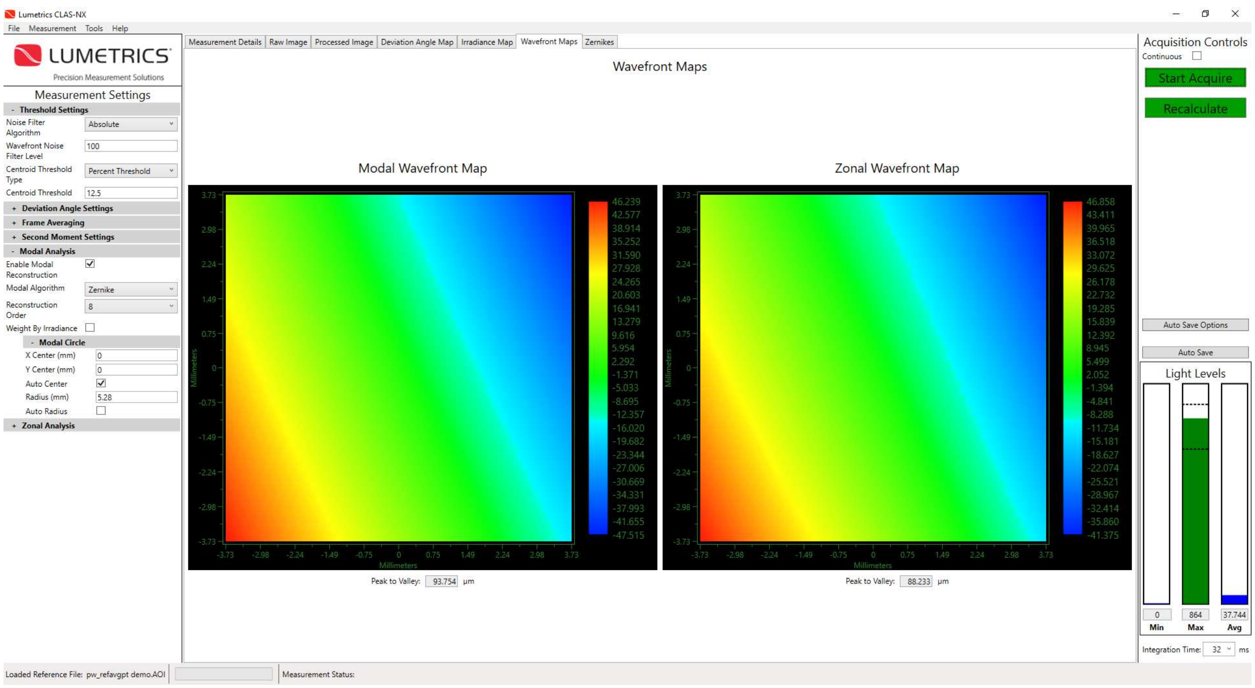
# CLAS-NX™

## Complete Light Analysis Software – Next Generation

## *Software Manual*

*Revision 1*



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# 1 Revision History

| Revision | Description | Author | Date |
|---|---|---|---|
| Revision 1 | Initial Release | D. Compertore | 2017-11-22 |

## 2 Introduction

Welcome to Lumetrics' CLAS-NX software. CLAS-NX (Complete Light Analysis Software -Next Generation) is a Shack-Hartmann wavefront sensor software application capable of controlling our suite of Lumetrics wavefront sensors. Our new USB3-based CLAS-FX wavefront sensors, as well as the legacy CameraLink communications based CLAS-XP, CLAS-HP, and CLAS-IR models, are supported and run on Windows 10.

CLAS-NX simplifies the most common operations of a Shack-Hartmann wavefront sensor. This manual will help you get started quickly, provide an overview of the software user interface, describe all the available functions, and walk through measurement examples. Figure 1 is an example of the CLAS-NX main screen.

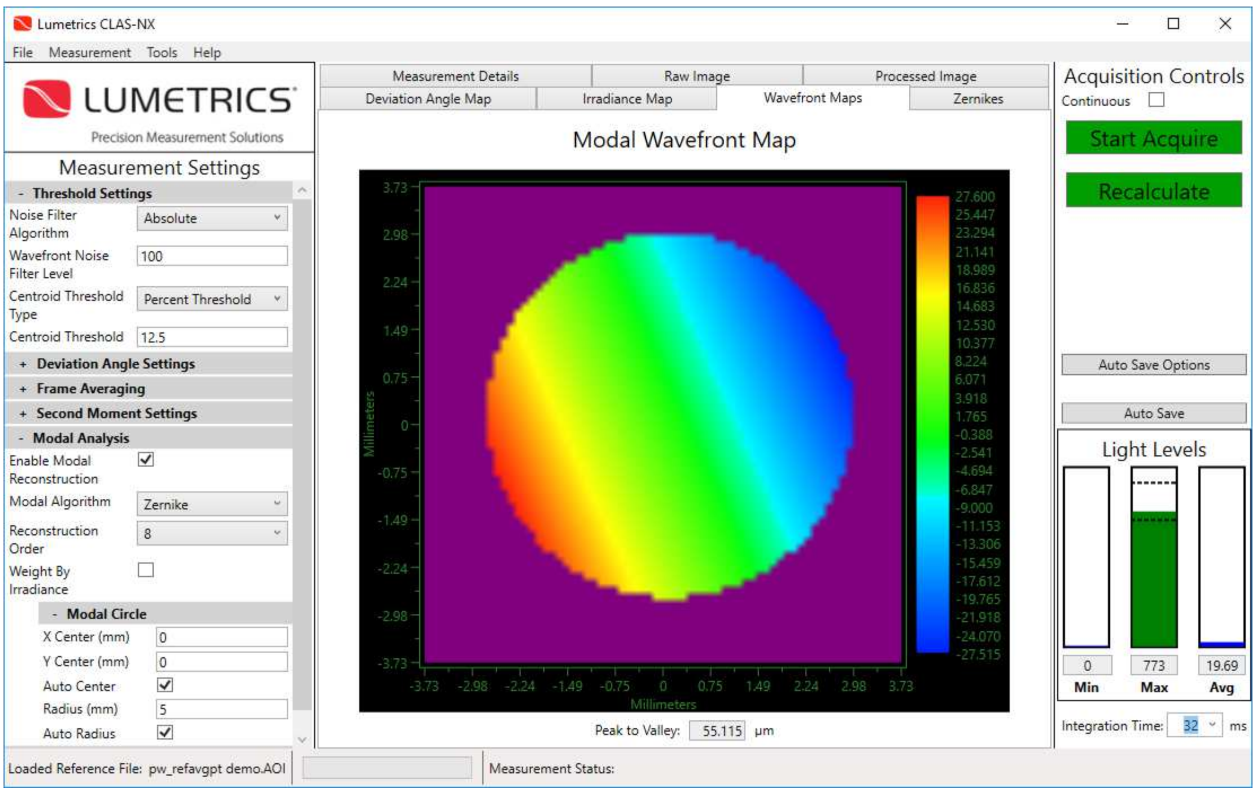


**Figure 1:** CLAS-NX Main screen

## 2.1 General Optical Tips

1. Work in a room where you can control the lights. Most importantly, be able to turn them off, and make the room very dark. Unenclosed optical systems are susceptible to ambient light and even small reflections from a distant monitor.
2. Be ready to become an optical alignment expert. Optical systems often have several optical elements used to create, steer, and modify the shape of a beam. You will likely require precision adjustment of XYZ+Tip/Tilt of your optical elements, or an opto-mechanical fixture that properly sets the element's precise location to achieve the desired beam or to measure the desired optical element under test.
    a. Consider the handheld optical magnifier (i.e. magnifying glass). It is the best example of an optical component, and it works best with the most complex opto-mechanical device ever put to use, the human hand.
    b. The next simplest optical device, the Galilean telescope uses two lenses. If you have ever tried to hold two lenses in your hands and attempted to align them into a Galilean telescope you will have an appreciation for how quickly the difficulty of optical alignment escalates as optical elements are added. The examples at the end of this manual will help hone your alignment skills.

## 3 Getting Started

1. Load the CLAS-NX software into your computer.
    a. Insert the software CD into your computer and run LumetricsInstaller.exe (if the installer does not automatically launch) to launch the splash-screen installation wizard.
    b. Install all software items, starting with the first in the list, and work your way down until all items are installed. A green checkmark will appear in the splash-screen when the item is installed successfully.
    c. Copy the Reference Files contained within the Reference Files directory on the software CD to the C:\Lumetrics\CLAS-NX\Reference files directory
2. Plug in your Lumetrics Shack-Hartmann wavefront sensor. Figures 2 and 3 show the data cable connections for a USB3 based sensor. Figures 4 and 5 show the data cables and communication cable connections for a CameraLink based sensor.

**Figure 2:** CLAS-FX wavefront sensor USB3 cable installed

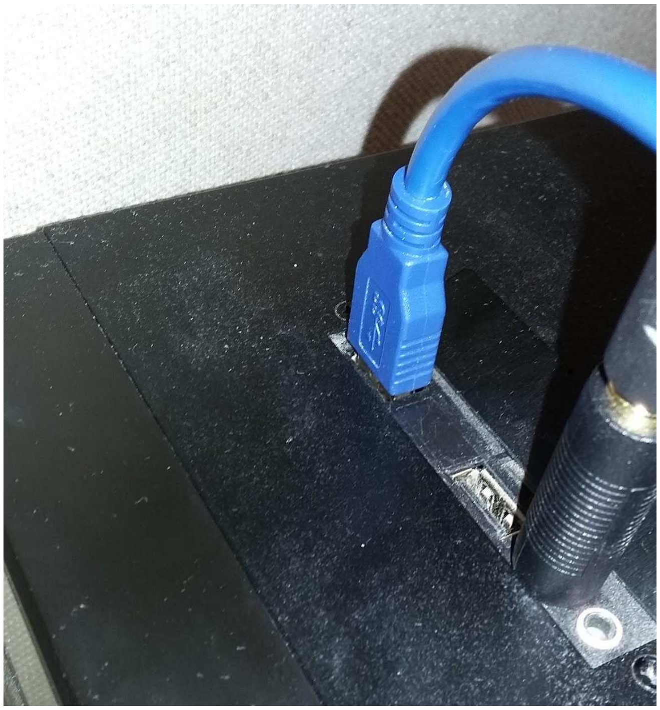

**Figure 3:** CLAS-FX wavefront sensor USB3 cable connected to the computer

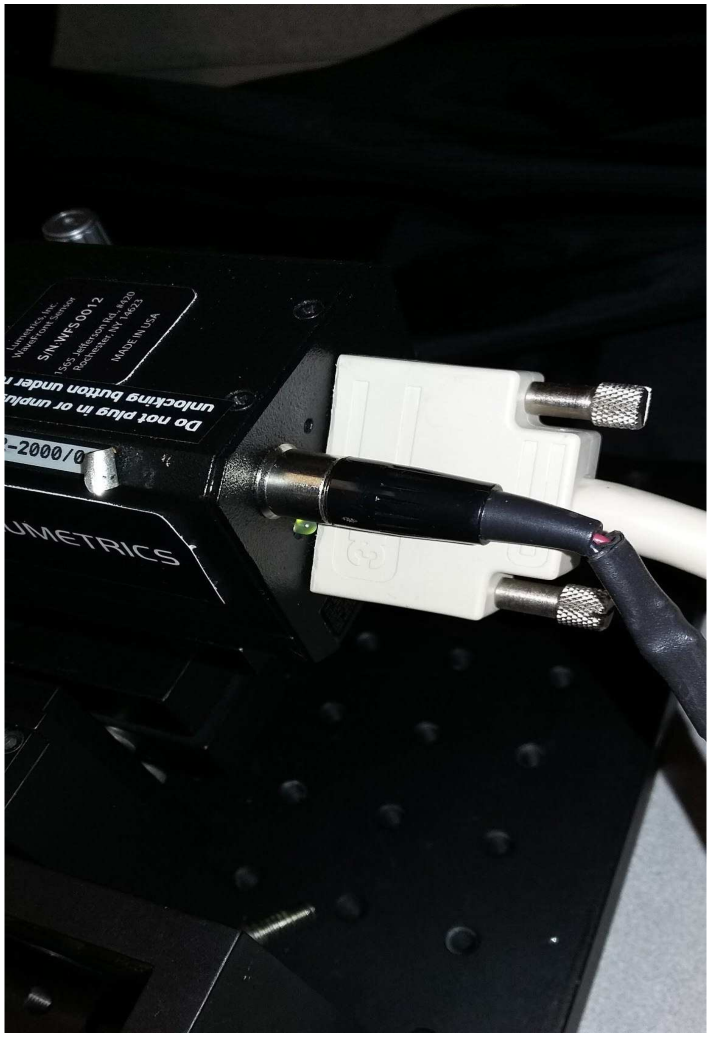

**Figure 4:** Legacy Cohu camera with white CameraLink communication cable and black DIN power cable

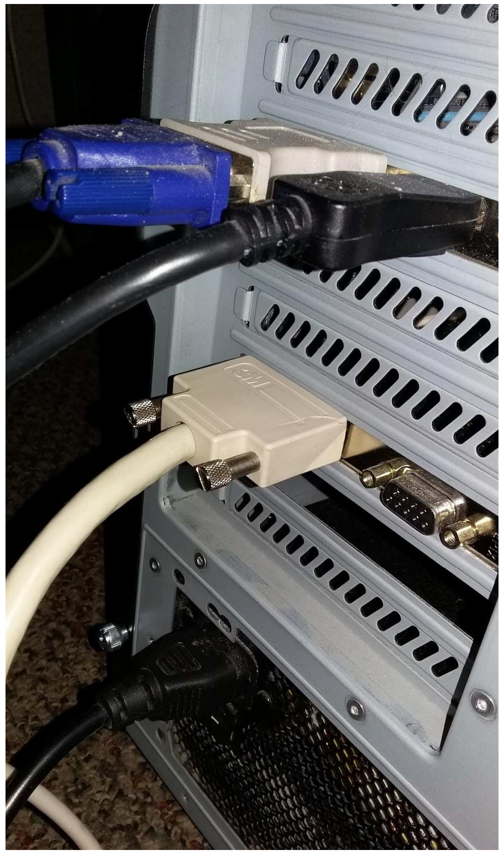

**Figure 5:** Legacy CameraLink framegrabber installed in computer with white CameraLink communications cable connected

3. Start the CLAS-NX software application, see Figure 6.


**Figure 6:** CLAS-NX start shortcut

   a. If this is the first time running CLAS-NX you will need to register it using your license key provided with the installation media.
   b. After the license key is installed CLAS-NX starts immediately after clicking the CLAS-NX startup icon.

c. You will see the wizard in Figure 7:

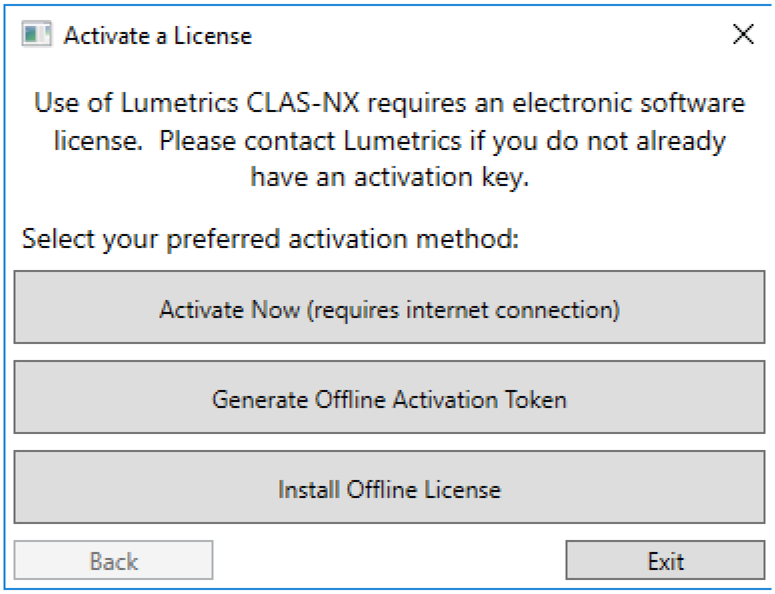


**Figure 7:** Activate a License window

d. Follow the instructions in the licensing wizard to activate using an internet connection, or to generate a token that must be sent to licensing@lumetrics.com for a license key.

4. Go to the **Measurement** menu option and select **Wavefront Sensor,** Figure 8.

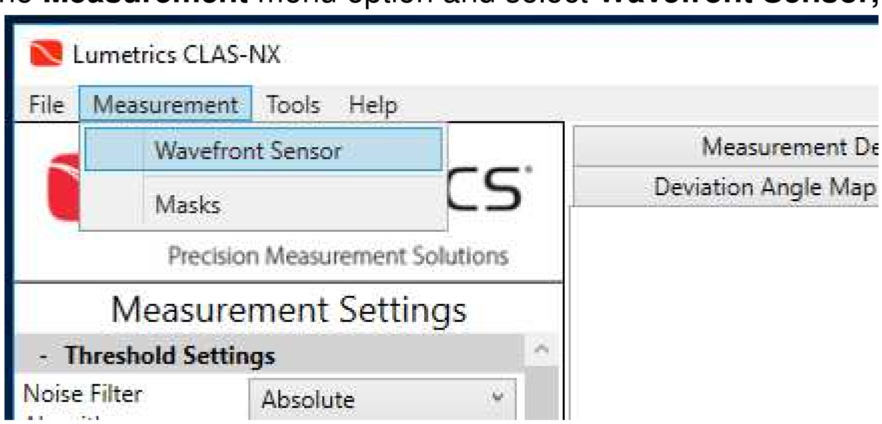


**Figure 8:** Selecting Wavefront Sensor

a. Within the **Wavefront Sensor** tab, select your model (CLAS-XP, CLAS-FX, etc.) from the list, followed by your framegrabber or camera type (if applicable). Cycle through the options until the status box turns green if these are unknown.

b. Figure 9 shows the selection of Wavefront sensor and Figure 9 shows the wavefront sensor tab open.

