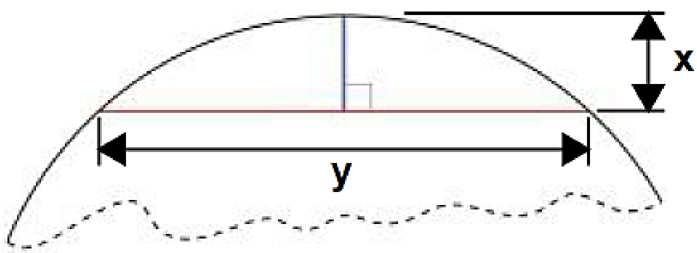
Since the normalized radial coordinate ρ ranges from 0 to 1 and the spherical shape achieves its minimum and maximum wavefront deviation at these points, the PV value is just the difference

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

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

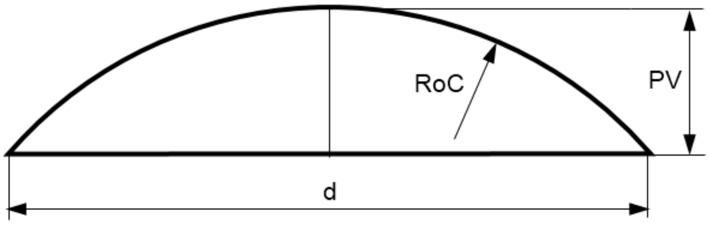
Q2: What Radius of Curvature (RoC) is related to this spherical wavefront when measured at a pupil diameter of d = 3 mm?

A2: To convert the PV value into a RoC result, a standard mathematimatical circle function is used. In literature [2] 137 under 'Sagitta' the following formula is given:



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

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:

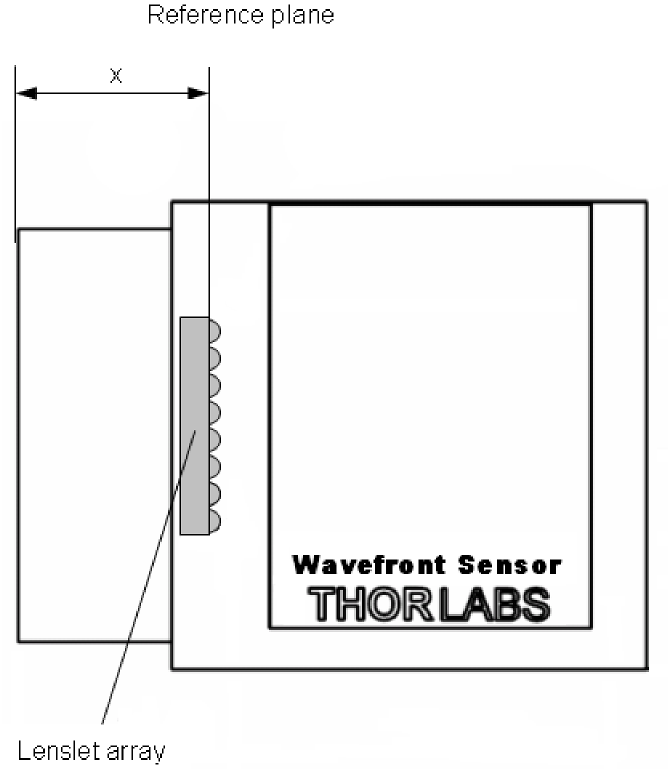
$$RoC \approx \frac{d^2}{8PV}$$

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

8.7 Drawings

8.7.1 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 WFS Series models and used MLA.

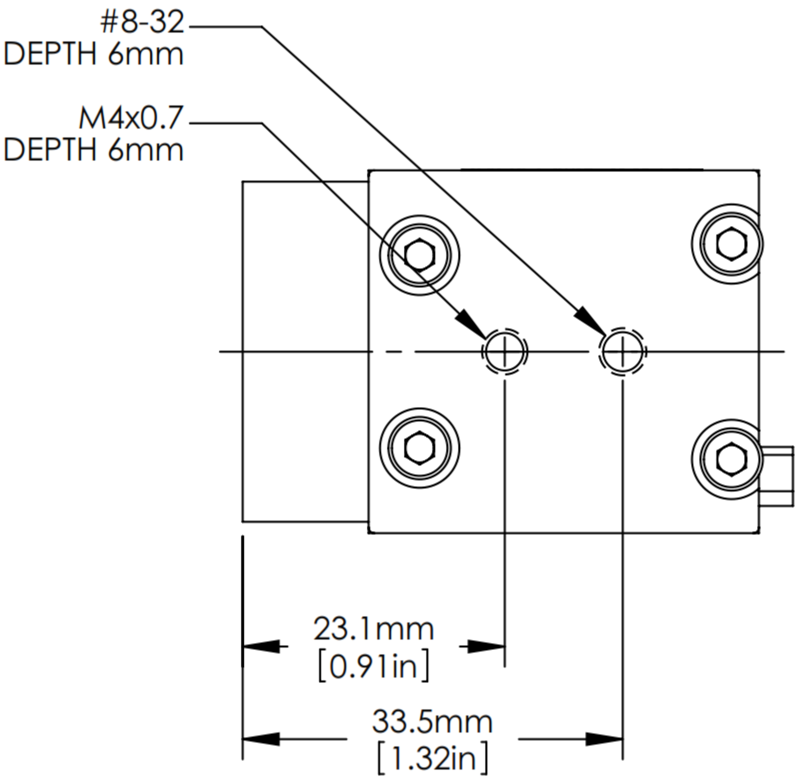


Model	Reference Plane - Distance "x"
WFS150-5C	14.2 mm
WFS150-7AR	13.0 mm
WFS300-14AR	3.6 mm
WFS20-5C	13.4 mm
WFS20-7AR	12.2 mm
WFS20-14AR	2.8 mm

