

User Guide

BEAMSQUARED®

BEAM PROPAGATION ANALYZER

FOR WINDOWS 10® AND WINDOWS 11®





Dear Customer,

Thank you for your recent purchase of the BeamSquared system.

We strive to provide the highest level of leading-edge photonic measurement technology and service possible. We hope that your experience with us is a pleasant one and anticipate the relationship we build will serve your photonic measurement needs for years to come.

As a valued customer, your comments and opinions are always very important to us. If you have any concerns, questions, or comments, bring them to our service department's attention. We are ready to help with everything from basic setup to working with you to find solutions for your most complex photonics measurement needs.

Please let us know if there is any way we can be of service. Thank you once again for your business.

Sincerely,

Ophir USA

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How to Use this Guide

It is recommended that users review this guide before setting up and using the BeamSquared system. This guide will assist users in becoming familiar with the M^2 measurement theory as well as acquire a basic understanding of the BeamSquared operation. Furthermore, familiarity with this guide will aid the user with system alignment and interpretation of M^2 results.

BeamSquared Measurements are based on beam propagation theory and employ ISO measurement standards. **Users who are unfamiliar with beam propagation theory** or those who wish to have a refresher on these concepts **please review Chapters 5 and 6.**

Chapter 1 General Information – Contains safety warnings, technical information, and specifications for hardware and software.

Chapter 2 Setup – Contains information on how to setup the BeamSquared hardware and software.

Chapter 3 Operating Controls and User Interface – Describes the controls and displays within the BeamSquared software. It is recommended to become familiar with these and their meaning before attempting to operate the BeamSquared system.

Chapter 4 Operation – Details the operating modes and how to use the BeamSquared System.

Chapter 5 M^2 Theory and Tutorial – Presents a tutorial on M^2 theory, practical insights behind the propagation measurements and the ISO measurement methods, and a description of the features in the BeamSquared software.

Chapter 6 M^2 Computations – Contains computational information on how M^2 is calculated.

Chapter 7 Troubleshooting – Contains troubleshooting tips and how to respond to error messages.

Chapter 8 BeamSquared Automation Interface – Provides details of the BeamSquared Automation Server properties, methods, and events.

Chapter 9 Manual M^2 Measurements – Presents set up instructions and details the manual mode operation.

Appendix A Lens Calibration Adjustments – Contains lens wavelength correction information for Plano-convex lenses.

Appendix B Warranty – Contains warranty information.

Appendix C BeamSquared Supported Cameras – Contains a list of cameras supported by BeamSquared with links to the camera specifications.

Appendix D Camera Information – Contains camera-specific controls and features.

Symbol Notation



Indicates general information that poses no risk.



Indicates important information about the product with little or no risk.



Indicates warning information. Failure to follow instruction may result in harm to the user or product damage.



Indicates that the instruction refers to operating BeamSquared in Manual Mode.

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Chapter 1 General Information

1.1 Safety

Optical Radiation Hazards



Use of this instrument requires the operator to work near the optical path of lasers. Exposure to radiation from these lasers may be sufficient to warrant the use of protective equipment.

Unless the laser's optical path is enclosed, the operator should protect against accidental exposure. Exposure to personnel other than the operator must also be considered. Hazards include direct beam exposure and reflected radiation.

When working with an unenclosed beam path, it is advisable to do so while the laser is powered down or at reduced power levels. Whenever there is a risk for dangerous exposure, protective eye shields and clothing should be worn.

1.1.1 BeamSquared® Model Numbers

All standard BeamSquared models are sold without a computer, or external optical accessories. An accessory model of BeamSquared is available for purchase that allows operation with an existing SP204S, SP920, SP1203, or XC-130 camera.

1.1.2 BeamSquared Manual Mode Models

The Manual Mode System requires the end user to provide a manually operated system (see Chapter 9). The optical train must include a focusing element, a means to translate the camera behind the focusing element, a laser beam attenuation system, and a way to block the beam from reaching the camera sensor during calibration. Accurate results depend on a well-designed optical system. The user has full responsibility for the system performance.

Part Number	Model Number	Description
SP90410	BSQ-PY-M	Pyrocam™ license for BeamSquared software.

1.1.3 Automated BeamSquared Models

Part Number	Model Number	Description
SP90630	BSQ-SP204S	SP204S camera and license with BeamSquared hardware.
SP90502	BSQ-SP920	SP920 camera and license with BeamSquared hardware.
SP90444	BSQ-XC130	XC-130 camera and license with BeamSquared hardware.
SP90445	BSQ-A	BeamSquared hardware accessory model, sold without a camera, for customers that already own a compatible camera system.
SP90644 SP90645	BSQ-SP1203	SP1203 camera and license with BeamSquared hardware. (both part numbers must be ordered for a complete system)

Standard Optics

Different lenses are required for different wavelength regions, spot sizes, and divergences. Four lenses are included with the SP204S system, five lenses with the SP920 system, and two lenses with the XC-130 & SP1203 systems. See below for nominal focal lengths. Additional lenses must be ordered separately.

Model	Lens
BSQ-SP204S	<ul style="list-style-type: none">• 266-440nm UV 500mm FL• 430-700nm VIS 500mm FL• 650-1000nm NIR 400mm FL• 1000-1550nm NIR extended 600mm FL*

BSQ-SP920	<ul style="list-style-type: none"> • 266-440nm UV 500mm FL • 430-700nm VIS 500mm FL • 430-700nm VIS 400mm FL • 650-1000nm NIR 400mm FL • 1000-1550nm NIR extended 400mm FL*
BSQ-XC130 BSQ-SP1203	<ul style="list-style-type: none"> • 650-1000nm NIR 400mm FL • 1000-1700nm NIR extended 400mm FL
BSQ-A	<ul style="list-style-type: none"> • 266-440nm UV 500mm FL • 430-700nm VIS 500mm FL • 430-700nm VIS 400mm FL • 650-1000nm NIR 400mm FL • 1000-1550nm NIR extended 400mm FL*
BeamSquared Pro	<ul style="list-style-type: none"> • 266-440nm UV 750 mm FL • 430-700nm UV 1000 mm FL • 430-700nm VIS 500mm FL • 1000-1700nm Extended NIR 600mm FL*

* The SP204S and SP920 cameras are only sensitive between 266-1100nm.

Optional Lenses		
SP98009	BSQ-Lens Kit UV-XNIR	266-440nm UV 500mm FL 430-700nm VIS 500mm FL 650-1000nm NIR 400mm FL 1000-1550nm NIR extended 600mm FL*
SP90449	BSQ-Lens Kit 266-1550	266-440nm UV 500mm FL 430-700nm VIS 500mm FL 430-700nm VIS 400mm FL 650-1000nm NIR 400mm FL 1000-1550nm NIR extended 400mm FL*
SP90450	BSQ-Lens Kit 650-1700	650-1000nm NIR 400mm FL 1000-1700nm NIR extended 400mm FL
SP90451	BSQ-Lens UV 500mm	266-440nm UV 500mm FL
SP90452	BSQ-Lens VIS 500mm	430-700nm VIS 500mm FL
SP90453	BSQ-Lens VIS 400mm	430-700nm VIS 400mm FL
SP90454	BSQ-Lens NIR 400mm	650-1000nm NIR 400mm FL
SP90455	BSQ-Lens XNIR 400mm	1000-1550nm NIR extended 400mm FL
SP90485	BSQ-Lens XNIR 600mm	1000-1550nm NIR extended 600mm FL

SP90554	BSQ-Lens UV 750mm	245-440nm UV 750mm FL
SP90555	BSQ-Lens VIS 750mm	430-700nm VIS 750mm FL
SP90556	BSQ-Lens NIR 750mm	650-1000nm NIR 750mm FL
SP90557	BSQ-Lens XNIR 750mm	1000-1550nm NIR extended 750mm FL
SP90558	BSQ-Lens UV 1000mm	245-440nm UV 1000mm FL
SP90559	BSQ-Lens VIS 1000mm	430-700nm VIS 1000mm FL

* The SP204S and SP920 cameras are only sensitive between 266-1100nm.



Additional lenses for the BeamSquared Pro can be made available by request. Please reach out to your MKS Ophir Sales Representative for more information.

1.2 Specifications

Environmental	
Storage Temperature	-30°C to 65°C
Storage Humidity	90% maximum (non-condensing)
Operating Temperature	10°C to 40°C
Operating Humidity	90% maximum (non-condensing)

Power Requirements*	
Input Voltage	90 – 264 V AC
AC Line Current	1.6 A
Line Frequency	47Hz to 63Hz
Output Voltage	24V DC @ 5 A
Output Power	120 W

* For the optical train only. The PC computer supplies the power for the system components and the SP204S and SP920 camera. The SP1203 & XC-130 cameras have a separate power supplies.

Physical	
Weight	26 lbs. (without camera)

Attenuation	
Attenuation Range	Nominally from ND 1.0 to ND 4.8. Actual values vary with wavelength.

Optical Limits	
Wavelength Range	266-1700nm limited by camera.
	The Silicon cameras are operational from 266nm to 1100nm. InGaAs camera operates from 900nm to 1700nm.
Beam Size	BeamSquared Auto Mode 1mm – 10mm.
	BeamSquared Manual Mode 1mm – 20mm.
	Varies with wavelength, waist size, location, and M ² . See section 5.4.3.

Damage Limits	
Silicon Camera*	.15 mW/cm ² CW mode
	1.0 μJ/cm ² pulse mode
	Both of the above for an M ² =1 @ 1064nm



** WARNING! Silicon cameras can be damaged by power in excess of .15 mW/cm² or energy in excess of 1 μJ/cm². BeamSquared employs a focusing optic. While it may be that the laser input power or energy density measures well below this damage threshold, it can easily exceed these levels when focused onto the camera sensor. Use caution and err on the side of safety. Cameras are costly to repair or replace.*

General	
Accuracy	±5% typical (Note: Accuracy can be degraded by a variety of situations, consult text.)
Measurement Cycle Time	< 1 minute typical, depending on setup conditions and operating mode.
Camera Attachment	Standard C-mount, 90° camera on axis rotation
Translation System	Step motor-driven ball screw
Translation Stage Resolution	.05mm

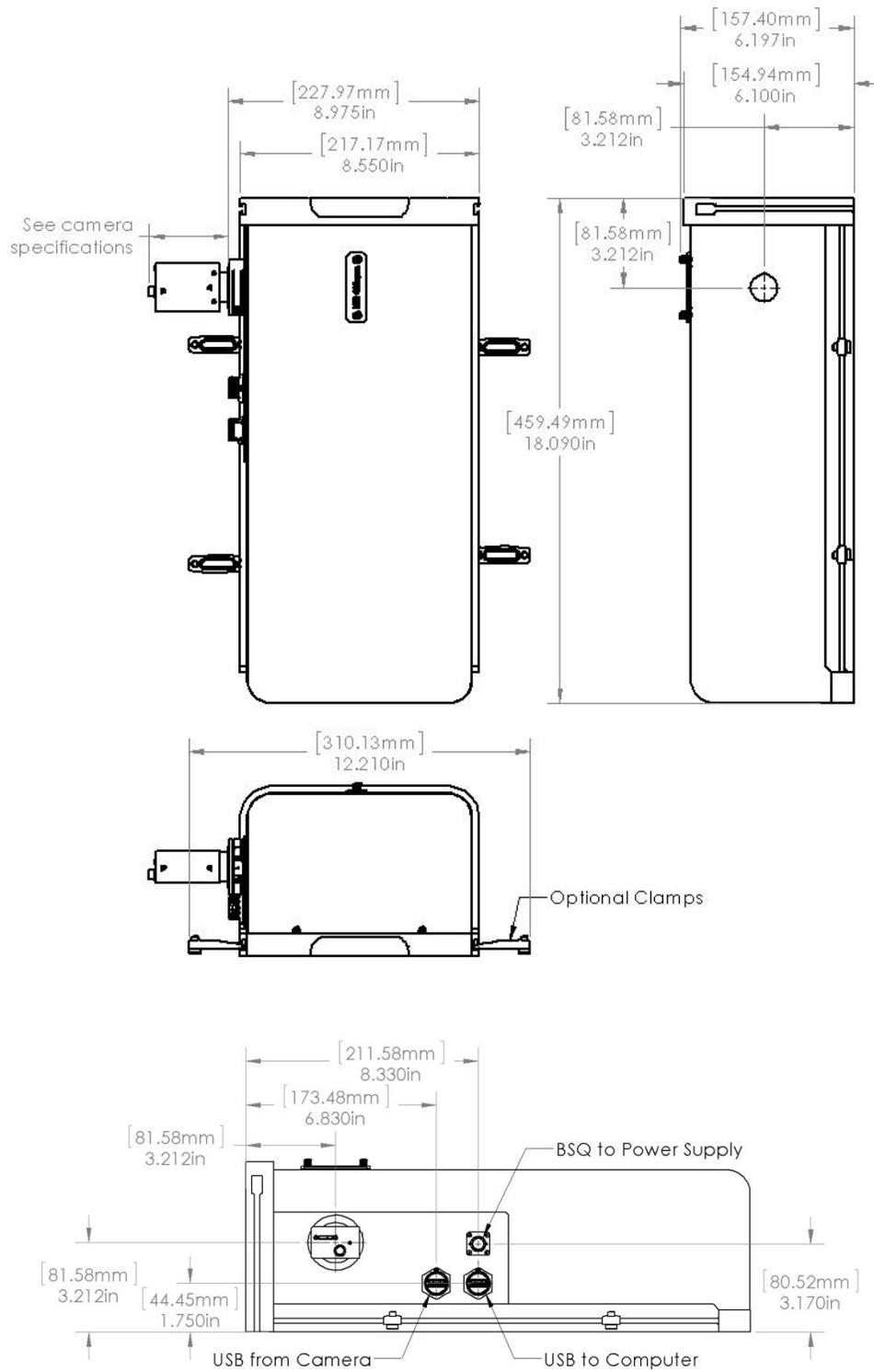


Refer to the Pyrocam user guide or the Ophir® website for camera specific specifications.



The following descriptions assume operations in Auto mode. Instructions that are specific to operating in Manual mode are indicated by a  symbol.

1.3 BeamSquared Optical Train Dimensions



1.4 Software Information

BeamSquared is designed to measure the propagation characteristics of UV, VIS, NIR, and extended NIR laser beams. For questions related to BeamSquared or compatible accessories, contact Ophir's service department (service.ophir.usa@mksinst.com).



Manual users can also measure THz laser beams in manual mode with a Pyrocam IV or IIIHR.



If you are using a camera that was purchased with a BeamGage® system, the camera should be returned to the factory to determine if it is suitable for automated beam propagation measurements.

BeamSquared measures propagation characteristics in both the X and Y axes and displays the following parameters:

- Waist diameters
- Full angle divergences
- Waist locations
- Rayleigh lengths
- M^2 or K and BPP factor
- Astigmatism
- Asymmetry

BeamSquared employs Ultracal™ to achieve the highest possible measurement accuracy.

Automated BeamSquared Required Equipment:

- A PC computer running Windows 10 or Windows 11
- BeamSquared hardware
- A SP204S, SP920, SP1203 or XC-130 camera
- A laser beam attenuation device

Automated BeamSquared Optional accessories:

- One pair of beam steering mirrors

Manual BeamSquared Required Equipment:



- A PC computer running Windows 10 or Windows 11
- A Pyrocam™ IV or IIIHR camera
- A beam-focusing element with known focal length
- A laser beam attenuation device
- A beam block to shield the camera during calibration
- An optical rail or other means of accurately positioning the camera in relation to the focusing element

PC Specifications

- A personal computer running Windows 10 or Windows 11 64-bit operating system.
- For best performance:
 - Graphics card with 1GB dedicated memory or Intel Processor Graphics Core i5 or better
 - At least 8GB of main memory
 - At least 50GB of hard disk space available
 - A high-resolution color monitor, 1920x1080 minimum recommended

1.5 BeamSquared Pro (Premium Optional Upgrade)

Introduced with the 3.0 release of the BeamSquared software application, a "Pro" Mode is introduced to enhance the already premiere laser measurements BeamSquared provides. This increased accuracy is the result of improved optical components and calibration.



Users with the standard BeamSquared offering can reach out to your MKS Ophir Sales Representative for information on upgrading to BeamSquare Pro.

BeamSquared Pro lenses are precision calibrated. The manufacturer specified focal length (accuracy $\pm 1\%$) is calibrated against master lenses that have been rigorously measured with an interferometer. The result is an accuracy ± 0.1 greatly reducing the chance for error.

Optical components are held to tighter specs and the remaining slight aberrations in the internal optics have been measured and corrected for. These corrections are specific to the camera and lenses with which the device is calibrated so the corrections are only applied when these lenses and camera are present.

Chapter 2 Setup

2.1 Equipment

The following components are found in your BeamSquared system:



BeamSquared System Components

1. BeamSquared M² Measurement System
2. BeamSquared Lens Kit
3. T-handle 7/64" Hex Wrench
4. TTL Camera Trigger Cable
5. Optional Use Leveling Feet (4)
6. AC-DC 24V 5A Adapter
7. Camera Certificates
8. Laser Profiling Grade Camera
9. Base Clamps (4)
10. USB-A 3.0 to USB-A 3.0 IP68 Cable
11. USB-A 3.0 to USB 3.0 Micro Cable
12. Gunsight Beam Alignment Tool

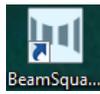
2.2 BeamSquared Software Installation

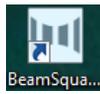
All installations must be performed with Administrator privileges.

1. Navigate to the Ophir software download page:
 - a. <https://www.ophiropt.com/en/g/software-download>
2. Select the BeamSquared software package to start the download.
3. Extract the contents of the zip folder to a local destination on the PC.
 - a. Do not extract the files to a network location as this may cause the installation to not execute properly.
4. Open the extracted folder and select the file "BeamSquared.Setup.exe"
5. Follow the directions on screen.



Ophir no longer verifies or certifies operation on Windows 7 machines.



The BeamSquared icon  appears on the desktop after installation completes.

2.3 Prepare the BeamSquared for Operation



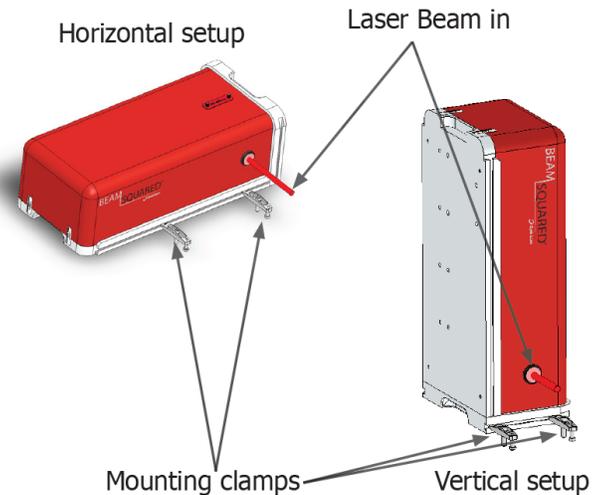
This section covers installation for the BeamSquared hardware. For manual mode installation see Chapter 9.

2.3.1 Mount the Optical Train



The optical train can be mounted either vertically or horizontally depending on the system needs.

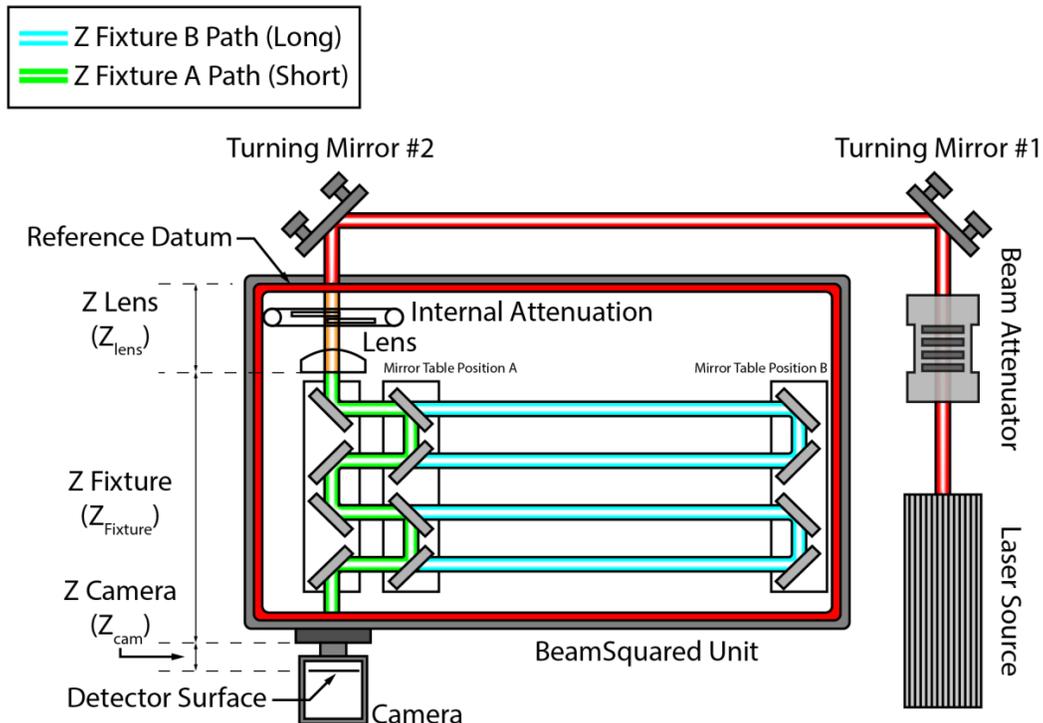
1. Place the input aperture on the same plane as the laser beam.
2. Allow enough space around the BeamSquared hardware to direct the laser beam through the input aperture.
3. Secure the optical train to the optical table with the provided mounting clamps.



An example of a typical setup can be seen below. The turning mirrors shown are optional accessories that are critical to alignment.



The center of the input aperture is 3.212" (81.58mm) high when mounted in either orientation.



2.3.2 Install the Camera

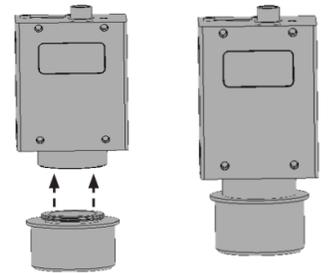


The camera imager is windowless and can be easily damaged if it comes in contact with any foreign objects. Only clean the camera imager by gently blowing on it with clean dry air or nitrogen.

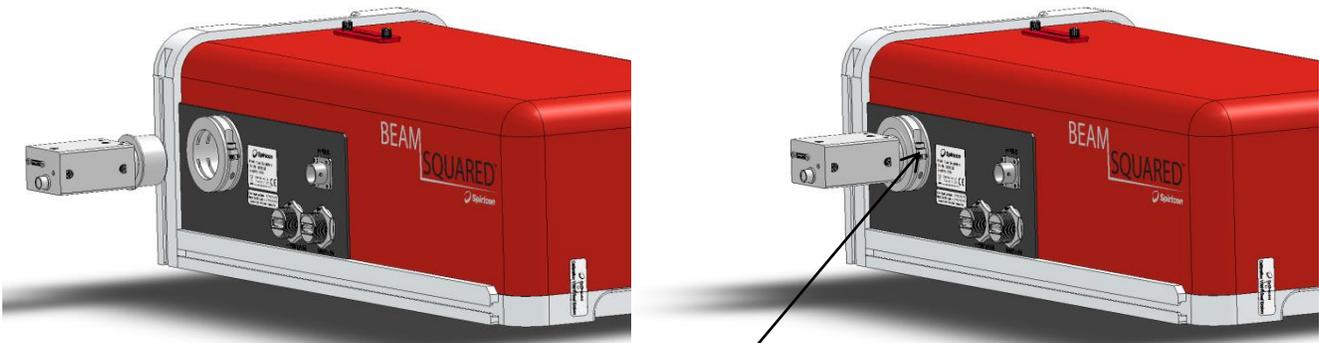
1. Remove the C-mount threaded insert from the camera mounting clamp.
2. Point the camera to the floor and remove the protective dust cover.
3. Thread the C-mount insert into the camera. Take care not to cross thread the components.



Keep the camera face down as you attach the threaded insert to prevent dust from contacting the imager.



4. Insert the camera completely into the optical train and re-secure the screw on the camera mounting clamp.



Re-secure the screw to hold the camera in place on the optical train.



For standard operation, orientation of the camera is not critical at this point and will be covered more in section 2.5.4.

Specific camera information can be found in Appendix C.

2.3.2.1 Camera Alignment for Pro Mode



Operation in BeamSquared ProMode requires a BeamSquared Pro compatible device and lens(es). See Section 1.5 BeamSquared Pro (Premium Optional Upgrade).



The camera must be properly oriented with respect to the BeamSquared device in order for calculations to be valid. It is the users responsibility to ensure that the camera is properly oriented.

In either vertical or horizontal operation, the camera must be installed with the USB cable parallel to the base as if it were horizontal.



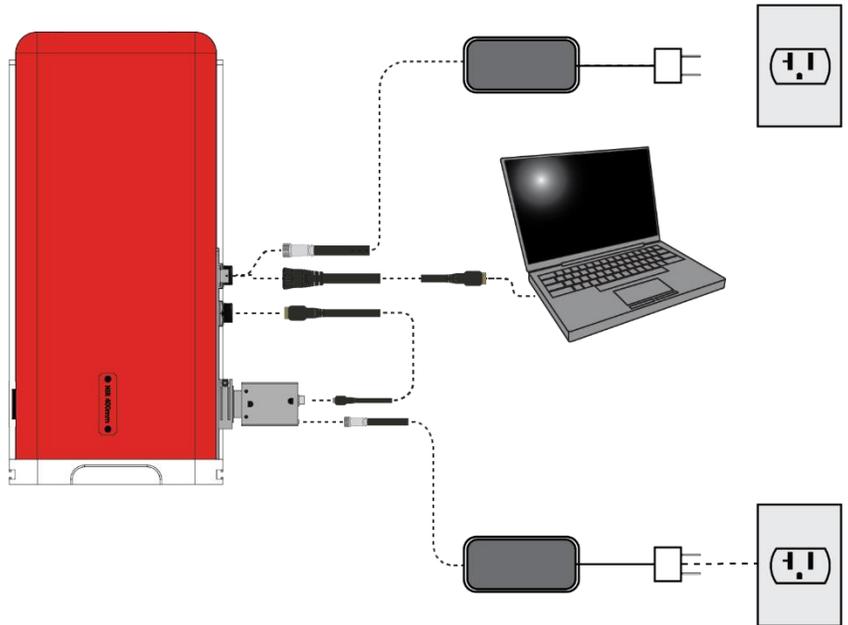


In this orientation, measurements of the laser properties are reported with respect to the axes of the BSQ device, as if it were in the horizontal position.

If the device is installed in the vertical position, the measured x axis would follow the vertical path of the BeamSquared device.

2.3.3 Connect BeamSquared

1. Connect the USB cable on the BeamSquared to an available USB 3.0 port on your PC.
2. Connect the short USB cable from the Camera directly to the BeamSquared Unit. (Connect the Camera Power Supply if applicable.)
3. Plug the BeamSquared power supply into a grounded A/C outlet.
4. When BeamSquared is connected for the first time, a Found New Hardware message appears. Wait for a notice of successful completion. If Windows reports a failure to install a driver, see Chapter 7.
5. Launch the BeamSquared software by double-clicking the BeamSquared icon or launch from the Windows Start button.
6. When the optical train initializes, the translation table and attenuator cycle the entire range of motion, confirming the table and attenuator are fully operational, and then sets them to the home locations.



Only connect one BeamSquared device at a time. If multiple devices are connected to a single PC, the camera or other components may not connect correctly.



The M²-200 and M²-200s required loading a configuration file specific to the wavelength, lens, and camera in use. This data is now preprogrammed into each unit and the system employs the stored calibration information as needed.



Do not align the laser through the BeamSquared until the beam has been properly attenuated per section 2.4. Setting an unattenuated beam through the BeamSquared may damage the optics.

2.4 External Attenuation of the Beam



Avoid eye or skin exposure to direct or scattered radiation!



Before allowing laser energy to enter the instrument, it is important to limit the beam intensity. Excessive laser energy may cause damage to the camera or the internal components of the BeamSquared hardware.

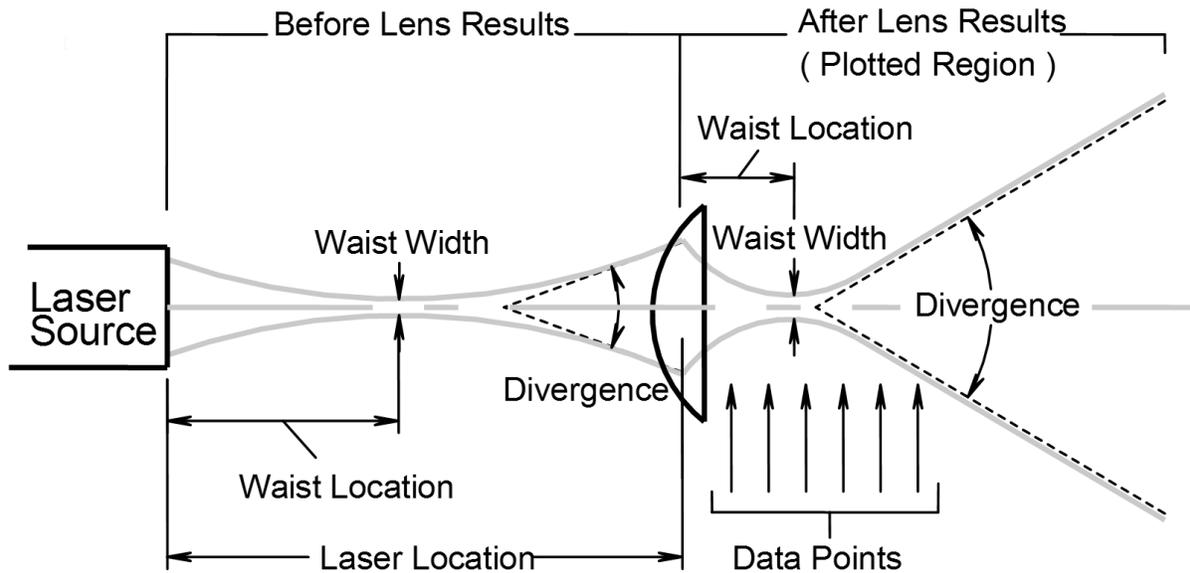
A Silicon camera imager is subject to damage at energy levels in excess of **1 μ J/cm²** or at average power levels greater than **.15mW/cm²**.

Beam splitters and/or filters may be used to attenuate the beam, but care must be used to prevent the introduction of distortions.

The peak energy density that reaches the camera changes, potentially over several orders of magnitude, during a measurement cycle. This is a result of the camera effectively moving from a large unfocused spot near the lens, into and through the focus at the waist then out again to an unfocused spot (see diagram below). During a regular run, the optical train automatically adjusts to accommodate these changes in beam intensity, so long as the user has prudently selected the intensity of the input beam. **It is the user's responsibility to properly attenuate the laser to operate within the safe dynamic range of the BeamSquared system.**



The internal attenuation is intended to compensate for changes in energy density as the beam is focused. Use caution to attenuate the beam sufficiently before presenting it to the BeamSquared device.



2.4.1 Attenuation

Distortions caused by insufficient or improper attenuation may be the largest source of error when measuring beam propagation characteristics of high-power lasers.

2.4.1.1 Beams < 1 Watt

Beams with very low power sources can be attenuated with Neutral Density (ND) filters. However, power densities that exceed $5\text{W}/\text{cm}^2$ can cause thermal lensing in the dark glass filter optic, distorting the beam. Front surface beam splitter(s) should be used to sample beams with power density exceeding $5\text{W}/\text{cm}^2$. Exceeding power density levels can also distort the beam. Distortion can occur at power densities as low as $5\text{W}/\text{cm}^2$.

2.4.1.2 Beams < 400 Watts

Beams with power from 1 to 400 Watts may be safely sampled with our LBS-300s family of beam attenuation products. The LBS-300s is available for UV, Visible, and NIR lasers.

2.4.1.3 Beams < 2000 Watts

Beams with power from 400 to 2000 Watts require additional attenuation optics. This can be accomplished with two LBS-300s systems, or by adding additional beam splitters to the LBS-300s system.

Do not exceed $2\text{MW}/\text{cm}^2$ or $50\text{Joules}/\text{cm}^2$ (10 nanosecond pulse width). This fluence will damage most beam sampling/splitting optics.

2.4.1.4 Beams > 2000 Watts

Beams with power greater than 2000 Watts require custom, cooled beam sampling optics. Alternatively, Ophir's BeamWatch® line of laser beam diagnostic products does not require any beam attenuation.

2.5 Beam Alignment and Setup for Auto Mode

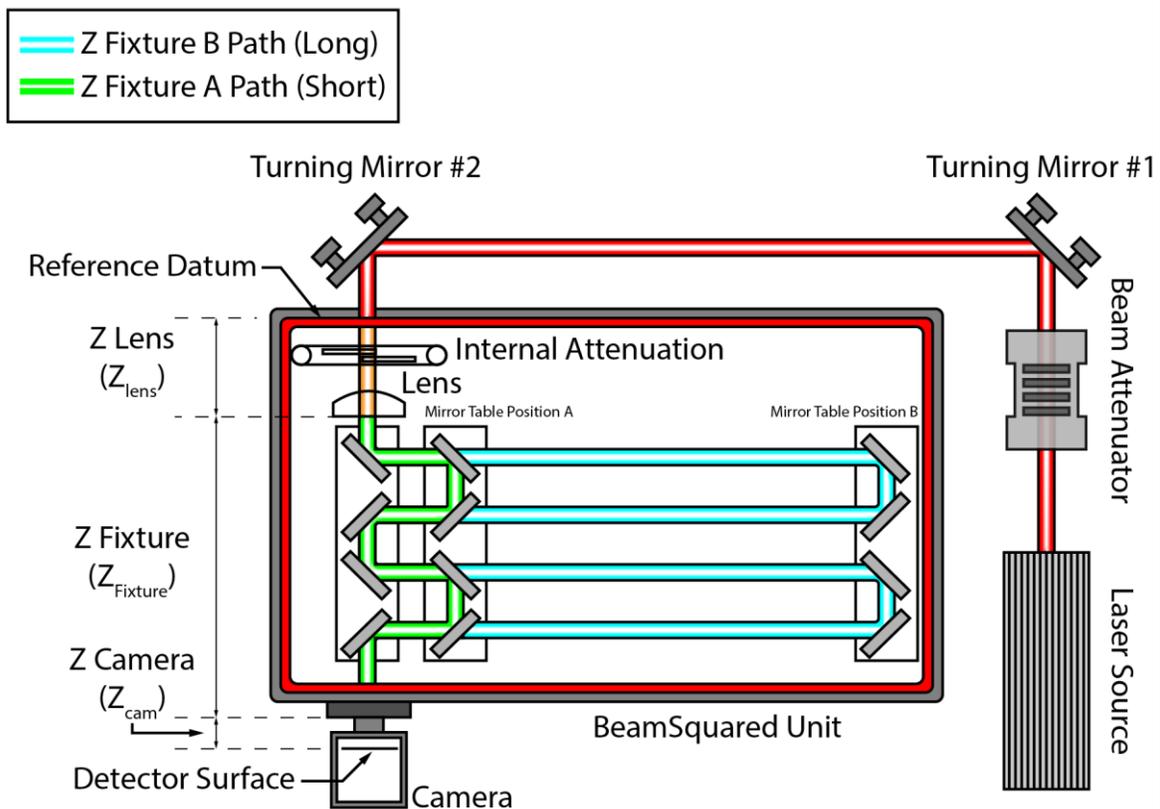


The following procedure should only be performed after attenuation of the laser beam. Failure to do so may damage the camera. Refer to section 2.4.

For BeamSquared to operate correctly, the beam must enter the instrument through the center of the input aperture and align along the instrument's optical axis so that the beam does not appreciably "walk across" the active area of the camera sensor. Improper alignment can add extra time to a BeamSquared measurement.

If the aperture needs to move to accommodate the beam location, additional calibrations will be needed which slows the measurement.

Using two external turning mirrors makes it much easier to direct the beam into the optical train along its optical axis as shown in the figure below. This axis runs perpendicular to the instrument's long axis.



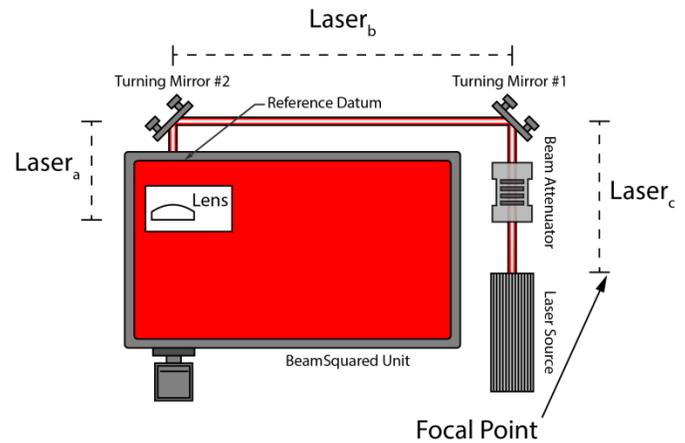
After initialization, the mirror table moves to "Mirror Table position A" in the above image.



The Z_{lens} distance begins at the edge of the red BeamSquared case.

2.5.1 Distance from Laser

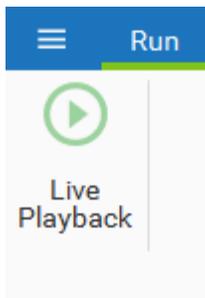
In order to get the best results, the distance between the natural beam waist and the lens should be between one-third and three times the focal length of the lens. This distance is the sum of $Laser_a$, $Laser_b$, and $Laser_c$ in the graphic on the right. In this example the natural beam waist is located at the laser source faceplate. See section 6.1.7 for computations.



The distance from the reference datum to the lens is approximately 95.5mm. The actual value is calibrated at the factory as the Z_{lens} value.

