ECOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

MASTER THESIS

Evaluation of optical aberrations using Phase Diversity

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A thesis submitted in fulfillment of the requirements for the degree of Master in Applied Physics

in the

Astrophysics laboratory
Basic Sciences

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Declaration of Authorship

I, Jordan VOIRIN, declare that this thesis titled, "Evaluation of optical aberrations using Phase Diversity" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

"Thanks to my solid academic training, today I can write hundreds of words on virtually any topic without possessing a shred of information, which is how I got a good job in journalism."

Dave Barry

ECOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Abstract

Physics
Basic Sciences

Master in Applied Physics

Evaluation of optical aberrations using Phase Diversity

by Jordan VOIRIN

The Thesis Abstract is written here (and usually kept to just this page). The page is kept centered vertically so can expand into the blank space above the title too…

Acknowledgements

The acknowledgments and the people to thank go here, don't forget to include your project advisor…

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List of Abbreviations

WFS	**W**ave**F**ront **S**ensor

Physical Constants

Speed of Light $c_0 = 2.997\,924\,58 \times 10^8\,\mathrm{m\,s^{-1}}$ (exact)

List of Symbols

a	distance	m
P	power	W ($J\,s^{-1}$)
ω	angular frequency	rad

For/Dedicated to/To my…

Chapter 1

Introduction

???

Chapter 2

Phase Diversity Experiment

2.1 Theoretical Background

2.2 Experimental Setup

The design of the experiment was already done by Bouxin (2017). The system is built according to her plans and specificationsS.

The experiment is mounted on a pressurized legs optical table. The assembly contains six main components : a light source, an entrance pupil, an imaging system, a converging lens to focus the beam on the camera, a camera and a wavefront sensor.

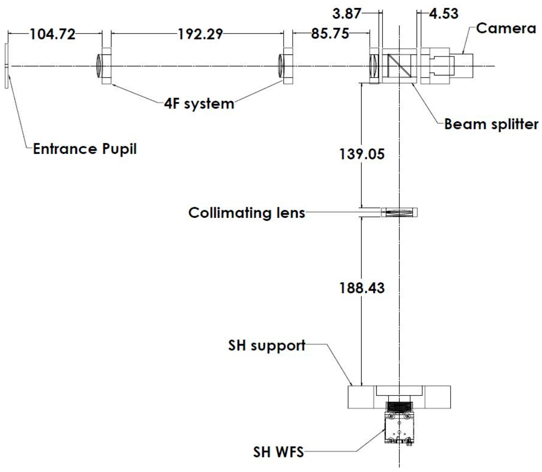


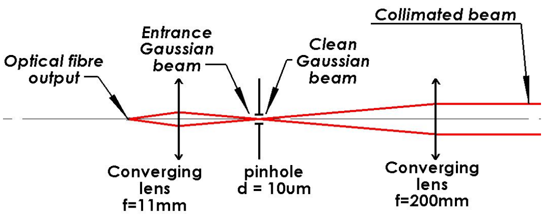
FIGURE 2.1: Experimental setup schema with the relevant distances, (Bouxin, 2017).

2.2.1 Light source

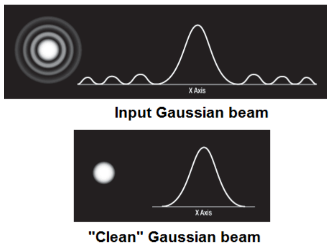
The final application of the phase diversity will be to characterize the optical aberrations induced by the imperfect optical path to a scientific detector of a telescope. For this reason, the light source has to simulate a distant

TABLE 2.1: Optical Components

#	Components	Model	Reference
1	Pigtailed laser diode	Thorlabs, LPS-635-FC	A.1
2	Converging lens, f = 11 mm	Thorlabs, A220TM-A	A.2
3	Pinhole, 10 μm	Thorlabs, P10S	A.3
4	Converging lens, f = 200 mm	Thorlabs, AL100200	A.4
5	3.2 mm Hole milled in metal sheet	...	...
6	Converging lens, f = 100 mm	Thorlabs, AC254-100-A	A.5
7	Converging lens, f = 80 mm		
8	Camera CMOS	Ximea, MQ013MG-E2	A.6
9	Converging lens, f = 100 mm		
10	Shack-Hartman WFS	Thorlabs, WFS150-5C	A.7



(A) Source ray tracing.



