Particle Image Velocimetry (PIV):

Theory of Operation

P/N 1990755A

Manual History

The following is a manual history of the Particle Image Velocimetry (PIV): Theory of Operations (Part Number 1990755).

Revision	Date
First Version	March 1995
A	September 1999

This manual was first published March 1995.

In revision A, Chapter 2 was revised and minor changes made.

Contents

Chapters

Figures

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CHAPTER 1

Manual Overview

This manual gives you theoretical details and practical tips on the various aspects of the PIV experiment.

Organization

This chapter gives an overview of the details covered in the other chapters of this manual.

Analysis

This chapter discusses:

- ❑ How PIV images are analyzed by the INSIGHT software using autocorrelation or cross correlation methods.
- ❑ Six rules of thumb to follow when capturing images to get the best results from a PIV experiment.
- ❑ Explanation of parameters and terms such as analysis grid and interrogation spot, peak search, resolution and accuracy.

Image Shifting

This chapter discusses:

- ❑ Concept of image shifting and how it is used it in a PIV experiment.
- ❑ How to select the direction and magnitude of the image shift.

Post Processing

This chapter discusses how editing vectors and computing flow properties is performed.

Synchronization

This chapter discusses how the Synchronizer controls the timing of lasers, cameras and the image shifter.

Lasers, Lightsheet Optics and Other Light Sources

This chapter discusses:

- ❑ Type of lasers used in TSI's PIV system
- ❑ Lightsheet optics
- ❑ Other type of lasers used for PIV
- ❑ Systems with no lasers, and
- ❑ Systems with non-pulse lasers

Image Capture and Digitization

This chapter discusses different aspects of the image capturing process, including a discussion of the different types of cameras.

Seeding

This chapter discusses the selection criteria for tracer particles.

Optimizing the Experiment

This chapter discusses how to optimize a PIV experiment.

CHAPTER 2

Analysis

This chapter discusses theoretical details and practical tips on the Analysis aspect of a PIV experiment.

As mentioned earlier, PIV processing is basically determining the distance that particles have moved in the time between laser pulses. The two most common methods to determine this distance are Particle Tracking and Correlation.

Overview of Cross-Correlation Processing

INSIGHT software can measure velocity using one of three correlation processes: Autocorrelation, 1-Frame Cross-Correlation and 2-Frame Cross-Correlation. The differences in these correlation techniques is the image window areas for the first and second particle images. In autocorrelation, the same image window is used for both the first and second image window. In 1-frame cross-correlation, the second image window is offset from the first image window on the same frame. In 2-frame cross, the first image window is on frame 1 and the second image window is on frame 2.

Each of these processing techniques has advantages for some applications. Autocorrelation is for multiple exposure images where the particle motion and image shift together give less than ¼ of the interrogation spot image displacement. This is the classical PIV processing technique.

1-frame cross-correlation is also a multiple exposure technique. It is used when the image shift displacement is large relative to the particle motion displacement. By offsetting the second image window from the first by the mean particle image displacement, distance high resolution measurements can be made. Otherwise, it would require prohibitively large interrogation spot sizes for autocorrelation processing. By offsetting the second image window by the mean particle image displacement, the interrogation spot size can be reduced and fewer lost pairs relative to autocorrelation will result.

2-frame cross-correlation measures the distance which particles have moved between exposures on two image frames. Each of these frames has only one pulse of light. By knowing the sequence of the first pulse images and the second pulse images, the processing signal-to-noise ratio relative to the single frame techniques is improved. 2-frame cross-correlation can measure zero displacements and reversing flows without image shifting. 2-frame cross-correlation can be used with image capture systems with an effective frame rate high enough so that the particle images on two successive frames give particle image displacements in the measurable range.

