Clarifi-3D™

Closed Loop Adaptive Optics System

Guide to Setup and Use

Version 4.6.3

September 20, 2007

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What's New in Version 4.6.3

General Overview

What Can Deformable Mirrors Do for You?

- Optical Aberration Correction
- Laser Beam Shaping
- Optical Image Enhancement

Deformable mirrors are revolutionizing laser and optical systems by replacing static components with dynamic optics. Deformable mirrors (DM) are adaptive optics with dynamic faces able to optimize or change the characteristics of reflected light for a specific application. With time-varying control, a DM can focus a beam at several different points at different times or it can replace a lens in an optical system. Deformable Mirrors can improve images in telescopes, cameras, and other imaging systems.

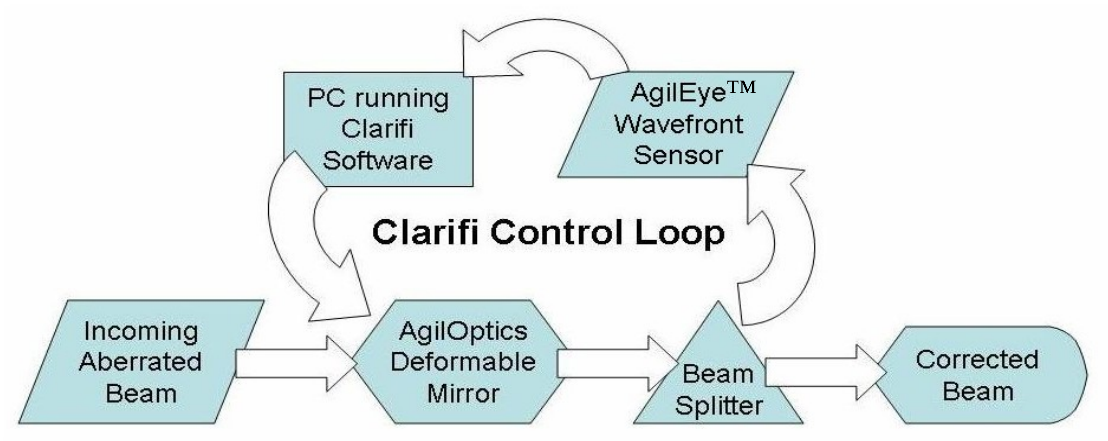
The Clarifi™ Closed Loop Adaptive Optics System is AgilOptics™ automated system for improving laser beam quality. The Clarifi-3D™ software takes data from a wavefront sensor and uses it to optimize the contour of an AgilOptics™ deformable mirror, producing a more perfect collimation, focus, image or wavefront.

The purpose of this manual is to get you up and running with the Clarifi™ system as quickly as possible. Please read it from cover to cover to get a feel for the system before you begin usage. The Clarifi™ manual is divided into two basic sections: an initial setup section and a section explaining the Clarifi™ system. In the **Initial Setup** section, you will find suggestions for an optical system to use with your deformable mirror, as well as the basic information to get you started with the software. The section entitled **Clarifi™ Software: Explanation and Usage** will help you to understand the software in order to optimize its performance for your application, as well as instructions on the use of the software. *(Caution: due to the delicacy of the mirror membrane damage to the mirror can result if this information is not thoroughly understood.)*

For more on Deformable Mirrors and how they work see Appendix B.

How the Clarifi™ Closed Loop Adaptive Optical System Works

A beam enters the optical setup and is reflected off an AgilOptics™ deformable mirror. The beam is then split into two parts: one beam continues on to a useful target, while the other is used for the control loop. The control beam is imaged onto an AgilEye™ Hartman Wavefront Analyzer (HWA) which determines the shape of the wavefront and sends this information to a PC running the Clarifi™ software. Clarifi™ takes this information, determines the necessary shape of the deformable mirror to correct for it, and then uses the deformable mirror to reshape the aberrated beam to the user specifications. Passing out of the control loop, the corrected beam can then be put to a useful application.



Clarifi™ Correction Process

Included with your Clarifi™ system

Below is a list of all of the basic components included in your Clarifi™ system, followed by a more detailed description of each component and an explanation of its purpose in the system. Please verify the receipt of each component before continuing with the setup of either the optics or Clarifi™ software.

The Clarifi™ system is a complete, ready-to-run adaptive optical system which includes:

- One complete personal computer running Microsoft Windows XP
- One AgilEye™ HWA in CCD (Charge Coupled Device) Camera
- Clarifi™ mirror control software (installed)
- HVDD (High Voltage Digital Driver) mirror control software (installed)
- One AgilOptics™ Deformable Mirror installed in Unifi™ High Voltage Driver
- Interconnecting cables

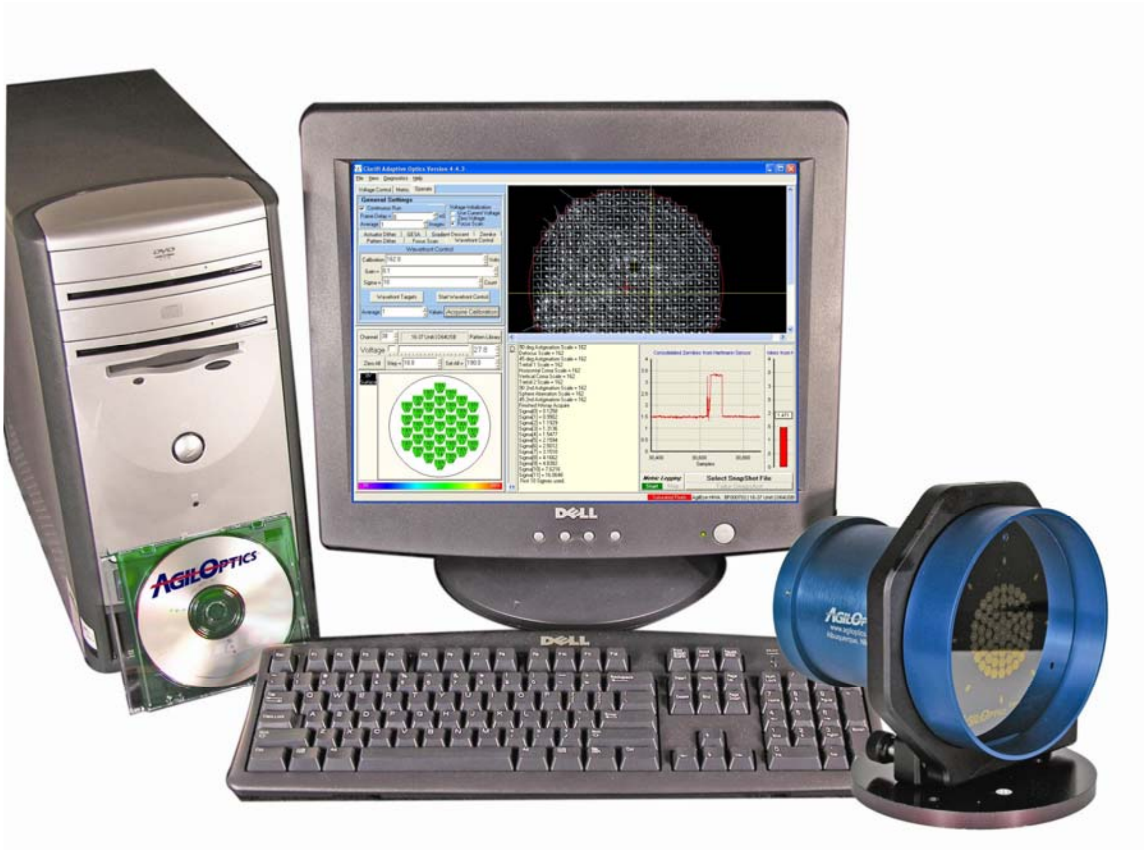


Figure 1: Typical Clarifi-3D™ System

Personal Computer

The personal computer is used as the control of the entire Clarifi™ system and may be either a desktop or notebook computer. Both Clarifi™ and HVDD run on the PC, and both the mirror and CCD camera are connected to the PC. The nominal specifications are listed here. See enclosed documentation for the specific performance details of your system.

- Pentium or Compatible Processor
- 512 MB RAM
- 60 GB Hard drive
- 40x CD-ROM Drive
- Graphics Accelerator
- Keyboard
- Mouse
- Windows XP Operating System

AgilEye™ HWA in CCD camera with PC interface:

This camera (see picture below) is used as a sensor of the beam intensity profile. The camera has one (1) connection that must be utilized for the Clarifi™ system: a USB cord must be run from the back of the camera to the PC. The blue camera mount ring fits conveniently into a 2" gimbaled optics mount which facilitates the setup and alignment of the AgilEye™ HWA.

Figure 2: AgilEye CCD Camera

Clarifi™ Mirror Control Software

This software is installed in the PC. The Clarifi™ software controls the mirror and is used to run the algorithms to alter the optical beam. It analyzes the data from the CCD camera and uses that information to alter the surface of the Deformable Mirror (DM) in order to make the desired corrections to the optical beam.

HVDD Mirror Control Software

The HVDD software is installed on the included PC and can be used for system checkout and diagnostics. It is NOT a part of the Clarifi-3D™ operation. This software allows direct control of the deformable mirror surface. It can also be used to set up patterns on the DM for use in the Clarifi™ software.

AgilOptics™ Deformable Mirror

The mirror included with the most basic system is a 25-61 with an aluminum surface, though there are a variety of mirrors that can be used (please check your packing list in order to see what type of mirror you have received). The first number of each mirror name indicates the diameter of the mirror surface in millimeters, and the second number indicates the number of actuators, or individual points of control on the mirror surface. For instance, the 25-61 is twenty-five millimeters in diameter and has sixty-one actuators. There are two types of mirror upgrades: a special coating can be applied for specific wavelengths of light, and the diameter and/or number of actuators can be increased in the mirror (e.g. a 50mm diameter 61 actuator mirror or 50-61). Please contact

AgilOptics™ for information on either of these upgrades. The mirror included in your Clarifi™ system will be in the Unifi™ housing and will resemble the picture below.

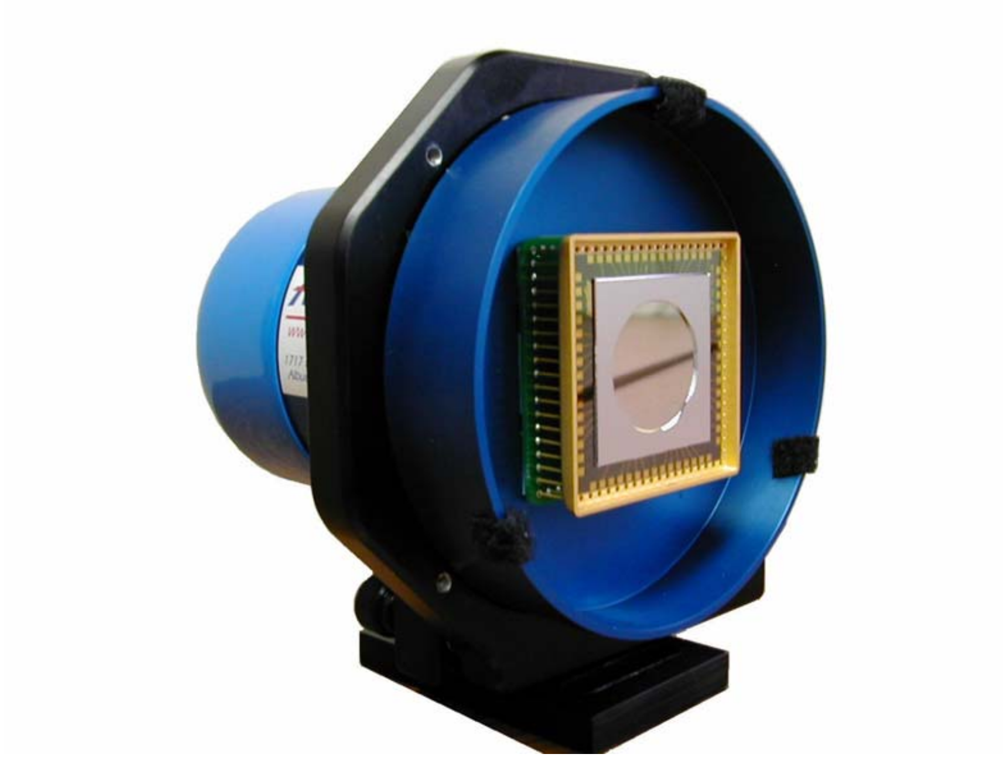


Figure 3: AgilOptics™ Deformable Mirror in Unifi™ Housing Shown with 25-37

Interconnecting Cables

In addition to the power cables, the cables included with your Clarifi™ system will be used to connect the components together and allow for data transfer. Cables connecting the components of the Clarifi™ optical system are included with the normal cables for use with your PC. Please see the setup section for a diagram of the system, including the placement of the cables.

Unifi™

The Unifi™ is a system that contains both the driver and Deformable Mirror in a single mechanical housing. From the back of the Unifi™ a USB cable connects to the PC and a DC power converter supplies the power to run the mirror. (*Note: always connect the power to the Unifi™ before connecting the USB, and disconnect in reverse order to avoid a PC operating system error.*)

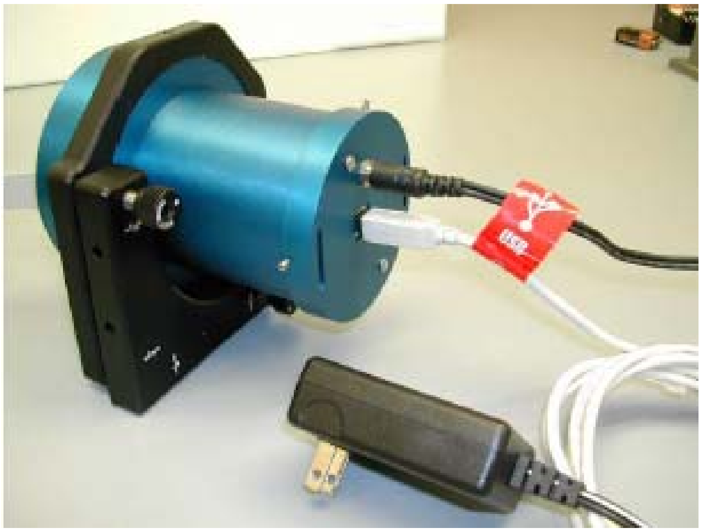


Figure 4: Unifi™ Mirror Driver

Important information

Please take note of the following recommendations in all circumstances.

1. The maximum voltage limit for your unit is: ___________
2. Please turn the mirror high-voltage driver on only when your Clarifi™ or HVDD software is running. This prevents spurious data from your computer's parallel or USB port from sending voltage that could damage the deformable mirror. This also prevents power surge damage to the high voltage driver and mirror.

Mirror and Driver Setup

Connecting the Clarifi™ System

Please Note: It is highly recommended that all electrical components be plugged into a surge protector to avoid damage.

PC Setup

Please follow the instructions included with your PC.

AgilEye™ HWA

This camera can be mounted to an optical table using a standard 2" optical mount. Only one cable is required for setup: a USB cable should be run from the back of the AgilEye™ to a USB port on the PC, which provides power to the AgilEye™ as well as allowing it to communicate with the PC.

High Voltage Driver: Unifi™

The Unifi™ can be set up in an optical system using standard optical (4" ring) mounts. For operation, two cables must be connected to it: the USB and the power adapter. The power adapter will plug into a round hole on the back of the Unifi™ housing, with the other end plugged into a standard electrical outlet or surge protector. One end of the USB cable should plug into the back of the Unifi™ and the other should be connected to a USB port on the PC. Please see diagram below.

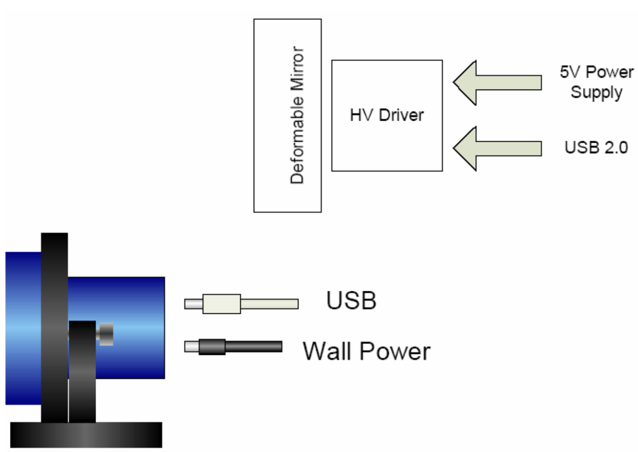


Figure 5: Unifi™ Connections

Recommended Optical Setup

Clarifi™ Optical Setup: Comments and Hints

The purpose of the Clarifi™ system is to correct aberrations in an optical system in real time or allow a user to shape a beam wavefront. The typical user has a laser beam that is aberrated and needs corrections in optical phase such that the beam wavefront is perfectly flat. In order to use the Clarifi™ system effectively, you will need to set up an optical system with the deformable mirror.

Though there are many potential successful optical setups, there are several key aspects that are necessary for optimal operation**:**

First, the aberrated beam must reflect off the deformable mirror with a minimal angle of incidence. If the angle of incidence is too large, when the mirror membrane is pulled, the beam will shift position causing erroneous readings and poor beam correction.

Second, for optimum operation, the basic Clarifi™ optical setup requires that your laser beam is matched to 1) the mirror diameter and 2) the CCD diameter on the Camera.

1) For Example: if your AgilOptics™ deformable mirror is a 16mm diameter mirror, for best utilization of all actuators and for best ability to affect the beam phase profile, a beam of about 12mm should be incident on the mirror.

2) The CCD camera has a 3.7mm diameter and therefore is best utilized when the beam into the camera is a large fraction (~90%) of that size. Using beam splitters and Neutral Density (ND) filters, adjust the intensity of the beam to an acceptable, non-saturated level (please continue reading for more).

The beam size can be adjusted using the AgilEye™ Telescope specialty AO product or another afocal collimating telescope.

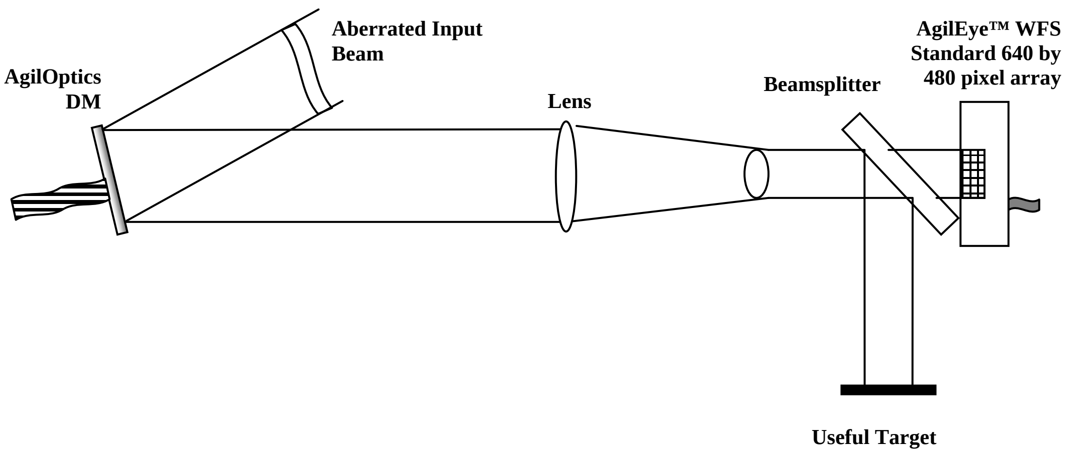
Third, a beam splitter will be necessary between the deformable mirror and the camera. This permits the camera to sample a small percentage of the beam energy for acquiring data for real-time correction while also allowing the majority of the beam's energy to be devoted to a useful purpose.

Finally, since the camera is very sensitive to beam intensity, it will likely be necessary to adjust the beam strength to below the saturation threshold (camera saturation is indicated by 'blooming' on the camera image). We suggest using one or more "Neutral Density" (ND) filters and/or a rotatable polarizer pair to allow continuous control of the beam intensity. These can be anywhere in the beam train before the CCD, but to avoid side light (which can come from room lighting and will disturb the calculation of the beam metrics), it is usually necessary to screw the ND filters directly on the front of the camera. Watch the image on the control screen and adjust the beam intensity to produce an array of bright, even spots without excessive edge interference patterns or sidelight.

The optical elements that AgilOptics™ provides are: 1) a deformable mirror that will adjust the phase front of the user's beam and 2) a Hartmann wavefront sensor to report the shape of the wavefront of the incoming beam. The user will need to provide:

- the laser beam
- fold mirrors to arrange the setup
- one or two telescopes for beam sizing such as the AgilEye™ Telescope
- neutral density filters for reducing the intensity on the CCD to an acceptable level
- a beam splitter to provide a sample beam

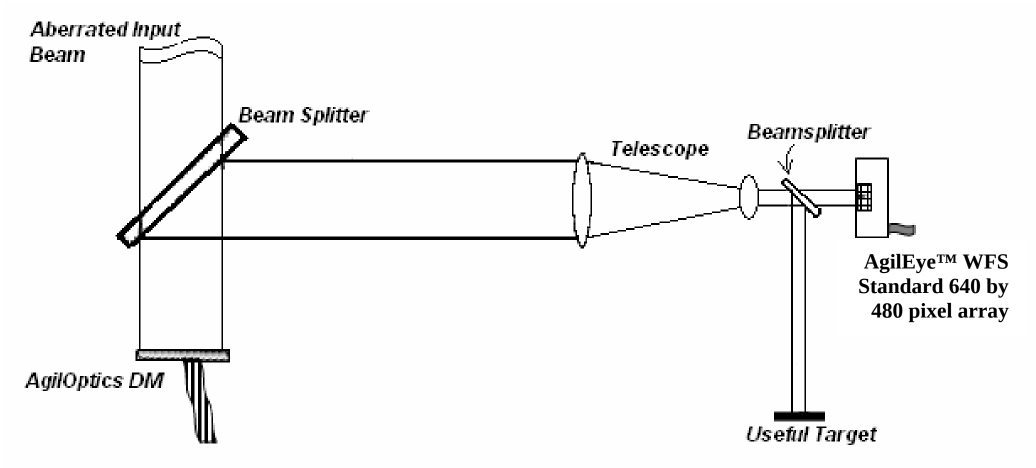
The optical setups recommended here are only a suggestions, basic systems for use that can be modified to suit your needs.