2.5.2 Initial Setup and Rough Beam Alignment

2.5.2.1 Live Playback



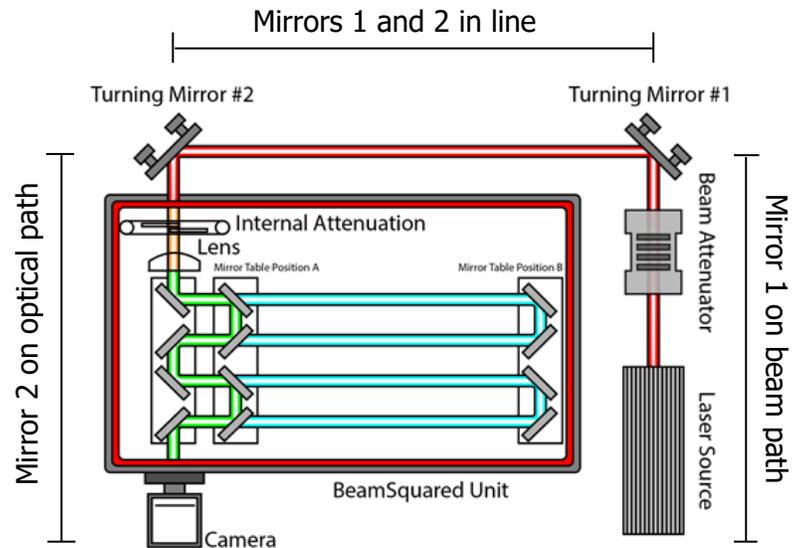
The **Live Playback** video mode is provided to assist with the alignment process and displays a video feed in the **2D Beam Display** window. Enable **Live Playback** on the **Run** ribbon to assist with aligning the beam **after attenuation has been completed**. Live Playback is also used to collect Positional Stability data when the **Positional Stability** window is open.



*The beam may not appear in the **2D Beam Display** window until after the alignment is completed.*

2.5.2.2 External Steering Mirrors

Position the pair of beam turning mirrors with Mirror #1 in the beam axis, and Mirror #2 on the optical axis of the BeamSquared with both mirrors in line with each other.



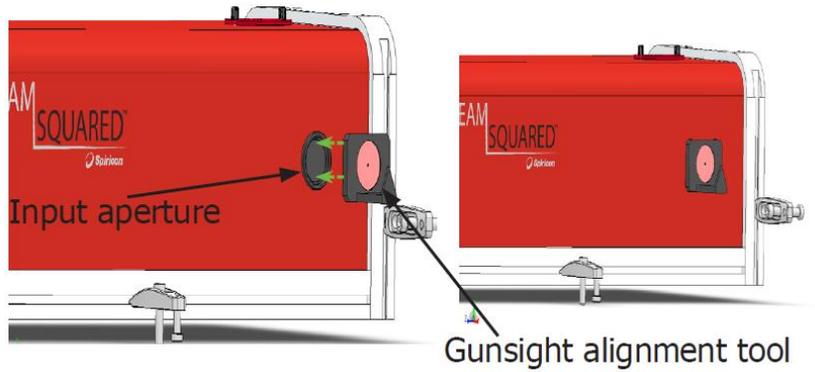
2.5.2.3 Laser Mounting Height

Where possible, the height of the laser source should be set to the same height as the optical train's optical axis. This makes centering the beam easier, as adjustments to the steering mirrors X and Y tilt adjustments have similar axial effects. Otherwise, a change in one mirror's X adjustment requires both an X and Y adjustment of the opposite mirror to bring it back to center.

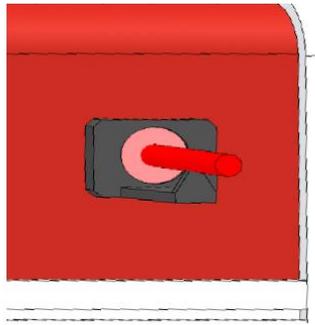
2.5.2.4 Gunsight Alignment Tool

An alignment tool is included to assist in aligning the beam with the instrument. The tool consists of a mounted pinhole and an alignment sight. The pinhole disk is coated with a material that fluoresces when exposed to NIR light.

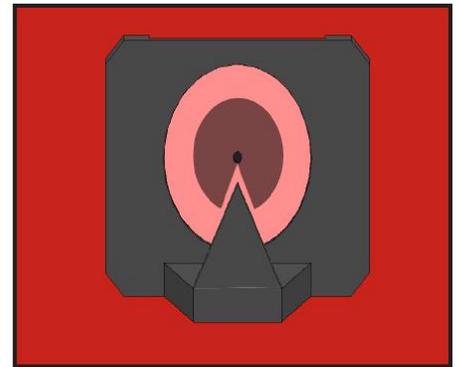
1. Place the Gunsight alignment tool over the input aperture. Magnets will hold the tool in place.



2. As the beam contacts the alignment sight, a shadow is cast on the pinhole disk. When the center of the laser beam and the tip of the shadow are aligned on the pinhole, the beam is aligned with the optical axis of the unit (see section 2.5.3).



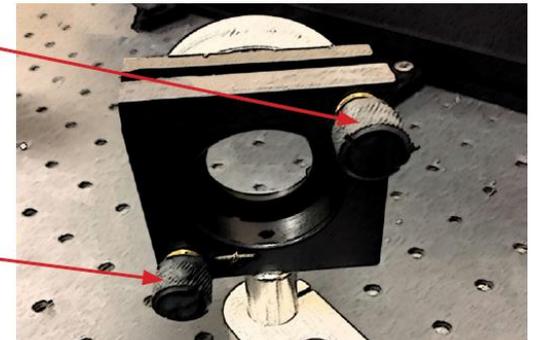
Beam Enlarged for display purposes.



3. Use the alignment mirrors to adjust the beam direction until it passes over the sight and into the pin hole. Alternate adjustments between mirror 1 and 2. Mirror 1 to center over the sight and mirror 2 to center over the pinhole.

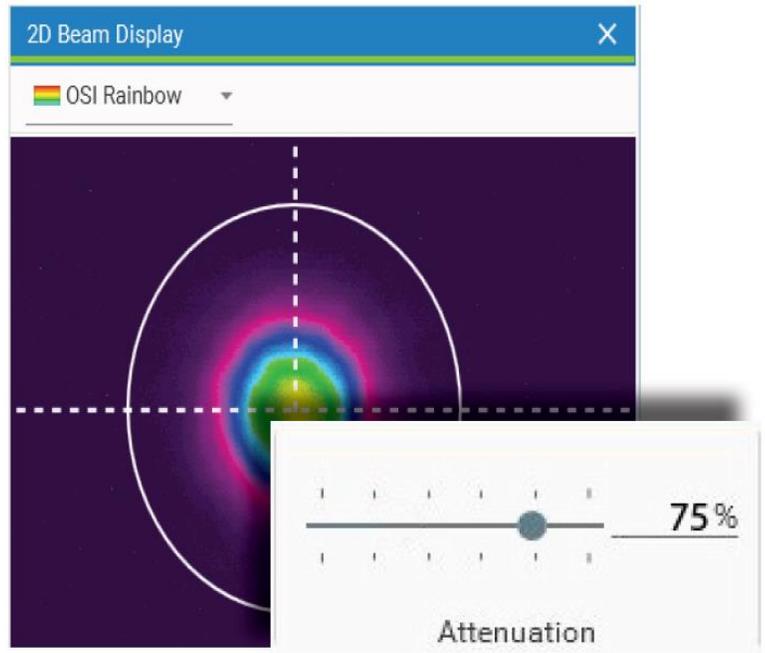
Controls the Vertical pitch

Controls the Horizontal pitch

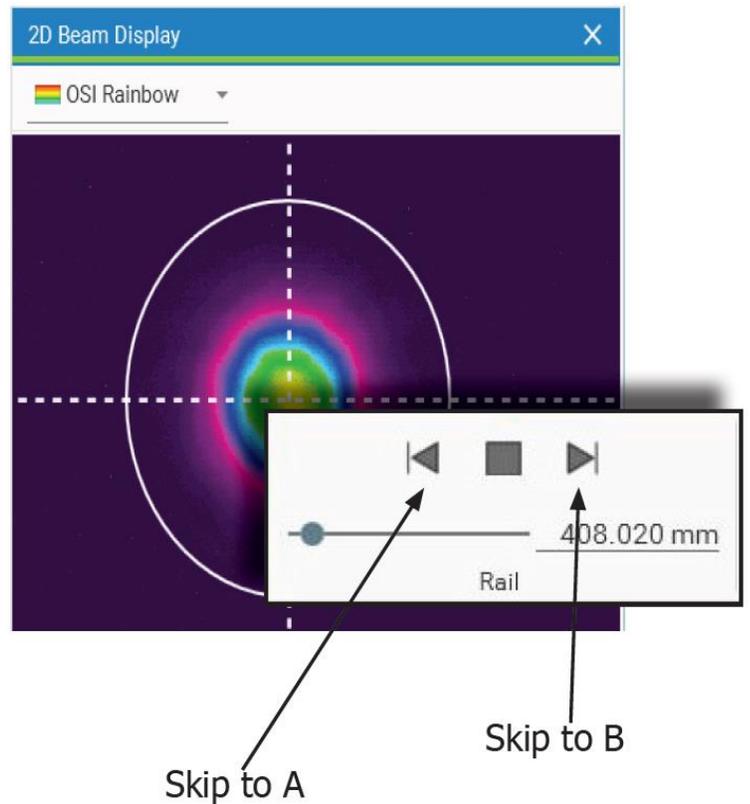


Adjustable mirror operations vary by mirror, but operate on a similar basis.

- Remove the Gunsight alignment tool from the input port.
- Watch the laser beam in the **2D Beam Display** window. Adjust the internal ND filters to 75% in the **Table** ribbon bar. It is beneficial to have excessive external attenuation in place at this time to protect the camera.



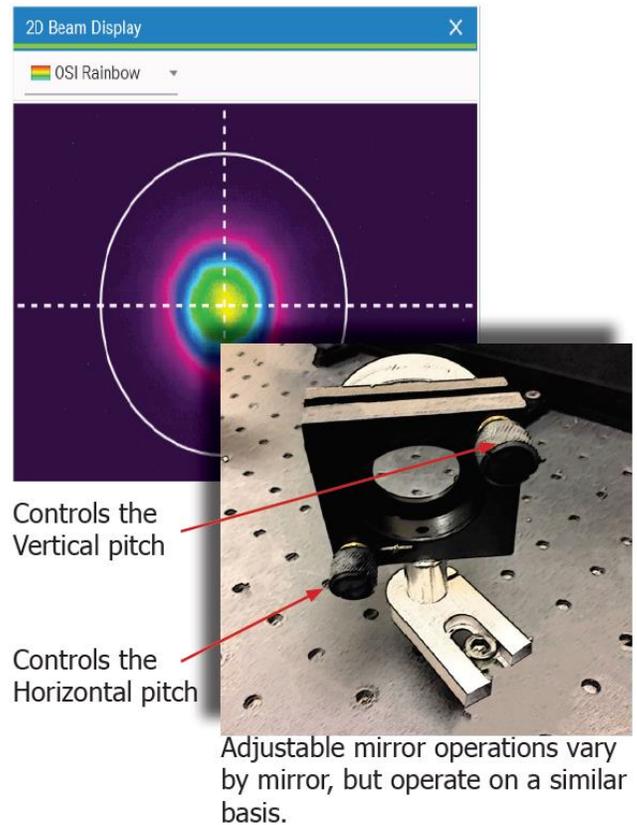
- Translate the table until the approximate minimum beam diameter is found. This is usually near the focal length of the lens, but not always. Gradually remove external attenuation until the beam intensity is at approximately 75% of camera saturation.
- Use the translation controls on the **Rail** panel under the **Table** ribbon bar to change the Z location of the camera.
- Watch the motion of the beam as the table moves between rail positions "A" and "B." The beam image should stay fairly centered in the camera array without wandering significantly.



2.5.3 Precision Beam Alignment

If the beam does not remain centered as the table translates make additional small adjustments of the steering mirrors. This is an iterative process where the mirror pair is adjusted in opposite directions and the table is translated between "A" to "B" as necessary. In general, it is best to align one axis at a time to keep the process simple.

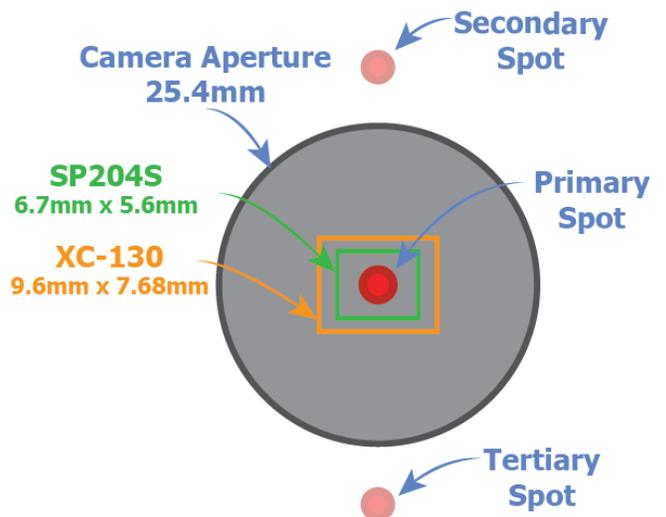
1. Move rail to position "A."
2. Enable **Live Playback** on the **Run** ribbon.
3. Move rail to position "B." During this step, watch the direction of beam movement on the **2D Beam Display**.
4. Move rail to position "A."
5. Adjust Mirror #1 to direct the beam in the same direction observed in Step 3.
6. Using Mirror #2, adjust the beam back to the center of the camera sensor array.
7. Repeat steps 1-6 as necessary until beam is centered on the sensor array through the entire propagation path.
8. Once a stable alignment is obtained, disable **Live Playback** on the **Run** ribbon to turn off the live video alignment mode.



Making adjustments greater than 1/2 to 2 times the width of the sensor array makes it easy to lose track of the beam.

2.5.3.1 Ghost Beams

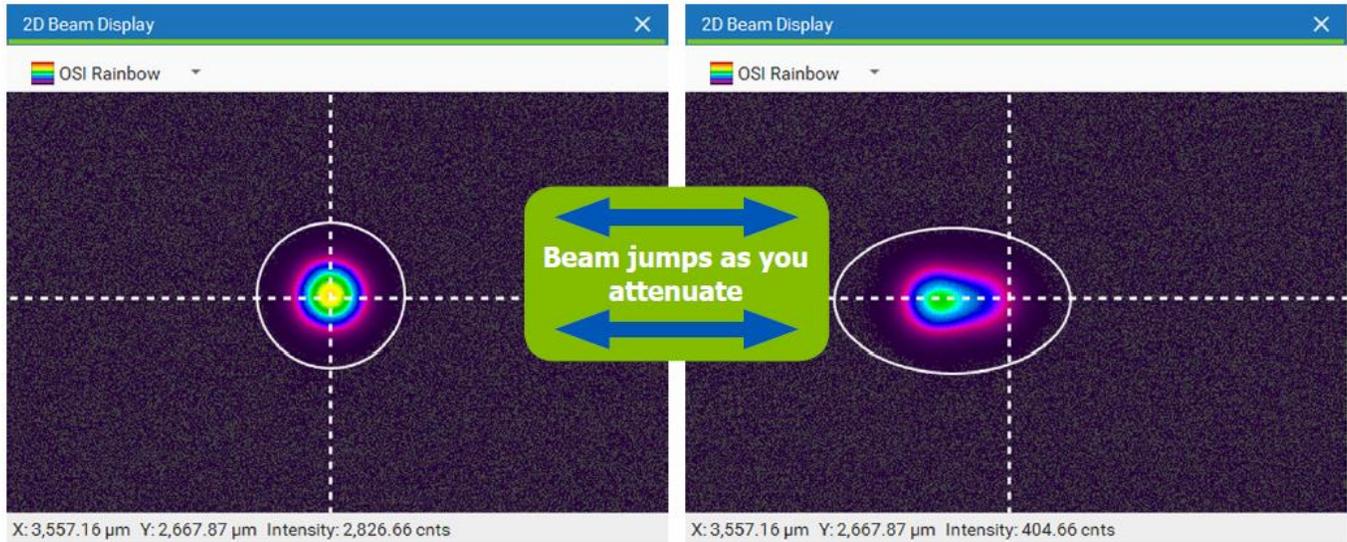
The optical path design of the BeamSquared system creates some natural reflections of the input laser. While most ancillary reflections are orders of magnitude below detection levels, the secondary and tertiary reflections of the input laser land near, but outside of the camera aperture and can be detected and aligned to if the user is unaware of them. These spots appear much dimmer, and issues may arise in the propagation measurements if you align to one of these "ghost beams."



The secondary and tertiary points in this depiction are shown along the Y axis of the camera. This only applies when the BeamSquared unit is mounted horizontally and the camera is upright. If the BeamSquared unit is mounted vertically and the camera is upright, the secondary and tertiary points are then found along the camera's X axis.

To identify a misalignment to a ghost beam, first follow the 2.5.3 Precision Beam Alignment instructions. Then adjust the attenuation level. If the laser spot on the sensor appears to smear and jump out of view when the internal attenuator is translating, then the system is aligned to either the secondary or tertiary reflections shown in the diagram above.

To correct for a misalignment to a ghost beam, adjust the alignment of the steering mirrors until you find the primary spot; then follow the 2.5.3 Precision Beam Alignment instructions to finalize beam alignment.



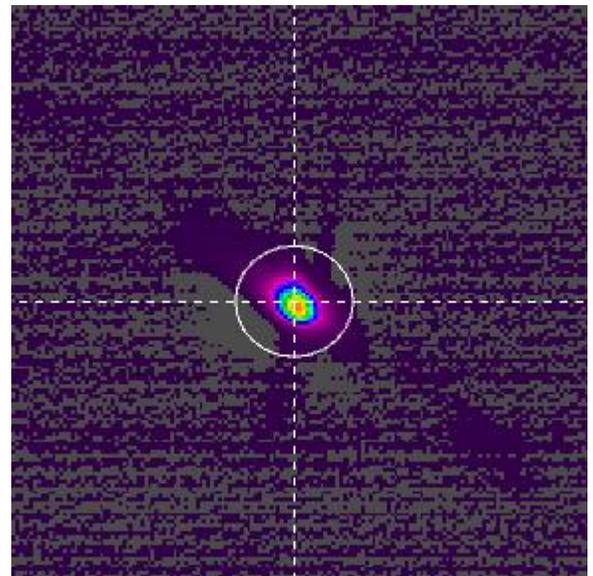
2.5.4 Beam Axial Alignment

In the image to the right the asymmetrical beam is poorly aligned with the camera axes. Unless the beam is circular, axial alignment is critical to obtain accurate results. ISO states that when the ratio of the beam widths exceeds 0.87 the beam can be considered circular.

For the beam shown, the profile is tilted approximately 45 degrees from the axes of the window. The calculations assume a nearly circular beam even though it is elliptical.

If the camera axes coincide with the natural axes of the beam, results calculated in rectangular coordinates have the largest range of variation and contain the largest amount of information about the beam.

Rotate the camera to bring the natural axes of the beam into alignment. The intensity profile should inhabit an approximate two-fold symmetry about the X and Y axes.



2.6 Step Size and Start/Stop Selection

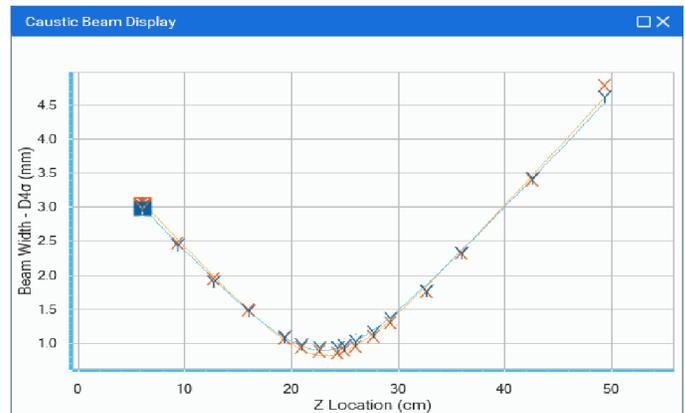
After the system is properly aligned and attenuated, perform an initial run (see section 4.2.1).

1. Select a step size that is approximately one tenth of the focal length of the lens in use. Use the default start and stop values.



The screenshot shows the 'Automated Stepping' control panel. It has a blue header with a back arrow and a close 'X' button. Below the header are three input fields, each with a question mark icon to its left and a dropdown arrow to its right. The first field is labeled 'Z Start' and has the value '60.00 mm'. The second field is labeled 'Z Stop' and has the value '1000.00 mm'. The third field is labeled 'Z Step' and has the value '50.00 mm'.

2. Allow the run to complete. Take note of the data point nearest the waist. About 230mm in the graph shown.



3. Begin a second run with the Z Start and Stop values being equidistant around the value found in step 2.

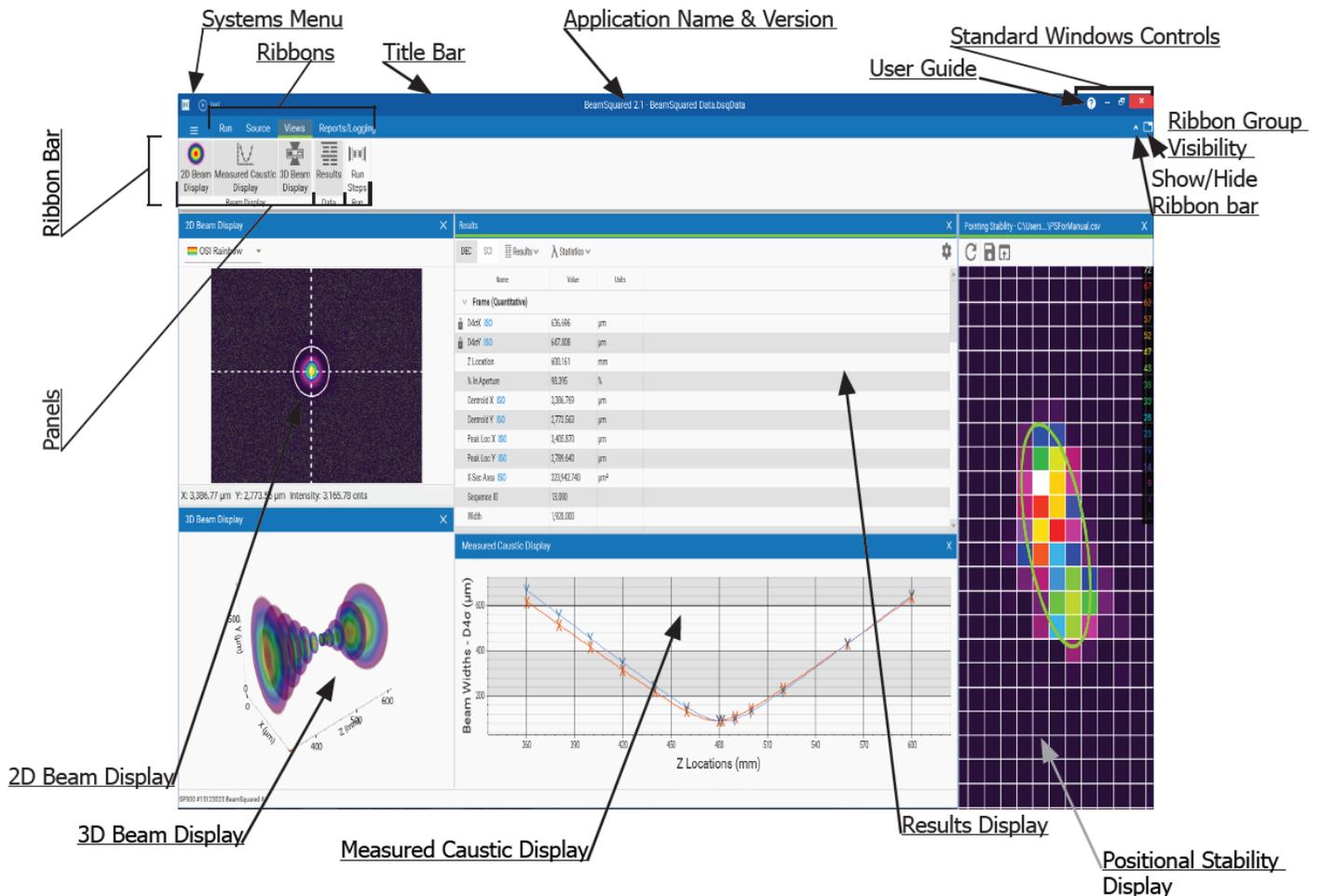


This screenshot is identical to the first one, but the 'Z Stop' value has been updated to '400.00 mm'. The 'Z Start' value remains '60.00 mm' and the 'Z Step' value remains '50.00 mm'.

Chapter 3 Operating Controls and User Interface

3.1 User Interface

BeamSquared employs the Windows ribbon control motif which provides intuitive access to control functions as well as the ability to hide the controls for better screen utilization. This chapter describes the various control features available in BeamSquared beginning with the terminology used to identify the basic control forms.



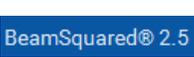
3.1.1 Title Bar



The topmost bar on the application. Contains, from left to right:

 **System Menu button**
Gives access to window controls.

 **Quick Access Toolbar**
The buttons shown here are **Live Playback** and **Start**.

 **Application Information**
Application name, version number, and file playback name if applicable.



Help

Select the help icon to bring up this user guide quickly without leaving the software.



Standard Windows Controls

Minimize, Maximize, and Close buttons.

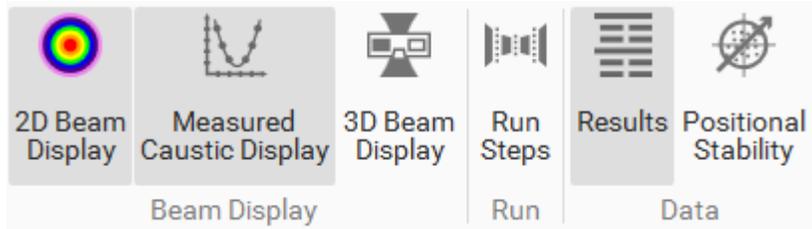
3.1.2 Ribbon Tab



Defines the current ribbon control being accessed. Double click on a blank space in this bar to minimize or maximize the entire display. Double click on a tab to minimize and maximize the ribbon bar.

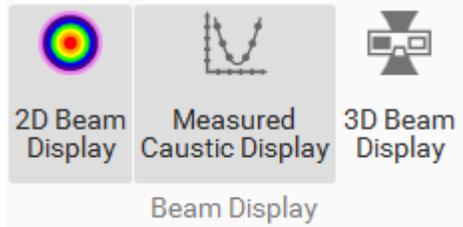
If the ribbon bar is closed, a single click temporarily opens the selected tab.

3.1.3 Ribbon Bar



Displays the current set of panel control options available within a selected ribbon tab. These panels contain all common control items.

3.1.4 Panels



Panels contain buttons, drop-down lists, edit controls, etc. Tool tips are available on most all controls, hover the mouse to view.

3.1.5 Display Area

The display area consists of all docked display windows. Each display can be disabled, resized, docked, or floated to any location on the screen. The content of the display area is explained more in section 3.8.

3.1.6 Status Bar

SP300 #16307848 BeamSquared #123456789



The BeamSquared status bar contains information about the connected camera and Automated BeamSquared unit. The icons on the right change based on how the system is setup. If multiple runs are initiated, then the current run is displayed Run 1 of 100. If Logging is enabled then the logging information is displayed



. These icons are for visual reference and have no other functions.

3.1.6.1 BeamSquared Pro Indicator



Operation in BeamSquared ProMode requires a BeamSquared Pro compatible device and lens(es). See Section 1.5 BeamSquared Pro (Premium Optional Upgrade).

After the BeamSquare software application detects BeamSquared Pro hardware and a compatible Pro lens, an icon appears at the right-hand side of the status bar. This Pro icon will illuminate when a compatible lens is inserted and appear grayed out if a non-Pro lens is inserted.



Pro lens inserted



Non-Pro lens inserted

3.2 Application Tools



Application tools can be found in the same bar as the ribbon tabs and give access to the **File Access** window and allow customization of the ribbons.

3.2.1 File Access Window

Select  to access the **File Access** window.

Open

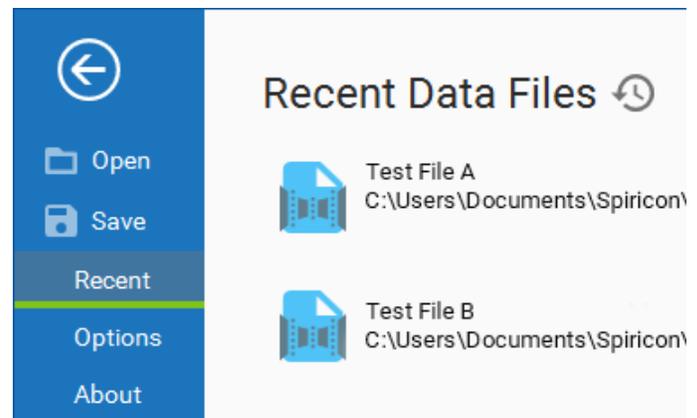
Opens **Windows Explorer** to navigate to a specific file to open for file playback. Data files saved as *.m2-scor-data from the legacy M²-200s-FW can also be loaded into the BeamSquared software.

Save

Opens **Windows Explorer** to navigate to a location to save the current data file. BeamSquared data files save with a *.bsqData extension.

Recent

Stores quick links to recent data files.



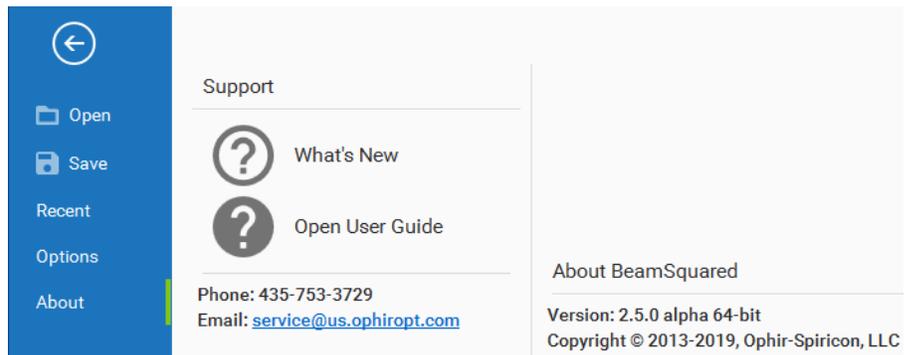
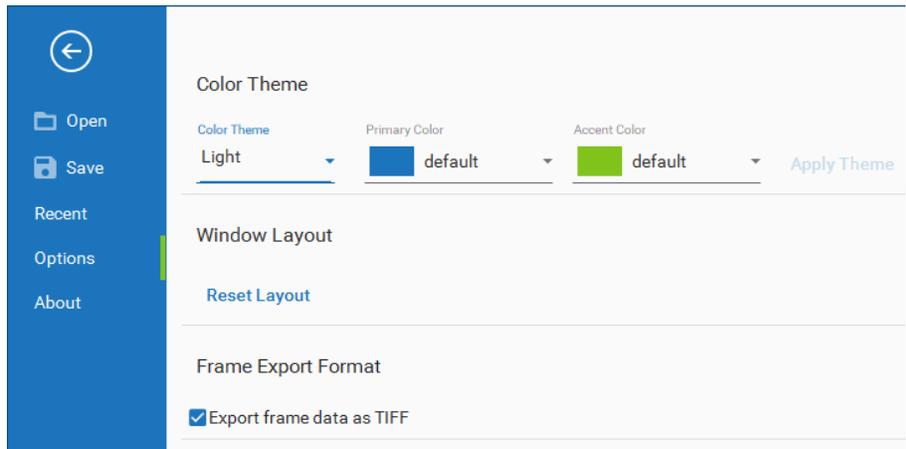
Options

Allows customization of the color scheme of the user interface. Choose a combination of a light or dark theme, a primary color, and secondary color. Select apply theme to accept changes. **Reset Layout** allows you to restore the windows to the default configuration.

Enable **Export frame data as TIFF** to save images in a tiff format (see section 3.2.1.1 for more information). If unchecked the data remains as an integer array.

About

Provides a link to this user guide, contact information for the Ophir Service department, and displays the current software version and copyright information. **What's New** opens the ReadMe which lists new features and improvements found in the current version.



3.2.1.1 TIFF Image Format

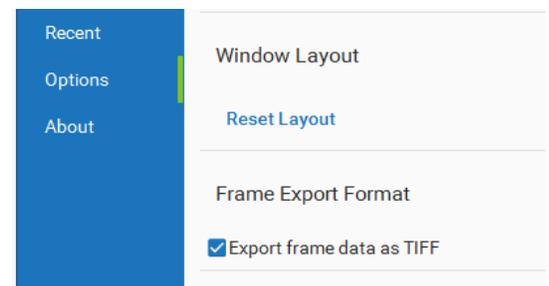
TIFF files are an encoded, compressed data file format that produces smaller data files and can be easily loaded into third party applications, such as MATLAB. Files saved as TIFF retain the *.bsqData extension but can be manually loaded into other applications that support TIFF formats.

TIFF data is stored using the gray32bppFloat pixel format. This format uses a single-color channel with 32 bits of precision. The pixel count is stored as a normalized floating point value between -1 and 1. The value is calculated using the minimum and maximum values of a signed 32-bit integer, namely $\pm 2,147,483,647$. The original per pixel values of the collected data can be obtained by multiplying the floating point value obtained from the tiff image by 2,147,483,647.

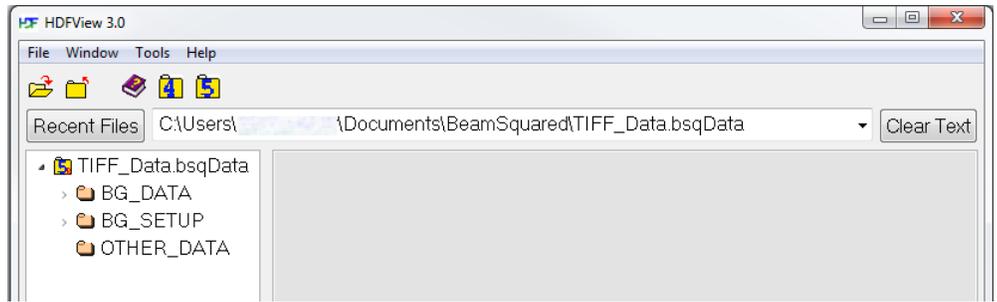
3.2.1.1.1 Exporting TIFF Images for use with HDF5

TIFF images can be exported for use with HDF5.

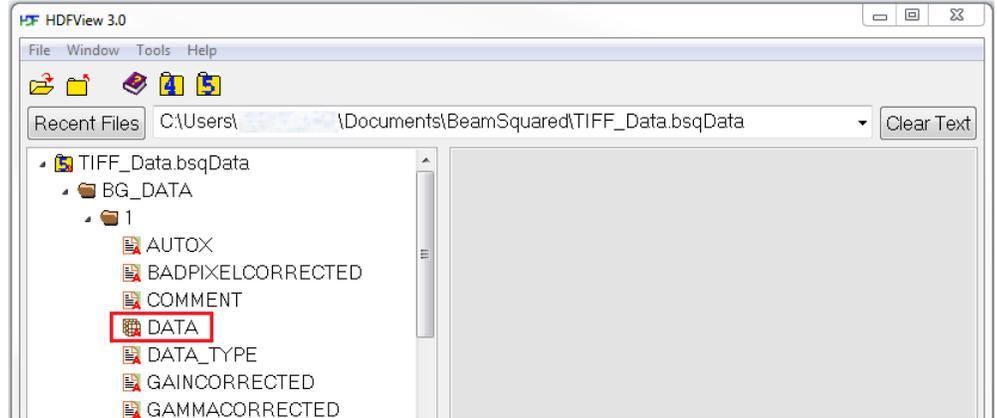
1. In the **Options** view, enable **Export frame data as TIFF**.
2. Save a data file.



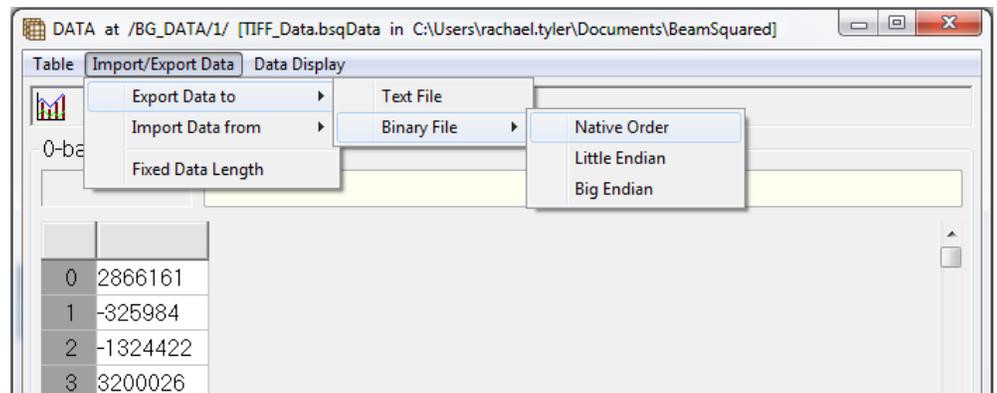
- Download and install HDFView.
- Run HDFView.
- Open the BeamSquared data file.



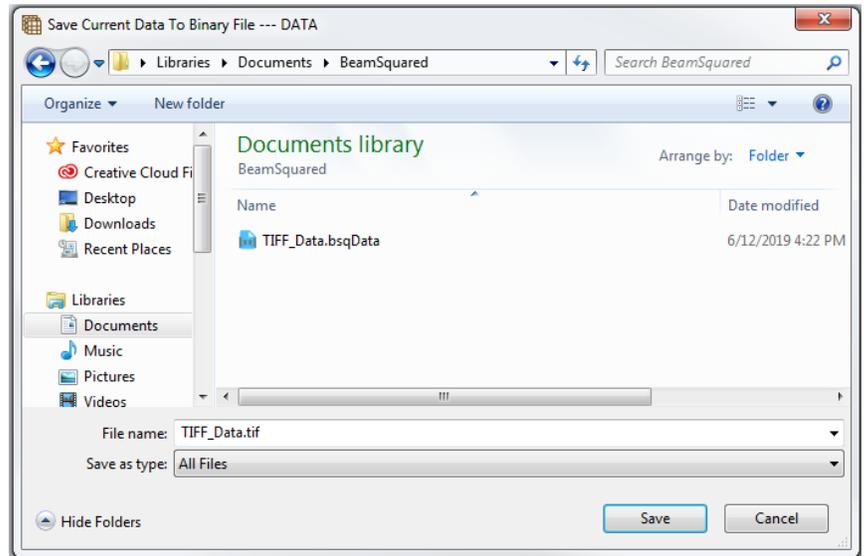
- Click and expand **BG_DATA**.
- Click and expand the desired frame number.
- Right-Click on **DATA**, select **Open**.



- Select **Import/Export Data -> Export Data to -> Binary File -> Native Order**.



