Shack-Hartmann Wavefront Sensors (Page 1 of 4)

NEW version

WFS10-14AR
High-Speed Wavefront Sensor

Features

- High Sensitivity Models up to λ/150 RMS
- High Speed Models up to 450 fps
- Wavelength Range:
  300 – 1100 nm or 400 – 900 nm
- Real-Time Wavefront and
  Intensity Distribution Measurements
- Nearly Diffraction-Limited Spot Size
- For CW and Pulsed Light Sources
- Flexible Data Export Options (Text or Excel)
- Live Data Readout via TCP/IP

Patent Pending

WFS150-5C
High-Resolution Wavefront Sensor

Introduction

A Shack-Hartmann wavefront sensor, which is designed to measure the wavefront deviation from a reference wavefront, uses a lenslet array to divide an incoming beam into an array of smaller beams, each of which is imaged onto a camera that is placed at the focal plane of the lenslet array (Fig. 1). A uniform plane wave that is incident on a Shack-Hartmann wavefront sensor normal to the lenslet array forms a focused spot along the optical axis of each lenslet, yielding a regularly spaced grid of spots in the focal plane. A distorted wavefront, however, produces focal spots that are displaced from the optical axis of each lenslet. The amount of shift of each spot's centroid is proportional to the local slope (i.e., tilt) of the wavefront at the location of that lenslet. The wavefront phase can be reconstructed from the spot displacement information obtained (Fig. 2).

Four parameters that influence the performance of a Shack-Hartmann wavefront sensor are the number of lenslets that cover the camera's active area, the dynamic range, the measurement sensitivity, and the lenslet focal length. The number of lenslets restricts the maximum number of Zernike coefficients that a reconstruction algorithm can reliably calculate. See the section on Zernike modes on the next page for more information regarding the number of lenslets and wavefront measurement.

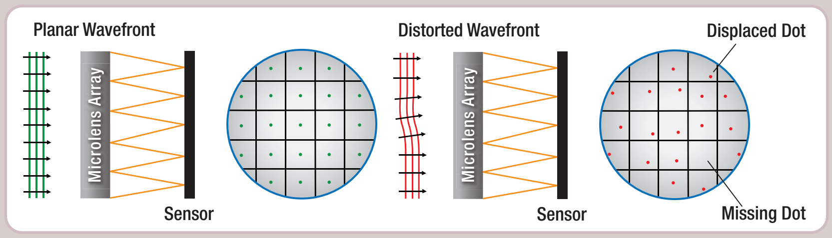


Figure 1. A planar wavefront incident on the Shack-Hartmann wavefront sensor's lenslet array and imaged on the CCD sensor will display a regularly spaced grid of spots. An aberrated wavefront, however, will cause individual spots to be displaced from the optical axis of each lenslet; if the displacement is large enough, the image spot may even appear to be missing. This information is used to calculate the shape of the wavefront that was incident on the microlens array.

