PIV Hardware

Operations Manual

Preliminary
January 1997

P/N 1990831

Manual History

The following is a manual history of the PIV Hardware Operation's Manual (P/N 1990831).

Revision	Date
Preliminary	January 1997

This manual was first published as a preliminary in January 1997.

Safety

WARNING
The use of controls, adjustments, or procedures other than those specified within this manual may result in exposure to hazardous optical radiation.

See the Laser Manufacturers Installation Manual for drawings showing the locations of all warning labels for your laser.

The Pulse Energy specification is laser specific, see the laser manufacturers installation manual for the specifications for your laser. The pulse energy can be has high as 2 Joules per Pulse.

Class IV Laser Product

Energy/Pulse	2 Joule Maximum
Pulse Duration	2–40 nanoseconds
Nd:YAG Wavelengths	1064 nm and 532 nm

The TSI LASERPULSE Imaging System requires a CDRH certified laser. Do *not* use the TSI LASERPULSE Imaging System with a laser that is not certified.

Nd:YAG Laser Safety Goggles are included in the Model 610019 Nd:YAG Laser Accessory Kit. If you did *not* purchase this Accessory Kit you should purchase Nd:YAG Laser Safety goggles.

Manufacturer's Declaration of Conformity

TSI Incorporated hereby certifies that, to the best of its knowledge and belief,

❑ The instrument documented in this manual meets the essential requirements and is in conformity with the relevant EC Directive(s)

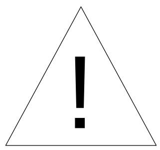
❑ The CE Marking has been affixed on the instrument

❑ The Declaration of Conformity certificate is included with the instrument.

Safety Labels

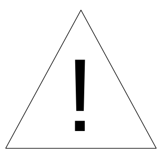
This section acquaints you with the advisory and identification labels on the instrument and used in this manual to reinforce the safety features built into the design of the instrument.

Caution



Caution
Caution means ***be careful***. It means if you do not follow the procedures prescribed in this manual you may do something that might result in equipment damage, or you might have to take something apart and start over again. It also indicates that important information about the operation and maintenance of this instrument is included.

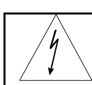
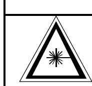
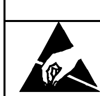
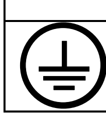
Warning



WARNING
Warning means that unsafe use of the instrument could result in serious injury to you or cause irrevocable damage to the instrument. Follow the procedures prescribed in this manual to use the instrument safely.

Caution or Warning Symbols

The following symbols may accompany cautions and warnings to indicate the nature and consequences of hazards:

	Warns you that uninsulated voltage within the instrument may have sufficient magnitude to cause electric shock. Therefore, it is dangerous to make any contact with any part inside the instrument.
	Warns you that the instrument contains a laser and that important information about its safe operation and maintenance is included. Therefore, you should read the manual carefully to avoid any exposure to hazardous laser radiation.
	Warns you that the instrument is susceptible to electro-static dissipation (ESD) and ESD protection procedures should be followed to avoid damage.
	Indicates the connector is connected to earth ground and cabinet ground.

Nd:YAG Laser Safety

This section of the PIV Operations Manual gives safety instructions to promote safe and proper use of the Nd:YAG-based PIV system.

WARNING
The use of controls, adjustments, or procedures other than those specified within this manual may result in exposure to hazardous optical radiation.

This PIV system uses an Nd:YAG laser which is classified as a Class IV laser. The laser beam is very powerful. If too much of this power reaches your eye, permanent damage will occur. The laser beam may have enough energy to burn skin or combustible materials.

WARNING
Harmful levels of radiation are emitted from this system. *Never* look into the laser beam, even reflections of the laser beam. *Never* allow the laser beam or lightsheet to point at anybody.

Always follow the safety rules recommended by the laser manufacturer. To control the danger, you must follow these cautions:

- ❑ *Never* look into the laser beam. If you must look at the beam, view it from an angle and in the direction the beam is traveling.
- ❑ Do *not* look at laser light scattered off a reflective surface.
- ❑ Control all reflected beams. The beam reflected off a surface may be as dangerous as the beam emitted directly from the laser. Block reflections wherever possible.
- ❑ Wear laser safety glasses.
- ❑ Avoid exposure to your skin
- ❑ The laser should be operated in an enclosed room.
- ❑ Operate the laser only with people who have been instructed in laser safety.
- ❑ Post warning signs outside the room.
- ❑ Do *not* use the laser near combustible materials.

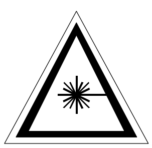
Labels

TSI's PIV systems use different models of the Nd:YAG lasers. Use only lasers certified with the Office of Compliance Center for Devices and Radiological Health. See the laser manual for labeling and safety information about your laser.

Argon Ion Laser Safety

This section of the PIV Operations Manual gives:

- ❑ Safety instructions to promote safe and proper use of the Argon Ion based PIV system
- ❑ Samples of warnings found in this manual, and
- ❑ Labels attached to the product.



WARNING

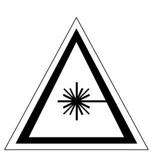
The use of controls, adjustments, or procedures other than those specified within this manual may result in exposure to hazardous optical radiation.

See the Laser Manufacturers Installation Manual for drawings showing the locations of all warning labels for your laser.

The Pulse Energy specification is laser specific, see the laser manufacturers installation manual for the specifications for your laser.

Class IV Laser Product

Power	20 Watts
Pulse Duration	CW Laser 1 µs– 1 second with Beam Modulator
Wavelengths	Argon Ion

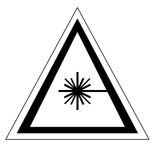


WARNING

The use of controls, adjustments, or procedures other than those specified within this manual may result in exposure to hazardous optical radiation.

The TSI LaserPulse Imaging System requires a CDRH certified laser. Do *not* use the TSI LaserPulse Imaging System with a laser that is not certified.

Argon Ion Laser Safety Glasses are included in the Beam Modulator Accessory Kit. If you did not purchase this Accessory Kit you should purchase Argon Ion Laser Safety Glasses.



W A R N I N G
The use of controls, adjustments, or procedures other than those specified within this manual may result in exposure to hazardous optical radiation.

This PIV System uses an argon ion laser which is classified as a Class IV laser. The laser beam is very powerful and can permanently damage eyes not protected by safety glasses. It has enough energy to burn skin or combustible materials.

Cautions

Always follow the safety rules recommended by the laser manufacturer. To minimize the danger, you must follow these cautions:

- ❑ Wear laser safety glasses.
- ❑ *Never* look into the laser beam. If you must look at the beam, view it from an angle and in the direction the beam is traveling.
- ❑ Do *not* look at laser light scattered off a reflective surface. Block beams from reflecting off a surface whenever possible. A reflected beam can be as dangerous as the beam emitted directly from the laser.
- ❑ Avoid exposing your skin to a laser beam
- ❑ Operate the laser in an enclosed room.
- ❑ Operate the laser only with people who have been instructed in laser safety.
- ❑ Post warning signs outside the room.
- ❑ Do *not* use the laser near combustible materials.

Labels

The TSI PIV systems use different models of the Argon Ion lasers. Use only lasers certified with the Office of Compliance Center for Devices and Radiological Health. See the laser manual for labeling and safety information about your laser. Figures 1 and 2 show the location of all the warning labels on the Beam Modulator.

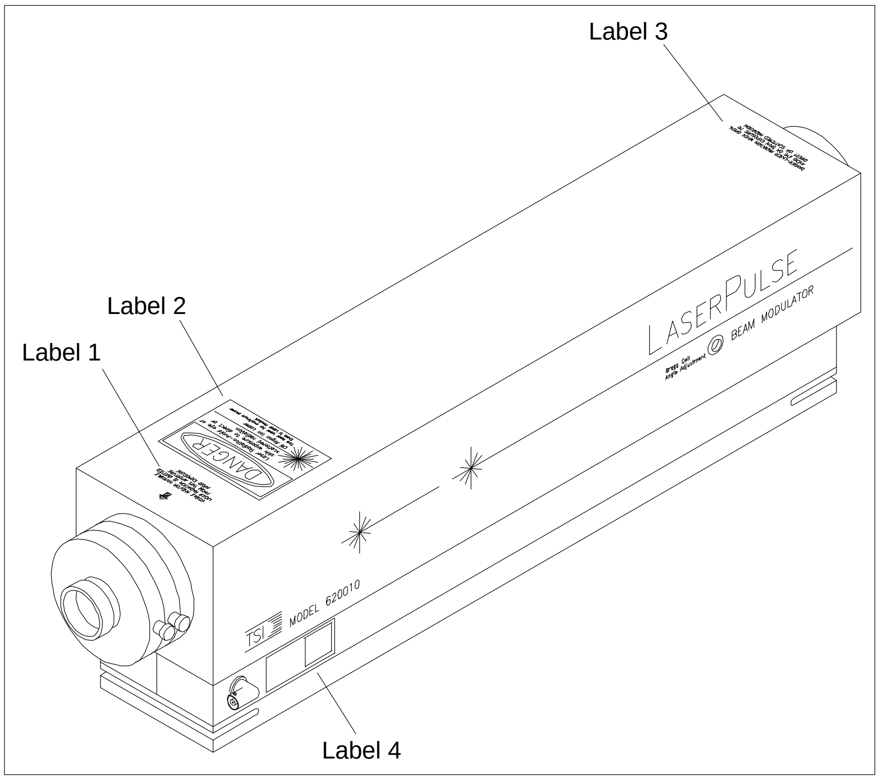


Figure 1
Location of the Warning Labels on the Beam Modulator

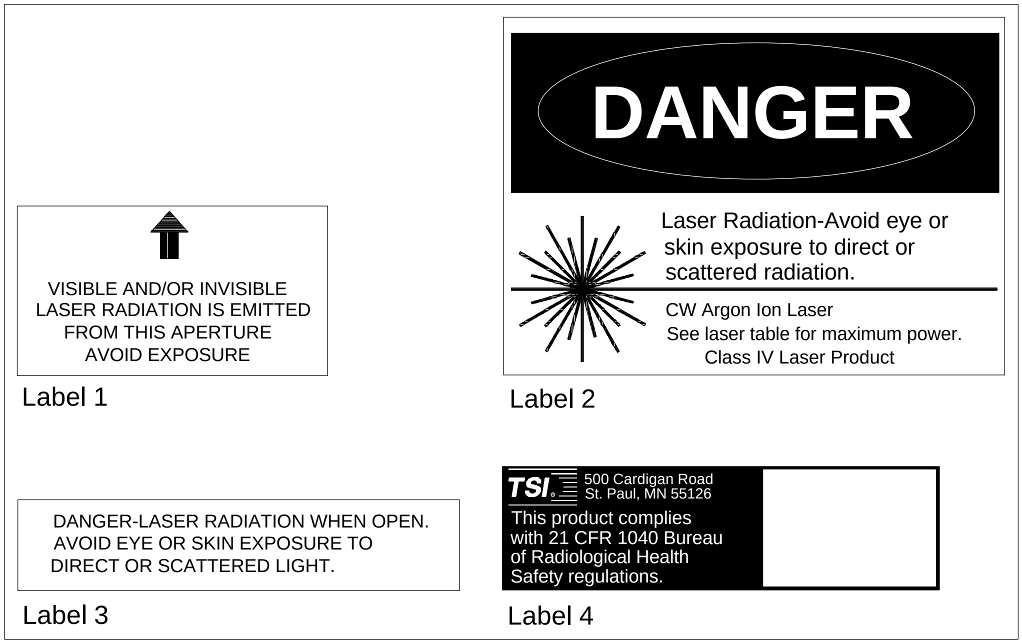


Figure 2
Warning Labels on the Beam Modulator

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CHAPTER 1

System Overview

This chapter of the PIV Hardware Operations manual gives a brief introduction to PIV technology and PIV system components to help you get an overview of your PIV system.

Particle Image Velocimetry is the simultaneous measurement of fluid or particulate velocity vectors at many (for example, thousands of) points, using optical imaging techniques. The measurements are made in planar *slices* of the flow field, but they can, in principle, be made over three-dimensional volumes. Accuracy and spatial resolution in PIV is comparable to Laser Doppler Velocimetry (LDV) or thermal anemometry. PIV is an ideal technology to capture unsteady flow fields.

PIV makes fluid velocity measurements by measuring the distance traveled by particles in the flow in the time between two pulses of light. Each time the laser is pulsed, the image of the particles in the lightsheet create an exposure on the camera (Figure 1-1). Double pulsing the laser gives two images of each particle in the lightsheet. By measuring the distance the particles have moved and dividing that by the time between pulses, the velocity for that particle is determined. By measuring the particle image displacements at many points in the image, the flow field is produced. With velocity measured at high accuracy on a regular grid flow, parameters such as vorticity and strain rates can also be computed.

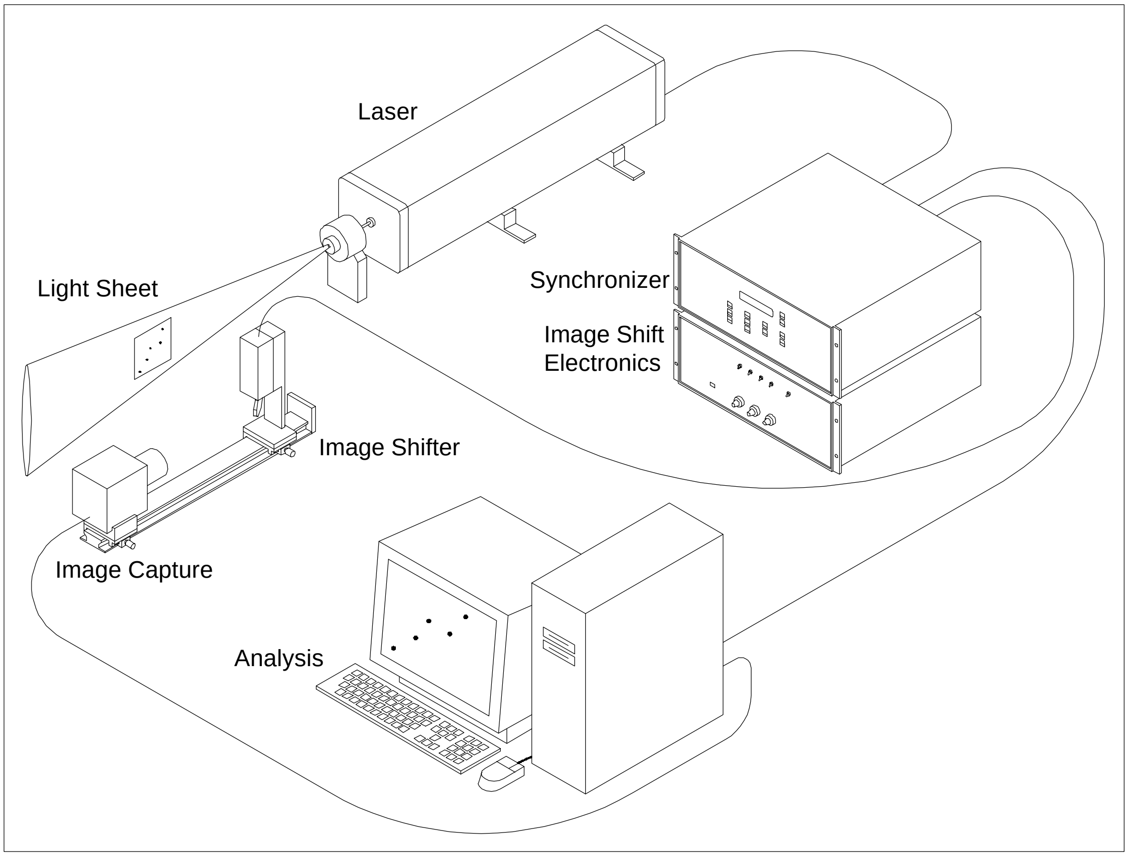


Figure 1-1
PIV Photography System

The TSI PIV LASERPULSE Imaging systems and INSIGHT software allow you to pick and choose the various components. A complete PIV system includes the following:

- ❑ Laser and lightsheet optics
- ❑ Image capture component
- ❑ Synchronizer
- ❑ Analysis components-computer hardware and software
- ❑ Image shifting component

The following is a description of a generic PIV system.

Laser and Lightsheet Optics

The pulsed laser and the lightsheet optics are part of the illumination system. The lightsheet optics includes cylindrical and spherical lenses. The cylindrical lens diverges the laser beam in one direction but keeps it the same thickness as the laser beam in the other direction. This gives a lightsheet that has some height but is thin. The spherical lens controls the lightsheet thickness. For most fluid measurements, a lightsheet thickness of less than 1 mm is desired. The spherical lens creates a beam waist at its focal distance. Moving away from the focal distance the lightsheet is thicker. With the proper selection of lightsheet optics the laser lightsheet can be set to the correct size for your experiment.

Image Capture

The image of the particle in the flow can be recorded with either a photographic film camera or a CCD video camera. In either case, the computer processes a digital image of the flow. When a film camera is used, the image is recorded on film and developed. The negatives are digitized and the digital image is analyzed, using the INSIGHT software. With a video camera system, the image is recorded on a CCD array. A Frame Grabber in the computer reads the camera image in from the video camera and stores it as a digital image in RAM. This digital image is processed using the INSIGHT software.

Synchronizer

To obtain a flow field image with PIV, the laser pulse and the camera must be triggered with the correct sequence and timing for the flow conditions that are being studied. The Synchronizer performs this task by controlling the timing of all the components, tying PIV imaging system components together so they function as an integrated system.

Analysis and Display

The analysis and display components of the PIV system consists of the INSIGHT software and a Frame Grabber and array processor. INSIGHT software processes the digital PIV images and measures the velocity throughout the flow field. The velocity vectors are displayed as a graphic overlay on top of the image. With post-processing flow properties like vorticity and strain rate are computed from the processed vector field.