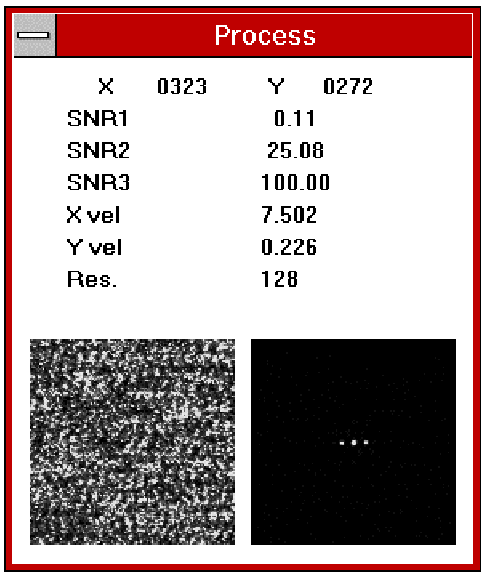

Figure 2-1
Status Box Showing Autocorrelation

Understanding Autocorrelation

The autocorrelation performed by the INSIGHT software uses two-dimension Fast Fourier Transforms (2D FFTs). The result of this correlation is the particle displacement field. The particle displacement field shows the distance between each particle and every other particle within the interrogation spot. The maximum intensity spot is in the center, at a displacement of zero. This peak represents the correlation of each particle image with itself. At the distance between the particle image pairs, the first displacement peak is found. The autocorrelation function is symmetrical so that each displacement peak has a peak of equal size in the opposite direction. One peak is the distance between the first and second particle images, the forward velocity, the other is the distance between the second and first particle images, the reverse velocity. If there are no negative velocities in the flow, then the correct peak is selected by choosing the search area. If there are flow reversals, image shifting is used to resolve the directional ambiguity.

Although the INSIGHT software performs autocorrelation using FFTs, to help you understand how to read the output of the autocorrelation that INSIGHT displays in the status box, the following paragraphs explain autocorrelation using examples of particle tracking histograms and convolution methods of computing autocorrelation. Following these examples is a brief non-mathematical discussion of how the actual autocorrelation using FFTs is performed.

Understanding Autocorrelation Using the Particle Tracking Method

Let us first consider the method of performing autocorrelation using the particle tracking histograms.

Selecting the Interrogation Spot and Identifying the Particle Images

First, from the entire flow field image, a small area, the interrogation spot is extracted to be interrogated. Each of the particle images in the spot is identified and the centroid locations are measured (Figure 2-2) and a list of particle centroid locations is compiled (Table 2-1).

Table 2-1
List of Particle Centroid Locations

Particle Number	X Centroid	Y Centroid
1	0.4	0.7
2	0.1	0.6
3	0.8	0.6
4	0.5	0.5
5	0.6	0.3
6	0.3	0.2

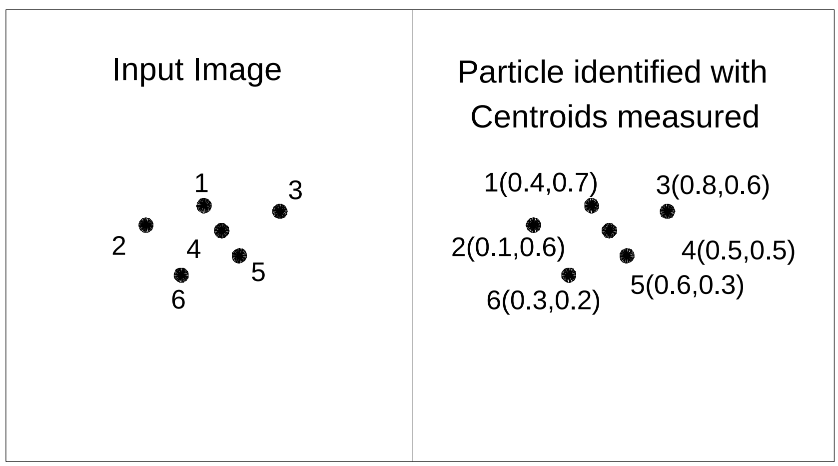

Figure 2-2
Identifying and Measuring Particle Centroids

Compiling Matrix of Particle Pairings and Displacement

From the list of particle centroid locations, a matrix of all particle pairings is made (Table 2-2). The matrix information is sorted by displacements and the frequency of occurrence of specific displacements (ΔX, ΔY) is tabulated as number of counts (Table 2-3).

Table 2-2
Table of Particle Pairings

	First Image: Particle Number (Position)					
	#1.(.4,.7)	**#2 (.1,.6)**	**#3 (.8,.6)**	**#4 (.5,.5)**	**#5 (.6,.3)**	**#6 (.3,.2)**
Second Image Particle Number (Position)						
1(.4,.7)	(.0, .0)	(.3, .1)	(-.4, .1)	(-.1, .2)	(-.2, .4)	(.1, .5)
2(.1,.6)	(-.3, -.1)	(.0, .0)	(-.7, .0)	(-.4, .1)	(-.5, .3)	(-.2, .4)
3(.8,.6)	(.4, -.1)	(.7, .0)	(.0, .0)	(.3, .1)	(.2, .4)	(.5, .4)
4(.5,.5)	(.1, -.2)	(.4, -.1)	(-.3, -.1)	(.0, .0)	(-.1, .2)	(.2, .3)
5(.6,.3)	(.2, -.4)	(.5, -.3)	(-.2, -.4)	(.1, -.2)	(.0, .0)	(.3, .1)
6(.3,.2)	(-.1, -.5)	(.2, -.4)	(-.5, -.4)	(-.2, -.3)	(-.3, -.1)	(.0, .0)