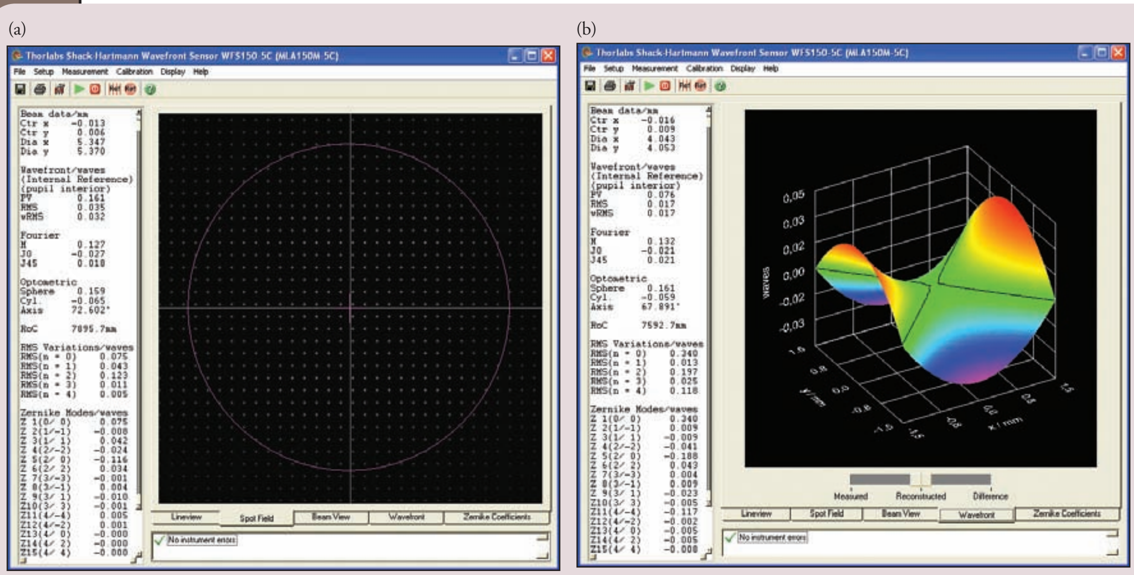


Figure 2. Two Shack-Hartmann wavefront sensor screen captures are shown: the spot field (a) and the calculated wavefront based on that spot field information (b).

Shack-Hartmann Wavefront Sensors (Page 2 of 4)

Sensitivity (θ_{min}) is a function of the minimum detectable spot displacement (δy_{min}), as described in Fig. 3. This parameter determines the minimum detectable phase. Dynamic Range (θ_{max}), however, is a measure of the maximum extent of phase that can be measured.

A Shack-Hartmann sensor's measurement accuracy (i.e., the minimum wavefront slope that can be measured reliably) depends on its ability to precisely measure the displacement of a focused spot with respect to a reference position. A conventional algorithm will fail to determine the correct centroid of a spot if it partially overlaps another spot or if the focal spot of a lenslet falls outside of the area of the sensor assigned to detect it (i.e., spot crossover). Special algorithms that allow a spot to be followed, even when outside its regular detection area, are implemented into the Thorlabs wavefront sensor software to overcome these limitations and consequently increase the dynamic range of the sensor. The dynamic range of a system can be increased by using a lenslet with either a larger diameter or a shorter focal length. Increasing the dynamic range by increasing the lenslet diameter decreases the number of Zernike coefficients available to represent the wavefront. Conversely, increasing the dynamic range by shortening the lenslet focal length decreases the sensor's sensitivity. Ideally, a lenslet with the longest focal length that meets both the dynamic range and measurement sensitivity requirements should be used.

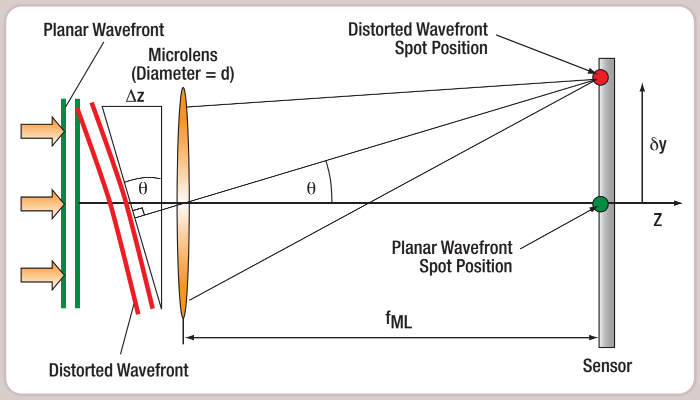


Figure 3. Detail of an individual microlens. The spot positions will only be directly behind the lens (green spot) if the incident wavefront is flat and parallel to the plane of the lenslets. A distorted wavefront will cause a spot to be deviated in X and Y (red spot) so that every spot lies away from the optical axis Z by an angle θ. The equations provided for the measurement sensitivity and the dynamic range below are obtained using the small angle approximation. θ_{min} is the minimum wavefront slope that can be measured by the wavefront sensor; the measurement sensitivity is inversely proportional to this angle. δy_{min} is the minimum detectable spot displacement and is limited by the pixel size, the centroid algorithm, and the signal to noise ratio of the sensor. θ_{max} is the maximum wavefront slope that can be measured by the wavefront sensor, and depends on d, the diameter of the microlens.