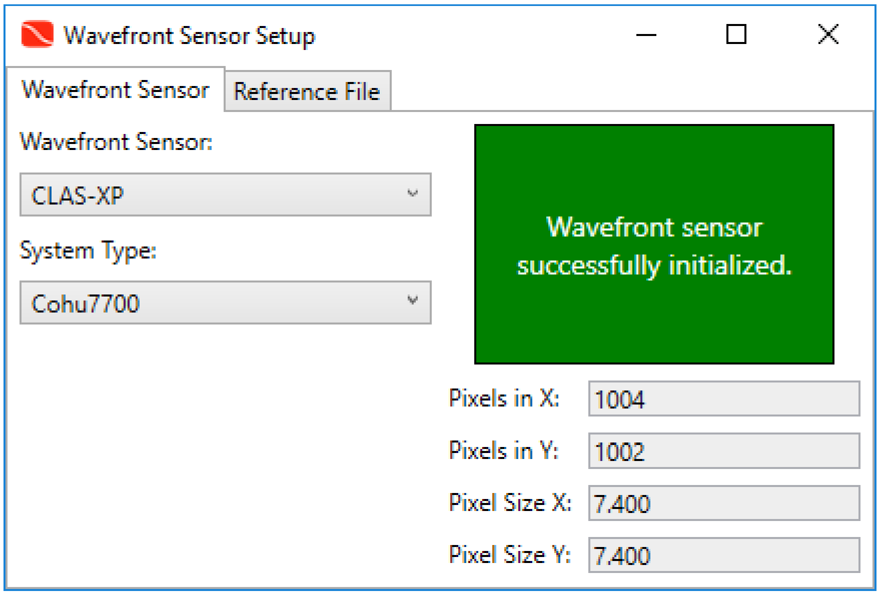


**Figure 9:** Wavefront sensor setup window

5. Go to the **File** menu option and select **Load Reference File**. Select the Lumetrics factory-supplied reference file.
    a. **FactoryRef_WFS0012.REF**, is a specific example and can be seen in Figure 10.
    b. Legacy CLAS-2D reference files often are named pw_refavgpt.aoi
    c. You may have noticed the reference file in use is shown in the bottom left corner of the CLAS-NX main screen. As an exercise, confirm if the reference file listed on the main page matches the reference file that was just loaded.

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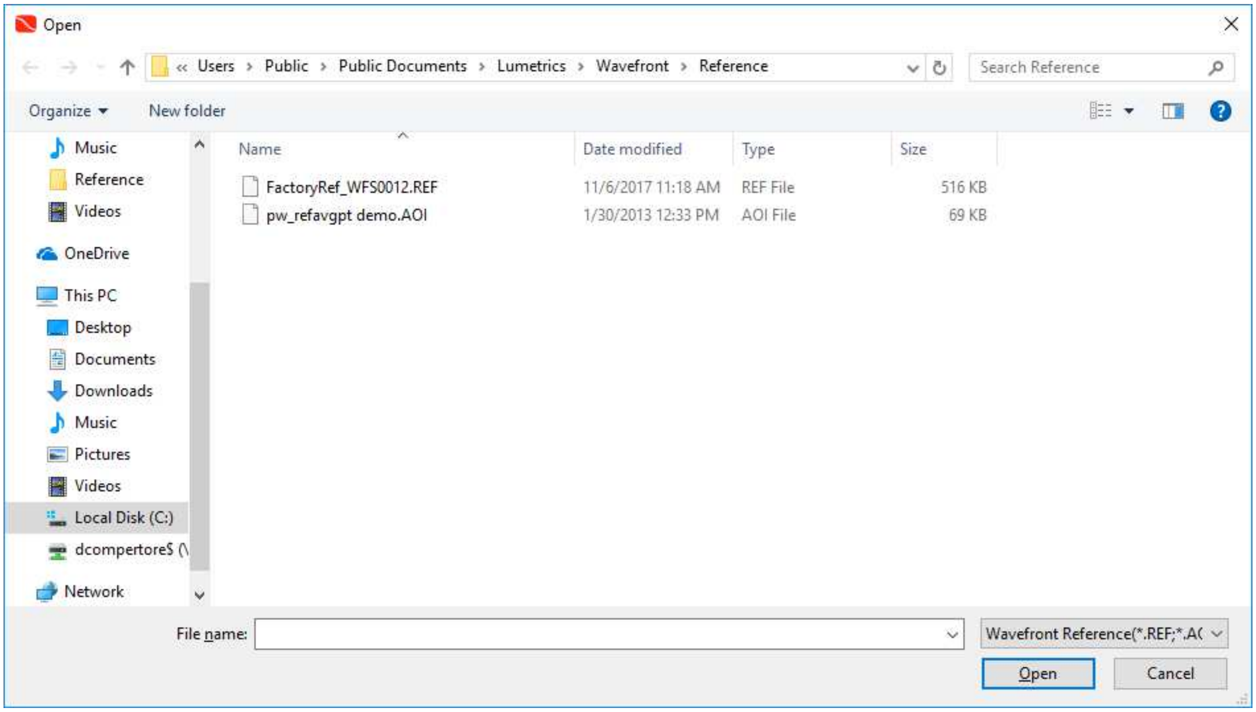


**Figure 10:** Loading a factory reference file

6. Use the setup sheet provided for your sensor to set the recommended starting settings.
7. Your system is now configured for use.

## 3.1 Other details you may need to know to get started:

1. Which wavefront sensor model am I using?
    a. See your Quote/Purchase Order/Packing List, or physical label on your wavefront sensor
    b. Typical models are CLAS-NX, CLAS-XP, & CLAS-HP
2. Does my computer meet the wavefront sensor's requirements?
    a. See Computer Requirements section of this manual, Table 1
    b. Tablets, desktops and laptops are all supported for USB3 based sensors
3. Does my computer have the proper communication port?
    a. USB3 or
    b. CameraLink (if applicable)
4. Do I have the cable to connect my wavefront sensor to my computer?
    a. USB3 cable or
    b. CameraLink framegrabber cable (if applicable)
5. Do I have easy access to the factory reference file for my wavefront sensor?
    a. Included on installation media provided by Lumetrics.
    b. Contact service@lumetrics.com if misplaced.
6. Do I have a simple collimated beam ready as an input light source to check my sensor? Contact Lumetrics for assistance, if needed.
7. Do I have alignment fixtures for the initial rough alignment? Contact Lumetrics for assistance, if needed.

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# 4 Computer Requirements

| | |
|---|---|
| **Operating System:** | Windows 10 |
| **RAM:** | 4GB or greater |
| **CPU:** | Intel i3 or better |
| **Hard Drive:** | 1GB Available |
| **Communication Port:** | USB3 for CLAS-FX, CameraLink for Legacy CLAS-XP, CLAS-HP, and CLAS-IR |

**Table 1:** Computer Requirements

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# 5 User Interface

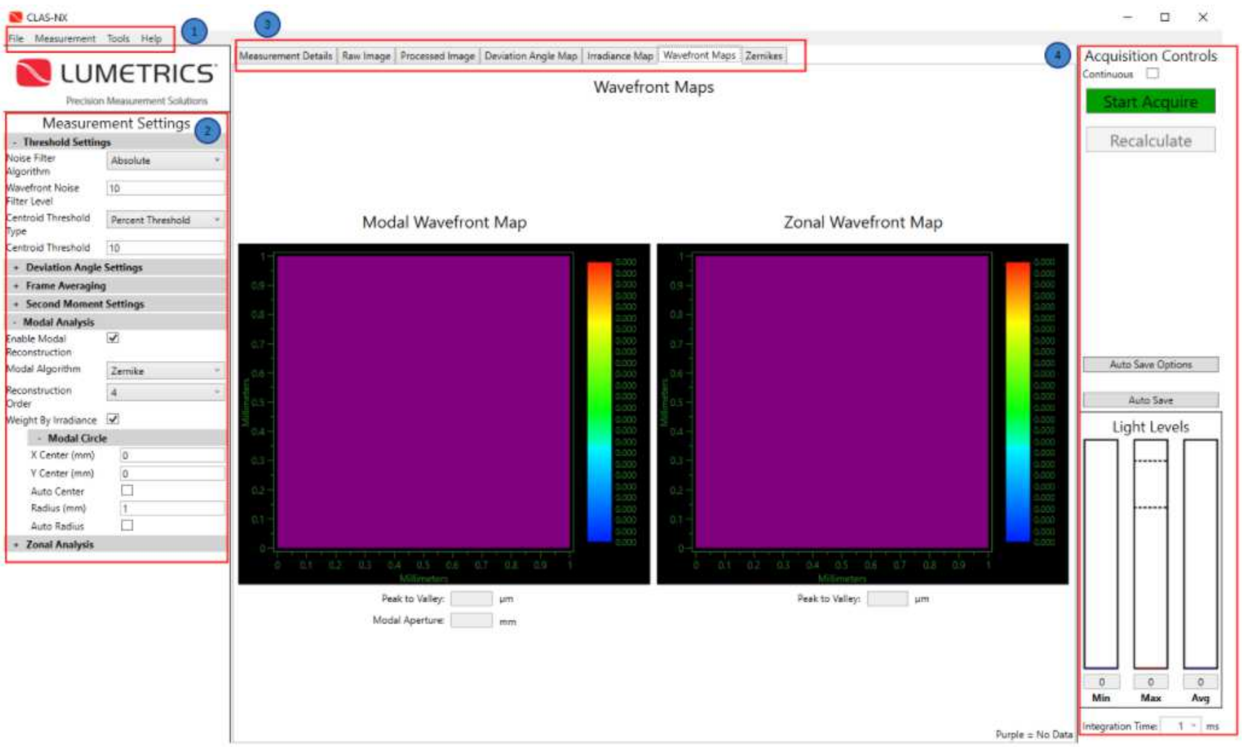


**Figure 11:** Main Screen

The CLAS-NX user interface (UI) has four primary areas, Figure 11:

1. Menu Bar
2. Measurement Settings
3. Measurement Results
4. Acquisition Controls

## 5.1 Menu Bar

The Menu Bar is just below the Title Bar (which contains a small Lumetrics logo with the software version number).

The Menu Bar. It contains the **File**, **Measurement**, **Tools**, and **Help** pull-down menus. Contained within these menus are various functions to load files, configure the hardware, and other useful tools.

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## 5.2 Measurement Settings

The leftmost section of the user interface is below the top pull down menus, and just below the large Lumetrics logo. It is titled **Measurement Settings**. An operator uses this section to prepare important parameters prior to taking a wavefront measurement. Clicking on the + or - signs to the left of the sub-section descriptions expands or hides the selection. In the measurements settings section an operator sets all their desired measurement parameters before launching a measurement. When a measurement or analysis is in progress the operator does not have access to this section. For example, an operator changes the Zernike analysis radius in this section. A full list is contained in the CLAS-NX Functions section.

## 5.3 Measurement Results

The central tab section allows a user quick access to visual and graphical results. A user accessing most or all the central tabs during a measurement is typical. The information in the tabs helps during the alignment process and in confirming the displayed results are as expected. The central tabs are **Measurement Details, Raw Image, Processed Image, Deviation Angle Map, Irradiance Map, Wavefront Maps,** and **Zernikes**. Clicking on a tab brings it forward and hides the prior tab.

## 5.4 Acquisition Controls

The rightmost section of the main window is titled **Acquisition Controls**. The user makes a measurement by clicking on the green **Acquire** button in this section. The light levels tools in this section facilitates the quick and easy evaluation of the sensor's status. A central green bar displayed in the light levels area typically means you are ready to take a measurement.

Applying operator changes in most windows and for most settings boxes requires some operator action, such as changing focus, pressing the space or tab keys. Not many setting boxes are live. One notable exception is the camera integration time, which is live.

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# 6 CLAS-NX Functions

## 6.1 Menu Bar:

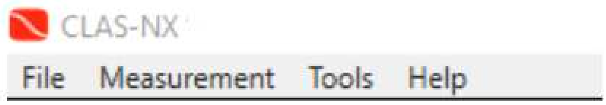


**Figure 12:** Menu Bar

**File**

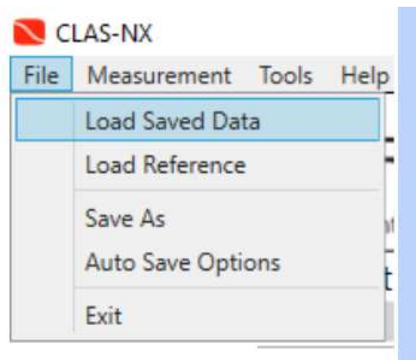


**Figure 13:** File Menu

**Load Saved Data -** Load Saved Data is used to import a previously saved wavefront data file for re-analysis, Figure 13.

**Load Reference -** Load Reference File is used to import a reference wavefront. The centroid locations in a reference file are compared to the centroid locations of a data acquisition, and deviation angles are calculated.

**Save As -** Save As allows you to save a wavefront file for re-analysis to a specified directory location, C:\Lumetrics\CLAS-NX\Data.

**Auto Save Options -** Auto Save Options provides settings to specify what types of files are saved automatically with every wavefront acquisition command

**Exit -** Exit closes the application

## Measurement

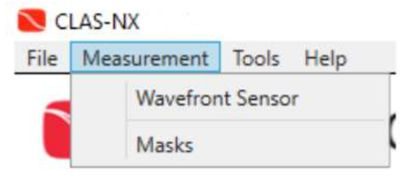


**Figure 14:** Measurement Menu

**Wavefront Sensor -** Allows one to configure the software for use with the sensor hardware.

**Mask -** Allows one to separate image regions for inclusion or exclusion in the analysis.

## Tools

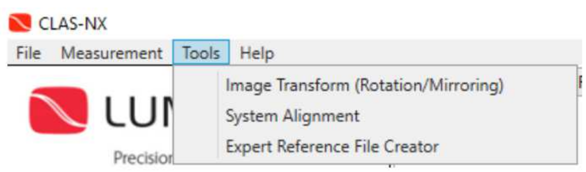


**Figure 15:** Tools Menu

**Image transform -** Allows the user to apply an image transform (rotation and/or flip) so the presented wavefront image aligns with the wavefront sensor camera's physical orientation.

**System alignment -** This provides the user an intuitive way to simply and easily align a system to minimize tip and tilt

**Expert reference file creator -** Provides the ability to create a custom reference wavefront. This is useful when comparing the relative wavefront error between multiple optical elements.

**Help** -

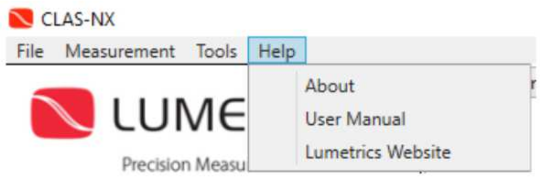


**Figure 16:** Help Menu

**About** - Provides software version information and Lumetrics contact information

**User Manual -** Provides a link to a PDF copy of the CLAS-NX user manual

**Lumetrics Website** - Provides a link to the Lumetrics website

## 6.2 Measurement Settings:

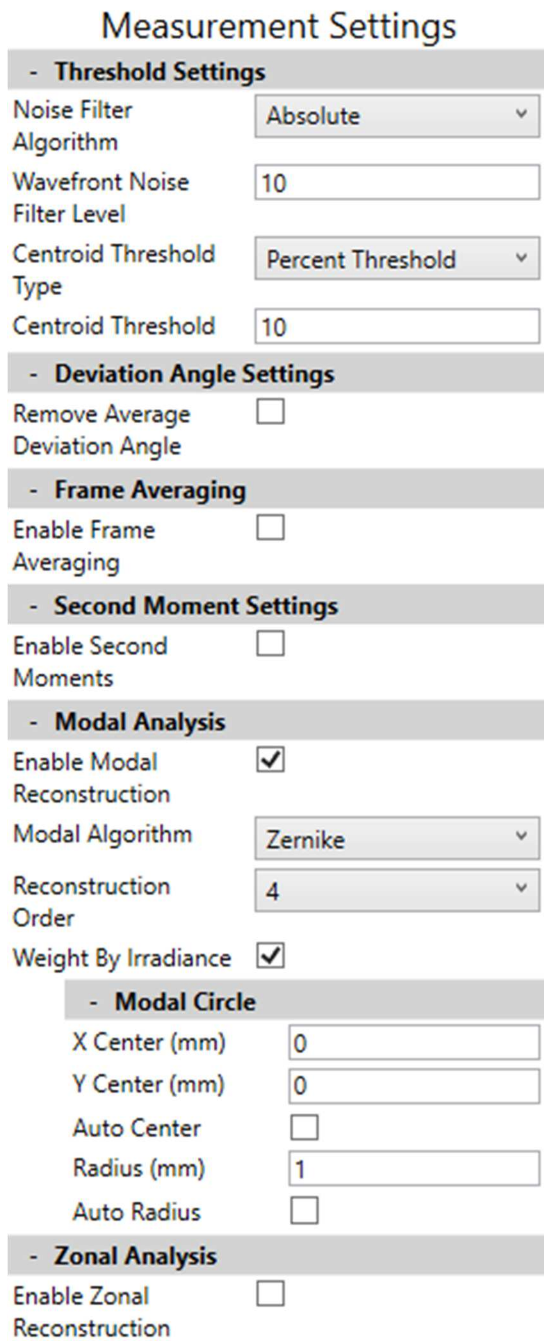


**Figure 17:** Measurement Settings

## Threshold Settings

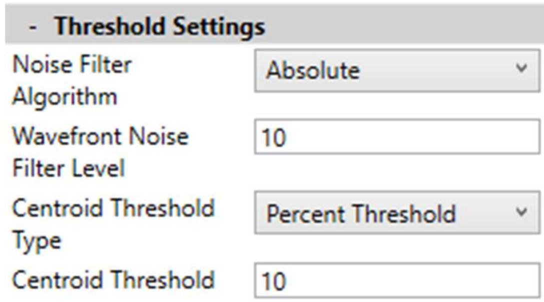


**Figure 18:** Threshold Settings

**Noise Filter Algorithm** - The noise filter algorithm, which by default, is set to **Absolute**. It is recommended you start with the setup values listed in the setup sheet supplied with your wavefront sensor. It is recommended you do not change from the setup values unless you either consult with Lumetrics or are experienced with the other options.

**Wavefront Noise Filter Level** - The wavefront noise filter level is determined at the factory and listed in the setup sheet. The factory setting is typically the best setting for taking measurements. This varies mostly by the bit depth of the camera.

**Centroid Threshold Type** - The centroid threshold type is set to **Percent Threshold** by default. It is recommended you do not change this unless you either consult with Lumetrics or are experienced with the other options.

**Centroid Threshold** - The centroid threshold default setting is determined at the factory and listed in the setup sheet. The factory setting is typically the best setting for taking measurements. This is typically about 12.5% and is driven by the diffractive pattern of the individual lenslet apertures.

Typically no changes to the threshold settings, listed in the setup sheet, are required for well-behaved input beams. In the measurement example section there is a brief discussion on identifying poorly behaved input beams.