Possible Simple Optical Setup

In the most straightforward setup (above), the user's aberrated laser beam is reflected off the DM then sent through a telescope to reduce beam size. A beamsplitter diverts most of the beam to a useful target while allowing a sample beam to pass through for the control software to sample. This setup is the simplest and most energy efficient, though it can often be difficult to get an angle of incidence small enough between the input beam and the reflection from the deformable mirror.

Another basic setup is shown below. This is very similar to the first, except the aberated beam is passed through a beam splitter initially so there is an angle of incidence of zero as the beam is reflected off the deformable mirror. This setup reduces the beam energy because of the split, and also improves alignment and thus enhances control.



Another Possible Optical Setup

The actual beam size will show up on the window devoted to the beam intensity, located in the upper right area of the main panel of the Clarifi™ software.

We have found that the best operation of the Clarifi™ system starts with a fixed spherical bias on the mirror, allowing the system to release voltage to provide reduced focus, and increasing voltage to provide increased focus. We suggest you align the system with the mirror "off", then set the mirror voltage to a midrange value (please see "Controls" for operation), such as 70% of the maximum voltage, and re-adjust the optical spacing of the lenses while watching the wavefront sensor output. Minimizing the defocus will allow the user to nearly collimate the beam coming off the deformable mirror at the middle of the mirror's range of movement.

Beam splitters are also recommended so that the system can provide the user with a useful "primary" beam while Clarifi™ cleans up the phase errors by watching the focus of the secondary beam. The user will find that the focus, watched manually and/or recorded by a separate CCD, will not only be fascinating to watch but will provide testimony to Clarifi™'s successful beam correction.

In addition to guidelines above, it is important to note that Clarifi-3D™ will work best when the incoming beam is exactly centered on the mirror membrane. For helpful hints on adjusting your optical setup in order to achieve this, please see Appendix C.

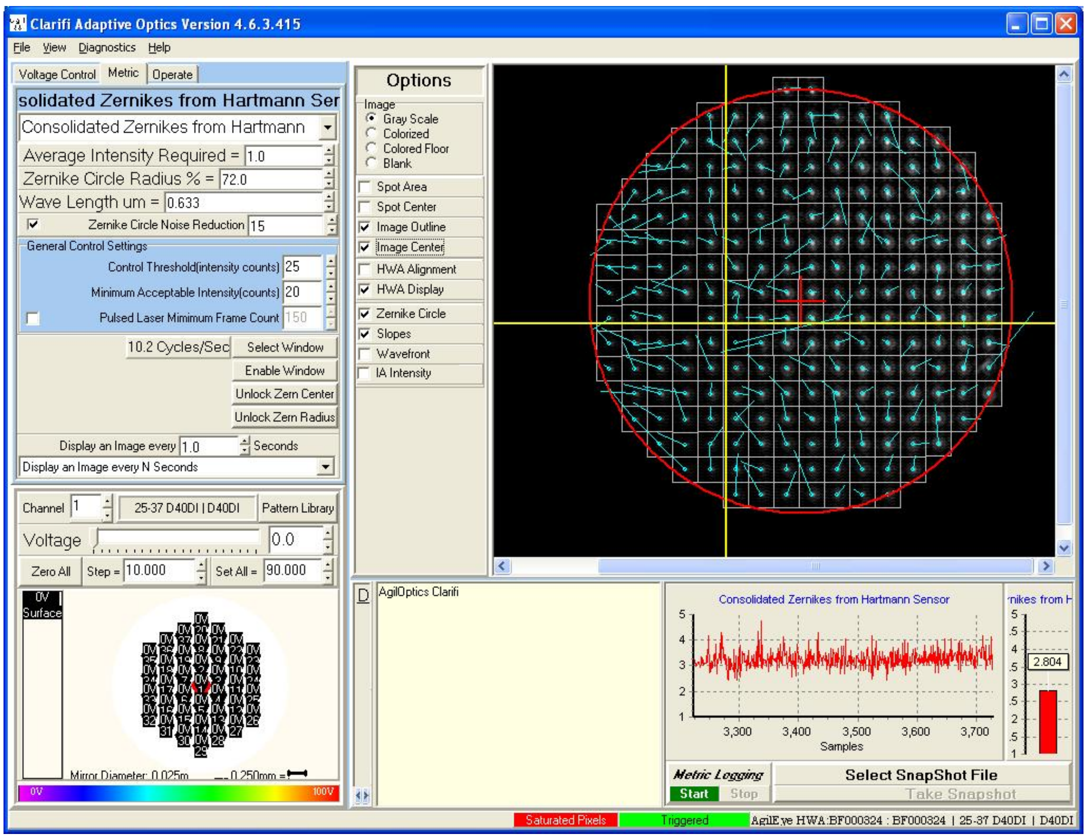
Please note that the Clarifi™ system is limited by the ability and knowledge of its operator. Many adjustments and many trials may be necessary to allow Clarifi™ to accomplish the full set of goals that the user has defined. However, we are certain that after you have experienced Clarifi™'s capabilities, you will never want to design an optical system without adaptive optics again.

Software Setup

This section will guide you through the setup of the Clarifi™ software for your optical setup. A brief explanation of each part of the setup will be provided, as well as instruction in the software's setup. Please follow the steps outlined in the "For Setup" areas at the end of each section.

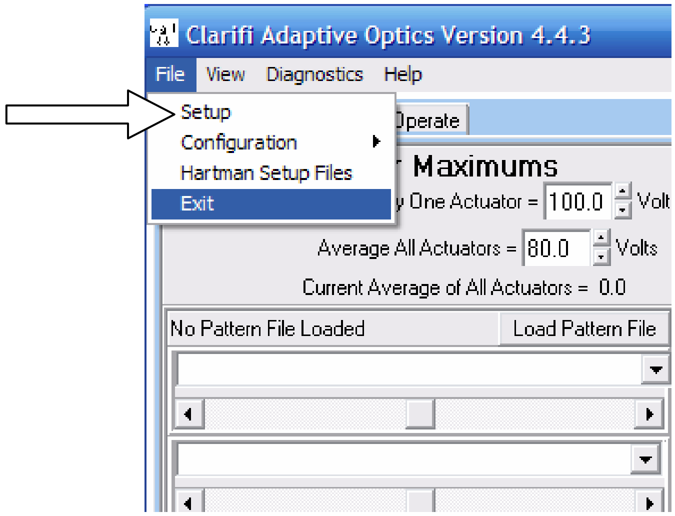
START UP: Your Clarifi™ software is already loaded on the included PC. To start the software, go to **Start, All Programs, AgilOptics™\Clarifi\Clarifi 4.6.3**.

When you start the Clarifi™ software, this window should appear:

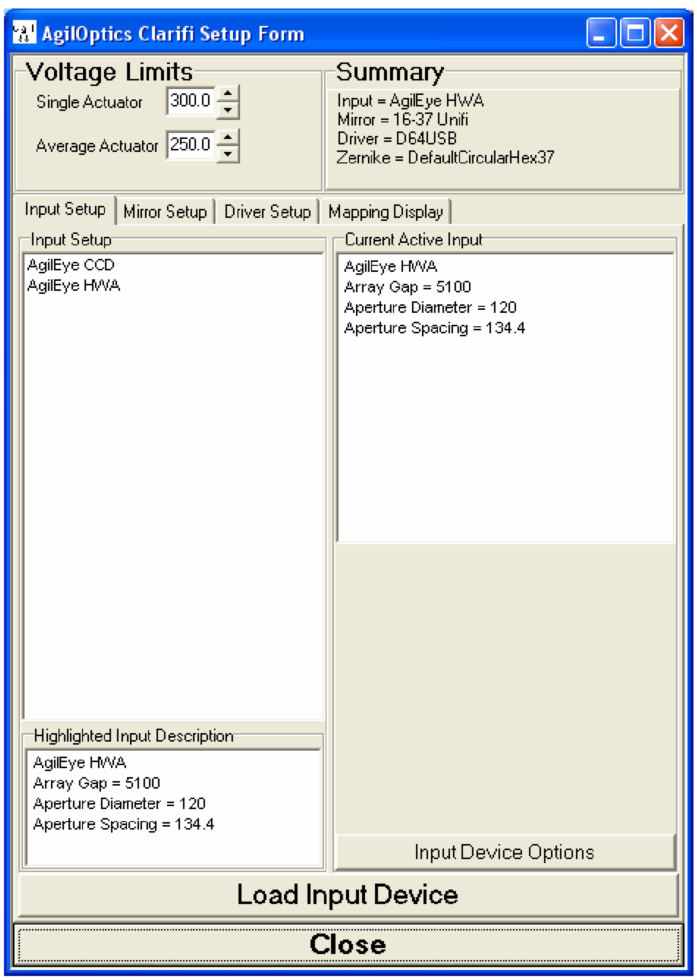


This window is the primary screen of the Clarifi™ software, and the one from which the setup will be started.

<u>For Setup</u>: click on File, then click on Setup:



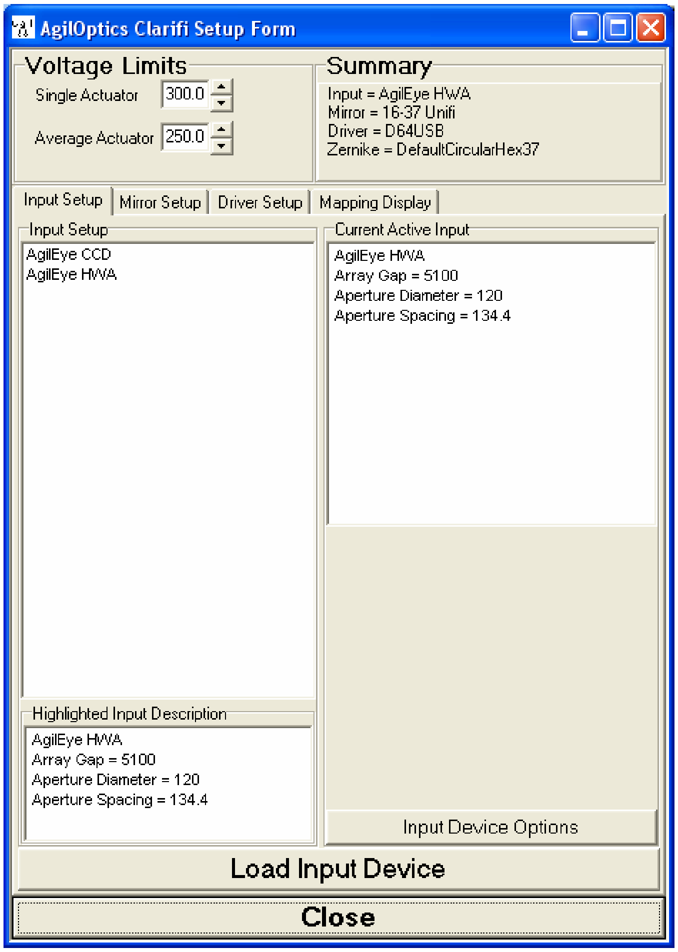
This will bring up the AgilOptics™ Clarifi™ Setup Form, from which the remainder of the setup will take place:



Voltage Limits

The upper portion of the window pictured above is where the voltage limits are set for the mirror. It is necessary to set these in order to avoid a condition known as “snapdown”. This is when the delicate surface of the mirror is pulled with too much voltage and actually contacts the pad array, which could result in a rupture. The two inputs are as follows:

- **Single Actuator** sets max voltage on any actuator
- **Average Actuator** sets the maximum average voltage for all actuators. In this case, the voltage of an actuator is defined as the absolute value of the difference between the actuator voltage and the voltage on the mirror membrane.



<u>For Setup</u>: It is recommended that the max voltage be set to _____, and that the average actuator voltage be set to _____. This may be accomplished by either using the arrows to the right of the field to increase or decrease the voltage, or by highlighting the field and entering the desired voltage. (Caution: setting these fields to more than their recommended values may cause snapdown and damage to the mirror.)

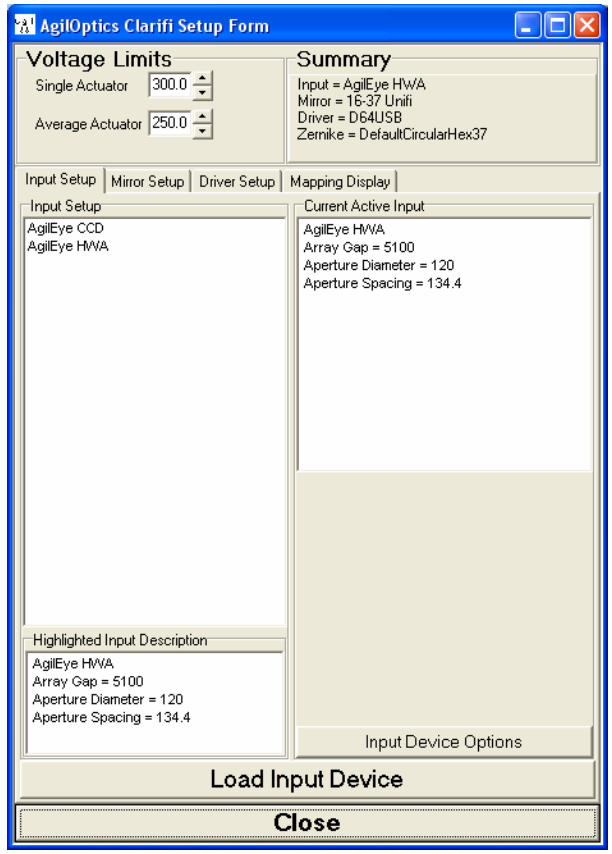
Input Setup Tab

The tab farthest to the left in the “Clarifi™ Setup Form” window is the input setup tab. There are three fields in this tab, as shown below:

The upper left field lists the available input device drivers, for example:

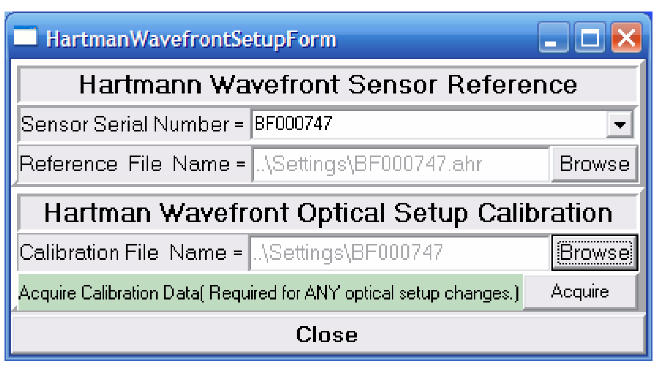
- Picolo Frame Grabber
- AgilEye™
- AgilEye™ HWA
- PMD-1208 Analog Measuring Device

Single-clicking a device name in the upper field gives a more detailed description in the lower window. The currently selected device details are shown in the right-hand field.



<u>For Setup</u>: Single-click on the name of desired device then press the **Load Input Device** button (located at the bottom of the window), or double-click on the name of the desired device.

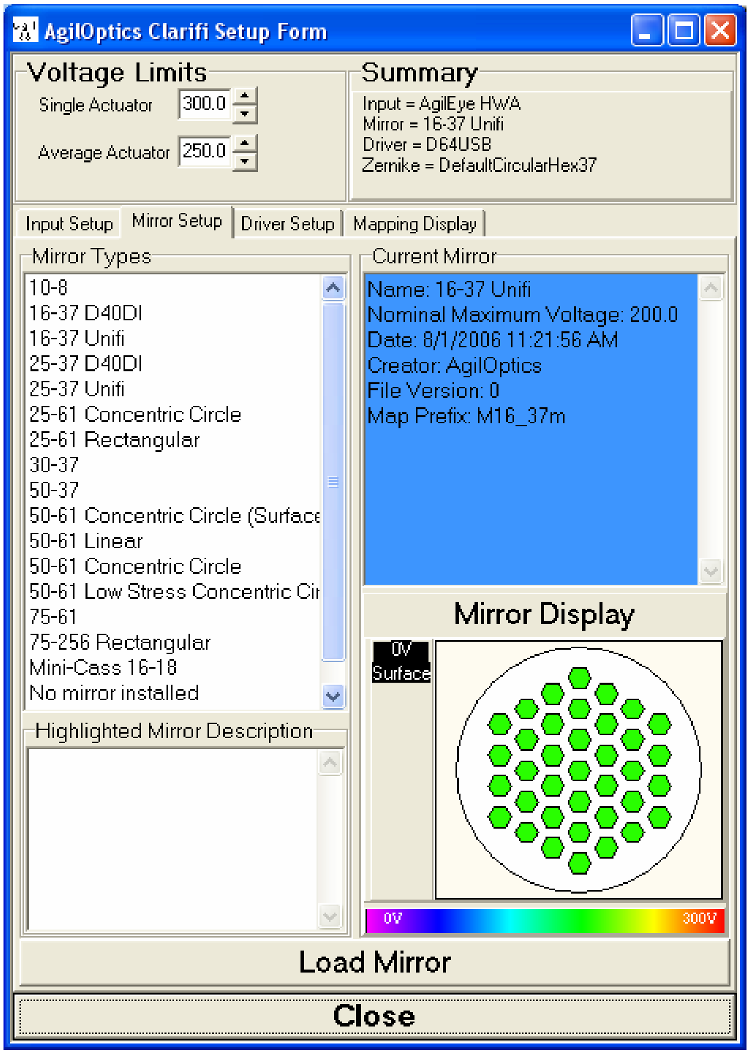
If the AgilEye™ HWA input device is selected, a dialogue similar to the one shown below will appear:



The Sensor Serial Number should be selected that matches the one on the AgilEye™ sensor included with your Clarifi™ system. The rest of the options on this tab should already be set when you receive your software.

Mirror Setup Tab

This tab is the second tab in the "Clarifi™ Setup Form" window and is shown below.



In the upper left field, a list of all the available mirror types is shown, for example:

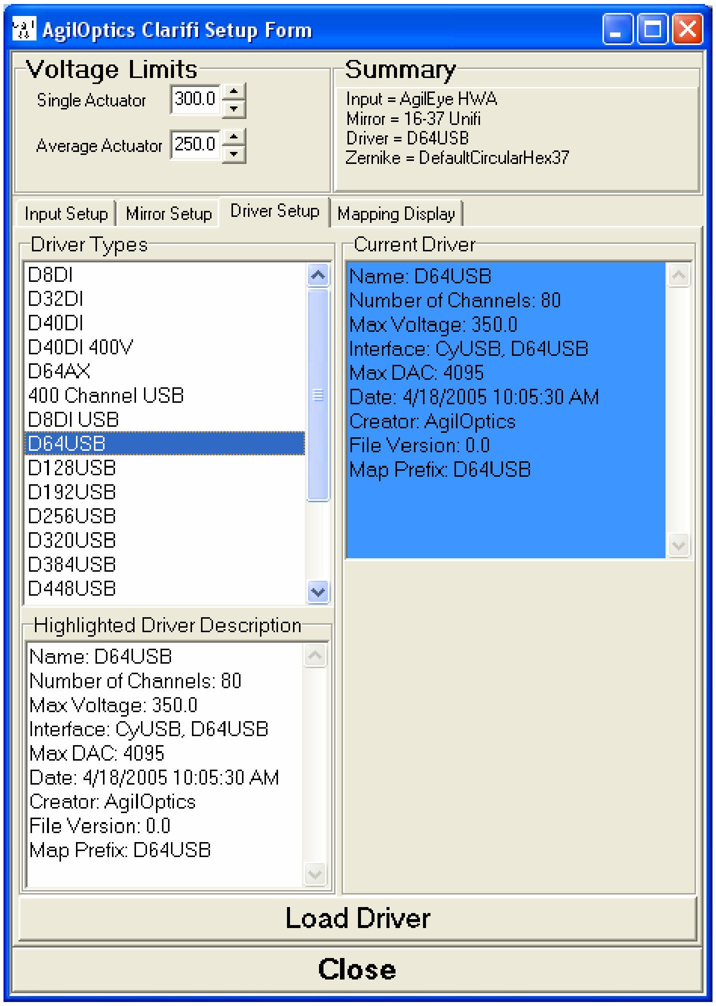
- Multi 10-8, Ophthalmic 8 actuator DM
- Multi 25-37, standard 25mm diameter DM

Single-clicking a device name in the upper window gives a more detailed description in the lower window. The currently selected device details are shown in the right-hand window. A picture of the actuator pattern of the selected mirror is shown in the **Mirror Display** section in the lower right. Please see the "General Overview" section for more information on types of mirrors. Note: Clarifi™ will list all mirrors that have driver info files in the "C:\program files\AgilOptics™\devices\" devices directory.

<u>For Setup</u>: Single-click on the name of the desired mirror then press the **Load Mirror** button, or double-click on the desired mirror name.

Driver Setup Tab

The third tab of the "Clarifi™ Setup Form Window" is the "Driver Setup" tab, and is shown in the figure below.