Minimum Slope:

$$\theta_{min} = \frac{\delta y_{min}}{f_{ML}}$$

Dynamic Range:

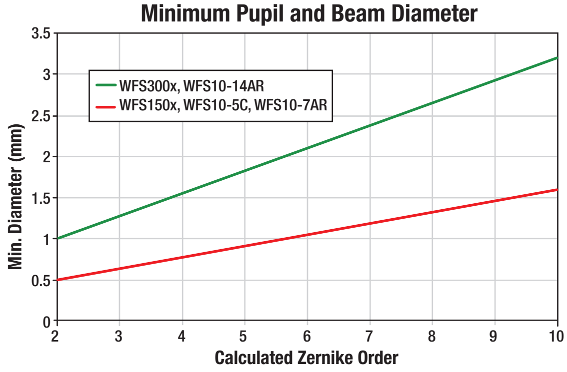
$$\theta_{max} = \frac{\delta y_{max}}{f_{ML}} = \frac{d/2}{f_{ML}}$$

Exchange Program: If you own a wavefront sensor from Thorlabs and would like to use a different microlens array, please contact Tech Support for details on our Exchange Program.

Shack-Hartmann Zernike Modes

Thorlabs' wavefront sensors (WFS) can fit the measured wavefront to a Zernike polynomial, up to the 10th order (i.e., 66 Zernike modes). In general, the minimum number of Shack-Hartmann spots required to fit a wavefront to a Zernike polynomial is equal to the number of Zernike modes to be fit. Therefore, in addition to the wavefront sensor's specifications, the number of WFS lenslets used must be taken into account to ensure the desired number of Zernike mode coefficients can be calculated.

Additionally, when using the wavefront sensor and a deformable mirror for AO control, the ratio of the number of used wavefront sensor lenslets to the number of deformable mirror actuators needs to be considered. Alfred Dubra's paper, "Wavefront sensor and wavefront corrector matching in adaptive optics", Optics Express, March 2007, **15**, No. 6, 2762 – 2769, is a good reference to better understand this concept. In this paper, Dubra finds that a 1:1 lenslet-to-actuator ratio does not yield the most stable AO control. The results show the performance is significantly improved with a ratio of roughly 2:1. A 1:1 magnification 4F optical relay (two equal focus lenses aligned in a confocal configuration) is used between the DM and the WFS in Thorlabs' AO Kits; therefore, the lenslet to actuator ratio is 2.7:1 (i.e., 400 µm / 150 µm). This ensures the AO Kits operate in a regime where stable AO control can be achieved.



WFS CAMERA RESOLUTION (PIXELS)	WAVEFRONT SPOTS		APERTURE SIZE
	WFS150-7AR WFS150-14AR	WFS300-14AR	
320 x 320	7 x 7 (49)	3 x 3 (9)	1.49 mm x 1.49 mm
512 x 512	13 x 13 (169)	5 x 5 (25)	2.38 mm x 2.38 mm
768 x 768	21 x 21 (441)	9 x 9 (81)	3.57 mm x 3.57 mm
1024 x 1024	29 x 29 (841)	13 x 13 (169)	4.76 mm x 4.76 mm
1280 x 1024	37 x 29 (1073)	17 x 13 (221)	5.95 mm x 4.76 mm

WFS CAMERA RESOLUTION (PIXELS)	WAVEFRONT SPOTS		APERTURE SIZE
	WFS10-5C WFS10-7AR	WFS10-14AR	
180 x 180	9 x 9 (81)	3 x 3 (9)	1.78 mm x 1.78 mm
260 x 260	15 x 15 (225)	7 x 7 (49)	2.57 mm x 2.57 mm
360 x 360	21 x 21 (441)	9 x 9 (81)	3.56 mm x 3.56 mm
480 x 480	29 x 29 (841)	13 x 13 (169)	4.75 mm x 4.75 mm
640 x 480	41 x 29 (1189)	19 x 13 (247)	6.34 mm x 4.75 mm

Shack-Hartmann Wavefront Sensors (Page 3 of 4)

Kits

In addition to the base camera unit, which is available with one of three microlens arrays, kits are also offered that combine two microlens arrays, the base CMOS or CCD camera with preloaded calibration data for both arrays, and a pickup tool for interchanging the mounted arrays. The kits are ideal for situations where more than one light source or optical setup needs to be analyzed.

Accessories

Each Shack-Hartmann sensor and kit comes in a convenient storage and carrying case. Mounting accessories include an external C-Mount to internal SM1 thread (1.035"-40) adapter for mounting Ø1" Lens Tubes and mounted optics such as neutral density filters (see page 827) and a base plate for attaching Ø1/2" posts. Power is supplied to the sensor via a USB 2.0 connection to a PC.

Each wavefront sensor includes a C-mount to SM1 adapter and a baseplate for attaching the sensor to a Ø1/2" post.