8.7.2 Mounting Adapter WFS150/300

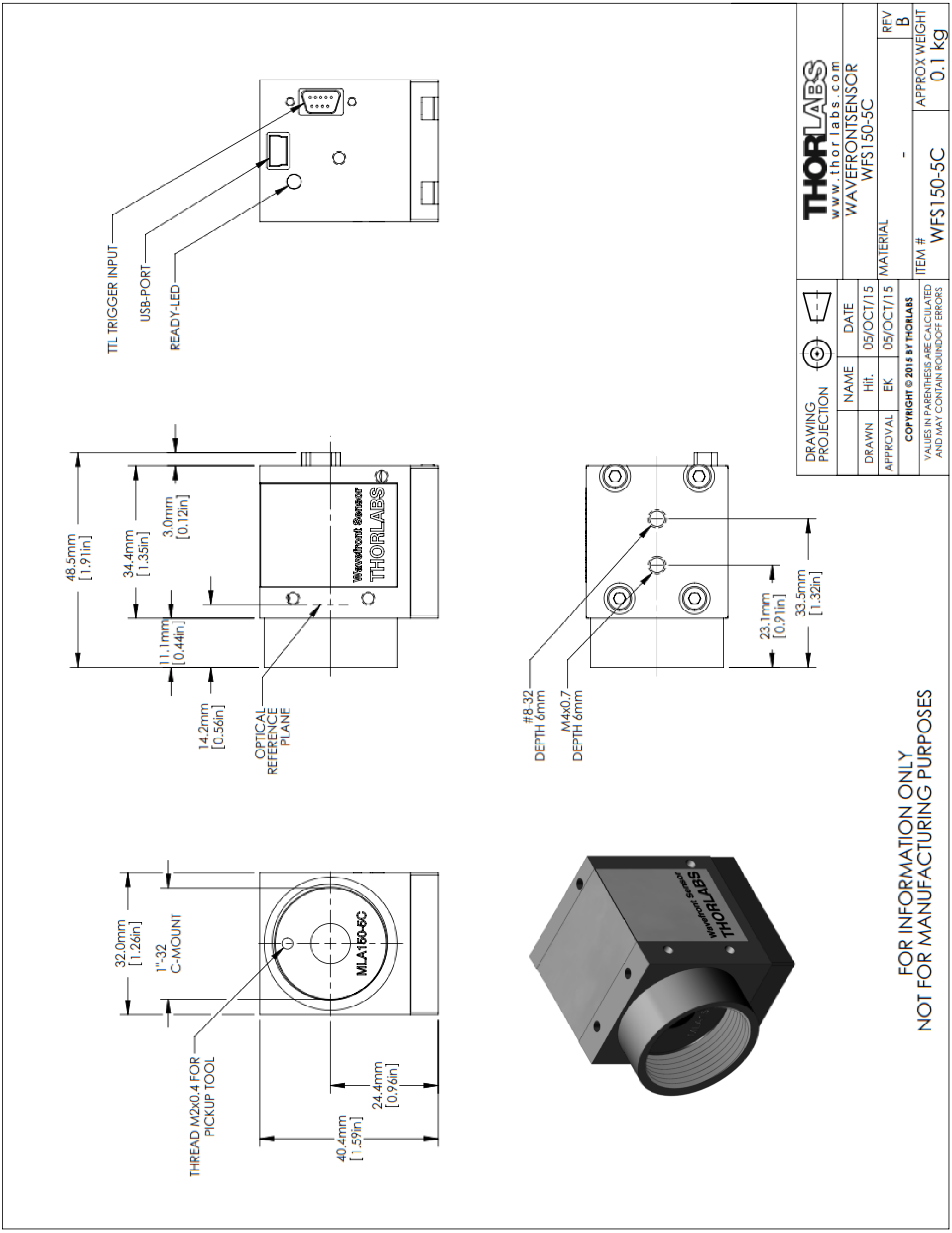
A mounting adapter is included with the WFS150 / WFS300 models to supply standard M4 and UNC8-32 threads that are compatible with Thorlabs mounts and posts.

This adapter plate can be mounted to the bottom side of the Wavefront Sensor using the supplied 4 M3x6 screws.