### Deviation Angle Settings

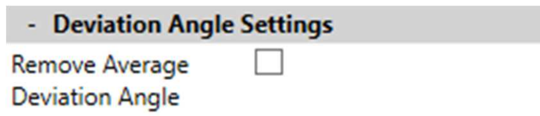


**Figure 19:** Deviation Angle Settings

**Remove Average Deviation Angle** - Enabling this function mathematically removes the average of all calculated deviation angles from the Deviation Angle Map and processes the Wavefront Maps and Zernikes, accordingly. This is useful when it is desirable to neglect the effects of Tip and Tilt from the incoming wavefront.

### Frame Averaging

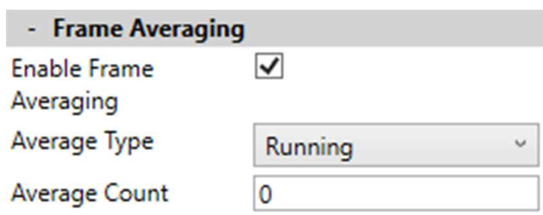


**Figure 20:** Frame Averaging Settings

**Frame Average Enabled -** When selected, the frame average selection box exposes the Average Type and Average Count functions.

**Average Type -** The average type defaults to **Running Average,** but **Boxcar** and **Exponential** are also options.

**Running Average** will equally weight and average a number of frames, and once the average count is reached, each subsequent frame will be added to the average while the earliest frame is removed from the average.

**Boxcar** will take “chunks” of frames. Once the Average count is reached, the average is displayed. When a new set of Average Count frames are acquired, a new average is calculated with those entirely new frames.

**Exponential** is similar to Running Average, but the most recent frames are weighted exponentially higher than older frames within the Average Count set.

**Average Count** - This sets the number of consecutive frames to process using the algorithm specified in **Average Type**.

**Second Moment Settings**

Second moments are the image spot size of the individual lenslet foci. Normally there is no reason to filter the centroid data using the second moment information, but in certain cases an examination of the raw image shows spots which are clearly malformed. These can often be filtered out with the second moment filter options.

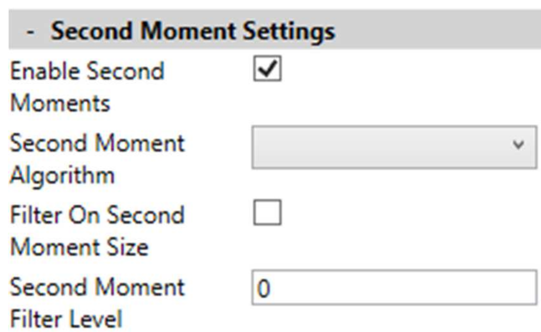


**Figure 21:** Second Moment Settings

**Enable Second Moments** - When enabled the Second Moment settings become available.

**Second Moment Algorithm -** Used for selecting the desired algorithm

> **Boolean Absolute** - A second moment calculation is made and weighted by 1 after the selected absolute value is subtracted from each pixel value in the AOI.
>
> **Intensity Absolute -** A second moment calculation is made and weighted by the pixel intensity after the selected absolute value is subtracted from each pixel value in the AOI.
>
> **Boolean Percent -** A second moment calculation is made and weighted by 1 after the selected percentage of the maximum pixel value for the AOI is subtracted from each pixel value in the AOI.

**Intensity Percent -** A second moment calculation is made and weighted by the pixel intensity after the selected percentage of the maximum pixel value for the AOI is subtracted from each pixel value in the AOI.

**Filter on Second Moment Size** - If selected second moments above the second moment filter level are not included in subsequent analyses.

**Second Moment Filter Level -** Second moments above this level are not included in subsequent analyses when the filter on second moment filter size is selected.

**Modal Analysis**

Modal analysis is often associated with the Zernike set of polynomials and the associated Zernike terms, often referred to as Zernike coefficients. CLAS-NX defaults to Zernike modal analysis, Figure 22.

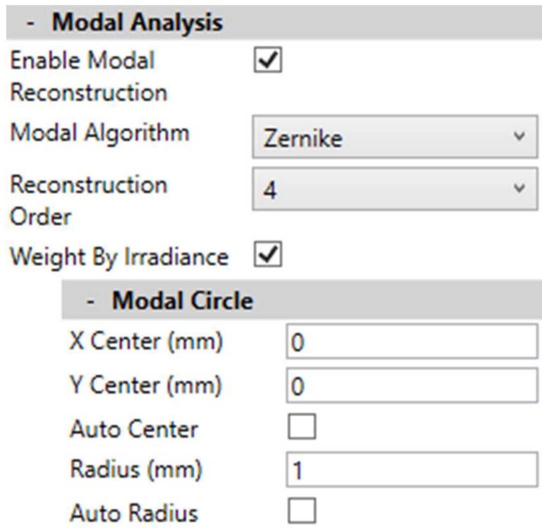


**Figure 22:** Modal Analysis Settings

**Enable Modal Reconstruction** - This enables modal analysis settings

**Modal Algorithm -** The **Zernike** modal algorithm is the only currently available modal algorithm.

**Reconstruction order** - The default reconstruction order are the Zernike polynomials up to and including the 4th order. The pull down menu allows for selection of 4th through 20th.

**Weight by Irradiance** - The weight by irradiance check box is used for selecting the weight by irradiance option. When selected it will weight the centroids of each AOI by the irradiance of that AOI as part of the least squared fit algorithm.

**Modal Circle**

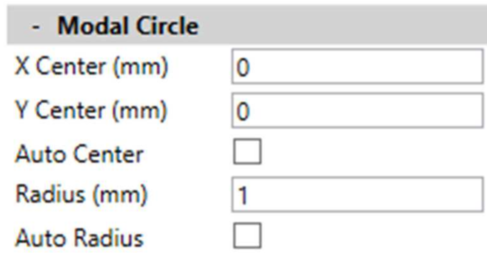


**Figure 23:** Modal Circle Settings

The modal circle sub menu of Modal analysis is where the Zernike, modal, radius is set and is an important part of gathering meaningful modal data.

**X Center (mm)** - X center is the location along the X axis of the measurement pupil plane where the center of the analysis is located.

**Y Center (mm)** - Y center is the location along the Y axis of the measurement pupil plane where the center of the analysis is located.

**Auto Center** - The auto center check box activates the auto center routine, where the center of irradiance is used to locate the center of the modal analysis.

**Radius (mm)** - The radius is important in any modal analysis. Modal analysis result vary greatly depending on the radius. For example, subsequent reports of Zernike coefficients or terms should always include the analysis radius size.

A radius larger than the sensor area may be selected. The fit to areas beyond those covered by AOI's is estimated from the full AOI data set. Small extensions may be useful and accurate, but more than 20 to 30 % beyond the end of the available data can give results that are misleading.

**Auto Radius** - The auto radius check box activates an algorithm which uses the irradiance information to select a modal analysis radius. The selected radius as

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determined by the auto radius algorithm maximizes the number of AOI's exhibiting good signal to noise ratios.

Below modal analysis is the zonal analysis section.

**Zonal Analysis**

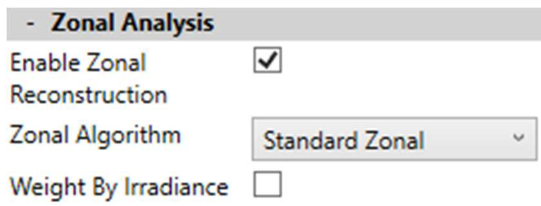


**Figure 24:** Zonal Analysis Settings

**Enable zonal reconstruction** - Selecting the enable zonal reconstruction activates the zonal reconstruction algorithm. It adds a zonal results map to the wavefront tab, which becomes live and active.

**Zonal algorithm** - The zonal algorithm pull down menu displays the standard Zonal Selection.

**Weight by Irradiance -** The weight by irradiance check box is exposed and deselected by default. Selecting it will weight the centroids of each AOI by the irradiance of that AOI as part of the least squared fit algorithm.

## 6.3 Measurement Results:

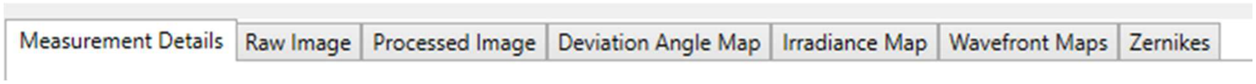


**Figure 25:** Measurement Results Tabs

There are seven types of results tabs:

**Measurement Details**
**Raw Image**
**Processed Image**
**Deviation Angle Map**
**Irradiance Map**
**Wavefront Maps**
**Zernikes**

Clicking on a tab brings it forward and hides the prior tab.

All tabs update after acquiring data. All tabs will update continuously when collecting data continuously at either the integration time rate, the Average Count rate, or the processing rate of the software, whatever has the longest duration.

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**Measurement Details -** The current measurement info tab lists many important parameters for the most recent or active measurement. The current measurement text boxes are all display only. The text displayed cannot be changed to modify the measurement in this screen.

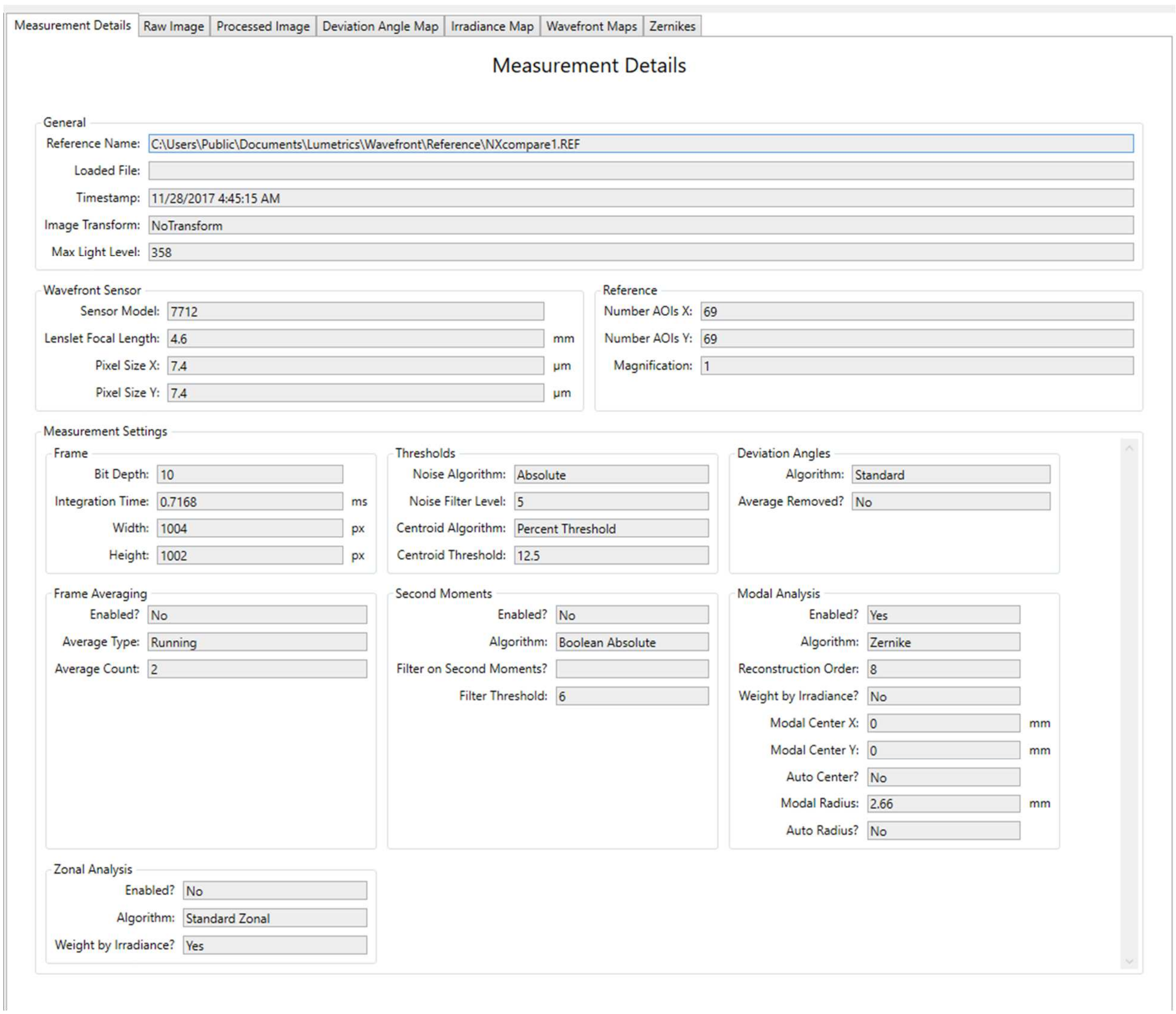


**Figure 26:** Example of the measurement details tab

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**Raw Image** - The raw image tab displays the unmodified image as it is captured by the camera.  There are additional user controls to zoom in, highlight inactive AOIs, mark centroid locations, Show AOI boundaries, and scroll between frames (if multiple frames were acquired).

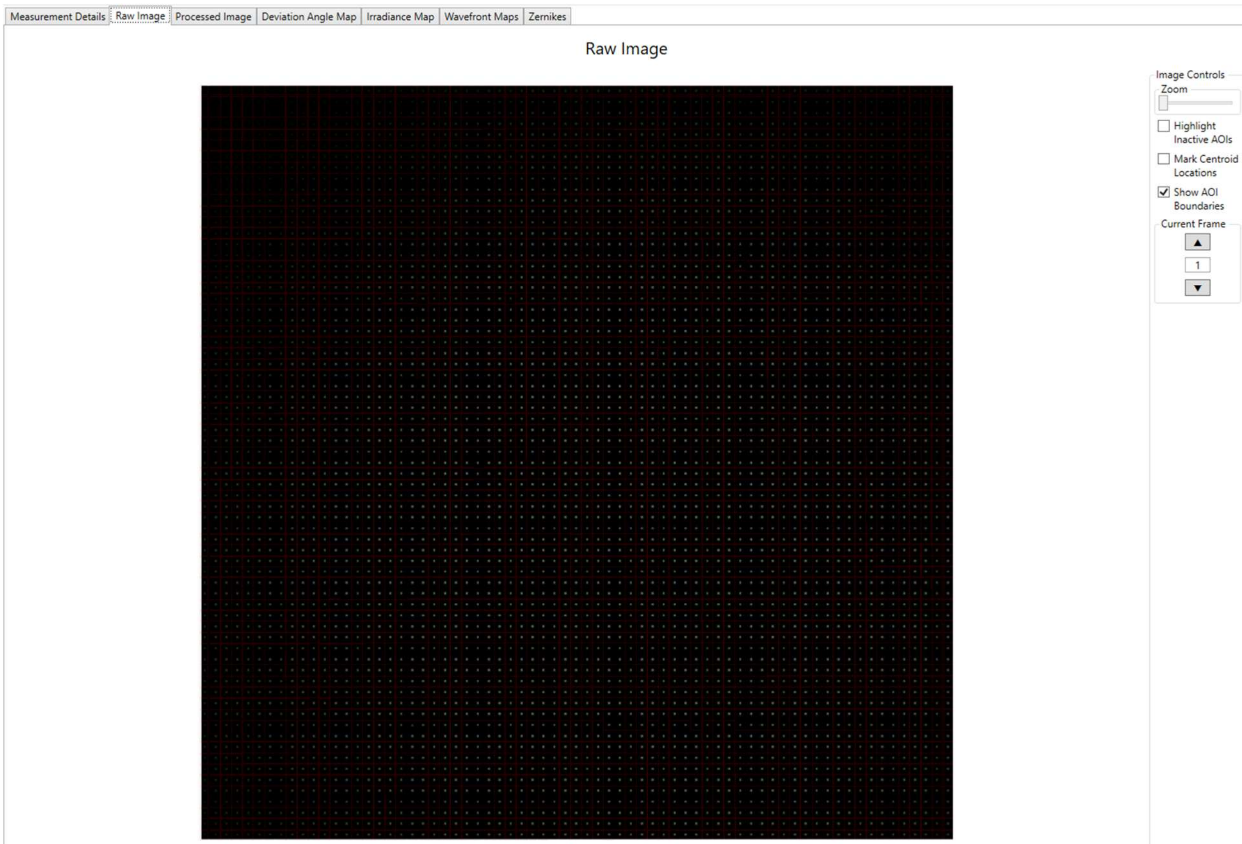


**Figure 27:** Raw Image Tab

**Processed Image** - The process image tab displays the image after the threshold settings have been applied. There are additional user controls to zoom in, highlight inactive AOIs, mark centroid locations, Show AOI boundaries, and scroll between frames (if multiple frames were acquired).

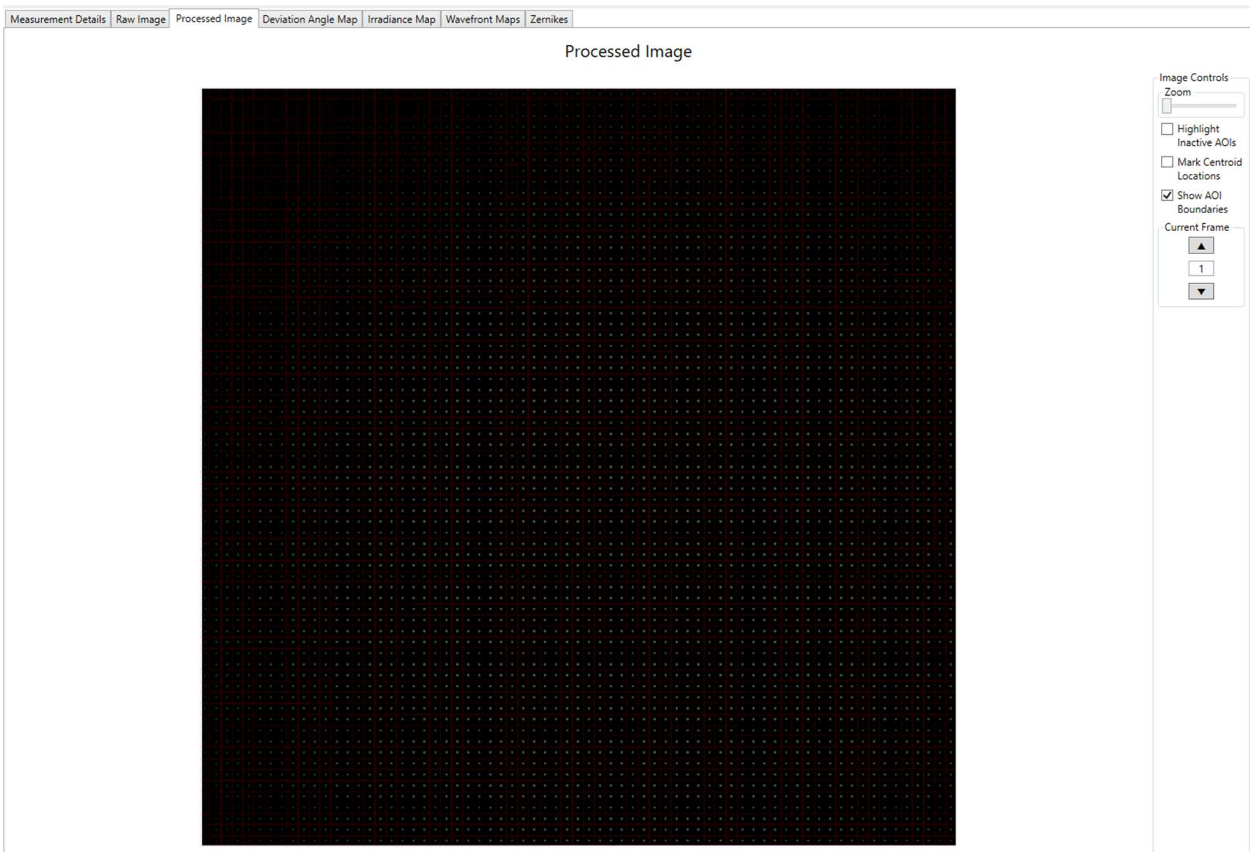


**Figure 28:** Processed Image Tab

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**Deviation Angle Map** - The deviation angles tab displays a map of deviation angle information in the form of vectors.  One vector for each AOI is drawn originating from the center of its AOI, where the length relates to the magnitude of the deviation angle and the direction relates to the direction of its vector.

