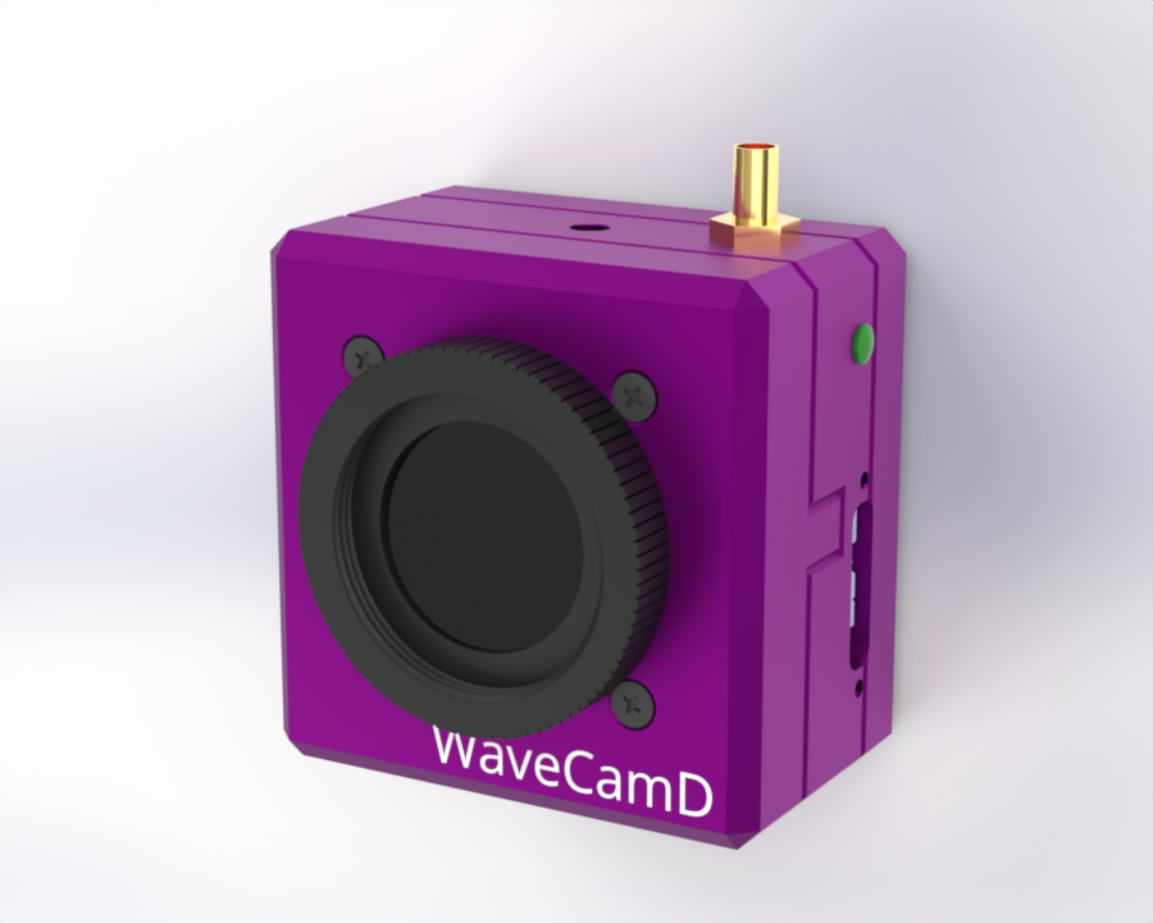
WaveCamD Manual



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Chapter 0

Very Important

Read this entire section first

0.1 Precautions and Safety Warnings

Do not skip this. If you do not take these precautions, you may damage the equipment or your eyes.

- Always look-up or measure the beam power and try to estimate the beam diameter before analyzing a laser beam for the first time. Ensure that it meets the maximum irradiance and maximum power limits in the specifications.
- Be aware of the laser beam path and its reflections. Where appropriate use beam blocks and wear proper eye protection for the wavelength being analyzed.

0.2 Quick Start Guide

- Register your product at https://dataray.com/resources/product-registration
- Install the software before connecting the camera from included USB drive or from the website.
- Connect USB cable to the WaveCamD using locking screws. Connect the camera to your PC, preferably to a USB 3.0 port of any compatible device.

- **Start the software**. Select the WaveCamD from the drop down menu in the top left corner. The camera LED will go from red to green. If it stays red, the port is not reporting itself as USB 3.0/2.0.
- Press Start to begin capturing data. Measurements will update live.
- To avoid camera damage, **observe the power/energy limits**. Damaged image sensors are replaceable but at customer's expense.

Centering. Stay within the imaging area for accurate measurements. If energy spills outside the imaging area, erroneous measurements may result.

Save files for future reference: In the top menu bar choose **File** → **Save** → **Save current image as HDF5 file** to save the current single profile/image. Or choose **Save all images as HDF5 file** to save the entire data sequence, particularly if you are seeing instability. The saved file (*.H5 format) includes setup data and image data, so it can be opened again on any PC to display the data exactly as seen when saved.

If you are getting strange results, e.g. corrupted screen layout, press Stop. Click **Change Settings→Set Defaults** to reset to default settings. You may also restart the software. If the problem persists, save an ***.h5** file (see above) and email it to support@dataray.com or to your distributor. Include your commentary and the S/N found on your camera. You may then wait for an answer or call support at +1-831-215-2200, Option 2.

Read the manual. Please familiarize yourself with each section of this manual. Reading the manual will allow you to properly and fully use the WaveCamD and software features.

Software Bugs? We attempt to deliver bug-free software, but it is difficult to test all permutations and combinations of beam size, capture block, processing option, etc. Some error messages are warnings only. Some require the software to be restarted. Take a screenshot (**Windows key+Shift+S**). Then press **OK** and see whether you can continue to use the software.

Additional Information. Our website provides additional documentation including

many Application Notes and blog posts that may be helpful.

If you have a problem, please note the details. *Wherever possible* capture a relevant ***.h5** data file, and email the file along with the details of the PC, the problem, and the WaveCamD S/N to support@dataray.com. We will attempt to resolve the issue as soon as possible.

Chapter 1

Introduction

This manual covers the DataRay Shack-Hartmann Wavefront Sensor (SHWFS), the WaveCamD, and the software, WaveSight, which controls it. The WaveCamD provides accurate measurement of the wavefront shape of incoming light. The WaveCamD utilizes a high-resolution CMOS sensor and a microlens array (MLA) to perform a single-shot reconstruction of an incident wavefront. When a wavefront is incident on the MLA it is focused into an array of spots on the sensor plane. The deviation of the center of each of these spots, called beam centroids, can be compared to the expected spot location for a planar wavefront. From this information, we can determine the local wavefront slope and reconstruct the wavefront, whether that be via Zernike fitting or numerical methods.

Each WaveCamD has calibration data stored on the camera hardware. The calibration is performed at the DataRay factory. The calibration data contains appropriate offset values to account for any deviation from ideal for each subaperture of the MLA. The calibration is described in detail in Appendix C. This calibration cannot be overwritten by the user. If the MLA is removed or damaged, the WaveCamD must be sent back to the factory for recalibration.

1.1 System Features

- 9 x 9 mm AR coated microlens array (MLA) with AR coating options:
  - UV (250-450 nm)

  - VIS (400-900 nm)
  - NIR (750-1350 nm)
- 60 x 60 lenslets, 150 μm pitch, 5.2 mm focal length
- λ/30 wavefront accuracy, λ/100 sensitivity
- Zonal (numerical) and modal (Zernike) wavefront reconstruction
- 5.5 μ m pixels, 4.2 MPixel
- Port-powered USB 3.0
- HyperCal™ – Dynamic Noise and Baseline Correction software
- C-mount or MagND filters
- 2,500:1 Signal to RMS Noise
- Global shutter with TTL trigger
- Electronic auto-shutter, 85 µs to 2 sec (44 dB)
- 12-bit ADC
- Full ROI frame rate >9 Hz
- Compatible with DataRay LaserLink for HTTP communication (see Chapter 4)

1.2 System Configuration and Description

- Wavefront Sensing Camera
- Cable
- USB Drive
- ND filters

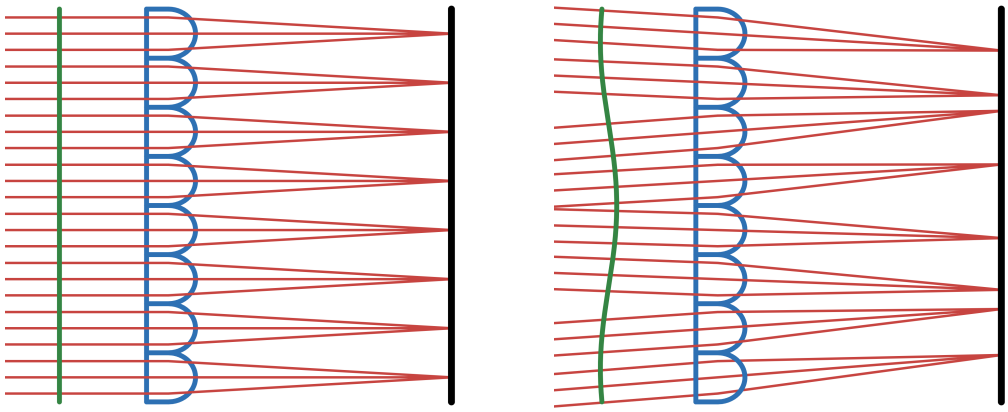
1.3 Applications

- One-shot wavefront measurements
- Beam collimation
- Real-time beam alignment
- Aberration characterization
- Adaptive Optics
- Optics Inspection

1.4 Theory of Operation

This section serves as a brief introduction to the theory of operation of the WaveCamD Wavefront Sensor. A more detailed discussion can be found in Appendix D.

The WaveCamD utilizes a Shack-Hartmann Wavefront Sensor (SHWFS). These sensors are composed of a microlens array (MLA) positioned precisely in front of a camera sensor such that focal plane of the MLA coincides with the sensor measurement plane, shown in Figure 1.1a.