Image Shifting

The image shifting component in a PIV system is used to resolve flow direction during the PIV image capture process. The image shifting component consists of a rotating mirror which is placed between the illuminated plane in the flow and the camera. The mirror is rotated in the time between the laser pulses and adds the image-shift displacement to the flow displacement. The additional particle displacement is subtracted during analysis by the INSIGHT software to give the correct velocity magnitude and direction.

PIV is a term that is sometimes used to describe a range of flow measurement techniques. These techniques are described in the following paragraphs:

Particle Image Velocimetry (PIV)

PIV uses correlation processing (a statistical approach) to give the average velocity within an interrogation spot. PIV performs best with higher seeding concentrations so that there are ten or more pairs per interrogation spot.

Particle Tracking Velocimetry (PTV)

PTV locates each particle image and pairs up individual particles to give the velocity of that particle. PTV typically performs best with low-image concentrations.

Laser Speckle Velocimetry (LSV)

LSV performs best when the seeding concentration is very high and the camera records an interference pattern from light scattered off groups of particles instead of the images from individuals particles. The speckelgram is processed using correlation techniques. A speckelgram can be processed using the INSIGHT software.

Flow Visualization

Flow visualization produces images of fluid flow. The velocity is seen in the image but not measured. Flow visualization is a qualitative technique.

PIV Hardware Operations

CHAPTER 2

Synchronizer

RS-232 Commands

The Synchronizer is controlled by use of RS232 commands from the computer to the Synchronizer. The communication between the computer and Synchronizer can be viewed in the LASERPULSE, Log, dialog.

It is also possible to have a program communicate directly with the Synchronizer. The Windows Terminal Application can be used to control the Synchronizer. This direct communications ability could allow the Synchronizer to perform special functions like taking images in coordination with a traverse movement or other application.

The Synchronizer Commands are listed here. The CONF: and TIME: commands consist of the command name, one space and then the input value. The command name may be in either capital or lower case letters.

Table 2-1
Synchronizer RS-232 Commands

Command	Name	Input
CONF:LASERT	Laser type	0 = Argon 1 = Nd:YAG
CONF:OPMODE	Mode of Operation	0 = Arrow Board Off 1 = Arrow Board On 2 = Run 3 = Stop 4 = Image Shifter On 5 = Image Shifter Off
CONF:PULSET	Pulse type	0 = Pulsed 1 = Continuous Pulse 2 = Continuous
CONF:NUMFRM	Number of Frames to Capture	0 = Continuous 1 or greater number of pulse sequences
CONF:TRIGER	Triggering Mode	0 = Internal 1 = External

(continued)

Table 2-1
Synchronizer RS-232 Commands (*continued*)

Command	Name	Input
CONF:POLRTY	Polarity Settings	Bit Field LSB 0 Camera Feedback 1 External Trigger In 2 Video In 3 Image Shift Trigger In 4 AUX 1 5 AUX 2 6 AUX 3 7 AUX 4 8 Image Shifter Trigger Out 9 Frame Grabber Trigger 10 Flashlamp 1 11 Flashlamp 2 12 Q-Switch 1 13 Q-Switch 2 14 Camera Trigger 15 0, Not used MSB
CONF:VIDTYP	Video Camera Output	0 = Even Field 1 = Odd First Field 2 = Progressive Scan 3 = Film
CONF:CAMTYP	Camera Type	2 = Video Master 3 = Synchronizer Control 4 = Shutter Feedback
CONF:YGFREQ	YAG Flashlamp Frequency	Hz * 10
CONF:FRAMES	Number of Video Frames per Flashlamp	For 30 Hz Camera Laser Pulse Repletion Rate: 1 = 30 Hz 2 = 15 Hz 3 = 10 Hz
CONF:QSWDIV	Q-Switch Divide	
CONF:ARGNFR	Argon Frame Rate	Hz * 10
CONF:ARGNDC	Argon Duty Cycle	Percent
CONF:APULSE	Active Pulses in Argon Mode, Bits set	8 Bit Field Bit = 1 On Bit = 0 Off
CONF:ARRWSH	Arrow Shaft Size	Percent of Head Size
CONF:ARWPER	Arrow Head Length	Percent of Arrow
TIME:PLSSEP	Pulse Separation Time dT	µs * 10
TIME:PDELAY	Pulse Delay	µs * 10

(continued)

Table 2-1
Synchronizer RS-232 Commands (*continued*)

Command	Name	Input
TIME:FRGRAB	Frame Grabber Trigger Delay	µs * 10
TIME:TRGDLY	Delay after trigger	µs * 10
TIME:IDELAY	Image Shift Delay	µs * 10
TIME:CAMDEL	Camera Shutter Open Delay	µs * 10
TIME:QSWTC1	Q-Switch 1	µs * 10
TIME:QSWTC2	Q-Switch 2	µs * 10
VER?	Synchronizer Version	Returns the Synchronizer Version
COMB	Transmit to COM Port B	Example to send camera MDE TR: COMBMDE TR
COMC	Transmit to COM Port C	Example to send camera MDE TR: COMBMDE TR

Synchronizer Input and Output Ports

The Synchronizer has many input and output ports on the back panel. The connections of these ports to equipment is described in detail in the components installation manuals. This section is only a brief explanation of the inputs and outputs and typical use.

The polarity of the TTL input and outputs is set using the INSIGHT, LASERPULSE, Polarity control.

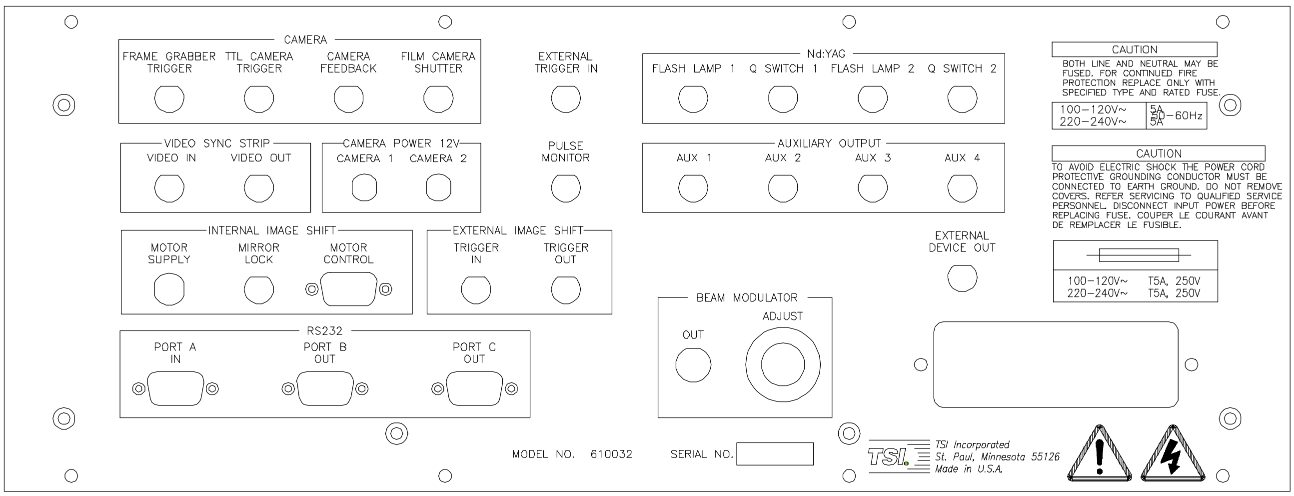


Figure 2-1
LASERPULSE Model 610032 Synchronizer Back Panel

Table 2-2
Synchronizer Connectors

Camera Group The Camera Group connects the Synchronizer the camera and Frame Grabber triggers.	
Frame Grabber Trigger	The Frame Grabber Triggers connects to the Frame Grabber and signals which video images have particle images and should be saved by the computer.
Camera Trigger	The Camera Trigger connects to a video camera and is used to start an exposure.
Camera feedback	Some cameras have a shutter that requires some time to open before the entire image area can be exposed. These camera typically have a Strobe Out, or Flash Sync, signal to signal that the shutter is fully open. When the Synchronizer is in Shutter Feedback Camera Mode it waits for this signal to go active before pulsing the laser.
Film Camera Shutter	The Camera Shutter output is used to connect the Synchronizer to 35 mm film cameras.

(*continued*)

Table 2-2
Synchronizer Connectors *(continued)*

Video Sync Strip Group The Video Sync Strip group of connectors attach the Synchronizer to an analog video camera allow the Synchronizer to lock onto the camera start of frame as the timing master for the experiment.	
Video In	The Video In connects to the analog composite video output of a camera. When the Synchronizer is in Video Triggered camera mode the video in connects to the Sync Strip circuit that determines the camera start of frame. This start of frame is the starting time for the pulse sequence.
Video Out	The video out port is the same signal as the video in. When the analog video signal is being digitized by the Frame Grabber it is this Video Out port that is connected to the Frame Grabber camera input. The 630044D and 630045 Crosscorrelation video cameras have both analog and digital outputs. The analog video output is used for Video Timing Master signal to lock onto. The digital image is captured by the Frame Grabber. The Video Out port is not used in these cases.
Camera Power 12V Group Provides 12 VDC power for video cameras.	
Camera 1	Camera power for video camera.
Camera 2	Camera power for second video camera in two camera systems.
Internal Image Shift Group The Model 610056 Spinning Mirror Image Shifter is a Synchronizer option. This Mirror image shifter is controlled by RS-232 commands from the computer.	
Motor Supply	The Motor Supply is the power supply for the 610056 Image Shifter Motor.
Mirror Lock	The 610056 Spinning Mirror can lock onto an external TTL trigger source and match the TTL frequency or harmonics of the frequency. This frequency matching between the mirror and the experiment allows the image system to make image shifted image captures are specific shaft rotation angles in a rotating machinery experiment.
Motor Control	The Motor Control is connected to the mirror motor and precisely controls the mirror rotation rate.

(continued)

Table 2-2
Synchronizer Connectors *(continued)*

External Image Shift Group The External Image shift connectors are used to with the Model 610050 Scanning Mirror Image Shifter or the Model 610055 Spinning Mirror Image Shifter. The Trigger Out and Trigger In signals from these image shifters allow the image shifting to be synchronizer with the system.	
Trigger Out	The Image Shift trigger out is used with the Model 610050 Scanning Mirror Image Shifter. With the scanning mirror in single shot mode it waits for this trigger signal to start mirror sweep. With spinning mirrors the Image Shift Trigger Out is not used.
Trigger In	The image shifters trigger the Synchronizer that the mirror is in position with the Image Shift Trigger In. When the synchronizer receives this trigger it starts the first laser pulse.
RS232 Group The RS232 Group connect the Synchronizer to the computer and other RS232 devices.	
Port A In	The RS232 Port A is connected to the computer. All instructions to the synchronizer come through Port A.
Port B Out	The RS232 Port B is used to connect the Synchronizer to other RS232 devices. Traverse controllers and RS232 controlled cameras are examples of devices that can be connected to the RS232 Port B
Port C Out	The RS232 Port C is to used to connect a second RS-232 device to the Synchronizer.
Nd:YAG Group The Nd:YAG group of outputs connect to the Nd:YAG laser to control the laser flashlamps and Q-Switches.	
Flash Lamp 1	Triggers Flashlamp on laser 1
Q Switch 1	Triggers Q-Switch on laser 1
Flash Lamp 2,	Triggers Flashlamp on laser 2
Q Switch 2	Triggers Q-Switch on laser 2

(continued)

Table 2-2
Synchronizer Connectors *(continued)*

Auxiliary Output Group The Auxiliary outputs are for future Synchronizer expansion and capabilities.	
Aux 1	For future use.
Aux 2	For future use.
Aux 3	For future use.
Aux 4	For future use.
Out	Connects to the Beam Modulator input. Use the Coaxial cable supplied with the Beam Modulator for this connection. Using a standard 50 Ω coaxial cable may pick up noise that prevents the beam from turning off.
Adjust	The Beam Modulator Adjustment knob controls the RF drive power delivered to the Beam Modulator. This adjustment is made by setting the knob for the maximum laser power with the Beam Modulator in continuous mode.
Connectors without a Group	
External Trigger In	The External Trigger is used to trigger a image capture timed off of an external trigger. An example of the use of the External Trigger is to connect this trigger to a once per revolution shaft encoder. By using this external trigger timing reference measurements can be made a specified shaft rotation angle. (The other system components must also be capable of asynchronous reset to do this.)
Pulse Monitor	The monitor is intended to be connected to an oscilloscope for trouble shooting. The monitor output shows the pulsing of the laser. For Argon lasers the signal is active when the laser is on. For Nd:YAG lasers the signal goes active when at the Flash Lamp and inactive on the Q-Switch. If the time between pulses is less than the Q-Switch delay then the signal goes active on Flash Lamp 1 and inactive on Q-Switch 2.
External Device Out	An External Device is a user supplied piece of equipment that can be turned on and off by the Synchronizer. The external device is connected to a trigger input or a relay to control the equipment. One example of the use of an external device is a solenoid valve could be attached to the external device through a relay circuit to turn a seeding system on and off.

Table 2-3
Model 610032 Synchronizer Specifications

<table>
<tr><td>Size</td><td colspan="4">(HWD) 17.8 cm × 48 cm × 41 cm
(7 in. × 19 in. 16 in.)
Standard 19 in. Rack mount</td></tr>
<tr><td>Input Power</td><td colspan="4">100/110/220/240 VAC 50–60 Hz</td></tr>
<tr><td rowspan="7">RS232</td><td colspan="4">The RS-232 Communications protocol is:</td></tr>
<tr><td></td><td>Port A In</td><td>Port B Out</td><td>Port C Out</td></tr>
<tr><td>Baud Rate</td><td>9600</td><td>9600</td><td>9600</td></tr>
<tr><td>Data Bits</td><td>7</td><td>8</td><td>8</td></tr>
<tr><td>Stop Bit</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>Parity</td><td>Odd</td><td>None</td><td>None</td></tr>
<tr><td>Flow Control</td><td>Xon/Xoff</td><td>Xon/Xoff</td><td>Xon/Xoff</td></tr>
<tr><td rowspan="5">RS-232 Parameters</td><td colspan="4">RS232 Cable for 9 Pin Computer Serial Port, Null Modem Cable for Port A:</td></tr>
<tr><td colspan="2">Signal</td><td>Computer Pin</td><td>Synchronizer Pin</td></tr>
<tr><td colspan="2">R×D Receive Data</td><td>2</td><td>3</td></tr>
<tr><td colspan="2">T×D Transmit Data</td><td>3</td><td>2</td></tr>
<tr><td colspan="2">GND</td><td>5</td><td>5</td></tr>
</table>

CHAPTER 3

Laser

This chapter of the manual discusses specific aspects of laser operation that you need to review to run your PIV experiment safely and successfully. For general information on the laser refer to the Laser Manual from the laser manufacturer.

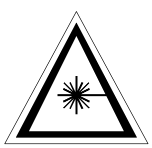
The LASERPULSE System can use three different types of lasers:

- ❑ Argon Ion
- ❑ Nd:YAG Pair
- ❑ Double Pulsed Nd:YAG.

There is choice of specific lasers of each type. This section will explain the operation of each type of laser system.

Argon Ion Laser

This section contains information and operating instructions for the Argon Ion laser.



WARNING

The use of controls, adjustments, or procedures other than those specified within this manual may result in exposure to hazardous optical radiation.

The LASERPULSE Beam Modulator is used to pulse a continuous wave argon-ion laser beam. The Beam Modulator is controlled by the Model 610030 LASERPULSE Synchronizer. With this combination, the time between laser pulses and the pulse duration can be selected to give the optimum timing for measuring your flow. The Beam Modulator uses a Bragg cell to switch the laser lightsheet on and off. The first order diffraction beam is used as the laser lightsheet. When the Bragg power is on, the lightsheet is on. The Synchronizer controls the Bragg cell.

With the optional Real Time Arrows board installed in the Synchronizer the laser lightsheet can be Modulated to create arrow streaks in the flow. This is useful for flow visualization.

The Pulsing Parameters specific to Argon Lasers are set in the **LASERPULSE | Argon Laser** dialog box. See the LASERPULSE menu manual for a description of these parameters. The pulse timing and pulse separation time dT are set in the **LASERPULSE | Timing** dialog also described in the LASERPULSE menu manual.

Argon Pulse Energy

There are two methods to set the pulse energy with an Argon PIV system. The laser power can be adjusted using the laser controls. A second method to set the pulse energy is by using the Pulse Duty Cycle. The pulse energy = laser power * pulse duration. The pulse duration = dT * Duty cycle. By increasing the duty cycle the pulse energy increases. When the duty cycle is increased the particle streak lengths also increase. Use short duty cycles to reduce the streak length and long duty cycles to increase the laser power. Typical duty cycles are 10% to 30% to freeze the particle motion with enough energy to capture the particle images.

This section reviews how the maximum velocity that a system can measure depends on the time between laser pulses (Δt). For details, refer to *PIV System: Theory of Operation* in the *System Overview* section in this manual. Figure 3-1 shows the relationship between velocity and pulse separation. The maximum velocity for Argon PIV system is determined by the energy per pulse. As the velocity increases the time between pulses decreases and the pulse duration also decreases. The maximum velocity is limited by the shortest pulse duration that produces enough energy to view the particles. For Argon-based PIV systems, it is about 5 m/sec for a 5 watt laser.

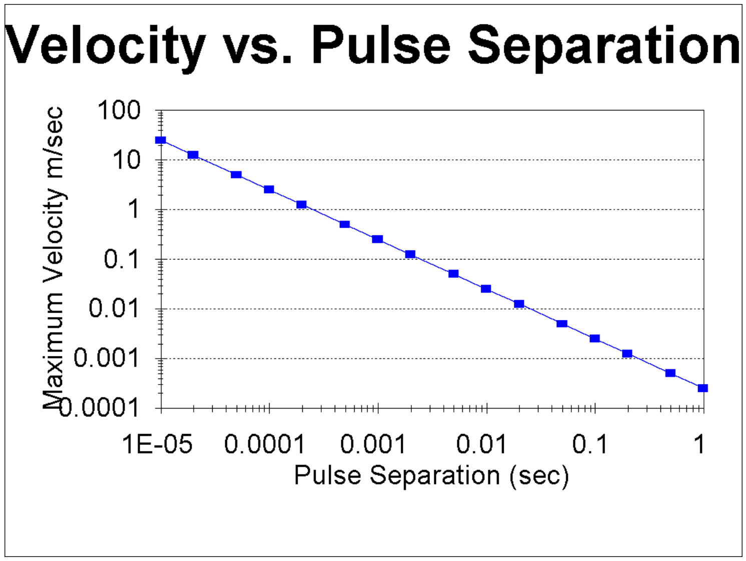


Figure 3-1
Velocity Versus Pulse Separation

Table 3-1 shows a graph of maximum velocity for three interrogation spot sizes with no image shift, 1:1 photo magnification and a range of pulse separations.