There is an option to change the scaling factor to better see very large or very small changes in magnitude.

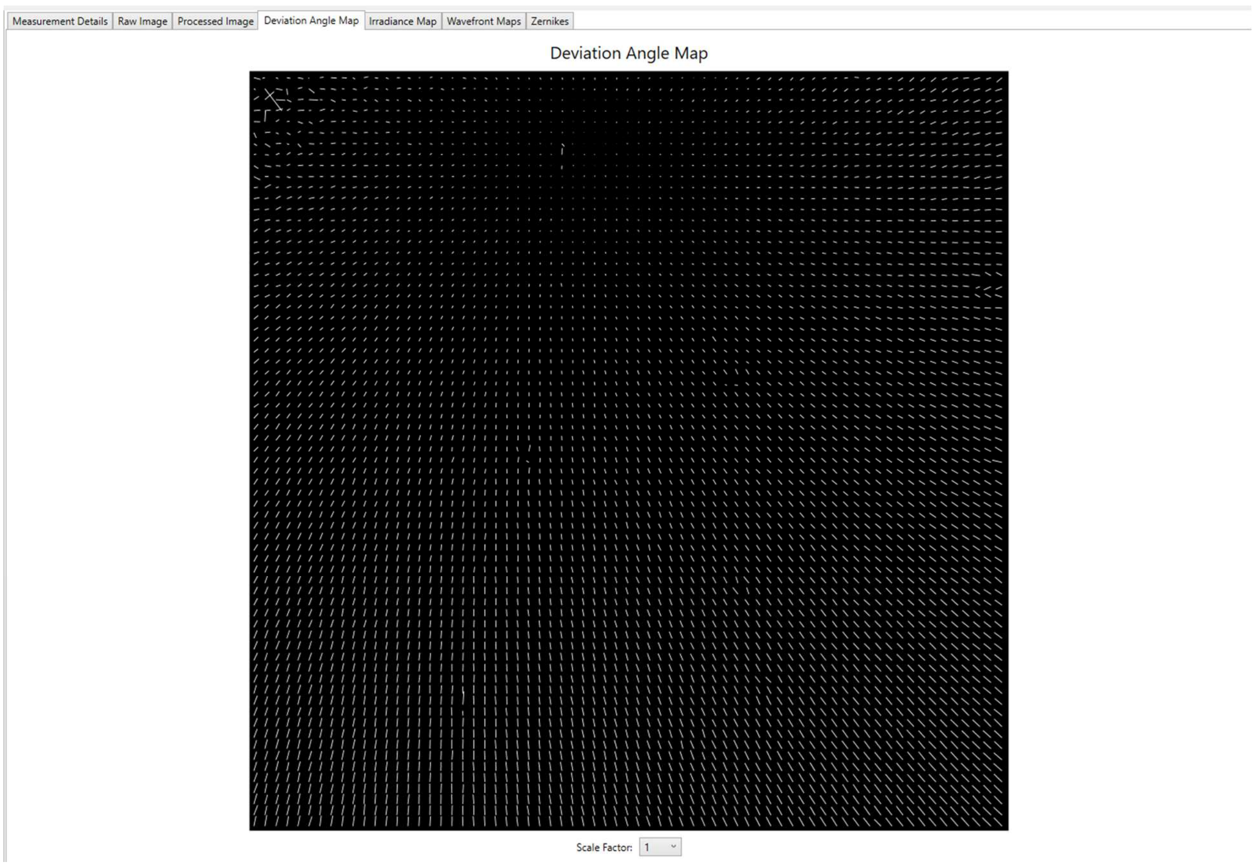


**Figure 29:** Deviation Angle Map

**Irradiance Map** - The irradiance tab displays a map of the irradiance of the wavefront sensor. Each AOI's irradiance is the sum of every pixel's pixel value after the threshold settings are applied. They are relative irradiance values without any units. If absolute irradiance values are required contact Lumetrics. The irradiance map is very helpful in determining how even the input illumination is.

In the irradiance map, a purple group of pixels corresponds to a region where no data was present.

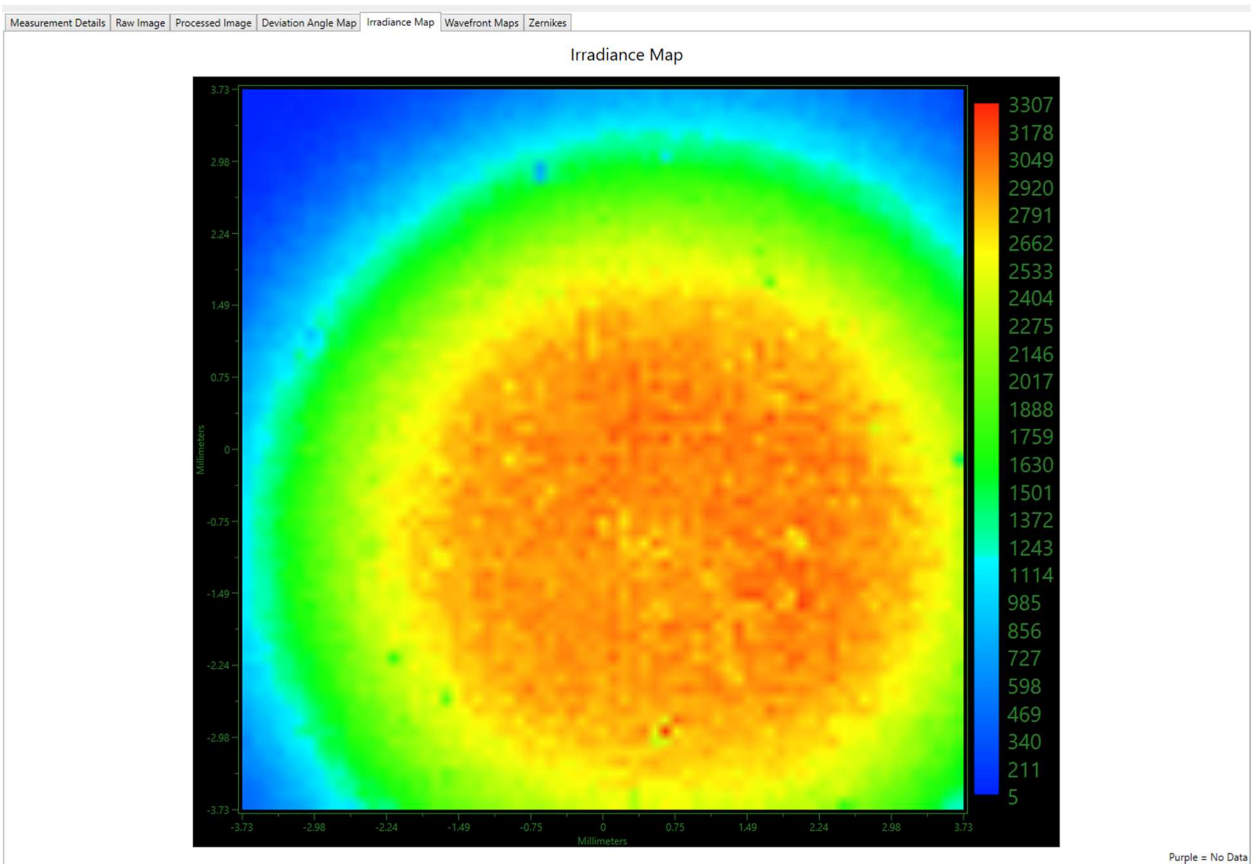


**Figure 30:** Irradiance Map

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**Wavefront Maps** - The wavefront tab will show any wavefront map the operator has selected to be active. A modal wavefront map and a zonal wavefront map can both be displayed together. The maps are scaled to the pupil plane measurement size, magnification is applied. A false color map scale is displayed for each map on the right hand side and has the units of microns. The peak to valley of each map is displayed below the map.

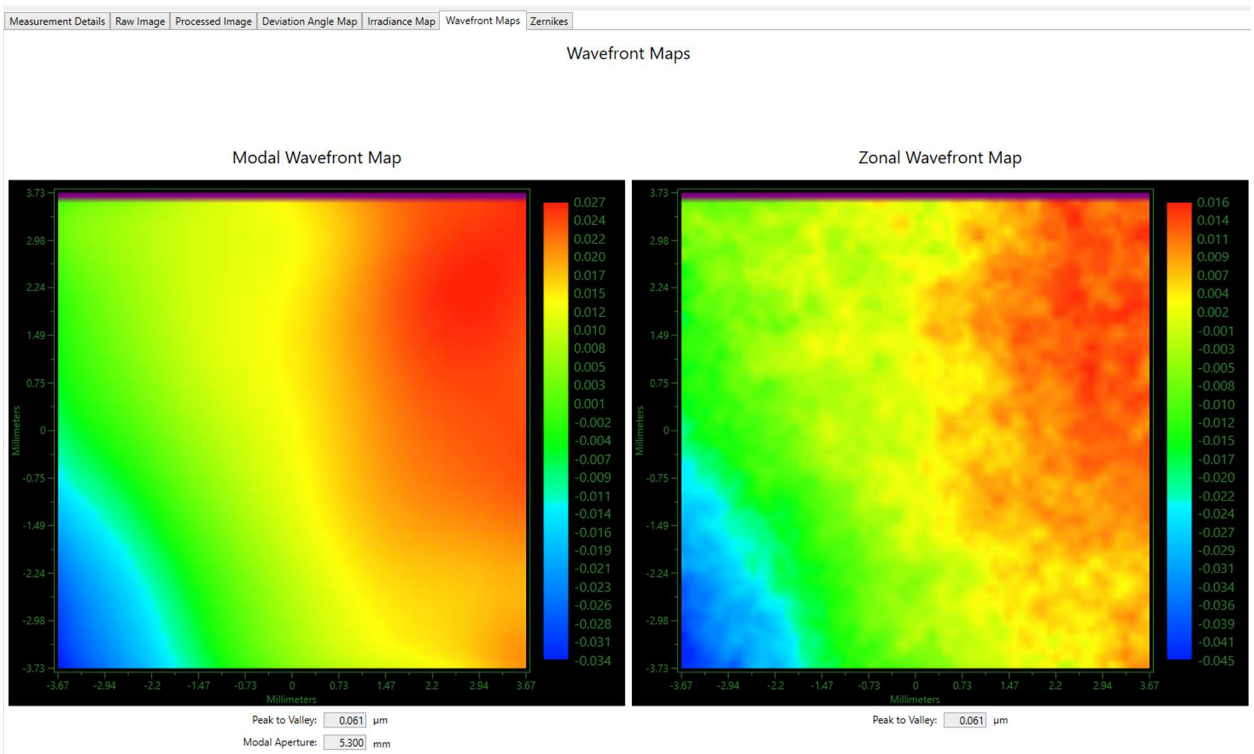


**Figure 31:** Wavefront Maps

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**Zernikes** - The Zernikes tab list the Zernike fit terms in the OSA format. If you need a different Zernike format contact Lumetrics.

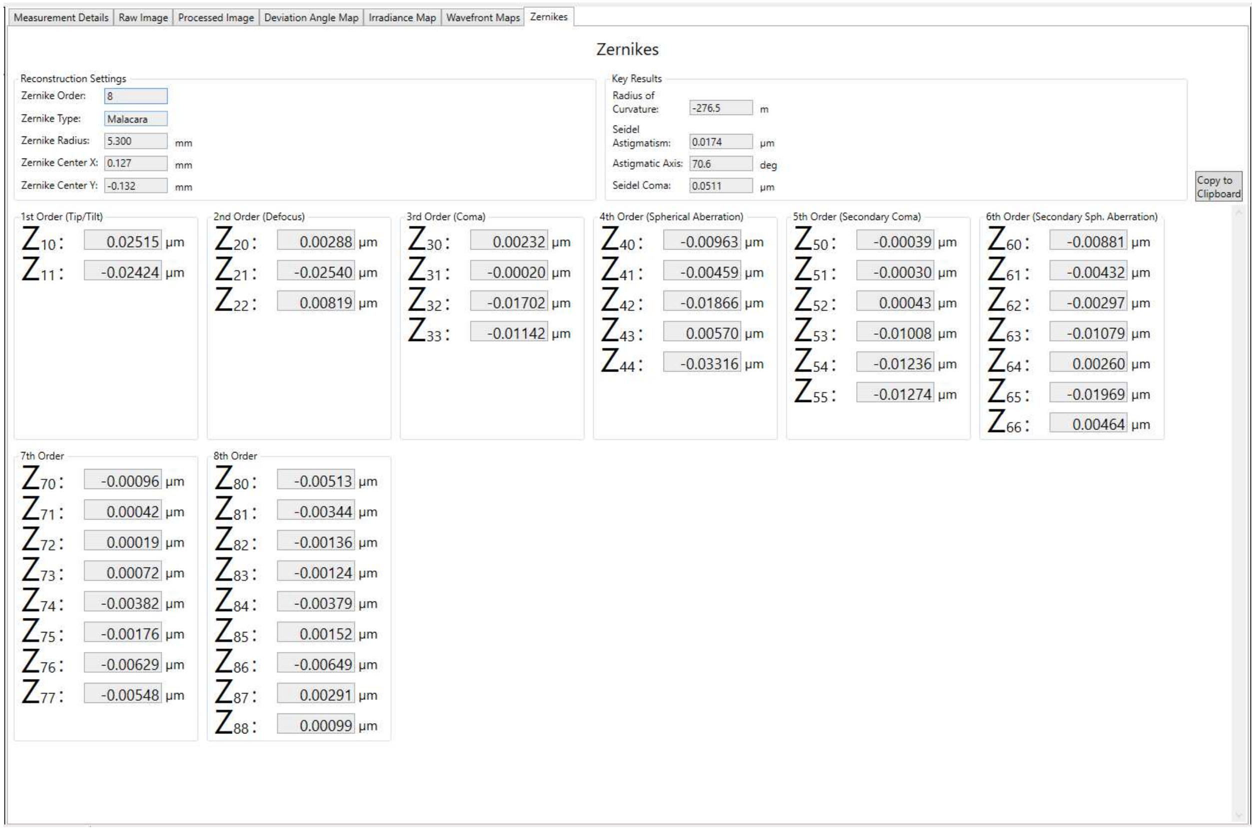

**Figure 32:** Zernike Tab

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## 6.4 Acquisition Controls:

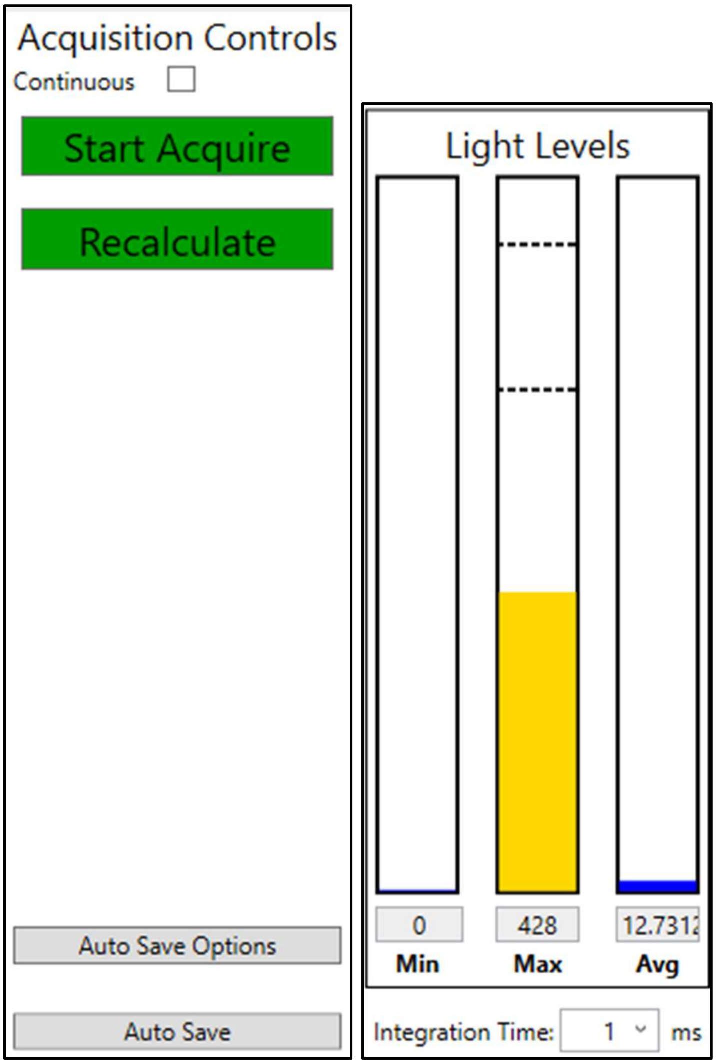


**Figure 33:** Acquisition Controls

**Continuous** - When selected the continuous check box takes measurements one after the other as quickly as the system allows, after the start acquire button is clicked.

**Acquire** - The **Acquire** button initiates a single measurement when the continuous button is unchecked or it launches the continuous acquisition of data if the continuous checkbox is checked.

Once clicked the button will change to **Cancel** (or **Stop** if continuous acquire is selected). Once a single acquire measurement is complete it automatically changes back to the **Acquire** state.