(a) Flat wavefront passing through MLA

(b) Distorted wavefront passing through MLA

Figure 1.1: Flat vs. curved wavefront

For a perfectly constructed wavefront sensor, a flat wavefront will produce a grid of evenly spaced beam spots on the camera sensor. The spacing of this grid is equal to the pitch of the MLA lenslets, with the centroid of each beam corresponding to the center of each lenslet. These centroid locations are called **Reference Centroids**. However, if light enters a lenslet at an angle, the resulting refocused beam spot will be offset in x and y on the sensor, shown in Figure 1.1b. These displaced centroids are referred to as **Measured Centroids**.

The slope of the wavefront in the x and y direction at each lenslet is directly related to the difference between the **Measured Centroid** positions and the **Reference Centroid** positions. The wavefront must then be reconstructed from these wavefront

slopes.

DataRay's WaveSight software currently features two separate methods to reconstruct wavefronts, **Modal Reconstruction** using Zernike polynomials and **Zonal Reconstruction** using numerical integration.

Modal Reconstruction fits a polynomial expansion to the measured wavefront slopes. For example, using Zernike polynomials, in addition to providing the reconstructed wavefront shape, allows users to gain valuable insight into specific types of aberrations present in the wavefront.

Zonal Reconstruction, in contrast to **Modal Reconstruction**, relies on numerically integrating the slope data directly. Many numeric integration methods exist, but the DataRay WaveSight software uses Southwell integration due to high accuracy and speed. Zonal reconstruction does not rely on a polynomial basis, so it avoids smoothing the wavefront. Additionally, zonal reconstruction is valid for rectangular apertures, while Zernike polynomials are best suited for circular pupils.

1.5 Coordinate System

While each individual beam centroid is measured on the WaveCamD's camera sensor, the measurement plane is actually at the MLA itself. We define this plane as the $x-y$ plane. The origin of x and y is at the bottom left corner of the MLA when viewed from the front of the camera. The surface of the wavefront itself extended perpendicularly from the $x-y$ plane in the z direction. Positions in front of the MLA correspond to positive z, positions behind corresponding to negative z. The coordinate system is shown in Figure 1.2

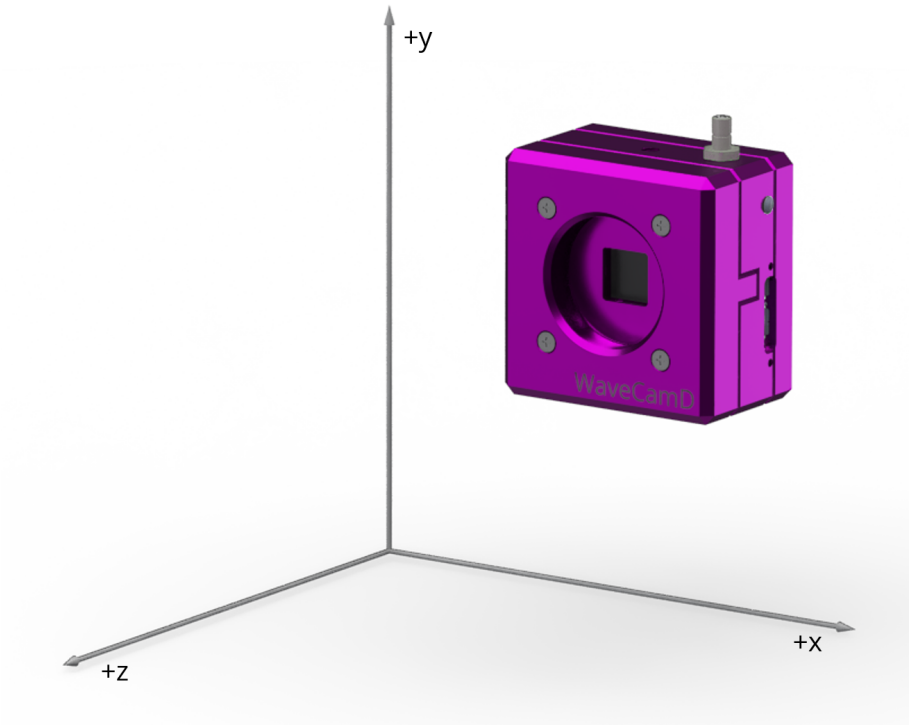


Figure 1.2: Coordinate System

Chapter 2

Software

2.1 Installation and Initialization

1. Run the WaveSightInstaller.exe file (either from the included USB drive or downloaded from the DataRay website).
2. The driver should be installed by the software installer automatically.
3. Connect the WaveCamD by plugging the camera into a USB port.
4. To check that the device was correctly installed, go to **Device Manager** and click the **>** next to **DataRay USB Device**, then double-click the device. If necessary, select the **Driver** tab and then click on **Update Driver** to access the Driver Wizard.

NOTE: The software can be used to view data whether or not the camera is installed.

2.2 Connecting the Camera

It is recommended that you mount the WaveCamD before connecting it.

1. The WaveCamD utilizes #8-32 threaded mounting holes in line with the sensor for easy alignment. See Figure 3.1.
2. Since the active measurement area is 9 millimeters in size, ensure that the Wave-

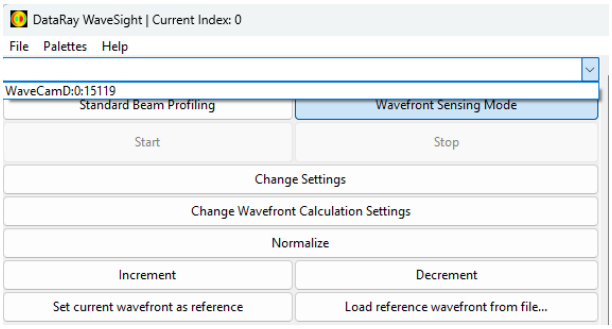


Figure 2.1: WaveCamD selection dropdown menu

CamD or the source assembly can be adjusted in x, y, z, tip, and tilt as necessary for proper alignment.

3. If present, remove the protective cap covering the WaveCamD aperture and install ND filters and attenuation accessories where needed.

4. Coarsely align your laser source with the camera. You can use the target on the c-mount cap.

5. Launch the WaveSight software.

6. Click the down arrow in the upper-left corner of the screen to display a drop down menu with all of the connected WaveCamD devices. See Figure 2.1

7. Select the camera you would like to connect to. The mouse cursor will indicate the software is busy while the camera connects and the calibration data is read.

8. Once the mouse cursor turns back to a pointer, the camera is ready to be used. Hit the Start button to initiate capture.

2.3 Capturing the wavefront

1. The software default mode will display the spot field in the upper 2D image. The spot field shows the array of spots generated by the MLA. The lower image will be raw wavefront as calculated via a 4th order Zernike decomposition.

2. To ensure accurate wavefront results, you must:

(a) Ensure the entirety of the beam falls within the MLA grid.

(b) Ensure at least 15 spots are visible with a strong enough signal.

(c) Adjust the tip/tilt alignment to minimize the Tip Y and Tip X coefficients displayed on the right-hand side of the screen.

3. Once these criteria are met, the software will display the Zernike decomposition on the right-hand side and a variety of calculated values on the left-hand side (see Table 2.4).

2.4 Configuration

To change the camera settings, click the **Change Settings** button. This will open the Settings Dialog (see Figure 2.3) where you can change camera-related settings. See Table 2.1 for more information. These camera settings are stored between WaveSight sessions.

To change settings related to the wavefront calculations, click **Change Wavefront Calculation Settings**. See Table 2.2 for more information. These settings are also stored between WaveSight sessions.

2.5 Image Capture

2.5.1 Saving Data

The best format to save data in is an HDF5 file. This can be done via the File->Save current image option. A HDF5 file contains all of the settings, raw data, and processed data from the measurement. It can be re-opened in WaveSight for review. You can also open it in an external HDF5 Viewer. A number of libraries exist for importing data from HDF5 files in other data analysis software.

Value	Description	Default Value
HyperCal	Toggles HyperCal. HyperCal is a type of background subtraction technique to remove unwanted background patterns from measurements. A dark frame with the lowest possible exposure time will be captured every 16 frames during live data capture and is continuously averaged with previous dark frames up to a 5 frame average. This continuously updated dark frame is subtracted from each full exposure during live data capture to remove unwanted background patterns. There is a minimum exposure time below which HyperCal is automatically disabled to ensure that it does not remove an appreciable amount of the actual beam. This exposure time is approximately 2.5×the minimum exposure time of the camera	Off
ROI_X/Y:	The number of columns/rows of pixels included in each frame	2048x2048
X/Y offset:	The position to start the ROI from bottom left corner. For example a 1024x1024 ROI with a 512x512 offset will result in a centered square half the width and length of the sensor.	(0,0)
Binning:	1x returns every pixel (Full resolution). 2x returns every other pixel on both the x and y axes (thereby returning only one fourth of the total pixels). 2x can increase frame rate at the cost of resolution.	1x
Trigger Mode:	Determines the trigger mode. Software (default) captures images as soon as start is enabled. TTL Positive/Negative will wait for a trigger pulse see Section 3.3 for more information.	Software
Exposure (μs):	Configure the exposure time. Checking "Auto Exposure Enabled" will allow the software to automatically adjust the exposure time such that the ADC Peak approaches 90%.	2000μs Auto Exposure On
Frames to Average:	The number of frames averaged up to a maximum of 20.	5
Auto Exposure Min/Max (μs)	The limits for the auto-exposure algorithm. The WaveCamD hardware limit is 85 μs and 2,000,000 μs.	85 μs and 100,000μs
Gain	Changes the gain of the WaveCamD. This is only recommended for low repetition rate pulsed lasers. For all other scenarios, increasing the exposure time will improve the signal-to-noise ratio more than increasing the gain.	1
Set Defaults	Restores all default values	
Save to/Load from File	Saves/Loads a settings file for easy recall of settings for different applications.	