Table 3-1
Graph of Maximum Velocity for 1 mm Spot Sizes with no Image Shift, 1:1 Photo Magnification over a Range of Pulse Separations

Time Bet. Pulses (Δt) (sec)	Max. Vel (m/s)
100 ms	0.0025
50 ms	0.005
20 ms	0.0125
10 ms	0.025
5 ms	0.05
2 ms	0.125
1 msec	0.25
500 µs	0.5
200 µs	1.25
100 µs	2.5
50 µs	5
20 µs	12.5
10 µs	25

The energy per pulse from an argon laser Beam Modulator system depends on the laser power, Pulse Duty Cycle % and the Pulse Separation Time.

Pulse Energy μJ = Laser Power W * Pulse Separation μs * Duty %

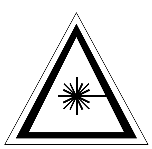
Table 3-2 shows some examples of the energy per pulse for a 1 Watt laser for two Pulse Separations and three Pulse Duty Cycles.

Table 3-2
Argon Pulse Energy as a Function of Pulse Duty Cycle and Pulse Separation for 1 Watt Laser.

Pulse Duty Cycle %	**Pulse Separation μs**	**Laser Beam On Time μs**	**Laser Beam Off Time μs**	**Pulse Energy 1 Watt Laser μJ**
10%	500	50	450	50
25%	500	125	375	125
50%	500	250	250	250
10%	1000	100	900	100
25%	1000	250	750	250
50%	1000	500	500	500

Nd:YAG Lasers

This section contains information and operating instructions for Nd:YAG lasers.



W A R N I N G

The use of controls, adjustments, or procedures other than those specified within this manual may result in exposure to hazardous optical radiation.

Using and Setting the Q-Switch

Nd:YAG laser pairs systems have two complete Nd:YAG lasers cavities and Q-Switches, and beam combination optics to create the collinear beams. In a Double pulsed Nd:YAG laser the Q-Switch is fired twice during a flashlamp to create a pair of laser pulses. With the Nd:YAG laser pair the Q-Switch can be used to adjust the laser pulse energy without affecting the time between pulses. With the Double Pulsed Nd:YAG there are more requirements on the timing of the pulses to get two pulses of equal energy. This section first explains the Q-Switch, then Nd:YAG Pairs and then Double Pulsed Nd:YAG lasers.

Pulse Energy

Q-Switch Divide & Pulse Frequency

A Nd:YAG laser is designed for best performance at a specific flashlamp frequency and voltage. The operation of the flashlamp generates heat that causes the YAG rod to expand. The ends of the Nd:YAG rods are concave at room temperature so that when they expand with thermal lensing the rod ends become flat. When the laser is operated at less that the design flashlamp voltage or frequency it may not come to full power and the beam quality will decrease. Some PIV system use a 10 Hz Nd:YAG laser and a camera that can only operate at four frames per second or less. In this case the Q-Switch Divide parameter is used to reduce the laser pulsing rate and keep it operating at the optimum frequency. The key to having the laser quality is the flashlamp frequency. The Q-Switch is required to release a laser pulse. By firing the flashlamp without a Q-Switch the Nd:YAG rod is keep at design temperature and the laser is not pulsed at a rate faster than the camera can accept.

Table 3-3
Q-Switch Divide Settings and Pulse Rates for 10 Hz Laser

Q-Switch Divide	Frequency	Time between Pulse Sequences
1	10	100 ms
2	5	200 ms
3	3.33	300 ms
4	2.5	400 ms
5	2	500 ms
6	1.67	600 ms
7	1.42	700 ms
8	1.25	800 ms
9	1.11	900 ms
10	1.0	1000 ms

If the maximum camera frame rate is 4 frames per second then a Q-Switch Divide setting of 3 is used to operate the system at 3.33 frames per second.

Laser Lightsheet Optics

Each laser system as a set of cylindrical and spherical lenses that are used to produce the lightsheet that illuminates the flow. The lenses are included in the lightsheet optics are selected to produce range of lightsheet sizes suitable for the laser. The discussion of lightsheet optics is uses an Argon laser as an example. See the Operation section for your laser to see the lightsheet dimension available with your laser.

Selecting the Appropriate Laser Lightsheet Optics

The lightsheet optics are controlled by using a cylindrical and a spherical lens. By choosing the correct lenses, you can obtain the optimum lightsheet for your experiment. The cylindrical lens controls the lightsheet height divergence angle while the spherical lens controls the lightsheet thickness. Since the cylindrical lens is much more powerful with a shorter focal length, the spherical lens has little effect on the lightsheet height.

When choosing your lightsheet optics you should pay attention to the beam divergence over the photograph area. The laser beam starts out round with a 1 to 2 mm diameter for an Argon laser. For most PIV experiments a lightsheet of less than 1-mm thick is desired. The spherical lens is used to reduce the lightsheet thickness. The lens creates a waist at the focal point. On either side of the waist the beam diverges. The shorter the focal length the higher the beam thickness divergence. Since the lightsheet intensity is proportional to the cross section area if the beam diverges too much across, the properties might vary too much.

You can use PIVSIM to compute the dimensions for your laser and lightsheet optics.

The lenses included with the laser system are:

- ❑ Spherical Lenses, 25 mm diameter
  610060 100 mm fl
  610061 200 mm fl
  610062 500 mm fl
- ❑ Cylindrical Lenses
  610080 –6.35 mm fl
  610081 –12.7 mm fl
  610082 –25 mm fl

Table 3-4 lists the lightsheet heights for different lens combination. To read the table, if you are using a 100 mm spherical lens and a -6.35 mm cylindrical lens, the lightsheet dimension would be 60 mm high and 56 µm at the waist.

Table 3-1
Lightsheet Heights (mm) for Lens Combinations

Spherical lens FL(mm)	100	200	500
Cylindrical lens FL (mm)			
–6.35	23	47	120
–12.7	12	24	60
–25.0	7	12	30
	—	—	—
Waist (mm)	.042	.085	.212
Divergence (mm/100 mm)	1.5	0.75	0.3

Argon 1.5 mm-beam diameter, 25-mm lens separation

Figure 3-2 lists the lightsheet dimensions.

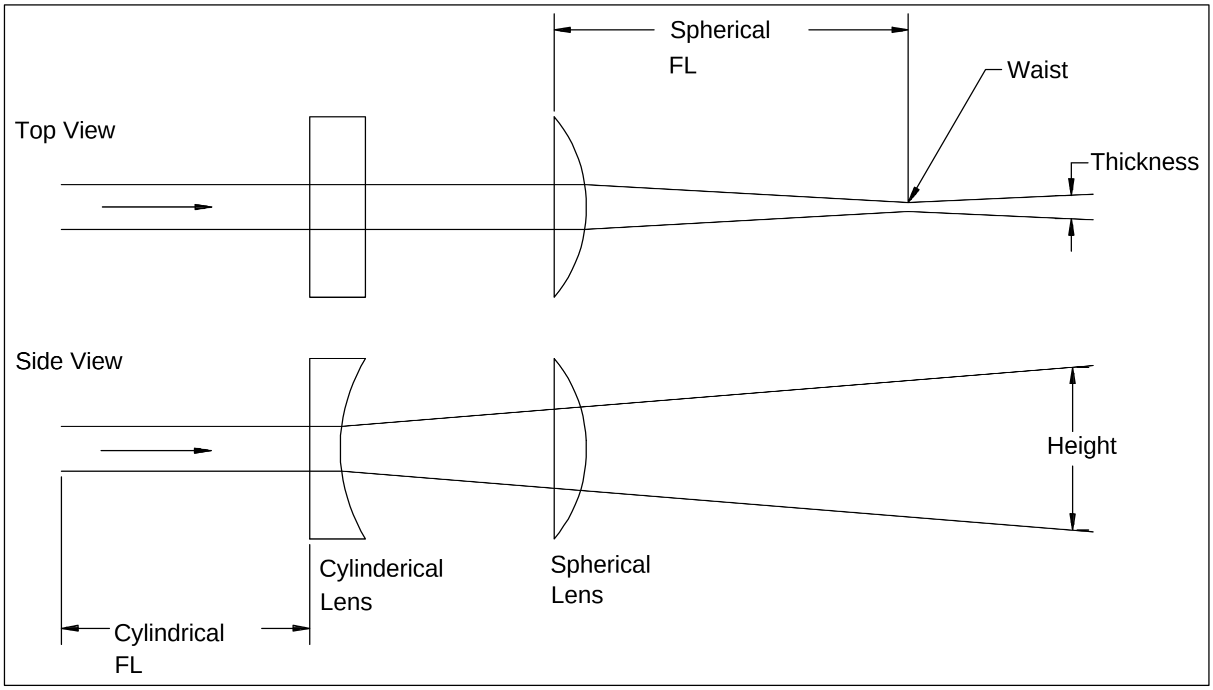


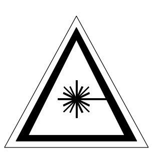
Figure 3-2
Argon Lightsheet Dimensions

New Wave Research PIV Mini/Lase Nd:YAG Laser Operation Instructions

This section contains information and operating instructions for the New Wave Research PIV Mini/Lase Nd:YAG laser.

Laser Safety

Read and follow the laser safety section of this manual, and the laser manual.



WARNING
The use of controls, adjustments, or procedures other than those specified within this manual may result in exposure to hazardous optical radiation.

See the New Wave Research Inc. Mini/Lase Nd:YAG Laser Operating Manual for drawings showing the locations of all warning labels for your laser.

Class IV Laser Product

Wavelength	Energy/Pulse	Pulse Duration
1064 nm	150 mJ	17 ns
532 nm	100 mJ	6 ns

Laser Startup and Shutdown Procedure

The following are startup and shutdown instructions for the New Wave Research PIV Mini/Lase Nd:YAG Laser.

New Wave Startup Procedure

After the installation procedure is complete and the laser safety section is thoroughly understood, the laser may be started. All covers must be installed and the reservoir filled with deionized (distilled) water before the laser may be started. The key switch on the power supply must be turned to the ON position prior to operating the laser.

1. Rotate the Shutter to the Closed position.
2. Set the Energy switch to **LO** on the remote control.
3. Turn the key switch to the **ON** position on the laser power supply.
4. Set the Trigger Selector to the **START** position.
5. Press and hold down the green **ON** button on the remote control until the red INTERLOCKED LED is off and the EMISSION LED is on.
6. Note that after the red EMISSION LED is on there is a delay of approximately 10 seconds before laser pulsing can occur.
7. Use the Trigger Selector switch to select the REMOTE to fire the laser controlled by the LASERPULSE Synchronizer.
8. In INSIGHT, open the LASERPULSE Menu, select: **Component Laser New Wave MiniLase 12**, the camera mode and other operating parameters.
9. Open the laser shutter.

10. In the INSIGHT | LASERPULSE dialog box select **RUN**, to start the laser, **STOP** to stop the laser.
11. Turn the Energy Switch on the remote to HI for making measurements.
12. Control the laser power using the INSIGHT | LASERPULSE | YAG Power dialog box.

New Wave Shutdown Procedure

1. Rotate the Shutter to the Closed position.
2. In **INSIGHT | LASERPULSE** dialog press the **STOP** button.
3. Set the Energy Switch to **LO** on the remote.
4. Allow the to run for a few minutes with the flashlamps off to cool the laser.
5. Push the **OFF** button the remote.
6. Close the shutter.
7. Turn the key switch to the **OFF** position on the power supply.
8. Press the INSIGHT, LASERPULSE **Stop** button.
9. Turn the laser power supply front panel KEY to **OFF**.
10. Turn the Synchronizer **OFF**.

Turning the Laser Beam On and Off

There are three ways to turn the laser beam off. You can use the one that is most convenient.

1. Synchronizer **RUN/STOP** button.
2. Laser remote Control Trigger Selector to **START** to turn the laser off. Remote will allow the laser to pulse.
3. Lightsheet Optics Beam Shutter.

Setting the Laser Power

The Nd:YAG laser power can be selected either by using the FLASHLAMP ENERGY control or by setting the Q-Switch Delay time. Using the Q-Switch delay is the preferred method. The flashlamps generate heat and the YAG rods are made with concave ends so that they will be flat when the laser comes to operating temperate. You will get the best beam quality by running the flashlamps at full power.

Troubleshooting Laser Starting

Nothing happens when key is turn on. Check that the laser is plugged in. The back panel of the laser has a Capacitor Discharge Switch. Make verify that it is in the out position.

The Interlock on the laser power supplies are on if all of the interlocks are closed. If one of the interlocks is open the interlock light will blink.

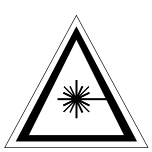
The Synchronizer must be on and triggering the laser for it to fire. Check that the Synchronizer is ON, and Set for YAG Lasers. If you are using Video Triggered Mode the camera must be on and driving the Synchronizer. If the Synchronizer is set for mirror image shifting EXTERNAL TRIGGER the image shifter must be triggering the Synchronizer.

Quantel Nd:YAG Operating Instructions

This section contains information and operating instructions for the Quantel Nd:YAG Laser.

Laser Safety

Read and follow the laser safety section of this manual, and the laser manual.



WARNING
The use of controls, adjustments, or procedures other than those specified within this manual may result in exposure to hazardous optical radiation.

See the *Quantel Brilliant Twins Installation Manual* for drawings showing the locations of all warning labels for your laser.

Class IV Laser Product

Energy/Pulse	2 Joule Maximum
Pulse Duration	10 nanoseconds
Nd:YAG Wavelengths	1064 nm and 532 nm

Laser Startup and Shutdown Procedure

The following are startup and shutdown instructions for the Quantel Nd:YAG Laser.

Quantel Start Up Procedure

1. Power supply front panel KEY switch on. The power supply fan runs at high speed for 20 seconds as it warms up.
2. Press the **Flashlamp EXT** button and check that the green Simmer light comes on.
3. Press the **Q-Switch EXT** button and check that the red light comes on.
4. Turn the other laser key on and set it for **Flashlamp EXT** and **Q-Switch EXT**.
5. In INSIGHT open the LASERPULSE tabbed dialog and verify that the Quantel laser is selected in components. Press the **Run** button.
6. Press the **Start** button on the laser remote for laser 1. The laser will start pulsing.
7. Press the **Start** button on the laser remote for laser 2. The second laser will start pulsing.

Shutdown Procedure

1. Press the INSIGHT, LASERPULSE Stop button.
2. Turn the laser power supply front panel KEY to **OFF**.
3. Turn the Synchronizer **OFF**.

Turning the Laser Beam On and Off

There are three ways to turn the laser beam off. You can use the one that is most convenient.

1. Synchronizer RUN/STOP button.
2. Laser remote Control Start/Stop buttons.
3. Lightsheet Optics Beam Shutter.

Setting the Laser Power

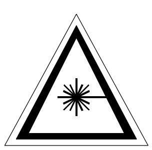
The Nd:YAG laser power can be selected either by using the FLASHLAMP ENERGY control or by setting the Q-Switch Delay time. Using the Q-Switch delay is the preferred method. The flashlamps generate heat and the YAG rods are made with concave ends so that they will be flat when the laser comes to operating temperate. You will get the best beam quality by running the flashlamps at full power.

Spectra Physics PIV Nd:YAG Operating Instructions

This section contains information and operating instructions for the Spectra Physics PIV Nd:YAG Laser.

Laser Safety

Read and follow the laser safety section of this manual, and the laser manual.



WARNING

The use of controls, adjustments, or procedures other than those specified within this manual may result in exposure to hazardous optical radiation.

See the Spectra Physics, Quanta-Ray Pulse Nd:YAG Lasers User’s Manual for drawings showing the locations of all warning labels for your laser.

Class IV Laser Product

Energy/Pulse	1.5 Joule Maximum
Pulse Duration	8 nanoseconds
Nd:YAG Wavelengths	1064 nm and 532 nm

Laser Startup and Shutdown Procedure

The laser circuit breaker power switch on the front panel should be left on unless the laser is not going to be used for weeks. Leaving the circuit breaker on keeps the harmonic generator heater on decreasing required warm up time and the heat helps prevent moisture from getting into the harmonic generator.

Start Up Procedure

1. Cooling water on if laser is equipped with a water-to-water heat exchanger.
2. Power supply front panel CIRCUIT BREAKER on (do *not* turn off unless the laser will be off for an extended period)
3. Power supply front panel KEY switch on.
4. Power supply front panel AMP DISABLE off.
5. Remote control LASER 1 & LASER 2 FLASHLAMP ENERGY set to **START**.
6. Remote control REP RATE set to **EXT**
7. Remote control Q-Switch set to **EXT**
8. Remote control INT/COMPUTER set to **INT**
9. Remote control SINGLE SHOT/REP set to **REP**
10. Remote control LAMP ON/INHIBIT to **LAMP ON**.
11. All covers must be on.
12. Temporarily depress the **ENABLE** switch.
13. Wait for the SIMMER lights to come on. Then slowly increase LASER 1 FLASHLAMP ENERGY to 10. Slowly increase LASER 1 FLASHLAMP ENERGY to 10.
14. Turn the Synchronizer **ON**.
15. Press the Synchronizer **RUN** button.