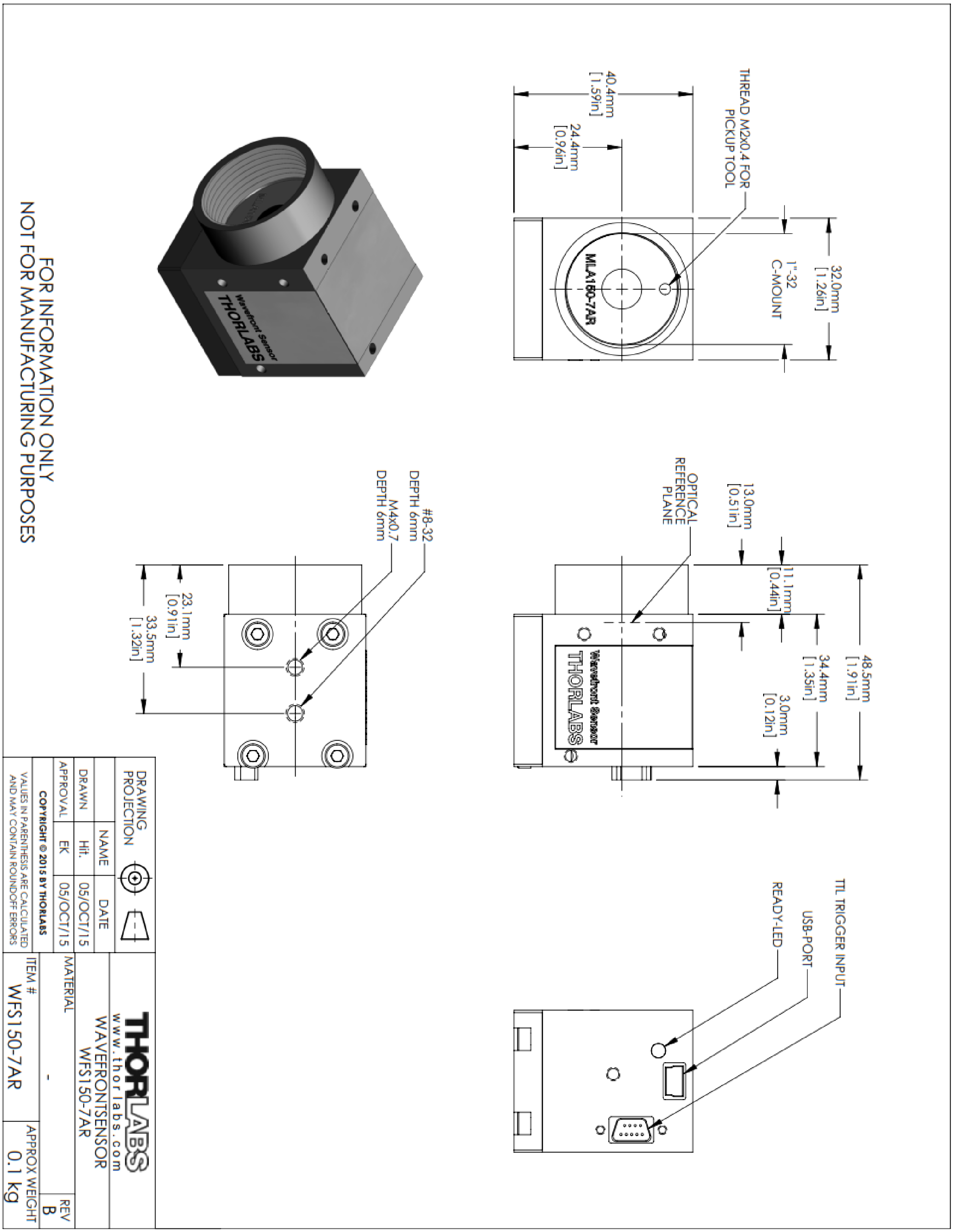


Adapter Plate WFS150 / WFS300

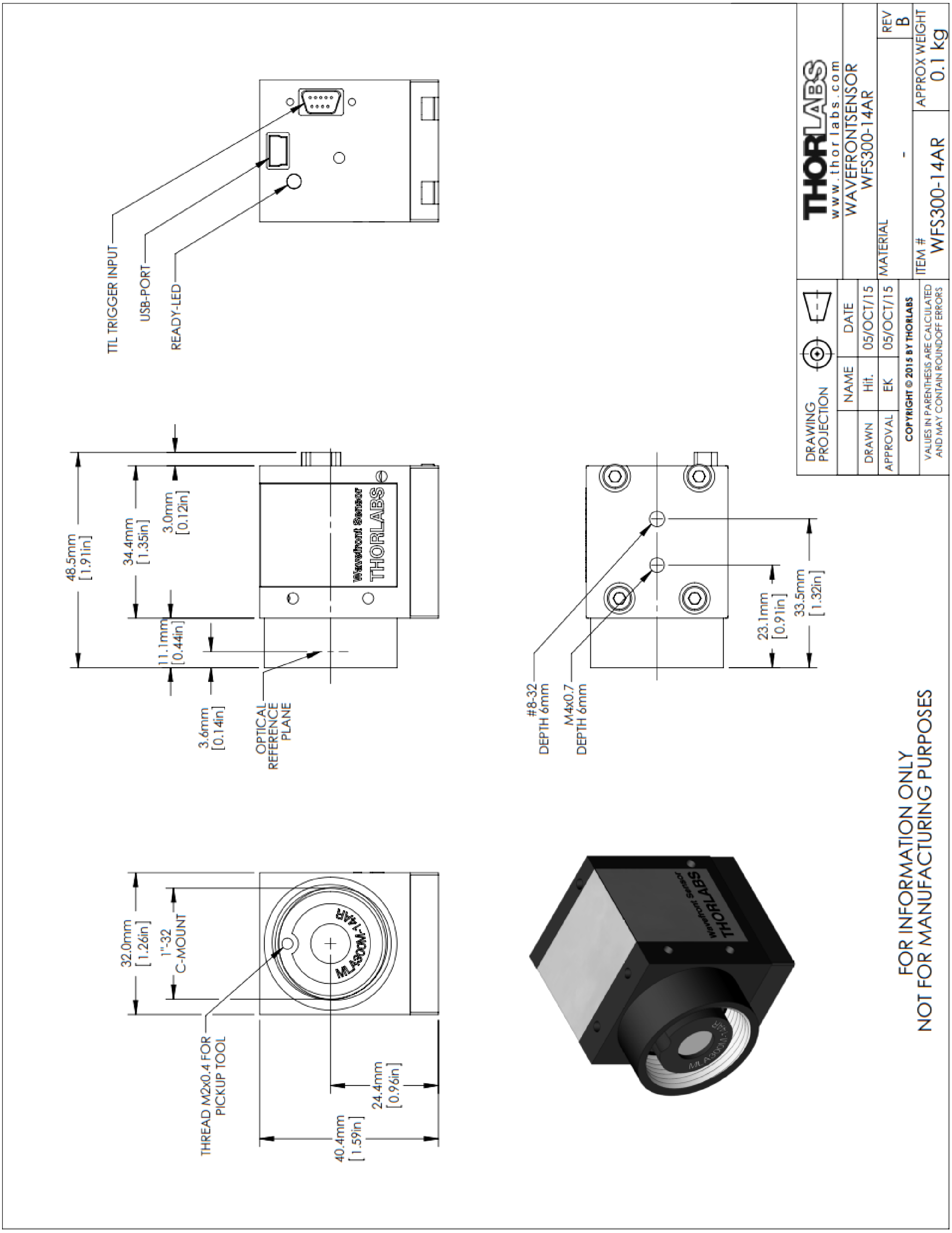
8.7.3 Drawing WFS150-5C



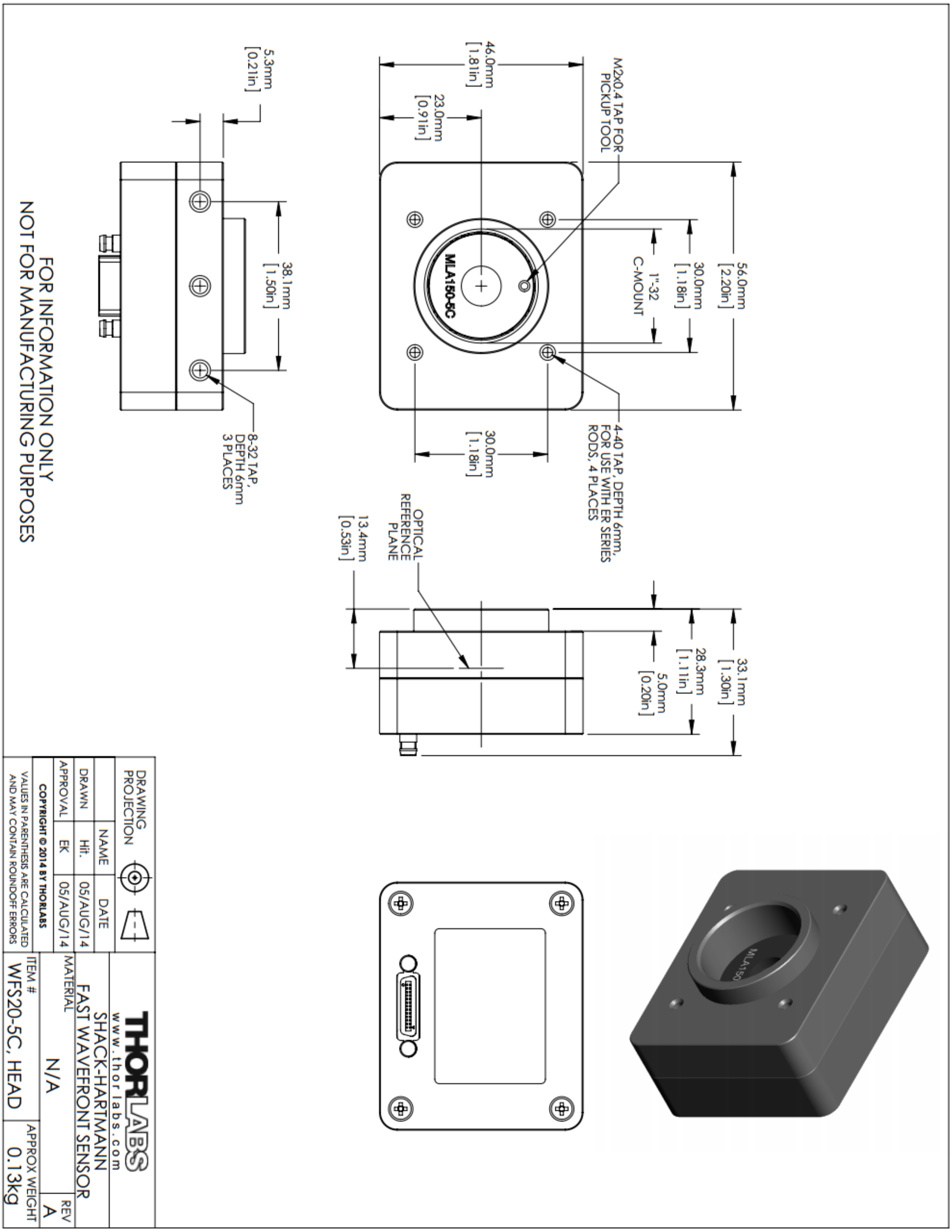
8.7.4 Drawing WFS150-7AR



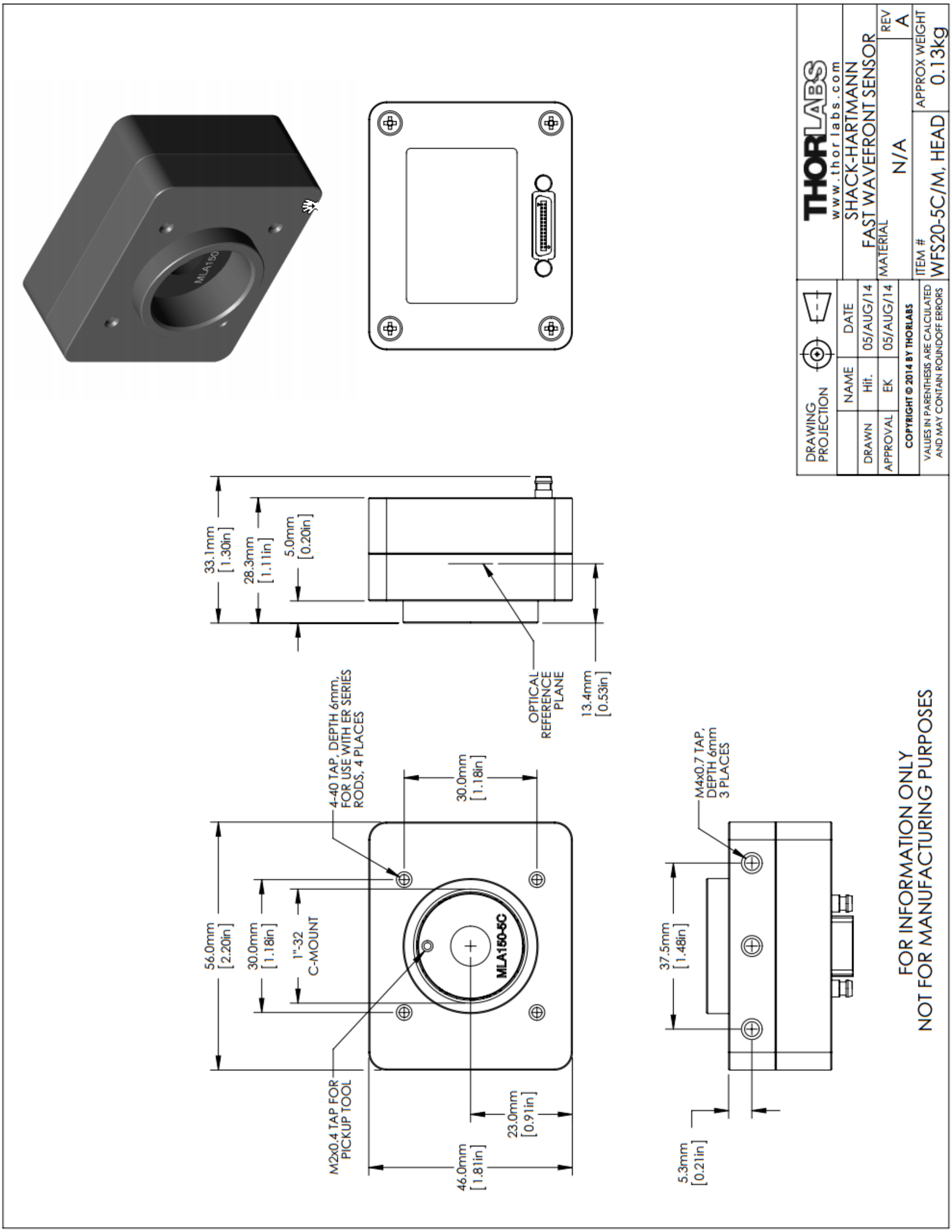
8.7.5 Drawing WFS300-14AR



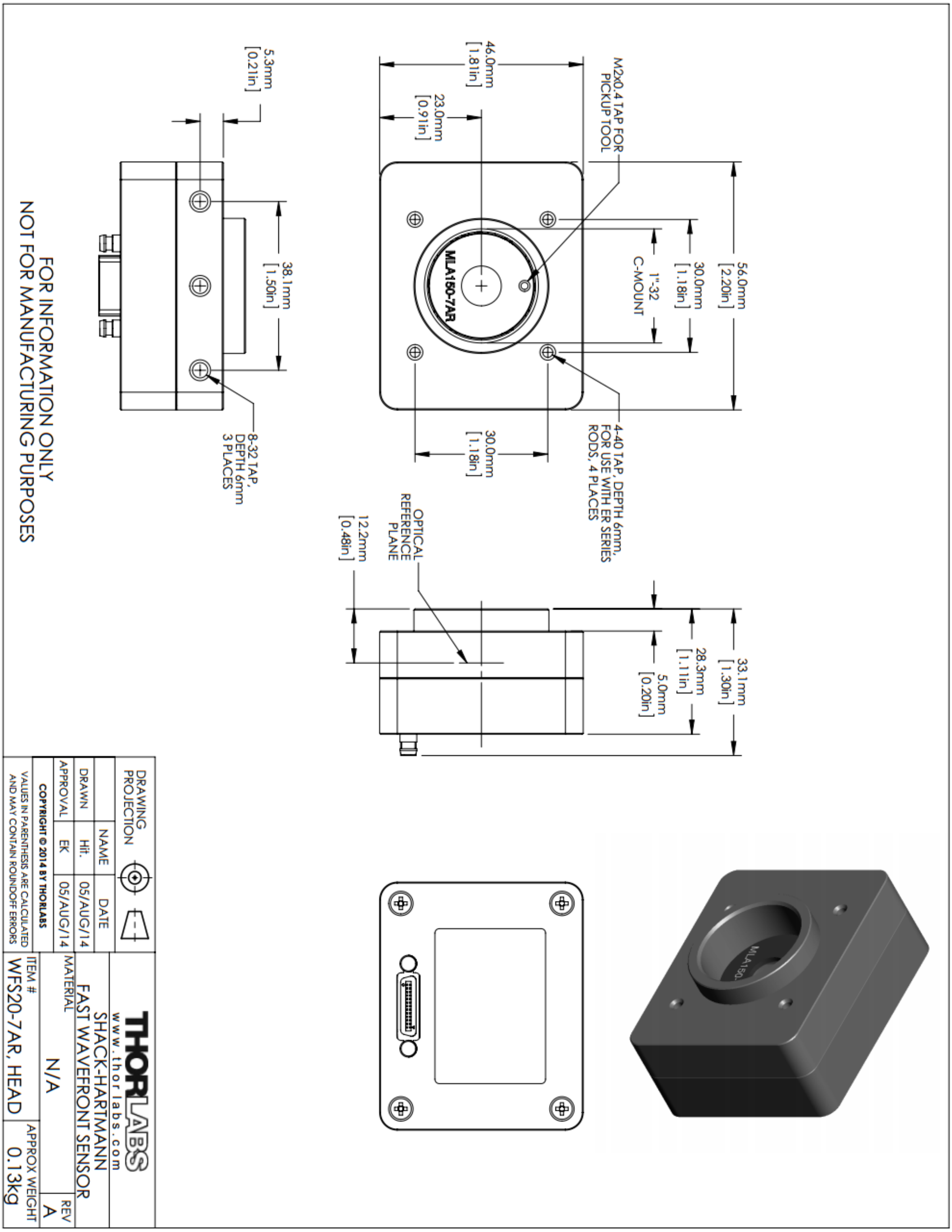
8.7.6 Drawing WFS20-5C



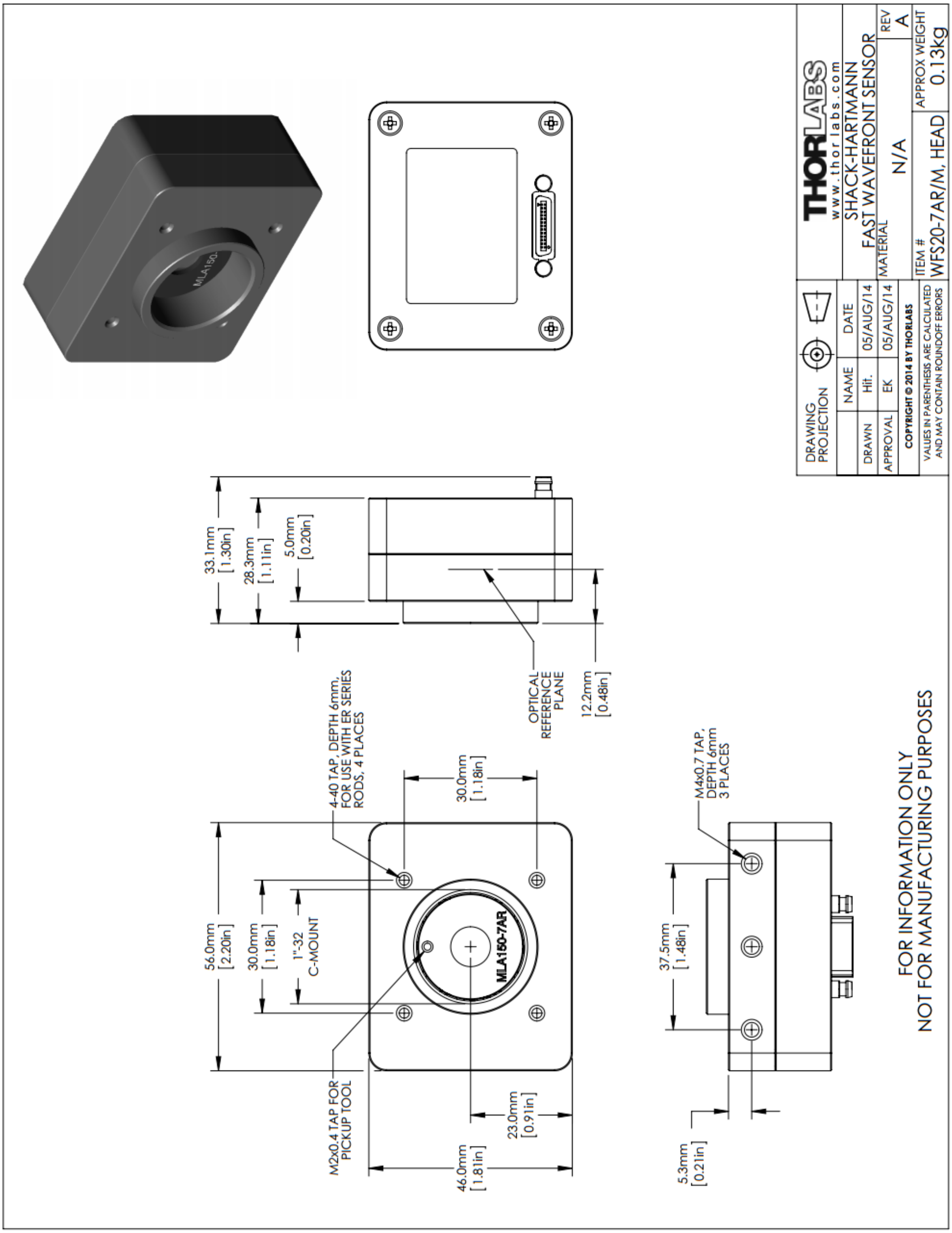
8.7.7 Drawing WFS20-5C/M



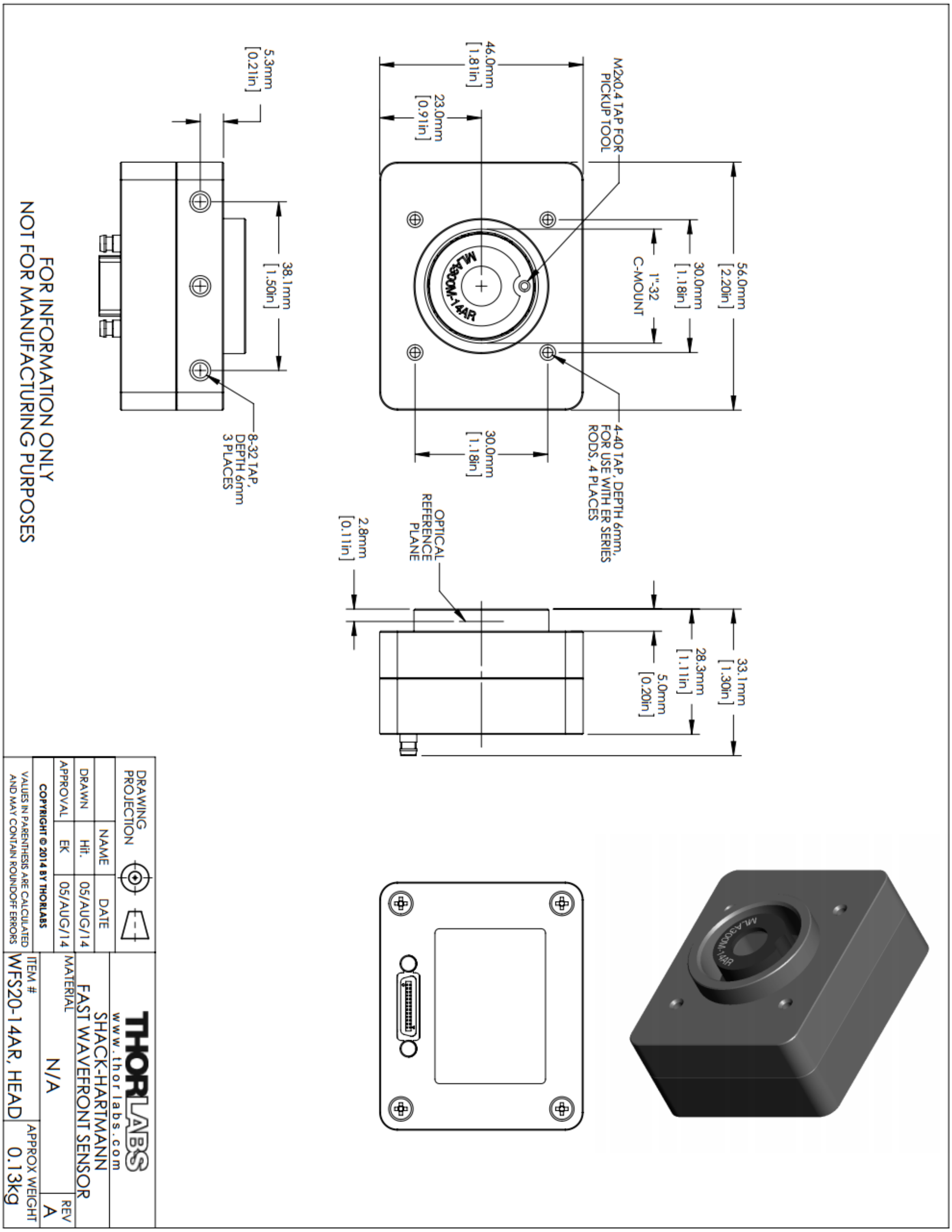
8.7.8 Drawing WFS20-7AR



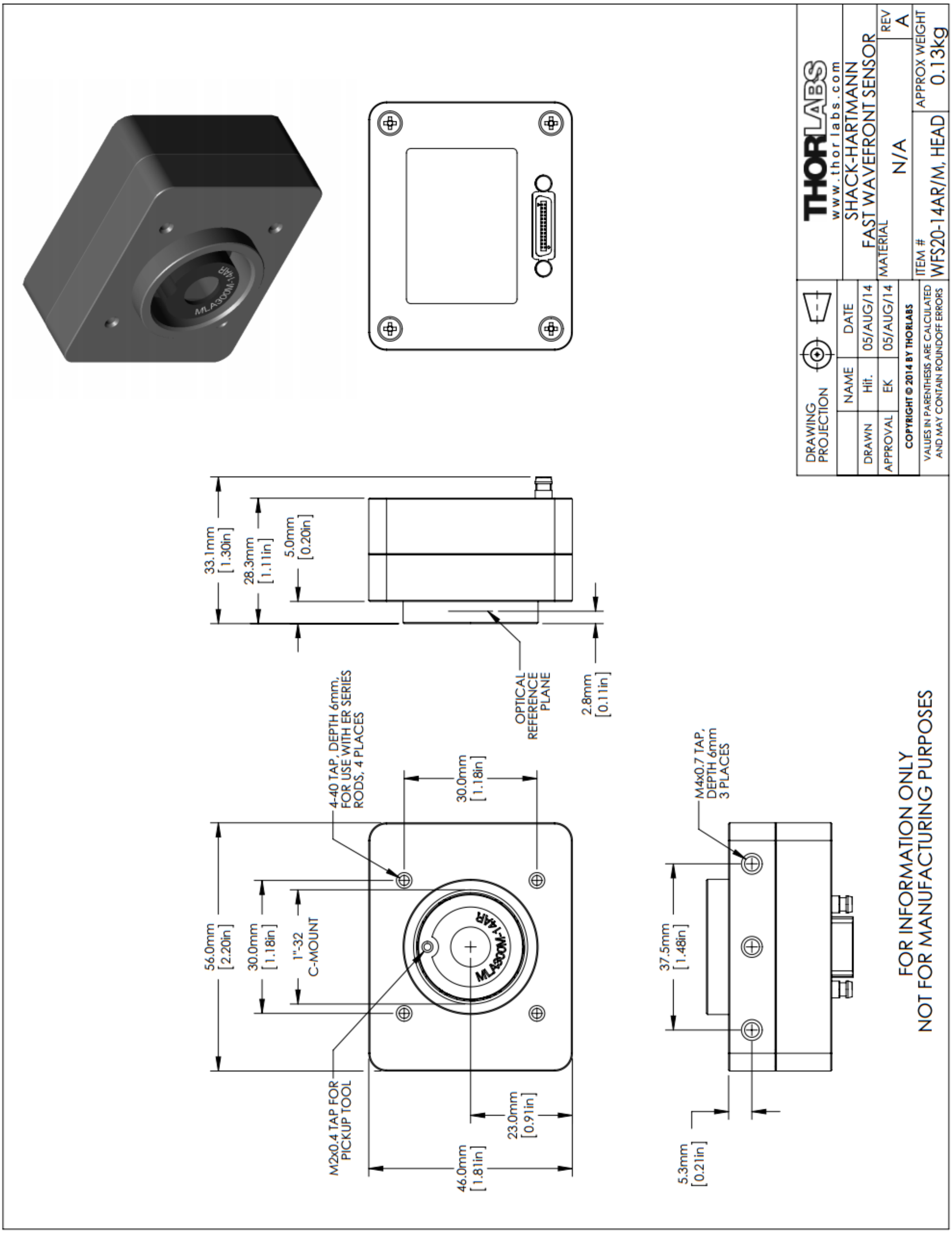
8.7.9 Drawing WFS20-7AR/M



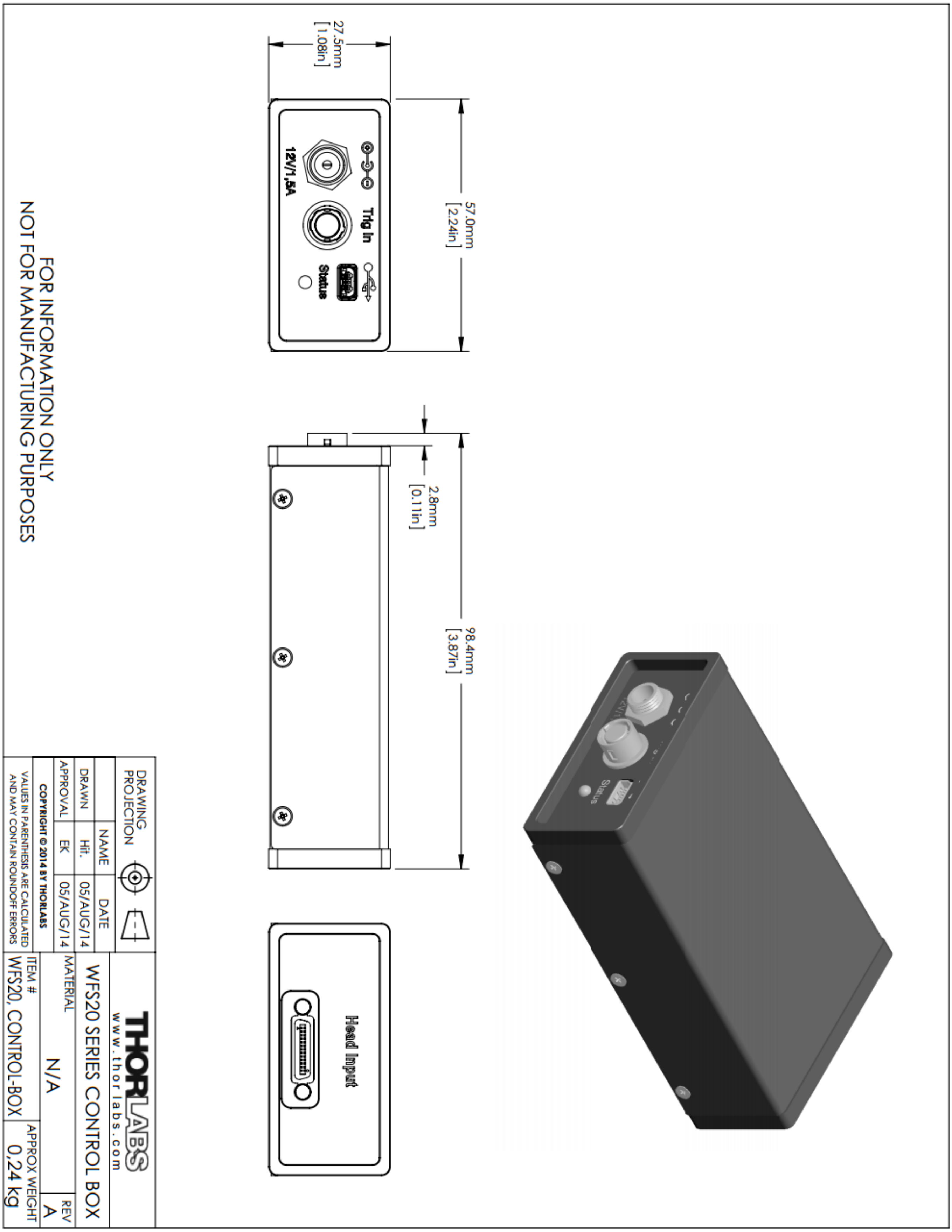
8.7.10 Drawing WFS20-14AR



8.7.11 Drawing WFS20-14AR/M



8.7.12 Drawing WFS20 Control Box



8.8 Certifications and Compliances

Category	Standards or description	
EC Declaration of Conformity - EMC	Meets intent of Directive 2004/108/EC [1] for Electromagnetic Compatibility. Compliance was demonstrated to the following specifications as listed in the Official Journal of the European Communities:	