Table 2.1: Settings Dialog Options

Value	Description	Default Value
Pupil Mode:	Allows to switch between automatically setting the pupil size, manually defining the pupil radius, and manually defining the pupil radius and position. When in Auto, the center of the pupil is calculated as the average x-centroid and y-centroid value over all filled sub-apertures. The pupil radius in Auto mode is calculated by considering the sub-aperture furthest from the center of the array. The pupil shape can be a circle or ellipse.	Auto
Pupil Radius (um):	When a Pupil Mode other than Auto is selected, a circle's radius can be defined.	
Xc/Yc Pupil:	When Fixed Pupil - Defined Radius and Center is selected, a circle's radius and center can be defined.	
MLA Method:	Allows the choice of either numerical or modal (Zernike) reconstruction.	Zernike
Zernike Order Selector	Selects the highest radial degree for the modal reconstruction (total number of radial and azimuthal terms shown in parenthesis). Note: For reconstruction, there need to be at least as many valid subapertures as total modes. Only shown when Zernike is selected for MLA method	4 (15 modes)

Table 2.2: Wavefront Calculation Settings Dialog Options

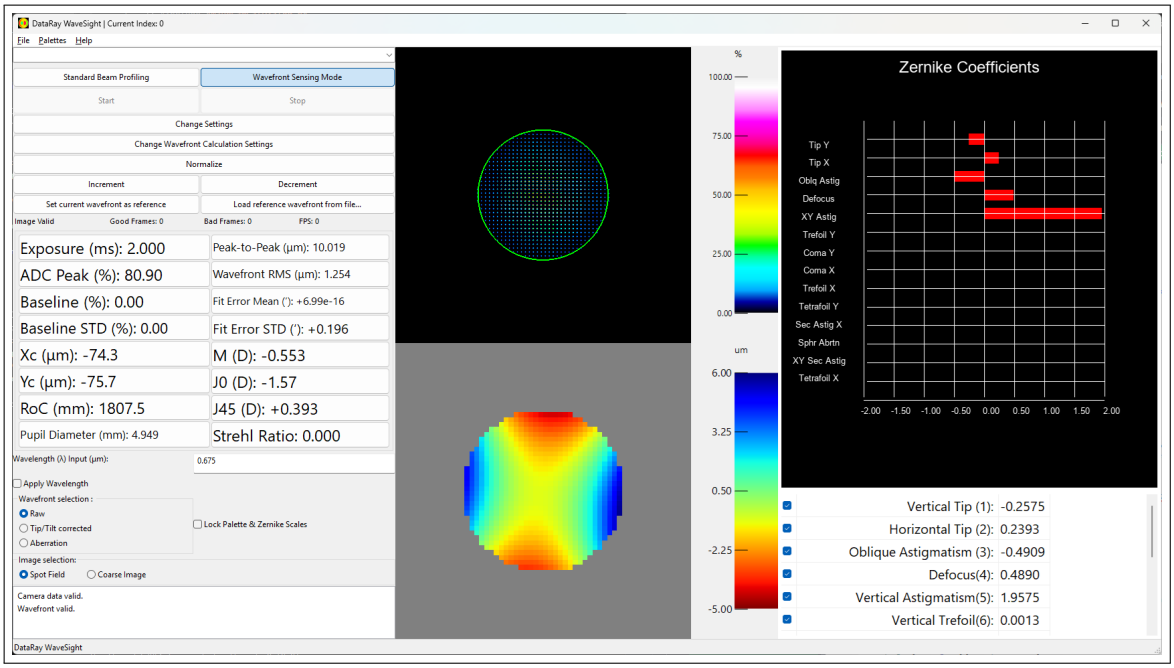


Figure 2.2: Image of the software window

2.6 Left Hand Panel

2.6.1 Standard Beam Profiling Mode

Select this button to treat your WaveCamD as a beam profiler. Each subaperture is treated as a single pixel and beam profiling metrics are calculated and displayed. Descriptions of these values can be found in Table 2.3.

2.6.2 Wavefront Sensing Mode

Selecting this button enables all the wavefront features of the WaveCamD, including wavefront relevant values, modal and numerical reconstruction, and many more.

2.6.3 Start and Stop

Start or stop currently connected wavefront sensor. Only enabled when a wavefront sensor is connected.

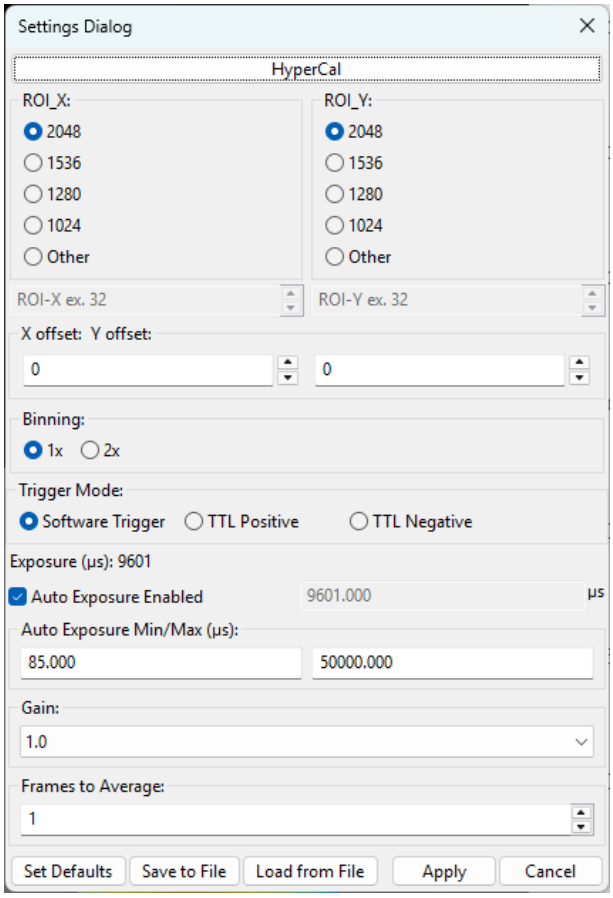


Figure 2.3: The Settings Dialog

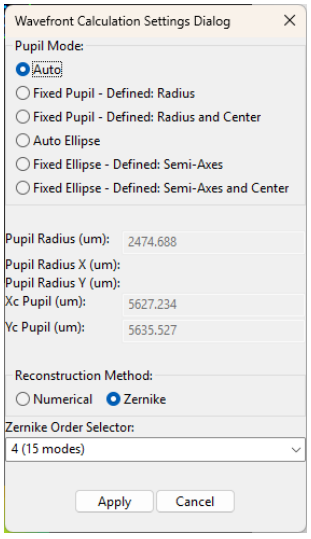


Figure 2.4: The Wavefront Calculation Settings Dialog

2.6.4 Change Settings

Brings up Change Settings Dialog (see Figure 2.3)

2.6.5 Wavefront Calculation Settings

Brings up the WaveFront Calculation Settings Dialog (see Figure 2.4)

2.6.6 Normalize

Normalizes the 2D image (spot field or coarse beam profile).

2.6.7 Increment and Decrement

Only available when an image buffer exists. This can be from a stopped camera or after opening a multi-image HDF5 file.

2.6.8 Set current wavefront as reference

Enables comparative measurements to the current measured wavefront. All subsequent wavefronts are relative to this wavefront. This mode is useful in instances where a reference unit or "golden unit" with the desired specifications exists. It allows users to see deviations from the expected wavefront. When a reference wavefront exists, this button changes to **Clear reference wavefront**. Clicking on it will switch the wavefront measurement back to absolute.

2.6.9 Load reference wavefront from file...

Opens a file selection dialog and enables comparative measurements to the wavefront in the selected file.

2.6.10 Display Options

The **Wavelength (λ) Input (μm)** options allow for calculating the wavefront in units of waves. Enter the wavelength in microns in the field and check **Apply Wavelength**. Now the 2D- plot and values described in Table 2.4 will be shown in waves. The Wavefront selection allows a choice of **Raw**, **Tip/Tilt corrected** or **Aberration**. This selec-

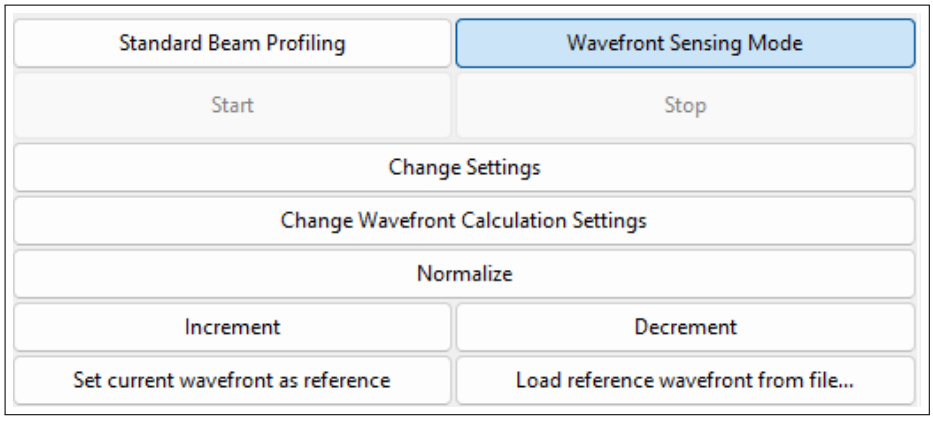


Figure 2.5: Buttons at top left of software

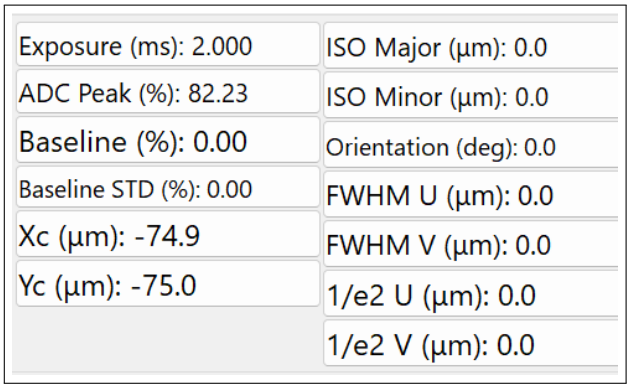


Figure 2.6: Standard beam profiling metrics

tion changes the wavefront used for visualization, the **Peak-to-Peak** calculation, and the **Wavefront RMS** calculation.