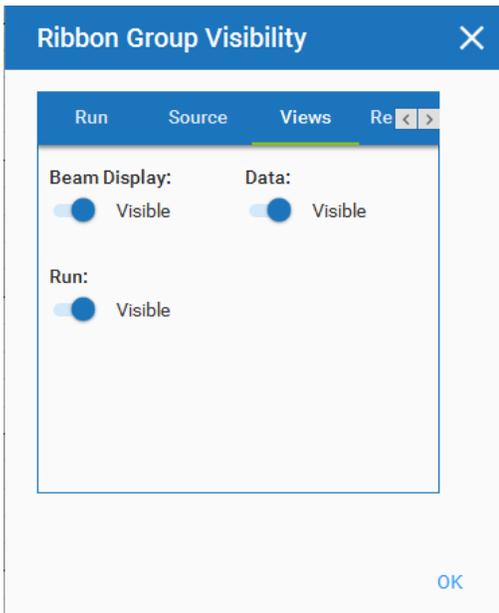
10. Locate and open the TIFF file with desired software.



3.2.2 Show/Hide Ribbon Bar

Select the caret icon  to display or hide the ribbon bar, or double click a tab as referenced in section 3.1.2.

3.2.3 Ribbon Group Visibility

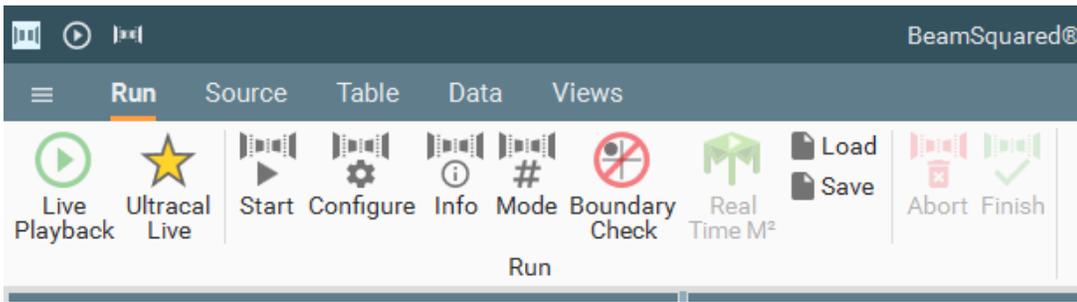


Located below the Windows Close button is the **Ribbon Group Visibility** configuration .

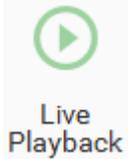
A dialog box opens that allows turning on or off ribbon panels. Select the tab of the ribbon to view and select the slider to turn the panel on or off.

3.3 Run Ribbon

The **Run** ribbon contains controls for operation.



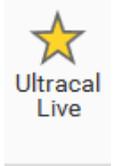
3.3.1 Live Playback



When enabled, the **2D Beam Display** is shown in real-time. This feature provides a laser alignment aid to verify the setup of the optical system.

Data frames collected in live mode are not stored and therefore cannot be saved or loaded. Results in the **Frame (Quantitative)** group are computed, but an Ultracal cycle cannot be performed during Live Playback, so results may not be accurate. Nevertheless, the Peak Energy level is useful in setting external attenuation such that the dynamic range of the camera is utilized.

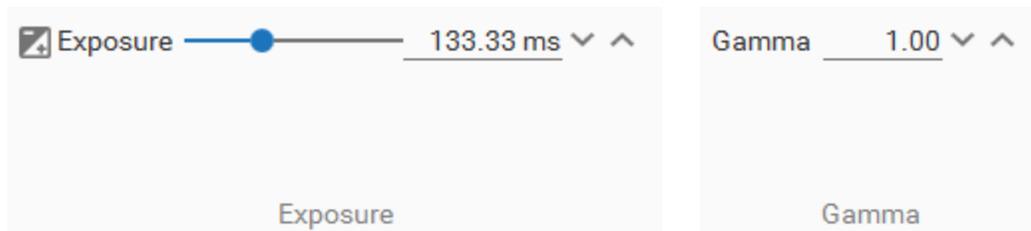
3.3.2 Ultracal Live



Ultracal Live performs an accurate baseline calibration on the camera and removes small amounts of light that may leak into the camera image. It preserves both positive and negative noise floor, and results in the most accurate beam width calculations possible with camera based technology. Live ultracal is used when you would like to view the beam without performing a run, or if the last run was so long ago that the baseline may have shifted.

Before performing an Ultracal, **Exposure** and **Gamma** must be adjusted in the **Source** ribbon (see Sections 3.5.2 and 3.5.3 Source Ribbon).

Use these settings to remove saturation in the beam profile (white pixels in the normal OSI Rainbow color palette).



A Green  (the **Ultracal indicator**) illuminates in the **Status Bar** at the bottom of the screen when Ultracal is active.



When a camera setting changes that can compromise the setup, the "U" indicator appears grayed out, and Ultracal processing is suspended. Hover over this indicator to see what changed to cause the suspension.

3.3.3 Start



Use **Start** to begin an M² run with the last programmed or loaded settings. View or change the settings in the **Configuration** wizard, accessed through the **Configure** button.

Start

3.3.4 Configure



Use **Configure** to open the **Configuration** wizard, input information about the system under test, select the operating mode (Automated Stepping, Automated ISO Setup, Four Cuts, or Step Table), and setup the measurement parameters. See section 4.2.1 for information on operation.

Configure

3.3.5 Info



Use **Info** to open only the **Run Info** window of the **Configuration** wizard. View and edit the model number, serial number, and comments for the next run. Changes in this window and the **Configuration** wizard are shared.

Info

Run Info

Laser Model

Laser Serial Number

Comment

OK

3.3.6 Mode



Use **Mode** to open only the **Run Mode** window of the **Configuration** wizard. Choose to run in **Single Run** mode or **Multiple Runs** mode. Changes in this window and the **Configuration** wizard are shared.

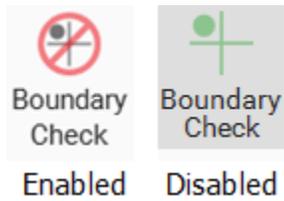
Mode

Run Mode

Single Run
Completes only a single run.

Multiple Runs
Completes a set number of runs.

3.3.7 Boundary Check



Click **Boundary Check** to toggle the detection and abandonment of runs for beams that cross the sensor array boundaries. This disables the warning of beams that are too big or misaligned.



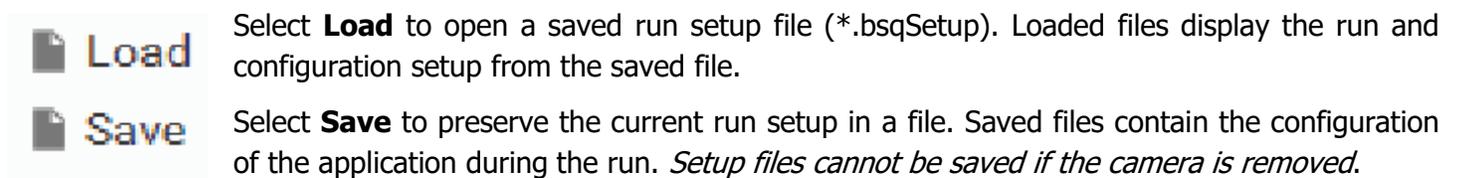
*Damage can result if **Boundary Check** is disabled and the beam is excessively misaligned.*

3.3.8 Real Time M²



Real Time M² is only available after a completed M² run. You can select **Real Time M²** to start real-time monitoring. Click again to disable and return to normal operation. See section 4.1.5 for information on running in Real Time M² mode.

3.3.9 Load and Save



Select **Load** to open a saved run setup file (*.bsqSetup). Loaded files display the run and configuration setup from the saved file.

Select **Save** to preserve the current run setup in a file. Saved files contain the configuration of the application during the run. *Setup files cannot be saved if the camera is removed.*



BeamSquared saves the application configuration upon close, so it opens in the same configuration as it was when it closed.

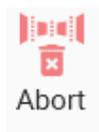


*The configuration file does not preserve (and thus does not restore) data sets. Data files must be saved and loaded separately from the **File Access** window, see section 3.2.1.*



Setup files from the legacy M²-200s-FW cannot be loaded.

3.3.10 Abort Run



Only available while after a run has started. Stops the run and discards data.

3.3.11 Finish Run



Only available after a run has completed. Closes the run and finalizes data.

3.4 Table Ribbon

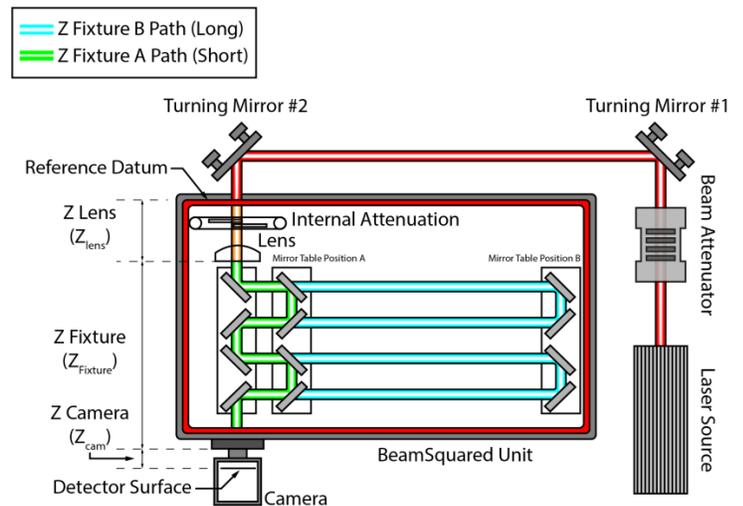
The screenshot shows the 'Table' ribbon with a navigation bar (Run, Source, Table, Data, Views). Below the navigation bar are three main sections: 1) Rail control with a slider set to 985.320 mm and buttons for previous, stop, and next. 2) Attenuation control with a slider set to 25%. 3) Table Info section with dropdown menus for Serial Number (2014955), Z Fixture (333.470), Focal Length (400.431), Calibration Wavelength (632.800), Table Version (2), Z Lens (96.480), Back Focal Length (398.170), Wavelength Range (NIR), Center Thickness (3.390), and Material (BK7).

The **Table** ribbon only appears with the Automated BeamSquared. The table has a range of 800mm. The start point of the table varies slightly between BeamSquared units. The start point or "A" location is set and calibrated at the factory as the Z Fixture value and cannot be changed.

3.4.1 Rail

The screenshot shows the 'Rail' control panel with a slider bar set to 914.310 mm. Above the slider are three buttons: a left arrow, a square stop button, and a right arrow.

This panel allows you to control the location of the optical train. The **Previous** button moves the table to the "A" location and the **Next** button moves the table to the "B" location. Drag and drop the slider bar to move the table to any location along the path. The user can also input specific table locations manually in increments of 15 microns (0.015mm).

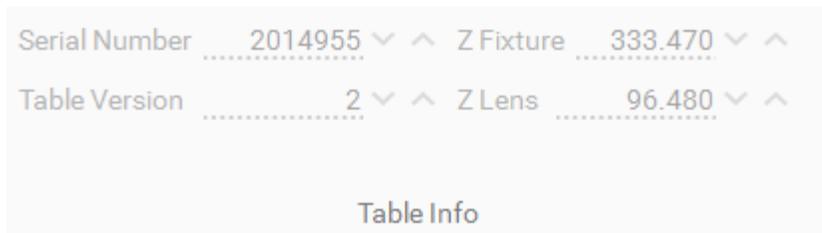


3.4.2 Attenuation

The screenshot shows the 'Attenuation' control panel with a slider bar set to 41%. The slider has several tick marks along its length.

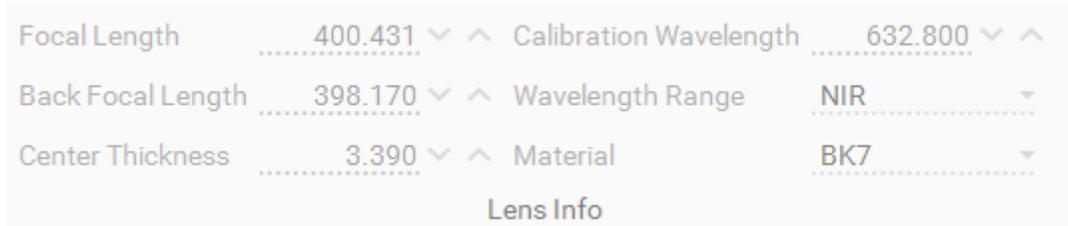
This panel controls the internal attenuation as a percentage of the total available attenuation. The user can drag and drop the slider bar or enter a percentage value between 0% and 100%.

3.4.3 Table Info



This panel displays the settings of the currently connected BeamSquared system. The values are informational and cannot be changed.

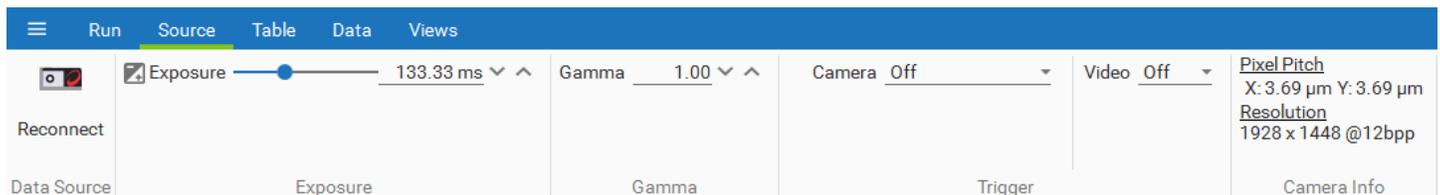
3.4.4 Lens Info



This panel displays the settings of the currently inserted lens. The values are informational and cannot be changed.

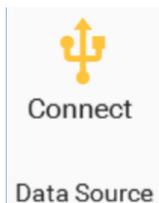
3.5 Source

Ribbon

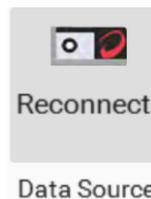


The **Source** ribbon contains controls that vary by camera.

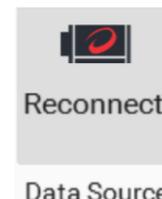
3.5.1 Data Source



Camera & BeamSquared not Connected

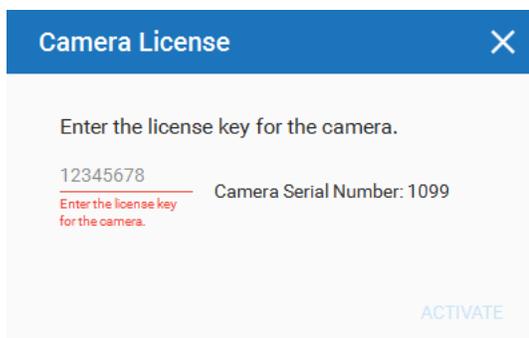


Camera & BeamSquared Connected



Just Camera Connected

On startup BeamSquared automatically connects to the first BeamSquared licensed camera found. If a camera is plugged in after the software launches, select **Data Source** to find the camera. The software can only view one camera at a time and is unable to switch to an additional camera.



Each camera must be licensed for use with BeamSquared. Contact Ophir's service department to purchase additional licenses. If a supported camera is connected but not licensed, an unlock button  is visible in the ribbon bar. Select **Unlock** to bring up the **Camera Licensing** dialog box.



Only Ophir's SP204S, SP920, SP1203 and XC-130 cameras are supported in Automated BeamSquared. Pyrocam IV and IIIHR are only supported in Manual BeamSquared.

3.5.2 Exposure

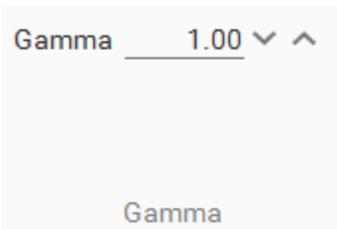


The **Exposure** panel is only available when a camera is connected. Use the slider or the text box to change the **Exposure** of the camera. **Exposure** determines the intensity and quality of the output image.



A gain setting is available when operating in manual mode with a Pyrocam.

3.5.3 Gamma

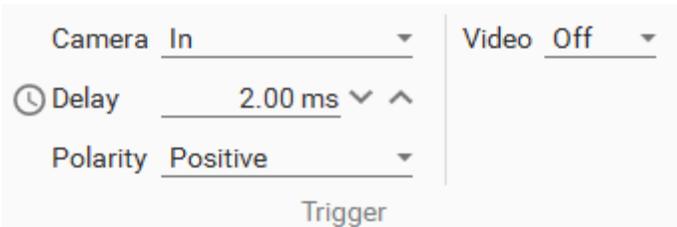


Solid state CCD or CMOS style detectors respond linearly to monochromatic light. For linearly responding cameras the **Gamma** setting should be set to 1.

For cameras that employ phosphors or other wavelength conversion materials the gamma of the material should be entered here to convert the nonlinear response back to a linear one.

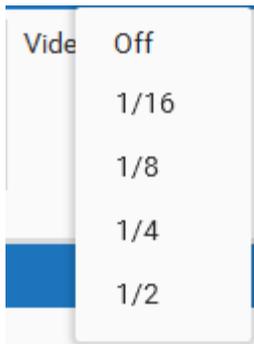
Ophir's Phosphor coated cameras require **Gamma** to be set to 1.95.

3.5.4 Trigger



The SP204S, SP1203, XC-130, and SP920 cameras are supplied with an external trigger input cable. The input to this cable should be a standard TTL level positive going pulse. The camera triggers and begins integrating light on the rising edge. A trigger pulse should be at least 5µs in duration.

When using an external trigger cable, set the **Camera Trigger** to **In**. Set a delay time in milliseconds for the start of the exposure if needed. The delay can be either positive or negative depending upon the duration of the laser pulse. If the pulse is short (<100µs) set a negative **Delay** of at least -1.0ms and set the **Exposure** to at least 2ms. If the laser pulse width is long, set a **Delay** of 0ms and the **Exposure** slightly longer than the pulse width. Finally, set the TTL edge polarity to Positive or Negative.



Video Trigger allows capturing laser pulses without the use of a trigger cable. The trigger threshold value in the drop-down sets the sensitivity of the trigger based on the camera bits per pixel. For example, a camera with 12 bits per pixel, 4095 counts full scale, and a threshold of 1/4 will trigger on a beam that has a peak amplitude >1023 counts.

3.5.5 Trigger Pyrocam



Trigger Mode **Chopped**
 Rate **50 Hz**
 Actual Rate **50.31 Hz**
 Trigger

In CW mode, the Pyrocam employs a rotating chopper that can operate at one of two different chopping rates, 25Hz and 50Hz. 50Hz is recommended to receive good response linearity. 25Hz should only be used in combination with an increased gain setting to extract the images of beams with extremely weak intensities.

Trigger Mode **Pulsed**
 Delay **10 μs**
 Actual Rate **50.24 Hz**
 Trigger

In pulsed mode, the Pyrocam must be externally triggered, and the delay value for the pulse width should be set slightly longer than the laser pulse. Refer to the Pyrocam User Guide for additional information on triggering the Pyrocam with a pulsed laser.

The **Actual Rate** value indicates either the current chopper frequency or the input trigger pulse rate in Hz.

3.5.6 Camera Info

Pixel Pitch
 X: 3.69 μm Y: 3.69 μm
Resolution
 1928 x 1448 @12bpp

This panel provides basic information about the camera source. The pixel size and detector size for the camera are shown.

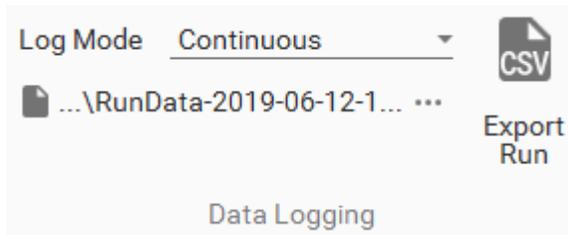
Camera Info

3.6 Data Ribbon

Run Source Table **Data** Views
 Log Mode **Disabled**
 CSV PDF
 Export Run Generate
 Data Logging Report

Contains the Data Management system within BeamSquared.

3.6.1 Data Logging



The **Data Logging** panel contains controls for exporting data as .csv files.



Log Mode

Select the drop down to enable or disable logging. Data logging can only be set to **Continuous**. When enabled, data will be saved while the run is in process. After setting **Continuous** logging a **Windows Explorer** box opens allowing you to select a location to export .csv data.



File Location

Displays the path where the .csv file will export. Select the ellipsis to change the save location or file name. If the file becomes read-only during a run, upon completion of a run, you are prompted to select a valid file in which to save the data.



Export Run

Export Run is only available after a run has been completed and exports data from only the most recent run into a .csv file. The file contains enabled results data from **Laser, After Lens**, and every frame from the run.

3.6.2 Report



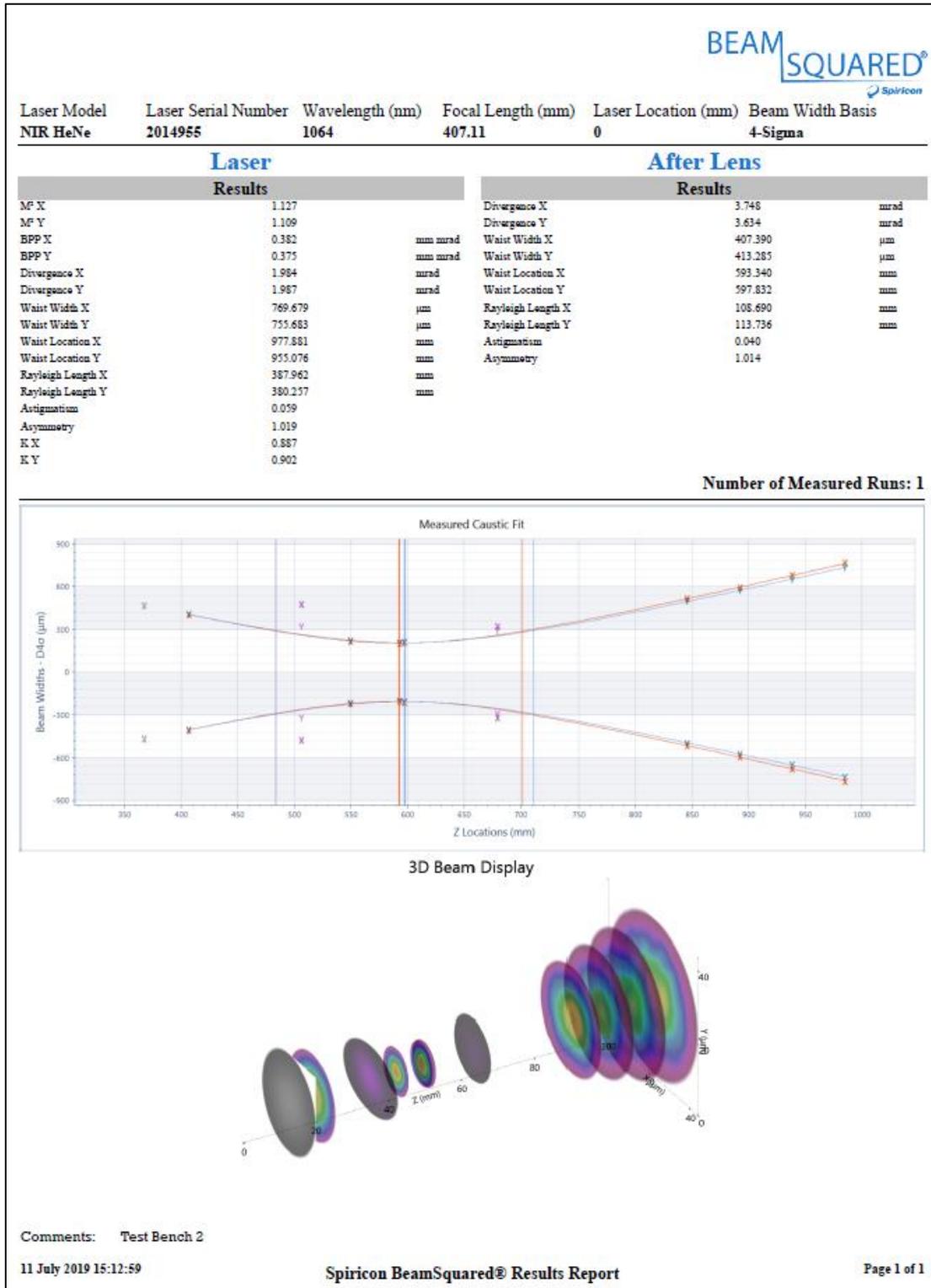
Generate PDF Report – The report feature generates a PDF file with data from the previous run. The report includes information entered in the **Configuration** wizard and all enabled results in the **Laser** and **After Lens** groups. Results from all other groups are not included.

Reports also display a **3D Profile** along with an altered **Measured Caustic Fit** chart that displays the X and Y profiles laid out like a beam caustic rather than side by side as they appear in BeamSquared. Vertical lines are drawn at the waist location and first Rayleigh length for each axis. Manually excluded points appear gray and automatically excluded points appear purple in both the **Measured Caustic Fit** and the **3D Profile** displays.

When clicked, a **Windows Explorer** dialog box opens. Enter a file name and select the save location, then select **Save**. The report will save and open automatically using your default PDF viewer program.

Single Run Report

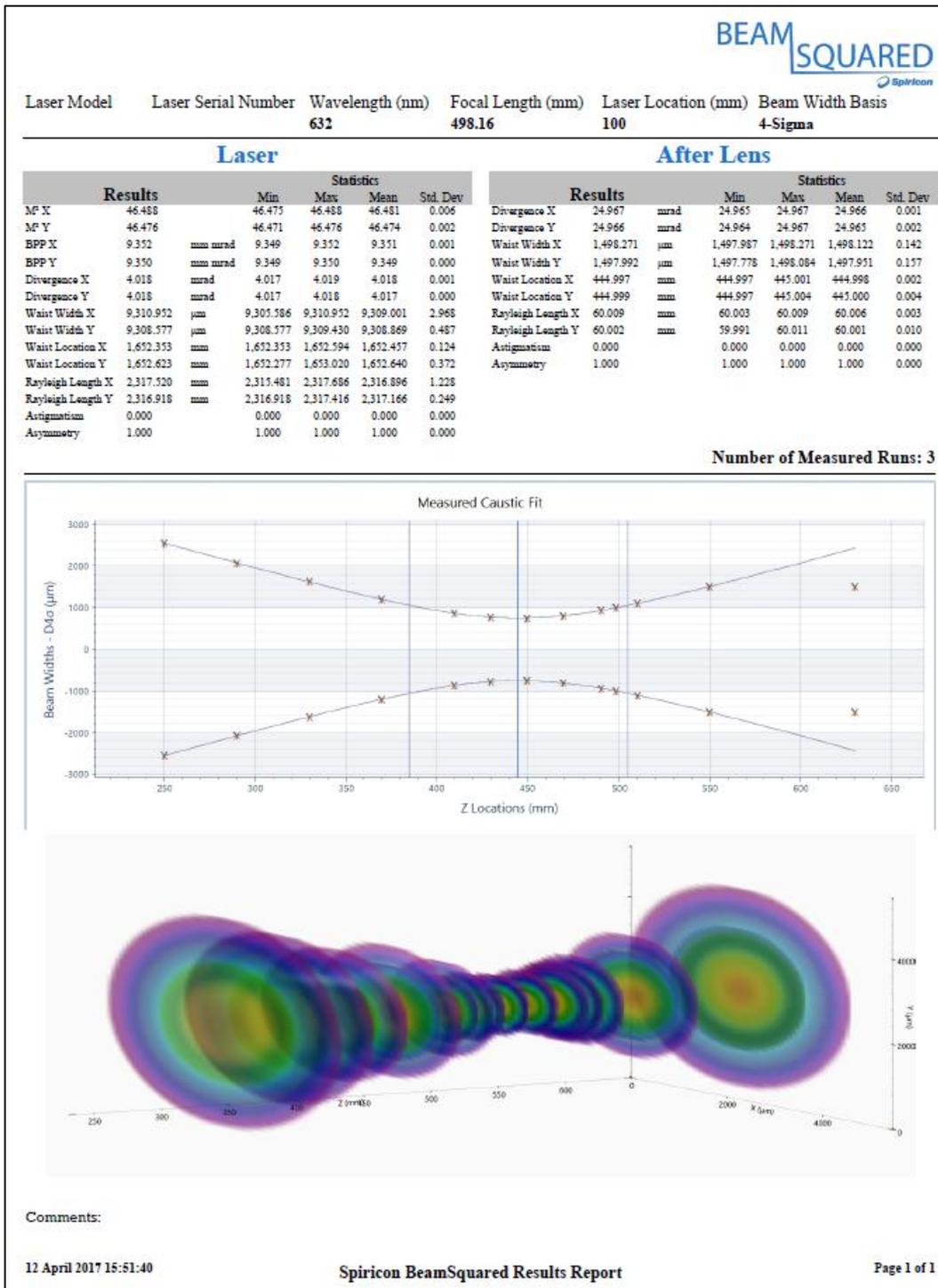
In the report shown, the first point has been manually removed and the third and seventh points have been automatically removed. These data points are not included in the M^2 calculations.



When operated in BeamSquared Pro Mode, the Results PDF generated will have a **PRO** icon appended at the top-right of the page.

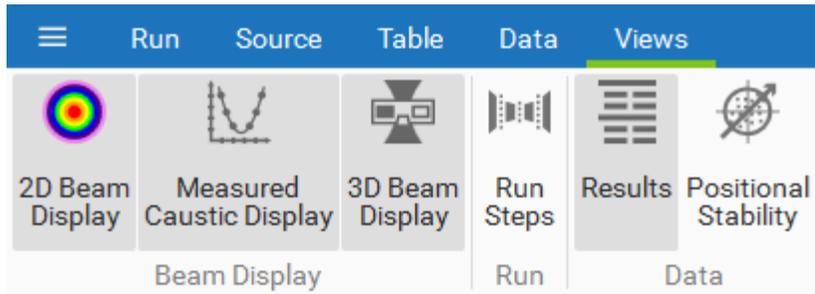
Multi Run Report

A Multi-Run Report displays the statistics for the run as well as all information found in the Single Run Report.



When operated in BeamSquared Pro Mode, the Results PDF generated will have a **PRO** icon appended at the top-right of the page.

3.7 Views Ribbon



This ribbon allows you to open and close windows in the display area.

3.7.1 2D Beam Display



The **2D Beam Display** presents the real-time data from the camera or the current frame in the **Measured Caustic Display** if a run has completed or a saved file is open.

Left click and drag to pan the display area and scroll the mouse wheel to zoom.

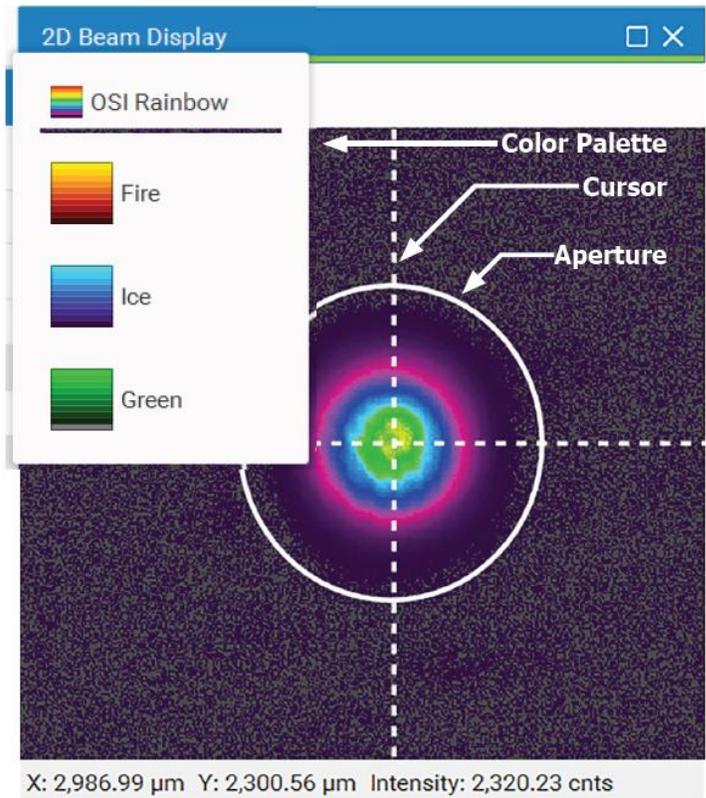
When **Live Playback** is enabled, the cursor position defaults to the center of the display. Left click and drag the cursor to move it manually.

The aperture around the beam marks the area where calculations are computed. The aperture is always circular or elliptical and is drawn automatically.

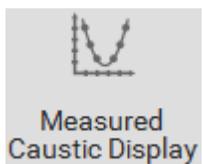
The X and Y values (bottom) display the cursor location in relation to the bottom left corner of the sensor. The units follow the width units selected in the **Results Settings** (see section 3.7.5.1).

The **Intensity** (bottom) displays the pixel value in digital counts at the cursor location.

The color palette drop-down (top left) displays color palette options for the beam profiles. Palettes are designed to work with a variety of laser safety eyewear.



3.7.2 Measured Caustic Display



The **Measured Caustic Display** window shows the after lens X and Y beam widths plotted against the Z axis locations. The units for each scale are selected in the **Results Settings** in the **Results** window, and the solid lines are the resulting curve fits of the beam propagation equation. The plotted data auto-scales to fit the window.

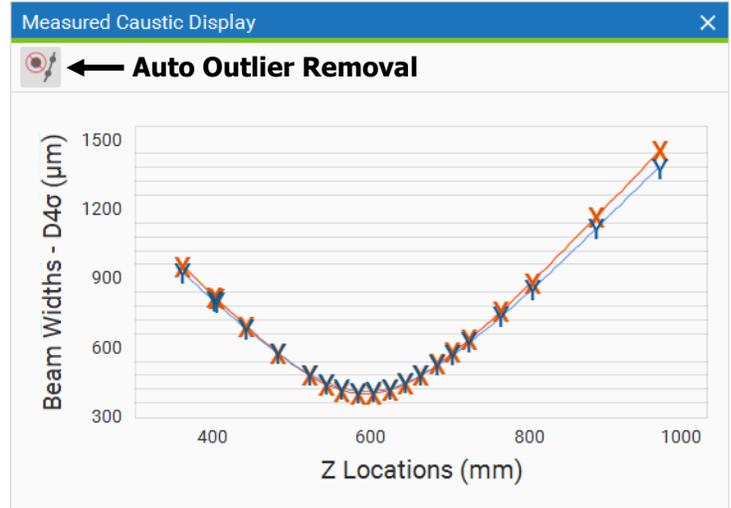
Scroll the mouse wheel to zoom and left-click and drag to pan the display area.

Single-click a data point to select and view it in the **2D Beam Display**. The results for the selected frame appear in the **Frame (Quantitative)** section of the **Results** window.

The left and right arrow keys can also be used to scroll between data points.

Enable/Disable **Auto Outlier Removal** in the top left corner of the window to have anomalous data points automatically excluded from the M^2 calculations. Automatically excluded points appear purple. This feature is on by default. We recommend its use as it will eliminate most, if not all, of the collected anomalous data points.

Double-click a data point to manually exclude it from the M^2 calculations. Manually excluded points appear gray. Double-click again to include it.



3.7.3 3D Beam Display

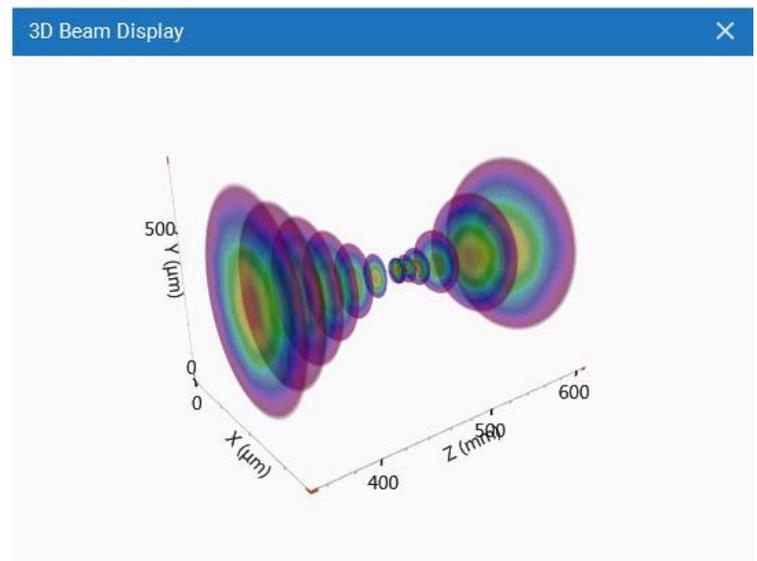


The **3D Beam Display** provides a 3D representation of the beam made up of the frames taken during a run. Each slice represents a data point in the **Measured Caustic Display** plot.

Left-click and drag anywhere in the display to rotate the image.

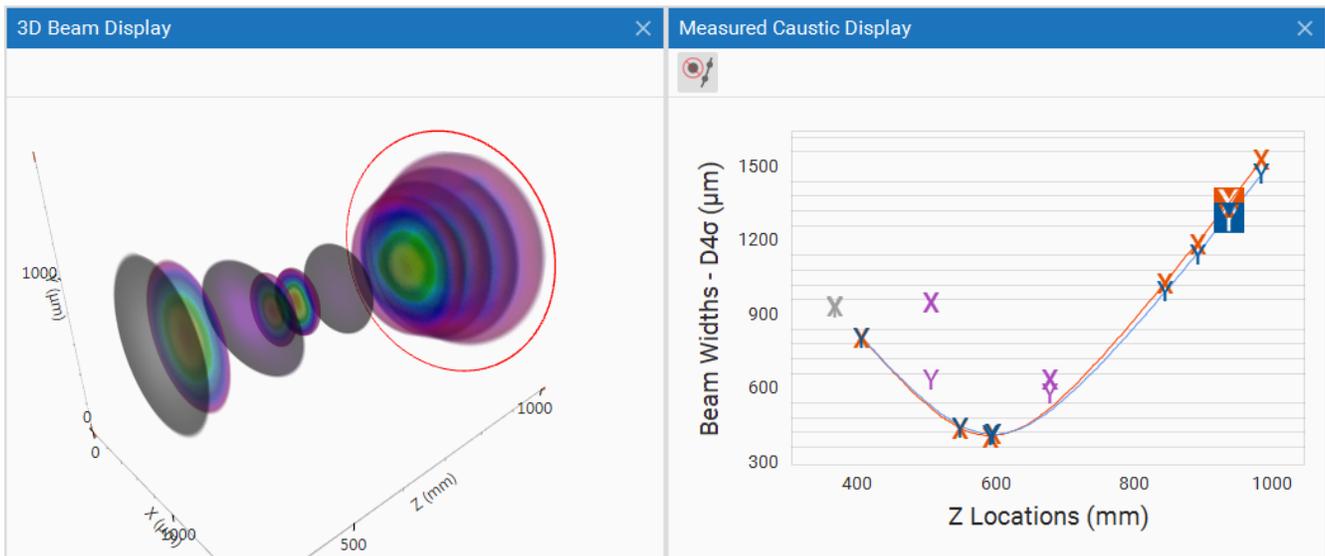
Right-click and drag anywhere in the display to pan the image.