Shutdown Procedure

1. Press the Synchronizer **STOP** button.
2. Decrease the remote control LASER 1 & LASER 2 FLASHLAMP ENERGY to START.
3. Let the water cooling pump run for 10 minutes to cool the flashlamps.
4. Temporally press remote control the **STOP** button.
5. Turn the laser power supply front panel KEY to **OFF**.
6. Turn the Synchronizer **OFF**.
7. Turn the Water **OFF** if your laser has a water to water heat exchanger. (The laser has a flow switch in the water to water heat exchange so the laser only uses the water necessary to keep the laser re-circulating distilled water at operating temperature. You can leave the water on if you want without wasting water.)

Turning the Laser Beam On and Off

There are three ways to turn the laser beam off. You can use the one that is most convenient.

1. Synchronizer RUN/STOP button.
2. Laser remote Control LAMP INHIBIT.
3. Lightsheet Optics Beam Shutter.

Setting the Laser Power

The Nd:YAG laser power can be selected either by using the FLASHLAMP ENERGY control or by setting the Q-Switch Delay time. Using the Q-Switch delay is the preferred method. The flashlamps generate heat and the YAG rods are made with concave ends so that they will be flat when the laser comes to operating temperate. You will get the best beam quality by running the flashlamps at full power.

Troubleshooting Laser Starting

The SIMMER lights will *not* come on and the laser will *not* start if the LASER 1 & 2 FLASHLAMP ENERGY controls are not set to START when the remote ENABLE switch is pressed.

The LAMP INHIBIT can be used to turn the laser beam off. The LAMP ON must be set for the laser to fire.

The laser power supply INTERLOCK FAULT lock is on because a cover is not on or there is a problem with the cooling system.

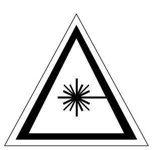
The Synchronizer must be on and triggering the laser for it to fire. Check that the Synchronizer is ON, and Set for YAG Lasers. If you are using Video Triggered Mode, the camera must be on and driving the Synchronizer. If the Synchronizer is set for mirror image shifting EXTERNAL TRIGGER the image shifter must be triggering the Synchronizer.

Continuum Nd:YAG Lasers

This section contains information and operating instructions for Continuum Nd:YAG lasers.

Laser Safety

Read and follow the laser safety section of this manual.



W A R N I N G

The use of controls, adjustments, or procedures other than those specified within this manual may result in exposure to hazardous optical radiation.

See the Continuum Surelite PIV-Lite Operation and Maintenance Manual for drawings showing the locations of all warning labels for your laser.

Class IV Laser Product

Energy/Pulse	2 Joule Maximum
Pulse Duration	2–40 nanoseconds
Nd:YAG Wavelengths	1064 nm and 532 nm

Daily Startup

1. The red toggle switch labeled **AC POWER** should have been left on after the last use. If not, do the following:

   On the front panel of the power supply, flip the red toggle switch labeled **AC POWER** up (this is the ON position). After a quick diagnostic check o f all LED's on the front panel, the display LED shows **8.8.8**, software rev. #, then **OFF.**

2. Insert the key into key switch and turn counter-clockwise to **ON**. The readout LED will momentarily display the flowing:

Total # of flashlamp discharges	Given a series of three displays of millions, thousands, and hundreds.
Water flow startup	Flo is displayed while system waits for water flow to be verified in laser heads.
Flashlamp discharge frequency	Last saved rep rate is displaced in Hz (flashes/sec).

3. Press **SELECT** button and toggle LED display though the six modes to verify accuracy of settings. Normal values are:

Rep Rate	Factory set for either 10 or 20 Hz.
Q-switch	Set the value listed in Quality Assurance Document at front of laser manual.
Pulse Division	P01 (laser output with every discharge of flashlamp)
Pump Voltage	Set to value listed in Quality Assurance Document at front of laser manual
Serial Mode	SoF (serial port off)
External mode	EoF (External mode Off)

4. Change the External Mode to External On **EoN**.

5. Start the Synchronizer and INSIGHT and press the **Run** button in the LASERPULSE Menu to start the laser triggers.

6. Press the laser power supply **START/STOP** button and its red LED comes on. The laser head will now flash at the designated frequency. Allow system to run for 15 to 20 minutes to thermally stabilize YAG head before proceeding.

7. Put on your laser safety goggles.

8. On the front of the laser head, slide the exit port shutter to the **OPEN** position. *** leave open all of the time use the TSI shutter ***

9. Press the **SHUTTER** button and it's red LED comes on. An audible click can be heard from the laser head as the intra-cavity shutter withdraws from the oscillator. The system should now lase.

Note: *For thermal stabilization of the Pockels cell and harmonic generators, the laser software will not allow the **SHUTTER** button to open for 30 minutes after the red **AC POWER** toggle is first turned on.*

10. Allow the laser to output light for at least 5 minutes to warm up the harmonic generator. Then optimize the harmonic generator for maximum power.

*** Maximum harmonic generator power ***

Daily Shutdown

1. Depress the **START/STOP** button. The red LED on the START/STOP button should go off and the red LED on the SHUTTER button should also turn off. An audible click can be heard as the intra-cavity shutter drops. The laser head flashlamps should stop flashing.

2. Close the lightsheet optics Shutter.

3. Turn key clockwise to **STANDBY** and the **LASER ON** light will go off. Afterwards, a 1-second beep will sound and the system will power down. The LED display should red OFF. Remove key.

4. Leave red toggle labeled **AC POWER** up and in the **ON** position.

Note: *The AC POWER can be toggled off if there are no plans to use the laser for an extended period of time.*

Nd:YAG Laser Maintenance

Your Nd:YAG laser requires periodic maintenance to keep it running well. The chart below shows a typical Nd:YAG laser maintenance schedule. See your laser manufacturers manual for your particular laser.

Table 3-2
Typical Nd:YAG Laser Maintenance Schedule

	Each Month	**Every Six Months**	**Every 12 Months**
Check System Alignment	X		
Clean/inspect optics	X		
Change DI filter in cooling unit		X	
Replace Flashlamps			X
Clean Cooling Radiator		X	
Inspect cooling water loop connections		X	

CHAPTER 4

Image Capture

INSIGHT works with many cameras, each of the cameras has some special features that make it a good choice for PIV measurements. The cameras vary in number of pixels per image, frame rate, time between exposures, and timing electronics. INSIGHT enables and disables the features for your camera. In this section the cameras are explained in five groups: PIVCAM 10-30; PIVCAM 4-30 and PIVCAM 10-15; RS-170 Crosscorrelation; RS-170 and CCIR; MegaPlus 1.4 MegaPlus 4.2 & 35mm Film. This section also includes an explanation of frame straddling for two-frame crosscorrelation measurements.

The detailed specifications of each camera are filled into the LASERPULSE | Components | Camera Setup dialog when the camera is selected. These specifications control several controls throughout the LASERPULSE system. The system timing varies depending on the camera, laser and image shifting. A single camera may be able to operate in several modes. The camera operations are be described by the image capture mode.

Model 630046 PIVCAM 10-30

The Model 630046 PIVCAM 10-30 camera. Has several design features that make it well suited for PIV measurements. The PIVCAM 10-30 has an Asynchronous Double Exposure mode. That allows a frame straddle pair of images to be captured less than 300 µs after an external trigger signal. This fast reset can be used for rotating machinery an other applications where capturing a crosscorrelation pair of image at an exact time is desired.

Computer Control of Operating Modes

The operating mode and setting of the PIVCAM are controlled by the computer through the LASERPULSE tabbed dialog box. The camera specifications can be viewed by pressing **the LASERPULSE | Configuration | Camera Setup** button to display the **Camera Setup** dialog box. **The Computer Controlled Camera** dialog box is opened pressing **the Camera Setup | Remote Setup** button. The parameters that can be adjusted are:

Digital Output

Gain	The Gain setting is used to adjust the slope of the conversion between pixel charge and digital pixel intensity. With a Gain setting of 1 the digital output pixel intensity is 255 when the pixel is holding its maximum charge. With a Gain of 4 the digital output pixel intensity is 255 when the pixel is holding ¼ of its maximum charge. Gain settings of 2 or 4 can be used to increase the image brightness. Having a Gain setting of 1 and enough exposure to give pixel intensities up to 255 is preferred over having to use the digital gain.
Offset	The Offset value is added or subtracted from each digital output pixel intensity value. By subtracting an offset value the signal to noise ratio of many images can be improved. When the Offset value equals the gray scale background light intensity level the gray values are converted to black.
Gain Balance	The PIVCAM 10-30 uses two digital output channels. One of the channels is for the even image lines and the other is for the odd image lines. If the Gain Balance is not correct every other image line will be bright. By adjusting the Gain Balance setting the Gain of the Odd and Even channels can be make equal.
Offset Balance	The PIVCAM 10-30 uses two digital output channels. One of the channels is for the even image lines and the other is for the odd image lines. If the Offset Balance is not correct every other image line will be bright. By adjusting the Offset Balance setting the Offset of the Odd and Even channels can be make equal.

Defect Conceal

The CCD chip contains over 1 million pixels. It is possible for some of the pixels to have too much or too little gain relative to the other pixels. The Defect conceal parameter replaces the pixel intensity of the bad pixels with the average of the neighboring pixels.

COM Port

The COM Port setting tells INSIGHT how the camera is connected to the computer. It can either be connected to one of the computer COM Ports COM 1, COM 2, COM 3, COM 4 or it can be connected through the Synchronizer Port B, Port C.

Triggered Double Exposure Frame Crosscorrelation

In Asynchronous Reset Two-Frame Crosscorrelation mode, the camera captures two images when triggered by the Synchronizer. The first exposure is very short, 255 µs, in duration, just enough time to fire a Nd:YAG laser flashlamp and Q-Switch. The second exposure is 32.4 ms in duration. The second exposure time must be long enough for the camera to transmit the first 255µs exposure to the Frame Grabber before the second image can be moved into the readout registers.

Shutter Feedback Camera Mode

The most precise frame straddling with the PIVCAM 10-30 is achieved using by setting the Synchronizer to **LASERPULSE | Operating Mode | Timing Master | Shutter Feedback**. In this mode the Synchronizer triggers the camera to start a double exposure sequence, and then waits for the camera feedback signal before starting the laser pulse sequence. On receiving a trigger from the Synchronizer the camera requires 20 µs to reset the image and start the exposure sequence. The camera Strobe trigger out marks the start of the first exposure. The camera Strobe output is connected to the Synchronizer Camera Feedback for precise timing. The Pulse Delay time starts on this Camera Feedback signal.

In the **LASERPULSE | Operating Mode** dialog select:

Option	Value
Timing Master	Camera Feedback
Computer Controlled Camera Mode	Triggered Double Exposure

In the **LASERPULSE | Timing** select:

Option	Value
Delay Times, Pulse	1 ms
Pulse Repetition Rate	14.9 Hz or less

In the **Acquire | Camera** dialog box select:

Option	Value
Trigger	Locked
Mode	Frame Straddle

For Triggered Double Exposure **Select LASERPULSE | Computer Controlled Camera Mode | Triggered Double Exposure**.

Table 4-1
Triggered Double Exposure Timing Sequence with Shutter Feedback Master External Trigger Off

Event	**Delay µs**	**Time µs**
Synchronizer Triggers Camera to Start Double Exposure	0	0 Pulse Sequence Start
Camera Strobe Out & Synchronizer Camera Feedback Trigger In	20	20
First Laser Pulse	252 Pulse Delay = .252 ms	272
End of Exposure 1 Start of Exposure 1 Readout Start of Exposure 2	255	275
Pulse Separation Time	30 dT = 30 µs	302
End of Exposure 1 Readout Start of Exposure 2 Readout	33,400	33,702
End of Exposure 2 Readout Ready to Start Next Pulse Sequence	33,400	67,103 = 14.903 Hz

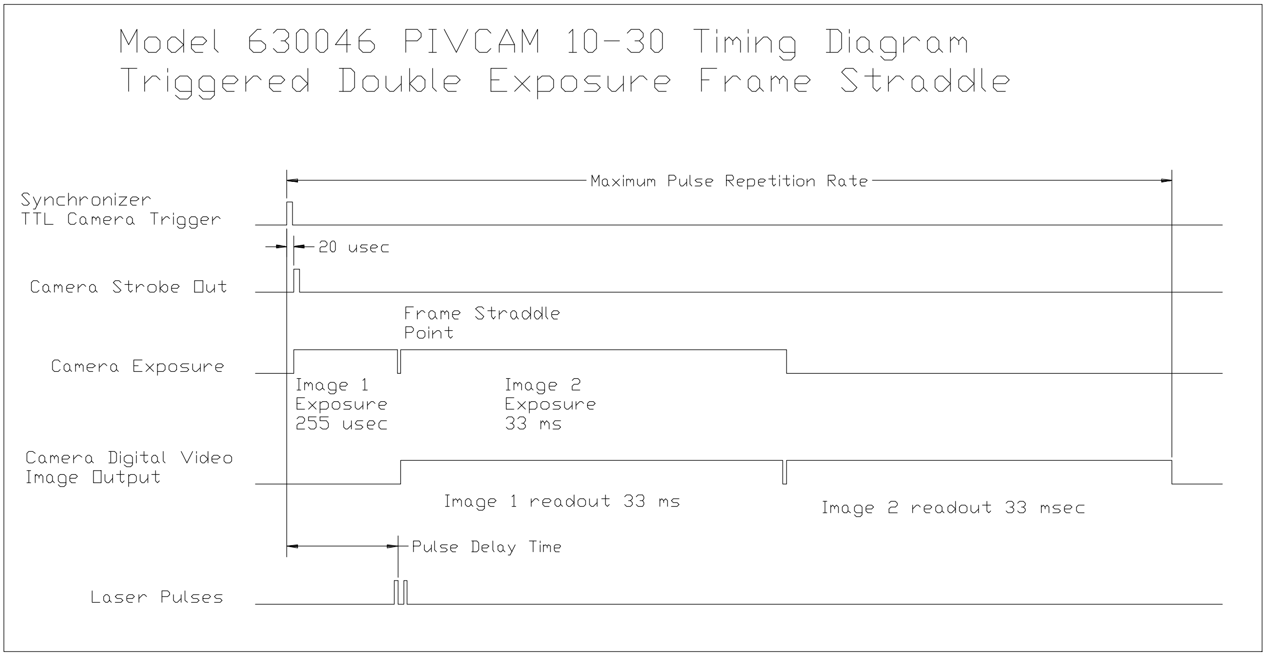


Figure 4-1
Timing Diagram of PIVCAM 10-30, Triggered Double Exposure Frame Straddle Timing Diagram

Triggered Exposure Image Capture for One Frame Processing

The PIVCAM can acquire triggered single exposure images for Autocorrelation or One-Frame Crosscorrelation processing. In this mode the camera starts an exposure when triggered by the Synchronizer. The exposure duration is 33.436 ms. To put the set the system for triggered single exposure capture open the **LASERPULSE | Operating** Mode select:

Option	Value
Timing Master	Synchronizer
Computer Controlled Camera Mode	Triggered Exposure

In the **LASERPULSE | Timing** select:

Option	Value
Delay Times, Pulse	1 ms
Pulse Repetition Rate	30 Hz *or* 0.1 to 15 Hz

In the **Acquire | Camera** dialog box select:

Option	Value
Trigger	Locked
Mode	Normal

This setting will generate the first laser pulse 1 ms after the camera has been triggered. This allows time for the camera to start the exposure and time an Nd:YAG laser to fire the flashlamp and Q-Switch.

***Note**: The minimum Pulse Delay Time = Q-Switch 1 Delay time for Nd:YAG laser systems. The pulse delay time is the time to the Q-Switch and laser pulse. The flashlamp must be fired the Q-Switch Delay time before the Q-Switch.*

The maximum Pulse Repetition Rate is 30.5 Hz. With 29.5 Hz to 30.5 Hz Pulse Repetition Rate the camera records an exposure for 33.436 ms then transfers the charge into the read out registers. The camera then starts the next exposure and starts the image readout, both take 33.4 ms to complete. When operating at 30 Hz the camera is constantly sending image data to the Frame Grabber.

When the Pulse Repetition Rate is 15 Hz or less, the camera starts an exposure when triggered by the Synchronizer. After the exposure 33.4 ms exposure time the image is transferred to the readout where it is transferred to the Frame Grabber for 33.4 ms.

If a Pulse Repetition Rate of 15 Hz to 29.5 Hz is selected then the camera will capture a 33.4 ms exposure when triggered by the Synchronizer, but the next trigger will occur before the entire image has been transferred to the Frame Grabber. The bottom of the image will be missing or contain a previous image when this happens.