- **Raw** is the raw wavefront with no correction applied.
- **Tip/Tilt corrected** has the Tip X and Tip Y subtracted out
- **Aberration** has the Tip X, Tip Y, and Defocus subtracted out, only showing higher order aberrations which may be more applicable for the user.

Lock Palette and Zernike Scales fixes the color bar values and Zernike Coefficient's x-axis to make easier comparisons and adjustments for dynamic sources.

The image selection allows a choice of **Spot Field** or **Coarse Image**. The **Spot Field**

Value	Units	Description
ISO Major	μm	Major diameter calculated according to ISO 11146
ISO Minor	μm	Minor diameter calculated according to ISO 11146
Orientation	degrees	The angle between the x-axis and the major or minor axis closest to the x-axis.
FWHM U	μm	The full-width at half maximum (50% clip level) beam diameter along the major axis[1]
FWHM V	μm	The full-width at half maximum (50% clip level) beam diameter along the minor axis[1]
$1/e^2$ U	μm	The $1/e^2$ (13.5%) clip-level beam diameter along the major axis[1]
$1/e^2$ V	μm	The $1/e^2$ (13.5%) clip-level beam diameter along the minor axis[1]
Xc	μm	X-Location of the crosshair center from the center of the full sensor[2]
Yc	μm	Y-Location of the crosshair center from the center of the full sensor[2]

[1] The data is first clipped at 13.5% and then the ISO 11146 method used to determine the orientation of the beam. Once the orientation has been found, the diameter of the beam along the Major and Minor axes is determined using the clip level method.

[2] Crosshair location is located at beam centroid, calculated based on the weighted intensity of the pixels.

Table 2.3: Parameters seen when **Standard Beam Profiling** is selected.

shows the spots focused from the MLA onto the sensor. This is the raw image from the CMOS sensor. The **Coarse Image** treats each sub-aperture as a single pixel, showing the relative spatial intensity of the incident beam.

2.6.11 Messages

WaveSight will give helpful notices to the user. Under nominal conditions, the box will say *Camera data valid* and *Wavefront valid*. If WaveSight detects an issue with the data, it will provide a useful message here. These are split between two categories: Camera and Wavefront. For invalid data due to the camera, some possible error messages are:

- *Poor signal-to-noise ratio. Try decreasing attenuation* which indicates that the signal strength is low compared to the noise. Try increasing power or decreasing attenuation.

Value	Units	Description
Peak-to-peak Wavefront	μm / Waves	The difference from the maximum wavefront to minimum wavefront for current displayed wavefront (raw or aberration). Click **Apply Wavelength** to display number in waves.
Wavefront RMS	μm / Waves	The RMS aberration of the currently displayed wavefront.
Fit error mean	arc-min	
Fit error std	arc-min	
M	Diopters	Average Spherical Power
J0	Diopters	0˚/90˚ Jackson cross-cylinder component for Astigmatism
J45	Diopters	45˚/135˚ Jackson cross-cylinder component for Astigmatism
Pupil Diameter	mm	Circle of interest for Zernike reconstruction. See Figure 2.4 for options.
RoC	mm	Radius of Curvature
Strehl Ratio		The Strehl ratio indicates optical quality. A 1 indicates a perfect system. As aberration increases, the Strehl ratio approaches 0.

Table 2.4: Parameters seen when **Wavefront Sensing Mode** is selected.

- *Check beam alignment. Calculated centroid outside camera sensor* which indicates the beam is not entirely on the microlens array. Try adjusting your alignment.
- *ADC saturated. Lower power or increase attenuation* which indicates the WaveCamD is being over-driven. Try decreasing power or increasing attenuation.
- *ADC offset still adjusting* which indicates the closed-loop ADC offset adjustment has not settled. After the background/ambient light is changed, the ADC often needs several frames to adjust. This message should clear on its own.
- *Frames still averaging* which indicates that the user has set the number of frames to average to greater than 1 and the camera has not yet captured that many

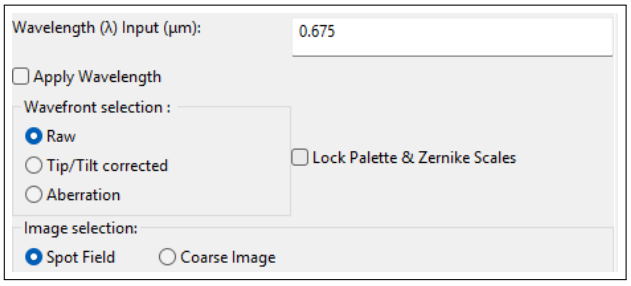


Figure 2.7: Various display options

images. This message should clear on its own.

- *HyperCal initializing* which indicates that HyperCal has been turned on but hasn't yet collected enough frames. This message should clear on its own.

For Wavefront, some possible error messages are:

- *Pupil too large (sensor over-filled)* which indicates that the beam is overfilling the microlens array. Try profiling where the beam diameter is smaller.
- *Not enough valid subapertures* which indicates the beam is not covering enough subapertures for an accurate wavefront reading. This could be caused by the total power in the subaperture being too low.

2.7 Visualizations

2.7.1 Spot Field

The 2D plot shows the output from the CMOS sensor. You can adjust the zoom on this image by rolling the mouse wheel or pinching in and out on a trackpad. There are several options available by right-clicking.

Export to PNG Exports the current image to a .png file. If clicked, a save dialog box will appear.

Enable Grid Overlay Enables a red grid that shows the sub-apertures that are aligned to the microlens array. There are white X's shown in the center. All spots should fall

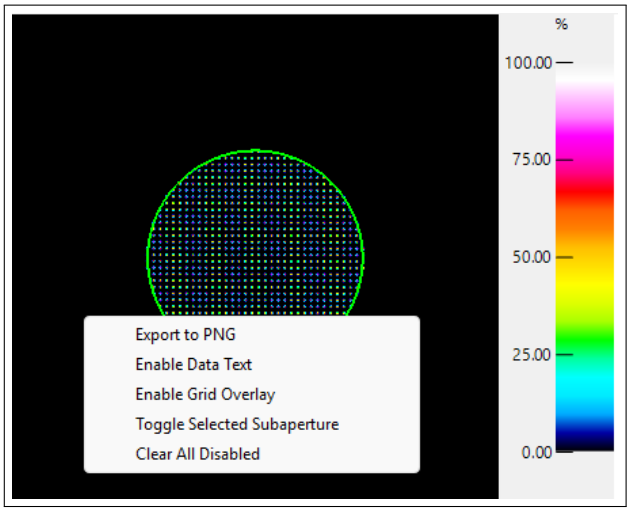


Figure 2.8: Raw spot field with right-click options

within this grid. If spots fall outside of the grid, X-tilt, Y-tilt, and/or defocus of the source may need to be adjusted. See Figure 2.9

Enable Data Text Shows relevant information for the pixels over the mouse cursor such as ADC peak, and X and Y positions.

Toggle Selected subaperture Disables subapertures that the user does not want to be included in the calculation

Clear All Disabled Re-enables all disabled subapertures.

2.7.2 Wavefront plot

False color plot of the reconstructed wavefront according to the settings chosen.

2.7.3 Zernike Coefficients

The Zernike Coefficients plot shows the value of each Zernike coefficient as a bar graph and values in microns.

Export as PNG Exports the current plot to a .png file. When clicked, a save dialog box will appear.

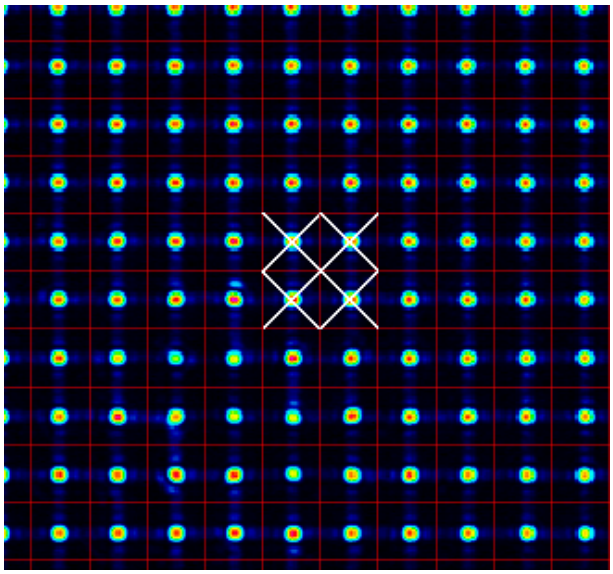


Figure 2.9: Spot field with grid enabled

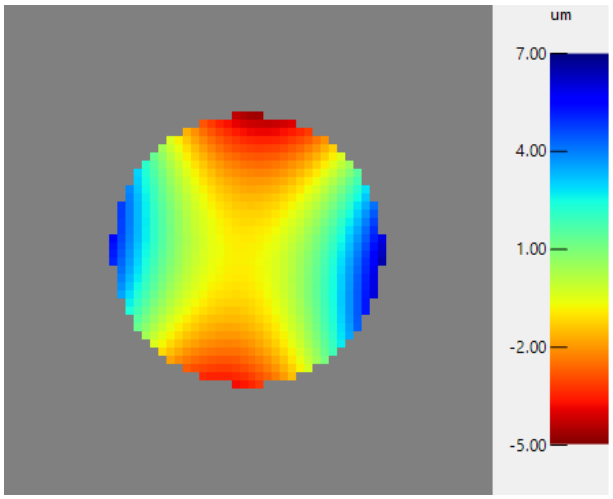
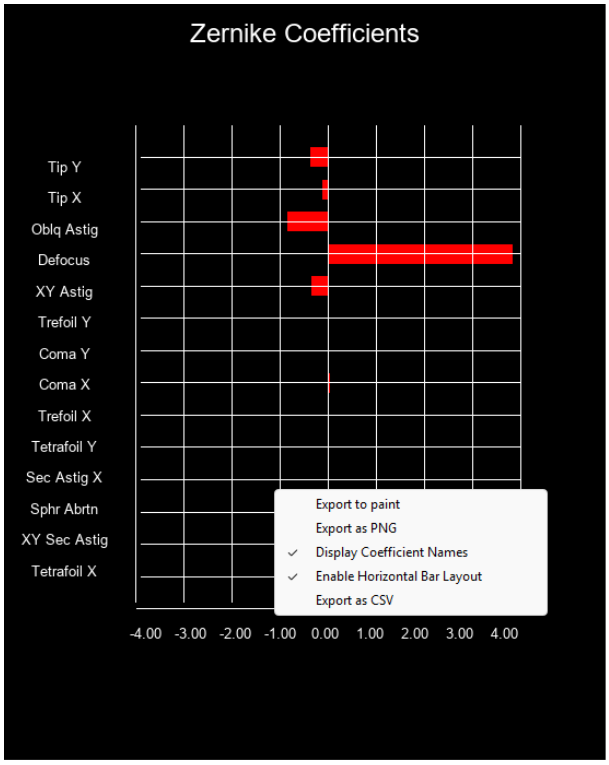


Figure 2.10: Wavefront plot with right-click options



Vertical Tip (1):	-0.3916
Horizontal Tip (2):	-0.1454
Oblique Astigmatism (3):	-0.8679
Defocus(4):	3.8257
Vertical Astigmatism(5):	-0.3544
Vertical Trefoil(6):	0.0016

Figure 2.11: Zernike Coefficients plot and values

Display Coefficient Names Toggles between names of aberrations and their index according to the ANSI scheme. See Table A.1.