(B) Beam view before and after the pinhole, (Thorlabs, 2017).

FIGURE 2.3: Source schema and pinhole effect on the beam.

star aberration-free wavefront. A distant star wavefront is considered planar since the object distance, z, is far greater than the telescope size, r, see Fig. 2.2. The source of our experiment must then be characterized by planar wavefront.

In order to obtain such a planar wavefront at the entrance pupil, the light source consist of a "pigtailed laser diode", a f=11mm converging lens, a pinhole and a f=200 mm converging lens, see Table 2.1. The pigtailed laser diode emits a Gaussian beam centred at 637.5 nm slightly diverging. The converging lens concentrates the beam at the center of the 10μm pinhole to filter the noise. The second converging lens collimates the beam, obtaining a collimated beam with a planar wavefront, see Fig. 2.3a and 2.3b.

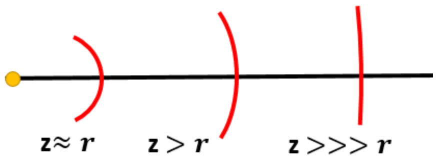


FIGURE 2.2: Wavefront curvature for different source's distances, z. r represents the characteristic size of the arc of interest.

2.2.2 Entrance pupil

The entrance pupil of our optical system is a circular aperture of 3.2 mm diameter placed after the collimating lens of the light source. It is milled in a metal plate and centred in his support, to avoid positioning with a XY table. The diameter is chosen in available material to fit in the different detector's surfaces.

2.2.3 Pupil imaging system

The phase diversity technique requires PSFs images as input, which means that the beam as to be focused onto the detector surface. To analyse the aberration in the pupil plane, one needs to focus an image of the beam passing through the entrance pupil. The simplest assembly to achieve this goal is the 4F system, which consist of two converging lenses of focal 100 mm. The two lenses are separated by 200 mm, see Fig. 2.1. This places the image of the entrance pupil 100 mm after the second converging lens.

2.2.4 Acquisitions

The image of the entrance pupil, obtained with the 4F system, is focused onto a CMOS Ximea camera by a f = 80 mm converging lens to acquire the PSFs for the phase diversity wavefront retrieval. The camera has surface composed by 1280x1024 pixels of 5.3 μm, see Appendix A.6. It is mounted on sliding support in order to be able to acquire in/out-of-focus images. A beam splitter is placed in the converging beam to separate it in two. The second beam is collimated and a Shack-Hartman WFS is placed on the entrance pupil image plane, to check the results of the phase diversity wavefront retrieval. The Shack-Hartman WFS has a 39 X 31 lenslet grid and a CCD with a resolution of 1280x1024 pixels of 4.65 μm, see Appendix A.7.

2.3 Results

This section presents the results of the phase diversity experiment, with the introduction of different sources of aberration.

2.3.1 Parallel plane plate

The first source of aberration studied in this work is a tilted parallel plane plate which is used as a calibrated source of astigmatism.

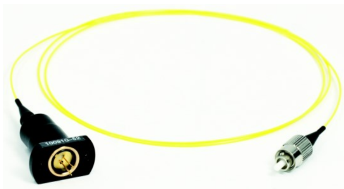
Appendix A

Optical Component Datasheets

A.1 Pigtailed laser diode

THORLABS

Pigtailed Laser Diode, SMF



Description

Thorlabs' Single Mode Pigtailed Laser Diodes are standard TO-packaged diodes that have been pigtailed to a 1 m long single mode fiber with an FC/PC connector. Each unit is tested before shipment. Please refer to the unit-specific test datasheet for optimal operating parameters.