	EN 61326-1:2006	Electrical equipment for measurement, control and laboratory use – EMC requirements: Immunity: complies with basic immunity test requirements [2,3]. Emission: complies with EN 55011 Class B Limits [2,3,4], IEC 610003-2 and IEC 61000-3-3.
	IEC 61000-4-2	Electrostatic Discharge Immunity (Performance Criterion B)
	IEC 61000-4-3	Radiated RF Electromagnetic Field Immunity (Performance Criterion A) [5]
	IEC 61000-4-4	Electrical Fast Transient / Burst Immunity (Performance Criterion B)
	IEC 61000-4-6	Conducted RF Immunity (Performance Criterion A)
FCC EMC Compliance	Emissions comply with the Class B Limits of FCC Code of Federal Regulations 47, Part 15, Subpart B [2,3,4].	
EC Declaration of Conformity - Low Voltage	Compliance was demonstrated to the following specification as listed in the Official Journal of the European Communities: Low Voltage Directive 2006/95/EC [6]	
	EN 61010-1:2010	Safety Requirements for Electrical Equipment for Measurement, Control and Laboratory Use - Part 1: General Requirements
U.S. Nationally Recognized Testing Laboratory Listing	UL 61010-1 2^{nd} ed.	ANSI/ISA-61010-1 (82.02.01) 3^{rd} ed.
Canadian Certification	CAN/CSA C22.2 No. 61010-1 3^{nd} ed.	
Additional Compliance	IEC 61010-1:2010	
Equipment Type	Test and Measuring	
Safety Class	Class III equipment according to IEC 61140	

[1] Replaces 89/336/EEC.

[2] Compliance demonstrated using high-quality shielded interface cables shorter than or equal to 3 meters.

[3] Compliance demonstrated with ....

[4] Emissions, which exceed the levels required by these standards, may occur when this equipment is connected to a test object.

[5] Ext. Modulation port capped at IEC 61000-4-3 test.

[6] Replaces 73/23/EEC, amended by 93/68/EEC

8.9 Warranty

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

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

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