Enable Horizontal Bar Layout Enabled by default, shows a horizontal bar graph. By disabling, the bar chart is shown vertically.

Export as CSV Exports the values as a CSV file. When clicked, a save dialog box will appear.

Below the plot shows the values for each Zernike coefficient. The check boxes to the left of plot allow the bar plots above to be disabled and the axis to adjust accordingly (as long as **Lock Palette and Zernike Scale is unchecked**). A useful feature if smaller aberrations are of interest, but larger aberrations are making the bars too small to discern. You can scroll down to see the higher-order terms if needed.

2.8 Menus

2.8.1 File

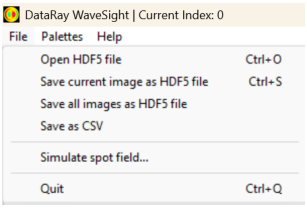


Figure 2.12: File menu options

Open HDF5 File Opens a dialog box to select a .h5 file to load. Once opened, the .h5 file will show all relevant parameters of the wavefront measurement, the spot field, and the reconstructed wavefront. The wavefront calculation settings on the opened file can be changed as needed.

Save current image as HDF5 file Saves the current image as an HDF5 file. These files can be re-opened in WaveSight.

Save as CSV Saves a series of CSV files containing the settings, results, and aberration wavefront for the current image.

Save All Images as HDF5 file Saves all images in the current image buffer as an HDF5 file. These files can be re-opened in WaveSight.

Simulate spot field... Brings up the Simulate Wavefront dialog. This dialog allows you to generate a spot field based on an artificial wavefront. The dialog (see Figure 2.13) allows the user to enter the MLA type, the focal length of the MLA, the standard deviation of the noise to add to the image, the pupil radius (circle), or pupil semi-axis (elliptical), and a series of Zernike terms. Wavesight will generate a wavefront based on these values and then back-calculate the spot field that this wavefront would generate with the given MLA. If the entered Zernike values will cause a centroid to move outside of its intended MLA sub-aperture, the software will give an error. This reflects the hardware limitation of the MLA's geometry.

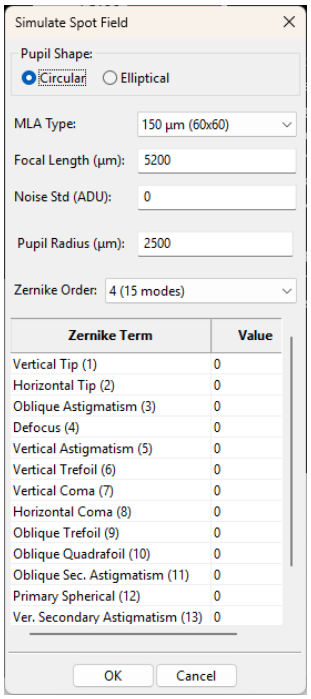


Figure 2.13: Simulate Wavefront dialog

Quit Quits WaveSight. Current camera and processor settings are stored such that they will be maintained between software sessions.

2.8.2 Palettes

WaveSight allows the user several customization options. These options are stored in a file when the software is closed and recalled when the software is re-opened such that your palette settings will stay consistent between sessions.

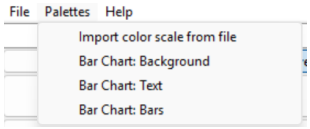


Figure 2.14: Palettes menu options

Import color Scale from file WaveSight uses the "jet" color palette which transitions smoothly from dark blue (most positive wavefront) to cyan, yellow, and dark red (most negative wavefront) by default. However, the user can change this. Selecting Import color scale from file will bring up a file dialog. The user can then select an appropriately formatted CSV file. The CSV file should be formatted with 16384 rows and 3 columns to represent Green-Red-Blue values for each of the 16384 discrete values WaveSight's wavefront image can contain. Each Green-Red-Blue value should be between 0 and 255. A CSV file jet_r_color_palette.csv is copied to the PC's local application data folder.

Bar Chart: Background Allows user to select the background color of the bar chart.

Bar Chart: Text Allows user to select the text color of the bar chart.

Bar Chart: Bars Allows user to select the bar color for the bar chart.

Select Data Button Palette Opens up the Data Button Palette Dialog (see 2.15). This allows the user to set colors for when a value is within the user-entered limits. To set limits for any data button, left-click on it to open the Pass/Fail dialog (see 2.16). In this dialog you can enter a max and min value to compare the current value to. If you check the Enable Test box, then this data button will become color coded.

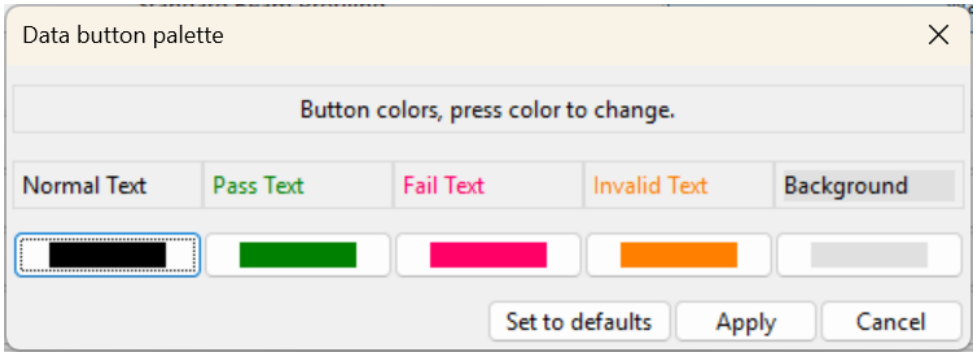


Figure 2.15: Data Button Palette Dialog

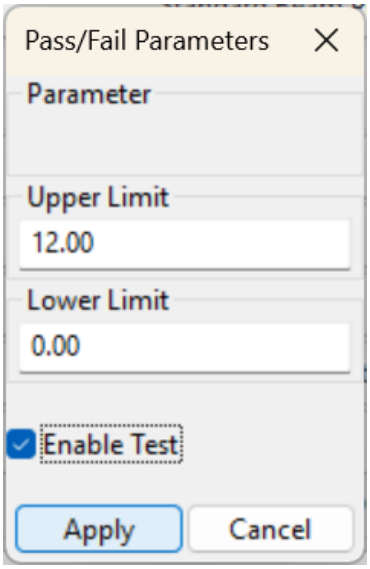


Figure 2.16: Data Button Pass/Fail Dialog

2.8.3 Help

About Displays information about the software including version numbers, copyright, and 3rd party libraries.

Chapter 3

Hardware

3.1 CMOS Sensor

The WaveCamD uses a CMOS sensor to detect incident laser radiation after being focused by the MLA. See Table 3.1 for more information.

Specification	Value
Resolution:	2048 x 2048 (4.2 MP)
Format:	1”
Size:	11.3 x 11.3 mm
Pixel Pitch:	5.5 μm
Response:	250-1350 nm
Shutter Type:	Global
ADC:	12-bit
Electronic Auto Shutter	85 μs to 2 s (44 dB)
Signal to RMS Noise	2,500:1
Frame Rate	>9 Hz at full ROI

Table 3.1: CMOS Sensor Specifications

3.2 Microlens Array

The WaveCamD uses a Microlens array to focus local wavefronts onto the CMOS sensor. See Table 3.2 for more information.

Specification	Value
Subapertures:	60x60
Lenslet pitch:	150 μm
Material:	Fused Silica
Focal Length:	5.2 mm
AR Coating:	-UV: 250-450 nm -VIS: 400-900 nm -NIR: 750-1350 nm

Table 3.2: Microlens Array Specifications

3.3 External Trigger

The WaveCamD features a TTL trigger using an SMB port to synchronize capture with laser pulses. There are options for both TTL Positive and TTL Negative where the capture can be started at the start or end of a 5V TTL pulse, respectively.

3.4 Frame Rate

The achievable frame rate of the WaveCamD is dependent on a number of factors: exposure time, ROI size, binning, wavefront calculation method, and pupil diameter. Table 3.3 shows the achievable frame rate for several permutations of these factors.