Zoom in and out by scrolling forward or back on the mouse respectively.



Select any point in the **Measured Caustic Display** to view it in the **3D Beam Display**. Selected points are indicated in the **3D Beam Display** by a red circle.

Manually excluded points appear gray in **3D Beam Display**, automatically excluded points appear purple. In the example below, the first point has been manually excluded and the third and seventh points have been automatically excluded.

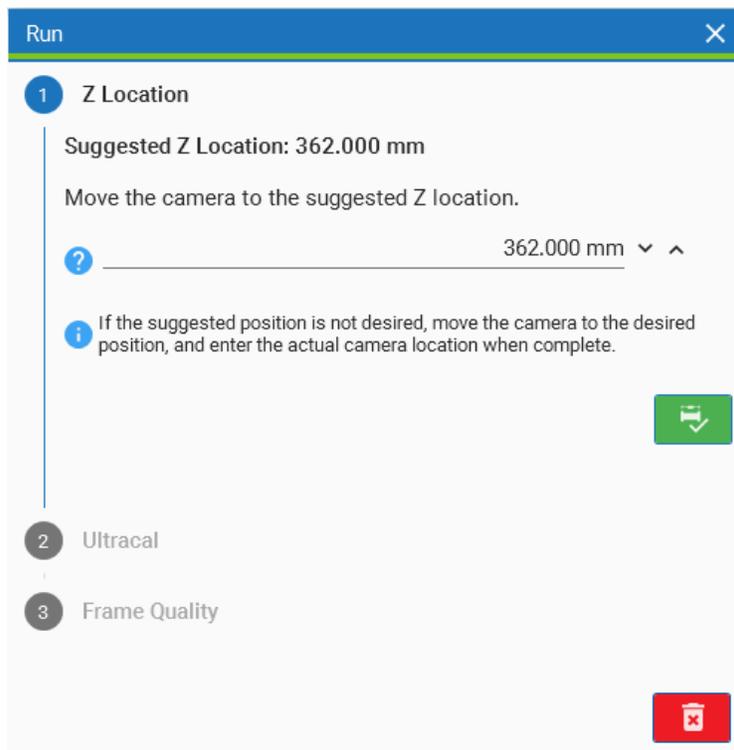


3.7.4 Run Steps



This button opens and closes the **Step by Step** wizard. To start a run, click **Start** in the **Source** ribbon or step through the **Configuration** wizard by clicking **Configure**. When a run is completed, the wizard closes. If the window is closed before the run is finished or aborted, it can only be reopened with the **Run Steps** button.

For more information on the **Step by Step** wizard, refer to section 4.2.2.



3.7.5 Results



The **Results** window displays all enabled results items. Most items can be disabled and each group can be collapsed using the caret icon at to the left of each section header.

Results items are separated into the following groups:

- Frame (Quantitative)
- Laser
- After Lens
- Twist
- Hardware Settings
- Real-Time*
- Positional Stability*

Click to collapse

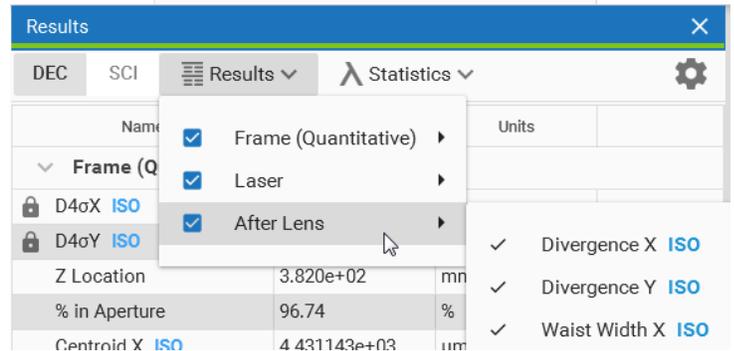
Name	Value	Units
Frame (Quantitative)		
D4σX ISO	4.428e+02	μm
D4σY ISO	4.236e+02	μm
Z Location	3.820e+02	mm
% In Aperture	96.74	%
Centroid X ISO	4.431143e+03	μm
Centroid Y ISO	2.793322e+03	μm
Peak Loc X ISO	4.442760e+03	μm
Peak Loc Y ISO	2.771190e+03	μm
X-Sec Area ISO	1.473e+05	μm ²
Sequence ID	3.000	
Width	1,928	
Height	1,448	
Timestamp	9/13/2016 10:22:2	
Pixel Scale	3.690	μm
Bits per Pixel	12	
Total ISO	18,371,128.06	cnts
Avg pwr Density ISO	1,697.95	cnts
Peak ISO	3,260.75	cnts
Min	-15.66	cnts
Laser		
After Lens		

* These results groups only appear when operating in their respective modes.

Enable or disable results items by selecting the **Results** drop-down at the top of the window.

The next to the group heading enables or disables all results in the group.

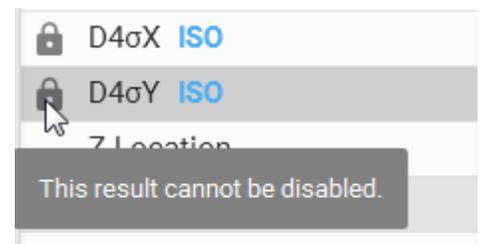
Hover over a group heading to open the list of all items in that set. Select an item to enable/disable it.



Results can also be disabled by hovering the mouse on the result item and selecting the close icon that appears next to the title. A **Close** tool tip appears below the icon.



Certain results are locked and cannot be disabled. Locked results display a .



Frame (Quantitative)

The **Frame (Quantitative)** results are computed in real-time when in **Live Playback** mode or for the selected data point in the **Measured Caustic Display** window. This group provides the basic beam calculations. When viewing a data point from a run, the Z location of that point is also shown. During **Live Playback** mode, these results may not be very meaningful although they do provide an idea of how high or low the peak energy is relative to camera saturation.

Result Name	Description
Beam Width	Measured beam width based on the selected beam width basis.
Z Location	The camera location when the frame was generated, measured from the lens.
% in Aperture	The percentage of the total frame energy that lies inside the aperture.
Centroid	The center of mass of all pixels within the aperture.
Peak Location	The pixel location inside the aperture that has the highest intensity.
X-Sec Area	The cross-sectional area of the beam contained by the computed beam width.
Sequence ID	The ordered sequence ID of the frame.
Width	The width of the frame based on the unit of measurement selected.
Height	The height of the frame based on the unit of measurement selected.
Timestamp	Indicates when the current frame was generated.
Pixel Scale	The pixel scale value of the camera used when the frame was generated.
Bits per Pixel	The bits per pixel of the camera used when the frame was generated.
Total	The sum of the digital counts of all of the pixels within the aperture; represents the intensity of the beam.
Average Pwr Density	The total beam intensity divided by the cross-sectional area.
Peak	The digital count of the pixel with the highest intensity within the aperture.
Min	The digital count of the pixel with the lowest intensity value within the aperture.

Laser

Results in the **Laser** group contain computed values for the laser under analysis. Both the X and Y axial results are computed where applicable. These items are:

Result Name	Description
M²	The beam propagation ratio.
BPP	The beam parameter product.
Divergence	The far field divergence of the laser. If the result name appears as Fitted Divergence , it denotes that the divergence results are obtained from the fitted curve rather than the beam width values at the lens focal length.

Waist Width	The waist width of the laser.
Waist Location	The location of the laser's waist measured from either the laser faceplate or BeamSquared reference datum.
Rayleigh Length	The Rayleigh length of the laser.
Astigmatism	A computed ratio indicating the degree to which the laser X and Y waist properties exhibit astigmatic behavior.
Signed Astigmatism	A computed ratio indicating the degree to which the laser X and Y waist properties exhibit astigmatic behavior. Can be either positive or negative depending on whether the X or Y axis comes first. If the Y axis comes first, the result will be negative.
Asymmetry	A computed ratio of the X and Y waist widths.
K	The beam propagation factor.

After Lens

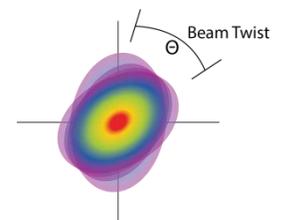
After Lens results are the computed results for the laser beam propagation after the lens. These properties are referred to as the "artificial results" since they only apply to the focused beam propagating in the 2 space. These items are:

Result Name	Description
Divergence	The artificial far field divergence.
Waist Width	The artificial waist width.
Waist Location	The artificial waist location measured from the lens.
Rayleigh Length	The artificial Rayleigh length of the focused laser.
Astigmatism	A computed ratio indicating the degree to which the artificial laser X and Y waist properties exhibit astigmatic behavior.
Asymmetry	A computed ratio of the artificial X and Y waist widths.

Twist

When a **Beam Twist** measurement is taken, it looks at **Ellipticity** first and then **Orientation**. If the **Ellipticity** is greater than 87% the beam is considered circular by ISO standards, and **Beam Twist** is not measured. If **Ellipticity** is less than 87% then the **Beam Twist** is measured by the degree of the change in Orientation.

The **Beam Twist** result is a pass/fail result. If it is greater than 10° the result turns red and the laser results do not meet ISO specifications.



Result Name	Description
Ellipticity	Only active when Beam Twist is active. The computed ratio of the major and minor beam widths of an elliptical beam. Beams with Ellipticity greater than 87% are considered circular by ISO standards.
Orientation	Only active when Beam Twist is active. The angle between the horizontal axis of the camera, and the major axis of an elliptical beam. Can be negative or positive.
Beam Twist	The rotational change in orientation for an elliptical beam.

Hardware Settings

The **Hardware Settings** group displays information about the BeamSquared system and lens in use when the data was obtained. These are for reference only.

Result Name	Description
Z Lens	The calibrated Z_{lens} distance of the BeamSquared unit.
Z Fixture	The calibrated Z_{fixture} distance of the BeamSquared unit.
Z Camera	The calibrated Z_{cam} distance of the BeamSquared unit.
Effective Focal Length	The wavelength-corrected focal length of the lens.
Back Focal Length	The calibrated back focal length value of the lens at the calibration wavelength.
Center Thickness	The center thickness of the lens.
Lens Material	The substrate of the lens.
Calibration Wavelength	The wavelength used to calculate the calibration focal length of the lens.
Calibration Focal Length	The calibration focal length of the lens at the calibration wavelength.
BeamSquared Serial Number	The serial number of the BeamSquared unit.
Laser Model	The user-entered laser model information. This value can be changed in the Run Info dialog box.
Laser Serial Number	The user-entered laser serial number. This value can be changed in the Run Info dialog box.
Camera Model	The camera model in use.
Camera Serial Number	The serial number of the camera in use.



The hardware settings were not saved with the data file prior to version 2.5 and therefore the values will not be displayed unless the data was collected using version 2.5 or later.

Real Time

Real Time results only appear when the application is running in Real Time M² Mode (section 4.1.5).

Result Name	Description
Divergence	The far field divergence of the laser. If the result name appears as Fitted Divergence , it denotes that the divergence results are obtained from the fitted curve rather than the beam width values at the focal length.
M²	The beam propagation ratio.

Positional Stability

When the **Positional Stability** window is open an extra set of results become visible in the **Results** window (section 3.7.6).

Result Name	Description
Center	The coordinate position of the centroid of the histogram.
Azimuth	The angular direction of movement.
$\Delta x / \Delta y$	The computed 4σ of the displacement positional result along the X/Y direction of the azimuth angle, orthogonal to the axis of the azimuth, and radially when the distribution of the motion is random and lacks a clearly definable azimuth direction.
Δs	The Δs standard deviation represents the radial Positional Stability value when the histogram plots a radially symmetric or random scatter plot having no meaningful azimuth angle.
Sample Size	The total number of data points in the histogram. Once 1000 frames are logged frames begin logging in a first in, first out method. A minimum of 1000 samples is required to satisfy the ISO requirement for the results items.

3.7.5.1 Result Settings



Select the **Settings** icon  to open the **Results Settings** window. These settings govern how results are calculated and displayed.

Beam Width

Beam Width Basis defines the method of how the beam width is calculated. Only beam width measurements that emulate the second moment are ISO approved for propagations analysis (D4 σ and ESPA Programmable). Knife Edge methods provide strong results and may be used when the standard beam width measurement methods appear to produce anomalous results. In some cases the caustic may not re-draw unless the beam width basis is changed.

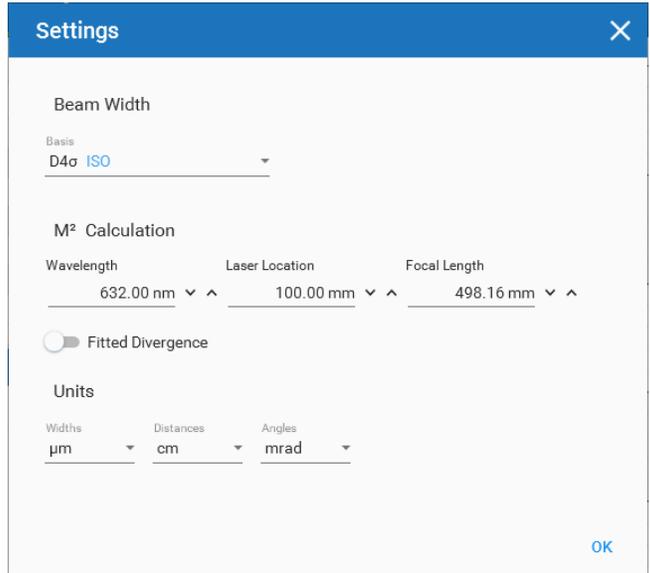
M² Calculations

The **Wavelength**, **Laser Location**, and **Focal Length** values are entered in the **Configuration** wizard. They are repeated here for reference and can be updated here if a value is entered incorrectly.

Check the **Fitted Divergence** box to calculate the divergence from the curve fit rather than the actual data point at the lens focal length. If the focal length is not accessible, the software automatically uses the fitted divergence. When enabled, the divergence result name changes to **Fitted Divergence** to indicate that the results were from the fit and not from a direct measurement.

Units

Select the desired units for calculating width results, distance results, and angle results. Changing the width and distance units also updates the **Measured Caustic Display** axes.

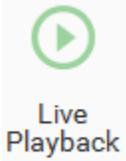


BeamSquared obtains the lens focal length and other lens information from a RFID feature that is integrated into the lens holder. If the system is operated at a different wavelength than where the lens was measured, the software automatically corrects and applies the corrected focal length information to the M² measurement application.

3.7.6 Positional Stability



Some laser beam centroids can drift over time. The **Positional Stability** chart is a 2D histogram plot of the movement of the centroid location. This type of chart can convey the relative motion of the beam in space. The chart granularity, or bucket, is sized based on the dimensions of the camera pixel. The colors indicate the number of times (frequency) that the computed centroid falls within the area of a pixel. The color palette follows what is selected in the **2D Beam Display** window. However, the palette is automatically ranged where the highest color intensity (usually white) is always applied to the bucket with the greatest population, and lower valued populations are proportionally spaced across the lower colors.



Remove the lens from the BeamSquared unit and select **Live Playback** from the **Run** ribbon to begin collecting **Positional Stability** data. **Positional Stability** cannot be enabled with the lens inserted.

This figure shows the **Positional Stability** histogram for a beam that displays negative angular movement in relation to the camera's X-axis.

The icons in the top left are specific to this window.



Reset

Clears the chart and results.



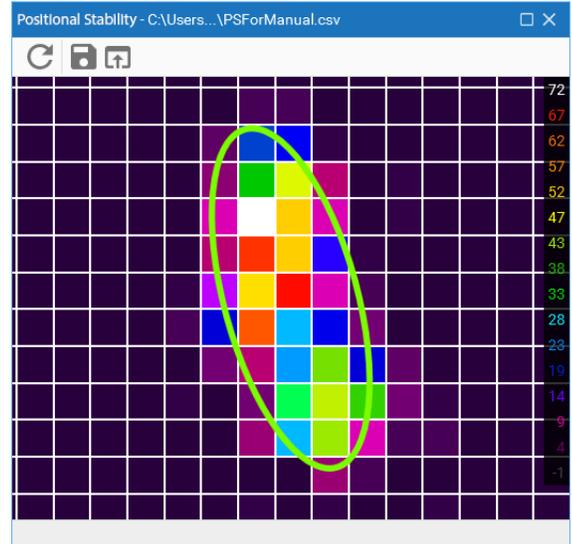
Save

Opens **Windows Explorer** to select a location to save a .csv file of the results.



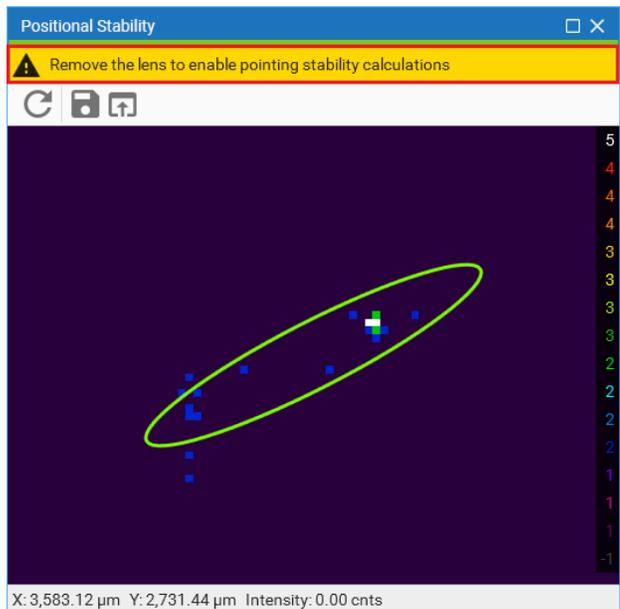
Load

Opens **Windows Explorer** to load a previously saved chart file.



If the lens is inserted, a yellow bar displays above the chart space meaning that **Positional Stability** cannot be run. Once the lens is removed the bar disappears and **Positional Stability** can be started by selecting **Live Playback**.

If a file is loaded and **Live Playback** is enabled, the file closes, the chart space resets, and begins collecting new data.

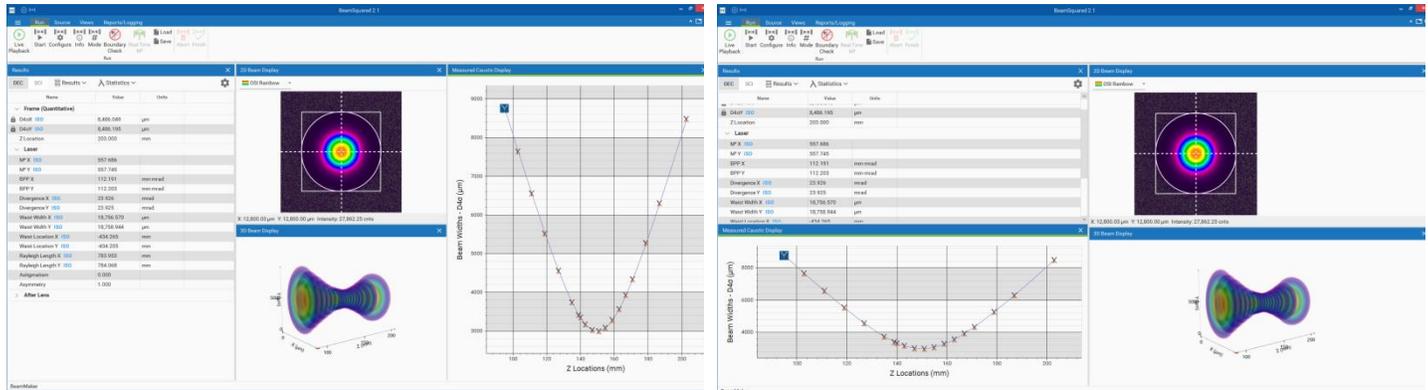


3.8 Interface Customization

BeamSquared has the ability to create flexible display environments to meet the user's specific needs. All windows can hide, float, and reposition on the screen. The application opens with the same configuration as when it was closed.

Default Layout

Custom Layout

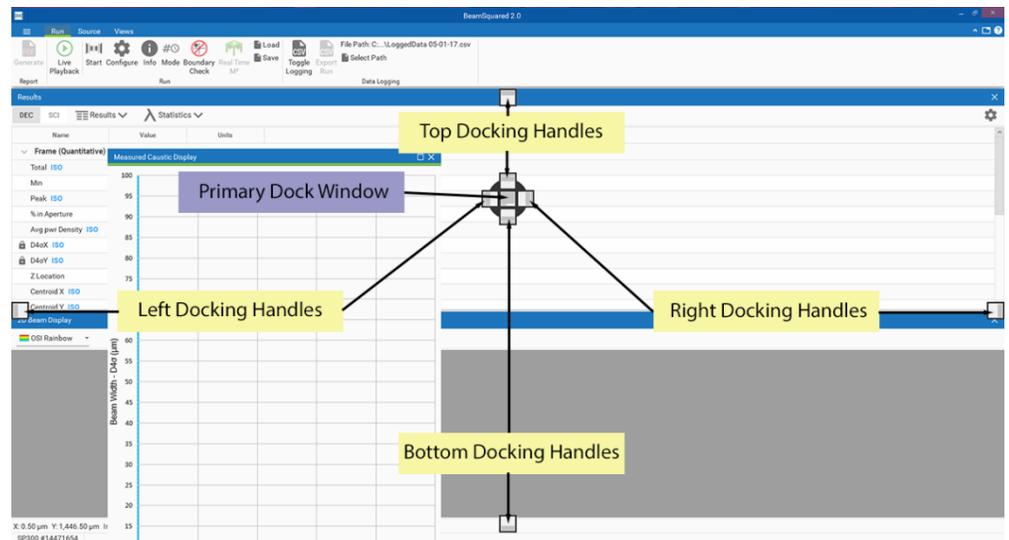


3.8.1 Docking Handles

To undock a window, grab the tab with the mouse and drag down into the window area. When dragged, a set of docking handles appear as shown. In this example, the **Measured Caustic Display** window is being dragged. Drag the display over one of the dock handles and release to place the window in that position. If the window is not released on one of the dock handles, it floats. All windows can be docked to any of the display handles or left to float anywhere on the screen.

Each window has its own set of dock handles, allowing child windows to be docked within each new window. Windows can be placed side by side, and over and under each other.

Floating windows can be maximized to fill the screen. They can also be re-docked into the main application by dragging the title bar into the main display window and dropping on a dock handle.



Chapter 4 Operation

4.1 Operating Modes

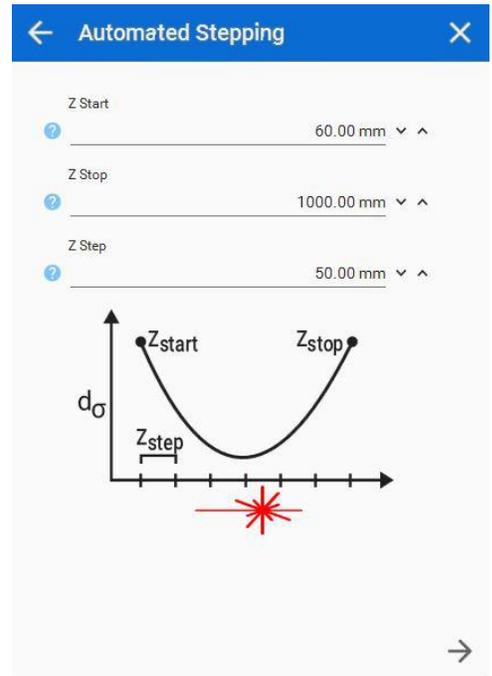
BeamSquared has five operating modes which give the user control over the measurement process and provide short cycle times for making M^2 measurements. The first four are found in the **Configuration** wizard, while the fifth is only accessible after an M^2 test is complete.

4.1.1 Automated Stepping

The **Automated Stepping** method allows the user to make a minimum number of input settings and obtain a reasonably fast set of M^2 results. The user sets the range over which the beam samples are acquired and the basic step distance between data points in the **Z** value edit controls.

Cycle times can be quite long if the user does not optimize **Z Start**, **Z Stop**, and **Z Step**. Making M^2 runs with 20 to 50 data points (much more than the 11 required by ISO) takes a significant amount of time to complete. Excessive samples may degrade the results.

This is the primary intended use of the BeamSquared system and provides the most accurate results that are ISO compliant.

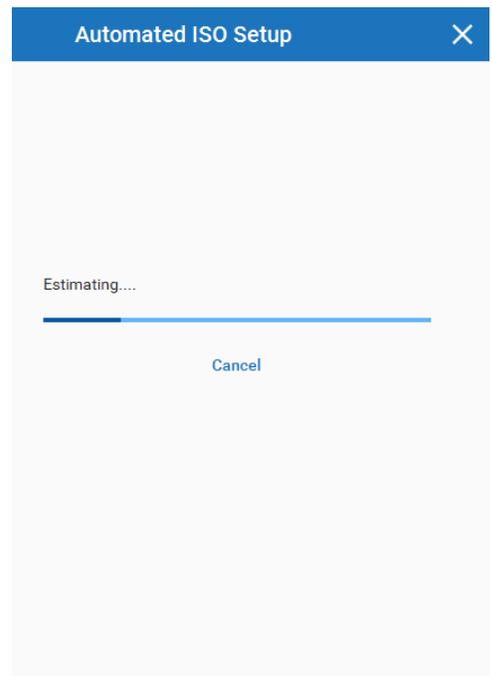


4.1.2 Automated ISO Setup

The **Automated ISO Setup** method was introduced for users desiring guidance in setting up the point locations for an M^2 run that conforms to the minimum ISO requirements. This method does not require any inputs from the user as it performs an initial scan of the beam propagation path to determine the point locations needed to conform to the minimum ISO requirements.

If the minimum ISO requirements can be determined with the current configuration, the **Automated ISO Setup** method will populate the **Step Table** with the recommended 11 points. The points are distributed according to the ISO 11146 specification with five points taken around the waist, five points taken beyond two Rayleigh lengths, and one point at the focal length of the lens. The user may modify the **Step Table**, if desired, before starting the run. Additional information on adjusting the **Step Table** is described in section 4.1.4.

If the minimum ISO requirements cannot be determined during the initial scan, the **Automated ISO Setup** method will populate the **Automated Stepping** inputs with the recommended **Z Start**, **Z Stop**, and **Z Step** values. The user may modify these values, if desired, before starting the



run. Additional information on adjusting the **Automated Stepping** values is described in section 4.1.1.

4.1.3 Four Cuts Method

The second mode operates off a novel, but non-ISO method. This method requires special setup conditions but in return can perform M^2 runs faster than other modes. The basis for this approach was introduced by Thomas Johnston.¹ This method teaches that making four well-chosen samples of the caustic provides an accurate set of results in much less time than the standard ISO method. Extensive testing by Ophir has shown that under most conditions the results correlate well with the ISO method.

BeamSquared has modified the method by taking 6 cuts. The nomenclature of Four-Cuts is maintained to preserve the link to Mr. Johnston and his original thesis. 6 cuts are used to account for the different X and Y axial results and to incorporate the direct divergence measurement at the lens focal length. Mr. Johnston persuades that the best place for taking the first 3 samples is between .5 and 2 Rayleigh lengths from the waist. Experimentation has shown that making these measurements in the far field region works just as well if not better.

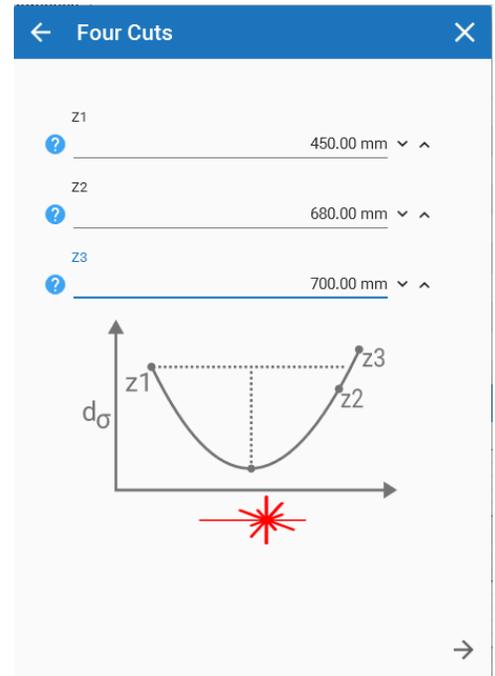
If the beam is highly astigmatic, the four-cuts method has been known to fail. In this case, the X and Y waist locations are far apart and it is difficult to find the 3 starting cut points that satisfy the initial conditions.

As part of the **Configuration** Wizard shown in section 4.2.1, the user must establish the first three Z cut points:

- Z1 should be selected before the waist.
- Z2 and Z3 should be selected after the waist relatively close together.
- Z2 should have a smaller beam width than Z1, and Z3 should have a larger beam width than Z1 as shown in the graphic in the Wizard (shown to the right).

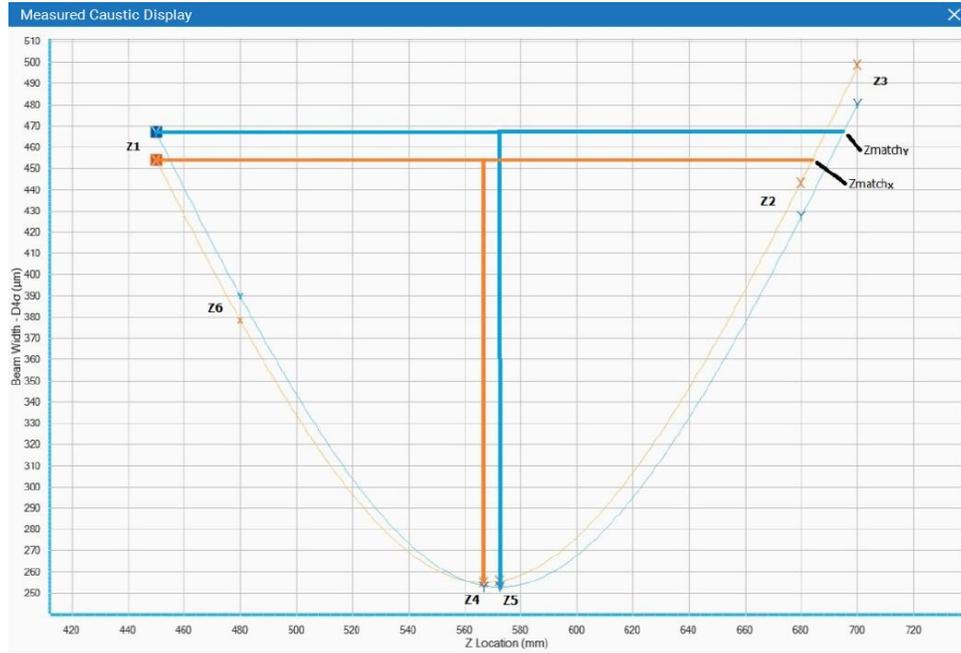
These conditions must apply to both the X and Y beam width plots. This is why only low astigmatic beams work with this method.

The Z locations for the first 3 cuts are entered into the configuration dialogs. These positions are used to predict the location of the X and Y waist locations, cuts Z4 and Z5. Measurements are performed at these locations and a final sample is taken at Z6, the lens focal length. A least squares hyperbolic fit to the data is performed and the final M^2 results computed.



¹ Published in *Beam Propagation (M^2) Measurement Made as Easy as It Gets: The Four-Cuts Method* published in the journal *APPLIED OPTICS* / Vol.37, No.21 / 20 July 1998.

The basic layout of the four-cuts method applied to a beam caustic plot in both the X and Y axes is shown.



4.1.3.1 When to use the Four-Cuts method

The Four-Cuts method may be employed when you have the following prior knowledge of the beam:

- The beam caustic shows little to no astigmatism.
- Or, if astigmatism is present, the X and Y divergence values are somewhat similar so as to keep the 3 data points beyond the Rayleigh range of both caustics.

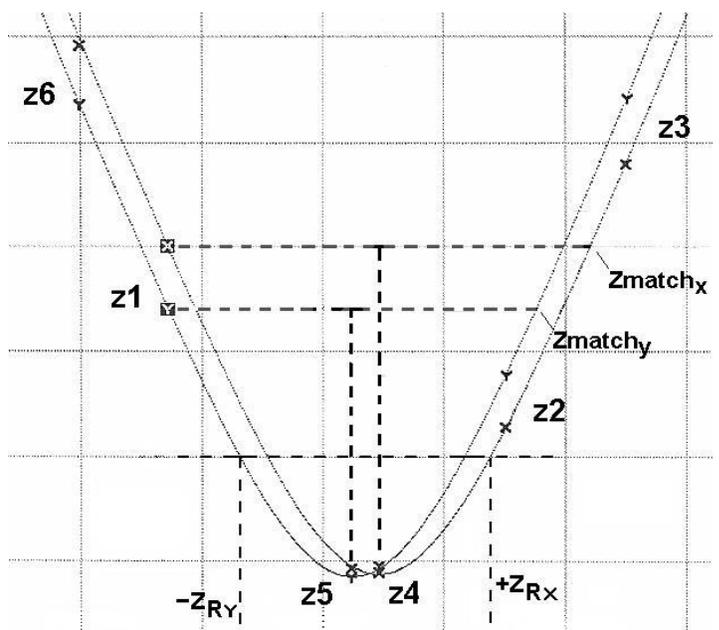
In all cases, the user must have a general knowledge of approximately where the focused waists are located and the Rayleigh lengths. A standard M^2 measurement should be performed on the actual, or similar, beam to obtain this information.

4.1.3.2 Four-Cuts on Two Axes

BeamSquared always treats lasers as if they have two orthogonal axes. Because of this, the Four-Cuts method is expanded further, and computes results separately along the X and Y axes.

This figure shows how the two axis samples are taken. In this example, the beam has little astigmatism, and the divergence is similar in each axis. The z1, z2, and z3 cuts are placed beyond the Rayleigh regions and apply the ZRY boundary on the left and the ZRX boundary on the right.

The z4 and z5 samples represent the computed X and Y waist locations, respectively. The z6 location is at the lens focal length.



When z2 and z3 are placed close together without crossing the Z match planes, the waist locations, z4 and z5, are calculated with higher accuracy. This occurs due to the curvature of the calculated fit between z2 and z3. When placed in a region of greater curvature (such as occurs inside the Rayleigh lengths), the linear interpolation becomes less precise with respect to the real curve.

4.1.4 Step Table

The **Step Table** allows each data point to be entered in manually which permits every beam propagation measurement to be taken at the same locations in the Z axis. Include as many or as few data points or Z locations in the **Step Table**.

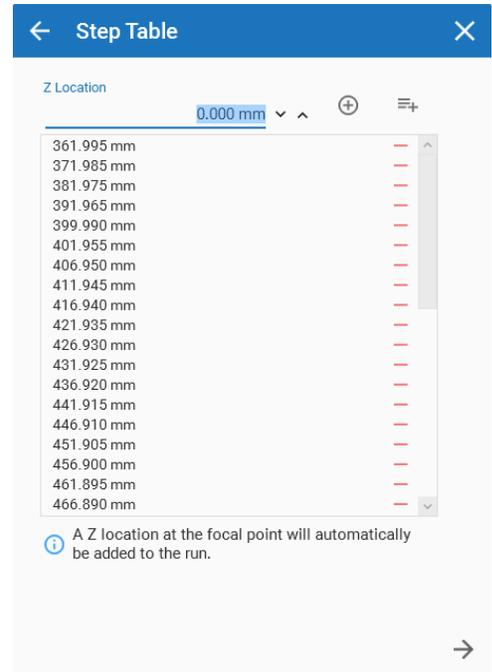
To minimize measurement time and optimize the measurement accuracy it is recommended the same scrutiny is used when selecting the Z locations for the **Step Table** as for any other method.

Start and **Stop** locations as well as the number and location of additional steps must follow the same criteria as mentioned for the other measurement methods.

Data points can be typed into the **Z Location** entry field or adjusted by increments of 1 with  . Select **Enter** or **Add Z Location**  to add a value to the list.

Fill From Run  fills the table with the Z locations from the last run.

Select the **Remove Z Location** icon  on any data point that is not desired to remove it from the list.



4.1.5 Real Time M² Mode



The **Real Time M²** mode provides continual, real-time monitoring of a laser beam. It may be used to monitor a laser while the laser cavity is under adjustment, providing a fast M² estimate to the technician during the tuning process. It may also be used to monitor laser output under normal operating conditions or may be used to monitor laser stability over any time span.

This technique has reduced accuracy and is not ISO compliant. It should not be used as a substitute for standard M² measurements. After laser adjustments are complete, another standard M² measurement should be made in order to obtain actual results.

Real Time M² only becomes available after a successful M² data collection run has completed. When enabled, the translation system places the camera at the focal length of the lens, sets the internal attenuation, and performs an Ultracal baseline calibration. It then computes, in real-time, the current divergence value and the estimated M² along

both the X and Y axes. The new M^2 value is estimated based on the change in beam divergence and the results from the previous run.

During laser cavity tuning, the **2D Beam Display** window becomes a valuable tool. This beam profile shows the energy distribution across the laser beam. Changes in the laser mode, optics, and beam energy can often be first observed here. Separate real-time results list appear in the **Results** window. Prior M^2 results are retained for comparison purposes.



Press the icon when it is green to start **Real Time M^2** . Press the icon when it is red to stop.



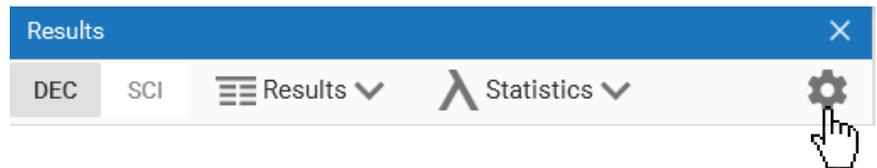
If the tuning operation continues for a long period of time, the camera baseline calibration may drift and cause errors in the results.

4.2 BeamSquared Operation

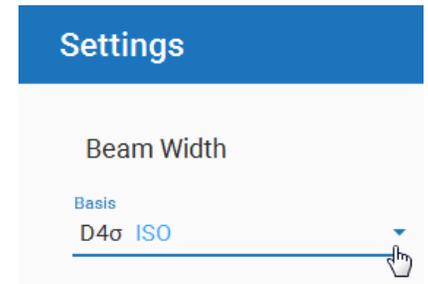
4.2.1 Configuration Wizard

The **Configuration** wizard walks the user through system settings to provide accurate results from an M^2 run.