This tab lists the available drivers, for example:

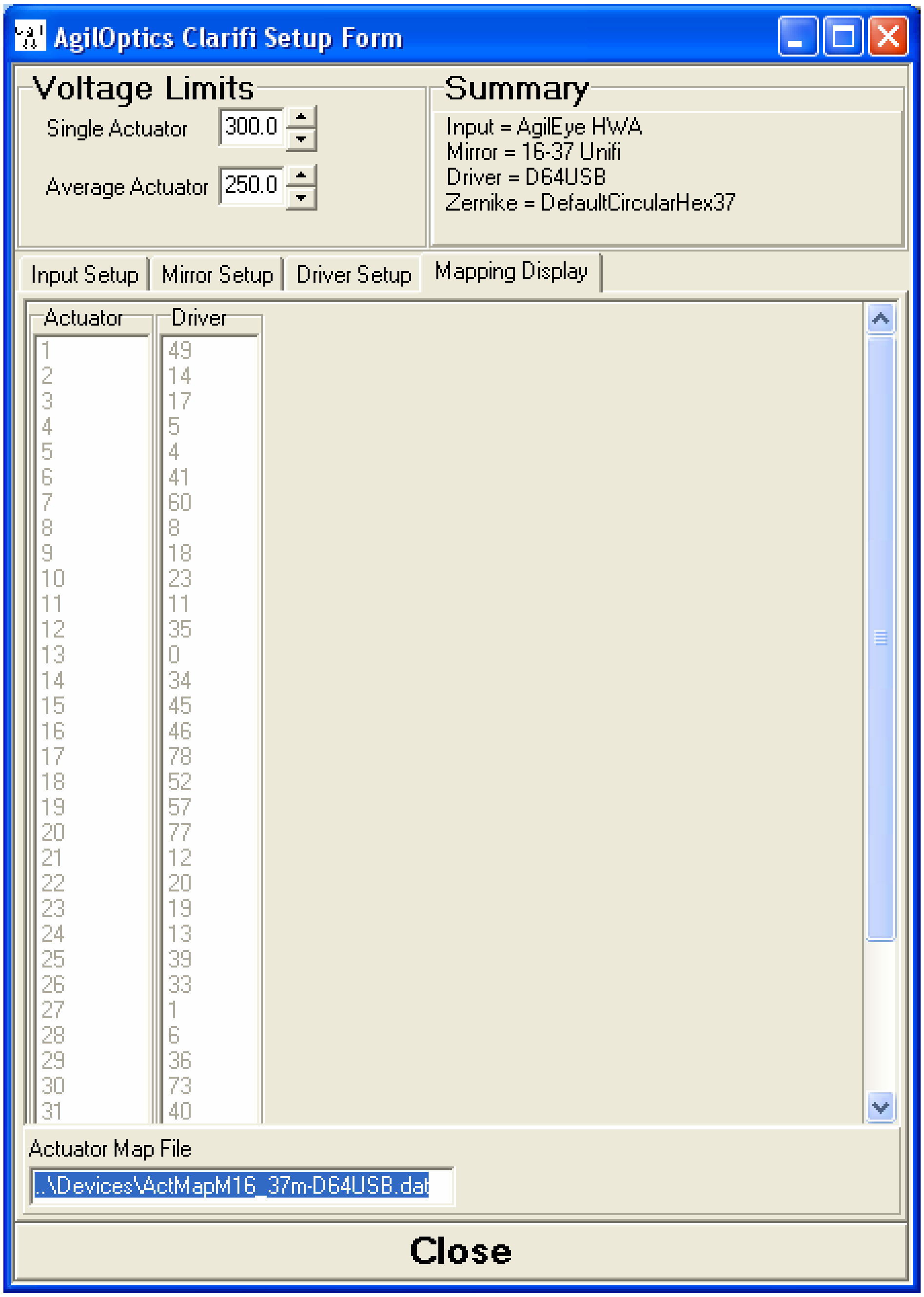
- D64USB, the 64-channel Unifi™ System driver
- D128USB, the 128-channel Unifi™ System driver
- D256USB, the 256-channel Unifi™ System driver

Single-Clicking a device in the upper window gives a more detailed description in the lower window. The currently selected device details are shown in the right-hand window. Clarifi™ will list all drivers that have driver info files in the "C:\program files\AgilOptics™\devices\" devices directory. All of the information in the Setup Menu is saved to the hard disk and loaded on startup. These selections should only have to be done once, unless the hardware is changed. More information on driver types is included in the "General Overview" section.

<u>For Setup</u>: Single-click the name of the desired driver then press the **Load Driver** button, or double-click the name of the desired driver.

Mapping Display Tab

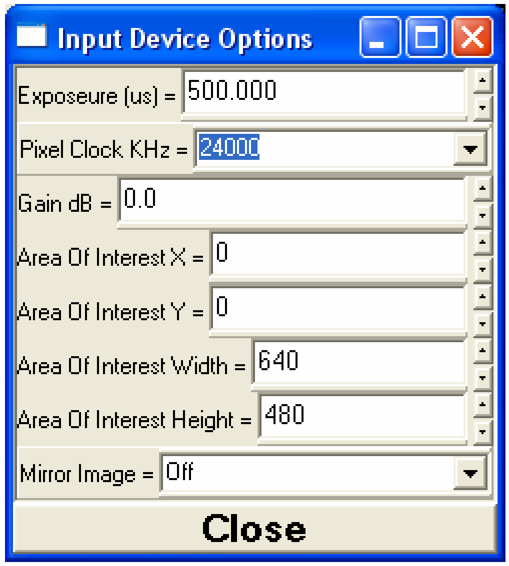
This tab, shown below, is the farthest right tab in the “Clarifi™ Setup Form” window, and is used as a diagnostic tool by AgilOptics™. During technical support calls you may be asked for the information on this page. It lists the information used by the software to perform the calculations of channel addresses and actuator numbers.



For Setup: This window is for technical assistance only. There are no setup steps in this window.

Input Device Options:

Right-click anywhere on the image display. The following dialogue box will appear.



From this box, all of the input device options may be set.

- **Expose (µs)** allows you to set the exposure time for the camera in microseconds. The higher the clock is set, the more light is gathered. This light level must be set as high as possible without overexposure, which can be seen by excessive interference patterns in the image. The display should be of an array of evenly spaced dots. If there are spots of light between the dots, then the image is overexposed.
- **Pixel Clock KHz** permits the setting of camera frame grab speed. This affects how many frames per second (fps) the camera sends to Clarifi™. *Example: a camera running at one-hundred fps with 400,000 pixels will have a Pixel Clock Setting of 40,000KHz.*
- **Gain dB** sets the amount of amplification the signal from the camera receives.
- **Area of Interest X** sets the horizontal beginning of the camera's scan area. This measure is from the left vertical edge (please see example below).
- **Area of Interest Y** sets the vertical beginning of the camera's scan area. This measure is from the top horizontal edge (please see example below).
- **Area of Interest Width** sets the width of the camera's scan area.
- **Area of Interest Height** sets the height of the camera's scan area.

Example of Area of Interest: if the beam to be corrected covers only the center of the camera's full scan area, then the process can be sped up by just scanning *the area of interest. Area of Interest Width could be set to 640/2=320pixels and Area of Interest Height could be set to 480/2=240pixels. Then Area of Interest X would be set to 160pixels and Area of Interest Y would be set to 120pixels. This would result in the geometry shown below, which effectively limits the scan area of the camera to the incoming beam.*

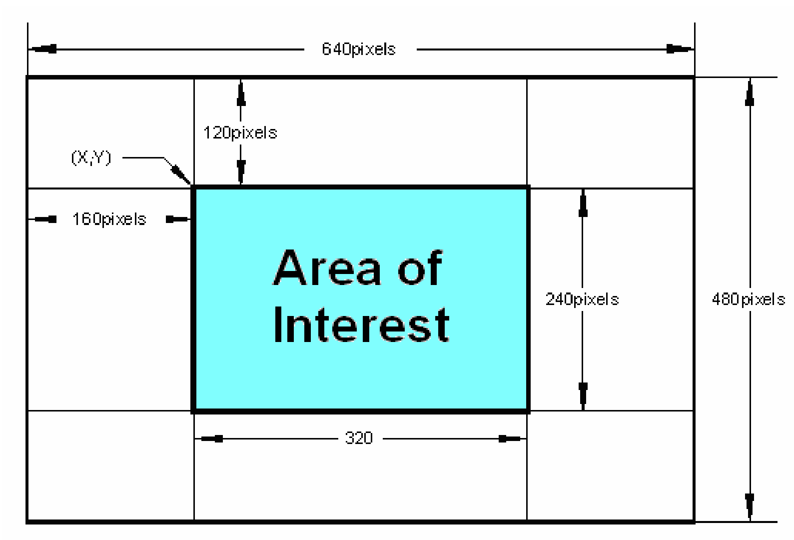


Figure 6: Diagram of Area of Interest

- **Mirror** sets image mirroring (Top Down, Left Right, Both, Off – default).

<u>For Setup</u>: Click on the Metric Tab in the Controls area. The Controls area should look similar to the following figure. Select **Consolidated Zernikes from Hartmann** as the metric.

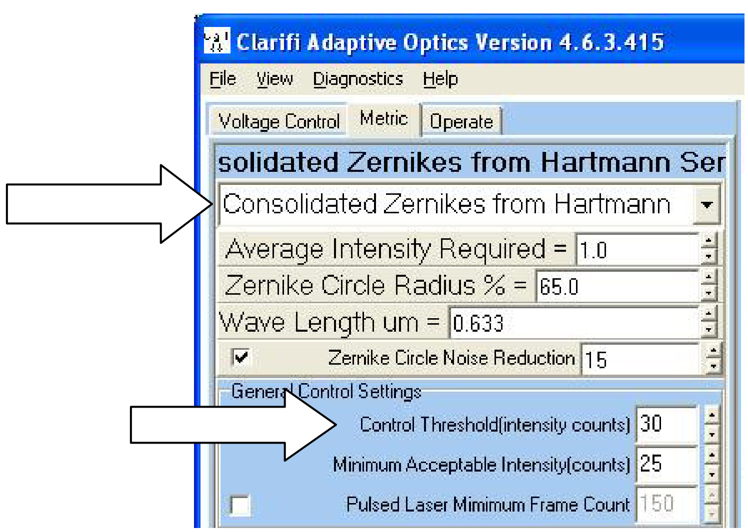


Figure 7: The Control Threshold

The rest of this tab is explained in the Metric Tab section of the manual, but for right now, only the **Control Threshold (intensity counts)** is important. Setting this number allows you to limit the value of the minimum intensity considered by the software. If set to 160, for example, only pixels with an intensity value of 160 or greater will be considered in calculations, zeroing all others. Set the value as high as possible while still maintaining a complete array of dots in the Image Display.

Adjust the **Exposure (µs)** to the lowest possible value while still maintaining a complete array of dots in the Image Display area.

Finally, adjust the **Gain dB** to make the array of dots in the Image Display constant and even. Several values for the Exposure, Control Threshold and Gain should be experimented with in order to determine which values will yield the best results.

Aligning the AgilEye™ HWA

Wavefront sensor alignment has always been a long and laborious process filled with trial, error and aggravation. After extensive research and testing, AgilOptics™ has developed a unique system to facilitate the basic alignment of our AgilEye™ HWAs. Now a basic wavefront sensor alignment can be achieved in minutes reducing both alignment time and frustration.

The AgilEye™ HWA is a compact CCD camera with a series of "focusing" pinholes placed a specified distance in front of it. The optimum distance is determined by the wavelength of the beam being measured. These pinholes cause an array of foci to be projected onto the camera. Each focus is, when using a perfect wavefront, projected onto the center of an integration area as shown in Figure 8 below.

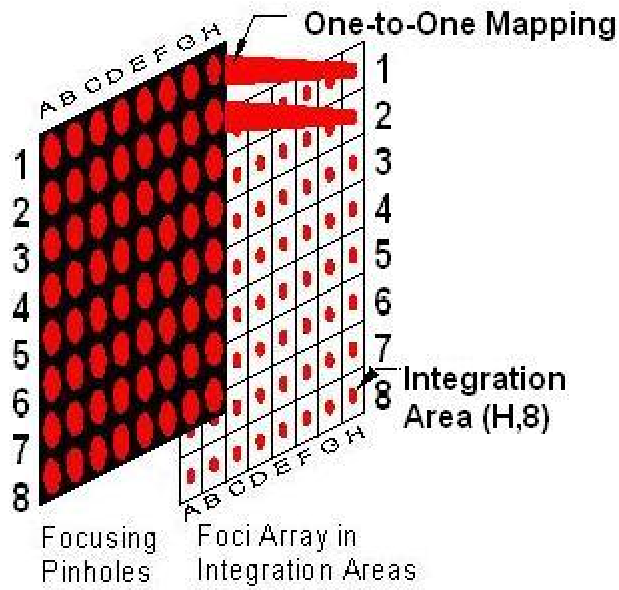


Figure 8: Pinhole Array Mapped onto Integration Areas

When the wavefront sensor is properly aligned, each pinhole maps one-to-one onto the corresponding integration area. As an example, pinhole A1 projects a focal spot onto integration area A1. Fine alignment is simply a matter of watching the output of the wavefront sensor and centering the focal dots in the integration areas. This is where problems have previously arisen. If the incoming wavefront has a section with a large enough aberration to shift a focal spot from one pinhole into a neighboring integration area, both integration areas yield unusable results causing the wavefront to be interpreted incorrectly. This places a limit on the range of aberrations over which the wavefront sensor is accurate. The wavefront sensor can only detect whether or not a spot is in an integration area, it cannot detect if the spot is in the *correct* integration area as illustrated in Figure 9.

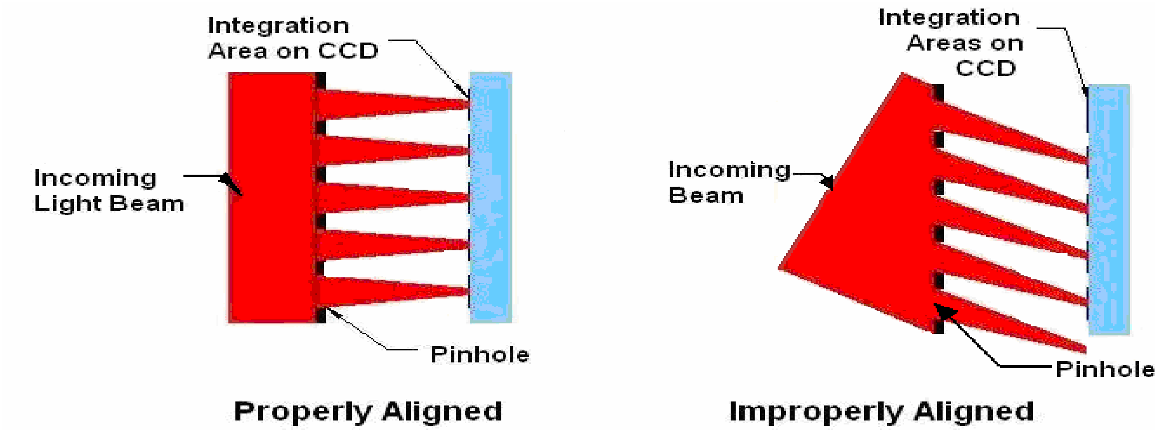


Figure 9: The two conditions in which a focus dot is centered in each integration area

In the factory, each AgilEye™ HWA is positioned in front of a beam with a flat wavefront to calibrate the wavefront sensor. Tip and tilt of the sensor is adjusted to align the pinholes with their corresponding integration areas. Alignment of a newly set up AgilEye™ wavefront sensor is a matter of getting the central pinhole of the pinhole array to project onto the center of the central integration area of the CCD array, precisely as it was during the factory calibration. But how does one know when the foci are in the correct integration areas?

The AgilOptics™ unique alignment system facilitates easy and accurate setup. When aligning a conventional Hartmann sensor pinhole to the input beam two concerns arise.

The first concern is that, in conventional Hartmann sensors, the alignment is done by visualizing the center pixel on the camera's array during setup. The AgilEye™ has been calibrated in the factory to electronically overlay a red cross on the camera image showing the user the center of the central integration area.

The second concern is being able to find and align the central pinhole in the array. AgilEye™ allows the user to visualize the center pinhole because the pinhole is purposely missing! (See Figure 10 below.) Consequently, when the dark center of the pinhole array is projected by the laser beam onto the exact center of the CCD pixel array (as marked by the red cross) the system is aligned. (We have found that the effect of the missing central pinhole is not significant in normal sensor operation.)

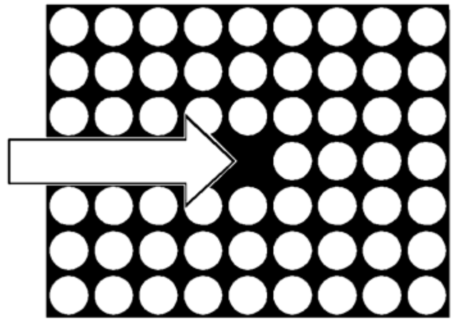


Figure 10: Pinhole Array with Missing Pinhole

When a wavefront sensor is subsequently positioned into a users' optical setup, the beam and wavefront sensor need to be re-aligned with each other. The screenshot below is what should be seen by the user at the beginning of this process.

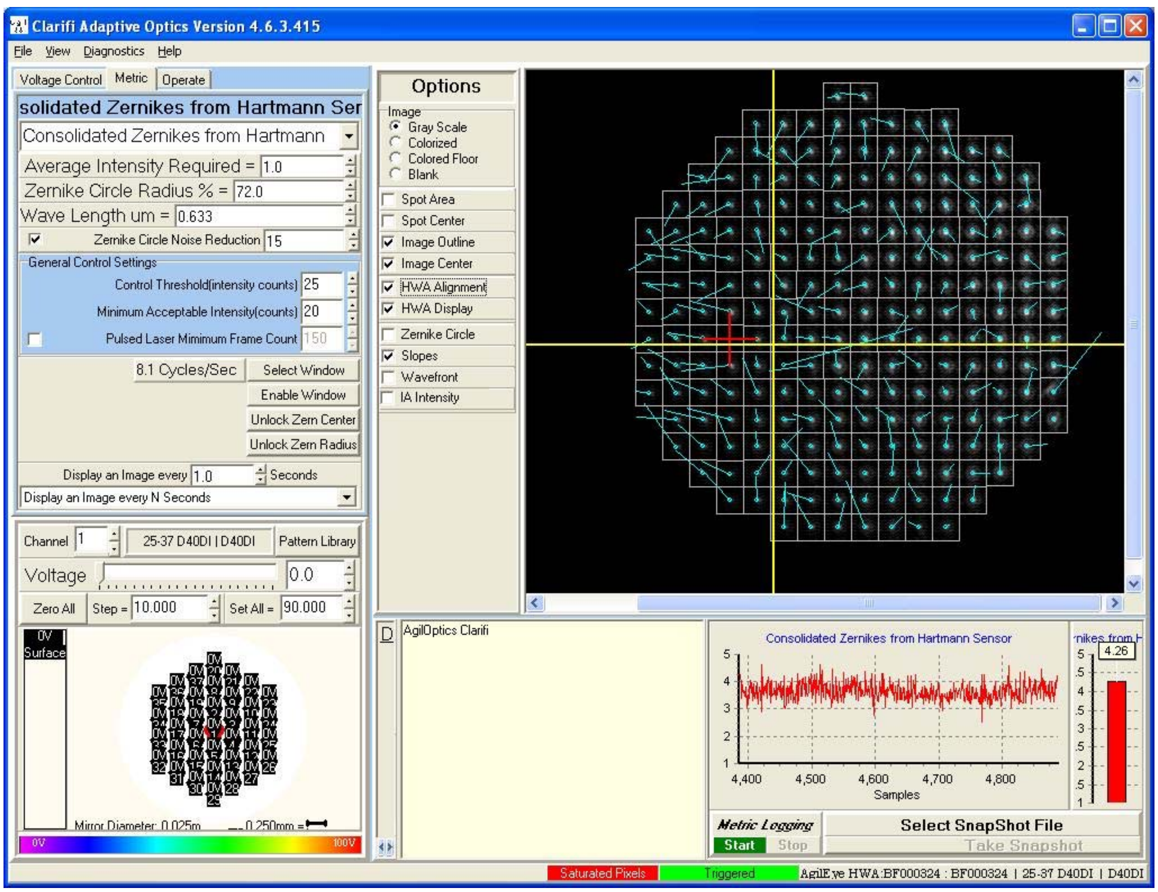


Figure 11: The image area with alignment cross

Figure 11 above shows the array of focal spots sensed by the CCD. In the center of this field two important things should be noted. The small red cross, mentioned above, has been set at the factory and represents the center of the central integration area. The array of focal spots is missing the central spot, marking the center of the pinhole array. This missing focal spot will be made coincident with the red cross to perfect the alignment.

The other two crosses in this area are not a part of the alignment process. The large yellow cross stretching all the way across the image depicts the center of the wavefront sensor's viewing area and stretches along the horizontal and vertical centerlines of the CCD pixels. In a perfect world, both of these crosses, crosshairs and the beam center would be coincident when aligned. Due to fabrication tolerances, it is not normally achievable to align the center of the Hartmann array over the precise center of the CCD array, so a slight displacement of a few pixels is normal and acceptable.

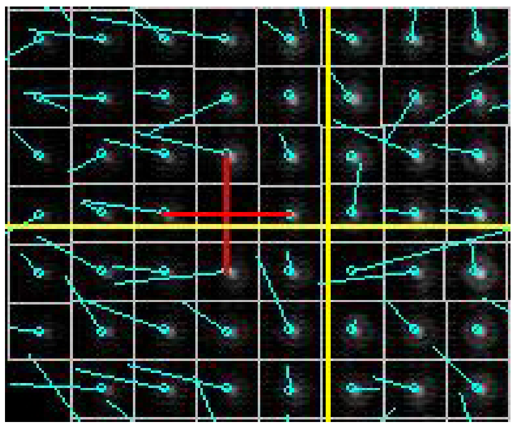


Figure 11: Center of focal dot array

For Setup: In the Options section to the left of the image display click on the radio button for HWA Alignment. This will display the alignment tool (the small red cross) which facilitate the remainder of the alignment procedure. Clicking on the Image Center button will bring up the big yellow cross.

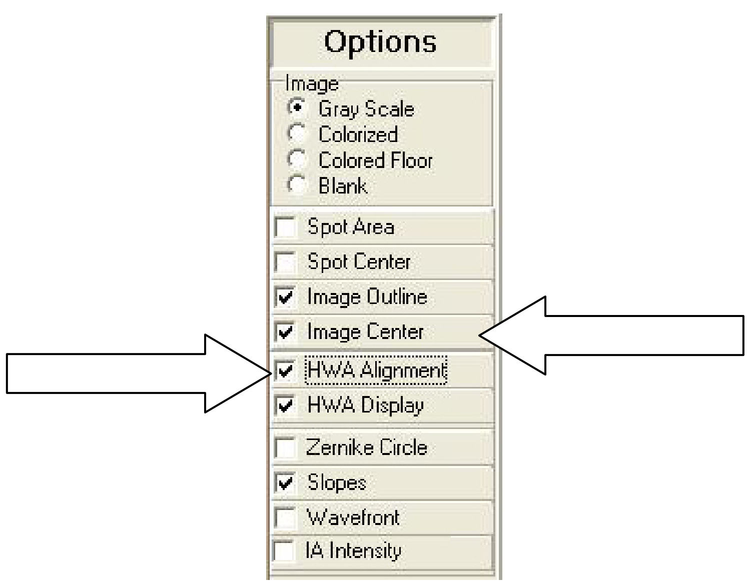


Figure 12: How to bring up the alignment tool

When your AgilEye™ HWA is properly adjusted for an optimum intensity of incoming light (the input device options are covered in the previous section), then your array should look like the one pictured above: an array of evenly spaced spots without interference in between. Once the beam intensities are set to reasonable values, you will be able to notice one spot missing near the center of the field, as shown below.