3.5 Outline and Mounting

An outline and mounting drawing can be found in Figure 3.1

Table 3.3: Frame rate vs. acquisition and wavefront reconstruction settings

Pupil Diameter (mm)	Exposure Time (ms)	ROI Width	ROI Height	Binning	Wavefront Method	FPS (Hz)
8	0.085	2048	2048	1	Zernike (10th order)	9.6
8	0.085	2048	2048	1	Zernike (2nd order)	9.6
8	0.085	2048	2048	1	Numeric	9.9
8	0.085	1024	1024	2	Numeric	22
8	0.085	1024	1024	2	Zernike (4th order)	22
8	40	1024	1024	2	Zernike (10th order)	11
8	30	1024	1024	2	Zernike (10th order)	12
1.2	0.085	512	512	1	Zernike (4th order)	45
1.2	0.085	512	512	1	Zernike (10th order)	45
1.2	0.085	512	512	1	Numeric	45

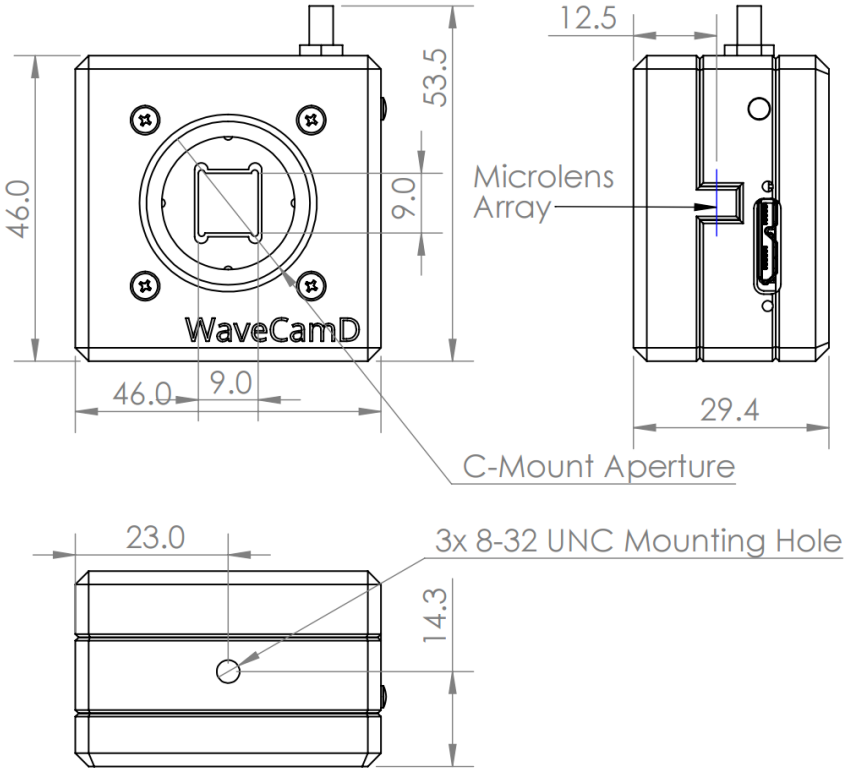


Figure 3.1: Outline and mounting of WaveCamD

Chapter 4

Interfacing

WaveSight is the primary application for interactively operating the WaveCamD, but many users also want to control the camera or retrieve measurement data from their own software — a custom test bench, a LabVIEW or Python automation script, or a larger instrument control system — without driving the WaveSight interface directly.

4.1 LaserLink

DataRay LaserLink is a companion application that exposes WaveCamD control and measurement data over a local HTTP interface, allowing the camera to be operated and read from external software instead of through the WaveSight GUI. LaserLink communicates via standard HTTP requests, so it can be integrated into most automation environments without specialized drivers.

For an overview of LaserLink and its capabilities, see dataray.com/resources/laserlink.

Complete LaserLink documentation, including its API reference, is installed locally with the DataRay software and can be opened from

```
C:\Program Files\DataRay Inc\Documentation
```

where the `index.lnk` shortcut opens the documentation index.

Appendices

Appendix A

Zernike Polynomials

Zernike polynomials are a polynomial basis commonly used to quantify aberrations in optical systems. Each polynomial term is described by an n, m pair and corresponds to a specific type of aberration. For example $n = 2, m = 0$ indicates defocus and $n = 2, m = 2$ corresponds to vertical astigmatism.

Each Zernike term is multiplied by a scalar factor (typically called a Zernike coefficient) which describes the magnitude of the aberration. DataRay's WaveSight software can automatically calculate these coefficients in real-time.

Identifying a Zernike term by the n, m pair is unambiguous, but it is often convenient to reduce these two values into a single index. DataRay's WaveSight software and this manual uses ANSI Z80.28/ISO 24157 indexing as explained in Appendix E. However, care should be taken when comparing single-index Zernike terms from other sources, because other indexing schemes exist.

While there are infinite Zernike polynomial terms, truncated sets of Zernike polynomials can still be used to quantify wavefronts with a high degree of accuracy. Up to 7th degree normalized polynomials are shown in Tables A.1 and A.2. DataRay's WaveSight software offers up to 10th degree polynomials (66 total terms).

Zernike polynomials are only defined on a unit disk ($0 < \rho < 1$). However, larger domains can be scaled to $\rho \leq 1$ and still be accurately described by Zernike polynomials. DataRay's WaveSight software allows users to scale using an automated pupil

radius algorithm or by manually entering a fixed pupil radius.

Index	Name	Radial Degree(n)	Azimuthal Degree(m)	Polynomial
0	Piston	0	0	1
1	Y-Tilt	1	-1	$2\rho \sin\phi$
2	X-Tilt	1	1	$2\rho \cos\phi$
3	Oblique Astigmatism	2	-2	$\sqrt{6}\rho^2 \sin 2\phi$
4	Defocus	2	0	$\sqrt{3}(2\rho^2 - 1)$
5	Vertical Astigmatism	2	2	$\sqrt{6}\rho^2 \cos 2\phi$
6	Vertical Trefoil	3	-3	$\sqrt{8}\rho^3 \sin 3\phi$
7	Vertical Coma	3	-1	$\sqrt{8}(3\rho^3 - 2\rho) \sin\phi$
8	Horizontal Coma	3	1	$\sqrt{8}(3\rho^3 - 2\rho) \cos\phi$
9	Oblique Trefoil	3	3	$\sqrt{8}\rho^3 \cos 3\phi$
10	Oblique Quadrafoil	4	-4	$\sqrt{10}\rho^4 \sin 4\phi$
11	Oblique Secondary Astigmatism	4	-2	$\sqrt{10}(4\rho^4 - 3\rho^2) \sin 2\phi$
12	Primary Spherical	4	0	$\sqrt{5}(6\rho^4 - 6\rho^2 + 1)$
13	Vertical Secondary Astigmatism	4	2	$\sqrt{10}(4\rho^4 - 3\rho^2) \cos 2\phi$
14	Vertical Quadrafoil	4	4	$\sqrt{10}\rho^4 \cos 4\phi$
15		5	-5	$\sqrt{12}\rho^5 \sin 5\phi$
16		5	-3	$\sqrt{12}(5\rho^5 - 4\rho^3) \sin 3\phi$
17		5	-1	$\sqrt{12}(10\rho^5 - 12\rho^3 + 3\rho) \sin\phi$
18		5	1	$\sqrt{12}(10\rho^5 - 12\rho^3 + 3\rho) \cos\phi$
19		5	3	$\sqrt{12}(5\rho^5 - 4\rho^3) \cos 3\phi$
20		5	5	$\sqrt{12}\rho^5 \cos 5\phi$

Table A.1: Zernike terms

Index	Radial Degree(n)	Azimuthal Degree(m)	Polynomial
21	6	-6	$\sqrt{14}\rho^6 \sin 6\phi$
22	6	-4	$\sqrt{14}(6\rho^6 - 5\rho^4) \sin 4\phi$
23	6	-2	$\sqrt{14}(15\rho^6 - 20\rho^4 + 6\rho^2) \sin 2\phi$
24	6	0	$\sqrt{7}(20\rho^6 - 30\rho^4 + 12\rho^2 - 1)$
25	6	2	$\sqrt{14}(15\rho^6 - 20\rho^4 + 6\rho^2) \cos 2\phi$
26	6	4	$\sqrt{14}(6\rho^6 - 5\rho^4) \cos 4\phi$
27	6	6	$\sqrt{14}\rho^6 \cos 6\phi$
28	7	-7	$4\rho^7 \sin 7\phi$
29	7	-5	$4(7\rho^7 - 6\rho^5) \sin 5\phi$
30	7	-3	$4(21\rho^7 - 30\rho^5 + 10\rho^3) \sin 3\phi$
31	7	-1	$4(35\rho^7 - 60\rho^5 + 30\rho^3 - 4\rho) \sin \phi$
32	7	1	$4(35\rho^7 - 60\rho^5 + 30\rho^3 - 4\rho) \cos \phi$
33	7	3	$4(21\rho^7 - 30\rho^5 + 10\rho^3) \cos 3\phi$
34	7	5	$4(7\rho^7 - 6\rho^5) \cos 5\phi$
35	7	7	$4\rho^7 \cos 7\phi$

Table A.2: Zernike terms cont.

Appendix B

HDF5 Files

DataRay has chosen to store all of WaveSight's settings, raw data, and results in a file format called HDF5. HDF5 (Hierarchical Data Format version 5) is an open-source file format and software library designed to store and manage large, complex, and heterogeneous datasets. HDF5 offers several significant advantages:

- It is widely used and is supported in a number of data analysis environments (Python, MATLAB, R).
- It allows us to store settings/results/etc. in a human-readable format. You can use a free program like HDFView to review results or settings.
- It allows for fast reading/writing

An HDF5 file saved in WaveSight can be re-opened in WaveSight, allowing the current user to see the data exactly as it was saved. Each image saved in an HDF5 file from WaveSight, will contain the following groups:

- Aberration Wavefront Results - this contains the 2 dimensional aberration wavefront data, This data has the tip/tilt and defocus correction applied to it.
- Camera Settings - contains all of the settings of the WaveCamD used to capture the data
- MLA Parameters - contains the calibration data from the camera for the MLA

- Wavefront Processor Settings - contains all of the settings used to process the data from the WaveCamD
- WaveFront Results - contains the 2 dimensional raw wavefront data. Also contains all of the calculated results based on the wavefront.

Appendix C

Calibration

The calibration of a Shack-Hartmann Wavefront Sensor accounts for imperfections in production– mainly MLA defects and non-uniformities–to ensure proper operation. These defects are typically misshapen lenslets in the MLA which causes variations in the focal length of the beam centroids across the array.