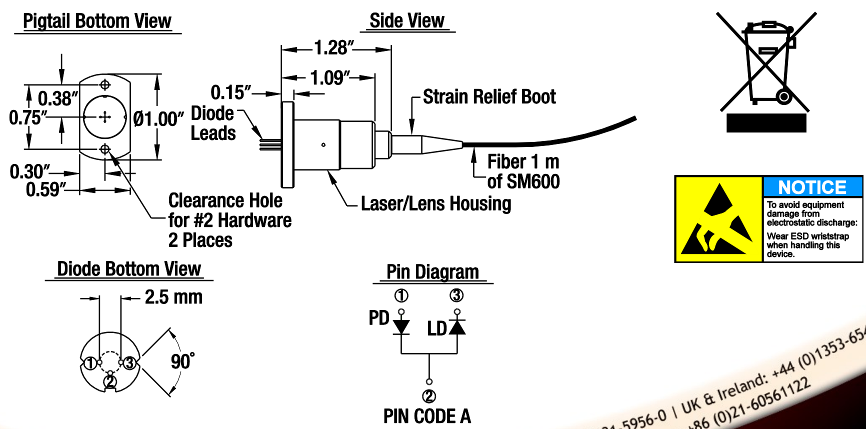
Specifications

LPS-635-FC Specifications		
LD Reverse Voltage (Max)	2 V	
PD Reverse Voltage (Max)	30 V	
Optical Output Power	2.5 mW (Typ.)	3.5 mW (Max)
Operating Temperature	0 to 50 °C	
Storage Temperature	-10 to 65 °C	
Pin Code	9A	
Laser Diode	HL6320G	
Fiber	SM600	
Connector	FC/PC	

LPS-635-FC Specifications			
	Min	Typ.	Max
Wavelength	625 nm	635 nm	640 nm
Threshold Current*	20 mA	50 mA	75 mA
Slope Efficiency*	0.13 mW/mA	0.18 mW/mA	-
Operating Current @ P_O = 2.5 mW*	-	70 mA	95 mA
Operating Voltage @ P_O = 2.5 mW*	-	2.2 V	2.7 V
Monitor Current @ P_O = 2.5 mW*	0.05 mA	0.17 mA	0.3 mA

*Temperature = 25 °C

Drawing



US, Canada, & South America: +1-973-300-3000 | France: +33 (0) 970 444 844 | Europe: +49 (0) 8131-5956-0 | UK & Ireland: +44 (0)1353-654440
Brazil: +55-16-3413 7062 | Scandinavia: +46-31-733-30-00 | Japan & Asia: +81-3-5979-8889 | China: +86 (0)21-60561122
www.thorlabs.com

June 6, 2013
5175-S01, Rev B

Source : www.thorlabs.com

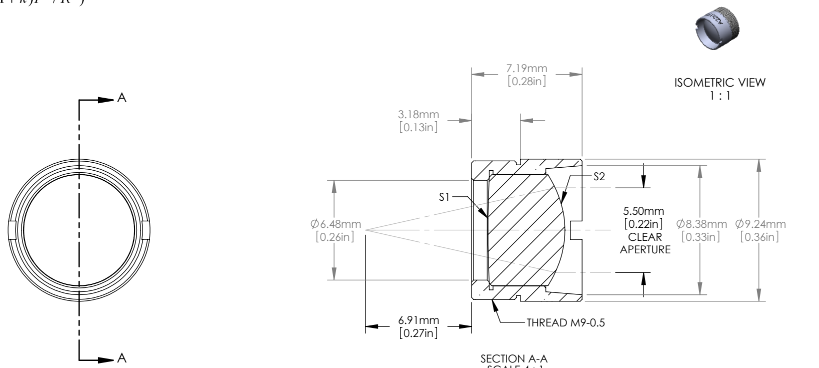
A.2 Converging lens A220TM-A, f = 11 mm

ASPHERIC COEFFICIENTS

	R	k	A_4	A_6	A_8	A_{10}	A_{12}
S1	72.47	-	-	-	-	-	-
S2	-5.97	-	3.3835580E-04	1.3053900E-05	-1.0982500E-06	1.3742680E-07	-5.49555E-09

$$z = \frac{Y^2}{R(1+\sqrt{1-(1+k)Y^2/R^2})} + A_4Y^4 + A_6Y^6 + A_8Y^8 + A_{10}Y^{10} + A_{12}Y^{12}$$