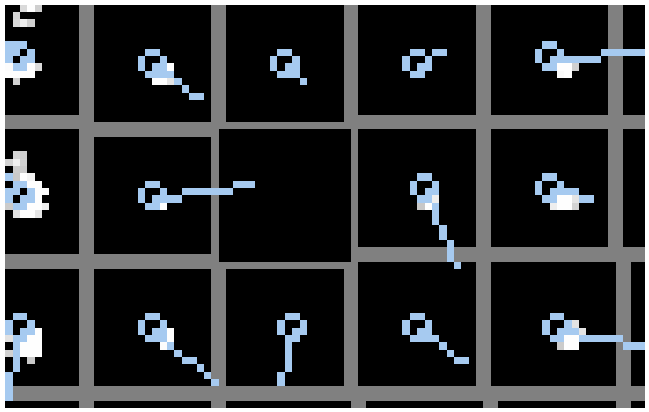


Figure 13: Missing array spot near center

By adjusting the tip and tilt of the camera, all of the spots, including the missing array spot, move in relation to the horizontal and vertical center lines. The white boxes are the individual integration areas derived by the software upon set up. Each area is assigned to one focal spot and represents the zone over which the spot is allowed to move. Adjust the camera's tip/tilt until the darkened array spot is made coincident with the red alignment cross. In order to center the missing spot accurately, make certain that each end of the cross arms is contacting a dot in the neighboring integration area, as shown below. As shown above, the missing array is easy to find and it should be obvious if the red cross is not aligned properly.

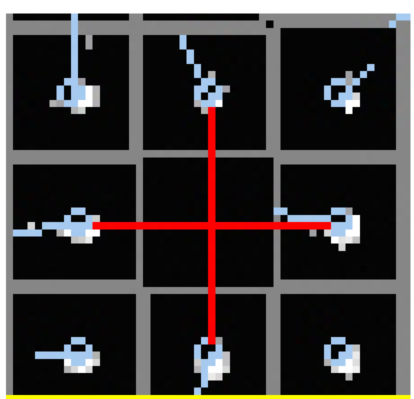


Figure 14: Cross ends touching spots in neighboring integration areas

Your basic alignment is now complete. That is how amazingly simple it is to align an AgilOptics™ wavefront sensing system.

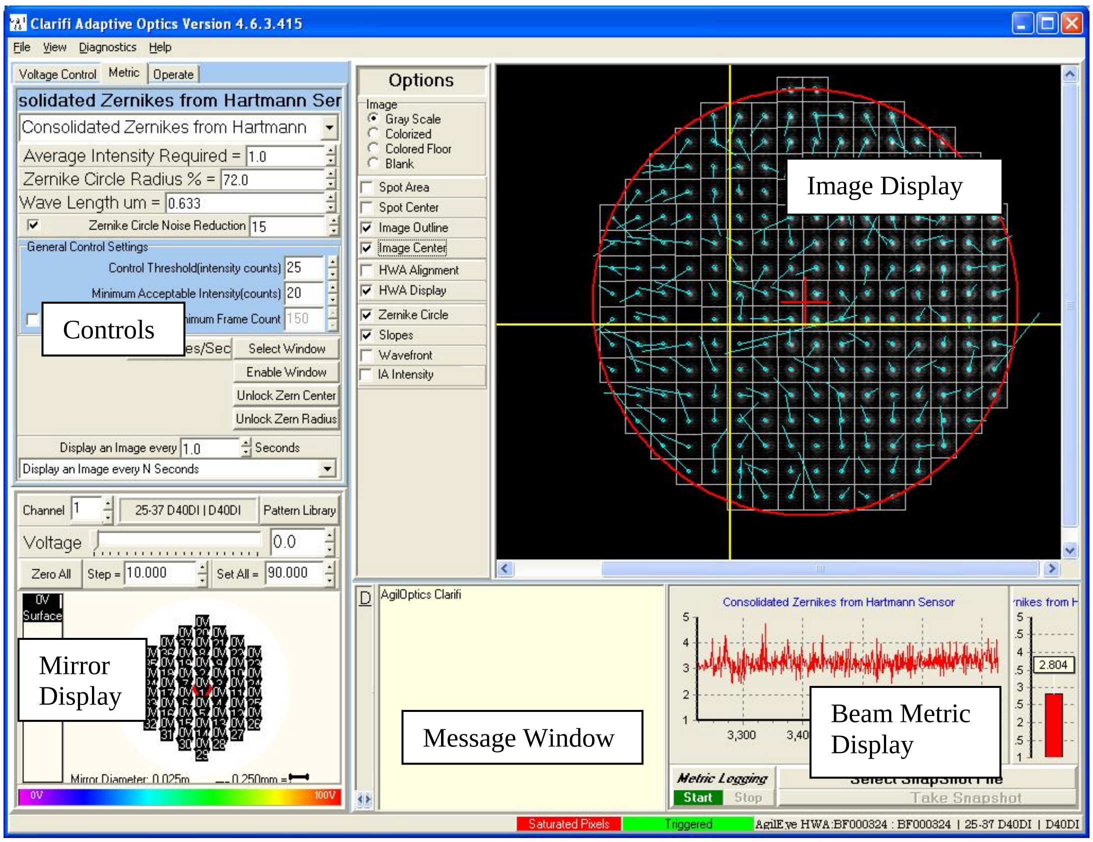
Footnote: Sometimes, you may be able to use the back reflection from the pinhole array to "rough-in" the alignment. Also, keep in mind that the objective is to align the projection of the missing hole onto the center of the red cross. Re-alignment of the beam going into the sensor can alternatively be used to accomplish the same result, and may be easier in certain installations.

For more hints on setup and fine alignment, please see Appendix C. For more information on the wavefront sensor dependence on wavelength, please see Appendix D.

Clarifi™ Software: Explanation and Usage

Main Window

The main window of Clarifi™ consists of five areas of interest: **Controls, Image Display, Mirror Display, Message Window,** and **Beam Metric Display**. These five areas are labeled on the following figure



Controls allow you to control the algorithms used by the software for mirror control.

Mirror Display displays the voltage on the actuators and mirror surface, and also allows you to control the voltage on each actuator.

Message Window displays information pertinent to the current operation.

Beam Metric Graph and **Beam Metric Meter** is a window that displays the progress of the control algorithm in aberration reduction.

Each of these areas will be described in more detail in the following pages.

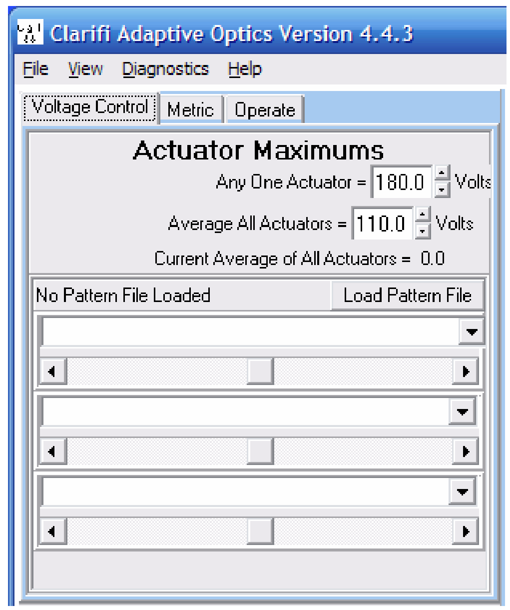
Controls

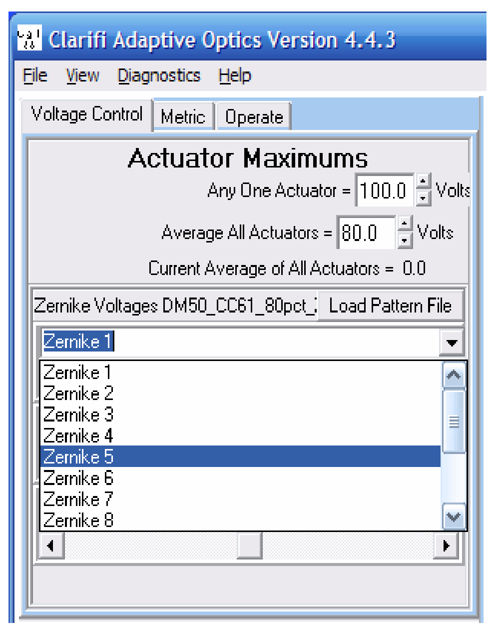
The controls section is subdivided into three sections: Voltage Control, Metric, and Operate - each of which has its own tab.

Voltage Control

The first of the three tabs in the Control Section brings up the Voltage Control window. The user can set the maximum actuator voltage, set the maximum average actuator voltage and load voltage patterns in this window.

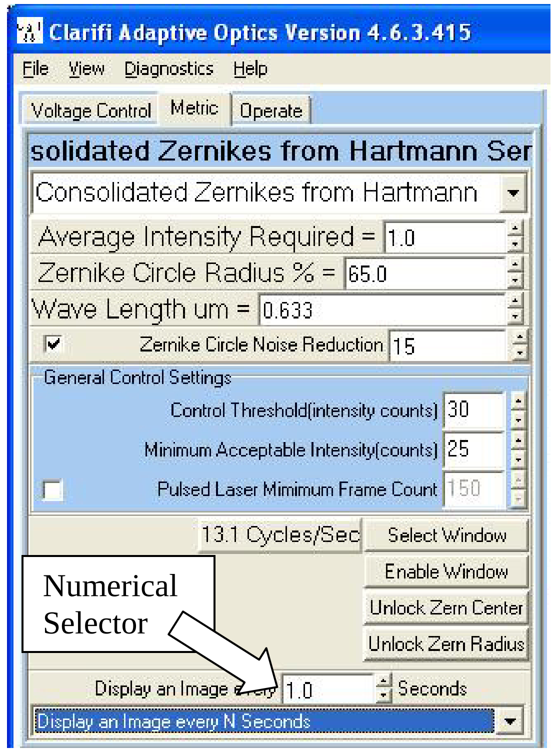
- At the top of this window, the **Any One Actuator** field allows you to set the maximum voltage applied to any of the mirror actuators.
- The **Average All Actuators** field allows the user to set the maximum average voltage for all actuators. In this case, the voltage of an actuator is defined as the absolute value of the difference between the actuator voltage and the voltage on the mirror membrane.
- Below both of these fields is shown the **Current Average of All Actuators** at any specific time.
- The **Load Pattern Files** button opens a dialog box, allowing preset voltage patterns saved as a pattern (.pat) file or as a voltage (.vlt) to be loaded in and put on the actuators.
- If the selected pattern file contains multiple patterns, the three pattern fields will each be loaded with a different pattern. The slider bar beneath the pattern description determines the extent to which the pattern is applied. *Example: If a pattern correcting for sphere is loaded, then by sliding the bar farther to the right, greater magnitude of spherical aberrations are corrected.*
- The arrow to the right of each pattern field drops down a menu containing all of the patterns in the currently loaded file. Each may be selected to apply that pattern to the mirror actuators.





Metric

As shown in the figure below, the second of the three tabs in the Control Section brings up the Metric window. In this window, the user selects the metric (e.g. spot size) to be optimized. Other controls related to the calculation of the feedback metric are also located here.



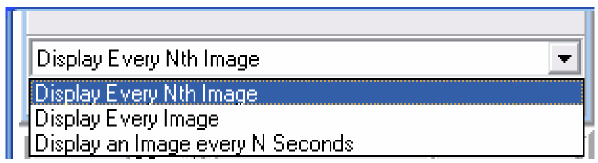
On the right, the window is shown as it appears when the **Metric** tab is first selected.

- The **Control Threshold** selected here is subtracted from the intensity of each pixel, with resulting negative numbers truncated to zero. This is extremely important for eliminating background noise from operation
- The **Minimum Acceptable Intensity** prevents the control from using outputs that cause the peak intensity to drop below this number. If the control does not see any intensity greater than this number, the metric is uncalculated and returns a value of 10^6.
- The **Pulsed Laser Minimum Frame Count** is for optical setups which use a pulsed laser. When this option is enabled, the number of frames selected will be averaged for metric evaluation to take out erroneous results otherwise caused by the pulsing.

The **Average Intensity Required** field sets the value for how much above the control threshold the integration area intensities must be in order to be accepted. The **Zernike Circle Radius %** field sets the percentage of the measured second moment of the beam that will be included in the Zernike circle. The **Wave Length µm** field is where the wavelength of the incoming beam, in microns, is set. When selected the **Zernike Circle Noise Reduction** field sets the number of consecutive images that an integration area is included in the Zernike circle in order to be used.

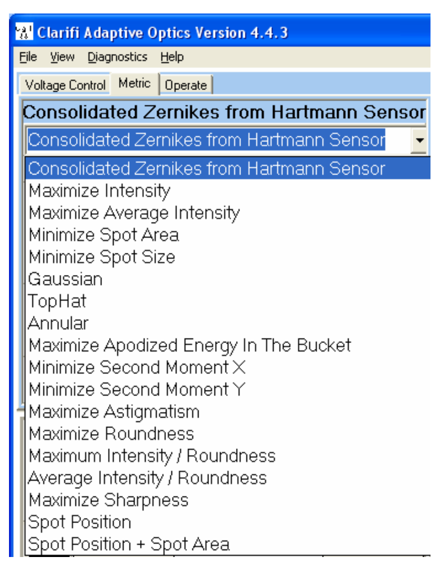
To speed up execution of the control algorithm by limiting calculations to a region of the image, a window function is provided. Press '**Select Window'** then drag the outline of the desired region on the Image Display. Pressing '**Enable Window'** will show the selected region outlined in yellow and limit calculations to just that area. Pressing the button again (now labeled 'Disable Window'), will enable the use of the entire frame. When the Spot Shape Metrics are being used the centroid and second moment oval are drawn on the image. If a camera interface is currently selected there will be a text box next to the Select Window button which will display the current **Image Frame Rate**. Beneath the Enable Window button are the **Lock Zern Center** and the **Lock Zern Radius** buttons. The Lock Zern Center button locks the center of the Zernike circle and will not allow it to be translated. The Lock Zern Radius button locks the radius of the Zernike circle and will not allow it increase or decrease. When these buttons are selected the buttons will change to **Unlock Zern Center** and **Unlock Zern Radius** which will allow for the lock to be released.

In order to change image performance options, click on the arrow on the right side of the **Display Option** box. This will cause a drop-down menu to be displayed, as shown below. Each of these options then causes a different numerical selector to be displayed, with uses explained below.



- **Display Every Nth Image** allows the user to display images based on the number of images acquired by the input device. *Example: if the number four is displayed in the numerical selector, then only every fourth frame from the camera will be shown. If the camera is set to an exposure of 500milliseconds, then a new image will be displayed every two seconds.*
- **Display Every Image** causes every image acquired from the input device to be displayed.
- **Display an Image every N Seconds** allows the user to display images based on time elapsed. *Example: if the number three is selected in the numerical selector, then an image will be displayed every three seconds.*

One of the Metrics is selected from the drop down menu to determine which metric will be used by the control algorithm as its input. They are listed below, along with an explanation of their functions.



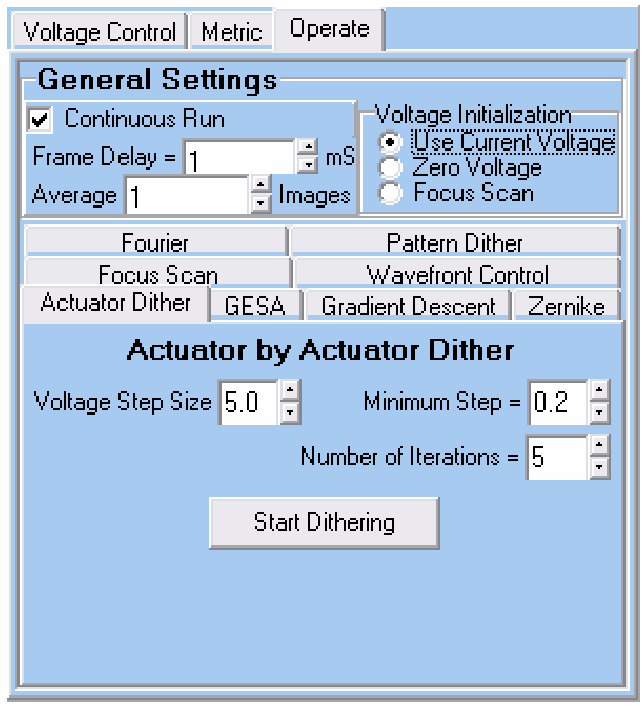
- **Consolidated Zernikes from Hartmann Sensor** is the heart of the Clarifi-3D ™ system. When this metric is selected, the wavefront of the incoming beam is measured, and the individual Zernike values are determined then the differences between each value and the ideal are summed, resulting in the consolidated metric. Any wavefront shape may be selected, and the metric will attempt to match the selected shape. *Note: this metric is the only one that is designed for use with a wavefront sensor; all other metrics are designed for use with a CCD camera.*

- **Maximum Intensity** maximizes the intensity of the brightest pixel.
- **Max Average Intensity** maximizes the average intensity of those pixels which are above the **Control Threshold.**
- **Minimize Spot Area** calculates the product of the X and Y RMS (root mean squared) deviations from the beam centroid.
- **Minimize Spot Size** minimizes the size of the spot.
- **Gaussian** attempts to match the beam intensity to a Gaussian distribution, with the brightest points in the center and the edges fading to zero intensity. The higher the order selected, the smaller the gradient (i.e., the steeper the sides of the bell curve).
- **Tophat** attempts to match the beam intensity to a Gaussian distribution of order infinity (a bell curve with perfectly vertical side). The diameter of the cylinder can be specified in this window.
- **Annular** attempts to match the beam intensity to a Gaussian distribution of order infinity with zero interior intensity (a perfect ring with vertical sides). Both the interior and exterior diameters can be specified.
- **Maximize Apodized Energy in the Bucket** maximizes the amount of energy (judged by pixel intensity) in a specified diameter within the image area. The intensity is shaped into a cone, with maximum intensity in the center and zero intensity around the outside, having a linear gradient between.
- **Minimize Second Moment X** minimizes the X RMS deviation from the beam centroid.
- **Minimize Second Moment Y** minimizes the Y RMS deviation from the beam centroid.
- **Maximize Astigmatism** takes the difference of the X deviation minus the Y deviation
- **Maximize Roundness** takes the absolute value of difference of the X deviation minus the Y deviation which, when minimized, causes them to be equal.
- **Maximum Intensity/Roundness** maximizes the result of the equation: (Maximum Intensity) / (Roundness + Hybrid Denominator)
- **Average Intensity/Roundness** maximizes the result of the equation: (Average Intensity) / (Roundness + Hybrid Denominator)
- **Maximize Sharpness** maximizes the average difference between adjacent pixels.
- **Spot Position + Spot Area** minimizes the product of the X and Y RMS (root mean squared) deviations from a specified spot center.
- **Spot Position** minimizes the difference between the calculated beam centroid and the specified desired spot center.

The metrics used in Clarifi™, with the exception of Hartmann Wavefront, are all similar in that they convert the image from the CCD into a single scalar number such that the lower the number, the better the intensity profile matches the desired profile. In every case, the program reads the entire image intensities pixel-by pixel, or the entire window if windowing is enabled. When a measurement is to be maximized, the measured value is multiplied by -1 so that minimizing the *metric* maximizes the *measurement*.

Operate

The third of the three tabs in the Control Section brings up the Operate window. Every control algorithm used in Clarifi™ seeks to minimize the selected metric by modifying the voltages on the actuators of the DM. They all operate in the same manner in that they first acquire an image from the CCD camera, call the routine that evaluates the selected metric, and then modify the DM voltages in some way. The algorithms repeat the above three steps, each time comparing the value of the metric to the previous value that was calculated before the voltage change. Based on the response of the metric to the latest voltage change, the algorithm then determines what the next voltage change will be.



At the top of this window are the **General Settings** common to all the control algorithms:

- The **'Continuous Run'** switch causes the control iterations to continue until it is deselected or the Stop button is pressed.
- The **'Voltage Initialization'** section allows you to choose what voltages to put on the actuators before the control iterations begin. There are three choices:
  - **Use Current Voltage** leaves the actuators where they are and begins the control. By first using Load Initial Voltages from the Voltage Control section (see above), this allows starting with an arbitrary voltage pattern.
  - **Zero Voltage** zeros all the actuators then starts the control.
  - **Focus Scan** puts increasing voltage on the actuators and monitors the resulting value of the metric. It then starts with all actuators set to the voltage that minimized the metric.
- When **Continuous Run** is selected, the metric will continue to run even after it has passed through the selected number of control iterations. *Example: If five is selected for the number of iterations for the* Actuator Dither *algorithm, and if Continuous Run is not selected, then the algorithm will run for five iterations then stop. With continuous run selected, the algorithm will continue to run until stopped by the user.*

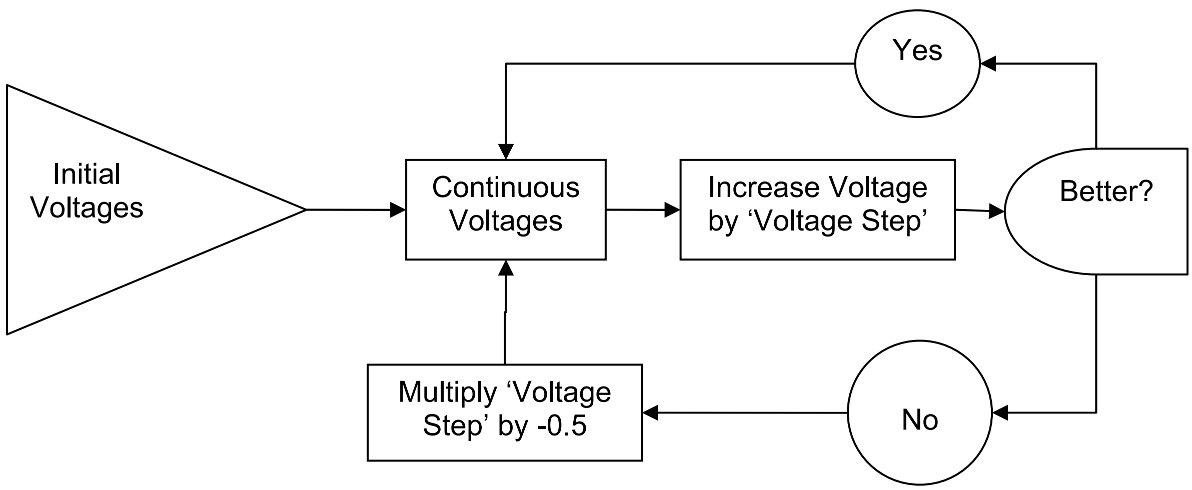
- **Frame Delay** causes the specified number of milliseconds to idle after each voltage update, before measuring the metric again.
- **Average _ [N] _ Images** causes the program to average the specified number of images from the input device for metric evaluation. This is especially useful for systems with vibration, since the average will help to eliminate the error which vibration causes.