Typically, this state change happens very quickly when a low order Zernike analysis is set as the analysis algorithm. When continuous acquire is initiated clicking the **Stop** is the best way to stop the acquisitions.

**Recalculate** - The recalculate button applies whatever **Measurement Settings** are currently configured to the last data acquired from or loaded into the software.

A new calculation is automatically performed every time the **Acquire** button is pressed or a file is loaded. Typically the recalculate button is not needed unless you wish to experiment with different **Measurement Settings** on a saved image or file. An example case where it is useful, is if the operator changes the center of analysis and wants to see how the data looks with the new center without taking a new measurement.

The recalculate option is not available for certain measurement conditions.

**Auto Save Options -** This button brings up a window to allow one to specify the folder where Auto Saved data will be stored, a File name, and to specify the types of files to be saved.

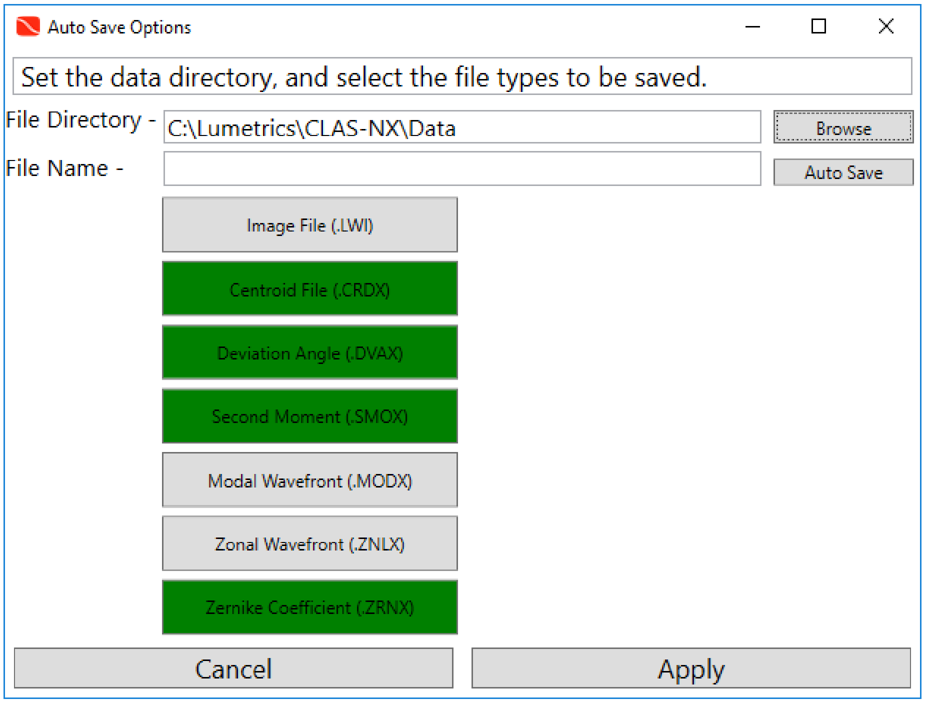


**Figure 34:** Auto Save Options

**Auto Save** - The **Auto Save** toggle button initiates the auto saving of data files. Caution is required when using this button when also using the continuous measurement mode.  Image files are large and can fill a hard drive quickly.  It is recommend that the auto save options be used to save one of two files, deviation angles or centroids.

**Light Levels** - The light levels display is active when CLAS-NX is running and the correct Wavefront Sensor is selected.  It displays the pixel brightness level of the second brightest pixel. The single brightest pixel is excluded to help reduce false readings from a single “hot” pixel, which sometimes happens even with the high-quality cameras used to build wavefront sensors.  Cameras may have a pixel that does not respond to input conditions correctly.

When the central bar (MAX) is green measurements are most likely to be accurate and repeatable and is considered the ideal beam intensity for the overall wavefront measurement. MIN and AVG bars are also provided for reference purposes.

**Integration time** - The integration time box allows the user to set the integration time which achieves an 80% ±12.5% maximum light level. A number may be selected from the pull down menu or typed in the box. Integration time is the exposure time used by the wavefront sensor when acquiring light.

# 7 Measurement Example 1: Measurement of a Collimated Beam

A Shack-Hartmann wavefront sensor is a scientific instrument designed to be used by an optical technician with optical breadboard experience. Experience working with interferometers is useful, but not required. Like an interferometer, a Shack-Hartmann wavefront sensor is different from a camera. Both an interferometer and Shack-Hartmann are not designed to capture an image. Like an interferometer, a Shack-Hartmann wavefront sensor is never exposed to an extended object source. Exposing a Shack-Hartmann wavefront sensor to an extended object will create an extended image behind each lenslet and would result in erroneous wavefront data. This and many other issues are clarified through this example; the measurement of a collimated beam, see Figure 35.

## 7.1 Equipment list:

- CLAS-NX driven Shack-Hartmann wavefront sensor
- Alignment fixture to hold the CLAS-NX sensor with X-Y translation and tip-tilt control.
- Rough squaring fixture
- Optical breadboard
- Pinhole with rear illumination light source, also known as the point source.
- Pinhole holder
- Collimating lens with a 100mm effective focal length is recommended
- Collimating lens holder with 50mm of Z axis travel and 10 mm X-Y translation
- Assorted holders and mounts to attach, align, and translate components with respect to the breadboard

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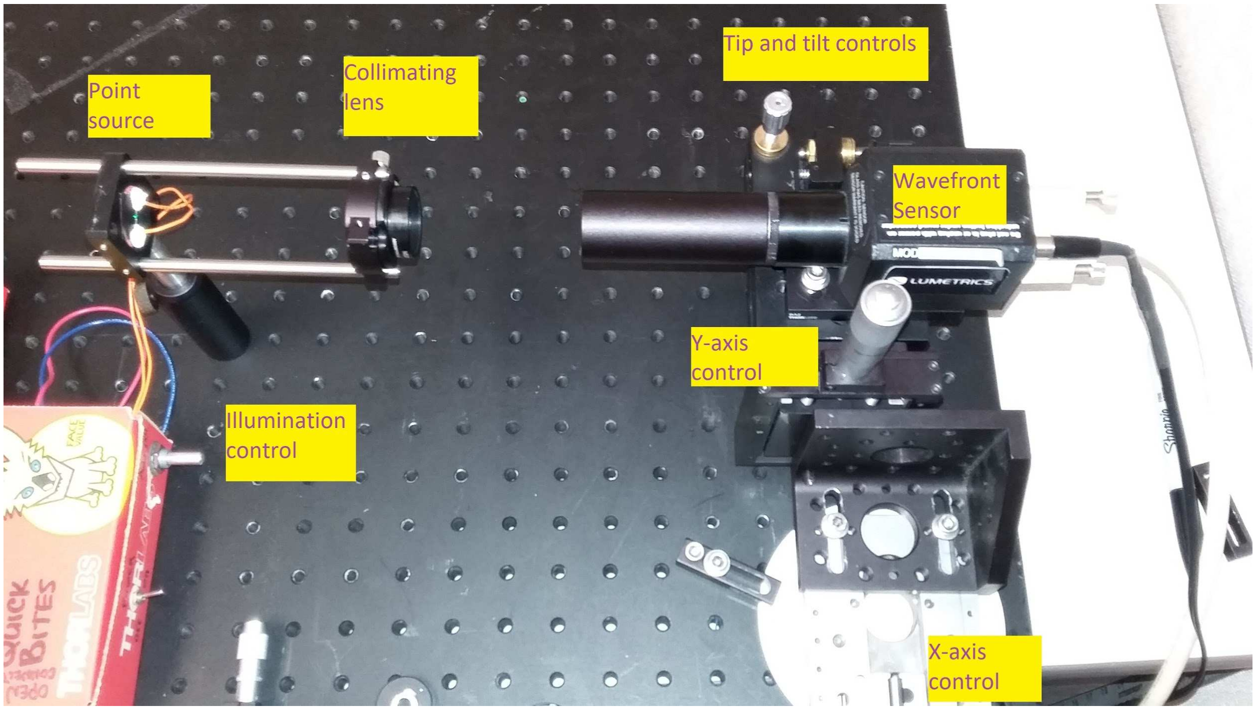


**Figure 35**: Example of a completed collimated beam measurement setup

Measuring the quality of a collimated beam is the most basic operation a Shack-Hartmann wavefront sensor performs. The quality of an optical setup employing a Shack-Hartmann wavefront sensor is equally contingent upon: the quality of the pinhole source, the quality of the collimating system and the quality of the alignment control on the Shack-Hartmann wavefront sensor.

An evenly illuminated pinhole that is smaller than the diffraction limit spot size of the collimating lens is ideal, but not necessarily required. A quick screen test helps determine if a pinhole is a good source. One of the best screens to perform this test is the back of a white business card. Place the screen as close to the pinhole as possible and observe the light pattern it creates, round and even is best. Pull the screen away slowly observing the light pattern as you move it. It should get larger in diameter, stay evenly illuminated and round. If the pinhole screen test looks good move onto the next two steps of coarse-rough squaring and coarse-rough collimating.

There are two main issues which can reduce the usefulness of a collimated input beam, too much residual defocus and too much tip-tilt. Either issue on its own is enough to mask useful information, or cause an out-of-range condition, in a wavefront measurement. Performing two simple optical alignment procedures helps ensure the setup is roughly square, meaning tip-tilt is minimized and roughly collimated.

Coarse squaring - Coarse squaring is a mechanical process, which is assisted by the use of an optical breadboard. Simply place and center all the optical components along the same row of tapped holes. Finally, rotate each optical component so that it is parallel to the optical axis. The tapped holes can be used as a visual guide to help set the optical components perpendicular to the optical axis.

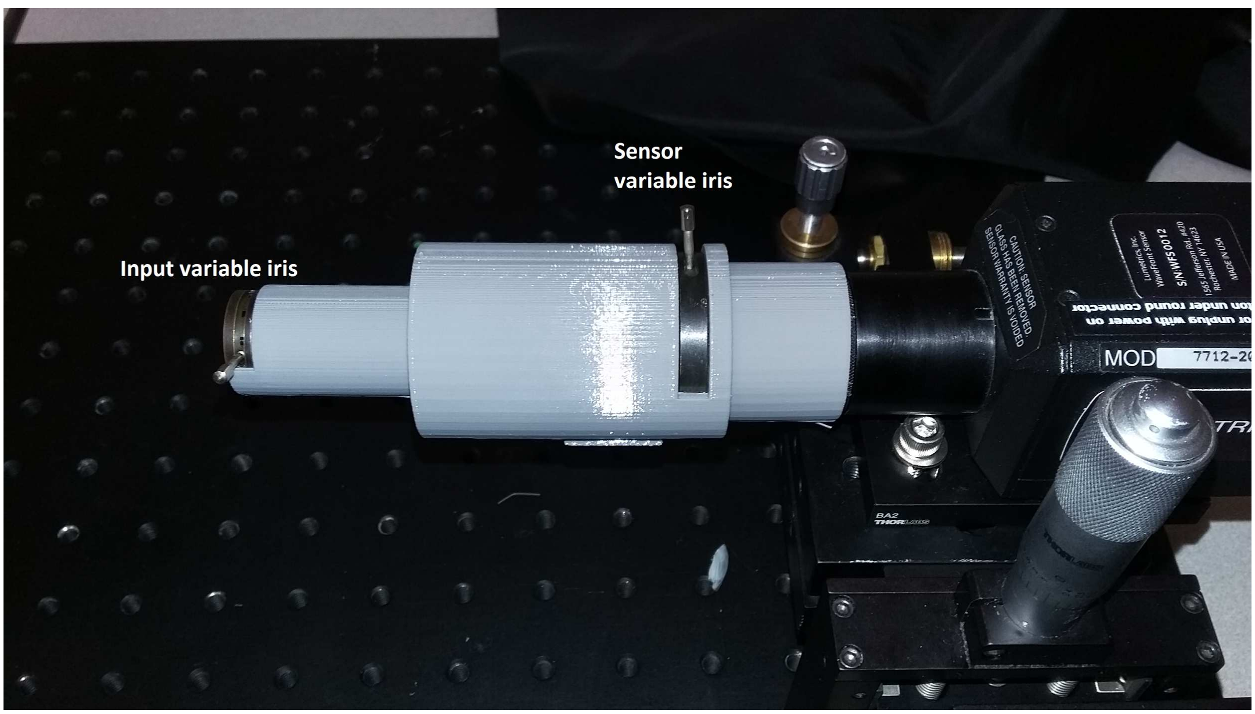


**Figure 36**: An example of a 3D printed dual iris alignment fixture suitable for rough squaring

Rough squaring - Rough squaring is an optical alignment process based upon the fact that two points form a line. In this case, the line is the optical axis. The two points, part of the rough squaring fixture, are two variable iris apertures separated by about 75mm, see Figure 36.

Start CLAS-NX and navigate to the raw image screen. Start a continuous measurement with modal and zonal analysis disabled. Iterate between opening and closing the input iris and sensor iris while adjusting the position of each component. With practice, the shape of the centroid spot pattern will indicate to the operator which components in the optical chain needs to be tipped, tilted, or repositioned. In general, adjusting the tip and tilt of the wavefront sensor has the greatest effect during rough squaring. Look for an evenly shrinking or expanding circle of centroids while closing and opening the iris apertures alternately. If a shape like a cat's pupil is observed while opening and closing either iris further alignment is needed. When changing either iris results in an evenly changing circular centroid spot pattern rough squaring is complete. Lumetrics can provide the variable iris aperture alignment fixture.

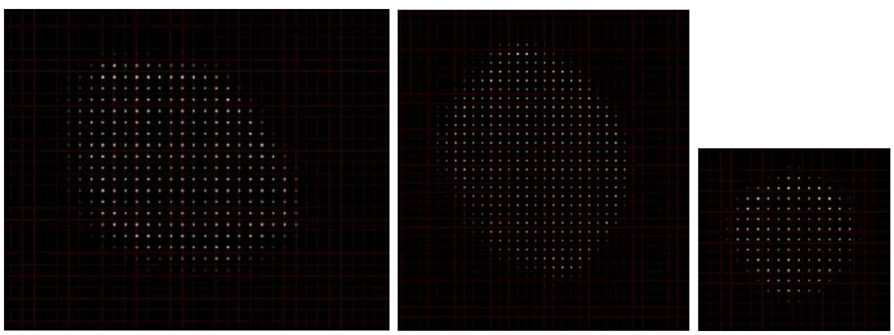

**Figure 37:** First two images show non-round centroid patterns and the third is a small round pattern signifying the system is roughly aligned for tip and tilt.

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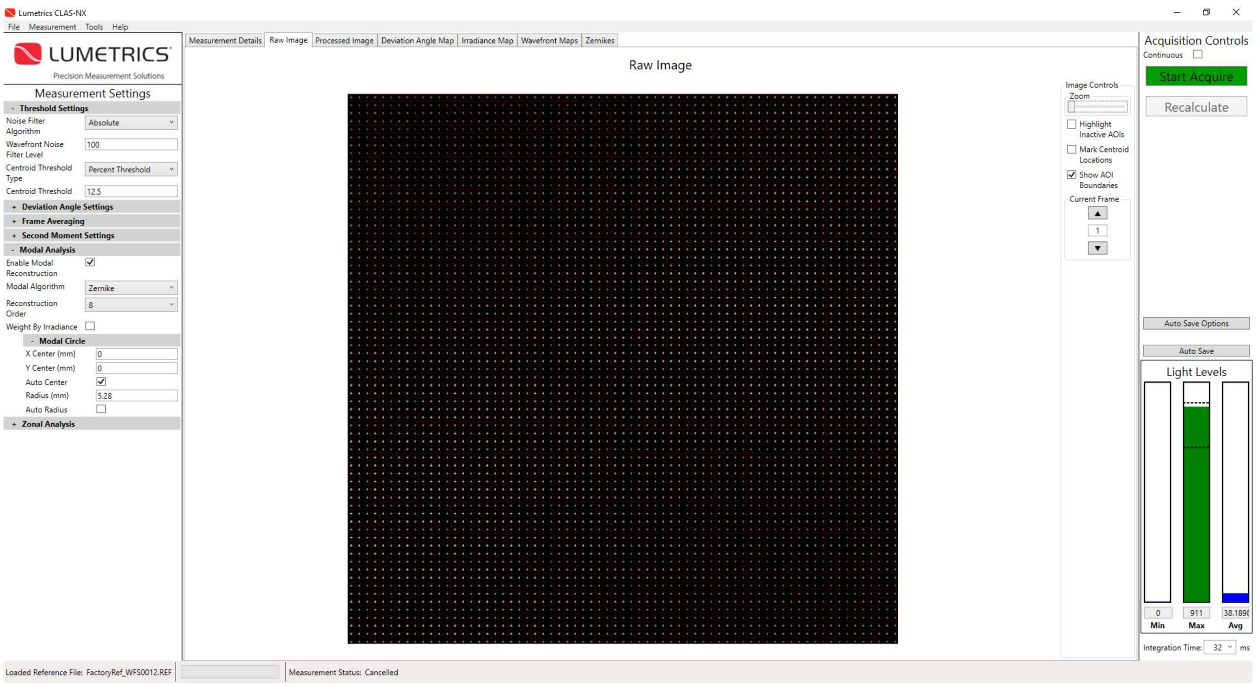

**Figure 38:** Raw image with the rough alignment fixture installed and both variable iris rings fully open; the full screen is illuminated

Coarse collimating - Using a ruler place the midpoint of the collimating lens 1 focal length away from the point source.

Rough collimating - After course collimating, rough collimating begins with a small white screen, often a business card. Place the screen close to the collimating lens and note the size of the light spot. Move the screen away from the collimating lens slowly observing if the spot increases or decreases in size. Adjust the distance between the pinhole and the collimating lens until the spot on the business card stays a constant size as the screen moves along the optical axis.

Review 5 to 10 lenslets' image spots using the processed image tab. Review some lenslets near the edge of the aperture and some near the center of the aperture. Typically, each lenslet's focal spot should be no larger than ⅓ of the AOI, and be symmetric. Elongated or line foci indicate the pinhole is not a good point source, not well aligned or that there are dirty or bad components in the optical chain.