Table 2-3
Table of Frequency of Particle Image Displacements

ΔX	ΔY	Number of Counts
–.7	0.0	1
–.5	–.4	1
–.5	.3	1
–.4	.1	2
–.3	–.1	3
–.2	–.3	1
–.2	–.4	1
–.2	.4	2
–.1	–.5	1
–.1	0.2	2
0.0	0.0	6
.1	–.2	2
.1	.5	1
.2	–.4	2
.2	.4	1
.2	.3	1
.3	.1	3
.4	–.1	2
.5	–.3	1
.5	.4	1
.7	0.0	1
	Total Count	36

Determining and Locating Displacement Peak

The data is then plotted on a 2D graph (Figure 2-2) with the peak diameter representing the number of counts of each displacement occurrence. The status box in the INSIGHT software shows the peak signal strength as a gray scale intensity (Figure 2-3).

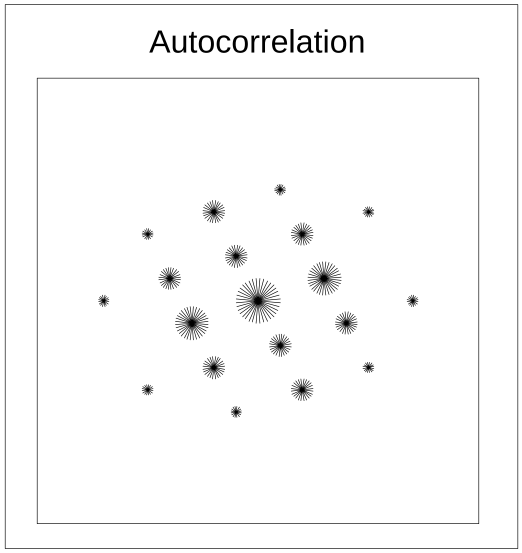

Figure 2-3
Autocorrelation Graph

From the displacement list (Table 2-3) or the histogram (Figure 2-2) you'll see that the most common displacement counts (6) are at (0.0, 0.0). This represents particles correlating with themselves at zero displacement. Since this does not contain any velocity information, INSIGHT blocks this information out during the peak search and so it is not measured.

Note: *In the histogram example, the zero peak does not have to be computed, it is included here to show that it appears in the autocorrelation computations using FFTs.*

After the zero peak is eliminated, the autocorrelation is searched for the maximum signal. This peak is found by finding the maximum intensity pixel in the autocorrelation search half-plane. In this example, the signal strength is 3 at (–.3, –.1) and (0.3, 0.1). Each peak in the autocorrelation has an associated peak of the same strength in the reverse direction. One of these peaks is the forward velocity peak and the other is the anti-velocity peak. In other words, one is the distance from the first image to the second, the other is the distance from the second image to the first. They have the same magnitude speed and signal strength and are 180° apart. However, since the image does not contain any information about which of the images came first the processing alone cannot make the correct decision on which to pick. You need to input the flow direction and select the half-plane in which to look for the peaks. This half-plane selection chooses which of the two peaks is considered the forward velocity peak.

In this example all of the particles have a pair in the interrogation spot, and there are no lost pairs. The displacement peak strength is half that of the zero peak. If there were some lost pairs the displacement would be less than 50% the zero peak. All of the other peaks are considered noise peaks. They happen because images of different particles correlate and produce some signal. Correlation processing relies on the signal from the pairs of particles being stronger than the noise peaks of random particle locations.

Understanding Autocorrelation Using Convolutions

Another way to understand autocorrelation is to use the example of computing autocorrelation with convolutions.

In the convolution method, two copies of the interrogation spot are used. One image is overlaid on top of the other with a pixel offset corresponding to the displacement being checked. The autocorrelation function is the sum of the products of the aligned pixel values. The summation of pixel intensity products is computed for each displacement of the correlation being checked. Graphing the summation at each offset gives the autocorrelation function.