Within the Operate tab there are eight individual tabs allowing you to pick a specific algorithm. These will be described one at a time in the following sections.

***Operate** - Dithering*

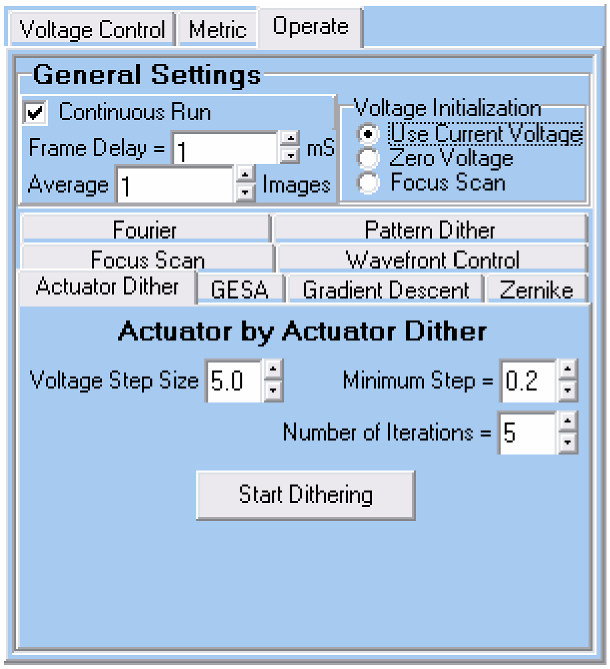
The Dithering algorithm is the slowest, but usually the most precise, control algorithm Clarifi™ uses. Beginning with actuator number one, Clarifi™ increases the voltage on the actuator by the number of volts specified in the Voltage Step Box. It then evaluates the metric. If the metric has decreased, it will continue increasing the voltage and evaluating the metric until the metric increases. At that time, Clarifi™ will multiply the voltage step by -0.5, cutting the step size in half and reversing its direction. It will continue the process, going back and forth with progressively decreasing step sizes until the step size is less than the minimum. Clarifi™ then selects actuator number two and performs the same procedure on that actuator. This continues until all of the actuators except the mirror itself have been optimized.

Dithering Flowchart



- **Voltage Step Size** sets the initial amount that each actuator voltage is increased.
- **Minimum Step** causes the control to move on to the next actuator when the decreasing step size falls below this number.
- **Iterations** causes the entire process described above to be repeated for the specified number of times.

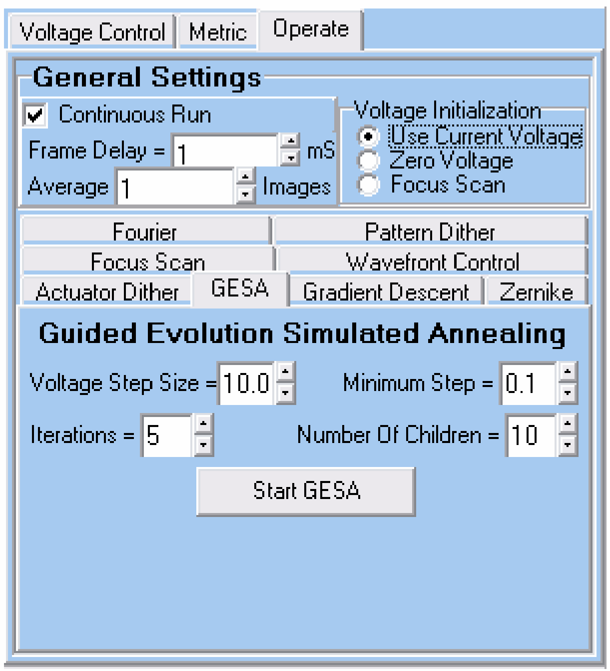
Operate - *Dithering* (continued)



- **Start Dithering** begins the control process. While the control is running, the caption on this button changes to **Stop Dithering.**

***Operate** – GESA*

The Guided Evolution with Simulated Annealing (GESA) algorithm is one of the two genetic algorithms implemented in Clarifi™. The algorithms are called genetic because each set of "parent" voltages is the starting point for generating a collection of "child" voltage sets which will be evaluated using the selected metric. If one of the child voltages results in a better metric than the parent, it becomes the parent for the next generation. In the GESA algorithm, Clarifi™ first generates N (set by the user in the Number of Children numerical selection box) sets of random voltages, selected randomly between 0 and specified step size. Each set of child voltages is evaluated and the one with the best metric value is selected to be the parent. The step size is then cut in half and N sets of child voltages are generated as before. This process continues, reducing the step size and generating new voltage sets, until the step size is less than the Minimum Step value.



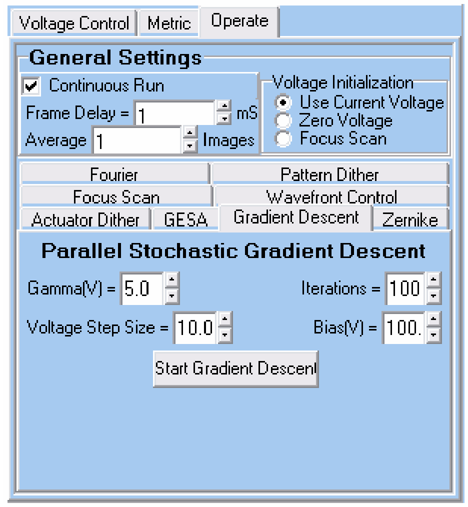
- **Voltage Step Size** sets the initial maximum of the random voltage selections.
- **Minimum Step** causes the control to move on to the next iteration when the decreasing step size falls below this number.
- **Iterations** causes the entire process described above to be repeated for the specified number of times.
- **Number of Children** sets the number of random variations ("children") tried at each step size.

The **Start GESA** button begins the control process. While the control is running, the caption on this button changes to **Stop GESA.**

***Operate** - Gradient Descent*

Parallel Stochastic Gradient Descent

The third genetic algorithm implemented by Clarifi™ is the Parallel Stochastic Gradient Descent, which is very similar to the GESA algorithm described above, except that it uses statistics to make smarter changes in the patterns. In other words, through analysis, Clarifi™ is able to generate smarter “children” from each set of parents.



This algorithm begins with a set of parent voltages all equal to the value of Bias selected in the Control Tab Bias Box. For each iteration, Clarifi™ generates a set of actuator voltages that differ from the parent voltages by plus or minus half the step size, the sign determined randomly. It then evaluates the selected metric. The change in the value of the metric is multiplied by the gain selected in the Gamma Box in the Control Tab. This is then divided by the change in actuator voltage on an actuator-by-actuator basis. In other words the new parent voltage for each actuator is given by $V_{j+1} = V_j + \frac{\gamma * \Delta \mathrm{err}}{\Delta \mathrm{V}}$, where Vj = parent voltage, γ = gain, Δerr = the change in metric = (metric – last metric), and ΔV = voltage change = (Voltage – Parent Voltage). The value of Gamma is then cut in half and the process repeats.

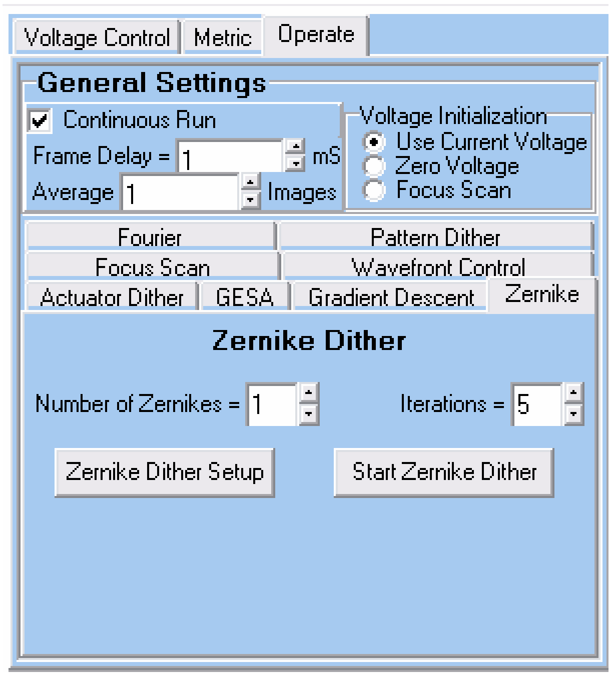
- The **Gamma** parameter is the gain term which sets how many volts to adjust the actuator per unit of error (in other words, how much to adjust actuator voltages based on how incorrect its current guess is). Since some feedback metrics vary more than others, this has to be selected carefully. The higher Gamma values yield faster results in metric reduction, but the metric also tends towards instability. Small Gamma values will yield more accurate, stable results, but with longer correction times.
- **Voltage Step Size** sets the initial maximum of the random voltage selections.
- **Iterations** causes the entire process described above to be repeated for the specified number of times.
- **Bias** is the voltage put on all actuators for the first measurement when Zero Voltage is selected in Voltage Initialization.
- **Start Gradient Descent** begins the control process. While the control is running, the caption on this button changes to “**Stop Gradient Descent**”.

Operate - *Zernike Dither*

In Zernike Dither, Clarifi™ uses a collection of scalable voltage sets; each one produces an aberration in the mirror surface corresponding to a Zernike function, which is a mathematical function that closely approximates different common optical aberrations. Currently there are 12 sets implemented, which represent the following Zernike:

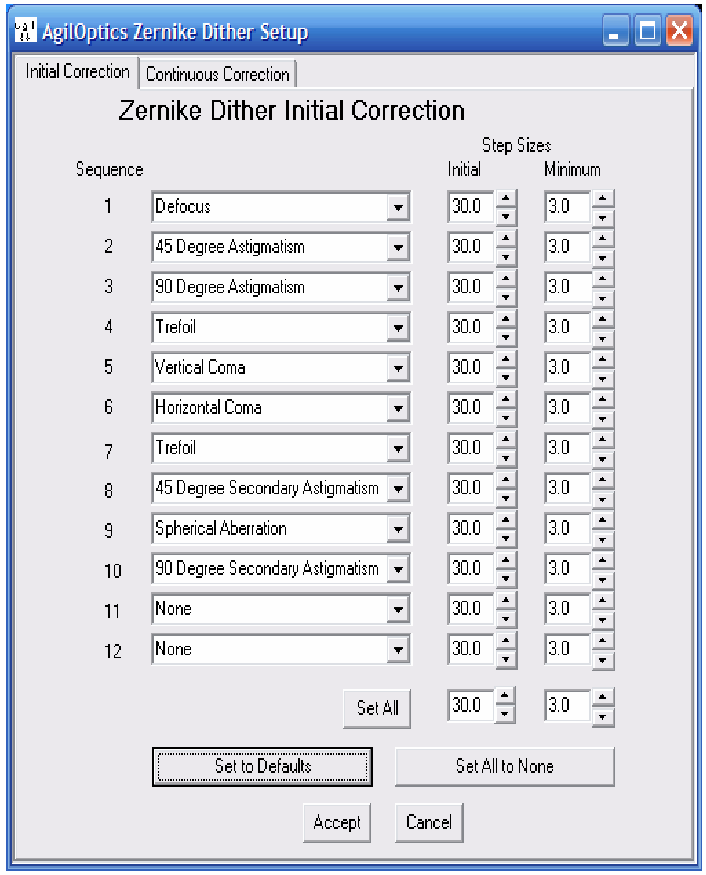
Zernike in software	Name
1	Focus
2	45° Astigmatism
3	90° Astigmatism
4	Trefoil
5	Vertical Coma
6	Horizontal Coma
7	Trefoil
8	45° Secondary Astigmatism
9	Spherical Aberration
10	90° Secondary Astigmatism
11	None
12	None

The algorithm dithers each of the above Zernike aberrations in turn in the same manner as the mirror dither described formerly. For a flowchart representation, please see page 39.



- **Number of Zernikes** sets the first N entries on your list as the ones which will be used. A sample list is shown on the next page. *Example: if your first three Zernikes were for Focus, Vertical Coma and Horizontal Coma, and a value of two was selected in this box, then only the voltage sets for Focus and Vertical Coma would be used.*
- **Iterations** causes the entire list to be repeated for the specified number of times.
- **Zernike Dither Setup** button brings up a list of Zernike aberrations which may be edited and rearranged to select which order the patterns will be dithered during the iterations.
- **Start Zernike Dither** begins the control process. While the control is running, the caption on this button changes to **Stop Zernike Dither**.

Operate – *Zernike Dither* – Zernike Dither Setup
Pressing the Zernike Dither Setup button brings up this window, which allows the selection of up to 12 patterns for the control to use while dithering.

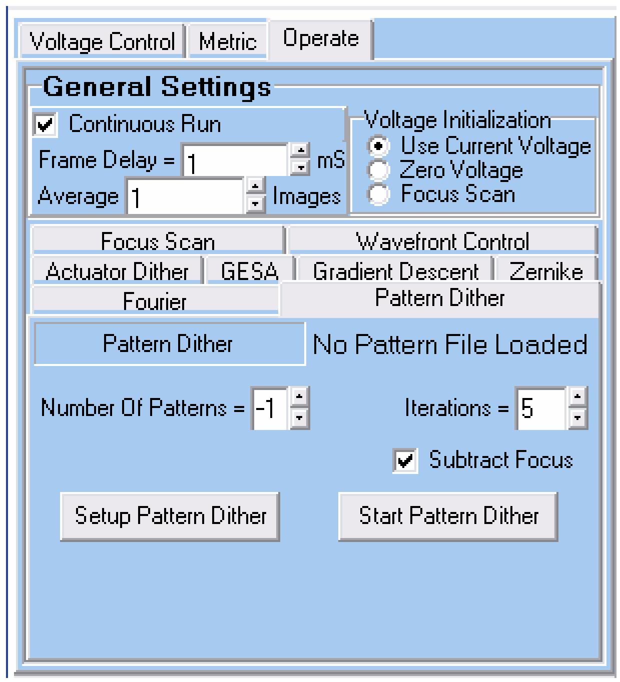


- **Sequence** is the order of progression for dithering.
- **Zernikes** are selected from pull-down boxes. The order in which they appear is the order in which they will be applied.
- **Step Sizes**
  - o ***Initial*** is the initial magnitude of the aberration, in average volts per actuator, which, as the dither progresses, will be reduced eventually to the value set in Minimum.
  - o ***Minimum*** is the voltage value at which the dither moves on to the next Zernike pattern.
- **Set All** sets the values of every pattern in the sequence to the values selected.
- **Set to Defaults** will return the list and all the step sizes to the default values, which are shown here.
- **Set All to None** clears the list of Zernikes, and returns all the step sizes to the default value of 30 and the minimum step sizes to 3.
- The **Initial Correction** tab only applies to the first iteration. All other iterations will use the list under the **Continuous Correction** tab, which looks and functions exactly like this one. The basic operation of these is shown by the Initial Voltage and Continuous Voltage fields of the Dithering Flowchart on page 39.

The **Accept** button saves your changes and closes the Zernike Dither Setup window. The **Cancel** button closes the window without saving any changes.

Operate – *Pattern Dither*

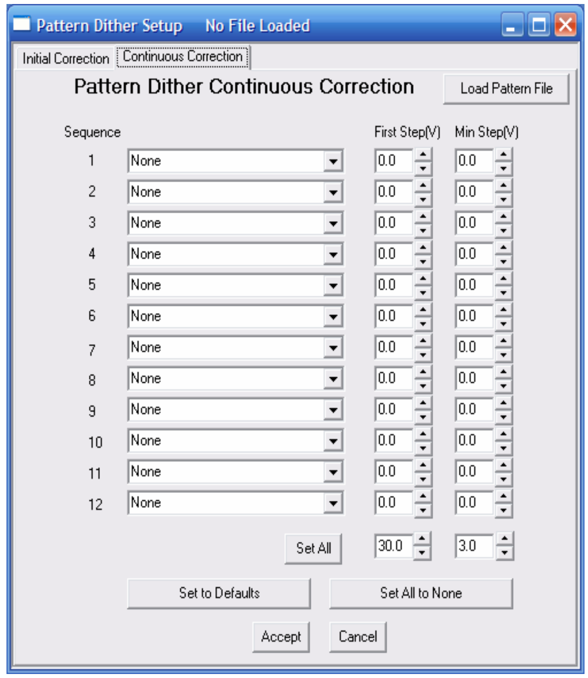
In Pattern Dither, Clarifi™ dithers through sets of preloaded voltage patterns. The patterns are those selected in the Pattern Dither Setup (see next page). One at a time, the mirror maximizes the metric for each pattern by dithering through voltages in that pattern in a way similar to the mirror dither described earlier (please see page 39 for details). When using one the metric is maximized for one pattern, then Clarifi™ begins dithering the next pattern, and so on through each of the loaded patterns.



- **Number of Patterns** sets the first N entries on your list as the ones which will be used. A description of this list is on the next page.
- **Iterations** causes the entire list to be repeated for the specified number of times.
- **Subtract Focus** causes Clarifi™ to automatically ignore the focus element of the beam when adjusting for the selected optimization.
- **Setup Pattern Dither** brings up a list of voltage patterns which may be edited and rearranged to select which order the patterns will be dithered during the iterations.
- **Start Pattern Dither** begins the control process. While the control is running, the caption on this button changes to **Stop Pattern Dither**.

Operate – *Pattern Dither* – Pattern Dither Setup

Pressing the Setup Pattern Dither button brings up this window, which allows the selection of up to 12 patterns for the control to use while dithering.

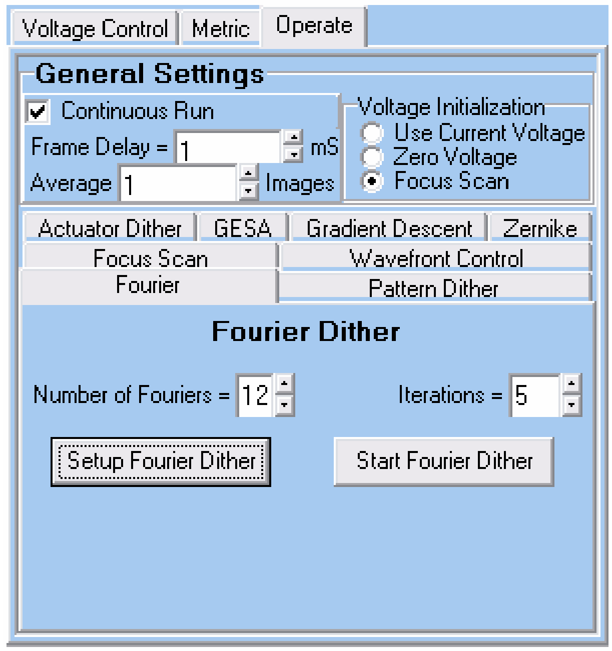


- **Load Pattern File** opens up a dialog from which you can load previously stored pattern files. These can be created using HVDD.
- **Sequence** is the order of progression.
- **Patterns** are selected from pull-down boxes. The order in which they appear is the order in which they will be applied.
- **First Step** is the initial magnitude of the aberration, in average volts per actuator. These will be eventually reduced to approximately 1 volt per actuator as the dither progresses.
- **Min Step** is the voltage at which the dither will stop for that pattern (see page 39 for more on the dithering process). The default value is one-tenth the First Step, though this value can be changed after First Step is set.
- **Set All** will set all the First Step and Min Step values to the values in the boxes to the right of the Set All button.
- **Set to Defaults** will return the list and all the step sizes to the default values, which are shown above.
- **Set All to None** clears the list of patterns, and returns all the step sizes to the default value of 30.
- The **Initial Correction** list only applies to the first iteration. All other iterations will use the list under the **Continuous Correction** tab, which looks and functions exactly like this one. The basic operation of these is shown by the Initial Voltage and Continuous Voltage fields of the Dithering Flowchart on page 39.

The **Accept** button saves your changes and closes the Zernike Dither Setup window. The **Cancel** button closes the window without saving any changes.