Typically, the calibration of a SHWFS follows one of two simple methods: the use of a collimated source or the use of a spherical source of known radius of curvature. For collimated sources, the primary concern is the wavefront error of the collimation package. There is no way to guarantee a collimated source is highly aberration-free, without using additional methods such as shearing interferometry to determine the integrity of a collimated source. Thus, we will be discussing the use of a spherical source, as it is the easier method of the two.

Spherical sources can be less prone to wavefront errors depending on how they are generated. The simplest spherical source is the end facet of a single mode optical fiber. The optical fiber guides light through its core in a way that lends itself to not experiencing aberrations that we would see with a lens, because there is only one potential propagation path through the fiber due to geometry. A singular propagation path correlates to a lack of wavefront error because the light exiting the fiber is uniform in phase. This, coupled with the fiber's core diameter being significantly smaller than the propagation distance to the wavefront sensor in this setup, allows us to treat measured spherical wavefronts from a fiber as a point source, and thus

perfectly spherical.

The calibration procedure involves a measurement phase and a calculation phase. The measurement phase has three steps: Rotational alignment, optical axis alignment, and the measurement of multiple spherical wavefronts which vary in radius of curvature.

Rotational alignment of the micro lens array is necessary to ensure it is properly oriented to the CMOS sensor of the SHWFS. Any misalignment can be mistaken for wavefront aberrations by the software. If the rotational alignment is correct, the raw results of wavefront measurement from the software are generally representative of the results we would expect. However, the proper calibration is done to ensure accuracy at a finer resolution.

The optical setup for the calibration is as follows: the source on a 5-axis stage, and the camera on a translation stage positioned at least 500 mm away from the source. Thus, the camera needs to be aligned to the source's optical axis.

Aligning the camera to the optical axis is important because we will be taking several snapshots of the wavefront along the optical axis, and it is important that the beam centroids stay within their sub-apertures. This will also eliminate major sources of tip/tilt between measurements which can contribute to calibration inaccuracy.

This alignment is done by using a collimated source to set the sub-aperture grid position. This tells us the approximate location of the centroids of a well collimated beam, which helps with aligning the center of the spherical wavefront to the camera in the next step.

The spherical wavefront snapshots come after this step. We ensure that no further adjustments of the tip/tilt of the source occur, only translational movements to align the center of the wavefront to the center of the sensor. We then move the camera along the optical axis using the stage, taking at least 4 measurements so metrics such as the sensor-MLA distance and distance between the source and the camera can be back-calculated and used to make calculation adjustments per-sub-aperture.

The calculation process consists of the determination of three terms: the distance

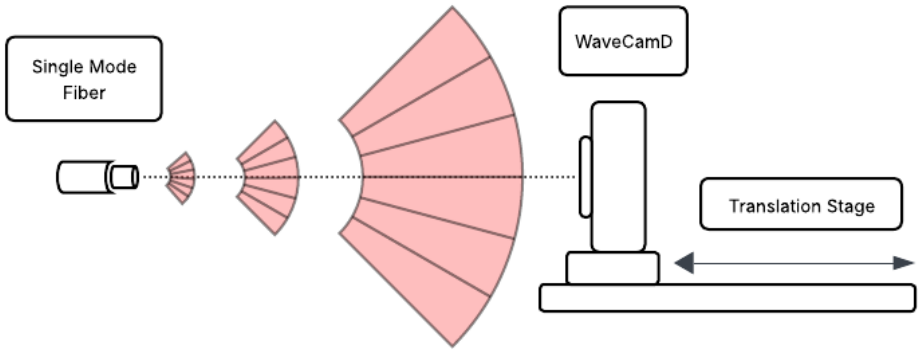


Figure C.1: Calibration Setup

between the MLA and the sensor (often incorrectly referred to as the focal length), the pixel spacing, and the lenslet pitch. These values are retrieved from a least-squares regression to reconstruct the wavefront in every sub-aperture.

Appendix D

Calculations

In this section, all vectors will be denoted with a vector arrow (i.e. $\vec{a}$) and all matrices will be denoted in bold (i.e. **B**).

The WaveCamD utilizes a Shack-Hartmann Wavefront Sensor (SHWFS). These sensors are composed of a microlens array (MLA) positioned precisely in front of a camera sensor such that focal plane of the MLA coincides with the sensor measurement plane, shown in Figure 1.1a.

For a perfectly constructed wavefront sensor, a flat wavefront will produce a grid of evenly spaced beam spots on the camera sensor. The spacing of this grid is equal to the pitch of the MLA lenslets, with the centroid of each beam corresponding to the center of each lenslet. These centroid locations are called **Reference Centroids**. However, if light enters a lenslet at an angle, the resulting refocused beam spot will be offset in x and y on the sensor, shown in Figure 1.1b. These displaced centroids are referred to as **Measured Centroids**.

The slope of the wavefront in the x and y direction at each lenslet is directly related to the difference between the **Measured Centroid** and the **Reference Centroid**, as shown in Equations D.1 and D.2.

$$\frac{\partial w}{\partial x} = \frac{x_c - x_r}{f} \tag{D.1}$$

$$\frac{\partial w}{\partial y} = \frac{y_c - y_r}{f} \tag{D.2}$$

where w is the wavefront evaluated at a specific lenslet, x_c is the measured x centroid location for a given lenslet, x_r is the reference x centroid location for a given lenslet, y_c is the measured y centroid location for a given lenslet, y_r is the reference y centroid location for a given lenslet, and f is the distance between the sensor plane and the MLA principal plane.

Since SHWFSs only directly measure the slope of the wavefront, the actual wavefront must be reconstructed from these data. This is achieved through either **Modal** or **Zonal** reconstruction.

Modal Reconstruction involves fitting a polynomial expansion to wavefront slopes. A general expression for a polynomial expansion is shown in Equation D.3.

$$w = \sum_{i=0}^{\infty} a_i P_i \tag{D.3}$$

where a_i coefficients for each polynomial term and P_i are the polynomial basis functions.

DataRay's WaveSight software currently features modal reconstruction using Zernike polynomials. In terms of Equation D.3, each polynomial P_i corresponds to a Zernike term, with the coefficient a_i corresponding to the magnitude of that term.

Since the mathematical form of each Zernike term is known, the partial derivatives of these terms are also known. Therefore, Equations D.1 and D.2 can be rewritten as Equations D.4 and D.5. Note that since it is not possible to compute these terms to infinity, we truncate the polynomial series to the Kth term. Also note, that since the first Zernike term ($i = 0$) is the constant piston term, the derivative with respect to x and y is always zero. Since this term only serves as a constant value added to the wavefront surface, it does not impact the general shape of the wavefront surface and will be disregarded for modal reconstruction.

$$\sum_{i=1}^{K} a_i \frac{\partial P_i}{\partial x} = \frac{x_c - x_r}{f} \tag{D.4}$$

$$\sum_{i=1}^{K} a_i \frac{\partial P_i}{\partial y} = \frac{y_c - y_r}{f} \tag{D.5}$$

Zernike polynomials are defined on the unit disk, so each P_i is evaluated at the normalized pupil coordinates $\hat{x} = (x - x_p)/R$ and $\hat{y} = (y - y_p)/R$, where (x_p, y_p) is the pupil center and R is the pupil radius, both set by the **Pupil Mode** option in the Wavefront Calculation Settings dialog. The derivatives in Equations D.4 and D.5 are taken with respect to the physical coordinates x and y, so by the chain rule

$$\frac{\partial P_i}{\partial x} = \frac{1}{R}\frac{\partial P_i}{\partial \hat{x}}, \qquad \frac{\partial P_i}{\partial y} = \frac{1}{R}\frac{\partial P_i}{\partial \hat{y}} \tag{D.6}$$

Omitting this factor of $1/R$ would scale every reconstructed coefficient by the pupil radius.

Equations D.4 and D.5 can be applied to each lenslet in the MLA. For an MLA with n rows of lenslets and m columns, this yields $2n \times m$ total equations. We can summarize this system of equations as Equation D.7

$$\mathbf{B}\vec{a} = \vec{\beta} \tag{D.7}$$

The full form of **B** is shown in Equation D.8.

$$\mathbf{B} = \begin{bmatrix} \frac{\partial P_1}{\partial x}\Big|_{x_0,y_0} & \frac{\partial P_2}{\partial x}\Big|_{x_0,y_0} & \cdots & \frac{\partial P_K}{\partial x}\Big|_{x_0,y_0} \\ \frac{\partial P_1}{\partial x}\Big|_{x_1,y_1} & \frac{\partial P_2}{\partial x}\Big|_{x_1,y_1} & \cdots & \frac{\partial P_K}{\partial x}\Big|_{x_1,y_1} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial P_1}{\partial x}\Big|_{x_{nm-1},y_{nm-1}} & \frac{\partial P_2}{\partial x}\Big|_{x_{nm-1},y_{nm-1}} & \cdots & \frac{\partial P_K}{\partial x}\Big|_{x_{nm-1},y_{nm-1}} \\ \frac{\partial P_1}{\partial y}\Big|_{x_0,y_0} & \frac{\partial P_2}{\partial y}\Big|_{x_0,y_0} & \cdots & \frac{\partial P_K}{\partial y}\Big|_{x_0,y_0} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial P_1}{\partial y}\Big|_{x_{nm-1},y_{nm-1}} & \frac{\partial P_2}{\partial y}\Big|_{x_{nm-1},y_{nm-1}} & \cdots & \frac{\partial P_K}{\partial y}\Big|_{x_{nm-1},y_{nm-1}} \end{bmatrix} \tag{D.8}$$

where x_0 and y_0 are the x and y coordinates of the center of the first lenslet (i.e. first row, first column), x_1 and y_1 are the x and y coordinates of the center of the second lenslet (i.e. first row, second column), x_{nm-1} and y_{nm-1} are the x and y coordinates of the center of the last lenslet (i.e. last row, last column), and so on.

The full form of $\vec{a}$ is shown in Equation D.9.

$$\vec{a} = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_K \end{bmatrix} \tag{D.9}$$

where a_1 is the coefficient of the first non-piston polynomial, a_2 is the coefficient of the second, a_K is the coefficient of the Kth polynomial, and so on. The piston coefficient a_0 is excluded, as noted above.