ASPHERIC LENS EQUATION



SECTION A-A
SCALE 4 : 1

NOTES/SPECIFICATIONS:

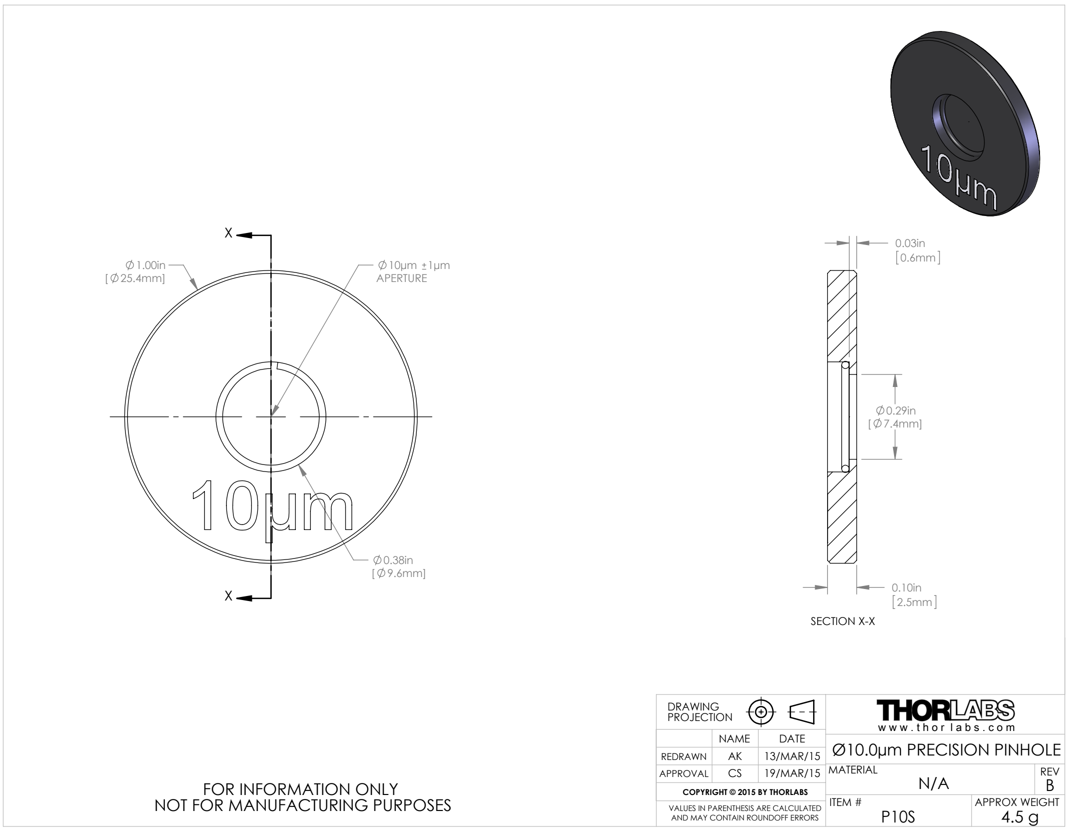
1. DESIGN WAVELENGTH: 633nm
2. EFFECTIVE FOCAL LENGTH: 11.00mm
3. EFL TOLERANCE: ±1%
4. NUMERICAL APERTURE: 0.26
5. WORKING DISTANCE: 6.91mm
6. DIAMETER TOLERANCE: +0.00mm/-0.02mm(HOUSING)
7. CENTER THICKNESS TOLERANCE: ±0.04mm(LENS)
8. LASER WINDOW THICKNESS: 0.275 (N-BK7)
9. SURFACE QUALITY: 60-40 SCRATCH-DIG (INCLUDES ENTIRE BULK MATERIAL)
10. RMS WFE(TYPICAL): 0.030 WAVES
11. MAGNIFICATION: INFINITE
12. REFRACTIVE INDEX (AT DESIGN WAVELENGTH): 1.513
13. COATING(S1&S2): NONE