Software Features

The included software package offers a user-friendly graphical interface with tools for choosing camera setting, calibration, analysis, and display options. The display options include the raw spotfield image, Zernike coefficients, measured and reconstructed 3D wavefront, and the irradiance distribution. Data export options include tabulated output, text or Excel file, and live data readout via TCP/IP or DataSocket Server. Drivers are also included for C Compilers, LabVIEW™, LabWindows/CVI™, and .Net for integration into custom system control and data collection software. Software screen shots are shown on page 1610.

Trigger Option

For applications where an external trigger is required, cables are available to connect the trigger signal to the wavefront sensor. Please see the trigger specifications in the table below.

	FAST WAVEFRONT SENSORS			HIGH-RESOLUTION WAVEFRONT SENSORS		
ITEM #	WFS10-5C	WFS10-7AR	WFS10-14AR	WFS150-5C	WFS150-7AR	WFS300-14AR
Camera Specifications						
Detector Array	CMOS			CCD		
Camera Resolution (Max)	640 x 480 Pixels, Software Selectable			1280 x 1024 Pixels, Software Selectable		
Pixel Size	9.9 µm x 9.9 µm			4.65 µm x 4.65 µm		
Aperture Size (Max)	6.34 mm x 4.76 mm			5.95 mm x 4.76 mm		
Frame Rate (Max)	450 Hz[a]			15 Hz		
Microlens Array Specifications						
Wavelength Range	300 – 1100 nm	400 – 900 nm		300 – 1100 nm	400 – 900 nm	
Effective Focal Length	3.7 mm	5.2 mm	14.2 mm	3.7 mm	5.2 mm	14.2 mm
Lenslet Pitch	150 µm		300 µm	150 µm		300 µm
Lens Size	Ø146 µm		300 µm x 300 µm	Ø146 µm		300 µm x 300 µm
Coating	Chrome Mask	Antireflection		Chrome Mask	Antireflection	
Substrate Material	Fused Silica (Quartz)			Fused Silica (Quartz)		
General Specifications						
Wavefront Accuracy @ 633 nm[b]	λ/10 rms		λ/30 rms	λ/15 rms		λ/50 rms
Wavefront Sensitivity @ 633 nm[c]	λ/30 rms		λ/100 rms	λ/50 rms		λ/150 rms
Wavefront Dynamic Range @ 633 nm[d]	>100 λ		>50 λ	>100 λ		>50 λ
Number of Lenslets (Max)	41 x 29		19 x 13	41 x 29		19 x 13
Local Wavefront Curvature[e]	>7.4 mm	>10 mm	>40 mm	>7.4 mm	>10 mm	>40 mm
Optional External Trigger Specifications						
Trigger Slope	Software Selectable: Low-High or High-Low			Software Selectable: Low-High or High-Low		
Maximum Low Level	1.5 V			2 V		
Minimum High Level	3.5 V			5 V		
Input Current (Max)	–			10 mA		
Input Impedance	>100 kΩ			–		

[a] For frame rates of 450 Hz, a resolution of 180 x 180 pixels must be used. This PC hardware-dependent speed is achieved without graphical display, assumes a 5th order Zernike fit at the specified camera resolution, and minimum exposure time.

[b] Absolute accuracy using internal reference. Measured for spherical wavefronts with a known radius of curvature.

[c] Typical relative accuracy with respect to a reference wavefront (user calibration). Reference and each measurement values are averaged over 10 frames.

[d] Over entire aperture of wavefront sensor.

[e] Radius of wavefront curvature over single lenslet aperture.

Shack-Hartmann Wavefront Sensors (Page 4 of 4)

Shack-Hartmann Wavefront Sensor

NEW versions

ITEM #	$	£	€	RMB	DESCRIPTION
WFS10-5C	$ 4,900.00	£ 3,528.00	€ 4.263,00	¥ 39,053.00	High-Speed Shack-Hartmann WFS, 150 µm Pitch, Chrome Masked, 300 – 1100 nm
WFS10-7AR	$ 4,900.00	£ 3,528.00	€ 4.263,00	¥ 39,053.00	High-Speed Shack-Hartmann WFS, 150 µm Pitch, AR Coated: 400 – 900 nm
WFS10-14AR	$ 4,900.00	£ 3,528.00	€ 4.263,00	¥ 39,053.00	High-Speed Shack-Hartmann WFS, 300 µm Pitch, AR Coated: 400 – 900 nm
WFS150-5C	$ 3,800.00	£ 2,736.00	€ 3.306,00	¥ 30,286.00	High-Resolution Shack-Hartmann WFS, 150 µm Pitch, Chrome Masked, 300 – 1100 nm
WFS150-7AR	$ 3,800.00	£ 2,736.00	€ 3.306,00	¥ 30,286.00	High-Resolution Shack-Hartmann WFS, 150 µm Pitch, AR Coated: 400 – 900 nm
WFS300-14AR	$ 3,800.00	£ 2,736.00	€ 3.306,00	¥ 30,286.00	High-Resolution Shack-Hartmann WFS, 300 µm Pitch, AR Coated: 400 – 900 nm