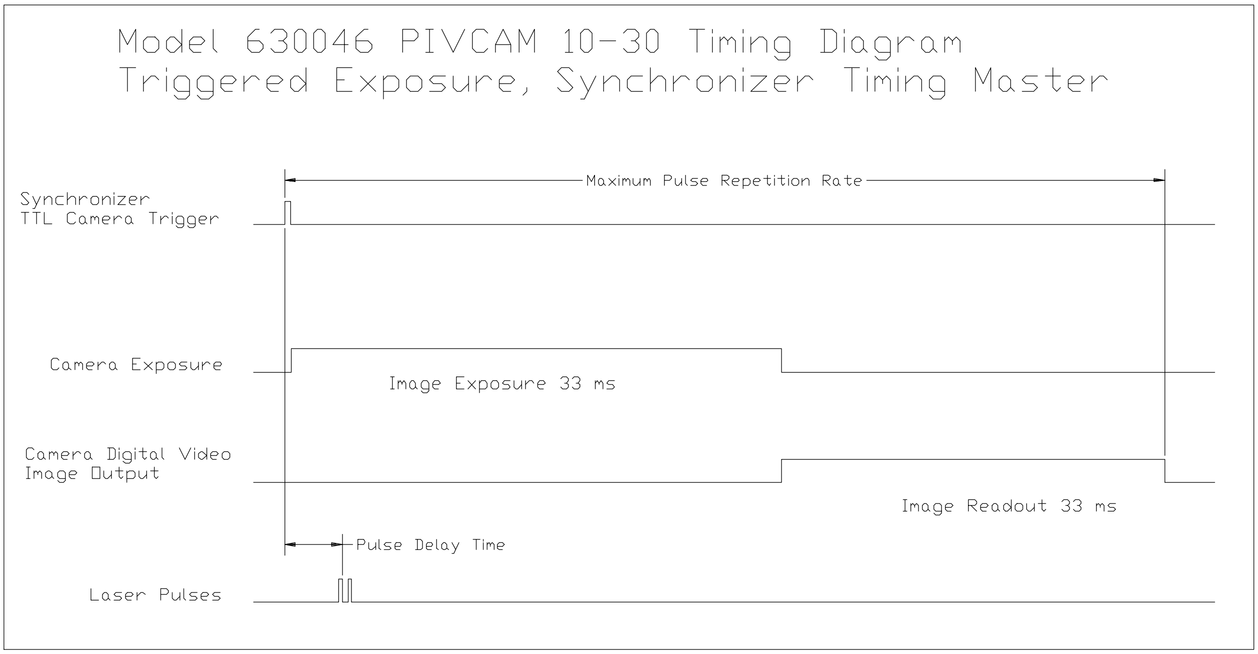


Figure 4-2
PIVCAM 10-30 Triggered Exposure with Synchronizer Timing Master Timing Diagram

Free Run Camera Mode

For installation and alignment the camera can be operated in Free Run. In Free Run there is no synchronization between the laser, and camera. This can be helpful when setting up a new experiment when you want to view images from the camera and not worry about timing yet. Free Run is set opening the **LASERPULSE | Operating Mode** dialog and selecting:

Option	**Value**
Timing Master	Off
Computer Controlled Camera Mode	Free Run

In the **Acquire | Camera** dialog box select:

Option	**Value**
Trigger	Free Run

With these settings the camera will run at 30 frames per second according to its internal clock. By setting the Timing Master to Off no Frame Grabber or camera triggers are generated by the Synchronizer. The image acquisition must be set for Free Run as well because there is no trigger signal to lock onto.

PIVCAM 10-30 Specifications

Table 4-2 lists the specifications for the PIVCAM 10-30 CCD Camera.

Table 4-2
Specifications for the PIVCAM 10-30 CCD Camera*

Sensor Specifications	
Maximum Frame Straddle Pulse Delay ms..........	0.252 ms with Camera in Triggered Double Exposure Mode with Camera Feedback Timing
Frame Straddle Min dT µs .... (*See PIV Theory for chart of minimum dT and laser power.*)	20 µs
Triggered Double Exposure Duration..................	255 µs Image 1 32.436 ms Image 2
Triggered Exposure and Free Run Exposure Duration	32.436 ms
Imaging Device	Solid State Charge Coupled Device (CCD), full-frame Imager
Light Sensitive Pixels	1,026,144 (1008 × 1018)
Pixel Aspect Ratio	1:1
Center-to-Center Pixel Spacing	9.0 µm H × 9.0 µm V
Active Area..	9.072 mm H × 9.162 V
Pixel Fill Factor	60 % effective with micro lens array
Video Performance...	
Video Output	8 Bit Digital
Gamma...	Unity

(continued)

Table 4-2
Specifications for the PIVCAM 10-30 CCD Camera* *(continued)*

Sensor Specifications *(continued)*	
Scanning..	Progressive Scan
Scanning Synchronization..................................	Internal Pixel Clock with Strobe Out; Asynchronous Frame Reset; Asynchronous Frame Reset Double Exposure
Pixel Clock Rate...	20 MHz x 2 Data Taps
Frame Rate..	30 frames per second
Mechanical Specifications	
Camera Head	
Dimensions Camera Body (LWH).........................	7.0" × 3.5" × 3.0" 178 mm × 89 mm × 76 mm
Weight	4.2 lb.
Tripod Mount	¼–20 and ⅜-16 threads
Environmental Requirements	
Temperature	
Operating..	0° to 35° C (32° to 95°F) non-condensing (Image quality will degrade with increasing temperature
Storage..	-25° to +80°C (–13° to 176°F) non-condensing
Humidity	
Operating..	<80% @ 40°C (95°F)
Storage..	<40% @ 80°C (176°F)
Vibration	3g, sinusoidal from 5 to 150 Hz
Shock..	20g

*All specifications are subject to change without notice.

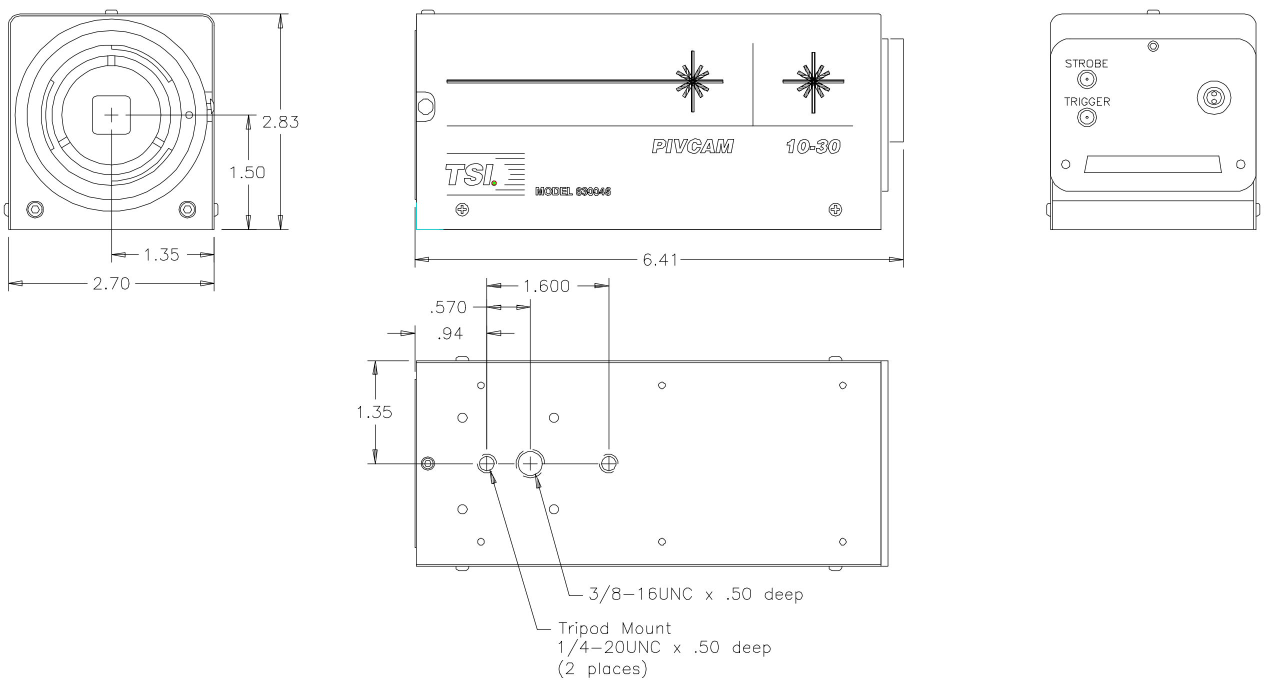


Figure 4-3
Dimensions for the Model 630046 PIVCAM 10-30 CCD Camera

Model 630044D PIVCAM 4-30 and 630045 PIVCAM 10-15

These two Crosscorrelation CCD cameras have a progressive scan digital video output connected to the Frame Grabber and an analog video signal connected to the Synchronizer video in for locking onto the camera start of frame. These are free running cameras and the Synchronizer locks onto their start of frame to start the timing for a pulse sequence.

The Crosscorrelation cameras have a very short time between the end of one exposure and the start of the next exposure. By delaying the first laser pulse until the last moment before the end of the first frame and then using a time between pulses longer than the minimum frame straddle dT the first pulse will be on frame 1 and the second pulse on frame two. This allows relatively high velocity flows to be measured with cameras with a frame rate of 15 or 30 Hz.

Frame Straddle at One-half Camera Frame Rate

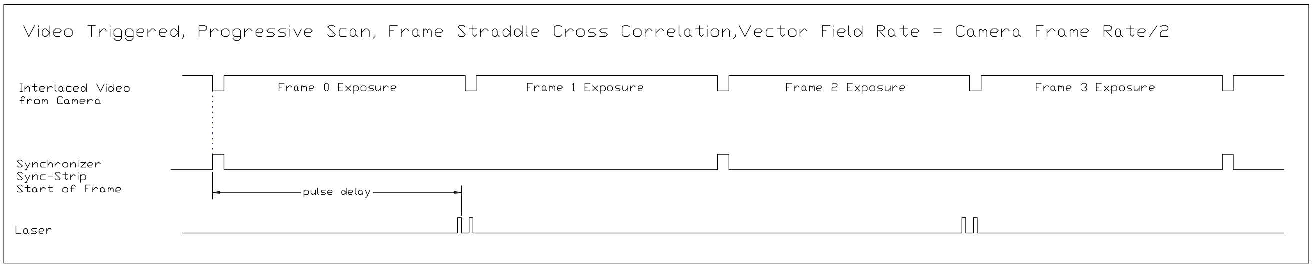


Figure 4-4
Frame Straddle at One-half Camera Frame Rate Timing Diagram

1. The 1K Crosscorrelation is the master clock for this system. The 1K crosscorrelation camera output is progressive scan composite video so there are no odd and even fields.
2. The Synchronizer locks onto the camera start of frame signal in the composite.
3. The Synchronizer waits the Pulse Delay time then starts the laser pulse sequence. The Pulse Delay time is selected so that the first pulse is just before the end of the first exposure and the second pulse is on the second exposure.

The next start of frame after the last pulse of the sequence starts the next vector field sequence.

Specifications PIVCAM 4-30 and PIVCAM 10-15

Table 4-3 lists the specifications for the PIVCAM 4-30 and PIVCAM 10-15.

Table 4-3
Specifications for PIVCAM 4-30 and PIVCAM 10-15*

	Model 630044D **PIVCAM 4-30**	**Model 640045** **PIVCAM 10-15**
Frame Straddle Pulse Delay ms.....	33.3	66.950
Frame Straddle Min dT µs .... *(See PIV Theory for chart of minimum dT and laser power.)*	30	30
Pixels H x V	768 x 484	1008 x 1018
Pixel Size H x V µm	11.6 x 13.6	9.0 x 9.0
Pixel Aspect Ratio (x/y)..................	0.8529	1.0
Image Size mm	8.9 x 6.6	9.1 x 9.2
Sensitivity......................................	10 µV/electron	12 µV/electron
Output...		
Frame Rate Hz...............................	30	15
Scan	Progressive	Progressive
Output...	8 bit digital	8 bit digital
Lens Mount	C-Mount	C-Mount
Power	12 V DC 500 mA	12 V DC 800 mA
Size...	44 mm × 48.5 mm × 136 mm (1.73” × 1.90” × 5.35”)	44 mm × 48.5 mm × 136 mm (1.73” × 1.90” × 5.35”)
Weight	330 grams (12 oz)	330 grams (12 oz)
Operating Temperature	-10 C to +50 C	-10 C to +50 C
Storage Temperature.....................	-30 C to + 60 C	-30 C to +60 C
Operating Humidity.......................	70 % Maximum	70 % Maximum
Storage Humidity...........................	90 % Maximum	70 % Maximum
Vibration	7 G (200 Hz to 2000 Hz)	7 G (200 Hz to 2000 Hz)
Shock	70 G	70 G

*All specifications are subject to change without notice.

Table 4-4
Specifications for Macro Zoom Lens 18-108 mm FL (P/N)

Focal Length Range mm.........	18 to 108
Aperture Range f/#................	2.5 to 16
Working Distance mm............	120 to 300 (Note this lens does not focus to infinity)
Mount....................................	C-Mount
Diameter mm.........................	62 mm maximum
length mm.............................	165 mm

*Specifications are subject to change without notice.

Table 4-5
PIVCAM 4-30 Camera with Macro Zoom Lens Specifications*

Object Image Distance (mm)	Working Distance (mm)	108 mm fl Horizontal Field of View	18 mm fl Horizontal Field of View
289	110	6.5	38
518	330	26	156

*Specifications are subject to change without notice.

Table 4-6
PIVCAM 10-15 Camera with Macro Zoom Lens Specifications*

Object Image Distance (mm)	Working Distance (mm)	108 mm fl Horizontal Field of View	18 mm fl Horizontal. Field of View
289	110	7.2	42.2
518	330	29.0	167.6

*Specifications are subject to change without notice.

Model 630044A PIVCAM 4-30

The PIVCAM cameras have a very short time between the end of one exposure and the start of the next exposure. By delaying the first laser pulse until the last moment before the end of the first frame and then using a time between pulses longer than the minimum frame straddle dT the first pulse will be on frame 1 and the second pulse on frame two. This allows relatively high velocity flows to be measured with cameras with a 30 Hz frame rate camera.

The 630044A PIVCAM 4-30 camera uses a CCD chip with memory next to each light sensitive pixel. All of the pixels integrate light for

33 ms, then they all transfer their charge from the light sensitive pixel to the memory simultaneously. The image is then readout from the camera using the RS-170 interlaced video standard. The image capture is all pixels exposed simultaneously and the readout is interlaced, the correct field pair, Odd + Even are used to capture a non-interlaced image. The Timing diagrams and image capture sequences show the timing for capturing Frame Straddle Pairs for two frame crosscorrelation processing.

The **LASERPULSE | Components | Setup | First Field** parameter is set to Even for the 630044A PIVCAM 4-30. This first field parameter is the start of the Synchronizer timing in Video Timing Master mode. The actual camera image starts with an Odd Field. The times are given for Even First Field for compatibility with the Model 610030 Synchronizer.

To capture images at 10 or 15 Hz for autocorrelation or 1-frame crosscorrelation processing, increase the pulse delay time so that the first pulse is in the second or third frame, the frame where pulse 2 is in the timing diagrams. To capture images for autocorrelation or 1 frame crosscorrelation processing use pulse delay = 0 ms and capture a sequence in free run mode.

If an image shifter is used the time delay including the pulse delay and image shifter delay must give a total delay time so that the laser pulses are in the second frame of a frame straddle pair, with normal image capture mode.

The RS-170 Crosscorrelation Camera is used as a Video Timing Master with the Synchronizer. The Synchronizer locks onto the camera start of frame. The delay times are all referenced to the camera start of frame. The pulse repetition rates are derived from the camera frame rate.

From the Frame Straddle time the first pulse can be from 0 to 33 ms before the frame straddle point and the pulse image will be on frame 1. The second pulse can end from 30 us to 16 ms after the frame straddle point. If the end of the second pulse extends beyond the 16 ms time system will decrease the pulse repetition rate for 10 Hz or 15 Hz pulse repetition rates.

630044A PIVCAM 4-30 15 Hz, Frame Straddle

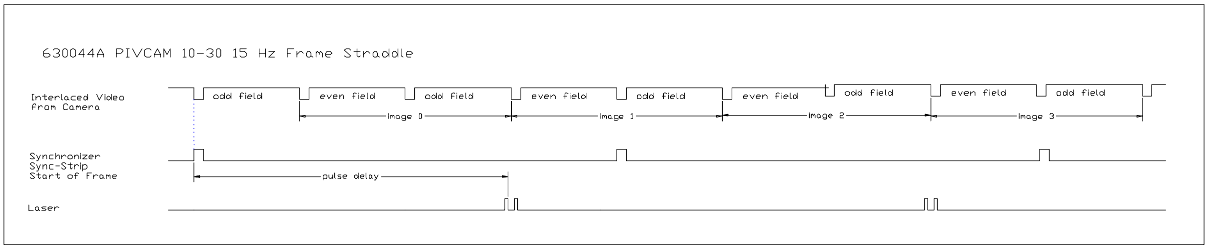


Figure 4-5
630044A PIVCAM 4-30 15 Hz Frame Straddle Timing Diagram

1. The camera is the master clock of the system. The times for pulsing the laser are based off the camera start of frame.
2. The Synchronizer locks onto the camera start of frame and starts the Pulse Delay Timer.
3. The Pulse Delay parameter is set so that the first laser pulse ends just before the end of the first frame, this time is 3 field times, about 50.1 ms.
4. The pulse sequence happens just before and after the end of exposure 1 and the start of exposure 2.

The next vector field will start on the next start of frame after the end of the last pulse in the sequence.

630044A PIVCAM 4-30 10 Hz, Frame Straddle

The RS-170 camera operates at 30 frames per second, many Nd:YAG lasers have a maximum pulse repetition rate of 10 Hz. To get these components operating together the Pulse Delay time is increased so that the laser is pulsed around the end of the second frame and start of the third frame. This creates a three frame sequence where the first image is blank, the second image has pulse 1 and the third image has pulse 2. The crosscorrelation image pair is frame 2 and 3. In the image capture the first frame is not captured, only images 2 and 3 are grabbed for processing.

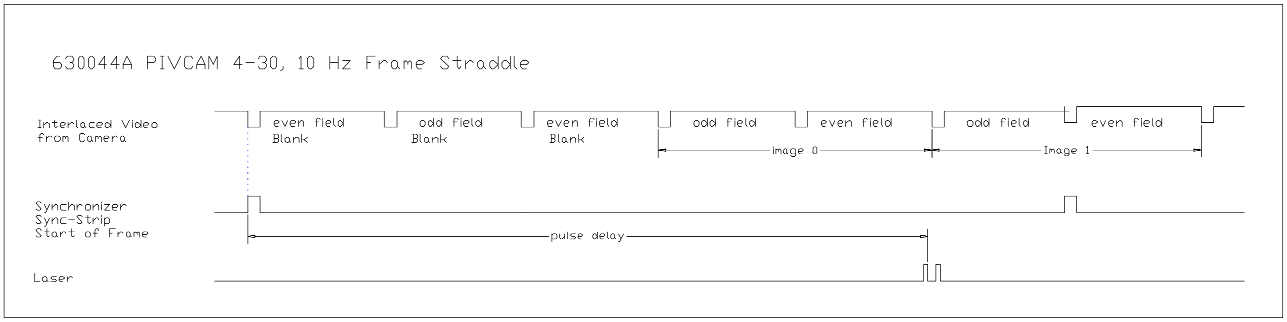


Figure 4-6
630044A PIVCAM 4-30 10 Hz Frame Straddle Timing Diagram

1. The camera is the master clock of the system. The times for pulsing the laser are based off the camera start of frame.
2. The Synchronizer locks onto the camera start of frame and starts the Pulse Delay Timer.
3. The Pulse Delay parameter is set so that the first laser pulse ends just before the end of the second frame. In the case of the RS-170 cross correlation camera this time is 5 field times, about 83 ms.
4. The pulse sequence happens just before and after the end of exposure 1 and the start of exposure 2.