FOR INFORMATION ONLY
NOT FOR MANUFACTURING PURPOSES

DRAWING PROJECTION			THORLABS www.thorlabs.com	
	NAME	DATE	MOUNTED UNCOATED ASPHERIC COLLIMATING LENS EFL=11.00mm	
DRAWN	SS	14/DEC/10		
APPROVAL	PM	25/MAR/13	MATERIAL D-K59	REV H
COPYRIGHT © 2010 BY THORLABS				
VALUES IN PARENTHESIS ARE CALCULATED AND MAY CONTAIN ROUNDOFF ERRORS			ITEM # A220TM	APPROX WEIGHT 0.2g

Source : www.thorlabs.com

A.3 Pinhole 10 μm



Source : www.thorlabs.com

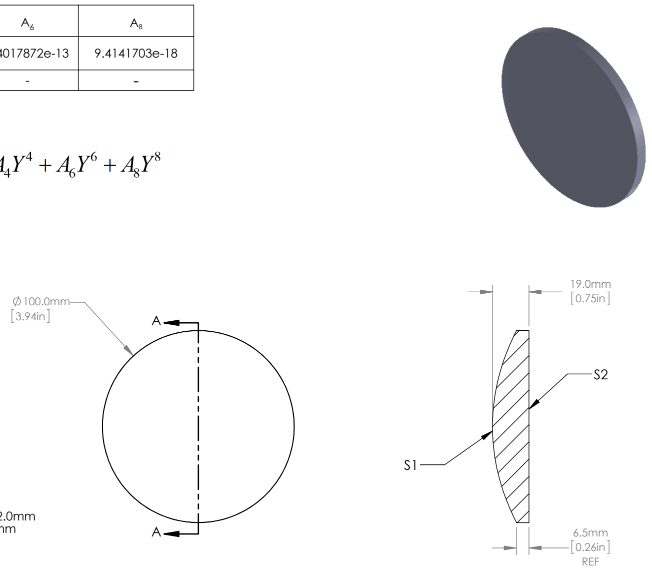
A.4 Converging lens AL100200, f = 200 mm

ASPHERIC COEFFICIENTS

	R	k	A_4	A_6	A_8
S1	102.24	-1	4.9646003e-08	7.4017872e-13	9.4141703e-18
S2	INFINITE	-	-	-	-

ASPHERIC LENS EQUATION

$$z = \frac{Y^2}{R(1+\sqrt{1-(1+k)Y^2/R^2})} + A_4Y^4 + A_6Y^6 + A_8Y^8$$



NOTES/SPECIFICATIONS:
1. CLEAR APERTURE (COLLIMATION): 92.0mm
2. CLEAR APERTURE (FOCUSING): 89.4mm
3. FOCAL LENGTH: EFL=200mm ±1%
4. Nd: 1.517 ±0.001 Vd: 64.167 ±1.0%
5. DESIGN WAVELENGTH: 780nm
6. NUMERICAL APERTURE: 0.23
7. WORKING DISTANCE (REF): 187.4mm
8. DIAMETER TOLERANCE: +0.00/-0.10mm
9. SURFACE QUALITY: 40-20 SCRATCH-DIG
10. RMS WAVEFRONT ERROR: <0.5µm
11. SAG DEVIATION (POWER)(S1): ±7.5µm
12. RMS IRREGULARITY (S1): <3 FRINGES
13. CENTRATION: <3arcmin
14. MAGNIFICATION: INFINITE