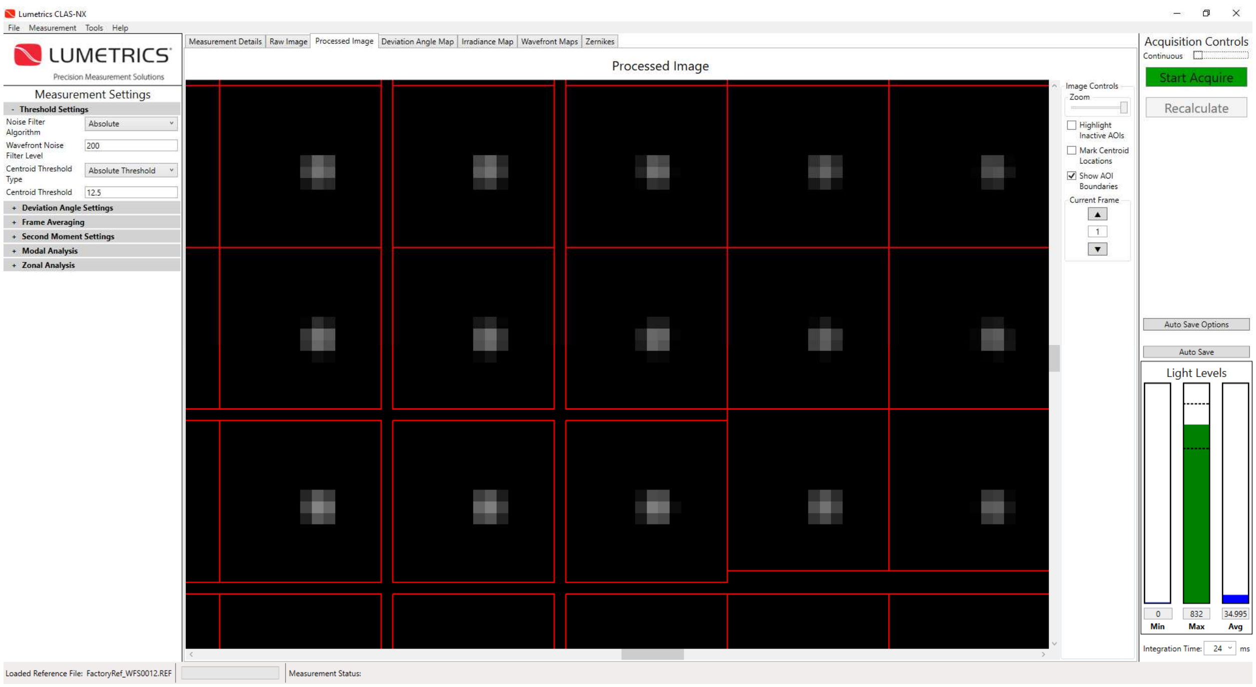


**Figure 39:** Central centroids in the processed image tab with maximum zoom

The central centroids seen in Figure 39 are near the center of their red AOI boxes and have around 6 to 16 white to gray pixels. The brightest pixels are in the center of the illuminated pixels. These are examples of AOI's foci which can be expected to give accurate analysis results.

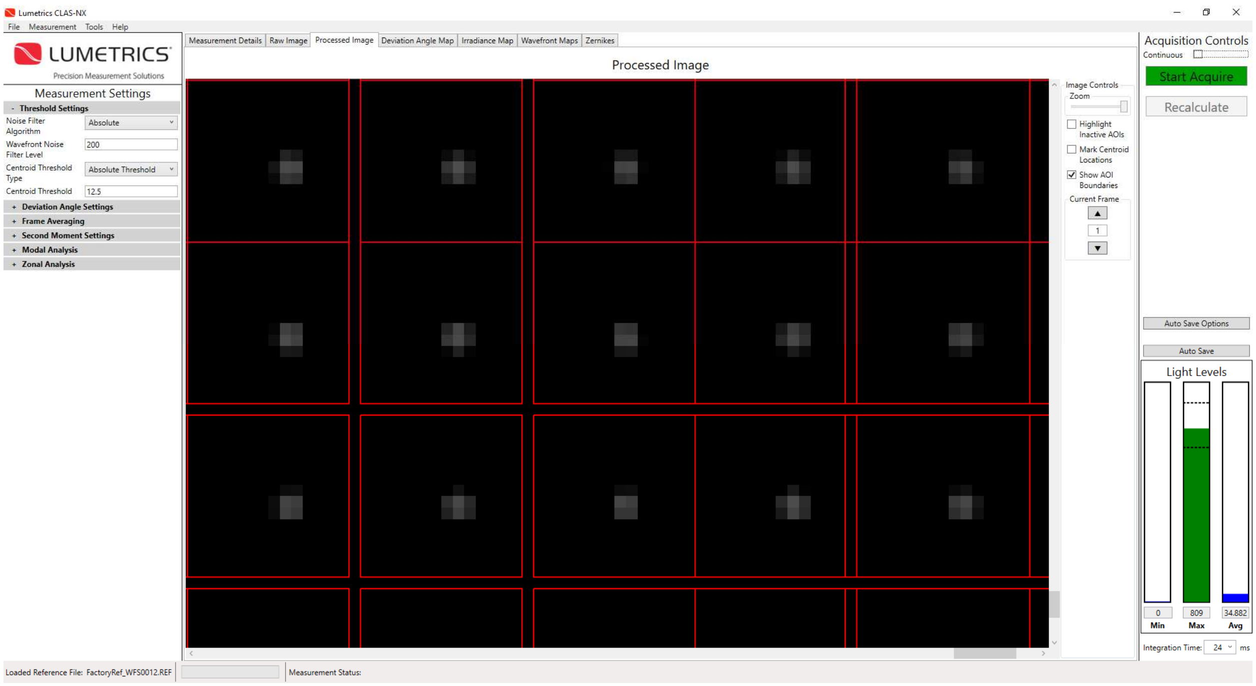


**Figure 40:** Lower right corner pixels

In the processed image tab, dragging the scrollbars to the lower right displays the lower right AOI's, as seen in Figure 40. Again, there are about 6 to 16 white and gray pixels relatively well centered in their red AOI boxes. Once your setup has similar results to Figures 40 and 41 your system is roughly square and roughly collimated. You can now use the analysis data from the wavefront sensor as feedback to achieve fine alignment.

As you set up your collimated beam, you may notice that collimating and squaring the beam really happen together. If the beam is too divergent then you will run out of light as you try to check for square. If the square is very far off you will have a hard time finding the beam to check it for collimation. The main advantage of the optical breadboard is that with a little care from the operator it will keep the optical system reasonably aligned during the setup process.

With a roughly squared and collimated beam run the Shack-Hartmann wavefront sensor's analysis tools and observe the outputs of tip, tilt, and defocus.

Check list:

1. Open the raw image tab and confirm the image is a series of uninterrupted dots, see Figure 41.
2. Open the irradiance tab and confirm the sensor is mostly evenly illuminated, see Figure 42.
3. Open the processed image, zoom in to confirm only one spot is in each red box, like Figure 40
4. Open the Zernike tab, see Figure 43.
5. Adjust the Z position of the collimating lens until the key result, residual radius of curvature in the upper right section of the Zernike tab, is maximized. See Figure 43. It should be greater than 50 meters.
6. Adjust the tip-tilt controls on the sensor until Z10, and Z11 are below 0.005 µm.
7. Open the wavefront tab. Typical results: The wavefront map should be very flat, i.e. the peak to valley reading should be low, approximately 0.01 to 1 µm depending upon the quality of the optics and alignment. See Figure 44.

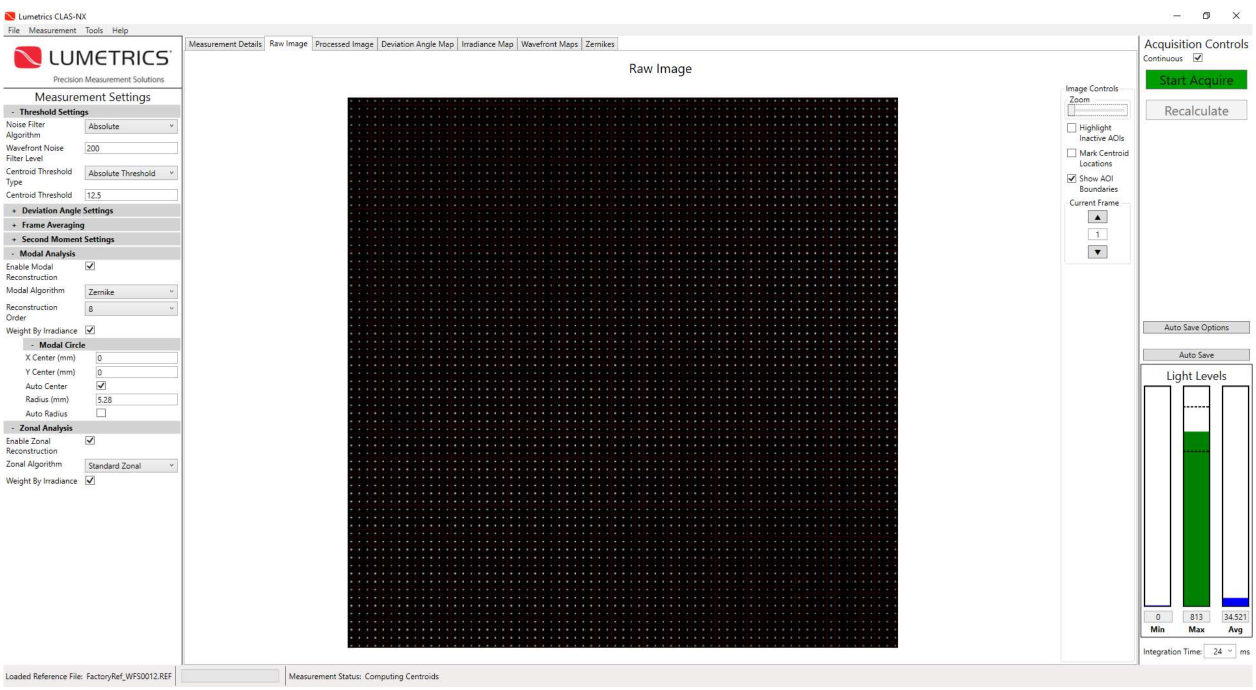


**Figure 41:** Raw image showing even spaced centroid foci

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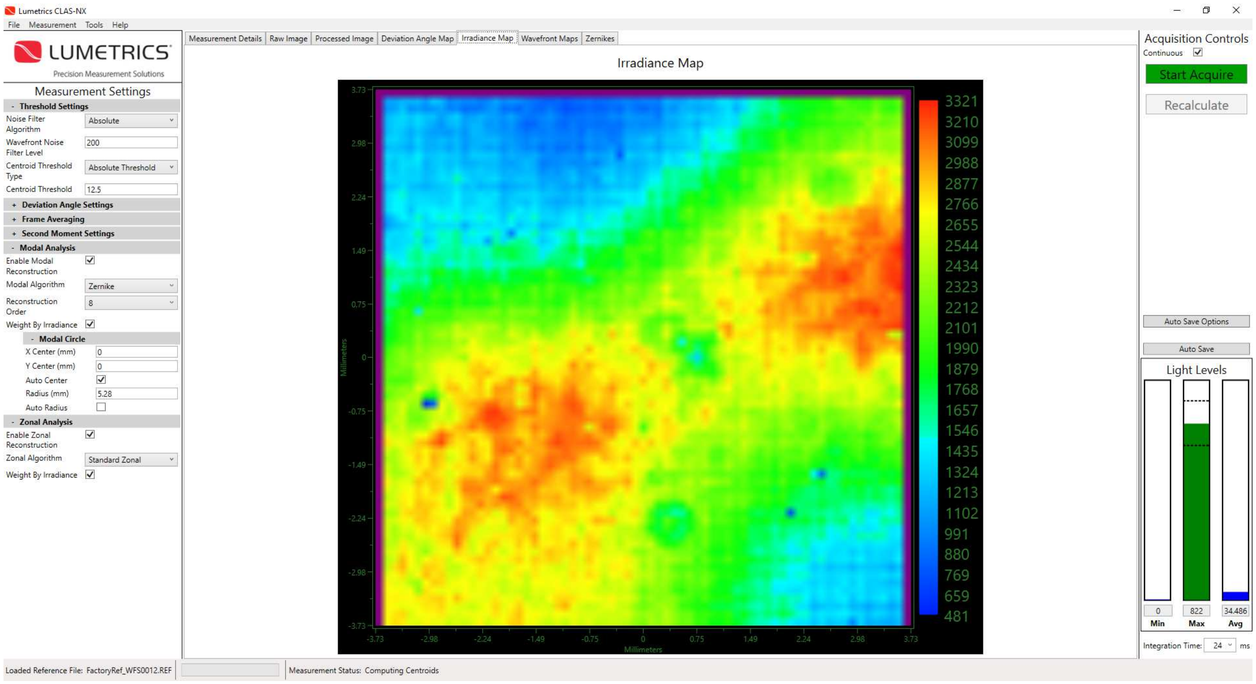


**Figure 42:** Irradiance showing fairly even illumination

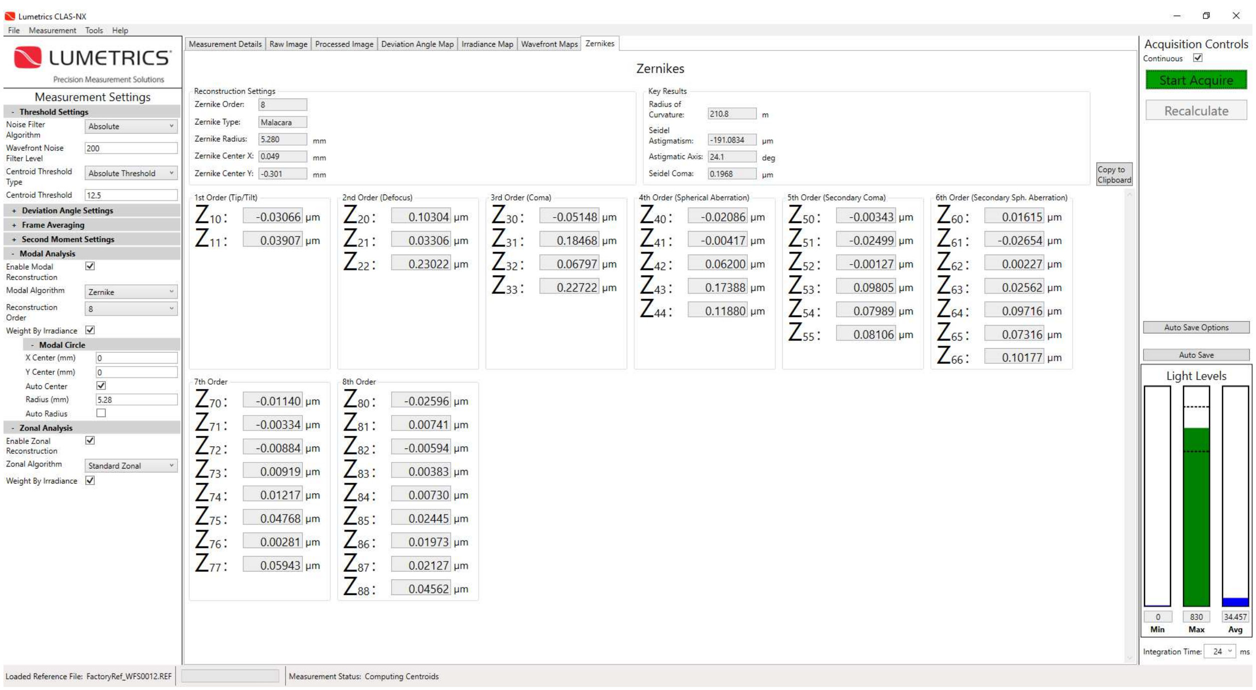


**Figure 43:** Zernike tab showing a long residual radius of curvature, low Z10 and Z11 results.

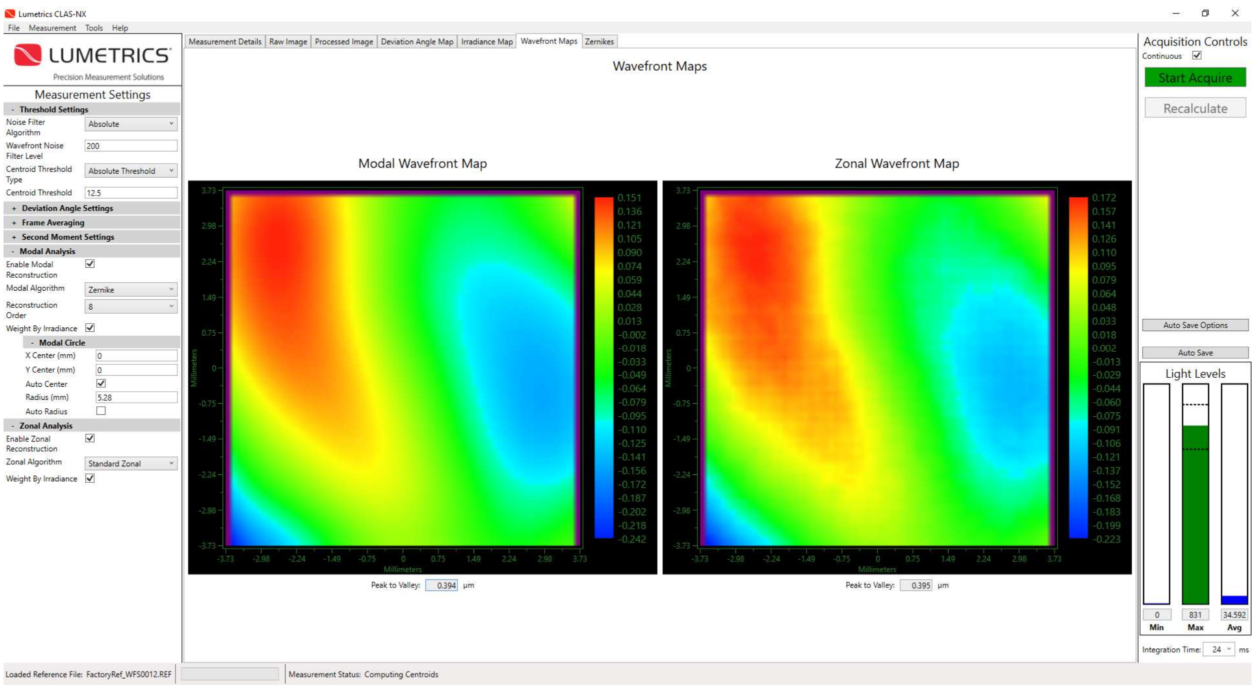


**Figure 44:** Wavefront maps tab showing flat wavefronts by both modal and zonal reconstruction methods.

# 8 Measurement Example 2: Front Surface Quality of a Front Surface Mirror

We recommend completing example one prior to starting example two. Example 1 can be classified as a transmitted wavefront measurement. In example one, the lens used to collimate the point source creates a flat wavefront, which is a single pass transmitted wavefront, passing through and emanating from the collimating lens and falling directly onto the wavefront sensor. Example two is a double pass measurement. Interferometer users are typically familiar with double pass measurements, for example Fizeau interferometers most often operate in reflection and are double pass measurements. The term double pass refers to the fact that light passes through the test sample twice. Any flaw encountered affects the wavefront twice, once as the beam is incoming and again after the beam has been reflected. Results from a double pass measurement must be divided by two to accurately describe the surface under test. In Example 2 we measure the front surface quality of a front surface mirror.