The next vector field will start on the next start of frame after the end of the last pulse in the sequence.

630044A PIVCAM 4-30 CCD Camera Specifications

Table 4-3 lists the specifications for the Model 630044A PIVCAM 4-30 CCD Camera.

Table 4-7
Specifications for the Model 630044A PIVCAM 4-30 CCD Camera*

Frame Straddle Pulse Delay ms............................	50.345 15 Hz 83.715 10 Hz
Frame Straddle Min dT µs .... *(See PIV Theory for chart of minimum dT and laser power.)*	30
Pixels H x V..	640 × 480
Pixel Size H x V µm...	13.3 × 13.6
Pixel Aspect Ratio (x/y)...	0.98
Image Size mm...	8.9 × 6.6
Sensitivity	10 µV/electron
SNR..	50 dB
Frame Rate Hz	29.97 Hz
Scan	Interlaced, Odd First Field
Output	RS-170 Analog Video 1 V p-p, composite video 75 Ω
Lens Mount..	C-Mount
Power	12 V DC 500 mA
Size	44 mm × 48.5 mm × 136 mm (1.73” × 1.90” × 5.35”)
Weight..	330 grams (12 oz)
Operating Temperature..	-10 C to +50 C
Storage Temperature..	-30 C to + 60 C
Operating Humidity..	70 % Maximum
Storage Humidity	90 % Maximum
Vibration	7 G (200 Hz to 2000 Hz)
Shock...	70 G

*Specifications are subject to change without notice.

Table 4-8
Specifications for Macro Zoom Lens 18-108 mm FL (P/N)*

Focal Length Range mm	18 to 108
Aperture Range f/#...	2.5 to 16
Working Distance mm	120 to 300 (Note this lens does not focus to infinity.)
Mount...	C-Mount
Diameter mm..	62 mm maximum
length mm	165 mm

*Specifications are subject to change without notice.

Table 4-9
PIVCAM 4-30 Camera with Macro Zoom Lens Specifications*

Object Image Distance (mm)	**Working Distance (mm)**	**108 mm fl Horizontal Field of View**	**18 mm fl Horizontal Field of View**
289	110	6.5	38
518	330	26	156

*Specifications are subject to change without notice.

Pixel Aspect Ratio

The RS-170 and CCIR video standards defines the timing of the video signal. It does not define the number of pixels in the image. The 640 × 480 RS-170 and 768 × 572 CCIR pixel resolutions have theoretically square pixels. But the digitized image may not have exactly square pixels. To account for this use the Pixel Aspect Ratio in the velocity calibration menu. The pixel aspect ratio is the *x*-size of the pixel divided by the *y*-size of the pixel. For the 630044A PIVCAM 4-30 with RS-170 output the Aspect Ratio is 0.98.

A coarse way to measure the pixel aspect ratio for a camera is to focus on a piece of graph paper. The pixel scale factor is measured by dividing the distance between lines by the line spacing in millimeters. The distance in pixels between lines can be measured with INSIGHT software either using the Process, Setup, Measure Image Shift commands, or the Process, Velocity Measurement, Measure Object Size commands. The Setup Measure command gives you both the *x* and *y* pixel displacements and you must compute the mm/pixel, the Velocity Measure gives you the line length in pixels, but computes the mm/pixel for you. Measure both the *x* pixel calibration factor and *y* pixel calibration factors. The Pixel Aspect Ratio is the *x* factor/*y* factor.

A more precise method to measure the pixel aspect ratio is to make cross-correlation measurements of a solid body rotation. In solid body rotation, the *u*-velocity component is a linear function of the *y*-position and the *v*-velocity component is a linear function of the *x*-position. The slopes of these two lines are equal for solid body rotation.

The test images are made using a laser printer plot of dots at random locations, sandpaper, or some other solid that simulates particle images. Attach the dot picture to a wheel. With the wheel fixed in position digitize and save the dot pattern image. Rotate the wheel a small amount and capture and save this second image. Cross correlate these two images.

Import the *.VEC cross-correlation output file into a spreadsheet. Compute two linear regressions:

Uf(*y*)	Independent = *y* 2nd data Col. Dependent variable *u*, 3rd data column
Vf(*x*)	Independent variable = *x*, 1st data column Dependent variable = *v*, 4th data column.

The slope of these regressions give the *x*- and *y*-calibration factors. The pixel aspect ratio is:

Pixel Aspect = Sqrt [slope *Vf*(*x*)/slope *Uf*(*y*)]

Note *The Model 630044D works with Model 600067 High-Speed PCI Frame Grabber only. To use this camera with the 600064, 600065 or 600066 Frame Grabbers, see the Model 6300044A camera and manual number 1990825. Model 630044 RS-170 Crosscorrelation CCD and Model 630044A PIVCAM 4-30 can be converted to Model 630044D PIVCAM 4-30 by using Camera to Frame Grabber Cable #13030502 and Model 600067 Frame Grabber.*

Cameras Model 630042 MegaPlus 1.4i and 630043 MegaPlus 4.2i and Model 600040 35mm Film Camera

The MegaPlus 1.4, MegaPlus 4.2 and 35mm Film cameras use a mechanical shutter to control exposure. This shutter takes some time to open and close. If the laser is pulsed when the shutter is partially open then some of the pixels or film will be exposed and some will still be covered by the shutter and not be exposed. The system Synchronizer has two operating modes that can be used with the MegaPlus and 35mm Film cameras **LASERPULSE | Operating Mode | Timing Master | Synchronizer or Shutter Feedback**. In both operating modes the Synchronizer triggers the camera to start an exposure. In Synchronizer Triggered Camera Mode the **LASERPULSE | Timing | Pulse Delay** parameter is set to wait for the shutter to open. In Shutter Feedback mode the camera Strobe or Flash Sync signal connected to the Synchronizer Camera Feedback used use to verify the shutter is opened before pulsing the laser.

Synchronizer Timing Master Operating Mode

With **LASERPULSE | Operating Mode | Timing Master | Synchronizer** selected the Synchronizer triggers the Frame Grabber or 35mm camera to start an exposure. The Synchronizer then waits the Pulse Delay time before pulsing the laser. The Pulse Delay Time must be set longer than the shutter opening time for the pulse to be recorded.

When image shifting is being used the Synchronizer then waits the Pulse Delay Time before triggering the image shifter. After the image shifter has been triggered the laser will pulse when the image shifter triggers the Synchronizer that the mirror is in position The Pulse Delay Time + Image Shift Wait time must be longer than the shutter opening time. With the Model 610050 Scanning Mirror Image Shifter the image shift delay time is constant for a an Image Shifter setting and the time can be accurately measured and used to compute the Pulse Delay time. With the Spinning Mirror Image Shifters the image shift delay time will be from 0 to 1 mirror cycle time. The Pulse Delay time should be set so double pulse images will be captured over the full range of image shifter wait times.

Synchronizer Triggered Camera Timing

1. The Synchronizer is the master clock in this setup. At the start of the sequence the Synchronizer triggers the camera to start an exposure and starts the Pulse Delay for the timing of the laser pulses.
2. The Synchronizer Camera Trigger Out starts a camera exposure. The exposure duration must be set long enough so that the shutter is still open for the last pulse of the sequence.
3. After the Synchronizer has waited the Pulse Delay time it starts the pulse sequence. The Pulse Delay in this system is configured to wait some time to allow the shutter to open. If the camera has an electronic shutter a Pulse Delay of 0 may be possible. For cameras that take some time for the shutter to fully open set the Pulse Delay a little longer than the Shutter Open Time for your camera.

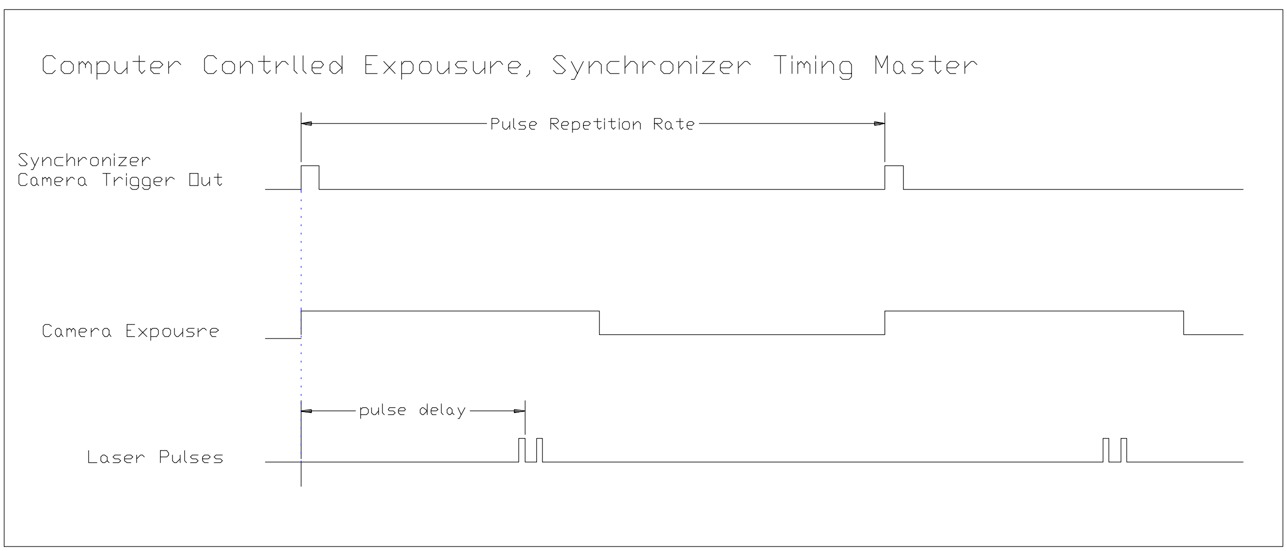


Figure 4-7
MegaPlus Camera with Synchronizer Timing Master Timing Diagram

Synchronizer Triggered Camera, with Image Shift Timing

1. The Synchronizer is the master clock in this setup. At the start of the sequence the Synchronizer triggers the camera to start an exposure and starts the Pulse Delay for the starting the Image Shifter.
2. The Synchronizer Camera Trigger Out starts a camera exposure. The exposure duration must be set long enough so that the shutter is still open for the last pulse of the sequence.
3. The Synchronizer Image Shift Out signals the image shifter to start. If a scanning mirror is being used in single sweep mode, this trigger starts the mirror rotation. The mirror shift wait time will be consistent from cycle to cycle. If a spinning mirror or scanning mirror in continuous sweep mode is being used, the synchronizer will accept the next trigger in from the image shifter. The time between the shutter open trigger and the mirror in position trigger will vary from 0 to 1 cycle time depending on the mirror position at the shutter open trigger.
4. When the mirror is in position, it triggers the Synchronizer to start a pulse sequence. Strobe Out Signal triggers the Synchronizer that it is OK to pulse the laser.
5. The Synchronizer starts the laser pulse sequence.

At the Synchronizer Vector Field Rate the image capture sequence will start again.

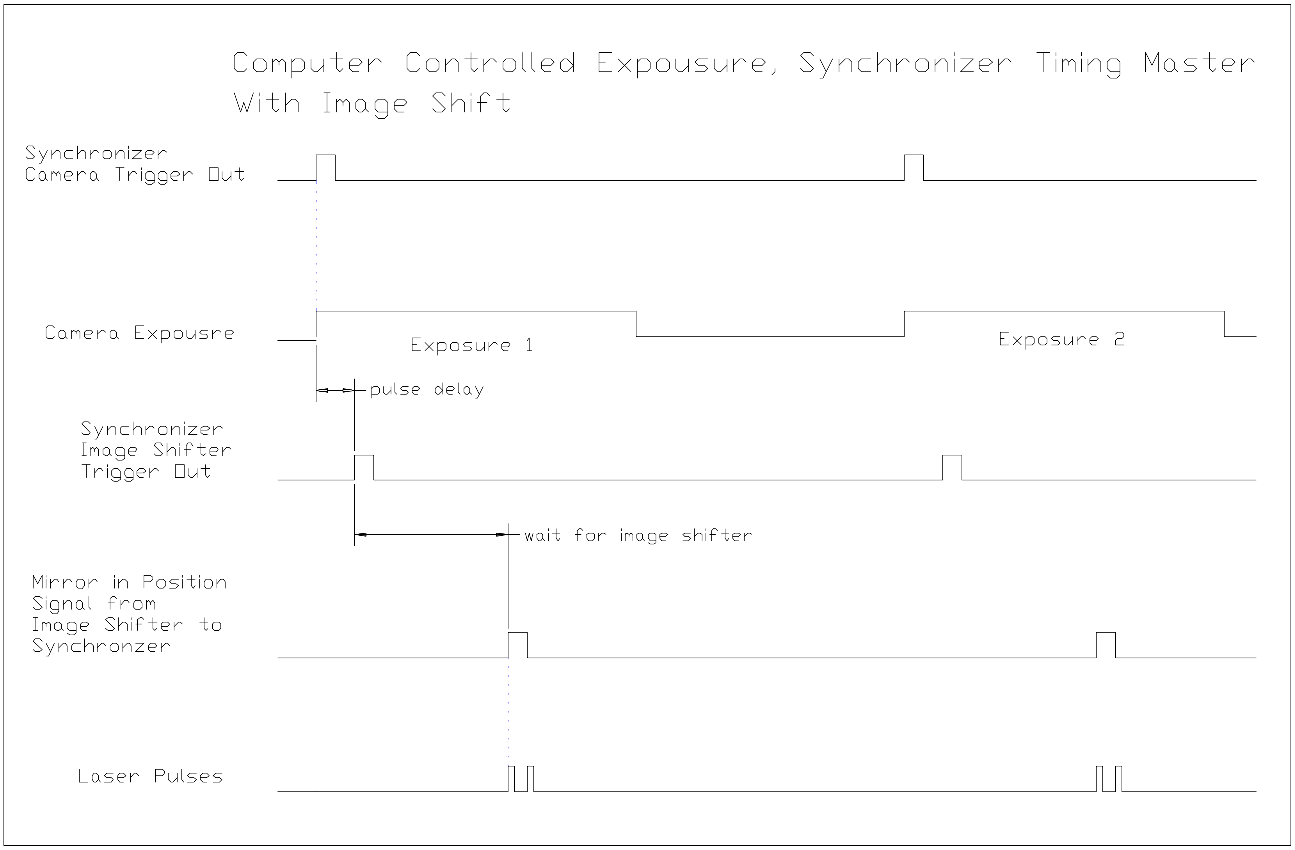


Figure 4-8
MegaPlus Camera in Synchronizer Timing Master Mode with Image Shift Timing Diagram

Camera Feedback Timing Master Mode

In Camera Feedback Timing Master Mode, the Strobe Out signal from the camera is used. The strobe out signal goes high when the shutter is fully open signifying that it is OK to pulse the laser. In Camera Feedback Timing Master Mode the Pulse Delay parameter can be set to 0 in most cases. If Pulse Delay is set the Delay time is added between the Shutter Feedback and the first pulse. When an image shift is used with Shutter Feedback Mode the mirror is triggered when the Shutter Feedback goes high. If a Pulse Delay is set it is added between the Shutter Feedback and the Mirror Trigger.

Camera Feedback Timing Master

1. Synchronizer Camera Trigger Out. The Synchronizer is the master clock in this configuration. The synchronizer starts the pulse sequence based on the selected vector field rate.
2. The Camera Trigger Out signals the camera to start an exposure.
3. The Camera Exposure lasts from the camera trigger point for the selected exposure period. The exposure period must be long enough so that the shutter is still open for the last laser pulse of the sequence.
4. The camera takes some time for the shutter to fully open. When the Shutter is open the Camera Strobe out signal goes off.
5. The Strobe Out Signal triggers the Synchronizer that it is OK to pulse the laser.
6. The Synchronizer waits the Pulse Delay time and then starts the laser pulse sequence. The pulse delay is typically 0, the shutter feedback has verified that it is OK to fire the laser.

An error happens if the Feedback signal does not report the shutter is open by the time the Synchronizer is ready to start the next vector field sequence.

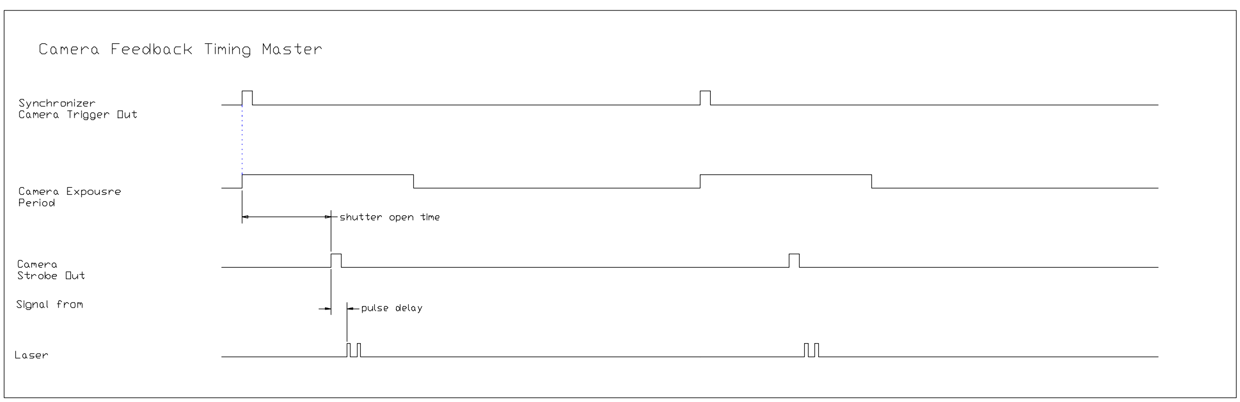


Figure 4-9
MegaPlus Camera in Camera Feedback Timing Master Mode Timing Diagram

Camera Feedback Timing Master Mode with Image Shift Timing

1. Synchronizer Camera Trigger Out. The Synchronizer is the master clock in this configuration. The synchronizer starts the pulse sequence based on the selected vector field rate.
2. The Camera Trigger Out signals the camera to start an exposure.
3. The Camera Exposure lasts from the camera trigger point for the selected exposure period. The exposure period must be long enough so that the shutter is still open for the last laser pulse of the sequence.
4. The camera takes some time for the shutter to fully open. When the Shutter is open the Camera Strobe out signal goes off.
5. The Strobe Out signals the mirror image shifter to start. If a scanning mirror is being used in single sweep mode, this trigger starts the mirror rotation. The mirror shift wait time will be consistent from cycle to cycle. If a spinning mirror or scanning mirror in continuous sweep mode is being used, the synchronizer will accept the next trigger in from the image shifter. The time between the shutter open trigger and the mirror in position trigger will vary from 0 to 1 cycle time depending on the mirror position at the shutter open trigger.
6. When the mirror is in position it triggers the Synchronizer to start a pulse sequence. Strobe Out Signal triggers the Synchronizer that is OK to pulse the laser.
7. The Synchronizer waits the Pulse Delay time and then starts the laser pulse sequence. The pulse delay is typically 0, the shutter feedback has verified that it is OK to fire the laser.