The full form of $\vec{\beta}$ is shown in Equation D.10.

$$\vec{\beta} = \begin{bmatrix} \frac{\partial w}{\partial x}\Big|_{x_0,y_0} \\ \\ \frac{\partial w}{\partial x}\Big|_{x_1,y_1} \\ \\ \vdots \\ \\ \frac{\partial w}{\partial x}\Big|_{x_{nm-1},y_{nm-1}} \\ \\ \frac{\partial w}{\partial y}\Big|_{x_0,y_0} \\ \\ \frac{\partial w}{\partial y}\Big|_{x_1,y_1} \\ \\ \vdots \\ \\ \frac{\partial w}{\partial y}\Big|_{x_{nm-1},y_{nm-1}} \end{bmatrix} \tag{D.10}$$

The **B** matrix in Equation D.7 is generally non-invertible. However, it can be solved using a pseudo-inverse matrix, resulting in a least squares solution. The polynomial coefficients are then solved for using Equation D.11.

$$\vec{a} = \mathbf{B}^{+}\vec{\beta} \tag{D.11}$$

where $\mathbf{B}^{+}$ is the pseudo-inverse of **B**.

Finally, once $\vec{a}$ is known, the wavefront is calculated using Equation D.12.

$$w = \sum_{i=1}^{K} a_i P_i \tag{D.12}$$

Zonal Reconstruction, in contrast to **Modal Reconstruction**, relies on numerically integrating the slope data from Equations D.1 and D.2 directly. Many numeric integration methods exist, but the DataRay WaveSight software uses Southwell integration due to high accuracy and speed.

The derivative of the wavefront with respect to x and y at each lenslet can be related to the actual wavefront using Equations D.13 and D.14. Note that Equation D.13 should not be applied when $i = tm - 1$ for any integer $t \geq 1$ (the last lenslet of each row, which has no neighbor to its right). Similarly, Equation D.14 should not be applied when $i \geq n \times m - m$ (the lenslets of the last row, which have no neighbor above them).

$$\frac{w_{i+1} - w_i}{p} = \frac{\frac{\partial w}{\partial x}\Big|_{i+1} + \frac{\partial w}{\partial x}\Big|_{i}}{2} \tag{D.13}$$

$$\frac{w_{i+m} - w_i}{p} = \frac{\frac{\partial w}{\partial y}\Big|_{i+m} + \frac{\partial w}{\partial y}\Big|_{i}}{2} \tag{D.14}$$

where i denotes the lenslet number (i.e. first row and first column is $i = 0$, second row, first column is $i = m$, etc.) and p is the lenslet pitch. The slopes on the right-hand side are already dimensionless (Equations D.1 and D.2 divide by f), so the wavefront difference between neighboring lenslets is divided by their spacing p, not by f.

Applying Equations D.13 and D.14 to each lenslet results in a total of $2n \times m - n - m$ equations. These can be summarized by Equation D.15. Note this form is identical to the form used in Equation D.7.

$$\mathbf{B}\vec{w} = \vec{\beta} \tag{D.15}$$

where **B**, $\vec{w}$, and $\vec{\beta}$ are shown in Equations D.16, D.17, and D.18, respectively.

$$\mathbf{B} = \begin{bmatrix} \frac{-1}{p} & \frac{1}{p} & 0 & \dots & \dots & \dots & \dots & \dots \\ 0 & \frac{-1}{p} & \frac{1}{p} & 0 & \dots & \dots & \dots & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \dots & \dots & \dots & \dots & \dots & 0 & \frac{-1}{p} & \frac{1}{p} \\ \frac{-1}{p} & 0 & \dots & 0 & \frac{1}{p} & 0 & \dots & \dots \\ 0 & \frac{-1}{p} & 0 & \dots & 0 & \frac{1}{p} & 0 & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \dots & \dots & 0 & \frac{-1}{p} & 0 & \dots & 0 & \frac{1}{p} \end{bmatrix} \begin{matrix} row = 0 \\ \vdots \\ \vdots \\ row = n(m-1) - 1 \\ row = n(m-1) \\ \vdots \\ \vdots \\ row = 2n \times m - n - m - 1 \end{matrix} \tag{D.16}$$

$$\vec{w} = \begin{bmatrix} w_0 \\ w_1 \\ \vdots \\ w_{n\times m-1} \end{bmatrix} \tag{D.17}$$

$$\vec{\beta} = \begin{bmatrix} \frac{\frac{\partial w}{\partial x}\Big|_{x_1,y_1} + \frac{\partial w}{\partial x}\Big|_{x_0,y_0}}{2} \\ \frac{\frac{\partial w}{\partial x}\Big|_{x_2,y_2} + \frac{\partial w}{\partial x}\Big|_{x_1,y_1}}{2} \\ \vdots \\ \frac{\frac{\partial w}{\partial x}\Big|_{x_{nm-1},y_{nm-1}} + \frac{\partial w}{\partial x}\Big|_{x_{nm-2},y_{nm-2}}}{2} \\ \frac{\frac{\partial w}{\partial y}\Big|_{x_m,y_m} + \frac{\partial w}{\partial y}\Big|_{x_0,y_0}}{2} \\ \frac{\frac{\partial w}{\partial y}\Big|_{x_{m+1},y_{m+1}} + \frac{\partial w}{\partial y}\Big|_{x_1,y_1}}{2} \\ \vdots \\ \frac{\frac{\partial w}{\partial y}\Big|_{x_{nm-1},y_{nm-1}} + \frac{\partial w}{\partial y}\Big|_{x_{nm-m-1},y_{nm-m-1}}}{2} \end{bmatrix} \tag{D.18}$$

Similar to modal reconstruction, the **B** matrix in Equation D.15 is generally non-invertible. However, it can be solved using a pseudo-inverse matrix, resulting in a least squares

solution, shown in Equation D.19.

$$\vec{w} = \mathbf{B}^{+}\vec{\beta} \tag{D.19}$$

where $\mathbf{B}^{+}$ is the pseudo-inverse of **B**.

Appendix E

Standards

The classification of Zernike Polynomials is not universally consistent. Thus, we describe three ISO standards, ISO 24157, ISO 14999-2, and ISO 15367 which are standardized instances of how these terms can be ordered. This is relevant because we must know which Zernike Polynomial scheme is being used to compare terms such as ”Z0” or ”Z13” between different measurement devices. Additional differences between Zernike Polynomial schemes includes how the terms are grouped and whether normalization is used.

E.1 ANSI Z80.28/ISO 24157

ANSI Z80.28, *Methods for Reporting Optical Aberrations of Eyes*, and its international counterpart ISO 24157, *Ophthalmic optics and instruments — Reporting aberrations of the human eye*, define the single-index Zernike ordering used throughout this manual. The index j is computed directly from the radial degree n and the (signed) azimuthal frequency m as

$$j = \frac{n(n+2)+m}{2} \tag{E.1}$$

which orders terms first by increasing radial degree, then by increasing m within each degree. This is the ordering shown in Tables A.1 and A.2, and it is the only indexing

scheme WaveSight uses for on-screen coefficient labeling, CSV export, and HDF5 storage.

Each polynomial in this scheme is normalized to unit RMS value over the unit circle, so a coefficient's magnitude reflects its actual contribution to wavefront RMS error regardless of aberration order — this is why, for example, a Defocus coefficient of 2 µm and a 6th-order coefficient of 2 µm contribute equally to the Wavefront Aberration RMS value reported in Table 2.4.

Because this family of standards originates in ophthalmic optics, it also underlies the M, J_0, and J_{45} values in Table 2.4. These are not Zernike coefficients themselves but clinically-oriented spherocylindrical terms derived from the low-order defocus and astigmatism Zernike coefficients according to the same ANSI Z80.28 conventions.

E.2 ISO 14999-2

ISO 14999-2, *Optics and photonics — Interferometric measurement of optical elements and optical systems — Part 2: Measurement and evaluation techniques*, governs how wavefront and surface error are reported for optical components and systems characterized interferometrically — for example, mirrors and lenses tested on an interferometer in an optical shop.

This standard is associated with an ordering scheme commonly referred to in the optics-fabrication industry as "Fringe" or "Zygo" ordering, most often presented as a fixed 36- or 37-term set. This ordering does *not* match the ANSI Z80.28/ISO 24157 scheme described in Appendix E.1 — the same aberration can carry a different index number, and results are frequently reported without RMS normalization, using peak-referenced coefficients instead.

This matters if you are comparing a WaveSight measurement against results from an interferometer or another instrument that reports "Zernike coefficients": do not assume that matching index numbers or coefficient names refer to the same term. Confirm which convention the other instrument uses before comparing values directly. WaveSight does not offer an ISO 14999-2 ordering option — all output uses the ANSI Z80.28/ISO 24157 convention from Appendix E.1.

E.3 ISO 15367

ISO 15367, *Lasers and laser-related equipment — Test methods for determination of the shape of a laser beam wavefront*, is the standard most directly applicable to the WaveCamD, since it addresses laser beam wavefront measurement specifically rather than ophthalmic aberrometry (Appendix E.1) or optical-component interferometry (Appendix E.2).

Part 1 establishes terminology and fundamental definitions for laser wavefront measurement — quantities such as reference wavefront, aberration wavefront, and radius of curvature, several of which appear directly in Chapter 1 and in Table 2.4 (Wavefront Aberration RMS, RoC, Peak-to-Peak Wavefront). Part 2 covers non-interferometric wavefront sensing methods, explicitly including Hartmann and Shack–Hartmann sensors — the class of instrument the WaveCamD belongs to — and defines test methods for evaluating a sensor's own measurement performance, such as the wavefront accuracy and sensitivity specifications quoted in Section 1.1.

ISO 15367 does not mandate its own Zernike ordering scheme the way ISO 24157 and ISO 14999-2 do. Where WaveSight reports a Zernike decomposition under this standard's terminology, it continues to use the ANSI Z80.28/ISO 24157 convention described in Appendix E.1.

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