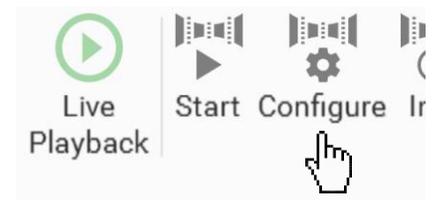
1. Select **Settings** from the **Results** window.



2. Select the desired **Beam Width Basis** method (see section 6.1.2.2).



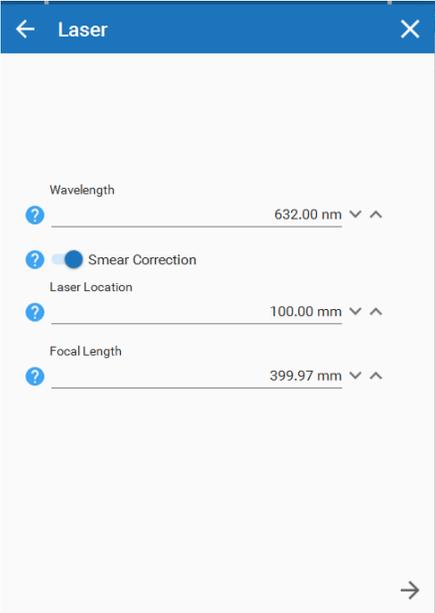
3. Select **Configure** from the **Run** ribbon to launch the **Configuration** wizard.



4. The **Run Info** screen that appears is optional. Values entered are included on the report. Select the arrow at the bottom of the window to continue.

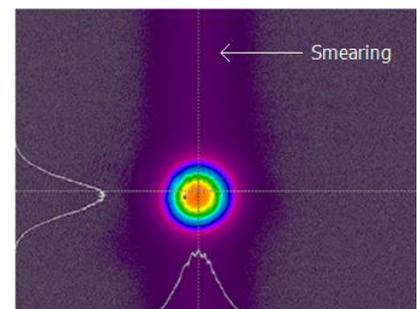


5. The **Laser** screen prompts you to enter information on the laser. These values must be correct to obtain accurate results. Hover over the  to get a description about each entry. This information must be entered for each laser under analysis. Once entered select the arrow to continue.
- Enter the **Wavelength** to get accurate measurements.
 - If you encounter smearing* in the image turn on **Smear Correction**.
 - Enter a value of zero for the **Laser Location** to locate the waist relative to the BeamSquared reference datum (the input aperture on the red BeamSquared case for automatic mode or the lens for manual mode). To locate the waist relative to the laser, enter the distance from the BeamSquared reference datum to the laser faceplate.
 - The Automated BeamSquared system collects the Focal Length from the lens cassette RFID feature and automatically corrects the value based on the entered wavelength.

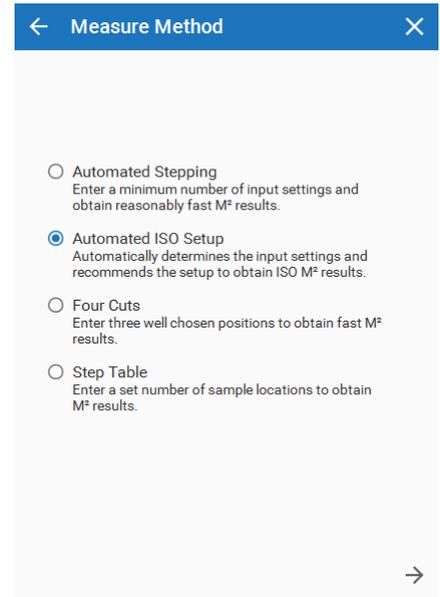


Enter the **Focal Length** of the lens used to create the artificial beam waist in millimeters.

* Smearing manifests as a streak along the vertical axis of the camera. It is caused by an excessive amount of incident power on the sensor, typically as a result of a poor match between the laser wavelength and the camera sensor's quantum efficiency. Silicon-based sensors have high quantum efficiency at visible wavelengths, and InGaAs sensors are most efficient in the NIR and IR range. Therefore, silicon sensors tend to experience smearing in the NIR and IR ranges while InGaAs sensors experience it in the visible.



6. Select the preferred operating mode from the **Measure Method** screen.



7. Enter the values for the selected method:

- a. **Automated Stepping** method



To obtain accurate waist location results, the distance from the front principal plane of the input lens to the sensor image plane of the camera must be accurately measured for each data frame and input as the Z location.

Selecting Automated Stepping Values

- i. Move the rail to either position "A" or until the beam fills about 2/3 of the camera's imager to get the **Z Start** value. All data runs must start somewhere between the focused beam waist and the lens.



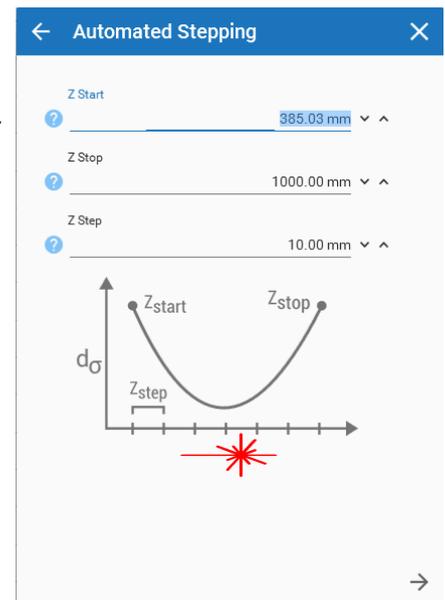
Enter the Z distance of the first measurement location as measured from the lens to the image plane of the camera sensor.

- ii. Move the rail to either the "B" position or until the beam fills about 2/3 of the camera's imager on the opposite end of the rail to get the **Z Stop** value.



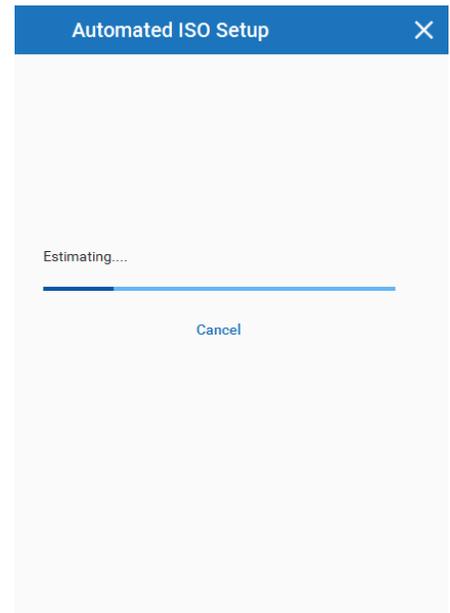
Enter the Z location that corresponds to the last measurement location of the sensor image plane as measured from the lens.

- iii. **Z Step** values vary by beam. Values between 30-50mm are typically appropriate. If your beam focuses quickly a smaller **Z Step** should be considered. If the **Z Step** value is too large a warning appears notifying that the step size may be too large to obtain enough points to meet the ISO specification.



b. **Automated ISO Setup** method

- i. No additional inputs are required when using this method. The software performs an initial scan of the beam and populates either the **Step Table** or **Automated Stepping** values with the points recommended to achieve an ISO measurement.



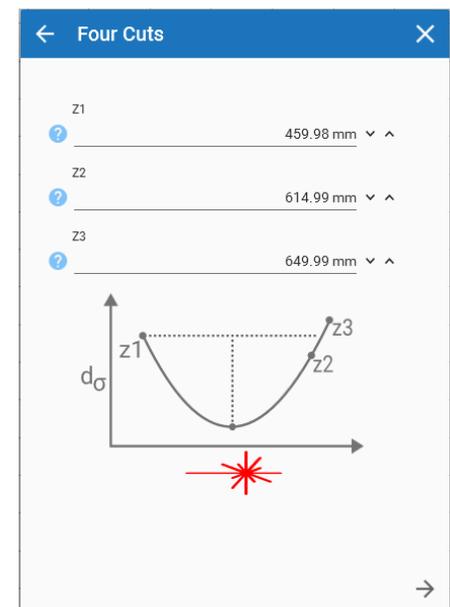
Automated ISO Setup is not available in Manual mode.

c. **Four Cuts** method

Choosing Four Cuts Values

- i. The **Z1** should be a point selected somewhere before the waist.
- ii. The **Z2** should be a point beyond the waist where the beam width is smaller than at **Z1**.
- iii. The **Z3** should be a point selected beyond the waist and should be a value close to **Z2** where the beam width of **Z1** falls between the widths at **Z2** and **Z3**.
- iv. The remaining cuts are populated automatically by the software.

If these criteria are not met, the wizard fails and an error appears, terminating the run. Should this occur, reenter proper values.



*During a run, the software usually prompts the user to collect point **Z6** after **Z1**. The run fails if **Z2** is taken instead of **Z6**.*



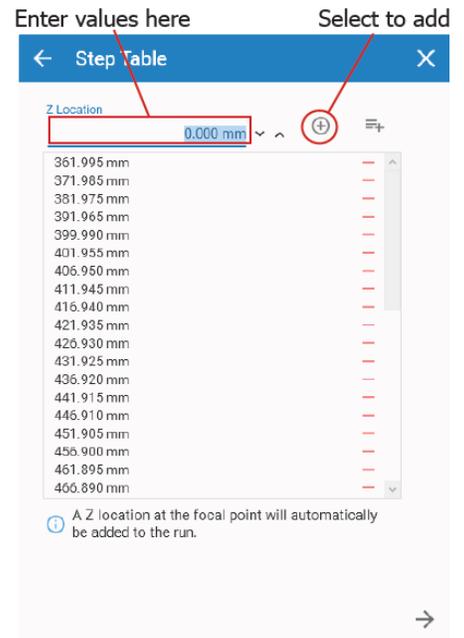
The Four Cuts method is not ISO standard but can supply quicker results that are just as accurate.

d. **Step Table** method

Choosing Step Table Values

Step Table works best if used after an automated run. This is the optimal way to statistically compare results from multiple measurements. Select **Fill From Run**  to auto-fill the data points from the last run.

Another option is to enter the data points manually. A minimum of 4 data points is required. The system encourages at least 11 to meet ISO standards. Make sure that the minimum and maximum points entered do not exceed the capabilities of the translation table. Select  to remove data points.



8. The final screen of the wizard allows you to select the run mode. Select **Single Run** to run a single test, **or Multiple Runs** to run many. Select the check mark to exit the Configuration Wizard and start a run.

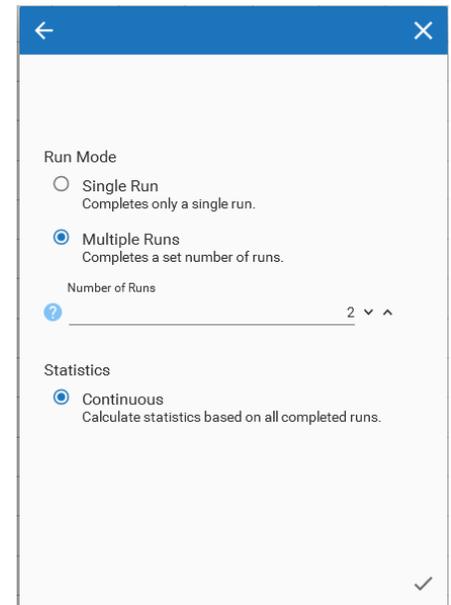
Selecting **Multiple Runs** opens additional settings. You can set the **Number of Runs** in the field. **Multiple Runs** gives the user statistical analysis of the enabled measurements. **Statistics** is always set to **Continuous**.

Statistical results contain the following items:

- Mean
- Standard Deviation
- Minimum
- Maximum

Statistics are only computed for the M² results items, not for the individual frames.

Statistical results are computed based on the number of M² data collection runs. At the conclusion of a statistical run, only the last run is saved. All prior data is lost.



4.2.2 Step by Step Wizard

After completing the **Configuration** wizard, the **Step by Step** wizard opens automatically in a new display window. Clicking **Start** in the **Run** panel also opens this wizard with the last used or loaded settings.

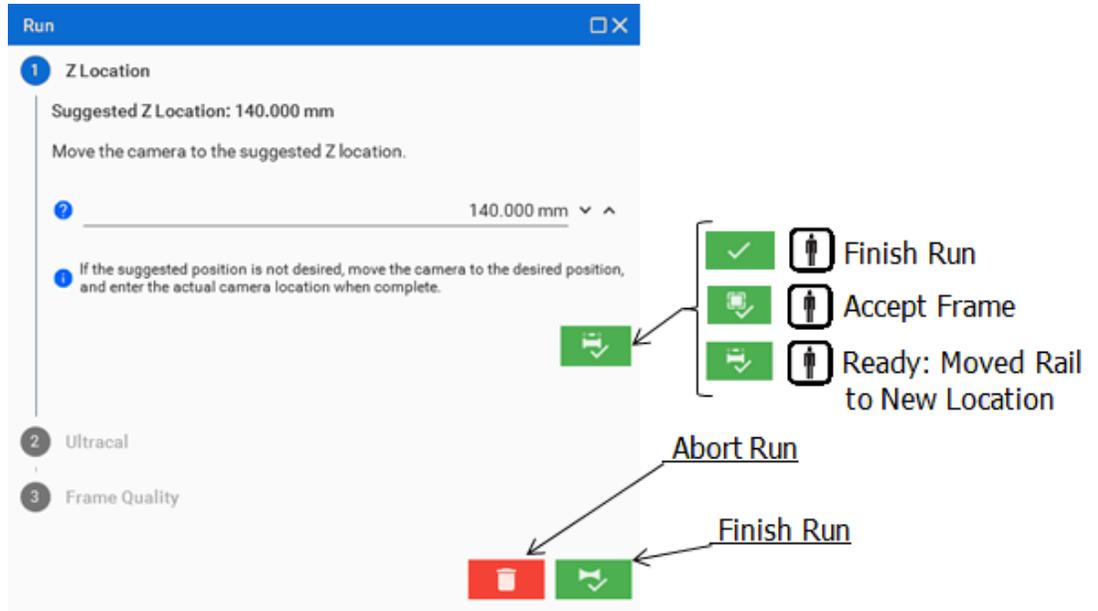


Verify the desired lens is inserted into the BeamSquared and secured with the lens screws. The BeamSquared software requires information stored on the lens holder and cannot initiate a run without the lens properly secured.



During the M^2 run, the system prompts you to move the camera to a series of locations. At your discretion, accept and use the suggested value or move the camera to a different location and enter the custom position.

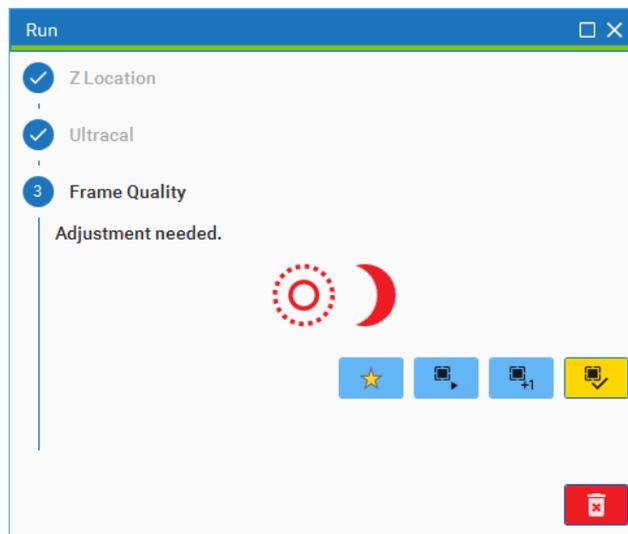
At any point, the run can be aborted by clicking the **Abort Run** button at the bottom of the window. If the window is closed before the run is complete or aborted, reopen it through the **Views** panel. Until the run has concluded, other controls are unavailable.



The **Finish Run** button does not appear until a beam caustic is computed.

Frame Quality

The software performs an image quality check and indicates if there are any recommended corrections.



A frame that has quality issues can still be accepted, but doing so is discouraged. The possible warnings are:



Misaligned – The edge of the beam has reached at least one edge of the sensor. Measurement accuracy could be degraded. Accept frame or abort the run, adjust the setup, and take a new measurement. Selecting **Disable Boundary Check** will suppress this message.



Too dim – The peak beam energy is below 50% of the camera’s dynamic range. Reduce attenuation of the beam, accept frame, or abort run.



Too small – The calculated beam diameter is below 10 pixels. Measurement accuracy will be lost. Accept frame or abort the run; adjust the setup and take a new measurement. This can be done by using a longer focal length lens or by moving the BeamSquared unit to where the beam has diverged less, and the beam at the input aperture is smaller.



Too bright – The peak beam energy is above 90% of the camera’s dynamic range. Add additional attenuation to the beam, accept frame, or abort run. **Failure to properly attenuate the beam may cause damage to the camera.**



Too big – The edges of the beam have reached the edges of the sensor. Measurement accuracy could be lost. Accept frame or abort the run; adjust the setup and take a new measurement.



Ultracal™ – If the camera exposure setting is changed during the run, a new **Ultracal** cycle must be performed before the frame can be accepted. Click **Redo Ultracal** to initiate the process. **Ultracal** is also used to compensate for small changes in the camera baseline due to changes in the camera temperature. This is caused by the camera’s natural warm up time or by ambient temperature changes.



As soon as a good frame is found, live playback stops. The user then has the following options:



Redo Ultracal – If the Ultracal cycle removed the beam or another error occurred, click this button to return to the **Ultracal** step. Block the beam to start the process.



Accept Frame – Accept the current frame and move on to the next Z location. If the beam has quality issues, this icon turns yellow. A frame cannot be accepted if live playback is running or if a new Ultracal is required. When accepting the frame on the last data point of the run, the **Step by Step** wizard automatically closes.



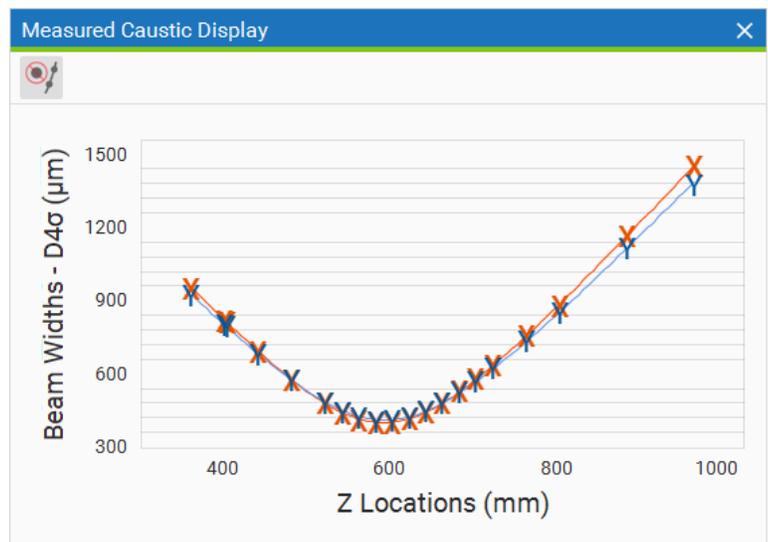
Live Playback – Re-enable live playback to view the beam in real-time.



Single Frame – Collect a single new frame from the camera.

After the setup completes, each accepted data point appears in the **Measured Caustic Display** window. An estimated curve appears as soon as enough data accumulates, stabilizing as the run progresses. The results also update as the collection process continues.

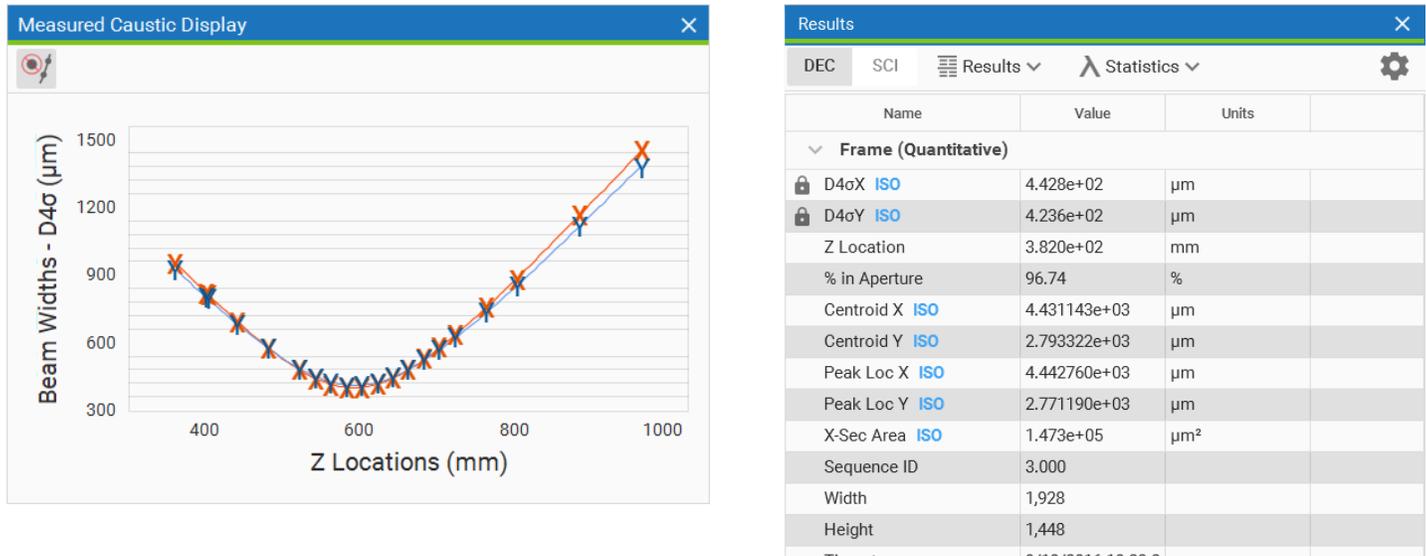
At the completion of a run, the data can be saved to a file for further analysis.



4.3 Data Collection in Auto Mode

Select **Start** from the run ribbon to begin collecting frames. The system activates and begins collecting frames until the run is complete or you select **Pause**.

Data points begin to be plotted on the **Measured Caustic Display**. A curve fit plot appears when the system has acquired enough data to make a strong estimation. The results update as data is collected.



4.4 Useful Operations and Functions

The following information describes topics that may be of less obvious value to the user.

4.4.1 Z Locations

During an M² run, some Z locations may not provide reliable measurements. The frame quality check in the **Step by Step** wizard notifies when concerns are detected.

When configuring **Start** and **Stop** locations there are inaccessible locations at each end of the translation space. The **Start** location must be greater than the minimum accessible location and the **Stop** must be less than the maximum.

4.4.2 Plotted Curve Fit

The X and Y axis results are reported and computed simultaneously. Two data points for each location and two plotted fits to the data appear in the caustic window. This plot shows the beam widths as functions of Z location. Z location is the distance from the lens to the camera image plane, so the plot has reference to the focused beam as seen in the beam sampling diagram below.

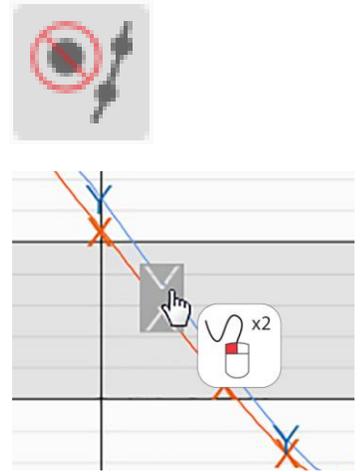


If using the EPSA beam width basis, the X and Y values in the caustic plot will overlap. Because of the always circular beam width measurement method, both axes will always report the same values. Thus it is only recommended for use with round beams.

4.4.3 Exclude Data Points

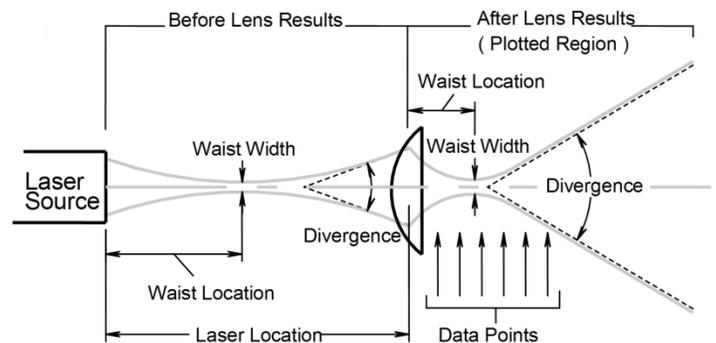
If the **Auto Outlier Removal** feature is enabled in the **Caustic Beam Display** window, the application will automatically remove data points that appear to be anomalous. Points that have been automatically removed will show up in the plot window as Purple X's and Y's. At the end of a run it is also possible to manually exclude data points. To do so, double click these data points. Manually removed points appear gray. Double click the point again to re-enable it. All points that have been removed, whether manually or automatically, are excluded from the M^2 calculations.

Outlier data points appear for a number of reasons. One of the most common occurs when a pulsed laser is triggered asynchronously to the video camera's scanning rate. Under this condition, distorted images may result. Sometimes these images are good enough to make it into the data plot.



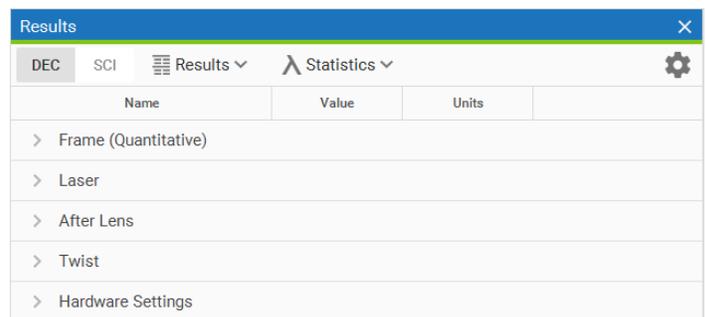
4.4.4 Interpreting Results

Three main windows in the BeamSquared software provide feedback to the operator. The **2D Beam Display** window shows the energy distribution profile of the beam. These are cross-sections of the beam at various distances (Z locations) after the lens (the "Data Points" in the image right). The X and Y widths of the beam at each of these locations are plotted in the **Caustic Beam Display** window, while the results are displayed in the **Results** window.



The five main results groups in the **Results** window provide information about:

- The current beam profile's Quantitative results
 - The **Frame (Quantitative)** group contains information about the currently selected beam measurements.
- The laser's M^2 analysis results
 - The **Laser** group contains information about the beam before the lens as calculated from the **After Lens** results.
- The laser's After Lens results
 - The **After Lens** group contains information about how the beam performs after passing through the lens as directly measured. This information is used to determine the actual laser propagation parameters including waist width, waist location, and divergence angle.
- Off Axis results
 - The **Twist** group contains information about the beam's Ellipticity and orientation.
- The settings used in data collection



- The **Hardware Settings** group contains information about the hardware setup when the data was taken.

4.4.4.1 Divergence

For the most accurate measurement of divergence, a data point should be taken at the focal length of the lens.

If it is not possible to obtain beam width measurements at the focal length of the focusing optic the software will use a Fitted Divergence feature.

Fitted Divergence calculates the divergence from the curve fit rather than the actual data point at the focal length.



Be sure to use converted focal length when measuring wavelengths other than the wavelength where the lens focal length was provided by the manufacturer.

Chapter 5 M² Tutorial and Theory

5.1 Introduction to M²

The M² model is the accepted standard for characterizing the general performance (or “quality”) of a laser beam. This one quantity, in each of the two orthogonal propagation planes, ties together the three interrelated beam parameters of beam waist width, divergence, and Rayleigh range. This measurement is based on how a real laser compares to a single mode beam. A single mode beam (referred to as the fundamental mode or TEM₀₀) has an M² value of 1. Beams of higher order mixed modes have an M² value greater than 1.

The M² value for a given laser beam is derived from propagation theory and is referred to as the “beam propagation ratio.” One practical consequence of the M² definition is that a beam with an M² value of 1 can be focused to a minimum spot diameter, whereas beams of higher M² values focus to larger spot diameters in proportion to the M² value. For example, a beam with an M² value of 2 will have a minimum focus spot 2 times as large as a Gaussian beam of M² = 1. Thus, knowledge of the M² value can provide meaningful information about lasers, especially if their application involves small focused spot sizes.

A second notation for beam quality has also been adopted. It is referred to as the Beam Propagation Factor (K) where: $K = 1/M^2$. And a third representation called the Beam Parameter Product (BPP) has come into use, where: $BPP = M^2\lambda/\pi$. BeamSquared calculates and reports all three values.

For the remainder of this discussion, we will only refer to the M² form.

The International Organization for Standards (ISO) subcommittee on electro-optical systems has created a standard for test methods relating to the measurement of laser beam parameters. BeamSquared employs algorithms that conform to the methods described in the ISO 11146-1 and 11146-3:2005(E) procedures. Copies of the measurement standard can be procured from ISO.

ISO 11146-1 describes the method for characterizing stigmatic and simple astigmatic beams. BeamSquared is designed to measure these types of lasers.

ISO 11146-2 details the method for characterizing general astigmatic beams (twisted beams). BeamSquared is not capable of measuring this class of laser.

ISO 11146-3 describes general measurement methods.

5.2 M² < 1

It has been suggested that if the M² results are computed to be less than one an M² = 1.0 should be displayed as the answer. The BeamSquared algorithms use the input settings and collected data points to make all calculations. No attempt is made to change or conceal data. This is done to provide useful information to the user and may indicate an error in the setup or input values.

There are two common occurrences when M² results are less than one. The first and most common is an incorrect wavelength entry. The wavelength can be corrected in the **Results Window Settings** (see section 3.7.5.1).

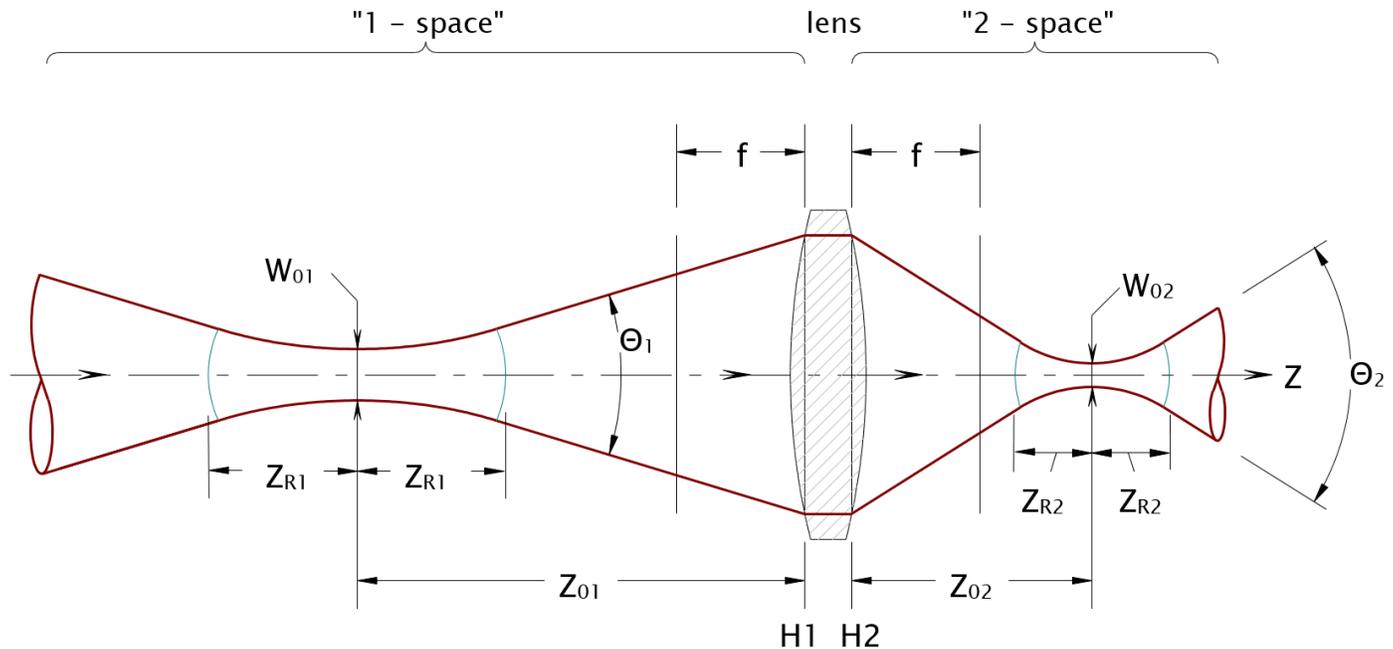
The second main cause for M² results less than one is due to nominal accuracy tolerances. These are normal and expected. Within the measurement tolerance, results can vary ±5%. Here the M² is likely to be between 0.99 and 0.90.

5.3 Laser Beam Parameters

Three parameters predict how a radially symmetric beam will propagate, namely:

1. Waist width (W_0)
2. Waist Location (Z_0)
3. Far field divergence angle (Θ)

Non-radially symmetric beams are characterized by a set of these parameters for both the X and Y axes. Since the methods for measuring the X and Y axes are the same, only one set will be referenced in the following descriptions.



The term beam width is used instead of beam diameter or radius since traditional beam measurement practices compute full beam widths along both X and Y axes. Also, beam diameter and beam radius suggest that the beam is circular. A laser may be circular, but this is considered to be a special case.



Different conventions and symbols are utilized by various authors. In the descriptions that follow we use W to represent the full beam width, while ISO uses d_{ox} and d_{oy} for the full beam widths and d_o for diameter and others use W or w to represent $1/2$ the beam width (or radius).

Θ is used to describe the full angle divergence. An "f" is used to indicate the focal length of the lens.

When a beam is transformed through a lens the input beam parameters are designated by a 1 and the output parameters are designated by a 2.

All distances are described along the axis of propagation or Z axis and are measured relative to the locus of the transforming lens. Distances z_1 are measured before the lens and z_2 measured after passing through the lens.

W_0 and Z_0 represent a beam waist width and its waist location, respectively. Z_R is used to represent the Rayleigh length from the beam waist location Z_0 . In the ISO procedures subscripts x and y are added to represent the axial directions. Only one axis is described here so the subscripts are omitted.

The below equations are applicable for the beam on both sides of the transforming lens as shown in the figure above.

Equation 1 – Beam Propagation

Given the three values (W_0 , Z_0 , and Θ), the beam width (W) can be predicted at any location (z) along the axis of propagation via the beam propagation equation:

$$W(z)^2 = W_0^2 + \theta^2(z - Z_0)^2$$

Equation 2 – Beam Propagation Ratio

The beam propagation ratio (M^2) is defined by the equation:

$$M^2 = \frac{W_0 \theta \pi n}{4\lambda}$$

Where:

- λ The laser wavelength in a vacuum
- n The index of refraction of the medium (assumed to be ~ 1)

Equation 3 – The Rayleigh Length

The Rayleigh length is defined by the equation:

$$Z_R = \frac{W_0}{\theta}$$

5.4 An M^2 Tutorial

In some cases, the preceding equations are used to characterize a propagating laser. The propagation parameters W_0 , Z_0 , and Θ are found using numerical analysis, and from these values M^2 , K , BPP, and Z_R are calculated. Measuring and finding the beam propagation parameters for a given laser system is difficult, if not impossible. Factors that limit the ability to characterize a laser include:

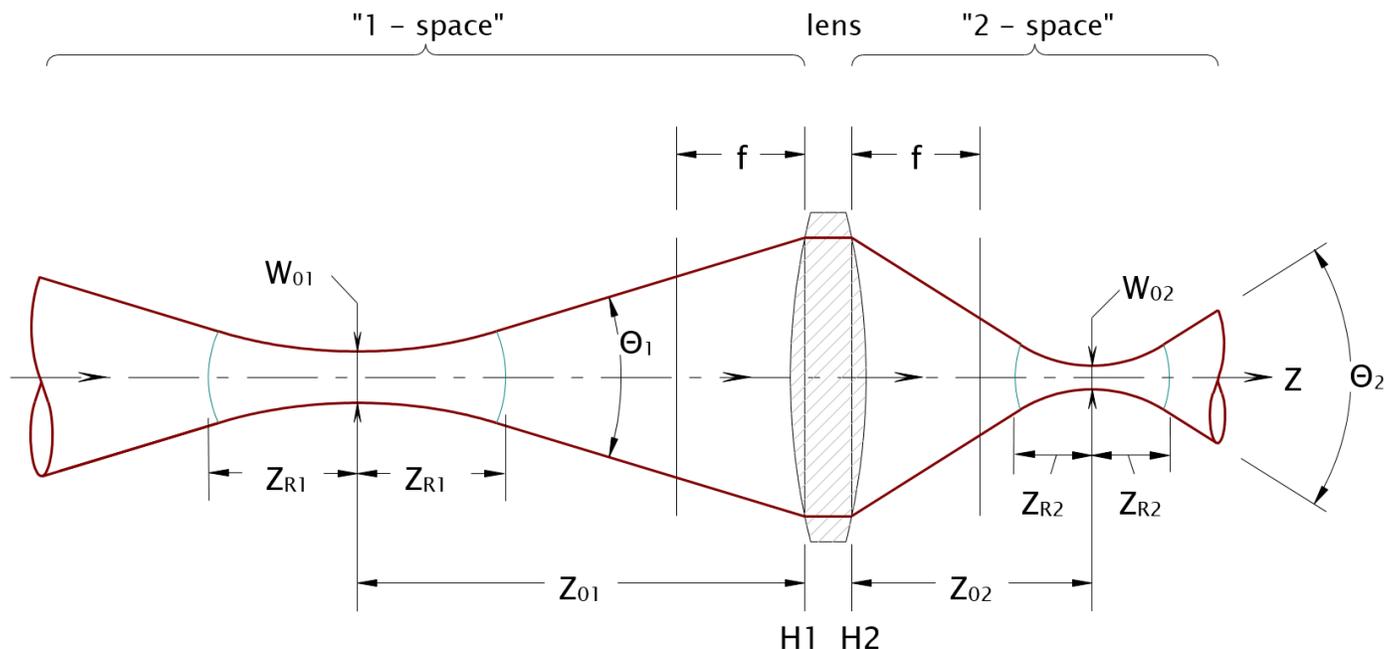
- The laser waist is in a non-accessible location, such as inside the laser cavity.
- The waist does not exist in real space, but rather behind the laser cavity in virtual space.
- The beam has a large W_0 making it difficult to locate with great precision. This causes a decrease in Θ and an increase in Z_R .
- The beam is too large to realistically measure using readily available detection methods.