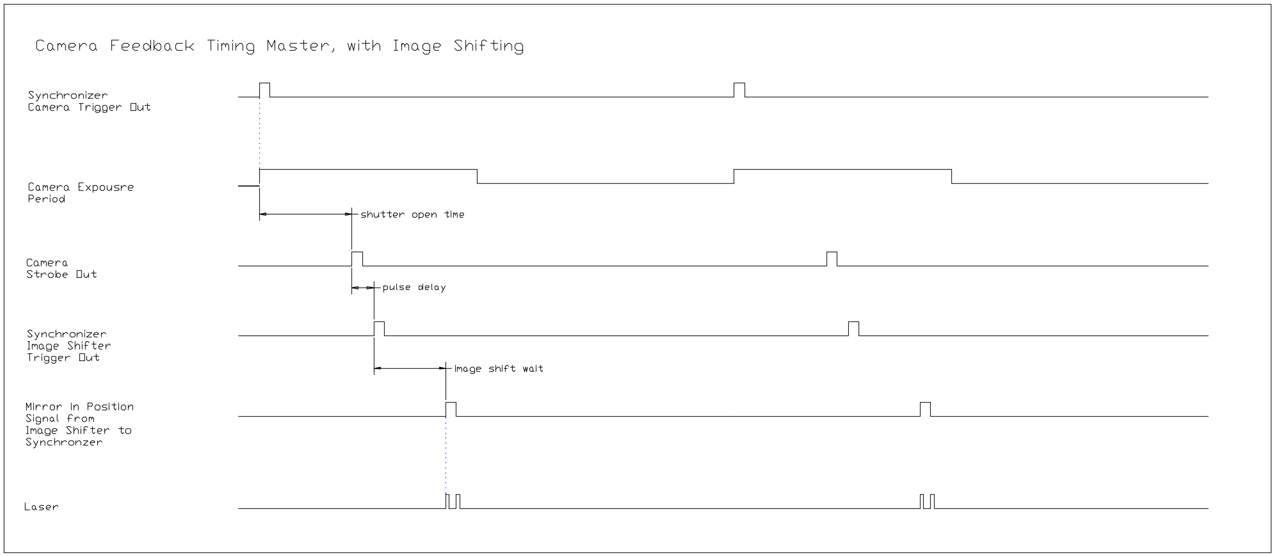


Figure 4-10
MegaPlus Camera in Camera Feedback Timing Master Mode with Image Shifting Timing Diagram

Shutter Camera Frame Rate

The MEGAPLUS camera frame rate is a function of the exposure time. The MEGAPLUS camera exposure time is set with the slider bar in the INSIGHT Acquire, Camera, dialog. When the Synchronizer triggers the Frame Grabber it starts a camera exposure for the set exposure time. The camera shutter then closes and then image is read out from the camera to the Frame Grabber. The image transfer rate is 10 million pixels per second. The MEGAPLUS 1.4 takes 144.6 ms to transfer an image and the MEGAPLUS 4.2 takes 485 ms to transfer an image. The time required for the camera to capture and readout an image is the exposure time + frame readout time.

MEGAPLUS 1.4 Frame Rate
Frame Rate Hz = 1,000 / (Exposure ms + 144.6 ms)

MEGAPLUS 4.2 Frame Rate
Frame Rate Hz = 1,000 / (Exposure ms + 485 ms)

When setting up your experiment it is important that the

For the 35mm Film Camera the maximum frame rate is determined by the exposure time, and the film winding time. The maximum frame rate is:

Frame Rate Hz = 1,000 / (Exposure ms + Film Winding Time ms)

Cameras with strobe out signals can be used either as Video No Sync or Shutter feedback cameras. In video no sync mode the synchronizer triggers each component to start its operation. It expects all of the system to be set up properly to capture the images. In shutter feedback mode the synchronizer waits for the feedback from the camera to signal and generates an error if the camera shutter does not open on time. The difference is that in shutter feedback mode the pulse delay is typically set to 0 and in shutter feedback mode the pulse delay time is set to wait for the shutter to open. Shutter feedback mode will generate an error if the shutter feedback signal is not received by the time the next pulse sequence is supposed to start. Video No Sync mode does not give this error checking.

MegaPlus Camera Specifications

Table 4-10 lists the specifications for the MEGAPLUS 1.4i and MEGAPLUS 4.2I CCD Camera.

Table 4-10
Specifications for the MEGAPLUS 1.4i CCD Camera*

Sensor Specifications	**MegaPlus 1.4I**	**MegaPlus 4.2I**
Imaging Device..............................	Solid State Charge Coupled Device (CCD), full frame Imager	Solid State Charge Coupled Device (CCD), full frame Imager
Light Sensitive Pixels.....................	1,363,095 (1317 × 1035)	4,147,276 (2,029 × 2044)
Pixel Aspect Ratio..........................	1:1	1:1
Pixel Size.......................................	6.8 × 6.8 µm	9.0 × 9.0 µm
Center-to-Center Pixel Spacing......	6.8 × 6.8 µm vertical and horizontal (unity fill-ratio)	9.0 × 9.0 µm vertical and horizontal (unity fill-ratio)
Active Area....................................	8.98 mm H x 7.04 V (⅔” format compatible)	18.5 mm H x 18.5 V (1" format compatible)
Video Performance		
Video Output.................................	8 Bit Digital	Unity
Gamma	Unity	Non-Interlaced
Scanning.......................................	Non-Interlaced	8 Bit Digital

(continued)

Table 4-10
Specifications for the MEGAPLUS 1.4i CCD Camera* (*continued)*

Sensor Specifications	**MegaPlus 1.4I**	**MegaPlus 4.2I**
Pixel Clock Rate............................	10 MHz	10 MHz
Shutter Open Time.......................	13 ms	25 ms
Frame Rate..................................	6.3 frames/sec @ 13 msec exposure time (shutter open time) 5.1 frames/sec @ 50 msec exposure time 2.9 frames/sec @ 200 msec exposure time Note Frame Rate = 1/(145 ms + exposure time)	1.9 frames/sec @ 25 ms exposure time (shutter open time) 1.5 frames/sec @ 200 msec exposure time Note Frame Rate = 1/(485 ms + exposure time)
Mechanical Specifications		
Camera Head		
Dimensions F mount....................	4.45" × 3.90" × 5.19"	4.45" × 3.90" × 5.19"
Weight	3 lb.	3 lb.
Tripod Mount................................	¼–20 threads	¼–20 threads
Environmental Requirements		
Temperature		
Operating......................................	0° to 35° C (32° to 95°F) non-condensing (Image quality will degrade with increasing temperature	0° to 35° C (32° to 95°F) non-condensing (Image quality will degrade with increasing temperature
Storage	-25° to +80°C (–13° to 176°F) non-condensing	-25° to +80°C (–13° to 176°F) non-condensing
Humidity		
Operating......................................	<80% @ 40°C (95°F)	<80% @ 40°C (95°F)
Storage	<40% @ 80°C (176°F)	<40% @ 80°C (176°F)
Vibration.......................................	3g, sinusoidal from 5 to 150 Hz	3g, sinusoidal from 5 to 150 Hz
Shock	20g	20g

*All specifications are subject to change without notice.

Table 4-11
Camera Field of View with 60 mm Nikon Lens*

Magnification	Object - Image Distance	MegaPlus 1.4 FOV	MegaPlus 4.2 FOV
1 / 1.0	219	9.0 ×7.0	18.5 × 18.5
1 / 1.3	225	11.7 × 9.1	24.0 × 24.0
1/1.5	235	13.5 × 10.5	27.7 × 27.7
1/1.9	250	17.1 × 13.3	35.1 × 35.1
1/ 2.8	300	25.2 × 19.6	51.8 × 51.8
1/ 4.6	400	41.4 × 32.2	85.1 × 85.1
1/ 6.3	500	56.7 × 44.1	116.5 × 116.5
1 / 9.7	700	87.3 × 67.9	179.4 × 179.4
1 / 14.7	1000	132.3 × 102.9	271.9 × 271.9
1 / 31.4	2000	282.6 × 219.8	580.9 × 580.9

*All specifications are subject to change without notice.

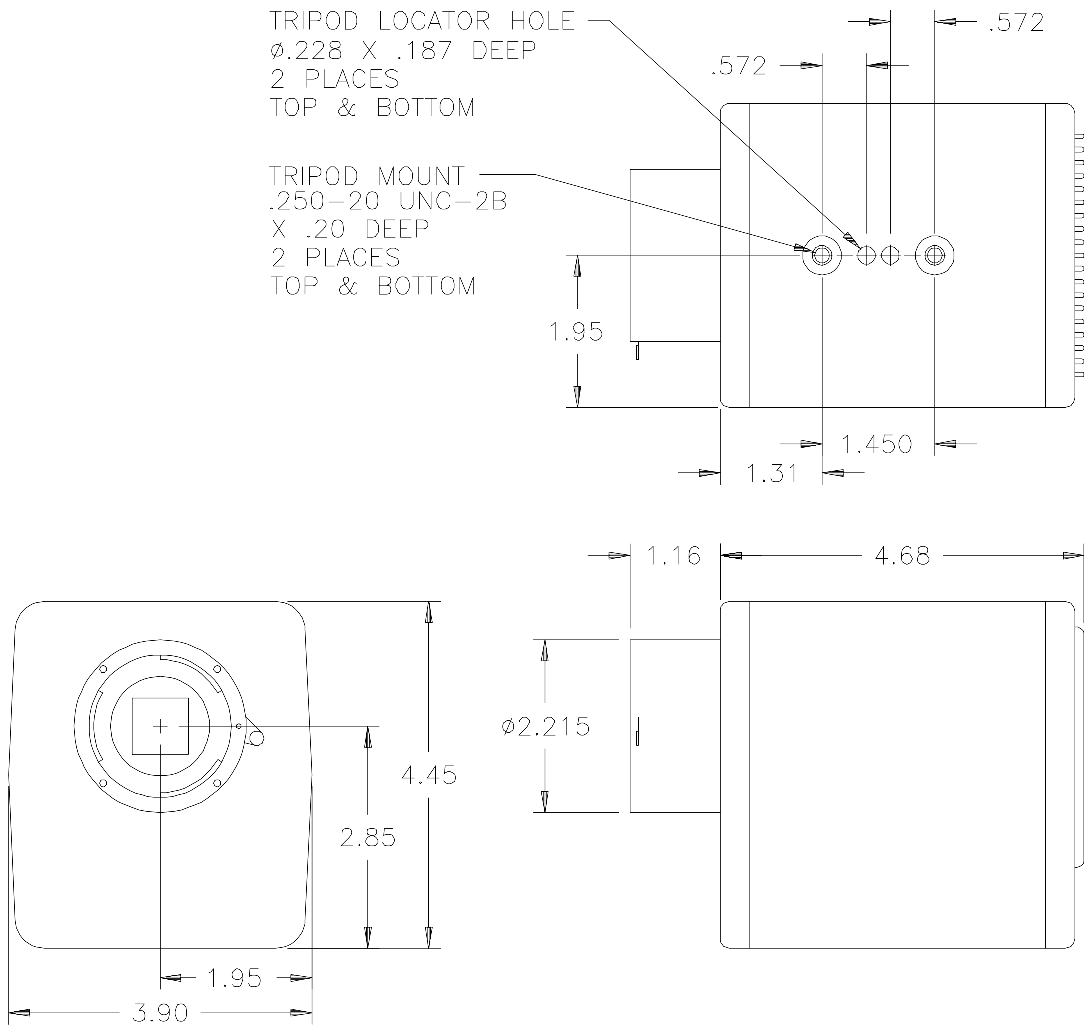


Figure 4-11
Dimensions for the KODAK MEGAPLUS 4.2I and MEGAPLUS 4.2I CCD Cameras

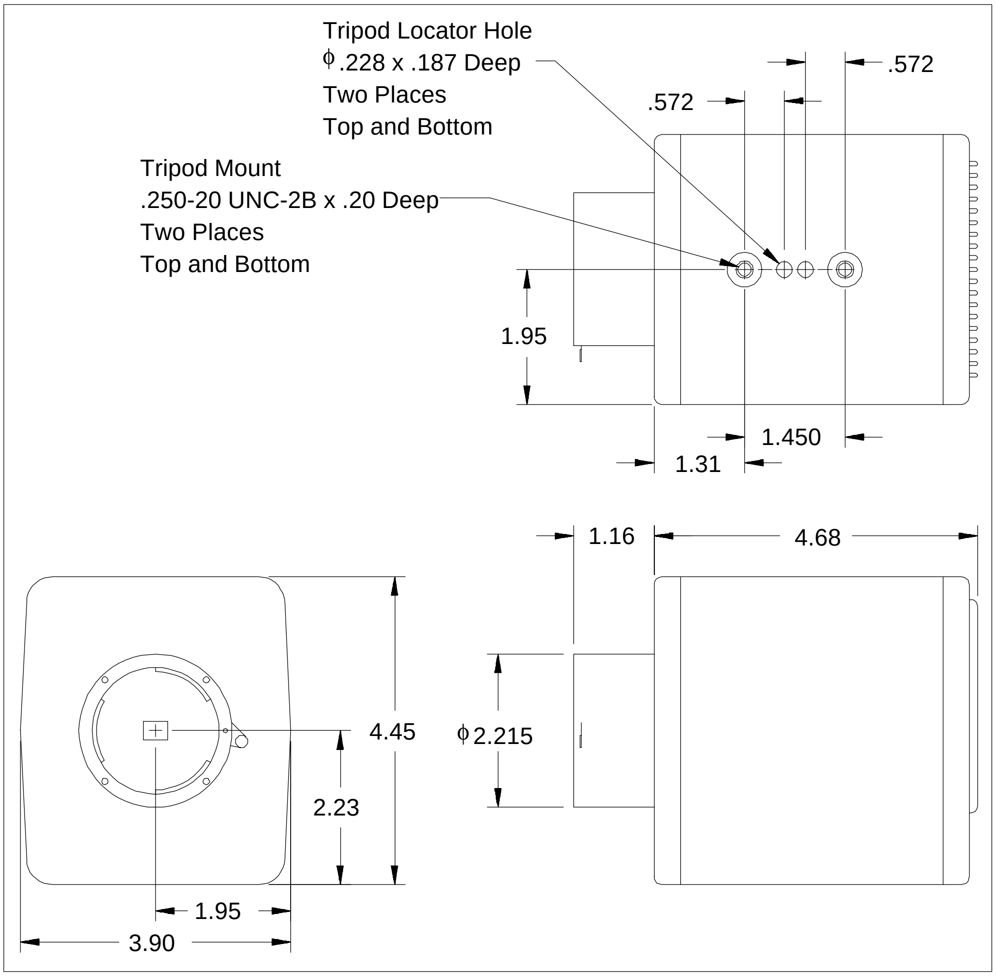


Figure 4-12
Dimensions for the KODAK MEGAPLUS 1.4 CCD Camera (MEGAPLUS 1.4I same dimensions as MEGAPLUS 4.2)

CHAPTER 5

Image Shifter

This section describes how to operate the Model 610050 LaserPulse Mirror Image Shifter.

Overview of Image Shifting

When dealing with flow field turbulence, resolving flow direction ambiguity is a major issue. Using image shifting helps measure flow reversals and resolves the direction ambiguity.

The Model 610050 LaserPulse Mirror Image Shifter is designed to introduce image shifting in your PIV experiment. The Mirror Image Shifter consists of a rotating mirror that is mounted either vertically or horizontally between the illuminated plane in the flow and the camera.

The mirror is rotated in the time between the laser pulses thereby adding the image-shift displacement to the flow displacement. The first image is recorded with the mirror at the trigger position; then the mirror rotates and the second image is recorded with the mirror at a different angle. An object with no movement is recorded at two locations. The distance between these images is the image shift. A particle with forward velocity has an image separation that is the displacement due to motion plus the image shift distance. A particle with negative velocity has an image displacement of the image shift distance minus the displacement due to motion. Refer to the PIV Overview Manual for details on image shifting. The software PIVSIM allows you to enter the Model 610050 settings so it can compute the image shift velocity for you.

System Components

The following components are included in the Model 610050 Mirror Image Shifter:

- 610051 Mirror Image Shift Electronics
- 610052 Mirror and Motor
- Horizontal Mounting Bracket
- Vertical Mounting Bracket

The LASERPULSE Model 610051 Mirror Image Shifter Drive Electronics has five toggle switches and three 10-turn adjustment knobs on the front panel. These controls along with the two mounting brackets give you a wide range of control when selecting the optimum image shift for your experiment. Refer to the *Model 610050 Mirror Image Shifter Installation Manual* for information on how to mount the mirror and camera in relation to the lightsheet for your experiment.

Refer to Figure 5-1 as you read the following descriptions of the user controls.