Operate – *Fourier Dither*

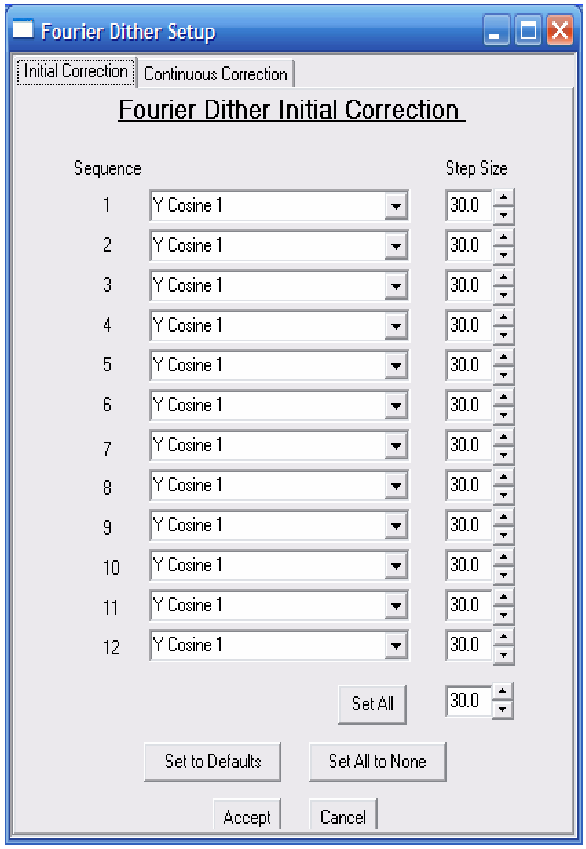
In Fourier Dither, Clarifi™ uses a collection of scalable voltage sets; each one produces an aberration in the mirror surface corresponding to a Fourier polynomial. The algorithm dithers each of the Fourier aberrations in turn in the same manner as the mirror dither described formerly. For a flowchart representation, please see page 39.



- **Number of Fouriers** sets the first N entries on your list as the ones which will be used.
- **Iterations** causes the entire list to be repeated for the specified number of times.
- **Setup Fourier Dither** button brings up a list of Fourier aberrations which may be edited and rearranged to select which order the patterns will be dithered during the iterations.
- **Start Fourier Dither** begins the control process. While the control is running, the caption on this button changes to **Stop Zernike Dither**.

Operate **–** *Fourier Dither* – Fourier Dither Setup

Pressing the Fourier Dither Setup button brings up this window, which allows the selection of up to 12 patterns for the control to use while dithering.

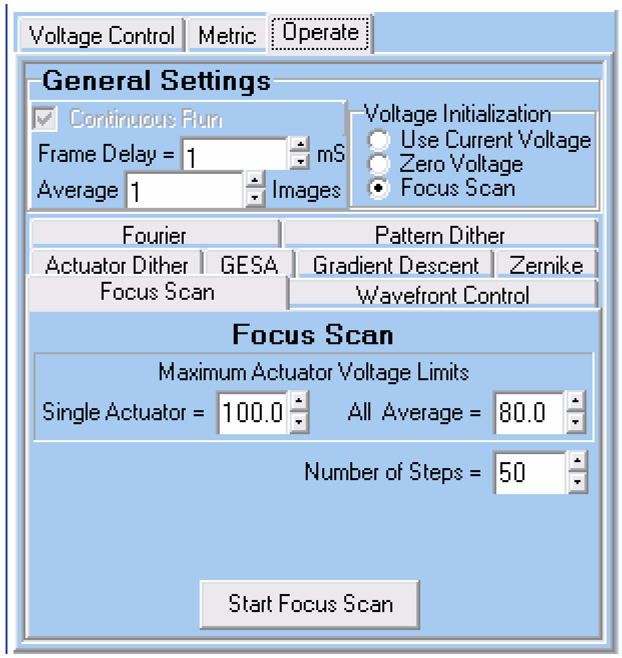


- **Sequence** is the order of progression.
- **Fouriers** are selected from pull-down boxes. The order in which they appear is the order in which they will be applied.
- **Step Sizes**
  - ***Initial*** is the initial magnitude of the aberration, in average volts per actuator, which, as the dither progresses, will be reduced eventually to the value set in Minimum.
  - ***Minimum*** is the voltage value at which the dither moves on to the next Fourier pattern.
- **Set All** sets the values of every pattern in the sequence to the values selected.
- **Set to Defaults** will return the list and all the step sizes to the default values, which are shown here.
- **Set All to None** clears the list of Fouriers, and returns all the step sizes to the default value of 30 and the minimum step sizes to 3.
- The **Initial Correction** tab only applies to the first iteration. All other iterations will use the list under the **Continuous Correction** tab, which looks and functions exactly like this one. The basic operation of these is shown by the Initial Voltage and Continuous Voltage fields of the Dithering Flowchart on page 39.

The **Accept** button saves your changes and closes the Zernike Dither Setup window. The **Cancel** button closes the window without saving any changes.

***Operate –** Focus Scan*

Focus Scan puts a uniform increasing voltage on the actuators and monitors the resulting value of the metric. It then sets all of the actuators to the voltage that minimized the metric.



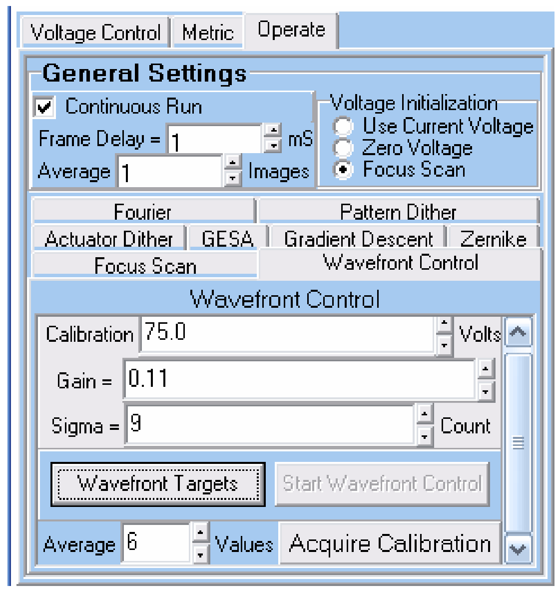
Maximum Actuator Voltage Limits

- **Single Actuator** sets the maximum value of voltage that will be applied to the actuators.
- **All Average** sets the maximum average value of voltage that will be applied to the actuators.

Number of Steps sets the number of individual voltage values that will be applied to the mirror. *Example: if* All Average *is set to 100V and* Number of Steps *is set to 50, then the voltage will be applied to all the actuators simultaneously from 0V to 100V by 2V increments.*

***Operate –** Wavefront Control*

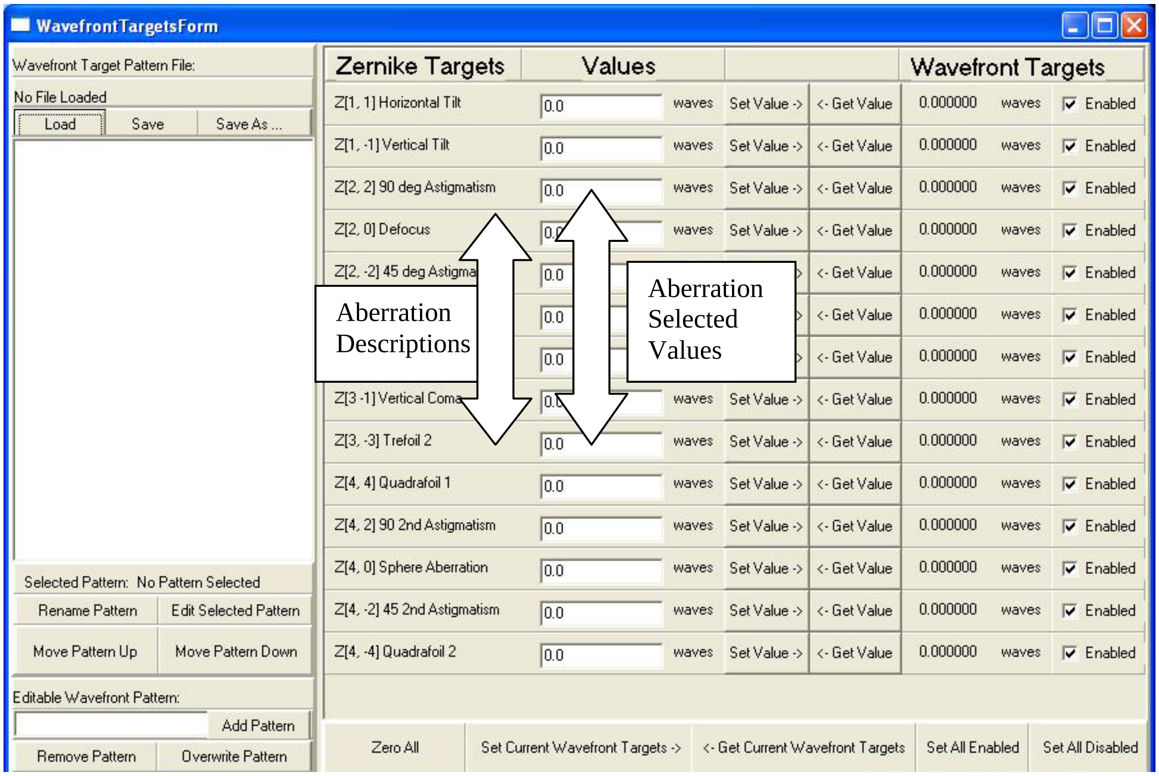
The Wavefront Control algorithm is unique to Clarifi-3D™, and is unlike any of the other Clarifi™ algorithms. It begins by applying a series of patterns on the mirror and measuring the wavefront that is created thus calibrating those patterns. Based on data from the wavefront sensor input device, it first measures the beam wavefront, and then selects voltage values from a set of pre-calibrated patterns in order to correct for the aberrations in the beam. This algorithm can also match the wavefront to user specifications, broadly increasing the versatility of the Clarifi™ Software.



- **Calibration** sets the average actuator voltage used for calibrating the correction patterns. This value should be approximately 75% of the "Maximum Actuator Average" found in voltage control.
- **Gain** is a value between 0.01 and 0.99 and sets the relative amount of correction applied to the mirror each iteration. Higher values are good for course correction, while smaller values allow for more accuracy.
- **Sigma** represents the number of terms in the gain matrix. When a new calibration is acquired, the Sigma value will automatically be set as high as the calibration allows. The user should set this based on the setup requirements. The higher values tend to be dominated by control 'noise'. Reducing this value will cause the control to converge with greater stability, but with less ability to make fine correction.
- **Wavefront Targets** brings up a dialogue where the user can set up the wavefront that this algorithm will attempt to create. More on this can be found below in the section on use of this algorithm.
- **Acquire Calibration** applies a series of preset voltage patterns to the actuators while recording the resulting wavefront. Once a calibration is run, the system is calibrated and the Start Wavefront Control button becomes selectable. A new calibration **must** be acquired any time there is **any** change to the optical setup, and it is recommended that a new calibration is run at the beginning of every session.
- **Average _ [N] _ Values** averages the data from N data sets from the input device helping to filter out time variant optical fluctuations such as table vibration.

Operate ***–*** *Wavefront Control* – Use Instructions

1. Make certain that the beam is centered on the deformable mirror (please see Appendix C) and that the camera is properly aligned (please see "Aligning the AgilEye™ HWA", page 25)
2. Left-click on the "Wavefront Targets" button. The following dialogue will be brought up in a new window. Use this to set-up the desired wavefront.

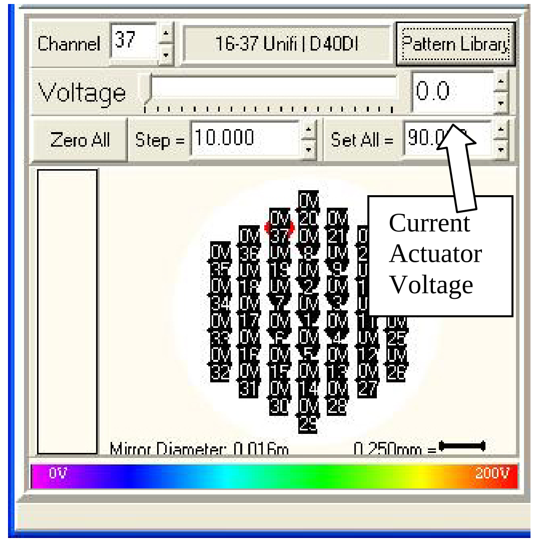


On the left of this screen there is an area to load a .ZPF file which contains a list of patterns which contain different values for the Zernike Targets. The list of patterns can be saved, moved, edited or renamed in this area. On the right of this screen are the controls for choosing the Zernike Targets and their values. Each of the Zernike Targets correlates to one of the Zernike aberrations. The name of the aberration is to the left of the value box for that Zernike. By checking the "Enabled" box, that aberration is considered as a part of the metric and considered in the wavefront correction. If you desire that particular aberration to be zeroed through the correction, then leave the value at zero. In order to shape the wavefront, however, different values of each aberration can be selected, and Clarifi™ will attempt to shape the wavefront to contain the specified amount of the given aberration. The Set Value button to the right of the value boxes sets that Zernike with the specified values as one of the targets. The Get Value button to the right of the value boxes takes the target value and stores it in the current pattern file.

- **Set All Enabled** enables all twelve aberrations for metric evaluation.
- **Set All Disabled** disables all twelve aberrations for metric evaluation.
- **Zero All** zeros all of the aberration values.

3. Left-Click on the "Acquire Calibration" button
    - **Acquire Calibration** applies a series of preset voltage patterns to the actuators while recording the resulting wavefront. Once a calibration is run, the system is calibrated and the Start Wavefront Control button becomes selectable. A new calibration **must** be acquired any time there is **any** change to the optical setup, and it is recommended that a new calibration is run at the beginning of every session.
4. Left-Click on "Start Wavefront Control". The algorithm will attempt to conform the incoming wavefront to the wavefront specified in "Wavefront Control Zernike Targets."
5. Make adjustments to Sigma and Gain values to allow for finer or more course correction depending on your first outcome. Usually, several iterations of adjustment are necessary in order to produce clean, consistent results.

Actuator Voltage Display



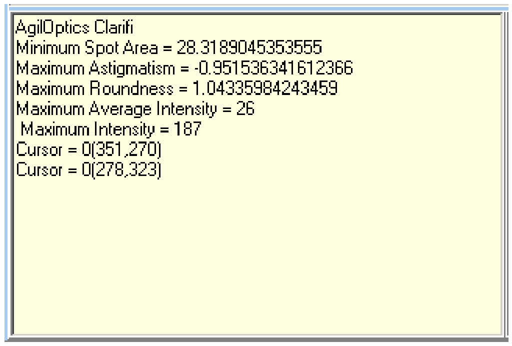
This is where the voltages currently applied to the mirror actuators are displayed. Current mirror selection is indicated by the text in the center across the top of this area. The voltage on each actuator is shown by a color, changing on the scale from violet (zero) to red (maximum); the scale is shown at the bottom of this window. The voltages can also be changed by clicking on this display.

- **Channel** selects the current actuator for change.
- The **Voltage Slider Bar** allows the user to analogically apply voltage to the current actuator.
- The **Current Actuator Voltage Box** displays the current voltage on the current actuator. The current actuator's voltage can also be digitally set from this box.
- **Left-Clicking** any actuator or mirror surface will *increase* the voltage on that actuator by the number of volts shown in the 'Step' box.
- **Right-Clicking** any actuator or mirror surface will *decrease* the voltage on that actuator by the number of volts shown in the 'Step' box.
- **Center-Clicking** any actuator or mirror surface will *zero* the voltage.
- **Zero All** puts zero volts on all actuators as well as on the mirror membrane.
- **Step** is the value, in volts, of change on any actuator when that actuator is left-clicked (to add step) or right-clicked (to subtract step).
- **Set All** button will apply the voltage shown in the box to all actuators except the mirror membrane.
- The **Mirror Display** shows each actuator in the mirror and on each actuator is displayed the voltage currently applied to it and under that the actuator number (note: these numerical values will only be displayed if the window is large enough; window size can be changed by clicking and dragging the edges). The mirror surface voltage is shown in the upper left and if there are any auxiliary actuators (e.g. a pull-up electrode) they will be shown below the mirror surface voltage. The current selected actuator is outlined in red. At the bottom of the display the Mirror Diameter is listed, along with a scale to show the actuator size.

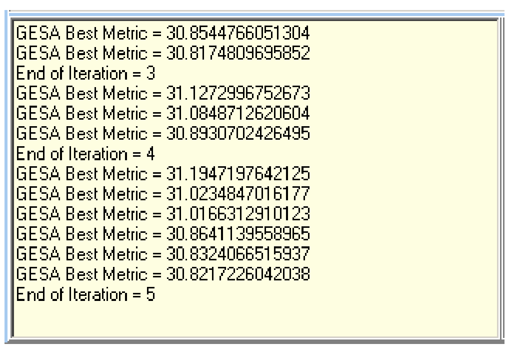
When a control algorithm is running, the voltages in this display will update once per second.

Message Output Window

The Message Window is where Clarifi™ posts information generated by the program as it runs a control algorithm, and information requested by the user, such as when pressing ‘Evaluate Metric’ in the Feedback tab or when the location of a point on the Image Display is clicked (see below).



- Pressing ‘Evaluate Metric’ will print the name of the currently selected metric and its value in this window. Several examples are shown above.
- Left-Clicking the mouse over a pixel in the Image Display will print “Cursor=” followed by the intensity value of that pixel and the (X, Y) location of the pixel. Two examples are shown above.



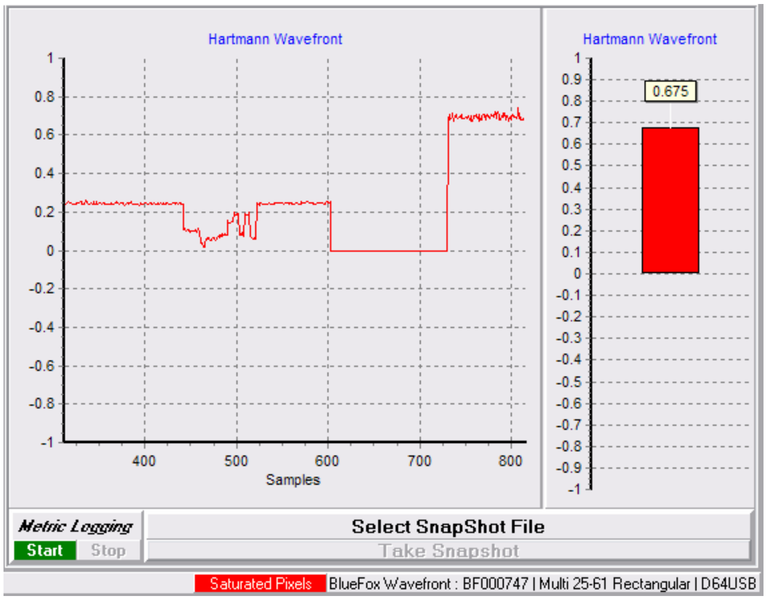
In the picture above, the new best corrections (“metrics”) are recorded in each iteration of the algorithm.

- While running a control algorithm, the program will report progress information such as iteration number and in some cases, steps within the iterations. It will also report when a new best metric has been measured.
- To keep the control from drifting off due to one bad measurement, the best metric is occasionally reset. In the example above, it is reset at the beginning of each iteration.

You can Right-Click on the Message Window and ‘Select All’. This will select every message since Clarifi™ started. Then Right-Click again and Cut, Copy or Delete the text. In this way all the messages since the beginning of the Clarifi™ session can be saved to a text file.

Beam Metric Display - Metric Measurement Display

The Metric Measurement Display is a useful tool for the alignment and setup of feedback parameters, as well as a handy way to observe the progress of the control algorithms.

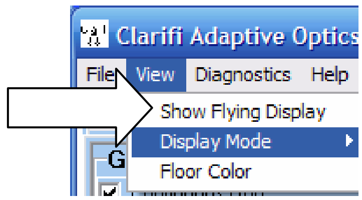


The two sections of this display are the **Beam Metric Graph**, on the left, and **The Beam Metric Meter**, on the right (the metric shown is "Round Maximum Intensity"). The heading for both the graph and the meter is the name of the currently selected metric.

- The graph will clear and start over from zero when it is **Left-Clicked**, or when the metric is changed in the Feedback Tab.
- **Right-Clicking** on either the Graph or the Meter will cause the image to be sent to the default printer.
- The Graph gives a good picture of the progress of the control. Typically, this is a great area to visually understand the magnitude of correction. In the picture above, you can see where the baseline reading was, what happened through the calibration acquisition, when the wavefront targets were zeroed, and when different targets were selected.
- The Meter gives a more precise measure of the current value of the feedback metric. Although it's hard to tell by looking at the Graph, the Meter clearly shows the Hartmann Wavefront metric to be 0.675.

Flying Display

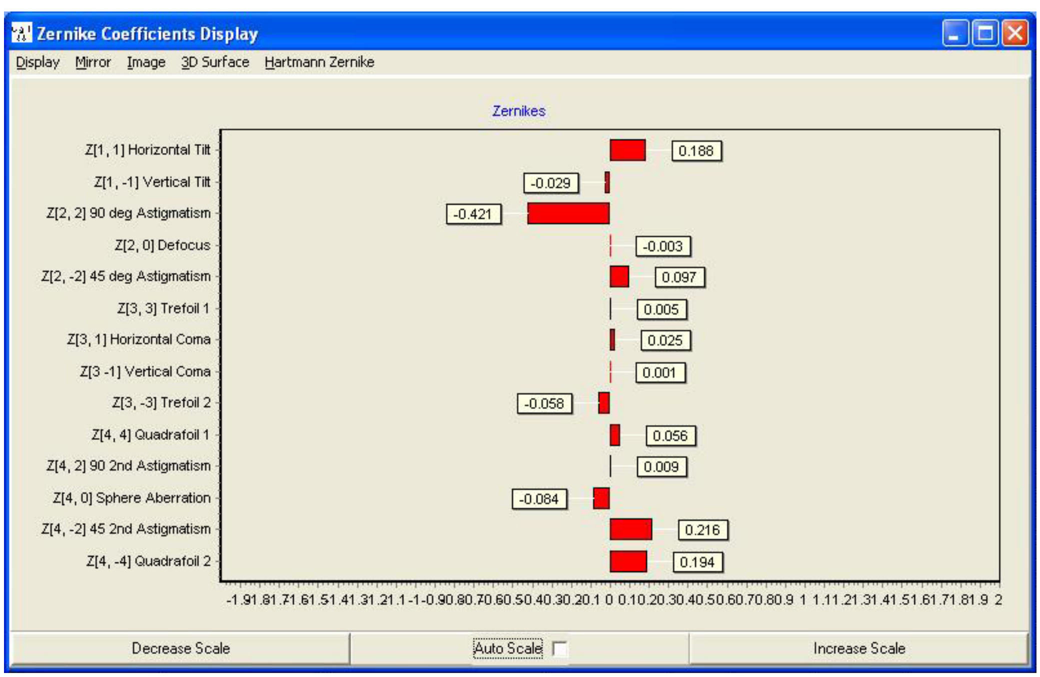
The **Flying Display** allows the user to view additional information about either the mirror or wavefront. In order to access this feature, first select View from the top tool bar then click "Show Flying Display".