These difficulties are solved by creating a measurable artificial waist via a simple focusing optic. This artificial waist retains all the fundamental properties of the original beam. In this new form, the beam is measured and mathematically transformed to reveal the input parameters.

To obtain a correct transform of the laser requires the focusing lens to be aberration free. Aberrations degrade beam quality and produce inaccurate results. To minimize this degradation, it is recommended to use a thin plano-convex lens with an $f\# \geq 20$.

5.4.1 The Transforming Lens

In the figure below, assume the input beam shown to the left of the focusing optic is a fundamental mode Gaussian beam. The beam is shown propagating to the right. The beam's wavefront radius of curvature is becoming shorter as the beam propagates towards the waist until it reaches Z_R , the Rayleigh length. After the Rayleigh length, the radius of curvature begins to increase until at the waist location, Z_0 , where the radius of curvature is infinite. As the beam passes through the waist the radius of curvature shortens until it reaches Z_R on the opposite side of the waist. Past Z_R the radius of curvature once again begins to increase towards infinity.



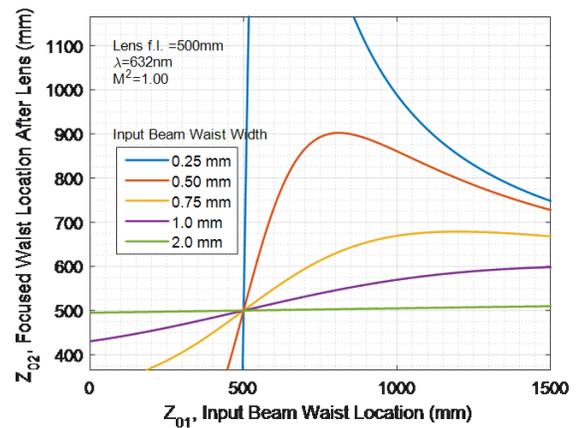
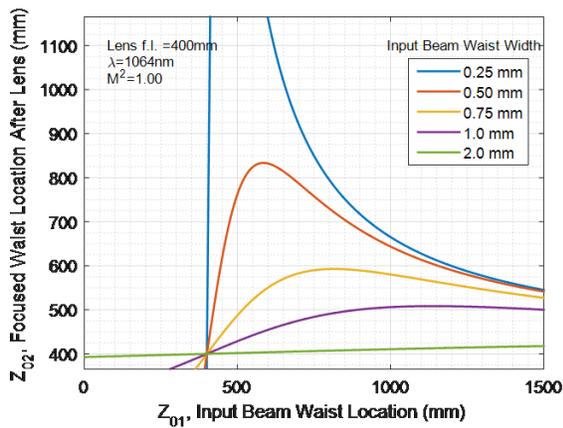
The changing radius of curvature of a propagating laser results in some non-intuitive behavior when applied to a measurement device that transforms with a focusing lens. The position of the focusing lens, relative to the input beam's waist, can alter the location of the waist formed after the lens, sometimes dramatically.

ISO 11146 instructs that at least 11 samples are required to make an accurate M^2 measurement, with a minimum of 5 taken within $\pm Z_R$ from the waist and 5 taken beyond $\pm 2Z_R$ from the waist.

The figures below show how the focused waist location moves relative to the input beam waist location for a range of input beam waist widths. Preferable placement of the input beam's waist is where Z_{01} is at least equal to the focal length of the lens. Observe that for small beams in this region, there is a drastic change in Z_{02} with small changes in Z_{01} . In these scenarios, Z_{01} is better situated farther from the lens.

Under most circumstances Z_{01} should avoid being less than the focal length of the lens.

Beams with a waist width $\geq 2\text{mm}$ the placement will almost always yield a focus near the lens focal length, thus placement is not critical.



5.4.2 Beam Width Measurement Criteria

All laser beam parameter measurements are computed based on beam width measurements. Therefore, accurate beam width measurements are essential to a high-quality laser propagation measurement system. Additionally, the basis chosen for making the beam width measurement must conform to beam propagation theory.

The beam width measurement method that conforms to beam propagation theory is referred to as the second moment method. One such method is $D4\sigma$, which defines the beam widths as 4 times the standard deviation (σ), evaluated in the transverse X and Y directions over the beam intensity profile. Making this 4σ measurement directly with great precision can be difficult. BeamSquared employs special algorithms that allow it to perform very accurate second moment measurements in accordance with the ISO 11146 procedures.

Under certain conditions, results using direct second moment measurements may be less than satisfactory. BeamSquared has included alternate beam width measurement techniques to compensate for this. These methods degrade accuracy but may provide more correct results when extraneous noise is present in the beam wings. The ISO procedure recognizes the problems with making direct second moment beam width measurements and allows for alternate measurement methods.

The knife edge method is described in the ISO procedure and has been adapted to BeamSquared.

A programmable **Encircled Power Smallest Aperture (EPSA)** beam width method is also included, commonly referred to as Power in a Bucket. A non-visible circular aperture is centered on the beam centroid, and the diameter is adjusted until it contains a percentage of the beam energy. This percentage is entered by the user. Because the aperture is always circular, the X and Y results always reports the same values when using this method. 86.5% is the default value and represents the second moment setting for a TEM₀₀ Gaussian beam.

Whichever method is employed, users should stay with one approach to maintain a good basis for comparison between similar lasers or setup conditions.

See section 6.1.2.2 for more details about the beam width measurement methods.

5.4.3 Spot Size and Resolution

All laser measurement systems have constrained operational limits due to the methods and materials employed. Two such constraints exist in BeamSquared due to the size of the imager and pixel dimensions in use.

1. Large Spot Size – Including frames with beam sizes that exceed 2/3 of the imager may decrease the accuracy of the beam propagation measurement. If the beam does cover 2/3 of the imager, BeamSquared will alert you the beam is too big and that including the frame in the measurement may degrade accuracy. Centered alignment of the beam is also critical.
2. Small Spot Size – Conversely, due to the pixel size, a small beam causes an even greater challenge. Experience has shown that measuring a beam less than 10 pixels wide in either the X or Y direction yields unsuitable results. BeamSquared will not prevent you from making such measurements, but the resulting accuracy will be degraded.

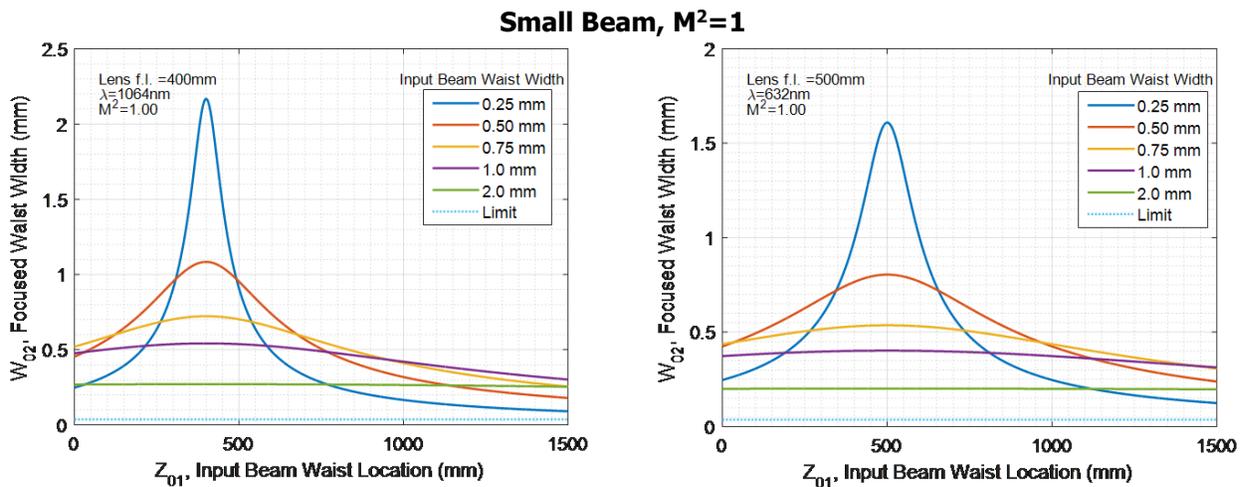


Camera	Pixel Pitch	Minimum Beam Width
SP204S	2.74 μm	27.4 μm
SP920	4.4 μm	44 μm
SP1203	15 μm	150 μm
XC-130	30 μm	300 μm



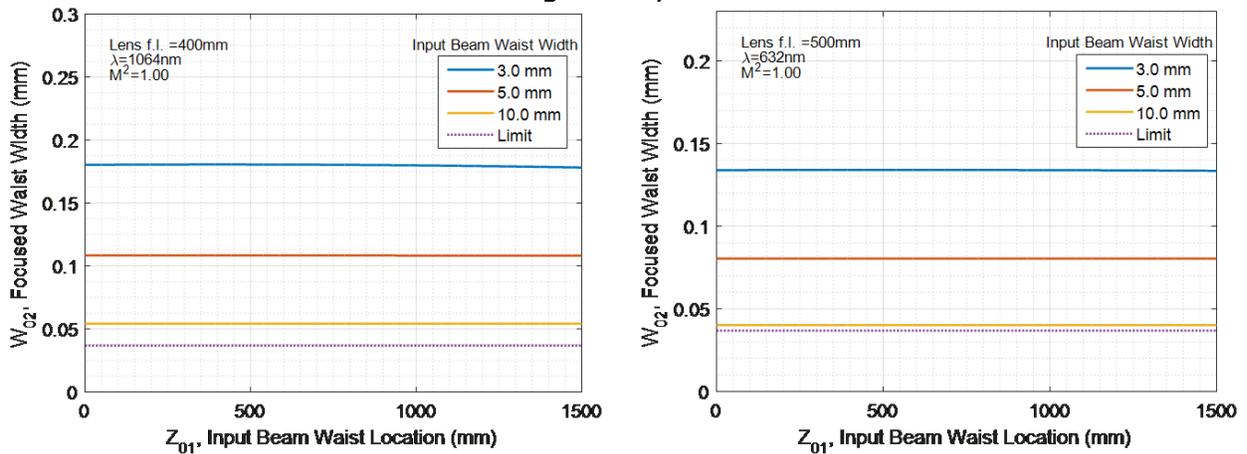
For information concerning the Pyrocam IV and IIIHR, see section 9.2.

The following figures show how the beam width of the focused input laser changes under a range of different conditions. In this image, the focused spot size is plotted against the input waist location for a variety of input beam sizes shown representing only $M^2 = 1$.



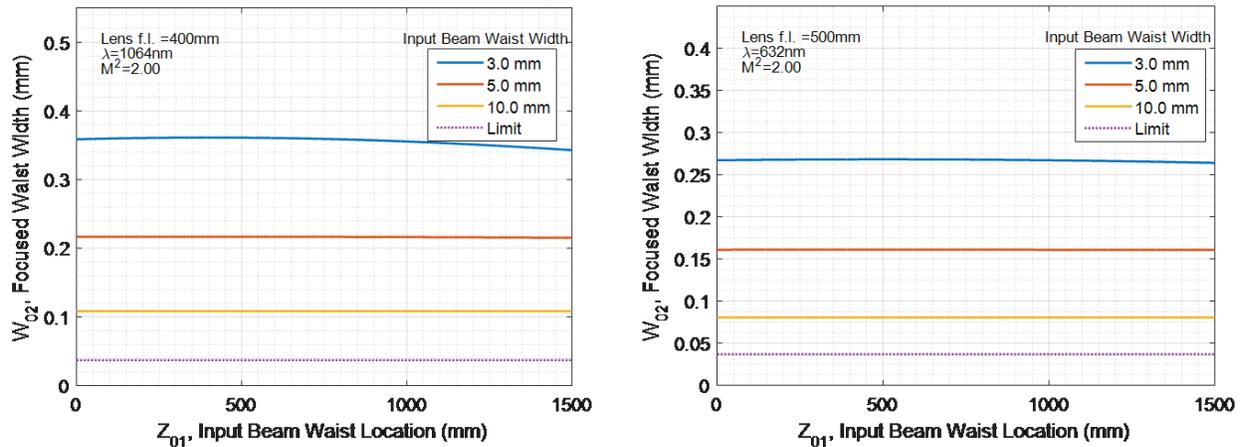
Focused spot sizes are always larger when $M^2 > 1$. This image depicts the focused spot sizes for larger input beam sizes also with $M^2 = 1$. Observe that a 10mm beam is near the resolution limit of the camera.

Large Beam, $M^2=1$



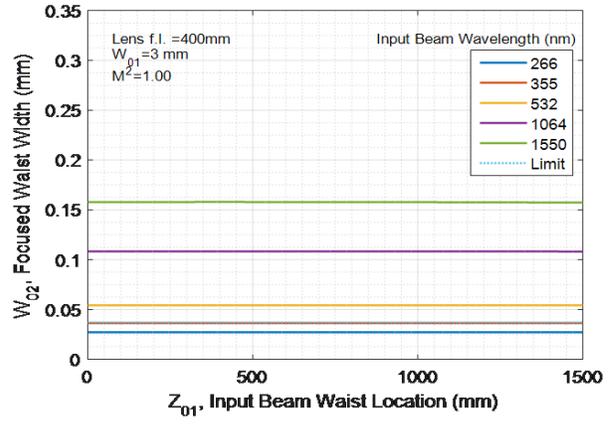
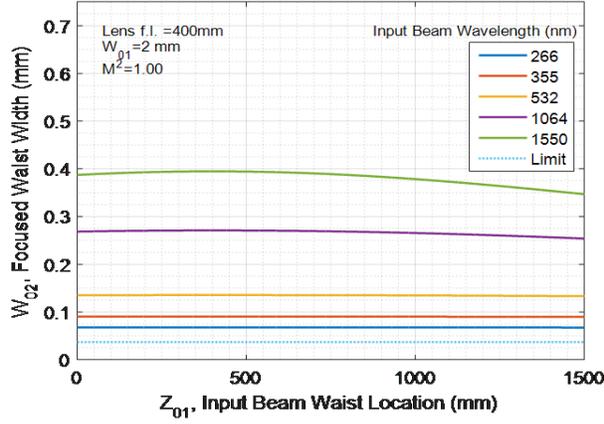
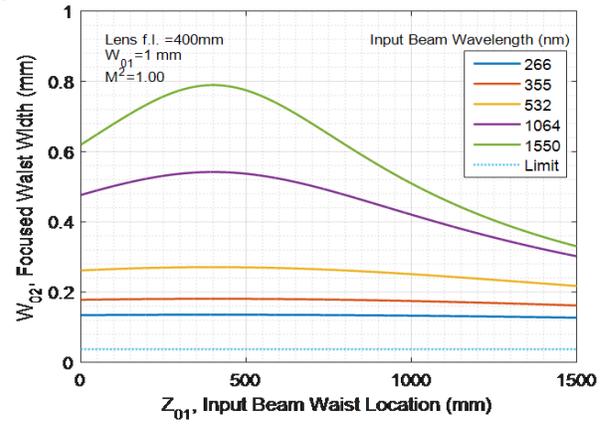
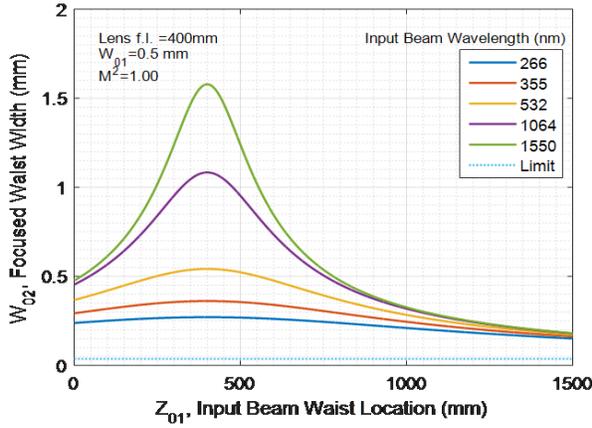
The next image shows these same large beams sizes with an $M^2 = 2$. Now none of the focused spot sizes of these examples are near the resolving limits of the camera.

Large Beam, $M^2=2$

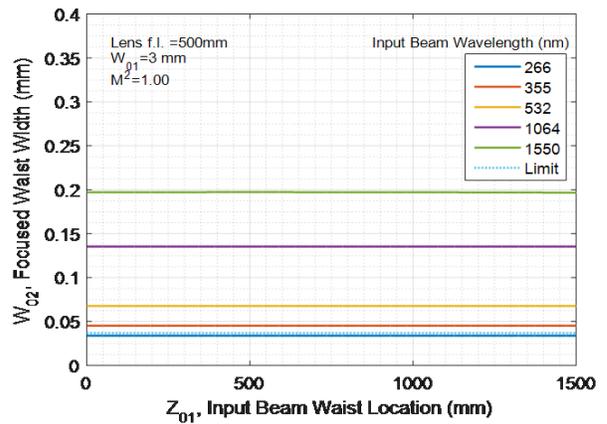
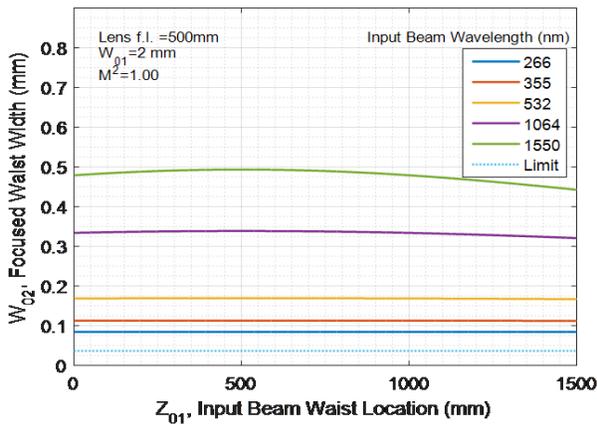
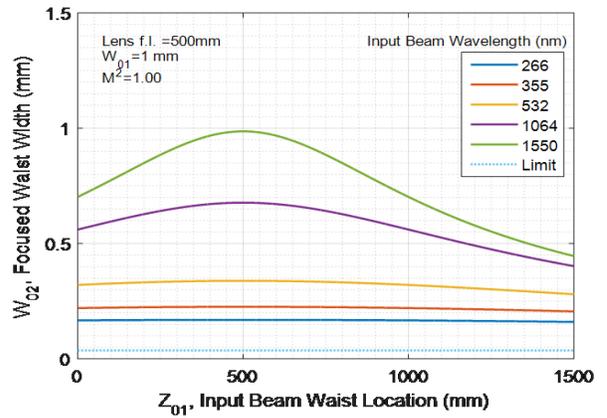
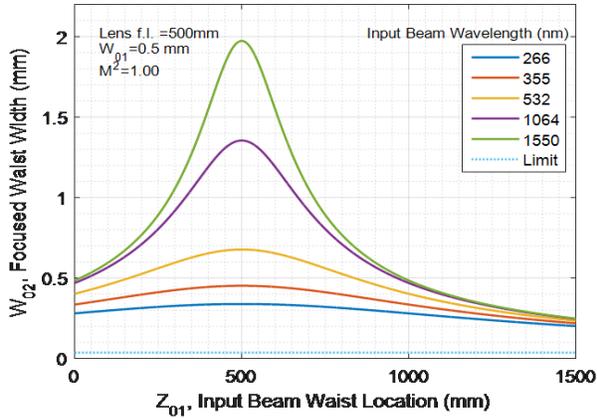


The next set of images demonstrates the effect of the focused spot size for variations in wavelength. Notice that shorter wavelengths focus smaller than longer wavelengths.

400mm Focal Length Lens, $M^2=1$



500mm Focal Length Lens, $M^2=1$



5.4.4 Attenuation and Distortions

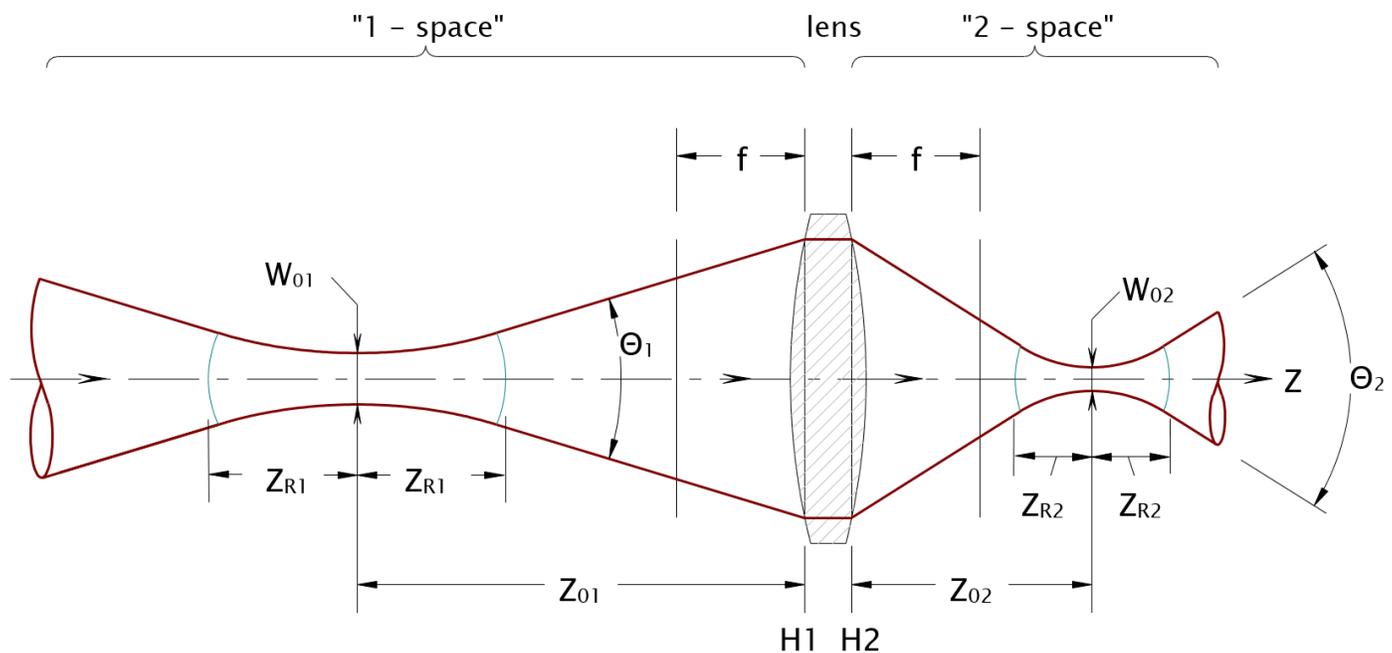
Ideally, no optical devices would be placed in the beam path since these can introduce distortions into the beam. However, most applications require attenuation. It is essential to reduce the total input beam power before the beam enters the camera to avoid damaging the detector.



Damage to the camera may occur if input power exceeds the limits listed in the camera specifications (see Appendix C). Notice that the highest power density levels occur at the beam focus. The camera sensors are very costly to replace and are not covered for damage under Ophir's standard warranty.

5.5 M² Theory of Operation

BeamSquared measures beam parameters by combining an aberration free lens, a detector translation system, and the requirements described in the ISO procedure.



The beam passes through the lens to create an artificial waist, or focus spot. The propagation of the laser beam through a focus has a direct relationship to how the real unfocused beam propagates in space and is described by the same equation used in **Equation 1**. A 2 subscript is used to denote a lens origin and the distance, z , is now measured from the lens.

Equation 4 – Hyperbolic Propagation

$$W_{02}(z)^2 = W_{02}^2 + \theta_2^2(z - Z_{02})^2$$

Where:

- W_{02} The beam width at the artificial waist (the minimum focused spot size)
- Z_{02} The artificial waist location (measured from the lens)
- θ_2 The artificial far field divergence angle

Although the values for W_{02} , Z_{02} , and Θ_2 differ from those before the lens, the M^2 value remains the same. This means the M^2 values remain constant as they propagate through optical devices, so long as those devices do not introduce aberrations. This relationship allows the BeamSquared to analyze the laser beam after the focusing lens and then calculate the beam's actual propagation parameters.

The method used by BeamSquared to determine the size and location of the artificial waist involves taking a series of beam width measurements on both sides of and passing through the artificial waist region. A curve fit is applied to the measured data based on the hyperbolic propagation equation (**Equation 4**). The results of this fit yield the artificial waist width (W_{02}), the artificial waist location (Z_{02}), and the artificial divergence angle (Θ_2). The solutions from the fit are then translated back to the real laser beam.

5.6 Operation Limitations

BeamSquared is subject to limitations not only due to the measurement technique employed, but also those existing in the ISO case of propagation theory. Of the three basic types of aberrations that effect laser beams (mode content, aperture induced diffraction, and optical defects), only mode content is suitable to the current M^2 measurement methods. The latter two types of defects, depending on severity, yield varying degrees of anomalous results using the present methods.

Because BeamSquared computes separate M^2 results for both the X and Y axes, the beam must exhibit either radial symmetry or bi-fold symmetry about these axes. Radially symmetric beams will produce nearly identical results for each axis. And conversely, non-radially symmetric lasers will produce differing results for each axis.

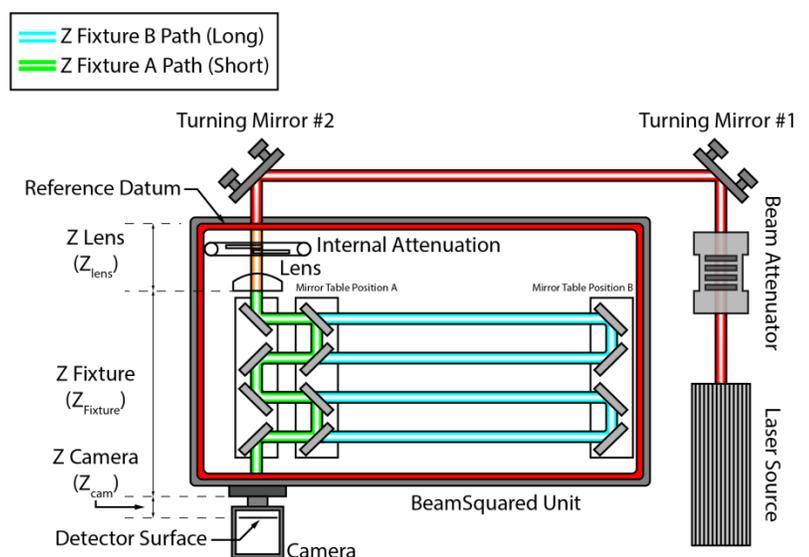
Beams that contain simple on-axis astigmatism are easily measured with BeamSquared. However, beams that are generally astigmatic (or twisted) cannot be accurately measured. If the laser is unstable in mode or wavelength during the measurement period, the measurement accuracy will be degraded.

5.7 Electro-Mechanical Operation

Mirrors effectively translate a stationary camera along the focused beam's optical path.

As the mirrors move from "A" to "B", the camera detects the changing laser beam profile. During the collection process the internal attenuation will automatically adjust for changes in the apparent brightness of the image.

Whenever the background energy of the camera drifts, the software automatically recalibrates the baseline.



5.8 Data Collection

The number of collected data points depends on how the operator configures the system. The operator can program the Z_2 axis data points along the Z axis in a number of different ways. Although collection of a frame exhibiting quality issues is permitted, it is discouraged as measurement accuracy could be degraded. If the frame contains anomalous, or otherwise suspect data points (referred to as “outliers”), the operator should remove these data points from the analysis. For more information on frame quality issues in BeamSquared, refer to the **Frame Quality** step in section 4.2.2.

Once enough data points are collected, the propagation parameters for the input laser beam are calculated, as well as astigmatism and asymmetry ratios. The sampled X and Y beam widths versus the distance from the lens are plotted and the hyperbolic curve fits are drawn. Using this information, measurements are obtained for the actual propagation of the laser (1 space) and the beam formed by the focusing optic (2 space).

To obtain a more accurate measurement, data points should be taken with smaller step sizes near the waist, and larger step sizes in the far field. One measurement should be performed at the focal length of the lens. This provides the focal length divergence results. The number of samples collected affects the time it takes to perform a run.

A standard sample step size of 1/10 the focal length of the lens is suggested to comply with the ISO standard’s recommendation:

“... measurements at at least 10 different z positions shall be taken. Approximately half of the measurements shall be distributed within one Rayleigh length on either side of the beam waist, and approximately half of them shall be distributed beyond two Rayleigh lengths from the beam waist.”

Experimentation has shown that at least five samples should be collected in the near field (within one Rayleigh length), and at least three should be collected in each of the two far field regions (beyond ± 2 Rayleigh lengths).

Chapter 6 M² Computations

This section describes the basic calculations used to compute the M² results. No attempt is made to disclose every possible feature of the algorithms employed, but rather to convey the techniques used that allow the reader to verify conformity to the ISO procedure. All optical and physical calibration values are also discussed in this section.

The computational methods described here apply equally to all the operating modes in BeamSquared.

6.1 Curve Fitting

The collected data points are fit to the hyperbolic beam propagation equation (**Equation 4**, repeated below) using a non-linear least squares technique.

$$W_{02}(z)^2 = W_{02}^2 + \theta_2^2(z - Z_{02})^2$$

The results of the fit yield values for W_{02} , Z_{02} , and θ_2 in both the X and Y axes.

6.1.1 M², K Factor, and BPP

Equation 5 – M² and K Factors

The M² or K factor is computed from the values obtained from the curve fit as:

$$M^2 = \frac{1}{K} = \frac{W_{02}\theta_2\pi n}{4\lambda}$$

Where:

- λ The laser wavelength in a vacuum
- n The index of refraction of the medium (assumed to be ~ 1)

Equation 6 – BPP Factors

BPP is computed from the M² results.

$$BPP = \frac{M^2\lambda}{\pi}$$

6.1.2 Translation Equations

The real laser beam's parameters are computed from the following three equations:

6.1.2.1 Full Divergence Angle

Equation 7 – Full Divergence Angle

$$\theta_1 = \frac{W_{f2}}{f_\lambda}$$

Where:

- W_{f2} The beam width at the focal length
- f_λ The focal length of the lens at the laser wavelength λ

6.1.2.2 Waist Width

Equation 8 – Waist Width

$$W_{01} = \frac{4\lambda M^2}{\pi\theta_1}$$

Beam Width Basis

As discussed in section 5.4.2, $D4\sigma$ is the preferred method for computing a beam width. For beams with M^2 values approaching 1, the Knife Edge 10/90 method is also very accurate.

The **Beam Width Basis** selection determines the technique used to compute the beam width results. Three of the methods ($D4\sigma$, Knife Edge 10/90, and EPSA) are computed based on industry standard definitions. The remaining Knife Edge choice can be used under rare circumstances where the other choices may not be optimum.

The $D4\sigma$ method directly computes second moment beam widths in the X and Y beam axial directions. $D4\sigma$ is most sensitive to noise; however, laser mode content does not influence the computations, a significant advantage.

The Knife Edge 10/90 method employs a fixed 10% and 90% of energy as the moving edge clip points. The correction multiplier is fixed at 1.561. These settings yield highly accurate second moment equivalent beam widths for beams that are predominantly TEM_{00} , as well as for many other mixed mode combinations. There are a few modes for which this method will not prove as accurate such as Top-Hat shaped beams.

If laser mode content is not suitable for measurement using either of the previous methods, use the Knife Edge Prog method and enter custom clip levels and a multiplier. Suggested multiplier values are:

- For a circular Top-Hat, enter a Multiplier of 1.455
- For a square Top-Hat, enter a Multiplier of 1.444

ISO presets clip levels of 16% and 84% with a multiplier of 2.0. This works well with beams that are mostly TEM_{00} .



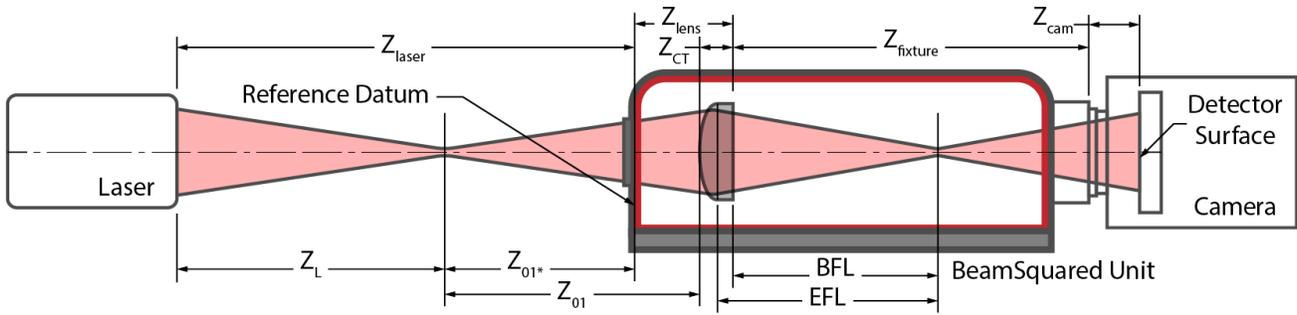
In general, the two Clip level settings will add up to 100%. Avoid clip levels <10% as this setting begins to approach the camera's noise floor.

EPSA Prog is the Encircled Power Smallest Aperture method, also commonly called the encircled power or power in a bucket method. Enter the percent of the total power for the reported beam diameter to encircle. Because the aperture is always circular, the X and Y results will always report the same values. 86.5% is the default setting and represents the second moment setting for a TEM_{00} Gaussian beam.

6.1.2.3 Waist Location

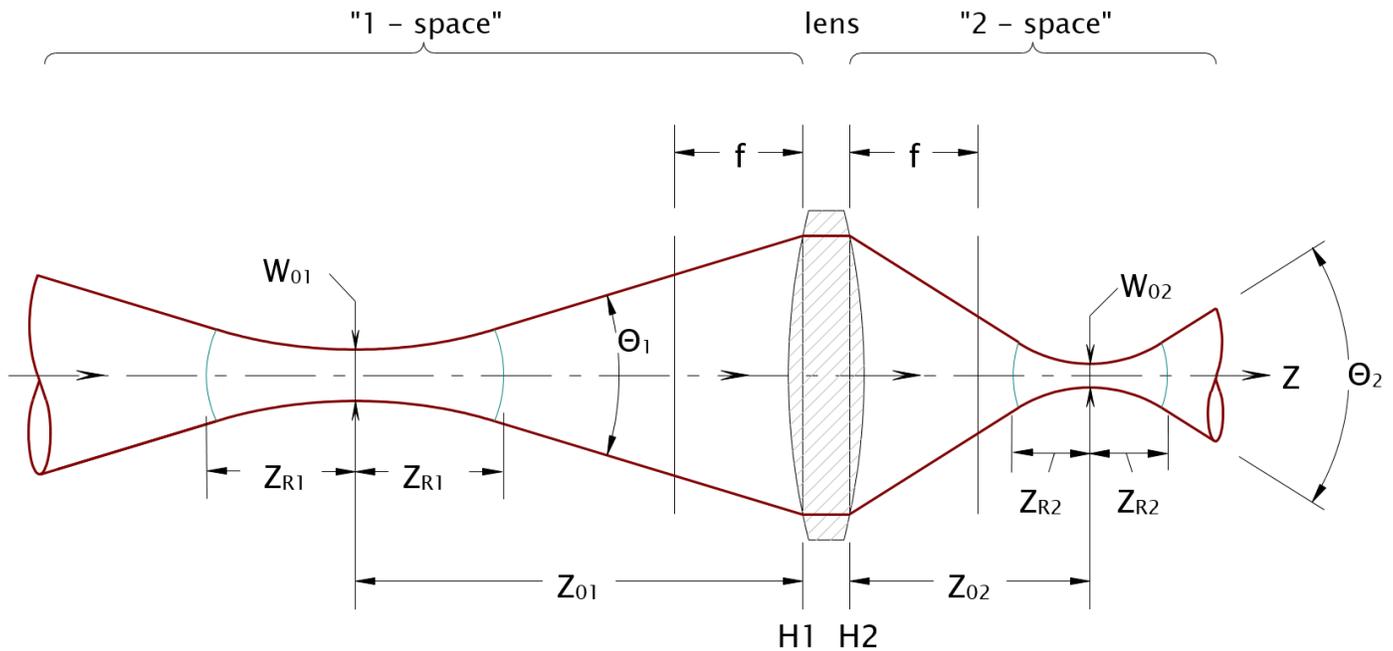
The Waist Location (Z_{01}) is normally referenced to the front principal plane of the input lens. However, in BeamSquared this location is not represented by any accessible physical structure. In some cases, the waist

location needs to be known relative to the laser faceplate. For this reason, two different ways to display the input beam waist location are included.



6.1.2.3.1 Waist Location Relative to Principal Plane

The first method applies when the Z_{laser} value is set to zero. Per ISO, the Waist Location results are computed from the first principal plane of the lens (location H1 in the figure below).



Equation 9 – Waist Location when $Z_{laser} = 0$

$$Z_{01} = \frac{f^2(Z_{02} - f)}{Z_{R2}^2 + (Z_{02} - f)^2} + f$$

Because the lens principal plane is not accessible in BeamSquared, the equation is modified slightly to be measured from the reference datum which is the red BeamSquared case at the input aperture.

$$Z_{01*} = Z_{01} - Z_{lens} + Z_{CT}$$

Using this convention, a positive result means that the waist is located before the reference datum; a negative result means that it is after the reference datum.



In Manual mode, the reference datum is the lens principal plane. The modified equation applies to Automatic mode only.

6.1.2.3.2 Waist Location Relative to Laser Aperture

The alternate method applies when the Z_{laser} value is non-zero. In this case, the entered value should represent the beam path distance from the reference datum to the laser aperture. For the BeamSquared, the reference datum is the red BeamSquared case at the input aperture. The displayed Waist Location results are now relative to the laser aperture.

Equation 10 – Waist Location when $Z_{laser} > 0$

$$Z_L = Z_{laser} - Z_{01*}$$

Using this convention, a positive result means that the waist is located in front of the laser aperture, a negative result means that it is behind the aperture, i.e. not accessible.

For convenience, all results are positive when the waist is in front of the BeamSquared or in front of the laser and negative when not accessible, either after the BeamSquared or behind the laser aperture. In this computation, no adjustment is made to correct for the small difference between the H1 and H2 principal planes.

6.1.3 Rayleigh Range

The Rayleigh range is the distance from the waist where a beam of a circular diameter increases to twice the area at the waist, or where the diameter increases by $\sqrt{2}$. This is also the distance where the wavefront radius of curvature reaches its minimum value. This latter definition is most appropriate considering non-circular beams and beams with astigmatism. The Rayleigh range value is computed for each axial beam orientation and is used to describe a region where a laser is generally regarded as being collimated. The separate X and Y results convey the region where the beam is likely collimated, especially where they coincide.