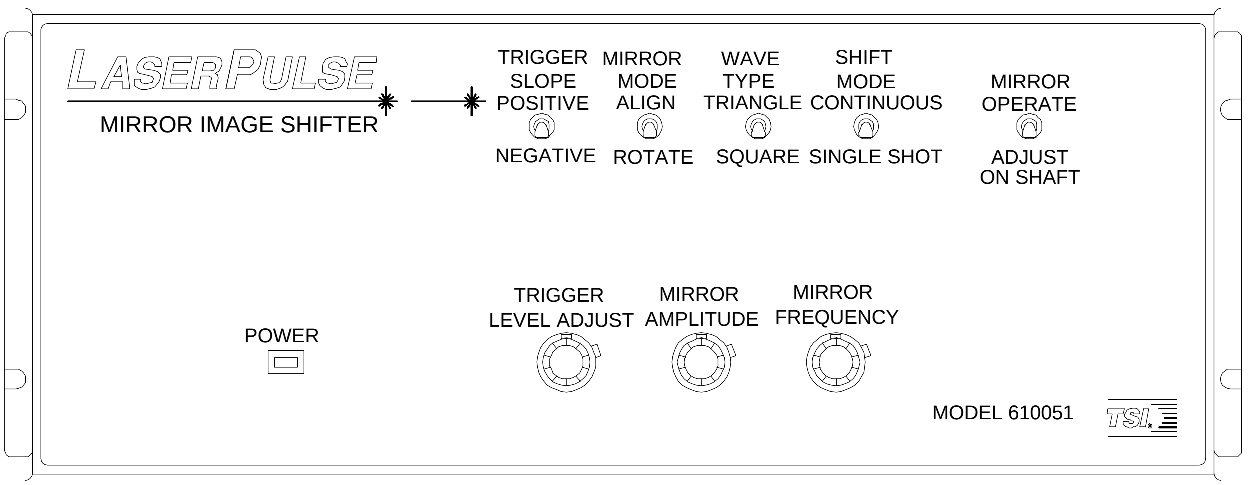


Figure 5-1
Front Panel of Model 610051 Mirror Image Shifter

Trigger Slope

This switch sets the direction of the image shift. If you are using vertical shift, then this switch selects Up or Down shift. For horizontal shift it selects Right or Left shift. The **TRIGGER SLOPE** allows you to select if the mirror should move in a clockwise or counterclockwise direction.

Mirror Mode

This switch works in conjunction with the **TRIGGER LEVEL ADJUST** switch and controls the mirror angles.

Align

In **ALIGN** mode the **TRIGGER LEVEL ADJUST** switch adjusts the mirror angle, and the **TRIGGER SLOPE** sets the direction. Setting the **TRIGGER LEVEL ADJUST** to 0 puts the mirror at the center of rotation, 10 at the maximum angle. The **TRIGGER SLOPE** changes from clockwise to counterclockwise mirror rotation. The **ALIGN** mode is used when focusing, aligning, and setting the system and before image shifting is introduced.

Rotate

In **ROTATE** mode the mirror dithers, cycling through the programmed movement. With **ROTATE** mode the **TRIGGER LEVEL ADJUST** controls the position at which the Mirror Image Shift Electronics triggers the Synchronizer to fire the laser.

Wave Type

This switch controls the speed at which the mirror rotates.

Triangle

In the **WAVE TYPE TRIANGLE** mode the mirror moves in the direction selected by the **TRIGGER SLOPE** switch at a cycle time selected by the **MIRROR AMPLITUDE** and **MIRROR FREQUENCY** controls. The mirror returns in the square wave form taking about 10 msec. Use this mode when you do *not* require the maximum mirror rotation rate.

Square

In the **WAVE TYPE SQUARE** mode the mirror rotates at the maximum angular rate. It accelerates to its maximum rotation rate and then maintains a constant rotation rate until in decelerates at the end of its travel.

In this mode the mirror moves to the selected amplitude in about 10 msec in each direction. The **MIRROR AMPLITUDE** switch sets the shift velocity and the **MIRROR FREQUENCY** switch affects the *length* of time the mirror spends at the end of stroke before returning.

Shift Mode

This switch allows you to select whether the mirror should rotate only when it receives a signal from the Synchronizer or continuously.

Continuous

In the **CONTINUOUS** mode, the mirror cycle repeats as soon as each cycle is completed. It is provided to allow you to see the mirror movement amplitude and frequency to that the controls can be adjusted. Use **CONTINUOUS** mode when aligning and setting up the experiment.

Single Shot

In the **SINGLE SHOT** mode the mirror moves for one cycle when the Mirror Image Shifter receives a trigger signal from the LASERPULSE Synchronizer. At the end of the cycle the mirror returns to the ready position and waits for the next trigger signal. Use **SINGLE SHOT** mode when you are ready to capture images.

Caution

Do ***not*** run the mirror at high **AMPLITUDES** and high **FREQUENCY** in **CONTINUOUS** mode. The mirror requires too much power and it will stop moving. If this happens too much, it may damage the Mirror Image Shifter. With the **MIRROR AMPLITUDE** set at 10, keep the **MIRROR FREQUENCY** below 5. With the **MIRROR FREQUENCY** set at 10, keep the **MIRROR AMPLITUDE** set below 5. The mirror can be used with both **AMPLITUDE** and **FREQUENCY** set to 10 in **SINGLE SHOT** mode.

Mirror

This switch is used to place the mirror in either a position where you can operate the Image Shifter or in a position where you can make adjustments.

Operate

When you are using the Image Shifter in your experiment, the mirror must stay at this position for all the other Image Shifter controls to take effect.

Adjust On Shaft

In this position, the motor shaft moves to the center of travel allowing you to fasten the mirror onto the shaft at the correct angle or to set up the camera with the mirror fixed at 45°.

Trigger Level Adjust

This control varies with the **MIRROR MODE-ALIGN/ROTATE** settings.

In the **MIRROR ROTATE** mode the **TRIGGER LEVEL ADJUST** sets the mirror position at which the Mirror Image Shift Electronics triggers the Synchronizer to fire the laser.

In the **MIRROR ALIGN** mode it sets the mirror angle.

Mirror Amplitude

The **MIRROR AMPLITUDE** switch controls the angular swing of the mirror cycle. The maximum mirror rotation is 20 degrees. and the **MIRROR FREQUENCY** controls the time duration of the mirror cycle.

The **MIRROR AMPLITUDE** and **MIRROR FREQUENCY** together set the rate at which the mirror rotates. When set for a **WAVE TYPE TRIANGLE** the mirror rotation rate can be increased by setting a larger amplitude, a higher frequency or both. For a square wave the mirror requires about 10 msec to complete a half cycle. To set the maximum slew rate select square wave and set the mirror amplitude to the maximum setting. The mirror frequency only affects the slew rate in square wave if the frequency is less than 50 Hz.

Mirror Frequency

The **MIRROR FREQUENCY** setting can be read from Table 5-1. This can be used for computing the approximate image shift velocity. For the most accurate results the image shift should be measured from a photograph of the flow model with a marker object.

Table 5-1
Mirror Frequency Settings and Mirror Cycle Times

Mirror Frequency Setting	Cycle Time ms
0.0	1,000
1.0	165
2.0	90
3.0	62
4.0	45
5.0	37
6.0	31
7.0	27
8.0	24
9.0	21
10.0	19

This chapter explains how to set the Mirror Image Shifter for High-Image Shift Velocities and Low-Image Shift Velocities.

Setting the Mirror Image Shifter for High-Image Shift Velocities

When setting the Mirror Image Shifter for High-Image Shift Velocities consider the following:

❑ Select **SQUARE WAVE TYPE**. It is designed for high-image shift velocities. It moves the mirror through its stroke in the shortest time possible, about 10 ms.

❑ Use the **MIRROR AMPLITUDE** control to adjust the shift velocity in the square wave. To get the maximum possible shift velocity use a **MIRROR AMPLITUDE** value of 10. Decreasing the **MIRROR AMPLITUDE** decreases the image shift velocity.

❑ If the maximum mirror rotation rate does *not* give enough shift velocity, the shift velocity can be increased by moving the camera back thus reducing the photograph magnification and increasing the shift velocity.

Setting the Mirror Image Shifter for Low-Image Shift Velocities

When setting the Mirror Image Shifter for Low-Image Shift Velocities consider the following:

- ❑ Select **TRIANGLE WAVE TYPE**. In this mode the mirror motion is set using both the **MIRROR AMPLITUDE** and **MIRROR FREQUENCY** controls. The **MIRROR AMPLITUDE** sets how many degrees the mirror rotates. The **MIRROR FREQUENCY** sets how long it will take the mirror to complete one cycle of motion. The mirror cycle uses most of the time period to move the set **MIRROR AMPLITUDE**, it then returns to the start position as quickly as possible, about 10 ms. The lowest image shift velocity is achieved with the **MIRROR AMPLITUDE** set to 0.0 and the **MIRROR FREQUENCY** set to 0.0.
- ❑ With the **AMPLITUDE** set very low, it is important that you accurately mount the mirror on the shaft at 45 degrees. If the mirror mounting is off, the measurement area may not be visible to the camera. To mount the mirror, set the **TRIGGER LEVEL ADJUST** control at 5.0 and the **MIRROR** control to **ADJUST** on **SHAFT**. See the Mirror Image Shift Installation Manual for details on mounting the mirror.

The most accurate way to determine the exact image shift distance is to take photographs with stationary objects in the lightsheet. Small objects such as needles can be used. By measuring the distance this object has moved, you can determine the exact image shift for your experiment. PIVSIM software can be used to help choose the correct image shifting parameters.

You can receive and monitor two signals from the back panel of the Mirror Image Shifter that can be very helpful in setting up the Mirror Image Shifter.

The output from **MONITOR** (Figure 5-2) shows the mirror angle as a voltage. This signal is from the mirror feedback showing the position of the mirror over time. When you set the mirror to square wave, the drive signal to the mirror is a step change in voltage. The mirror takes some time to respond to this step change. The monitor shows how the mirror actually moves.

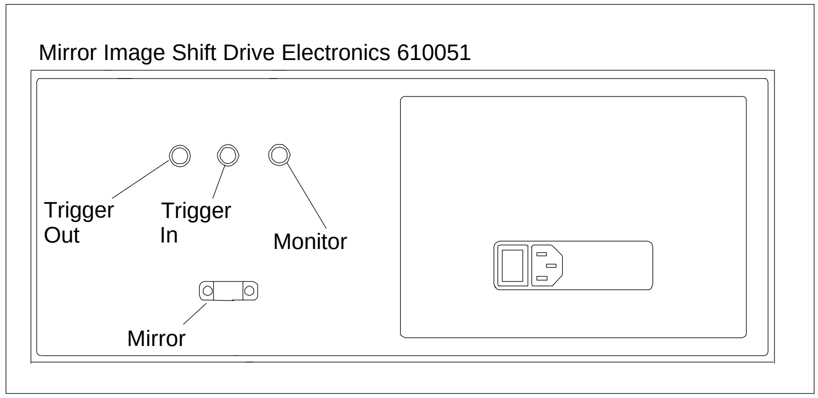


Figure 5-2
Back Panel of the Model 610050 LaserPulse Mirror Image Shifter Electronics

The calibration of this signal is 2 volts per degree of rotation. (The reflected image moves at twice the mirror rotation rate.)

TRIGGER OUT shows when the trigger is active. This TTL signal goes high when the mirror reaches the trigger amplitude point and stays high until the mirror crosses the trigger point in the other direction. This signal goes to the Synchronizer **TRIGGER INPUT**. By using a BNC T and setting the Oscilloscope to 1M ohm termination, you can monitor this signal and operate the system.

By looking at the **MONITOR** and **TRIGGER OUT** signals you can see the position that the mirror is triggering. This can be very helpful if the laser is not firing with image shifting.

The image shift velocity is a function of the mirror rotational speed and the distance from the mirror to the laser lightsheet. For PIV applications the mirror rotation between the laser pulses is usually less than 1 degree. For computing the image shift for the image shift formulas, the small angle approximation can be used replacing the SIN with the angle in radians.

$$\text{ShiftVel} = 2 * \omega * (\text{Mir-Sheet})$$

where:
ShiftVel = image shift velocity
ω = mirror rotation rate (rad/s)
(Mir-Sheet) = mirror to lightsheet distance (m).

In setting up the experiment, the desired image shift velocity is chosen to be a little larger than the largest flow reversal. The mirror to lightsheet distance is usually determined by the selection on the photograph magnification for the lens used. The mirror rotation rate is then set for the desired image shift velocity.

The image shift distance is:

ImageShift = ShiftVel * dT

where:

ImageShift	=	image shift distance (mm)
ShiftVel	=	image shift velocity (m/s)
dT	=	time between laser pulses

Table 5-2 lists the problems you may encounter and the solutions to these problems.

Using the Model 610050 Image Shifter with Nd:YAG Lasers

Nd:YAG lasers operate best when the flashlamps are fired at a constant frequency. When an image shifter is used the Synchronizer waits for the mirror to be in position before the Laser is fired. This image shifter wait time can cause the Nd:YAG laser to dropout of rhythm and possible cause an error in the Nd:YAG laser. The Model 610032 has some features that keep the laser operating at a constant flashlamp frequency.

With the Model 610050 Scanning Mirror Image Shifter in single sweep mode the mirror sweep starts on the Trigger In signal, (Mirror Trigger Out on the Synchronizer). The time from the this Trigger In till the mirror is in position and the Image Shifter triggers the Synchronizer to fire the lasers is constant for a given Model 610050 setting. The wait time will change with any change to the settings. By setting this time as the Image Shifter Wait time in the LaserPulse | Timing | Delay Image Shift edit field the Synchronizer can adjust for this wait and fire the flashlamps at a constant frequency.

Pulse Repetition Rate and Image Shifter

The Nd:YAG laser Pulse Repetition rate is reduced by not firing the Q-Switch on every flashlamp pulse. When the Pulse Repetition Rate is reduced with the Q-Switch divide timing errors caused by incorrectly setting the Image Shift Delay Time can happen. The error is that the flashlamp trigger on the pulse after the laser was Q-Switched could be faster than the laser allows. When this happens the laser can generate an error and shutdown, making it difficult to configure the system for your experiment. When the Synchronizer is used with less than the maximum Pulse Repetition Rate the flashlamp trigger after the Q-Switch is dropped. This dropout can be heard as the laser misses a beat.

Measuring the Image Shift Wait Time

1. Connect the Image Shifter Trigger In signal to an oscilloscope channel 1 using a BNC “T” connector and a coaxial cable.
2. Connect the Image Shifter Trigger Out signal to an oscilloscope channel 2 using a BNC “T” connector and a coaxial cable.
3. Set the Image Shifter to **Single Sweep**.
4. Configure the other Image Shifter controls for your experiment.
5. Operate the LaserPulse Imaging System with the Image Shift.
6. Trigger the oscilloscope on the positive edge of the Trigger In signal on channel 1. The Trigger Out signal from the Synchronizer is a 300 µs positive TTL pulse.
7. Set the oscilloscope to view channel 1 and channel 2. Channel 2 has the Image Shift Trigger Out signal. This TTL signal goes high when the mirror passes the threshold angle on the forward sweep and goes low when the mirror passes the threshold angle on the return sweep.
8. Measure the time from the rising edge to the Trigger In to the rising edge of the Trigger Out.
9. Enter this time as the Image Shift Wait Time.

Verifying the Image Shift Wait Time

When the Image Shift Wait Time is entered accurately the Nd:YAG Q-Switch frequency will be the value entered in the LaserPulse |

Timing | Pulse Repetition Rate. If the time between Q-Switches is longer than it should be the IDELAY time is too short. If the time between Q-Switches is longer than it should be the IDELAY time is too long.

1. Connect an oscilloscope to the Synchronizer Q-Switch 1 output using a BNC “T” and a coaxial cable.
2. Trigger the oscilloscope on this Q-Switch signal.
3. Measure the time between Q-Switches
4. If the time between Q-Switches is too long then increase the IDEALY time by the time error. If the time between Q-Switches is too short then decrease the IDELAY time by the time error.

Synchronizer Triggered and Shutter Feedback Camera Modes with the 610050 Scanning Mirror Image Shifter

When the 610050 Scanning Mirror Image Shifter is used with a Shuttered camera like a 35mm Film Camera or the MEGAPLUS 1.4 or MEGAPLUS 4.2 there is a wait time for the shutter to open and a wait time for the mirror to get into position. In many cases these wait times can be combined.

The **LaserPulse | Timing | Pulse Delay Time** is used to allow the camera shutter time to open when the camera is in Synchronizer Triggered Mode. The Synchronizer Image Shifter Trigger Out signal the mirror to start rotation at the end of this Pulse Delay Time. When the Image Shifter Wait time is longer than the required Pulse Delay Time the Pulse Delay Time can be set to 0 and the camera shutter will still have time to open before the laser pulses.

With the Synchronizer in Camera Shutter Feedback Mode the exposure time must be long enough for the shutter to open and then the mirror to rotate into position.

Table 5-2
Troubleshooting the Mirror Image Shifter

Problem	Solution
The mirror moves in **CONTINUOUS** mode but only moves once in **SINGLE SHOT** with the Synchronizer.	Check that the mirror **TRIGGER LEVEL ADJUST** is set to a level that triggers the Synchronizer. A setting of 5 triggers the mirror in the center of travel. When the amplitude is low, the trigger level must be near 5 to produce a trigger. When the amplitude is higher, the trigger level can be larger.
The mirror rotates in **CONTINUOUS** mode but *not* **SINGLE SHOT** with the Synchronizer.	Check that the cables between Synchronizer and Mirror Image Shifter are: **TRIGGER IN** to **TRIGGER OUT** **TRIGGER OUT** to **TRIGGER IN**

Table 5-3 lists the specifications—which are subject to change—for the Mirror Image Shifter.

Table 5-3
Specifications of the Mirror Image Shifter

Shift Directions	Up, Down, Left, Right
Maximum Rotation Rate	2000 degrees/sec (20 degrees/10 msec)
Maximum Angle	±10 Degrees