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

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

Restriction of warranty

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

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

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

8.10 Copyright and Exclusion of Reliability

Thorlabs GmbH has taken every possible care in preparing this Operation Manual. We however assume no liability for the content, completeness or quality of the information contained therein. The content of this manual is regularly updated and adapted to reflect the current status of the software. We furthermore do not guarantee that this product will function without errors, even if the stated specifications are adhered to.

Under no circumstances can we guarantee that a particular objective can be achieved with the purchase of this product.

Insofar as permitted under statutory regulations, we assume no liability for direct damage, indirect damage or damages suffered by third parties resulting from the purchase of this product. In no event shall any liability exceed the purchase price of the product.

Please note that the content of this User Manual is neither part of any previous or existing agreement, promise, representation or legal relationship, nor an alteration or amendment thereof. All obligations of *Thorlabs GmbH* result from the respective contract of sale, which also includes the complete and exclusively applicable warranty regulations. These contractual warranty regulations are neither extended nor limited by the information contained in this User Manual. Should you require further information on this product, or encounter specific problems that are not discussed in sufficient detail in the User Manual, please contact your local *Thorlabs GmbH* dealer or system installer.

8.11 Thorlabs 'End of Life' Policy

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

This offer is valid for Thorlabs GmbH electrical and electronic equipment

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

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

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

Waste treatment on your own responsibility

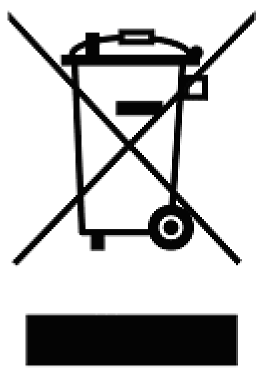
If you do not return an “end of life” unit to Thorlabs GmbH, you must hand it to a company specialized in waste recovery. Do not dispose of the unit in a litter bin or at a public waste disposal site.

WEEE Number (Germany) : DE97581288

Ecological background

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

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



Crossed out "Wheelie Bin" symbol

8.12 List of Acronyms

The following acronyms and abbreviations are used in this manual:

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

8.13 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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