The Rayleigh range, Z_R , for both the artificial and real laser is computed, respectively, by:

Equation 11 – Rayleigh Range – Artificial

$$Z_{R2} = \frac{W_{02}}{\theta_2}$$

Equation 12 – Rayleigh Range – Real

$$Z_{R1} = \frac{W_{01}}{\theta_1}$$

6.1.4 Astigmatism and Asymmetry

The Astigmatism and Asymmetry values are not covered in the ISO procedure but are provided as ancillary values that may be of use depending on the laser and individual concerns.

The Astigmatism result provides a figure of merit that indicates the presence and severity of on-axis astigmatism. The equation that defines this value was created by Ophir and may or may not agree with other conventions in use. The results from this equation provide the following information:

- Results near 0 indicate a lack of significant astigmatism.
- Results from 0 to 1 indicate increasing degrees of astigmatism, but the two waist locations are contained within the other's Rayleigh range.
- Results from 1 to 2 indicate higher degrees of astigmatism. The waist locations no longer fall within the other's Rayleigh range, but the two Rayleigh ranges overlap.
- Results greater than 2 indicate significantly large amounts of astigmatism, where the Rayleigh ranges no longer have any region of overlap.

Equation 13 – Astigmatism

$$Ast = \frac{|Z_{01X} - Z_{01Y}|}{(Z_{R1X} + Z_{R1Y})/2}$$



The equation for the signed astigmatism is the same, with the exception that the upper values are not absolute.

$$Ast = \frac{Z_{01X} - Z_{01Y}}{(Z_{R1X} + Z_{R1Y})/2}$$

The circularity of the beam is depicted with the Asymmetry result. This value compares the two waist widths and therefore only has significance if there is little or no Astigmatism. Asymmetry values approaching 1 indicate that the beam appears circular in the waist region. Values greater than 1 indicate Ellipticity or asymmetric behavior.

Equation 14 – Asymmetry

$$Asy = \text{the_greater_of} \left\{ \frac{W_{01X}}{W_{01Y}} \right\} \text{ or } \left\{ \frac{W_{01Y}}{W_{01X}} \right\}$$

6.1.5 Focal Length Calculation

The focal length of a lens is a function of the wavelength of interest. To obtain accurate results, the focal length of the lens must be corrected for the wavelength in use. Lenses of similar design can vary in focal length due to the substrate and wavelength of interest.

When choosing a lens, the wavelength-adjusted focal length must be computed using Equation 15 and the calibration data supplied with the lens. The Automated BeamSquared version loads lens information and calculates the new focal length automatically according to the laser wavelength entered by the user.

Equation 15 – Focal Length at a new λ

$$f_{\lambda} = \frac{f_{cal}(n_{cal} - 1)}{(n_{\lambda} - 1)}$$

Where:

f_{cal} The calibration focal length of the lens

n_{cal} The index of refraction of the lens substrate at the calibration wavelength

n_{λ} The index of refraction of the lens substrate at the new wavelength, λ



This equation is not valid for achromatic lenses.



A table of the index of refraction for BK-7 and UVFS at a number of wavelengths is supplied in A.2 Refractive Index of Common Lens Materials.

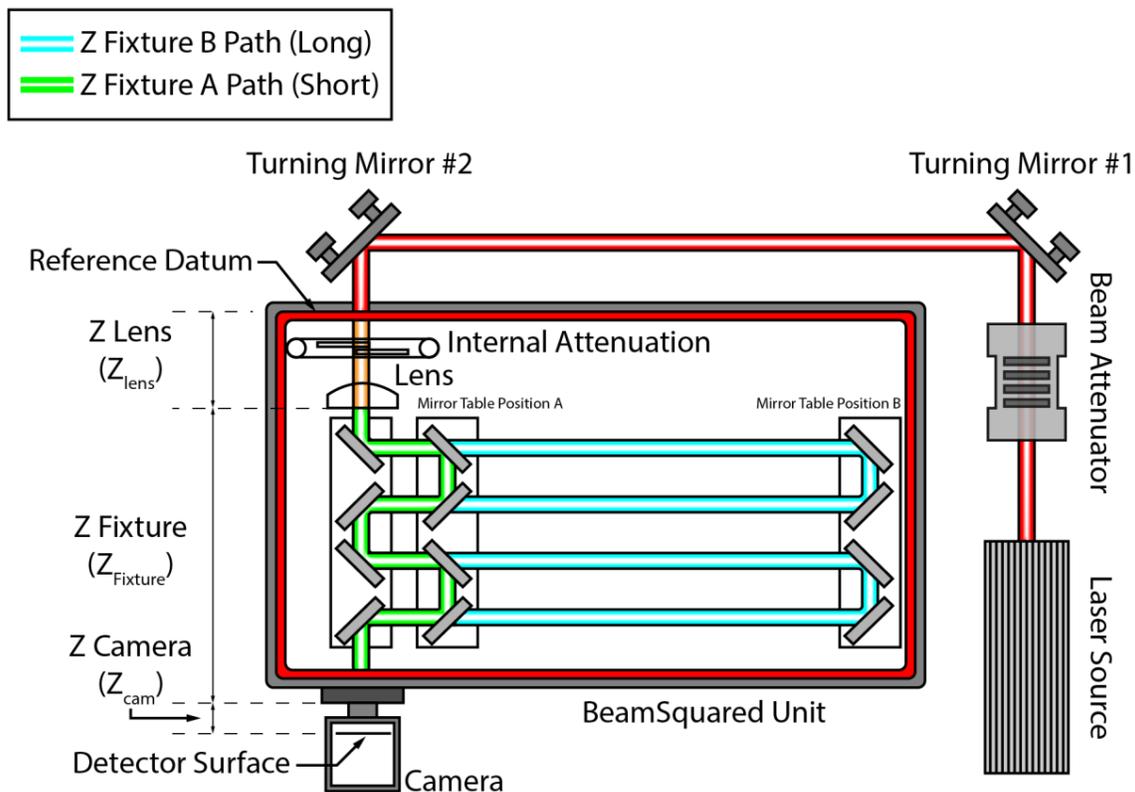
6.1.6 Path Length Calibration Values

Three path length values are used to calibrate each BeamSquared. These path lengths are factory calibrated and pre-programmed into the BeamSquared device.

The 3 path length values are defined as follows (refer to image below):

- Z_{lens} = the distance from the red BeamSquared case to the reference plane of the lens.
- $Z_{fixture}$ = the internal beam path length from the reference plane of the lens to the camera mount when the mirrors are in the "A" or minimum position (green path).
- Z_{cam} = the distance from the camera mount to the camera detector surface.

The sum of these three values equals the minimum distance that the camera can be positioned from the reference plane.





In manual mode, none of these Z path length entries have any meaning. They only apply to automatic operations.

6.1.6.1 Z Lens

The Z_{lens} values for the standard supplied lenses are determined at the factory and stored with each lens. When a lens is inserted into BeamSquared, the data is automatically loaded into the software.

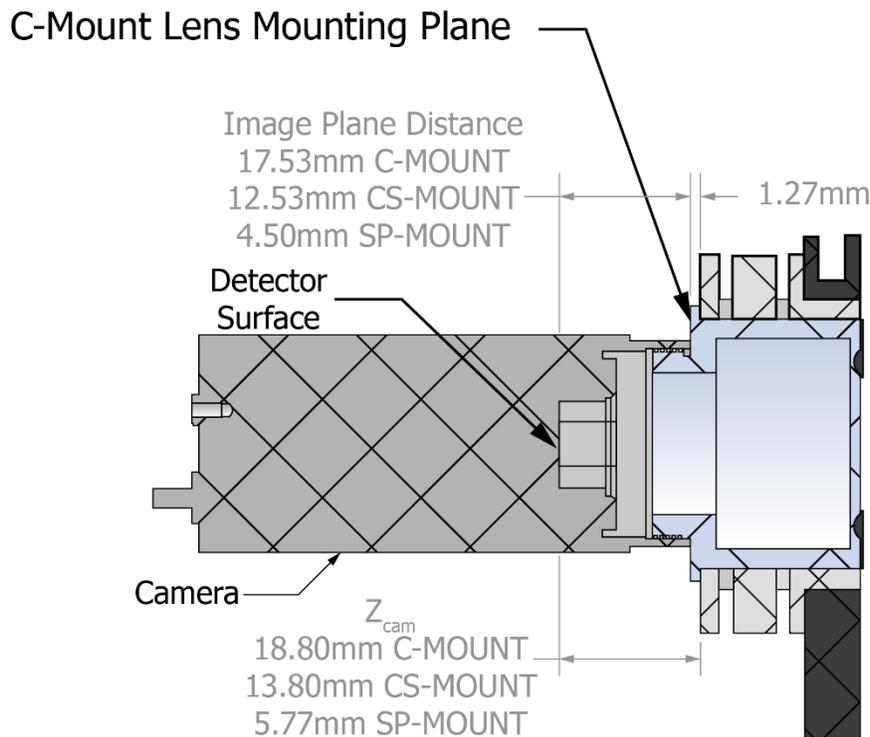
Most lens makers supply a Focal Length and a Back Focal Length value with each lens. Each lens supplied by Ophir is mounted in a lens holder. Ophir lens holders place the back surface of the lens at 95.50mm from the reference plane (Z_{lens} equals 95.50mm).

6.1.6.2 Z Fixture

The Z_{fixture} value is determined at the factory and does not change unless the unit is damaged and repaired at the factory. This value is always associated with a particular BeamSquared serial number and is automatically loaded on software startup or device connection.

6.1.6.3 Z Camera

The Z_{cam} distance can vary depending on the physical characteristics of the camera. BeamSquared is supplied with an adapter that supports C-mount, CS-mount, and SP-mount cameras. The distance from the camera mount to the C-mount lens mounting plane is 1.27mm (see image below). The standard C-mount lens mounting plane to imager distance is 17.53mm, the CS-mount distance is 12.53mm, and the SP-mount distance is 4.5mm.



Thus the Z_{cam} distance would be the sum of these two values:

- C-mount = 18.80mm
- CS-mount = 13.80mm
- SP-mount = 5.77mm

6.1.7 BeamSquared Distance

The typical thin lens equation is as follows:

$$\frac{1}{Z_{01}} + \frac{1}{Z_{02}} = \frac{1}{f}$$

Where:

- Z_{01} The distance from the object to the lens
- Z_{02} The distance from the lens to the image
- f The focal length of the lens

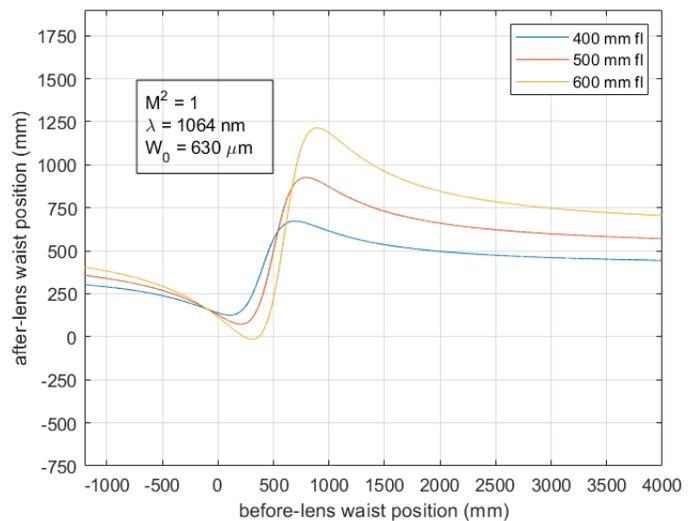
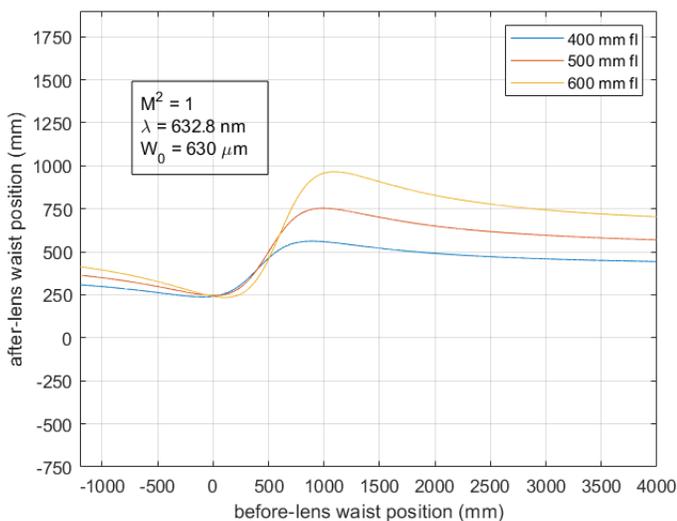
However, for a Gaussian-type beam the thin lens equation is as follows²:

$$\frac{1}{Z_{01}} + \frac{1}{Z_{02} + \frac{Z_{R2}^2}{M^4(Z_{02} - f)}} = \frac{1}{f}$$

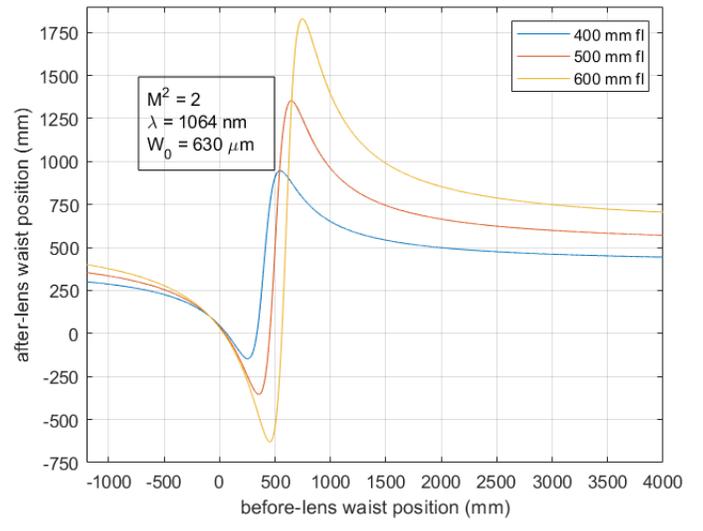
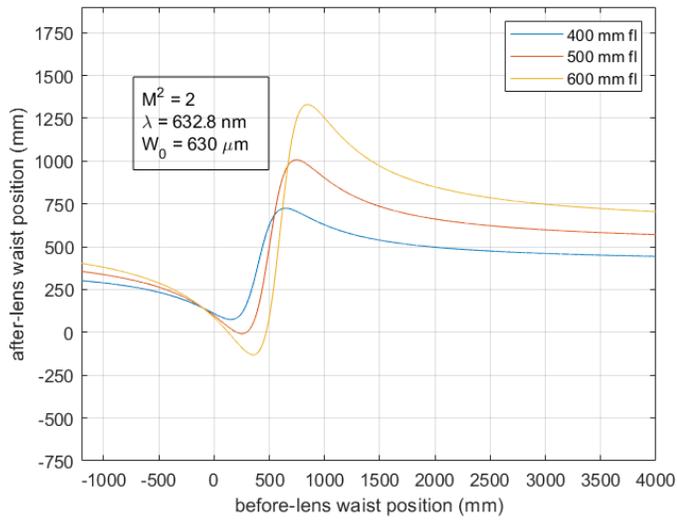
Where:

- Z_{01} The before-lens waist location
- Z_{02} The after-lens waist location
- M^4 The beam quality factor (M^2) squared
- Z_{R2} The after-lens beam Rayleigh length

The above equation can be used to aid in the determination of laser placement relative to the BeamSquared lens. What follows are four example plots of after-lens waist location, Z_{02} , versus before-lens waist location, Z_{01} .



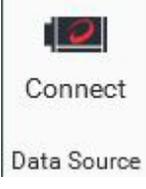
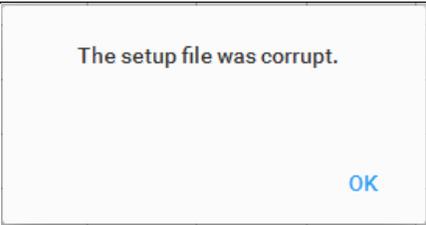
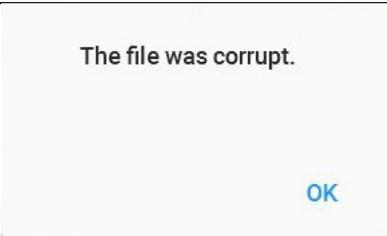
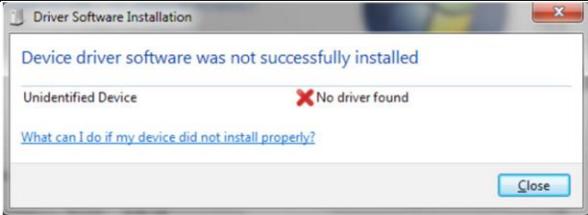
² Sun H., "Thin lens equation for a real laser beam with weak lens aperture truncation", Opt. Eng. 37(11), Nov. 1998, 2906-2913.



Chapter 7 Troubleshooting

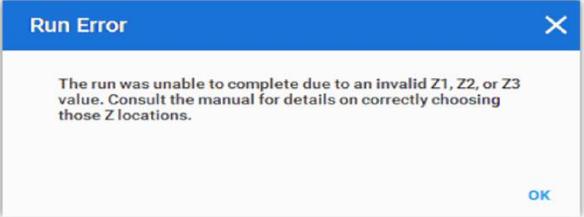
Dialog boxes may occasionally appear in the software as warnings and error messages. This chapter is intended to assist the operator in identifying and correcting the most common problems. In many instances, the message is informative and is not a cause for concern.

7.1 Setup and Startup Problems

Problem	Symptoms	Possible Solutions
BeamSquared does not connect at all.	<p>Data Source panel on the Source ribbon looks like this:</p>  <p>Clicking on this button results in a wait cursor for several seconds then returns to the above image.</p>	<ul style="list-style-type: none"> • Ensure AC power is connected. • Is a USB3 cable from BeamSquared to PC connected? The cable MUST be labeled for SuperSpeed USB 3 or USB 3.1. USB 2 cables do not provide satisfactory performance. • Did the installation complete successfully? There should have been no error messages during installation. If so, retry the installation.
Only the BeamSquared camera connects.	<p>Data Source panel on the Source ribbon looks like this:</p> 	<ul style="list-style-type: none"> • Ensure AC power is connected.
Table calibration fails.	No table movement sound during initial calibration.	<ul style="list-style-type: none"> • Ensure AC power is connected.
Setup file fails to load.		<ul style="list-style-type: none"> • The setup file is corrupted and no longer readable. Configure the same settings again. Save the setup, overwriting the corrupt file.
Data file fails to load.		<ul style="list-style-type: none"> • The data file is corrupted and no longer readable. There is no recovery from this error.
Windows reports a failure to install a driver.		<ul style="list-style-type: none"> • Reboot the computer. Attempt to connect the BeamSquared unit again. If the driver still does not install, please call Customer Service.

7.2 Operation Problems

Problem	Symptoms	Possible Solutions
An Automated Mode M ² measurement run stalls	The run has stopped with one or more beam image quality issues that the automated system is unable to overcome.	<ul style="list-style-type: none"> • If the beam image is too dim or too bright, adjust either external attenuation or camera exposure time. A new Ultracal is required before the run can continue. • If the beam image is misaligned stop the run and repeat the alignment procedure in section 2.5.3. Alternatively, use the Boundary Check option to ignore the misalignment (compromises accuracy). • If the beam image is too large it is typically a result of samples taken too far away from the waist with highly divergent beams. Try adjusting the run configuration to start or stop the run closer to the waist. • If the image is too small, then it is because the diameter of the beam is less than 10 pixels. Change to a longer focal length lens or adjust the position of the BeamSquared unit along the beam propagation path.
BeamSquared reports that the step spacing in Automated Mode may be too large.		<ul style="list-style-type: none"> • Determination of the appropriate step size by BeamSquared is only a heuristic. You may still be able to achieve an ISO defined 11 sample run. Try an experimental run using your preferred settings. If at least 11 samples are taken, in the correct location in relation to the Rayleigh lengths and the results are otherwise satisfactory you may safely continue to use the configured step size. • If ISO compliance is not necessary, you may set the step size at whatever best meets your needs.
BeamSquared performs an excessive number of Ultracal operations during a measurement run.	Run times are very long, as each Ultracal requires additional time.	<ul style="list-style-type: none"> • The most likely cause is bad pixels in the camera detector. Contact Customer Service for assistance. • Silicon cameras are sensitive to ambient temperature. Do not place the BeamSquared unit near an air conditioning or heater vent that may be cycling off and on during the run.

<p>A Four-Cuts Mode M² measurement is incorrectly configured.</p>	 <p>The run was unable to complete due to an invalid Z1, Z2, or Z3 value. Consult the manual for details on correctly choosing those Z locations.</p>	<ul style="list-style-type: none"> Return to the Configuration Wizard (via the Configure button on Run ribbon). Review the Z locations of Z1, Z2, and Z3. Ensure that they meet the criteria described in section 4.1.3.
<p>After a run you are unable to click to select (or double click to disable) sample points in the caustic.</p>	<p>Mouse clicks on points in the Caustic Display do nothing.</p>	<ul style="list-style-type: none"> If Live Mode is enabled, turn it off. If Live Playback is enabled, turn it off.
<p>The measurement run does not include a sample taken at the effective focal length of the lens.</p>	<p>The Divergence result in the Results window displays as Fitted Divergence.</p>	<ul style="list-style-type: none"> The Z position at the effective focal length is less than the first sample Z position. Re-configure your run parameters to start the run somewhere between the minimum table position and the effective focal length.
<p>Error generating a PDF report.</p>	<p>Generating a PDF Report shows the following error. Continuing will generate a report but the 3D display is missing.</p>  <p>Some elements of the report could not be generated.</p> <p>A report image could not be exported. This usually indicates that the display adapter is outdated.</p> <p>Would you like to create the report anyway?</p>	<ul style="list-style-type: none"> The graphics card in the PC may be outdated. Replace the graphics card or generate the PDF Report on a different PC.

Chapter 8 BeamSquared Automation Interface

BeamSquared provides an application programming interface (API) via .NET components to allow users the ability to build custom applications that incorporate the laser beam analysis and processing power of BeamSquared. The BeamSquared Automation Interface allows custom applications to open/close BeamSquared, control settings and M² settings, access camera data and calculated results, and export measurement data to files.

The ability to base control decisions for a second application on the results and behaviors of BeamSquared allows users to meet their manufacturing/analysis goals quickly and efficiently with minimal human interaction. Another popular use of the Automation Interface is to create companion applications to augment regular user-assisted operations in BeamSquared.

Ophir is dedicated to protecting users from changes in underlying implementation as BeamSquared evolves. To facilitate this goal, it is important that the user be given stable abstractions to program against, and to allow BeamSquared to evolve as new features are added.

To this end, the BeamSquared automation interface is presented as a set of interfaces that collectively expose the functionality of the application. Access to these various interfaces is provided by programmatically creating one concrete class known as AutomatedBeamSquared. The BeamSquared interfaces may grow over time but will not be renamed or fundamentally modified to change the inputs and outputs of each interface.

8.1 Evolution of the Automation Interface

Ophir's older products used an ActiveX/COM server to provide an automation interface. More recent technologies, like .NET, provide more fully featured programming functionality. Recent developments in remoting technologies allow nearly transparent interaction between machines on the same domain. This allows the user to leverage more than one PC while using BeamSquared for analysis. COM remote operation is more difficult to use and setup when compared to its .NET counterpart. For this reason, the BeamSquared Automation Interface was developed using Microsoft's .NET infrastructure. Any .NET application should be easily integrated and be able to interact with the core functionalities provided by BeamSquared.

8.2 Recommended Skill Set

Over the years, Ophir has learned that to design a proper automation client for products similar to BeamSquared requires a skill level comparable to that of a degreed and experienced computer programmer. Even with this background, a learning curve is necessary to achieve an acceptable level of competency. Very often Ophir's Service and Engineering departments are contacted by individuals that are assigned to design an automation interface but lack a sufficient technical background. To assist your company in making a good employee fit for this type of work, we offer the following guidelines for the minimal skill sets needed.

To interface with LabVIEW you need:

- An understanding of .NET programming methods.
- An understanding of LabVIEW .NET Connectivity objects.
- Prior, and recent, experience designing and deploying National Instruments LabVIEW VI's in an automation environment.
- Review Ophir's Automation Documentation (see section 8.3). If you don't know immediately what this means and how to use it, we strongly recommend that you contract a consulting LabVIEW developer to design your company's automation client.

To interface with a program written in Visual Basic (VB), C++, or C# you need:

- A minimum BS degree in Computer Science or Computer Engineering, or equivalent.
- Three (3) or more years of software design experience using Microsoft Visual Studio design and debugging tools.
- Demonstrated proficiency in writing programs in Microsoft Visual Basic, C++, and/or C#
- A background in .NET programming methods
- Review Ophir's Automation Documentation (see section 8.3). If you don't know immediately what this means and how to use it, we strongly recommend that you contract a consulting software engineer to design your company's automation client.

8.3 Documentation

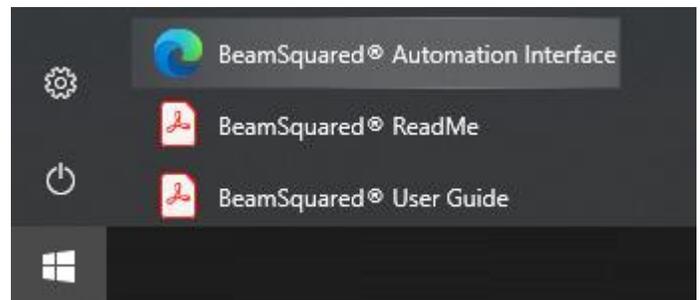
The Automation API reference is presented in a software industry standard html format* which provides cross-referenced access to all interfaces and functionality provided for automation application development. The BeamSquared Automation API Documentation may be accessed via the following link:

[Automation Documentation](#)

-or-

Via the start menu in the Ophir product folder.

* Complete class documentation is generated from annotated source code using [Doxygen](#).



8.4 Examples

Simple examples of automation applications are provided in the installation directory located at:

[C:\Program Files\Spiricon\BeamSquared\Automation\Examples](#)

Step-by-step walk-throughs for the examples are provided in the Automation Documentation.

Chapter 9 Manual M² Measurements

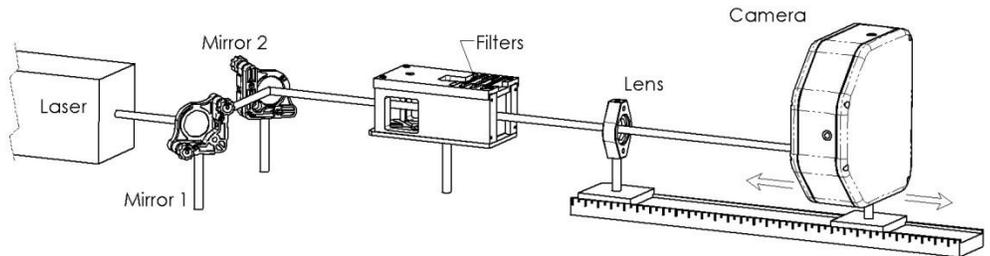


This chapter describes the setup and controls that are specific to Manual Mode operation only.

9.1 Electro-Mechanical Operation

Operating BeamSquared in Manual Mode requires a manually operated system (not included). At each measurement location, BeamSquared detects, measures, and displays the changing laser beam profile. During the collection process, the user may be required to adjust the attenuation to avoid damaging the sensor. Whenever the background energy of the camera drifts, the system requires a camera Ultracal (baseline recalibration cycle).

Once enough data points have been collected, BeamSquared calculates and displays the propagation parameters for the input laser beam, as well as astigmatism and asymmetry ratios. The sampled X and Y



beam widths versus the distance from the lens are plotted and the hyperbolic curve fits are drawn. Results are reported for the actual propagation of the laser (1 space) and the fitted beam formed by the focusing optic (2 space).

If the data plot contains anomalous data points (outliers), the operator can selectively remove these data points from the analysis by double clicking them in the **Caustic Beam Display**.

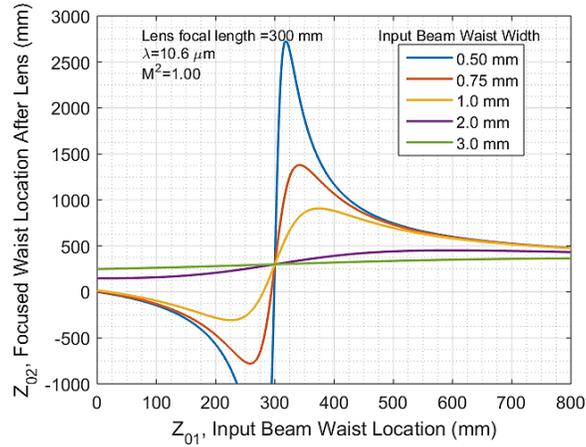
In manual mode the user has the ability to change the measurement location at each step of the run.

9.2 Spot Size Resolution

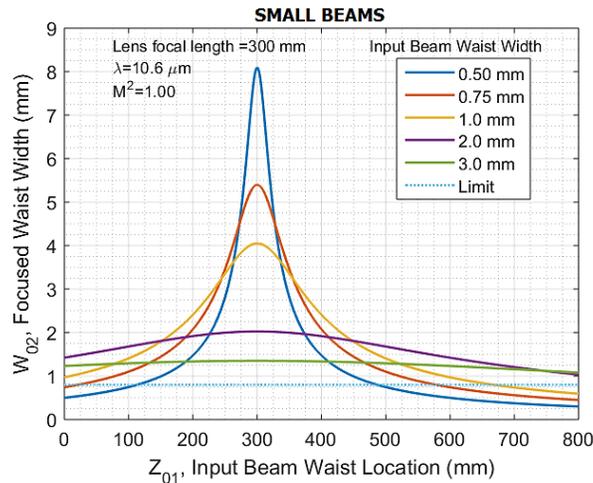
The figure below shows how the focused waist location moves relative to the input beam waist location for a range of input beam waist widths. Preferable placement of the input beam's waist is where Z_{01} is at least equal to the focal length of the lens. Observe that for small beams in this region, there is a drastic change in Z_{02} with small changes in Z_{01} . In these scenarios, Z_{01} is better situated farther from the lens.

Under most circumstances Z_{01} should avoid being less than the focal length of the lens.

For beams with a waist width $\geq 3\text{mm}$ the placement almost always yields a focus near the lens focal length, therefore placement is not critical.

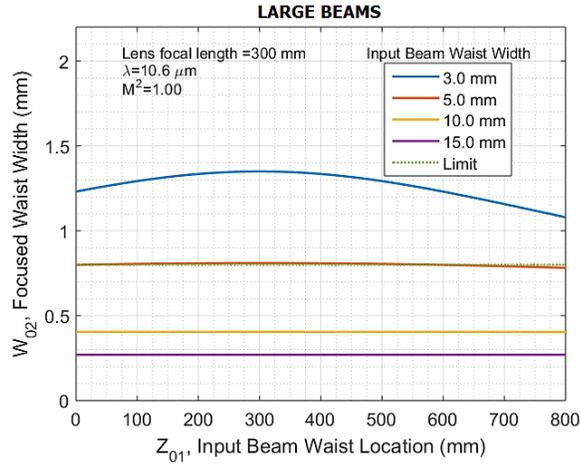


The following figures show how the beam width of the focused input laser changes under a range of different conditions. In this image, the focused spot size is plotted against the input waist location for a variety of input beam sizes shown representing only $M^2 = 1$.

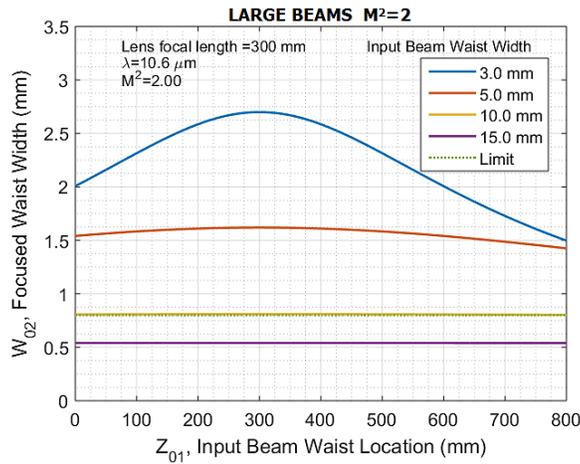


Focused spot sizes are always larger when $M^2 > 1$. The next image depicts the focused spot sizes for larger input beam sizes also with $M^2 = 1$. Notice that around 5mm the focused spot size falls below the 800 μm dotted

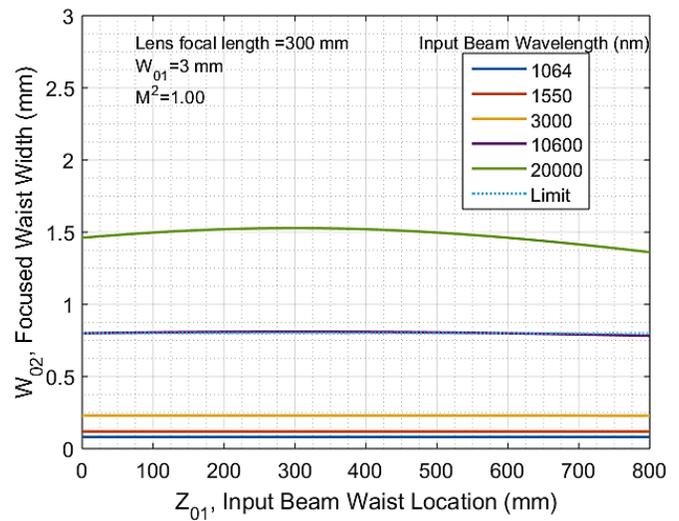
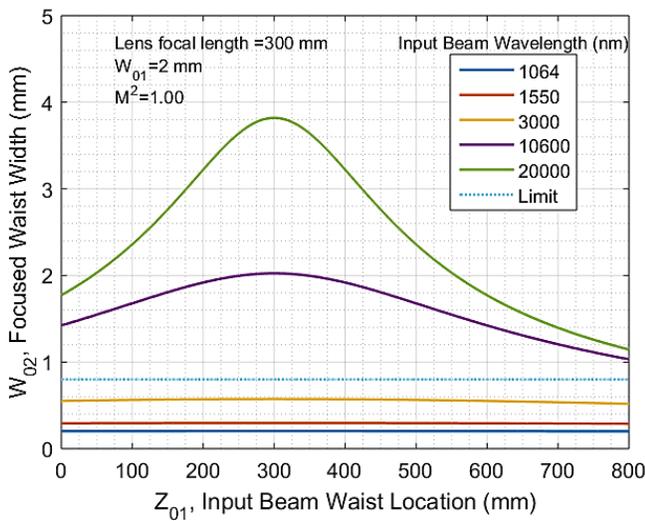
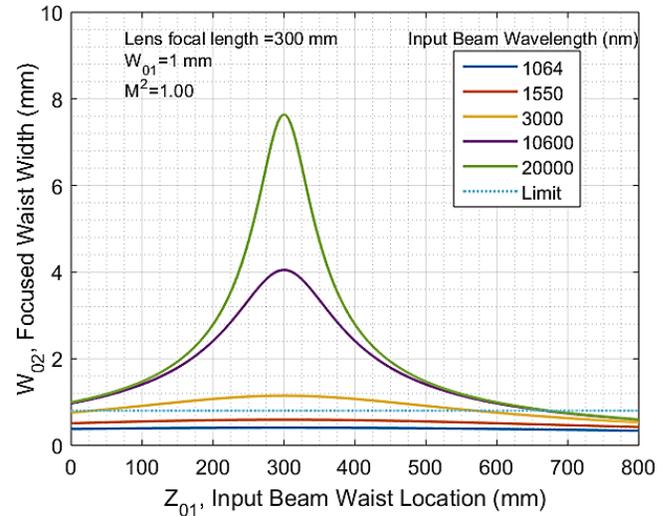
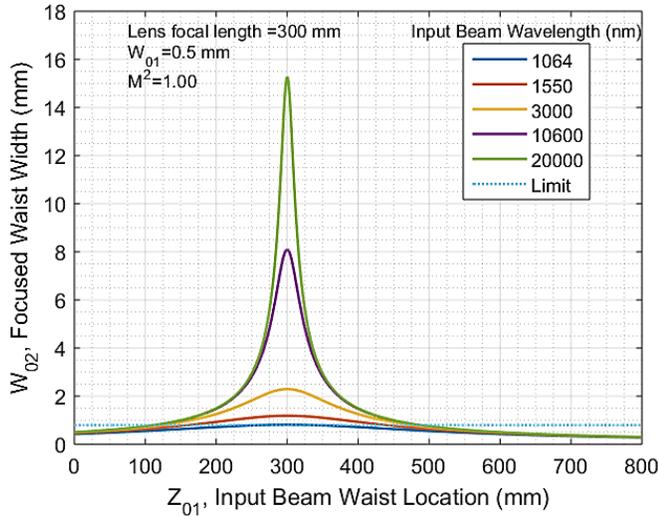
line which represents the resolution limit of the camera. For these larger beams, a change in the M^2 value will significantly impact the operating range.



The next image shows these same large beams sizes with an $M^2 = 2$. Observe that now a 10mm beam is around the resolution limit of the camera.



The next set of images demonstrates the effect of the focused spot size for variations in wavelength. Notice that shorter wavelengths focus smaller than longer wavelengths.



9.3 Manual Mode

An optical rail assembly and a focusing element of a known focal length are required. ISO/DIS 11146-1 must be used as the basis for your rail design. The focusing element must be an aberration-free mirror or a plano-convex lens.

In the following example we have used a lens-based approach. The focusing element should be selected to provide a smallest focused spot width of at least 10 camera pixels across. For a Pyrocam IV or IIIHR, the focused spot must be at least 800µm. The rail must be long enough to allow the camera to translate at least 2 Rayleigh lengths on both sides of the waist region.