Zernike Coefficients Display

The default view is the **Zernike Coefficients Display**, shown below. It can also be brought up by clicking on "Hartmann Zernike" on the far right in the tool bar.

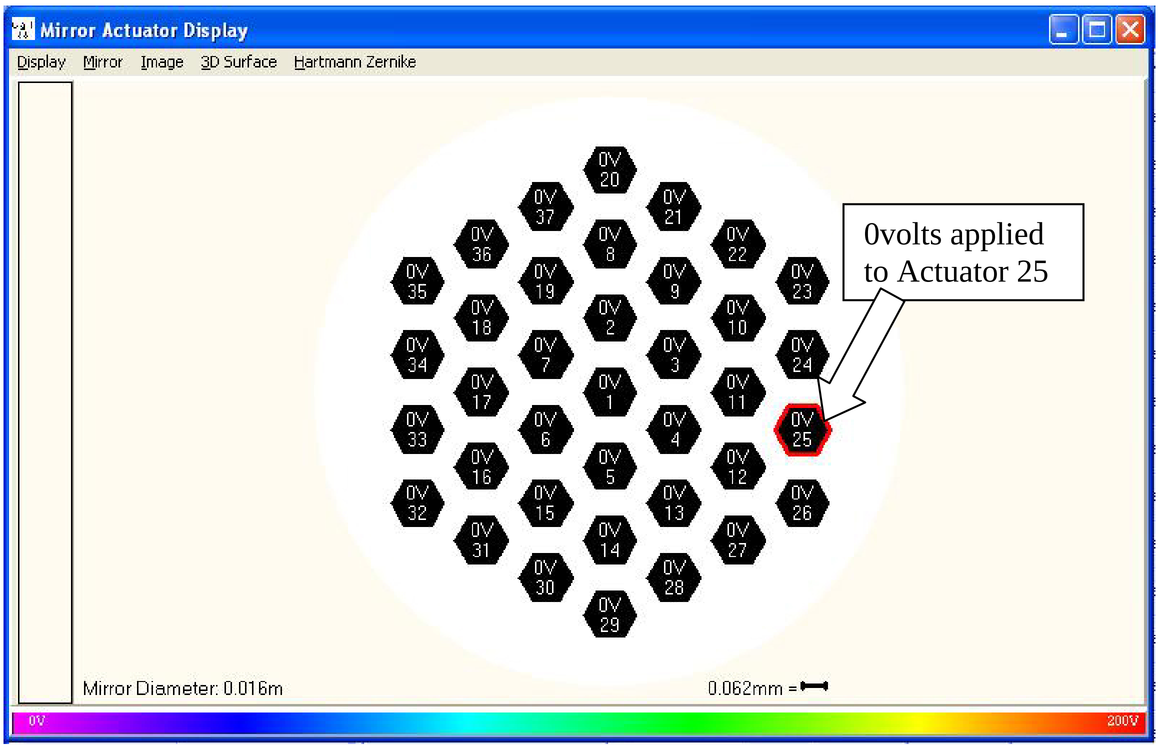
- Each bar represents one of the Zernike Aberrations, with the description of the aberration in text on the left and the value tagged next to the respective bar.
- **Decrease Scale** scales down the data so that a larger range can be viewed.
- **Auto Scale** automatically adjusts the scale to fit the largest bar on the graph. When deselected, the graph will be sized such that the largest bar covers approximately 60% of the graph.
- **Increase Scale** scales up the data such that more accuracy and detail can be seen.



Flying Display*-Mirror Actuator Display*

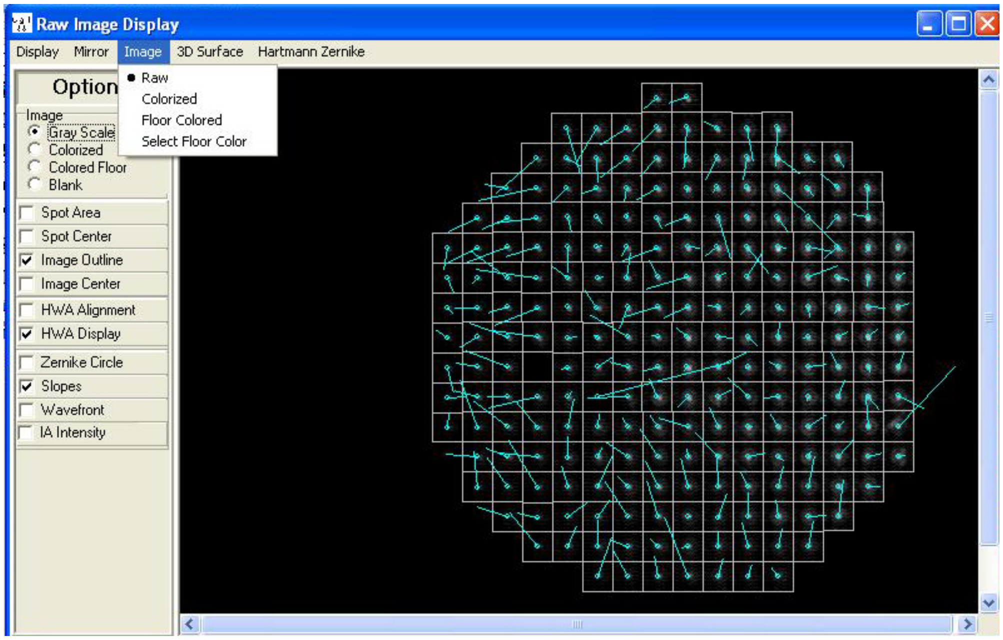
The Mirror Actuator Display allows the user to view the mirror actuators in greater detail then the Actuator Voltage Display in the primary window. This can be maximized which allows for both a better view and more detailed printing. To access this window, click on “Mirror” in the top toolbar.

- On each of the actuators, the voltage is displayed as the top number.
- The lower number is the actuator number.
- At the bottom of the window is a color scale interpreting the actuator colors into voltages. As shown, a red actuator would be 200V, a purple actuator would be 0V and a green actuator would be approximately 120V.



Flying Display *- Image Display*

The Image Display shows the data from the input device. Click on "Image" in order to bring up this display. There are several viewing options for the data, described below.



- **Raw** displays the incoming image as a black and white image exactly as it is received.
- **Colorized** applies a color scale to the pixels based on intensity.
- **Floor Colorized** allows the user to set the image background (floor) to a color other than black.
- **Select Floor Color** is where the color is selected for the preceding option.

To the left of the Image Display is a list of Options, the function of these options are explained below.

Image

- The Image radio buttons have the following effects:

1. *Gray Scale* – Displays the main image in gray-scale.
2. *Colorized* - Displays the main image in rainbow colors based on pixel intensity. Low-intensity pixels are purple, high-intensity pixels are red, and the pixels in-between range from blue to orange in rainbow color order. Zero-intensity pixels are colored black, while maximum intensity pixels are colored white.
3. *Colored Floor* – Any pixels at or below the Noise floor are colored light-blue.
4. *Blank* – Cannot be selected if no other Input Camera

options are selected. Otherwise, it removes the camera image from the background of the image, allowing all the features of the other option(s) to be seen by themselves.

Spot Area

- When HWA Display is not selected, Spot Area shows the second moment of the beam in X versus the second moment of the beam in Y. When HWA Display is selected, Spot Area shows the second moment of each beamlet in X versus the second moment of the same beamlet in Y.

Spot Center

- When HWA Display is not selected, Spot Center shows the first moment of the beam. When HWA Display is selected, Spot Center shows the first moment of each beamlet in the wavefront.

Image Outline

- When HWA Display is not selected, Image Outline draws a rectangle around the entire input beam. When HWA Display is selected, Image Outline draws a rectangle around each active integration area in the wavefront.

Image Center

- Draws two lines that intersect at the center of the image display, not the center of the beam. This assists in centering the beam at the image center during alignment of the camera.

HWA Alignment

- Draws a crosshair that, when the wavefront is aligned with the camera, should be centered on the blank integration area near the middle of the wavefront. If the crosshair is not centered on the blank integration area, the incoming beam is not aligned with the camera. Adjust the camera tip and tilt until the beam and camera are aligned.

HWA Display

- When selected, HWA Display excludes from view all integration areas outside of the unit Zernike circle of the wavefront. Three more options become available when HWA Display is selected:

1. *Zernike Circle* – Draws the unit Zernike circle around the wavefront.
2. *Slopes* – Draws the slopes for each integration area inside the unit Zernike circle. The slope starting points are centered on their integration area, with the end-point pointing the direction the beamlet is sloping in that integration area. The length of the line shows how

steep the slope is.

3. *Wavefront* – Draws the integration areas as colored squares, with the color of the square determined by how close that integration area is to a perfect wavefront. Almost perfect integration areas are purple, while mostly incorrect integration areas are red. All integration areas in between them range from blue for near-perfect to orange for high imperfections, in rainbow color order. Perfect integration areas are black, while completely imperfect integration areas are white.
4. *IA Intensity* – Show the intensity of the integration areas in a color scale, with the color of the integration area determined by the intensity with low intensity integration areas colored purple, and high intensity integration areas colored red, and the integration areas in between range from blue to orange in rainbow color order.

Each of the Image Display options has colors associated with it. To change the colors, right-click on the option. A new window will appear. This window contains the basic color choices. Left-click to choose one of the basic colors, or select Define Custom Colors to extend the colors window. The extension contains a color map, hue, saturation, and luminosity edits, red, green, and blue color edits, and a darkness slider. You can define any custom color you would like and save it as one of the 16 possible custom colors by selecting Add to Custom Colors. These custom colors can then be chosen just like normal colors. Select OK once all the colors you wanted are chosen.

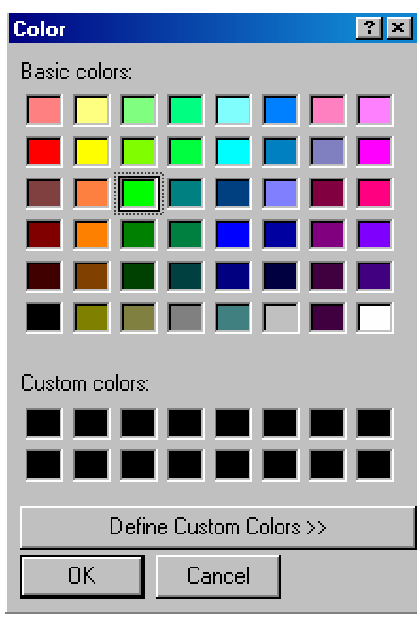


Figure 15. Basic colors screen

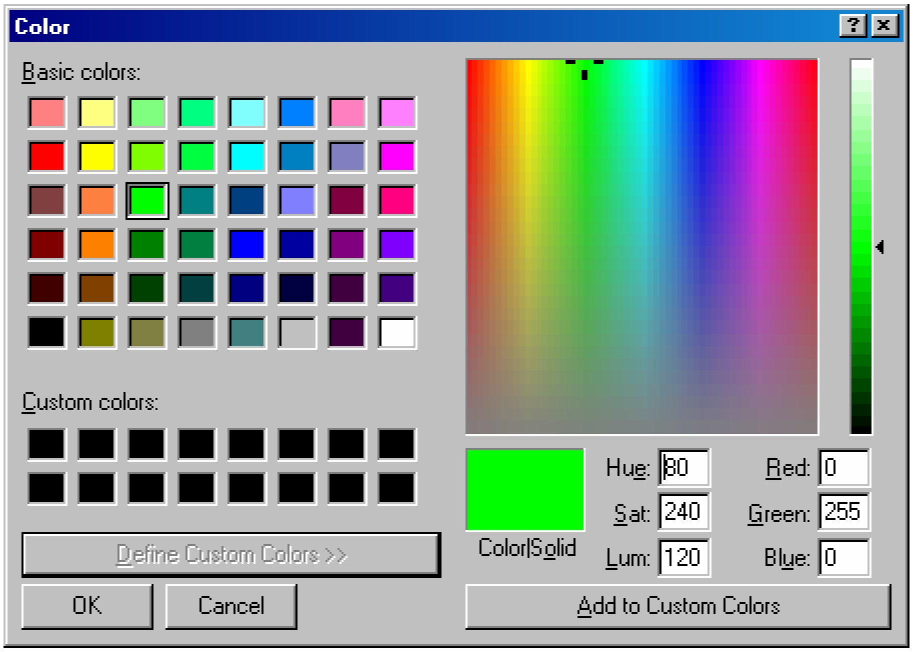
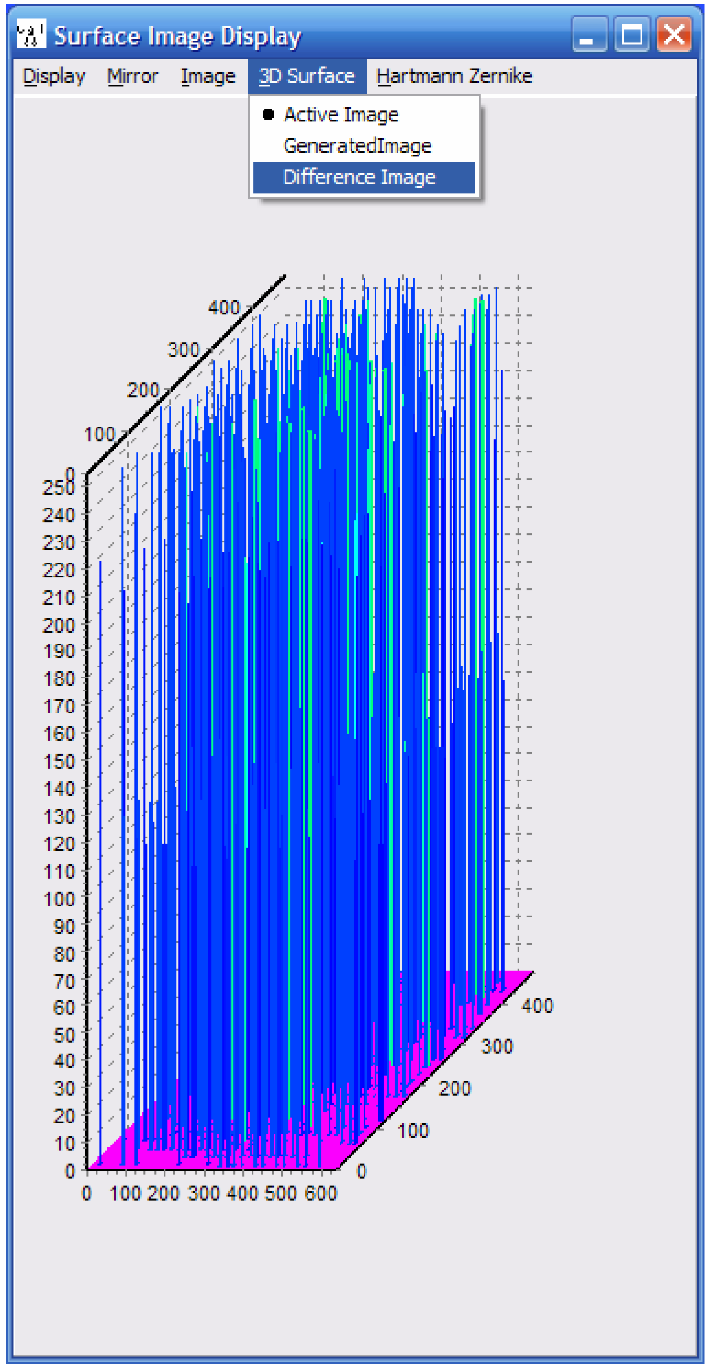


Figure 16. Custom colors screen

***Flying Display** – 3D Surface*

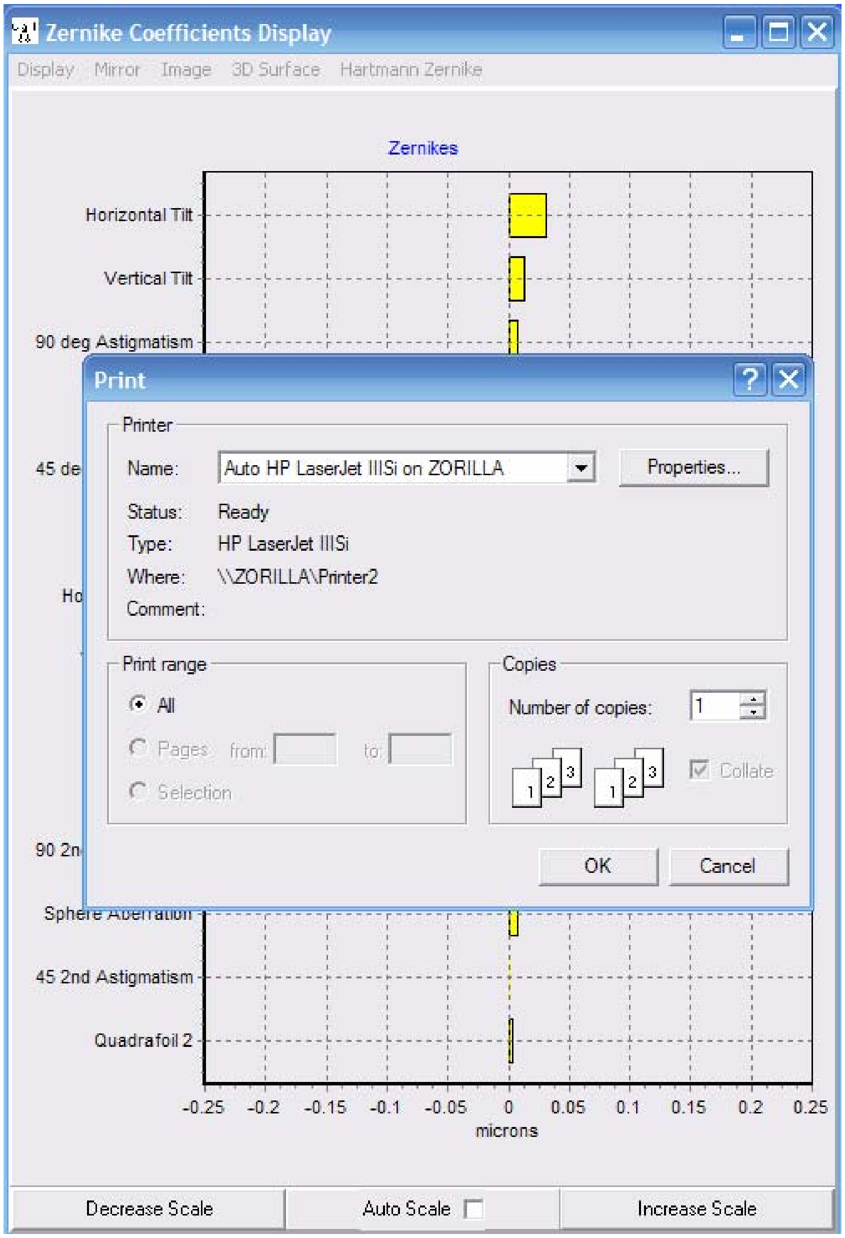
3D Surface generates a three dimensional representation of the input device data based on pixel intensity. Higher intensities are displayed as greater heights for each point on the graph. This image display option may be reached by clicking on "3D Surface" in the toolbar.

- **Active Image** is the image as it comes from the camera, a real-time 3D display of pixel intensity.
- **Generated Image** is the user defined goal image that Clarifi™ is trying to match. This option is only available if one of the statistical metrics (Gaussian, Top hat, Apodized energy or Annular) is selected.
- **Difference Image** is the difference between the user defined goal image and the current input. This option is only available if one of the statistical metrics (Gaussian, Top hat, Apodized energy or Annular) is selected.



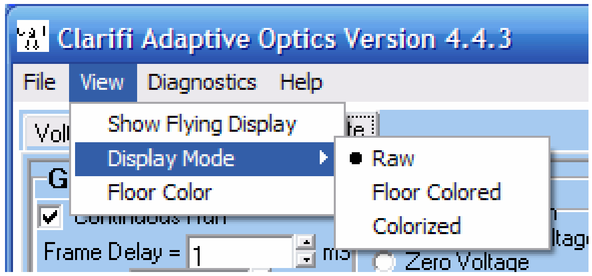
Flying Display *– Printing the Image*

Any of the images from the Flying Display may be printed by clicking on "Display"→print. The following dialogue box will be brought up, from which printing options can be selected.



***Main Window Toolbar** – View*

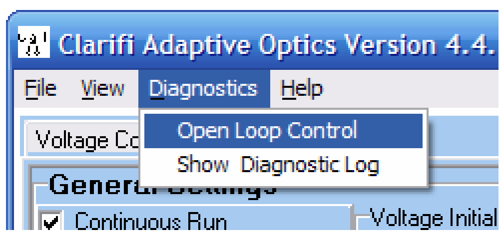
To change the viewing options of the primary window's Image Display, click on View → Display Mode. Three options are available:



- **Raw** displays the incoming image as a black and white image exactly as it is received.
- **Colorized** applies a color scale to the pixels based on intensity.
- **Floor Colorized** allows the user to set the image background (floor) to a color other than black.
- **Floor Color** is where the color is selected for the preceding option.