FOR INFORMATION ONLY
NOT FOR MANUFACTURING PURPOSES

DRAWING PROJECTION

	NAME	DATE
DRAWN	NE	10/OCT/14
APPROVAL	BW	18/NOV/14

VALUES IN PARENTHESIS ARE CALCULATED AND MAY CONTAIN ROUNDOFF ERRORS

THORLABS
www.thorlabs.com

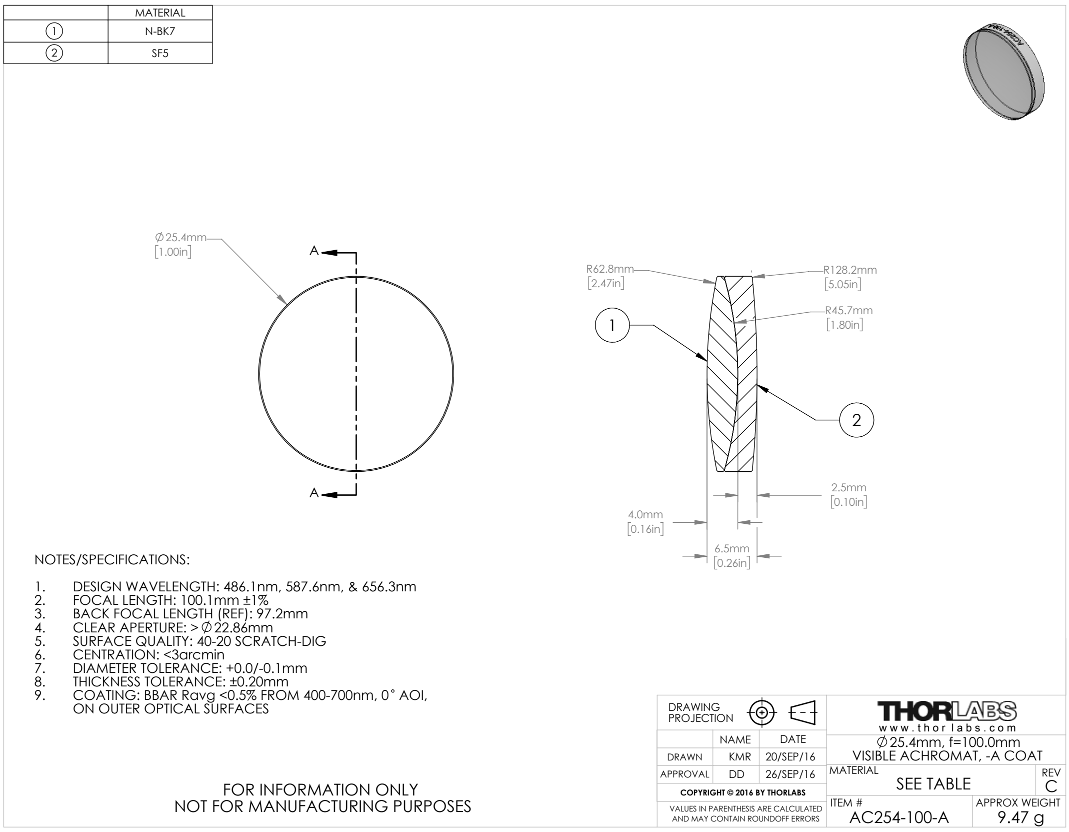
Ø 100.0mm ASPHERIC LENS, NA=0.23, f=200mm

MATERIAL: N-BK7 — REV: A

ITEM #: AL100200 — APPROX WEIGHT: 0.6 kg

Source : www.thorlabs.com

A.5 Converging lens AC254-100-A, f = 100 mm



Source : www.thorlabs.com

A.6 Ximea Camera, MQ013MG-E2

Specifications:

Resolution:	1.3 MP 1280 × 1024 pixels
Sensor type:	CMOS Matrix B/W
Sensor model:	e2V EV76C560 ABT-EQV
Sensor size:	1/1.8"
Sensor active area:	6.9 × 5.5 mm
Pixel size:	5.3 µm
Bits per pixel:	8, 10
Dynamic range:	60 dB
Frame rates:	60 fps
On-chip binning:	1x1, 2x2
Image data interface:	USB 3.0
Data I/O:	GPIO IN, OUT
Power requirements:	0.9 Watt
Lens mount:	C or CS Mount
Weight:	26 grams
Dimensions WxHxD:	26 x 26 x 26 mm
Operating environment:	50 °C
Customs tariff code:	8525.80 30 (EU) / 8525.80 40 (USA)
ECCN:	EAR99

Source : www.ximea.com/en/products/usb3-vision-cameras-xiq-line/mq013mg-e2

A.7 Shack-Hartmann wavefront sensor, WFS150-5C

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)

Source : WFS Series Operation Manual, www.thorlabs.com

Bibliography

Bouxin, A. (2017). "Phasor diversity to measure the static aberrations of an optical system". MA thesis. HEIG-VD.

Thorlabs (2017). *Principles of Spatial Filters*. Thorlabs. URL: https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=1400.