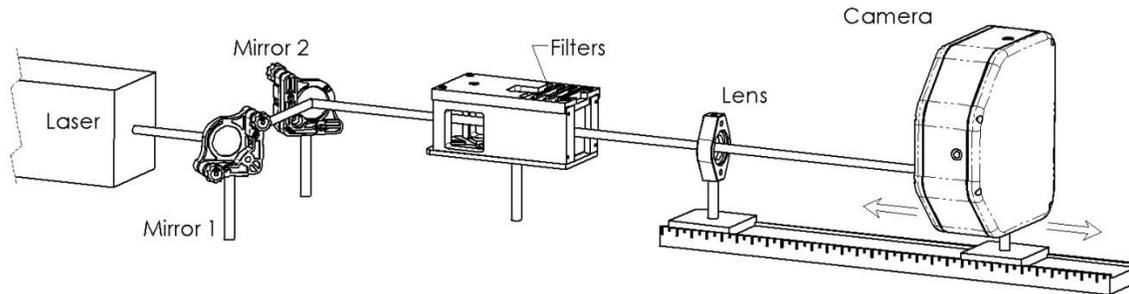
When using Manual Mode, the user is required to:

- Change the camera position on the rail
- Adjust the aim of the beam
- Adjust the attenuation of the beam
- Block the beam when prompted
- Determine whether to accept each data frame

- Accurately set the distance from the lens to the sensor inside the camera for each data point

9.3.1 Optical Rail Setup

The figure below depicts the general features of the optical rail arrangement. The rail must be parallel to the incoming laser beam, the lens and camera must be at the same height on the rail, and the camera must be able to slide along the rail. A two-mirror arrangement for aiming the beam along the rail is suggested.



Also, as shown in the figure above, it is often advisable to employ attenuation. The necessity for this arrangement increases proportionally to the output energy/power of the laser.

While not shown in the image, a device that can completely block the laser beam from the camera is a necessity. Each time the camera performs an Ultracal or Ultracal check, the beam must be completely shielded from the camera sensor.

It is also a good idea to place a relatively large ND filter immediately in front of the camera. This filter is helpful in blocking out ambient background light.



It is recommended that measurements be performed in a low light or a darkened room setting.

9.3.2 Beam Alignment and Setup for Manual Mode



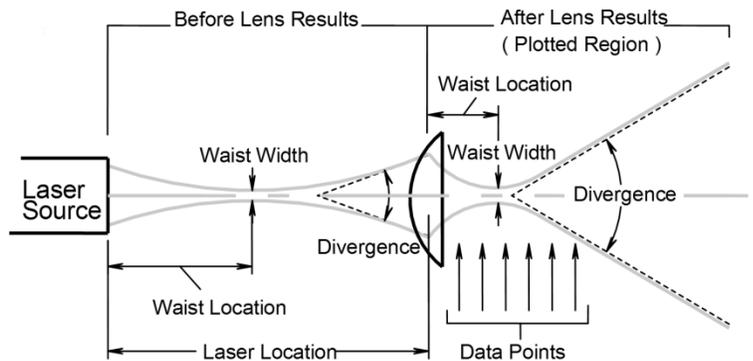
Avoid eye or skin exposure to direct or scattered radiation!



Before allowing laser energy to contact the camera sensor, it is important to limit the beam intensity. Excessive laser energy will damage the camera.

The Pyrocam imager can be damaged at energy levels above 20 mJ/cm² (1ns pulse) or at power levels greater than 4 W/cm². Adjust these input limits downward based on the focused spot size. Beam splitters and/or filters may be used to attenuate the beam, but care must be taken to prevent the introduction of distortions.

During an M² measurement operation, the peak energy density that reaches the camera changes, potentially over several orders of magnitude. This is a result of the camera effectively moving from a large unfocused spot near the lens, into and through the focus at the waist, and then out again to an unfocused spot. It is the user's responsibility to ensure the correct amount of attenuation is used in order to prevent damage to the camera.

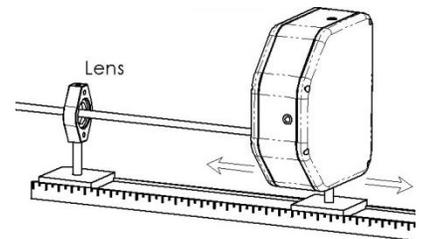
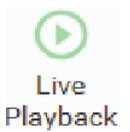


Use ND filters near the laser head to attenuate the beam to a safe level. Additional ND filters can also be added in front of the camera to further adjust beam brightness.

If camera or other configuration parameters need to be changed, do so now or restore the required configuration. This will not be necessary if the last configuration saved corresponds to the current setup.

The following steps describe how to setup the rail with the lens and the camera:

1. Click **Live Playback** from the **Run** ribbon. The live video mode is provided to assist with the alignment process. Live video will appear in the **2D Beam Display** window.
2. The laser must be directed along an axis parallel to the rail, centered on the lens, and centered on the camera. The beam must stay centered on the camera as the camera is translated.
3. The X and Y axes of the camera must also be aligned with the X and Y axes of the laser beam to collect meaningful beam propagation results. To obtain proper alignment, it may be necessary to rotate either the camera or the laser.
4. After making this adjustment, recheck the pointing accuracy by translating the camera along the rail and confirming that the beam remains centered in the beam window.
5. When the camera can travel the full length of the rail and the beam stays centered on the detector, alignment is complete.
6. In the **Results** window, select the desired **Beam Width Basis** (see section 3.7.5.1) and enter information about the laser being analyzed. This information should be updated for each laser under analysis. It is absolutely necessary to enter the correct **Wavelength** of the laser light and the **Focal Length** of the lens at that wavelength (refer to section 6.1.5).



If using the Four-cuts method, some information about the caustic should already be known. Select the Z values as described in section 4.1.3.

7. Identify a good Z Start value. Enable **Live Playback** and move the camera towards the lens until the beam is large enough to fill approximately two-thirds of the camera's imager. Note the Z position. Round this value off to the nearest 10mm; this is the Z Start value.

Live Playback cannot be accessed when in the **Configuration** wizard so the Z values must be determined beforehand.



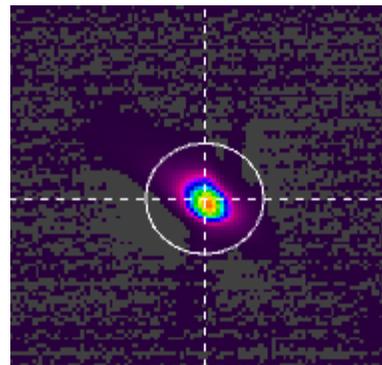
8. Find a good Z Stop value. Move the camera away from the lens until the beam again fills approximately two-thirds of the imager. Note the Z position. Round this value off to the nearest 10mm; this is the Z Stop value. Move the camera back to the Z Start position.
9. Determine a Z Step value that seems reasonable for the range between the Z Start and Z Stop values. Typically a value between 30mm-50mm or 1/10 the focal length of the lens is appropriate. If the beam focuses quickly, consider reducing the step size.
10. Once the Z values are known, follow the steps in the **Configuration** wizard (see section 4.2.1) to enter all the information for the system under test.
11. All of the settings required to analyze the beam are now set.
12. After completing the **Configuration** wizard, the **Step by Step** wizard automatically opens to perform a run. See section 9.3.4 for more information about the data collection process. You may now save this configuration file for this specific set of testing conditions in order to easily retrieve them for later use.



Make sure to update the configuration whenever the system settings change.

9.3.3 Adjusting Beam Alignment

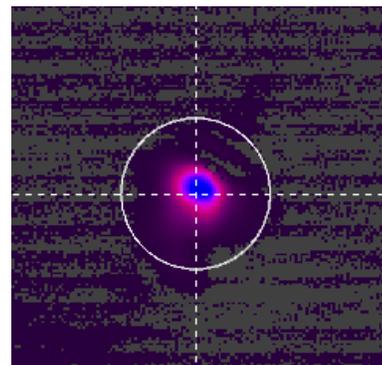
The operator is responsible for adjusting the beam intensity. The peak energy should always be kept within 50% to 90% of the camera's dynamic range.



Beam Energy too Low

When the peak energy reported in the **Results** window falls below 50% of the camera's dynamic range, the beam profile does not present sufficient contrast from the background. The beam energy is too low.

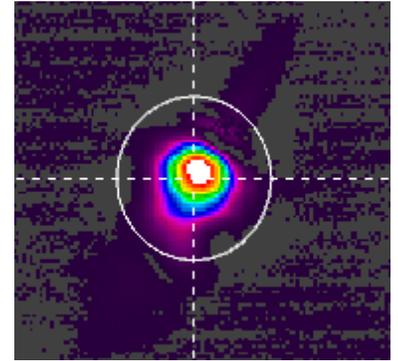
To remedy this situation, reduce the attenuation. If this cannot be done, accept the low quality frame or end the run. Use judgment when deciding if the beam intensity is too low to be useful. If the noise level is low, a reasonably good measurement can still be made if the peak energy is above 30%. Low beam energy often occurs at the extreme ends of an M² run, particularly when measuring a low power laser.



Beam Energy too High

When the peak energy reported in the **Results** window is above 90% of the camera's dynamic range, the beam profile displays saturated areas where the beam intensity on the camera is too high. The color of the saturation depends on the selected color palette. When using the OSI Rainbow, these appear white.

The beam intensity must be decreased in order to obtain an accurate measurement. This can be accomplished by adding attenuation or modifying the measurement setup.

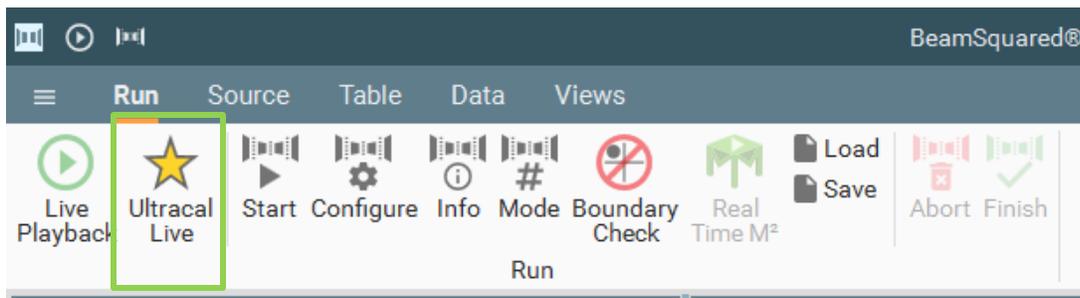


Failure to properly attenuate the beam may cause damage to the camera.

9.3.4 Ultracal Live

For best results, use the **Ultracal Live** feature.

1. Navigate to the Run ribbon.
2. Click Ultracal Live. A dialog will appear directing you to block the beam.



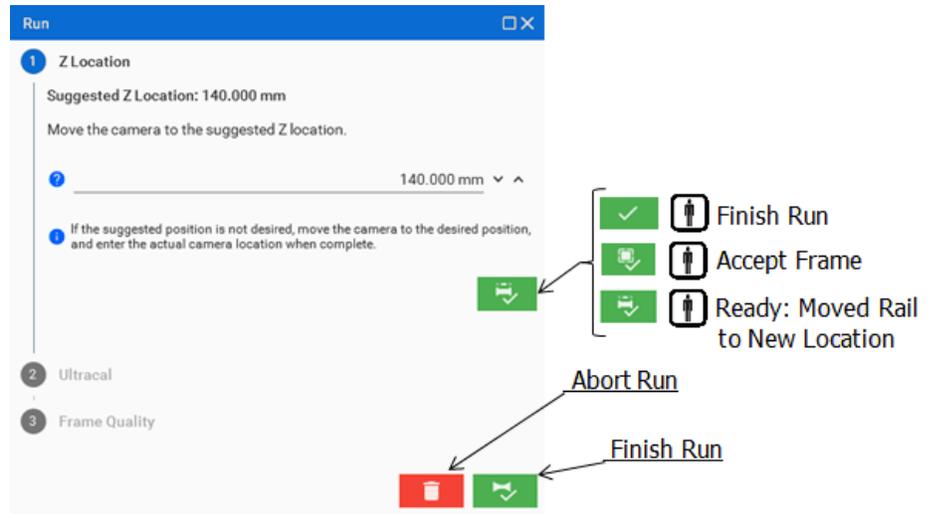
3. After blocking the beam, click **OK**.

A progress bar will appear in the status bar. Once complete, the progress bar will disappear and the **Ultracal indicator** will illuminate green if successful.

9.3.5 Step by Step Wizard

Follow the steps to collect data at each of the positions configured in the **Configuration** wizard.

At any point, the run can be aborted by clicking the **Abort Run** button at the bottom of the window. If the window is closed before the run is complete or aborted, reopen it through the **Views** panel. Until the run has concluded, other controls are unavailable.



*The **Finish Run** button does not appear until a beam caustic is computed.*

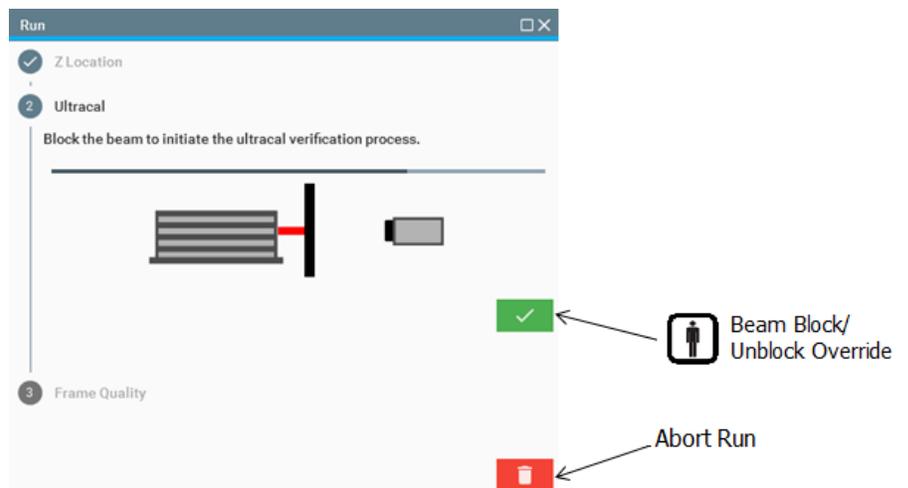
Z Location

The suggested Z location appears at the top of the window. These values are computed from the information entered in the **Configuration** wizard. Move the camera to the suggested Z location. If an alternate position is desired, place the camera at the desired position and enter that location in the edit field. Accept the location to move to the next step.

Ultracal

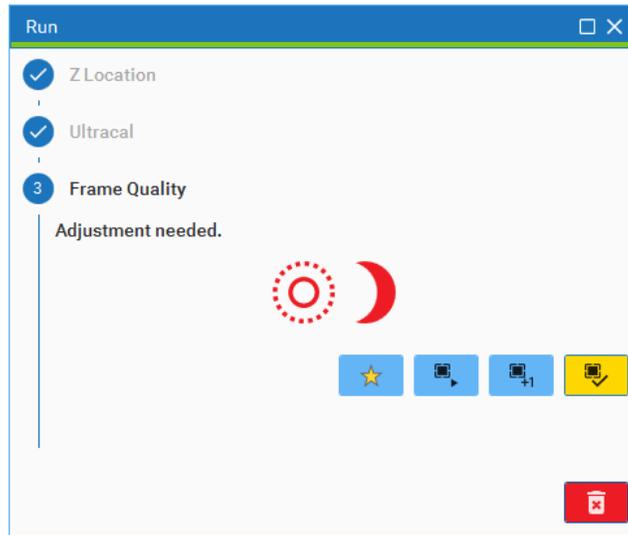
Block the beam when indicated. The software determines if an Ultracal is necessary. If Ultracal is needed, the software automatically starts the calibration. When prompted, unblock the beam and the software moves to the next step.

Occasionally the Ultracal process may fail. If this is the case, the user can redo the Ultracal in the **Frame Quality** step by clicking Redo Ultracal.



Frame Quality

The software performs an image quality check and indicates if there are any recommended corrections.



A frame that has quality issues can still be accepted, but doing so is discouraged. The possible warnings are:



Misaligned – The edge of the beam has reached at least one edge of the sensor. Measurement accuracy could be degraded. Accept frame or Abort Run, adjust the setup, and take a new measurement. Selecting **Disable Boundary Check** will suppress this message.



Too bright – The peak beam energy is above 90% of the camera’s dynamic range. Add additional attenuation to the beam, Accept frame, or Abort Run. **Failure to properly attenuate the beam may cause damage to the camera.**



Too dim – The peak beam energy is below 50% of the camera’s dynamic range. Reduce attenuation of the beam, Accept frame, or Abort Run.



Too big – The edges of the beam have reached the edges of the sensor. Measurement accuracy could be lost. Accept frame or Abort Run; adjust the setup, and take a new measurement.



Too small – The calculated beam diameter is below 10 pixels. Measurement accuracy could be lost. Accept frame or abort the run; adjust the setup, and take a new measurement. This can be done by using a longer focal length lens, or by moving the lens and camera to where the beam has diverged less and the beam at the lens is smaller.



Ultracal – If the camera exposure setting is changed during the run, a new **Ultracal** cycle must be performed before the frame can be accepted. Click **Redo Ultracal** to initiate the process. **Ultracal** is also used to compensate for small changes in the camera baseline due to changes in the camera temperature. This is caused by the camera’s natural warm up time or by ambient temperature changes.

As soon as a good frame is found, live playback stops. The user then has the following options:



Redo Ultracal – If the Ultracal cycle removed the beam or another error occurred, click this button to return to the **Ultracal** step.



Accept Frame – Accept the current frame and move on to the next Z location. If the beam has quality issues, this icon turns yellow. A frame cannot be accepted if live playback is running or if a new Ultracal is required. When accepting the frame on the last data point of the run, the **Step by Step** wizard automatically closes.



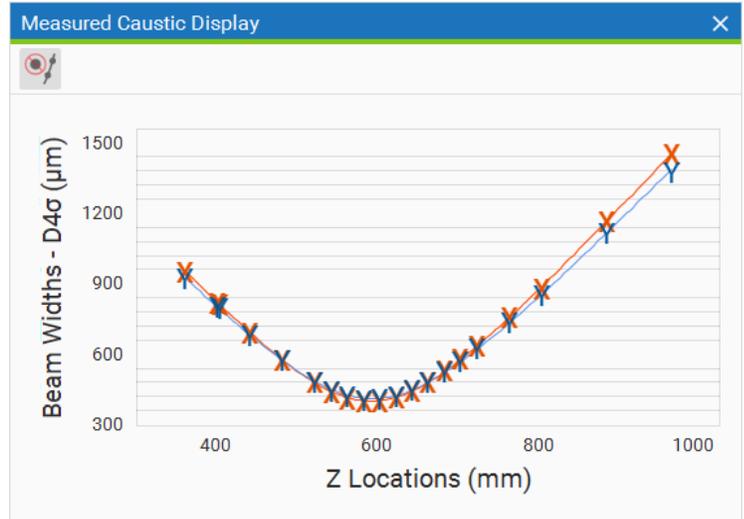
Live Playback – Re-enable live playback to view the beam in real-time.



Single Frame – Collect a single new frame from the camera.

After the setup completes, each accepted data point appears in the **Measured Caustic Display** window. An estimated curve appears as soon as enough data accumulates, stabilizing as the run progresses. The results also update as the collection process continues.

At the completion of a run, the data can be saved to a file for further analysis.



9.3.6 Exposure



Only available when a camera is connected to the software. Use the slider or the text box to enter the Exposure for the camera. This determines the intensity and quality of the output image.

When operating in Pulsed mode, the Pyrocam must be externally triggered and the **Exposure** control must be set to a value slightly larger than the input pulse width.



Changing the exposure during a run is highly discouraged. Doing so could significantly affect the results and requires a new Ultracal.

Appendix A Lens Calibration Adjustments

A.1 Plano convex Lens Calibration

When a lens is used at a wavelength different from the calibrated wavelength, a correction needs to be made. Equation 15 provides the formula for calculating the new focal length. Do not apply these equations to achromatic lenses.

$$f_{\lambda} = \frac{f_{cal}(n_{cal} - 1)}{(n_{\lambda} - 1)}$$

Where:

- f_{cal} The measured focal length of the lens at the calibration wavelength
- f_{λ} The calculated focal length of the lens at the desired wavelength
- n_{cal} The index of refraction of the lens substrate at the calibration wavelength
- n_{λ} The index of refraction of the lens substrate at the desired wavelength, λ

Section A.2 provides index of refraction values for common lens materials at various wavelengths.

A.2 Refractive Index of Common Lens Materials



This table only applies to plano-convex lenses.

Wavelength (nm)	BK7	UV Fused Silica
180.0	-	1.58529
190.0	-	1.56572
200.0	-	1.55051
213.9	-	1.53431
230.2	-	1.52008
248.3	-	1.50840
265.2	-	1.50003
280.3	-	1.49404
296.7	-	1.48873
330.3	-	1.48054
351.1	1.53894	1.47671
404.7	1.53024	1.46962
435.8	1.52669	1.46669
441.6	1.52611	1.46622
457.9	1.52462	1.46498
476.5	1.52310	1.46372
486.1	1.52238	1.46313
488.0	1.52224	1.46301
496.5	1.52165	1.46252
514.5	1.52049	1.46156
532.0	1.51947	1.46071
546.1	1.51872	1.46008
587.6	1.51680	1.45846
589.3	1.51673	1.45840
632.8	1.51509	1.45702

643.8	1.51472	1.45670
656.3	1.51432	1.45637
694.3	1.51322	1.45542
706.5	-	1.45515
786.0	1.51106	1.45356
820.5	1.51037	1.45298
830.0	1.51021	1.45282
852.1	1.50981	1.45247
904.0	1.50894	1.45170
1014.0	1.50731	1.45024
1060.0	1.50669	-
1064.0	-	1.44963
1100.0	-	1.44920
1200.0	-	1.44805
1300.0	1.50371	1.44692
1400.0	-	1.44578
1500.0	1.50130	1.44462
1550.0	1.50068	1.44402
1660.0	-	1.44267
1700.0	-	1.44217
1800.0	-	1.44087
1900.0	-	1.43951
1970.1	1.49500	-
2000.0	-	1.43809
2100.0	-	1.43659
2325.4	1.48929	-

Appendix B Warranty

LIMITED WARRANTY; DISCLAIMER OF WARRANTIES. Ophir warrants that the Goods sold hereunder shall be free from material defects in workmanship or materials and conform in all material respects to Ophir specifications, which are available upon request, or Purchaser's supplied and accepted specifications, for the following Warranty Period: Two (2) years from the original date of shipment from Ophir for Laser Beam Diagnostic products; and one (1) year from the original date of shipment from Ophir with respect to laser power meters, laser energy meters, laser measurement tools and spectral analysis instruments. This warranty does not cover: (i) Purchaser-furnished materials; and (ii) damage to sensor.

All warranty claims must be submitted in writing to Ophir within the applicable warranty period and all nonconforming Goods must be returned to Ophir, at purchaser's cost and expense, before Ophir replaces the same or refunds the purchase price to the Purchaser as set forth below. No Goods shall be returned to Ophir without obtaining a Return Material Authorization (RMA) number first which must be clearly marked on the outside of the shipping container. The warranty for products repaired after the expiration date of the new products warranty, as stated above, is limited to the repaired portion and is valid for ninety (90) days from the date of reshipment.

Ophir's liability for breach of warranty shall be limited to, in Ophir's sole discretion, (i) repairing or replacing Goods that Ophir determines do not conform to the foregoing warranty, or (ii) refunding the sales price received by Ophir in respect of the non-conforming Goods. This remedy shall be the Purchaser's sole and exclusive remedy for any defect or nonconformity in the Goods. This warranty extends only to the immediate purchaser from Ophir and does not extend, expressly or impliedly, to any other party.

In no event shall Ophir incur any obligation to repair or replace Goods which are determined by Ophir, at its sole discretion, to be defective due to (i) installation, maintenance, operation, modification, alteration, accident, neglect or use in any way other than in strict compliance with Ophir's published specifications for the Goods, (ii) the failure to maintain appropriate environmental conditions, as communicated by Seller, (iii) as the result of the use of unauthorized parts or repairs, or unauthorized modifications, (iv) any repair work on the product that is performed by the Purchaser or any third party on behalf of the Purchaser (other than Ophir), or (v) modification or alteration of the Goods such that Ophir is unable to verify the defect with its standard test equipment.

EXCEPT FOR THE EXPRESS LIMITED WARRANTY STATED HEREIN, THE GOODS ARE SUPPLIED ON AN "AS IS" BASIS AND PURCHASER'S USE OF THE GOODS IS AT PURCHASER'S RISK. OPHIR DOES NOT MAKE AND HEREBY DISCLAIMS ALL OTHER EXPRESS AND/OR IMPLIED WARRANTIES WITH RESPECT TO THE GOODS, INCLUDING WITHOUT LIMITATION ANY WARRANTIES OF MERCHANTABILITY OR FITNESS FOR PARTICULAR PURPOSE OR ANY WARRANTIES ARISING FROM A COURSE OF DEALING OR USAGE OF TRADE AND ANY WARRANTIES OF NONINFRINGEMENT AND TITLE.

Appendix C BeamSquared Supported Cameras

BeamSquared supports the following cameras to best suit your measurement application. This table displays the cameras BeamSquared currently supports. Select a model to view the camera specifications.

Model	Automated BeamSquared	Manual Mode	Section
SP204S NEW	X	X	C.1
SP920	X	X	C.2
SP1203 NEW	X	X	C.3
XEVA XC-130	X	X	C.4
Pyrocam IIIHR		X	N/A
Pyrocam IV		X	N/A

C.1 SP204S

C.1.1 Supplied Accessories

The SP204S is a single tap, back-side illuminated CMOS camera and is supplied with the following accessories:

- USB3.0 Certified Standard-A to Micro-B cable
- Coax External Trigger Cable – JST NSHR-09V-S to SMA
 - Pins 7 & 9 – External Trigger, SMA Bulkhead, Female
 - Pins 1-6 & 8 – Not connected, see reference table
- 1/4-20 tripod adapter

C.1.2 External Trigger Control

The SP204S camera is supplied with an external trigger input cable. The input to this cable should be a standard TTL level positive going pulse. The camera triggers and begins integrating light on the rising edge. A trigger pulse should be at least 5µs in duration.

To operate in external trigger mode set this control to **Trigger In**. Select **None** when operating in CW mode.

C.1.3 GPI/O Connector Description

The camera has a 9-pin GPIO connector on the side of the case; refer to the diagram below for wire color-coding. The header connector is JST part number BM09B-NSHSS-TBT and the wire plug connector is JST part number NSHR-09V-S. The wire contacts are SSSL-003T-P0.2.

Diagram									Pin #	Color	Function	Description
9	8	7	6	5	4	3	2	1	1	Red	V-External	External power input terminal (5V +/- 7.5%, 2A) Takes priority over USB3 power
Opto In	Opto Out	Opto Ground	Ground	GPIO3	GPIO2	3.3VDC Out	Ground	5VDC In	2	Black	GND	External power ground reference terminal
									3	Grey	3.3 Vdc Output	Output supplying a maximum of 150 mA
									4	Blue	GPIO2	Bi-directional general purpose I/O #2 terminal
									5	Purple	GPIO3	Bi-directional general purpose I/O #3 terminal
									6	Black	GND	External power ground reference terminal
									7	Brown	Opto GND	External ground reference for Opto signal
									8	Orange	Opto Output	Optically isolated output
									9	Yellow	Opto Input	Optically isolated input

C.2 SP920

C.2.1 Supplied Accessories

The SP920 is supplied with the following accessories:

- USB3.0 Certified Standard-A to Micro-B cable
- Coax External Trigger Cable – Hirose HR25-7TP-8P(72) to BNC
 - Pins 2 & 5 – External Trigger, SMA Bulkhead, Female
 - Pins 1, 3, 4, & 6 – Not connected, see reference table

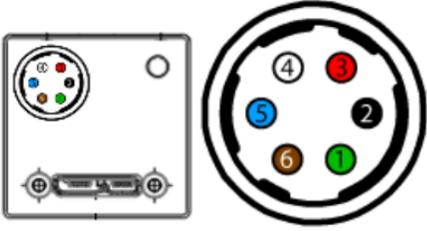
C.2.2 External Trigger Control

The SP920 camera is supplied with an external trigger input cable. The input to this cable should be a standard TTL level positive going pulse. The camera triggers, and begins integrating light on the rising edge. A trigger pulse should be at least 5 μ s in duration.

To operate in external trigger mode set the trigger control to **Trigger In**. Select **None** when operating in CW mode.

C.2.3 GPI/O Connector Description

The camera is equipped with a 6-pin GPIO connector on the back of the case. The connector is a Hirose HR10A-7R-6PB, the mating connector is a Hirose HR10A-7P-6S(73).

Diagram	Color	Pin	Function	Description
	Green	1	V _{EXT}	+12 V DC Camera Power
	Black	2	I/O	Opto-isolated input (GPIO 0)
	Red	3	NC / +3.3 V	+3.3 V output. Current 120 mA (nominal). Firmware enabled
	White	4	O1	Opto-isolated output (GPIO 1)
	Blue	5	OPTO_GND	Ground for opto-isolated I/O, not connected to camera ground
	Brown	6	GND	DC camera power ground

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C.3 SP1203

C.3.1 Connection Information

These cameras are PoE (Power over Ethernet). This requires the GigE port on the PC to be powered. If it is not, the power side of the supplied Power/Trigger cable must be used. The cameras can be triggered for pulsed lasers by using the BNC connector on the Power/Trigger cable.

C.3.2 External Trigger Control

The cameras have an external trigger input cable. The input to this cable should be a standard TTL level positive going pulse. The trigger cable does not provide external power, only triggering. The camera triggers and begins integrating light on the rising edge. A trigger pulse should be at least 5µs in duration.

To operate in external trigger mode, set this control to **Trigger In**. In most cases, it is best to select the maximum frame rate available on the camera when operating in pulsed mode with external triggers. The laser pulse should start no sooner than a few µsec after the rising edge of the trigger pulse. The exposure time should be set just long enough to contain the entire pulse width, and short enough to exclude pulses that may start before the imager has had time to be read out. This prevents laser pulse doubling in the captured image.

Select **None** when operating in CW mode.

C.3.3 NUC Files

Cameras with InGaAs sensors require nonuniformity correction in order to produce sensor output useful for beam propagation measurements. The SP1203 cameras employ special nonuniformity correction (NUC) files that are loaded into the camera. These correction files are supplied by the manufacturer and are unique to each camera. NUC files provide gain, offset, and bad pixel correction, as well as specific operating settings, e.g. exposure, gain, black level, imager temperature, etc. The camera loads these files automatically based on the selected settings.

C.3.4 Bad Pixel Correction

Bad pixel correction is automatically enabled whenever the camera is operating in full resolution mode. If new bad pixels present a problem, the camera can be sent back to Ophir to be serviced and add new bad pixels to the bad pixel correction map embedded in the camera.

C.3.5 GPI/O Connector Description

The camera has a 12-pin GPIO connector on the back of the case; refer to the diagram for wire color-coding and line information.

Diagram	Pin	Function	Level	Description
	1	In/Out	GND for RS232 and external power	External Ground
	2	In	10.8 V to 3	Power Supply
	3	Out	N/A	Video Iris
	4	In	V_{in} (low) 0.0 V to 0.8 V V_{in} (high) 2.0 V to 5.0 V	Input 1 non-isolated
	5	Out	Open emitter, max 20 mA	Output 3 opto-insolated
	6	Out	TTL (5 V, max. 20 mA)	Output 1 non-isolated
	7	In	Common GND for opto-isolated inputs	Camera Common Input Ground
	8	In	RS232	Terminal Receive Data
	9	Out	RS232	Terminal Transmit Data
	10	In	Common supply voltage for outputs max. 30 VDC	External Power Input for Digital outputs
	11	In	V_{in} (low) 0.0 V to 1.0 V V_{in} (high) 3.0 V to 24.0 V	Input 2 opto-insolated
	12	Out	Open emitter, max. 20 mA	Output 2 opto-insolated

C.4 XEVA XC-130

C.4.1 Camera Installation



To use a XenICs USB XEVA XC-130 camera install the BeamSquared software from the Ophir website and the Xeneth software supplied on the XenICs USB flash drive. The order of installation is irrelevant.

Run the XenICs USB flash drive and follow the directions for installing Xeneth. You cannot successfully use the XenICs camera in BeamSquared unless the camera driver and calibration pack NUC files are available for BeamSquared. The XEVA camera cannot be connected to both Xeneth and BeamSquared at the same time.



The correct version of Xeneth must be installed for proper operation.

- 1. Insert the Xenics flash drive into the PC.*
- 2. Open Windows Explorer and select the flash drive.*
- 3. Navigate to the folder 2_Software\Xeneth-SW_and_Manual\Xeneth_Advanced.*
- 4. For 64-bit operating systems run Xeneth-Setup-Advanced64.*
- 5. Restart the computer. The camera cannot connect without a system restart.*

The operating controls for XEVA model cameras are simplified to provide the best possible measurement accuracy for BeamSquared.

The InGaAs imager in the Xeva camera requires image correction processing to provide a useful image output. Xenics cameras, including Xeva, employ special NUC (non-uniformity correction) files that must be downloaded to the camera. These correction files are supplied by the manufacturer and are unique to each camera. NUC files provide gain, offset, and bad pixel correction for specific operating settings such as exposure, gain, black level, imager temperature, etc. BeamSquared provides controls to employ the necessary NUC file.

There are two (2) types of NUC files: TrueNUC files and standard NUC files. Both can be used with Xeneth.

NUC files end with a file extension of .xca and are also referred to as “calibration packs” or “camera correction” files. Xenics provides a CD with each camera that contains the factory generated NUC and TrueNUC files as well as a utility called Xeneth. This utility allows the user to test the camera and make additional NUC files if necessary.

NUC and TrueNUC files fall into 2 general classes: High Gain (HG) and Low Gain (LG). For laser beam analysis the High Gain NUC files are most frequently employed. High Gain NUC files give exceptionally better response linearity than Low Gain.

TrueNUC files can be used over a broad exposure range and maintain good pixel correction. **Only the TrueNUC_HG file is recommended for use with BeamSquared.**

Regular NUC files are specified for operation at or very near the preset exposure in effect when the NUC file was created. Using them outside of their set value degrades the camera’s image correction performance.

C.4.2 Getting Started with Xeva XC-130 camera

Once you have installed the above required software do the following:

1. Before applying power to the camera, plug in the USB cable from the camera to the PC.
2. Apply power to the camera.
3. Open BeamSquared.
4. A **Camera License Key** window appears. If not, go to the **Data Source** panel and select **Connect**.
5. Locate the camera license key supplied with the BeamSquared CD or camera and enter the code. You must enter a license on each computer where the camera is used.
6. Select **Live Playback** in the **Run** ribbon. The camera should start running and collecting frames from the camera.
7. Pause **Live Playback**.
8. Go to the **Correction** panel in the **Source** ribbon and select the ellipses to browse for a NUC file.
9. Go to the folder: C:\Program files\Xeneth\CalibrationPacks\
10. Click on an .xca file name that contains TrueNUC_HG and click **Open**.
11. Click **Live Playback** on the **Run** ribbon.
12. The camera should start displaying data frames with a well corrected image with a raised black level baseline.
13. The preset cooling temperature is normally 17°C. Wait for the readout temperature to stabilize at this setting.
14. Attenuate the laser and adjust the **Exposure** time to an appropriate setting.
15. You are now ready to start a run.



To disconnect a XEVA XC-130 camera always first remove power to the camera, then unplug the USB cable.



There is a known bug with the XEVA XC-130 camera where unplugging the camera's USB cable with the camera under power crashes the camera firmware. If this occurs, you must power cycle the camera to restart it, and re-enter the Camera License Key to restore operation with BeamSquared. (XenICs has indicated that they are not going to fix this bug.)

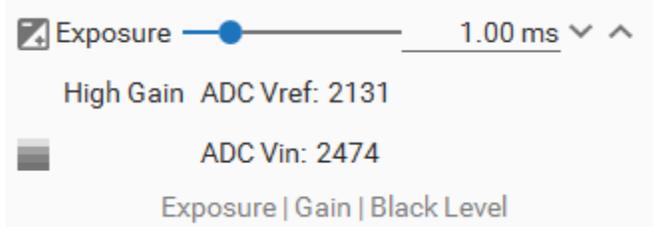


Custom NUC files created with Xeneth do operate correctly when used by BeamSquared.

C.4.3 XenICs XEVA XC-130 Camera Operation

This section describes the camera controls that are unique to the XenICs XEVA XC-130 camera. Common controls are covered in other sections of this manual.

C.4.3.1 Exposure | Gain | Black Level

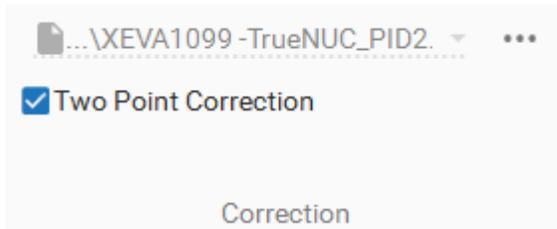


The following settings are preset in the TrueNUC or NUC file to optimize the camera dynamic range for best beam measurement accuracy. Only the **Exposure** setting can be altered by the user. The **Exposure** setting is saved in a BeamSquared setup file.

The **Exposure** control operates much like any other type of camera. It sets the exposure duration in milliseconds. When operating in external trigger mode, the exposure time begins upon receipt of the electronic trigger pulse. When using a regular NUC file (not a TrueNUC) the exposure setting should not be changed.

The **Gain** setting, **ADC Vref**, and **ADC Vin** indicators are preset to the value that corresponds to the TrueNUC/NUC file. Displayed here for verification purposes only.

C.4.3.2 Camera Correction File



To successfully use an InGaAs camera, such as the XC-130, a camera correction file must be applied. The file must match how the camera is setup for use. When the Xeneth software is installed it copies the camera correction NUC files into a folder called:

C:\Program files\Xeneth\CalibrationPacks\...

This folder contains 2 or more .xca NUC files specific to each camera's serial number. The name of the file gives details about when it should be applied. A file that contains the letters LG or HG are for low gain/high gain settings respectively.

To load a NUC file click on **Ellipses**, and then browse to the **CalibrationPacks** folder shown above. Select the appropriate TrueNUC/NUC .xca file and click **Open**.

The **Two Point Correction** box should always be checked to operate with the NUC table applied. If unchecked you can observe what the camera output looks like without NUC.

This file name is saved in a setup file and automatically applied to the camera upon opening the setup if the camera is already attached. If the camera was not connected then you may need to manually restore it.



Use of the NUC file reduces the maximum frame rate of the camera by an amount corresponding to the impact of the NUC effort required. Typically this yields a 10-20% reduction in maximum frame rate.

C.4.3.3 Temperature

Target Temp: 17 °C

Current Temp: 16 °C

Temperature

The XEVA camera has a thermoelectric cooler that is used to stabilize the imager temperature. The InGaAs imager is very sensitive to changes in temperature. To ensure a stable image baseline the temperature should be set to a value below the room temperature. Since 27°C is a nominal room temperature, and an operating camera will warm somewhat above this, all TrueNUC files force a temperature value of 17°C.

The camera has a cooler that can lower the imager temperature, but relies on normal heating of the camera to raise it. The readout from the camera indicates that the cooler is functioning and tracking to the target value. There is a nominal error between the set and the reported value.

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