- *Diagnostics-Show Diagnostic Log*

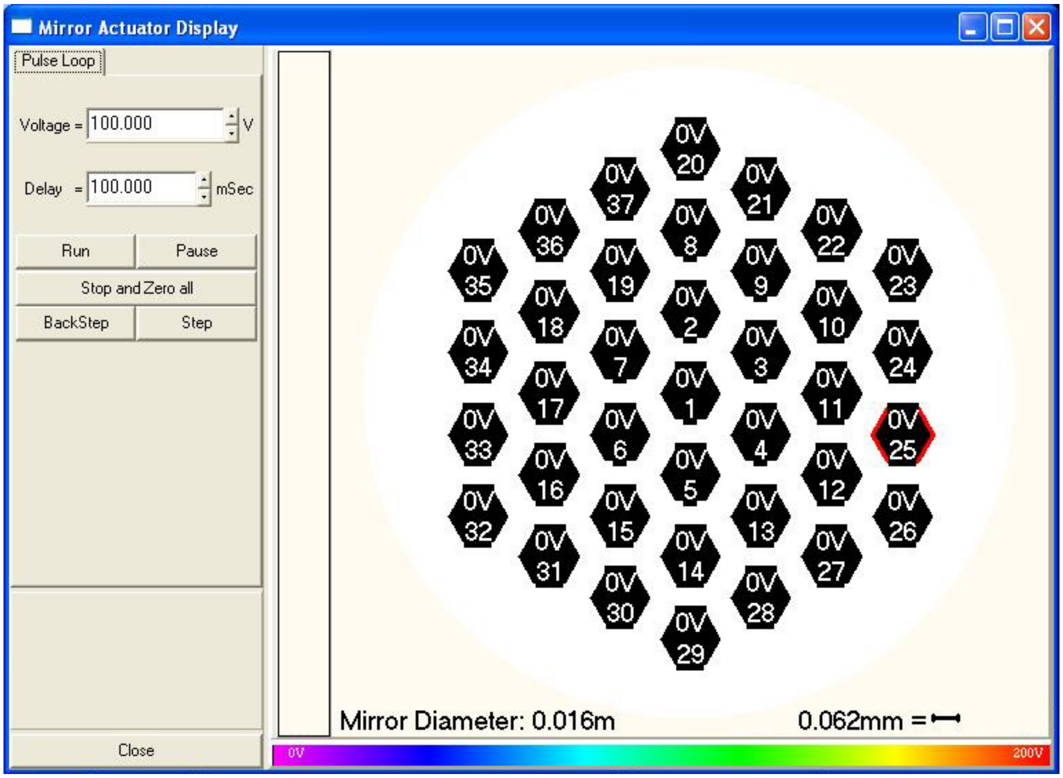
To open the Diagnostic Log, go to Diagnostics → Show Diagnostic Log.



The diagnostic log is used for system diagnosis. A sample of this window is shown below.

Main Window Toolbar *– Diagnostics*

To open the Pulse Loop Control click on Diagnostics → Open Loop Control. The Pulse Loop is an important tool for mirror testing that allows you to apply a given voltage to each actuator cyclically (one at a time, one right after the other in turn).



- **Voltage** sets the actuator voltage level to be used in the pulse loop.
- **Delay** sets the amount of time that the voltage will be applied to an actuator before moving to the next actuator. *Example: if 100mSec is selected and voltage is set to 175V, then starting with actuator one 175V will be applied to each actuator in turn for one-tenth of a second before returning to 0V and 175V being applied to the next actuator in sequence.*
- **Run** starts the pulse loop.
- **Pause** pauses the loop but leaves the voltages where they were when the user clicked this button.
- **Stop and Zero all** stops the pulse loop and returns all actuator voltages to a value of zero volts.
- **BackStep** causes the voltages to return to the position they were in one step previously in the loop.
- **Step** automatically advances the voltage pattern one position forward in the loop. Both this option and BackStep can be selected while the loop is paused to allow the user to control the loop manually.

Appendix A

Software Installation

Please Note: The software comes installed on the PC included in your Clarifi™ system. The following is for installation in another machine, or re-installation in the included PC.

1. Start Windows
2. Close all other Windows applications
3. Place the AgilOptics™ CD into your CD drive
4. Select "My Computer" from the start menu
5. Double click on the name of the CD drive containing the AgilOptics™ CD
6. Double click on "SETUP.EXE"
7. Install shield will guide you through the remainder of the installation

NOTE: After the installation, you will be required to restart your Windows before running the AgilOptics™ software.

Appendix B

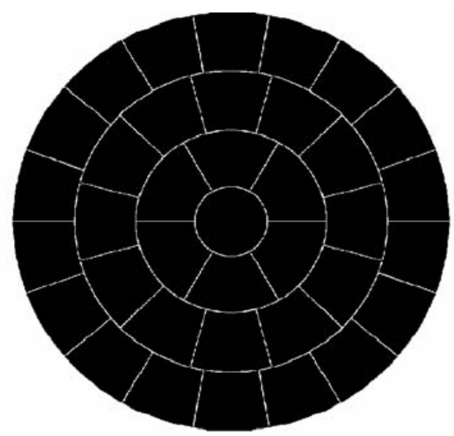
Deformable Mirrors

The deformable mirror in your Clarifi™ system consists of two primary parts: the mirror membrane and the actuator pad array. These two parts work together with the Clarifi™ control software in order to correct the optical beam projected onto them.

Diagram of a Deformable Mirror

The mirror membrane is made of silicon nitride with a reflective coating, typically an aluminum alloy, though other coatings are also available. It is exceptionally thin (~10^{-6} m) and should be handled with care. This membrane is mounted to the back of a silicon wafer frame that both supports the membrane and keeps it in tension.

The actuator pad array is mounted behind the mirror and by electrostatic attraction causes the deformation. It consists of a thin wafer with a pattern of gold pads on the surface, with small separation between these pads and mirror membrane. Each of these pads is connected to a channel of the electrical driver, so that the user can cause a voltage to be applied to each pad. These pads are arranged in specific patterns that are setup to maximize the correction of different common optical aberrations.



Sample Actuator Pad Array

When a voltage is applied to one of the gold pads of the actuator pad array, it attracts the mirror membrane at that point. By varying the amount of voltage and which pads the voltage is applied to, the surface shape can be changed. When an optical beam is reflected off of it, the beam wave front is changed with the mirror. Using control software and an optical sensor, the beam shape can be altered in specific ways to correct optical distortions caused by different parts of the optical setup. In this way, the different parts of the deformable mirror work together to restore optical clarity to a variety of optical setups.

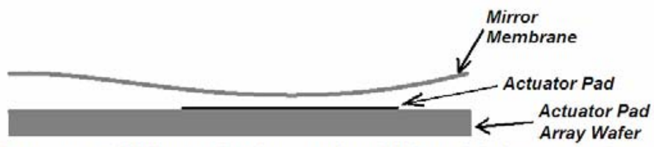


Diagram of Mirror Deformation When Voltage Is Applied

Appendix C

Aligning a Clarifi-3D™ Optical Setup

Optical alignment of the deformable mirror and wavefront sensor are of supreme importance when using Clarifi-3D™. Without the aberrated beam perfectly centered on the mirror, camera and each lens it passes through, your software may not reach the desired performance level. The following has been found through trial and error to assist in the alignment of these two critical hardware components.

In order to obtain a basic alignment on the center of the camera, please follow these steps:

- Zero the voltage on all the mirror actuators
- Set the voltage on the center actuator to the maximum
  - A bright spot should appear in the Image Display. This corresponds roughly to the position of the center actuator.
- Adjust the DM until this spot is in the center of the display.

To center the beam through the lenses, the following is recommended. For this entire operation the Zernike Coefficients Display is used for the measure of each step. Please bring up this flying display now (for more information, please see the "Flying Display" section).

- In order to manage focus, it is recommended that the optical setup have the most focus when approximately 75% of the maximum average voltage is applied to all of the actuators, which will be referred to as voltage two. Voltage one is when all actuators have zero volts applied. To create this focus, apply voltage two, and then adjust the optical system focus until the Zernike coefficient of defocus is zeroed.
- The second major point of alignment is that both the vertical and horizontal tilt ought to be the same when voltage one and voltage two are applied. Though this is an unreasonable and idealistic expectation, a reasonable approximation is that neither should vary more than one-tenth of a micron between the applications of these two voltages. In order to achieve this, the following procedure is provided.
  1. Set mirror to voltage two (75%). Zero the defocus by adjusting the optical lenses.
  2. Set mirror to voltage one (0V). Adjust the camera kinematic mount to zero vertical and horizontal tilt.
  3. Set mirror to voltage two. Adjust the deformable mirror kinematic mount to zero vertical and horizontal tilt.
  4. Set mirror to voltage one. Adjust the camera kinematic mount to zero vertical and horizontal tilt.

5. Set mirror to voltage two. Check to see the difference between the two mirror voltages.
6. Repeat steps 1-5 until the difference in horizontal and vertical tilt is each less than 0.1microns between the voltage one and voltage two.

Appendix D

Wavelength Effects on Hartmann Array Performance

By Keith Bush

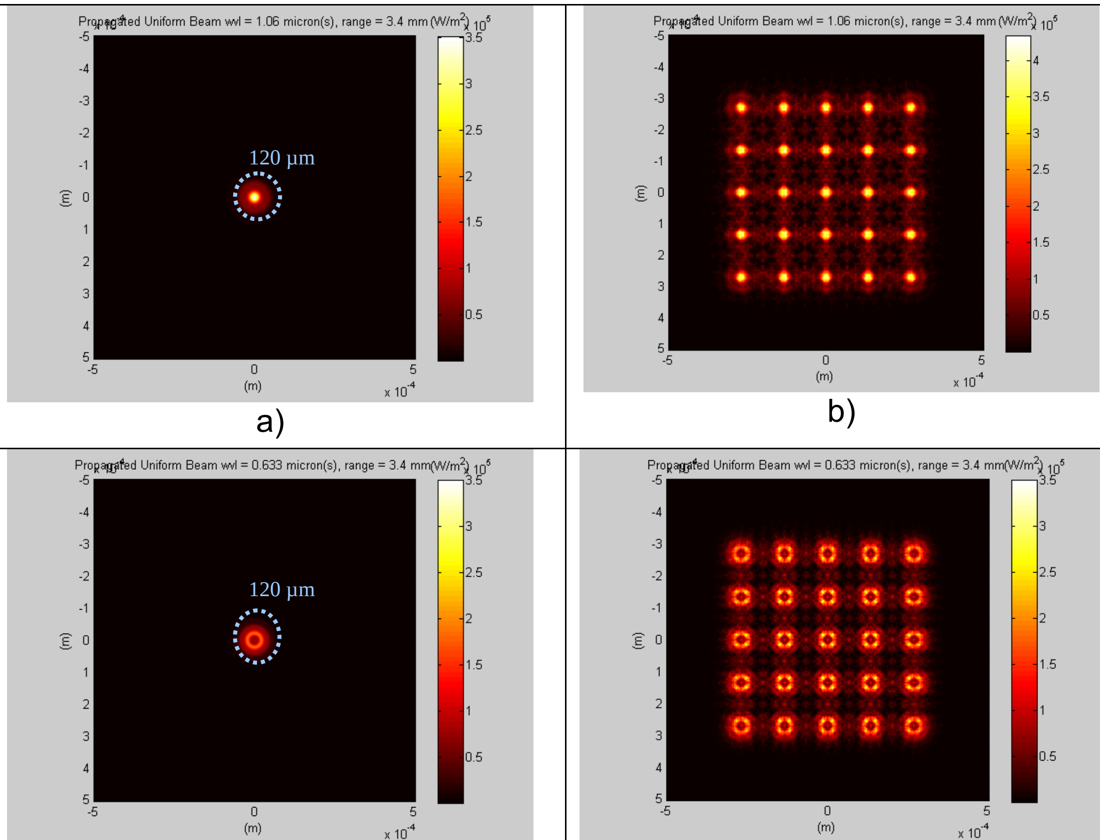
The wave-front measurement accuracy of a given Hartmann WaveFront Sensor (HWFS) design is sensitive to the wavelength of the laser light and the propagation distance to the detector array. The Hartmann array is an array of small apertures or pinholes that sample the wavefront at regular fixed locations across the laser beam incident on the HWFS.

A pinhole aperture is used as a replacement for a lens to cause the incoming beam to focus as a set of independent beamlets. The edges of the pinhole cause the beamlets' light to bend (diffract) toward the centerline axis of each beam, until a minimum diameter (focus) is reached some fixed distance after the pinhole. Since the diffraction is directly correlated to the wavelength, the performance of the Hartmann array is strictly wavelength dependent. Longer wavelengths diffract more and come to a focus sooner. Shorter wavelengths focus more gradually toward a more distant focal point. This makes the design of the HWFS a critical function of the wavelength, although some latitude in the design is usually possible. Consequently, using a HWFS designed for 633nm, for instance, at 1064nm is generally not recommended, and the sensor may not function correctly.

Ideally, the light entering each aperture is diffracted to yield a far-field spot that is incident on detector array elements. Local wavefront slope or tilt at the aperture location is calculated from the displacement of this spot from a calibrated spot position, which is the position for a flat or zero slope wavefront, on the detector array. The best accuracy of the spot displacement measurement is obtained when the spot intensity is maximized and spot size minimized so that minimum interference occurs between adjacent Hartmann array spot distributions. Diffracted spot size is a function of aperture diameter, wavelength and propagation distance. Thus, the HWFS is generally built to perform best at a specific wavelength. The following example calculations provide some insight into this HWFS design issue.

Consider a square Hartmann array having 120 micron diameter apertures separated by 134.4 microns in both the X and Y directions. The array is placed a given distance in front of a detector array with 7.4 micron square pixels. Using wave optics propagation simulation the effects of wavelength, propagation distance and beam interference can be simulated for this particular Hartmann array. The blue-dotted ring depicts the outline of the 120 micron pinhole. Note that the focal spot is considerably smaller than the projected diameter of the pinhole.

Figure 15 shows the single aperture and multiple aperture diffraction spots obtained at a propagation distance of 3.4 mm when 1064 nm and 633 nm wavelengths are used. At this distance, the 1064 nm wavelength is optimized to give a small spot with minimal interference between adjacent apertures. The 633 nm wavelength has a larger spot with a null on-axis and considerable interference is seen between adjacent spots. Good spot displacement measurements should occur at 1064 nm for this propagation distance.



a) b) c) d)

Figure 15. Single and multiple aperture spots for 3.4 mm propagation distance a) & b) 1064 nm wavelength, c) & d) 633 nm wavelength

As the propagation distance is increased to 4.25 mm the results shown in Figure 16 are obtained. Now the 633 nm spots have decreased in size and have a peak on axis. The 1064 nm spots are still relatively small and have some lower intensity secondary interference peaks. This propagation distance may be a good compromise distance to obtain reasonable spot displacement measurements at both wavelengths. However, it is not optimum for either wavelength.

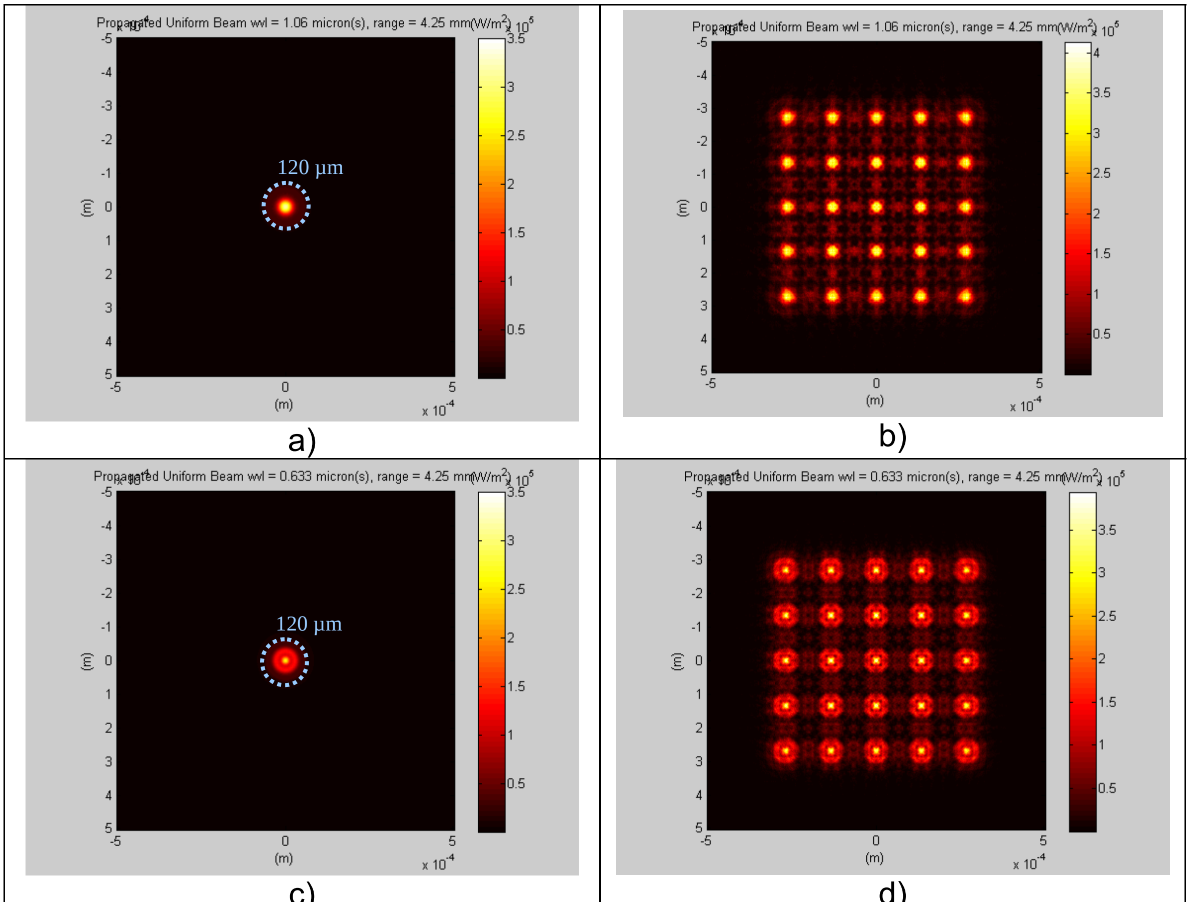


Figure 16. Single and multiple aperture spots for 4.25 mm propagation distance a) & b) 1064 nm wavelength, c) & d) 633 nm wavelength

The 633 nm wavelength is optimized at a 5.7 mm propagation distance as shown in Figure 17. In fact, the single and multiple aperture spots at 633 nm are identical to those obtained for 1064 nm at the 3.4 mm distance (by the ratio of the wavelengths!). The 1064 nm spots shown in Figure 3 are considerably larger than at shorter distances and exhibit significant interference peaks between adjacent apertures. Thus, with the Hartmann array at 5.7 mm distance from the detector array the 633 nm wavelength is expected to give the best spot displacement measurements.

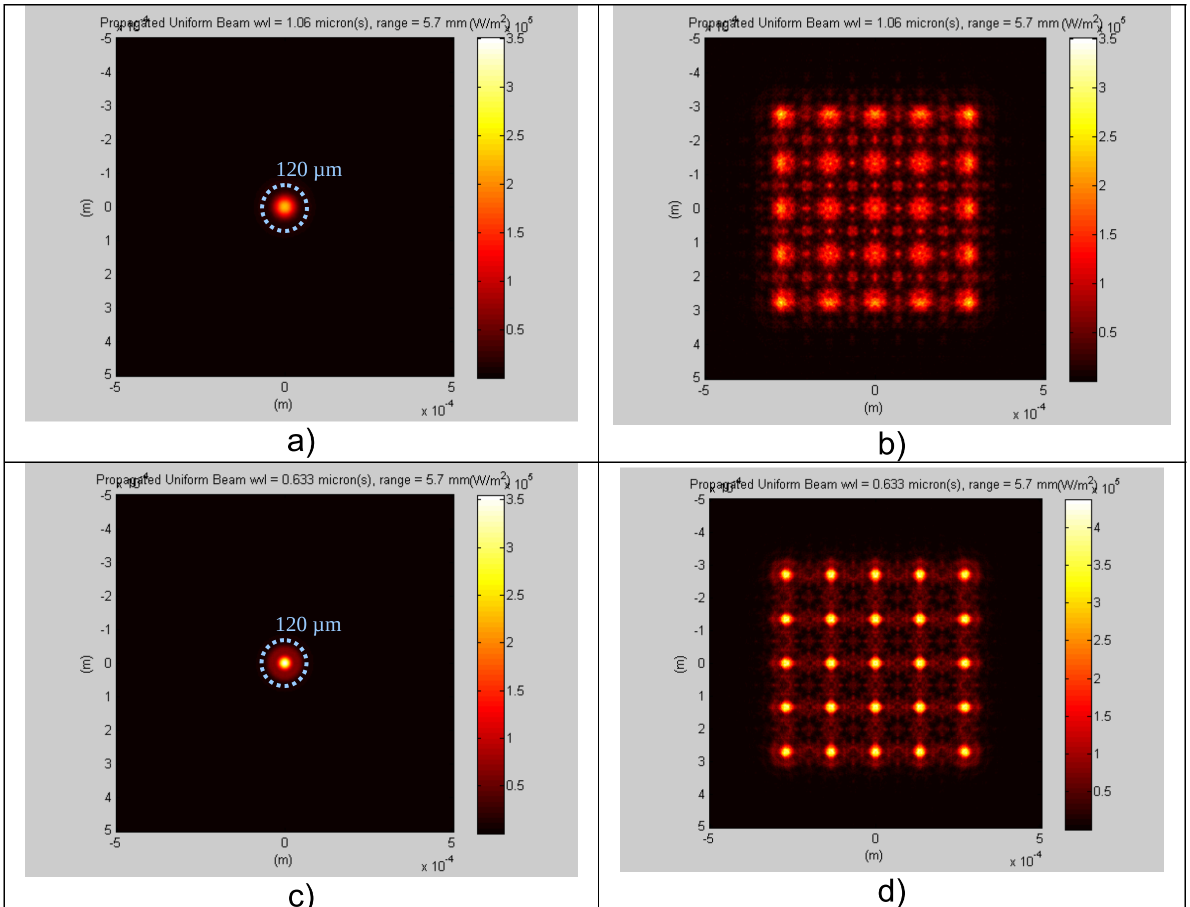


Figure 17. Single and multiple aperture spots for 5.7 mm propagation distance a) & b) 1064 nm wavelength, c) & d) 633 nm wavelength

The most efficient HWFS system is designed to maximize the focus of the beamlets at the plane of the camera, and minimize the diffractive interference between adjacent pinholes which causes confusion by producing ghost spots on the focal plane camera. Fortunately, the best focus of the individual spots corresponds to the same distance where the diffractive effects are minimized, because the light energy is concentrated on-axis and is not available to create diffractive effects off-axis.