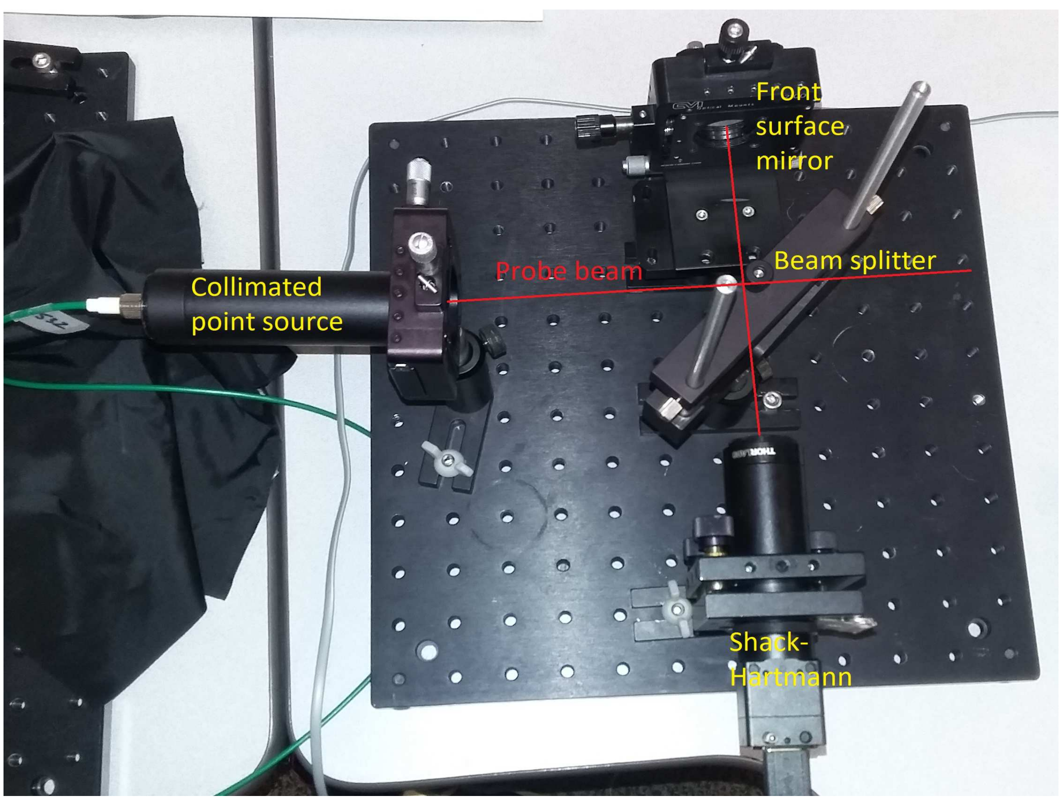


**Figure 45:** Layout for example two

## 8.1 Equipment list:

CLAS-NX driven Shack-Hartmann wavefront sensor
Alignment fixture to hold the CLAS-NX sensor with X-Y translation and tip-tilt control.
Rough squaring fixture or a mirror which can be mounted onto the front of the sensor
Optical breadboard
Pinhole with rear illumination light source
Pinhole holder with 10 mm X-Y translation
Collimating lens with a 100 mm effective focal length is recommended
Collimating lens holder with 50 mm of Z axis travel and 10 mm X-Y translation
Assorted holders and mounts to attach, align, and translate components with respect to the breadboard
1 inch 50/50 pellicle beam splitter
Mount for 1 inch pellicle beam splitter
1 inch front surface mirror as the device to measure
1 inch front surface mirror as an alignment tool
Small aperture alignment fixture
Mirror mount with tip-tilt adjustments

## 8.2 Instructions:

Measuring the quality of a front surface mirror starts by setting up a well collimated beam, see example one. Since we will be using the collimated beam of example one to probe the surface of the mirror, let's label the collimated beam as the probe beam. To make our test results easy to understand we want the probe beam to be incident upon the test mirror exactly perpendicular to the mirror's front surface. A common method of directing a probe beam perpendicular to a test surface while creating a space to place the sensor where it can detect the reflection off of the test sample is by using a pellicle beam splitter, see Figure 46. Place the pellicle beam splitter into the probe beam at a 45 degree angle. A portion of the beam will continue forward and a second portion of the beam will reflect 90 degrees relative to the undeviated forward propagating beam. The reflected beam is a well collimated beam, and is suitable for testing the surface quality of a front surface mirror. Place the mirror under test into the reflected beam.

The mirror under test can also be used to refine the alignment of the system. The reflection off the mirror will cause an image of the point source to be formed back at the plane of the point source itself. When the mirror and pellicle beam splitter are co-aligned along the same axis the image of the pinhole will be placed on top of the pinhole itself. By adjusting the tip and tilt of the mirror while adjusting the rotation of the pellicle the system can be aligned to retro-reflect an image of the point source back onto the point source. Unfortunately, a good retro-reflection does not guarantee the pellicle is exactly at 45 degrees. However, the pellicle being a few degrees off of 45 degrees is not detrimental to the final measurement as the sensor can be squared to the mirror in a separate alignment step. In this example, we will rely upon the mechanical layout of the optical breadboard to ensure the pellicle beam splitter is set sufficiently close to 45 degrees with respect to collimated beam setup in example one.

With the test mirror in place and the collimated light source on, inspect the area directly across from the mirror on the other side of the beam splitter. There should now be another beam in the area across from the test mirror and beyond the beam splitter. The CLAS-NX driven wavefront sensor measures this beam. Place the sensor coarsely in the center of this beam.

Next, square the CLAS-NX driven Shack-Hartmann wavefront sensor to the mirror being measured. In example 1, we aligned the sensor using the variable iris rough squaring fixture. We will use a different method to square the sensor in example 2. In fact, the procedure of using a mirror to square up an optical component to the collimated beam has already been performed in the earlier step when the test mirror was added. The same process works for the sensor by mounting a mirror onto the sensor’s face. After the mirror is mounted to the sensor’s face observe the point source plane for the image formed by the reflection of the mirror temporarily placed in front of the sensor. Adjust the tip and tilt of the sensor until the reflected spot, at the pinhole plane, is coincident with the pinhole. Remove the mirror from the wavefront sensor after it is aligned. Note, if you see two spots at the at the pinhole plane then the test mirror became misaligned, realign it.

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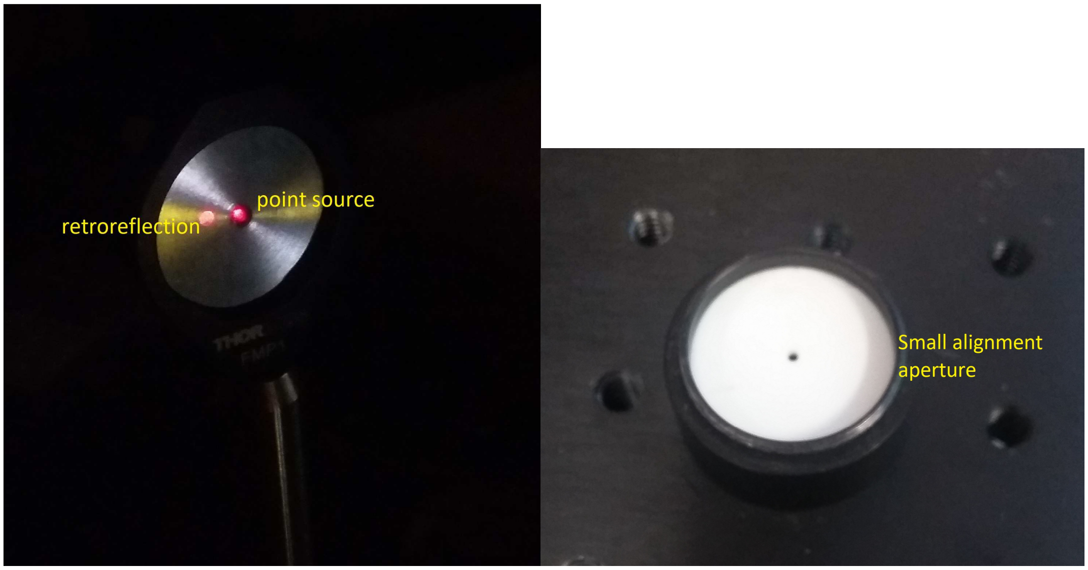


**Figure 46:** Retro-reflected focal spot and small aperture alignment fixture

Now that the retro-reflection mirror process has squared the sensor to the collimated beam, we can center it.  Remove the 1 inch alignment mirror from the face of the sensor.  Add the small aperture alignment fixture to end of the collimator.  The small alignment aperture fixture trims the collimated beam down to a small thin beam which is centered on the collimated beam.  For ease of use and increased stability, the small aperture alignment fixture should thread onto the same mount which holds the collimating lens.  When the trimmed down beam hits the sensor it shows up as a dot.  Adjust the X-Y stage of the sensor until the dot is in the center of the sensor's output.  Now the center of the collimated beam is coincident with the center of the wavefront sensor.  Remove the small aperture alignment fixture from the end of the collimator.

After the course and rough alignment steps are complete start CLAS-NX.  In the raw image tab confirm each red box AOI has only one white focus spot.  If not change the tip and tilt of the wavefront sensor until each red box has one white focus spot.  Set modal analysis to active.  Go to the Zernike tab and use Z10 and Z11 to fine align the CLAS-NX driven wavefront sensor, by adjusting the tip and tilt controls until Z10 and Z11 are within ±0.1 µm. The system is ready to read the surface of the test mirror.

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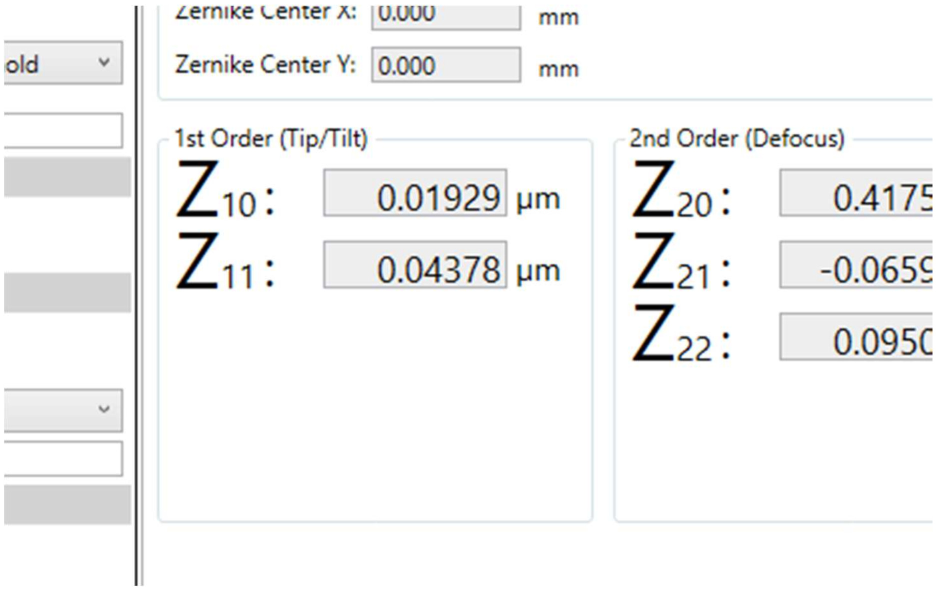


**Figure 47:** Zernike tab zoom in showing low levels of tip and tilt $Z_{10}$ and $Z_{11}$

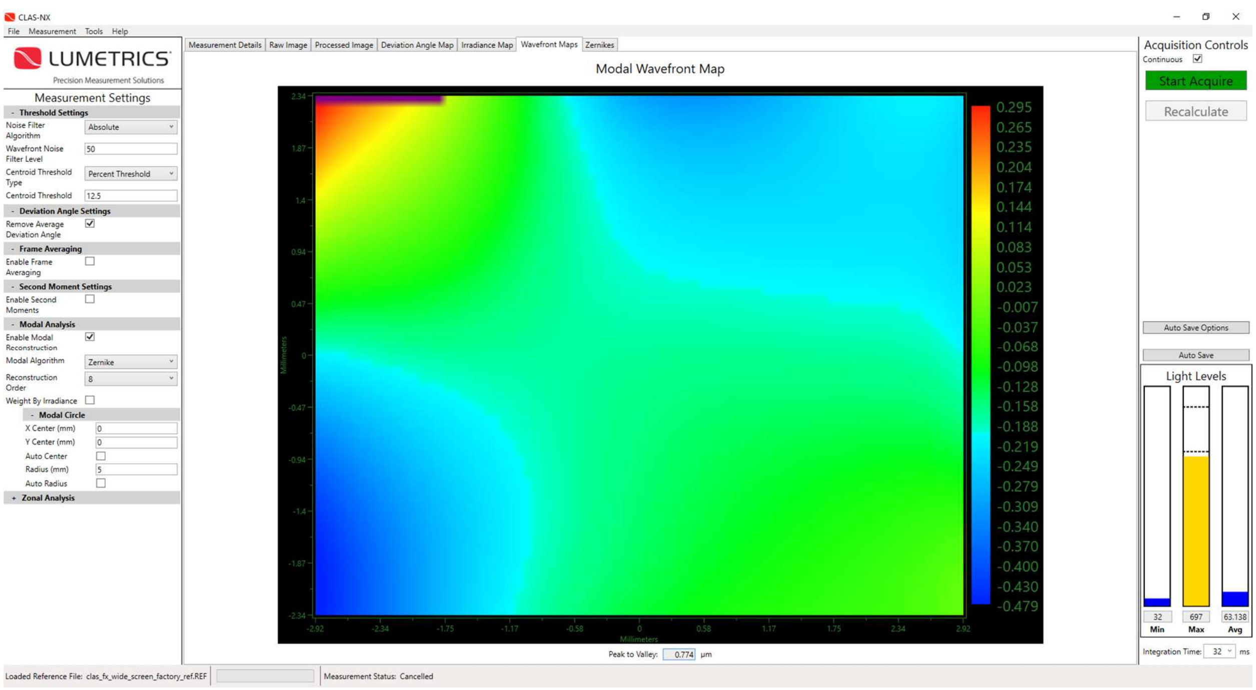


**Figure 48:** Wavefront tab example

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# 9 Measurement Example 3: Plano-Plano Window Transmission Quality

We recommend completing example one prior to starting example three, testing the transmission quality of a plano-plano-window. While this example is good for illustrating the concept of measuring the transmission quality of a window, it is not the ideal setup for testing the transmitted wavefront of a window in practice. The addition of a relay lens system would greatly improve upon the final test setup, and we leave this as an exercise for the user to further their experience. Also, we introduce the concept of creating a reference file in this example. If you are new to the CLAS-NX you can complete this example without creating a reference file by continuing the example leaving the factory reference file in place. For a new user, we recommend you skip the reference file creation step in this example.

## 9.1 Equipment list:

CLAS-NX driven Shack-Hartmann wavefront sensor
Alignment fixture to hold the CLAS-NX sensor with X-Y translation and tip-tilt control.
A mirror which can be mounted onto the front of the sensor
Optical breadboard
Pinhole with rear illumination light source
Pinhole holder with 10 mm X-Y translation
Collimating lens with a 100 mm effective focal length is recommended
Collimating lens holder with 50 mm of Z axis travel and 10 mm X-Y translation
Small aperture alignment fixture
Assorted holders and mounts to attach, align, and translate components with respect to the breadboard
Plano-plano window to test
Fixture to hold the test window in the collimated beam

## 9.2 Instructions:

We assume example one's collimated beam is still aligned, but that the sensor has been removed and needs to be place back into the system.

First, using the optical breadboard's threaded holes as guides secure the CLAS-NX driven wavefront sensor in position in front of the collimated beam. Onto the face of the sensor place a mirror. Observe the reflected spot as illustrated in Figure 46 in Example 2. Adjust the tip and tilt angles on the sensor until the reflected spot is coincident to the fiber point source. Remove the mirror. Place the small aperture alignment fixture, Figure 49, into the center of the collimating lens holder. Adjust the X-Y translation stages on the wavefront sensor until the spot in the raw image is centered. Remove the small aperture alignment fixture. The system is now roughly aligned and ready for fine alignment. You may use the Tools → System Alignment wizard to complete the fine alignment, but for this example we will continue using a different method, both are equally effective. Confirm modal analysis is active, start a continuous measurement and open the Zernike tab. Adjust the tip and tilt of the sensor until the Z10 and Z11 Zernike terms are minimized, typically between -0.1 and 0.1 microns.

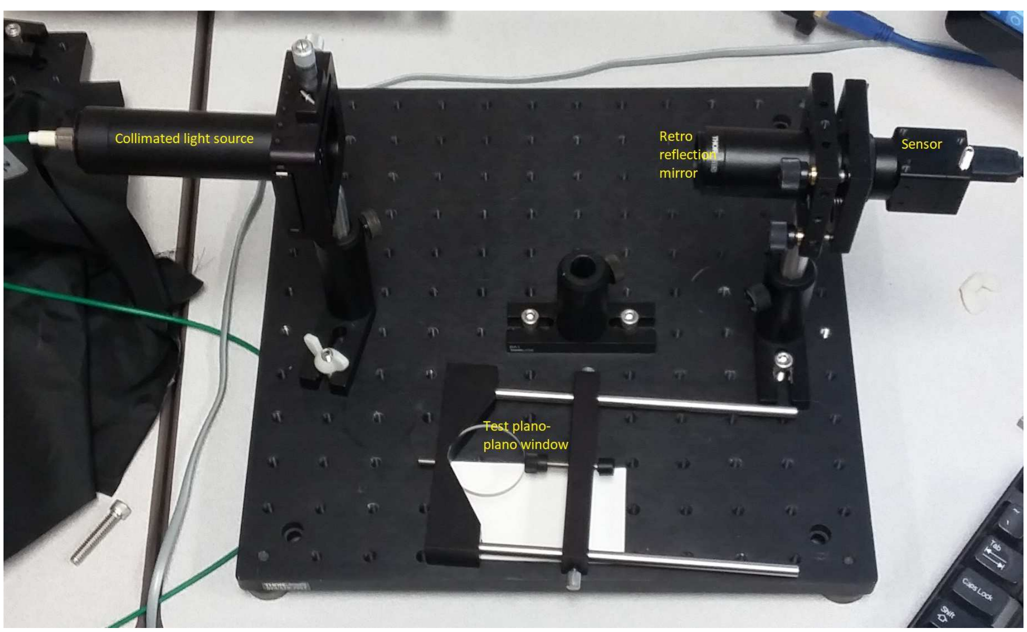


**Figure 49:** Test Setup

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Next open the wavefront tab and observe the peak to valley (P-V) reading below the Zernike map. If your system is moderately well aligned and is made up of reasonably good optics a typical P-V is 0.4 microns or less when the factory reference file is in place.