Shack-Hartmann Wavefront Sensor Kits

NEW products

ITEM #	$	£	€	RMB	WAVEFRONT SENSOR TYPE	MICROLENS ARRAY 1	MICROLENS ARRAY 2
WFS10-K1	$ 5,700.00	£ 4,104.00	€ 4.959,00	¥ 45,429.00	High-Speed (450 Hz) WFS	150 µm Pitch, Chrome Masked, 300 - 1100 nm	300 µm Pitch, AR Coated: 400 – 900 nm
WFS10-K2	$ 5,700.00	£ 4,104.00	€ 4.959,00	¥ 45,429.00		150 µm Pitch, AR Coated: 400 – 900 nm	
WFS-K1	$ 4,600.00	£ 3,312.00	€ 4.002,00	¥ 36,662.00	High-Resolution (1.3 Megapixel) WFS	150 µm Pitch, Chrome Masked, 300 – 1100 nm	
WFS-K2	$ 4,600.00	£ 3,312.00	€ 4.002,00	¥ 36,662.00		150 µm Pitch, AR Coated: 400 – 900 nm	

Shack-Hartmann Sensor Trigger Cables

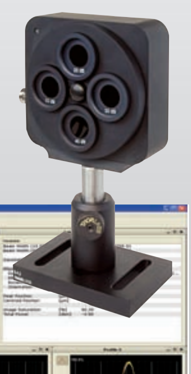
ITEM #	$	£	€	RMB	DESCRIPTION
CAB-WFS10-T1	$ 69.00	£ 49.68	€ 60,03	¥ 549.93	Trigger Cable for Fast Shack-Hartmann Wavefront Sensors
CAB-DCU-T2	$ 78.00	£ 56.16	€ 67,86	¥ 621.66	USB and Trigger Cable for 1.3 Megapixel Shack-Hartmann Wavefront Sensors

Exchange Program:
If you own a wavefront sensor from Thorlabs and would like to use a different microlens array, please contact Tech Support for details on our Exchange Program.

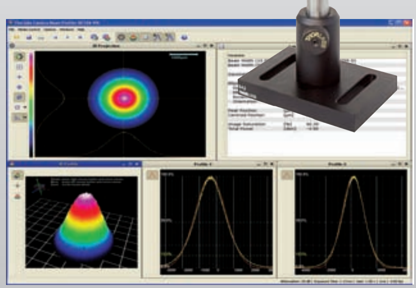
Have you seen our...

Beam Profilers: Scanning and CCD

- High Dynamic Range CCD Camera with High Resolution and Low Noise
- Wavelength Range: 190 – 1100 nm
- CW and TTL Triggered Single Pulse Detection

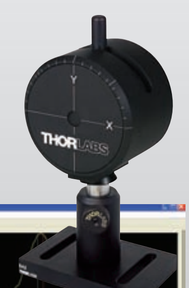


Thorlabs' CCD-camera-based beam profilers, compared to scanning slit profilers, offer true 2D analysis of the beam's power density distribution. This greater detail allows complex mode patterns to be identified while optimizing laser systems.

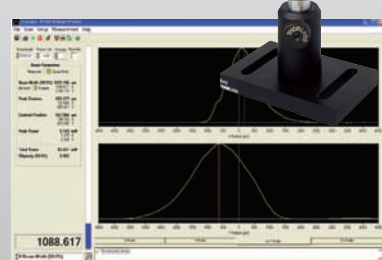


See page 1615

- Scanning Slit Profiler with 4 Models Covering the 200 – 2700 nm Range
- Si, Ge, and INGaAs Sensors
- CW and Pulsed Sources ≥10 Hz
- High Dynamic Range



Thorlabs' Scanning Slit Profilers are high-precision instrument with a dynamic range of 72 dB that can analyze the power distribution of laser beams with diameters from 10 µm to 9 mm.



See page 1614