When testing a plano-plano window, or any optical element, with a wavefront sensor you want to start with a test setup with the lowest P-V achievable. A test setup with a low enough P-V guarantees that the test setup is contributing an insignificant amount of wavefront error relative to the measured part's tolerance requirements.

First time users should skip this portion of the example and proceed to installing the test window. There is a risk of creating a reference file which when used will give inaccurate measurements. In this example, we will not cover all the possible errors that may arise while creating a reference file. Contact Lumterics for further information on reference file creation.

To create a custom reference file which minimizes the wavefront error contributions from test system navigate to the expert reference file creator in the tools pull down menu.

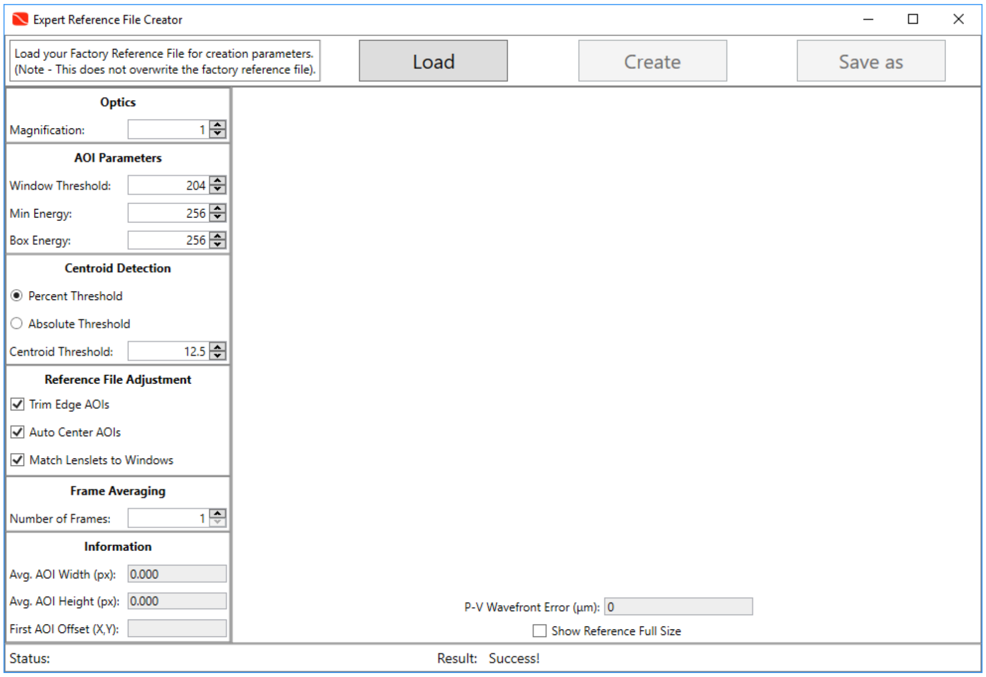


**Figure 50:** Example of the expert reference file creator

You create a custom reference file by proceeding in order, from left to right, along the top buttons of the expert reference file creator. Load the factor reference file. Use your expert experience and knowledge to set the left side parameters, then press the create button. The screen will change to look like Figure 51.

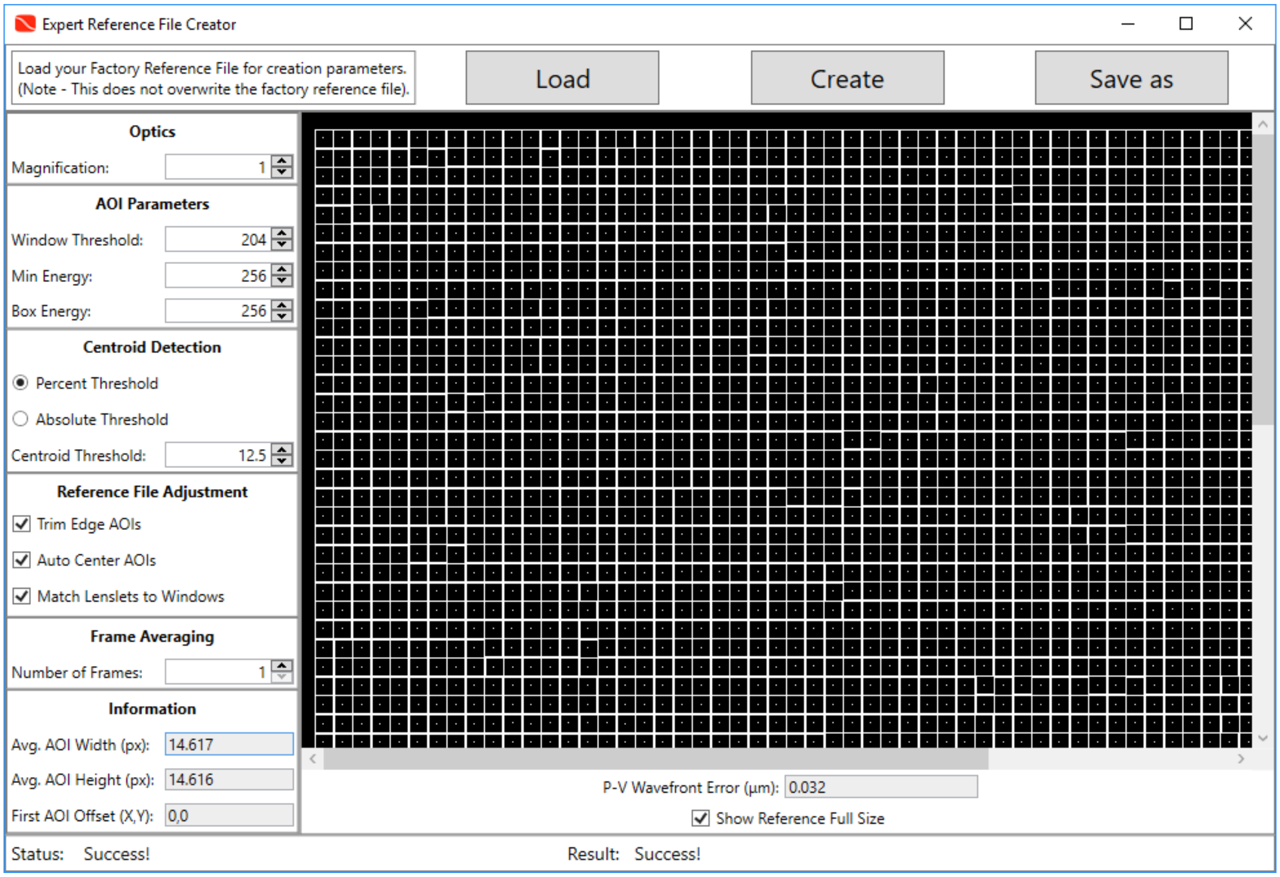


**Figure 51:** Example of the expert file creator after loading the factory reference file and creating

Typically, a good custom reference file will have, at a minimum, regularly spaced, even boxes displayed. To save and make the file active in the currently running CLAS-NX application click the save as button. We recommend giving it a name describing the setup as custom reference files are often associated with a particular optical setup. As a test take a measurement with the new custom reference file. The P-V should be significantly lower. Prior to creating a reference file the lowest P-V achieved through our best alignment efforts was 0.295 micron. Figure 51 shows the a wavefront map using the custom reference file having a P-V reading of 0.083 microns, which is a 3.5 times decrease in P-V and about 1/7th of a wave. An operator should take care to view the whole reference image by scrolling up and down or side to side if required.

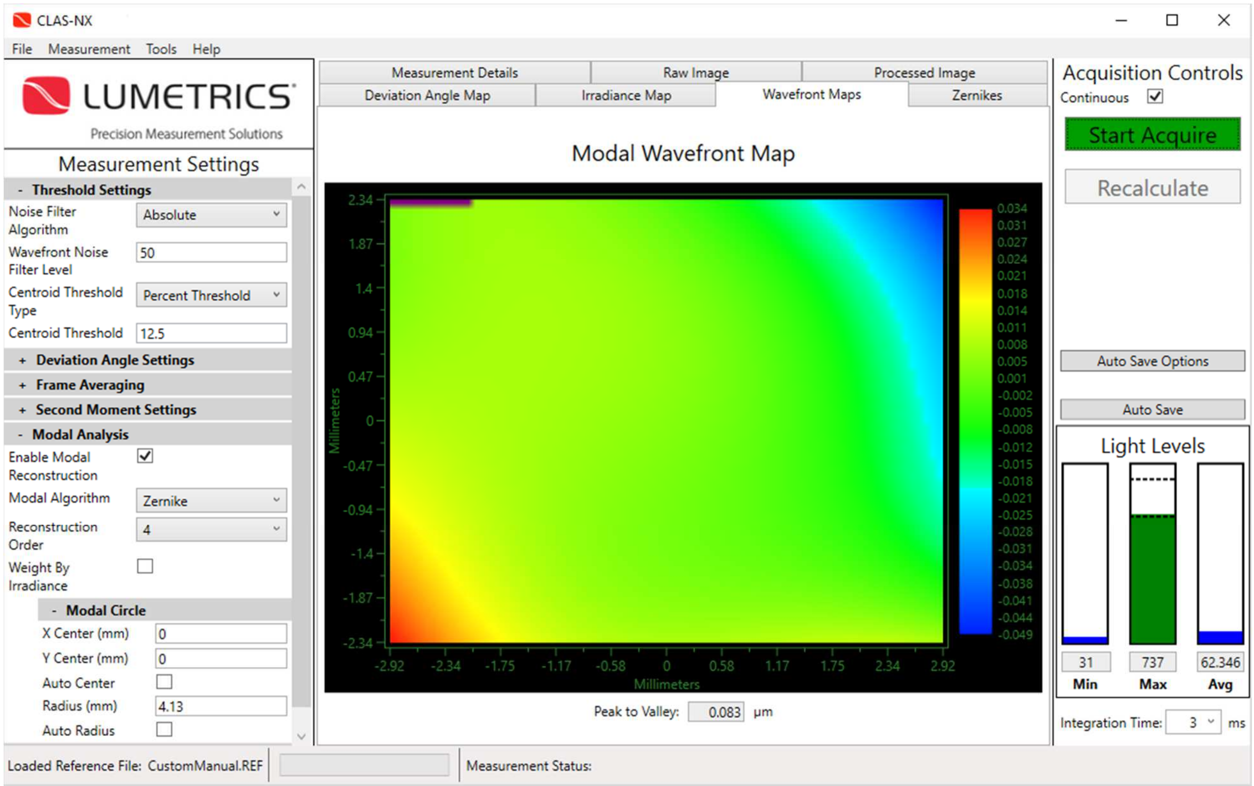


**Figure 52:** Wavefront tab example with a flat wavefront having low P-V

Install the plano-plano window under test into the collimated beam between the output of the collimated beam and the input of the sensor. Take a wavefront measurement. The results of the wavefront measurement include the measurement system error and the window under test error. With the test window in place the P-V increased to 0.121 microns, see Figure 54.

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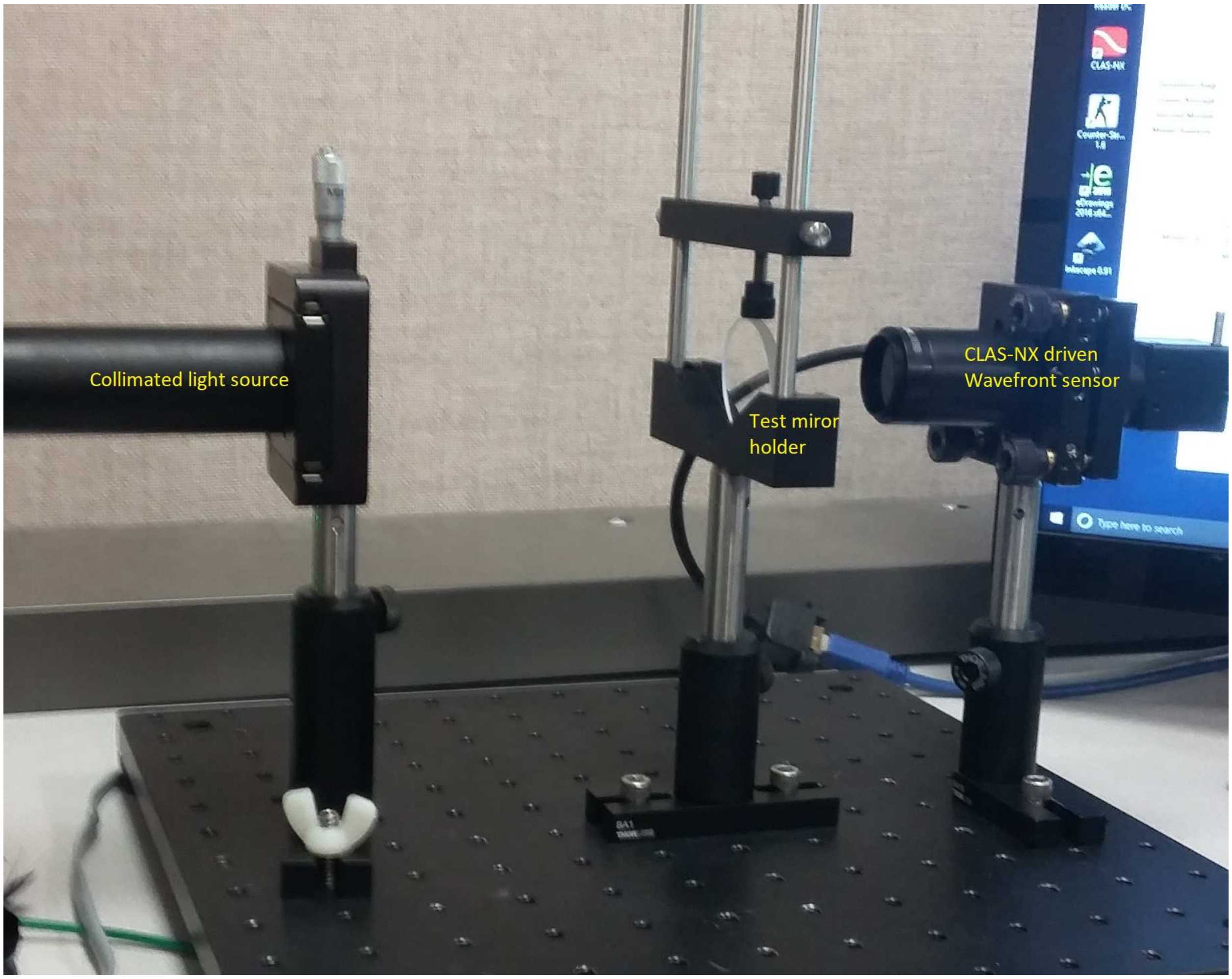


**Figure 53: Test setup**

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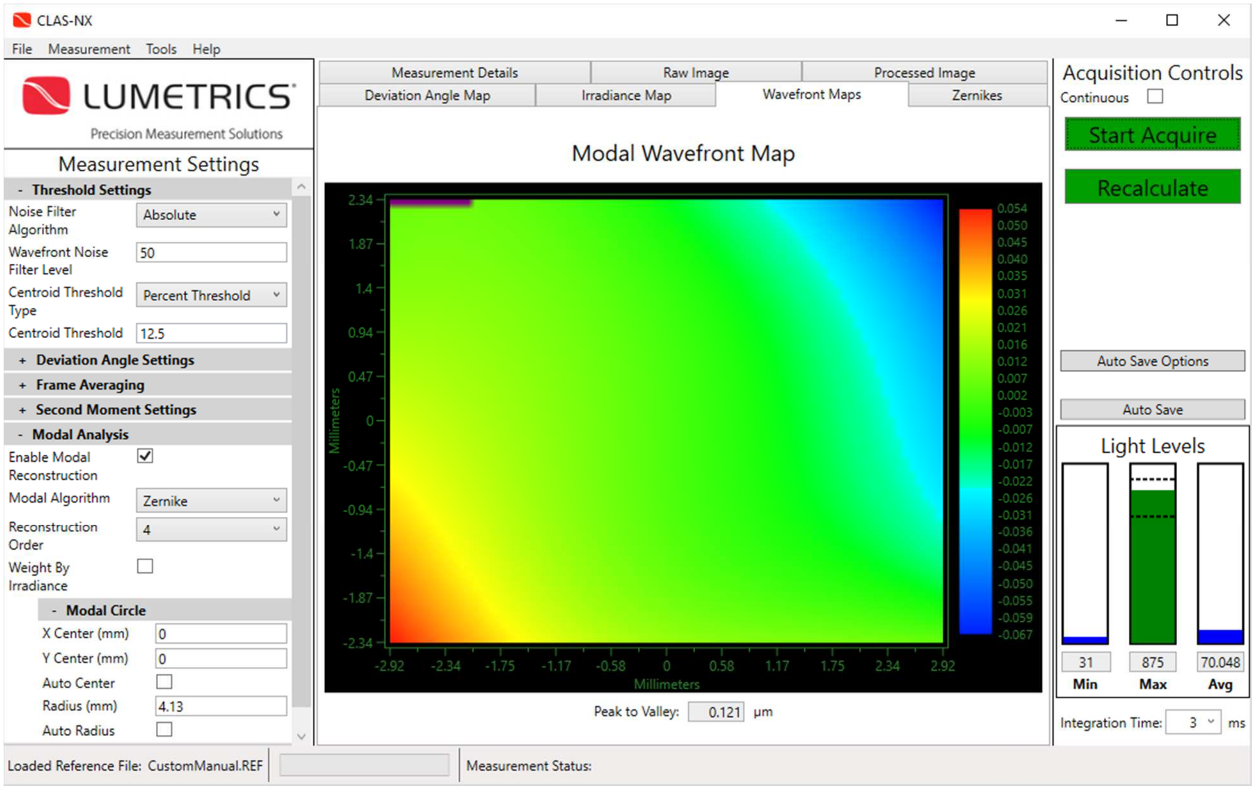


**Figure 54:** Wavefront tab example with a wavefront having an increased P-V due to adding a plano-plano window into the collimated beam