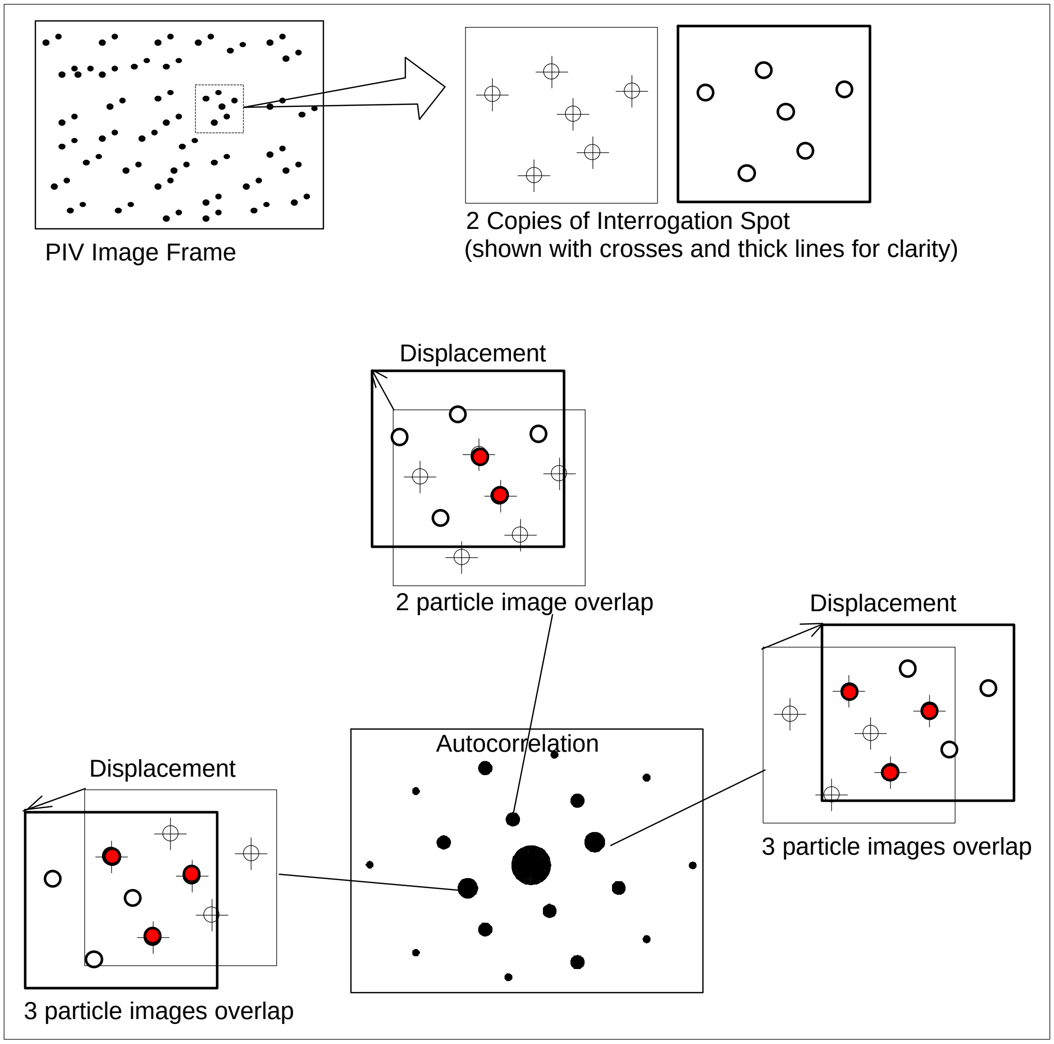

Figure 2-4
Direct Correlation

Correlation by convolution can be done using two positive transparencies and an overhead projector. Each of the positive transparencies has a black background with clear particle images. You'll see that light passes through areas where two particle images are lined up while in areas where a particle image aligns with the black background of the other transparency, no light is transmitted. The total light transmitted through both transparencies is the correlation function.

When the two transparencies are overlaid with no displacement, all of the particle images from the first transparency are aligned with a particle image in the second transparency and transmit light. This is the zero peak and produces the strongest correlation possible.

To measure the correlation for a given particle displacement ,the second transparency is translated by the particle displacement distance relative to the first transparency. The transmitted light though the transparencies is the correlation at that displacement. To compute the autocorrelation function each possible displacement is tried and the results are plotted on a graph. The displacement the highest correlation is the particle image displacement.

Autocorrelation Using FFTs

Having seen the particle tracking and convolution methods of performing autocorrelation, let us now examine how INSIGHT performs autocorrelation using FFTs. Following is a non-mathematical explanation of how 2D FFTs are performed in the INSIGHT software.

Note: *If you need detailed mathematical-based information on FFTs, refer to one of the many books that are available on this subject.*

A two-dimension FFT is a one-dimensional FFT performed on each column of data followed by a one-dimensional FFT on each row of data. The input image data is real, the FFT output is complex, with real and imaginary components. The complex FFT output data is converted into the real power spectrum, without the phase information. The power spectrum contains the information about the distance between particle images, while the phase contains information about the particle location.

1-Frame Cross Correlation

1-frame cross-correlation uses a double exposure image similar to the image used for autocorrelation. The difference is that the image window area for the second particle images is offset from the first image window area, typically by the image shift, or mean particle image displacement distance. The processing of the 1-frame cross-correlation depends on the amount of overlap between the first and second image windows.

Non-Overlapping 1-Frame Cross Correlation Windows

When the image shift distance is larger than the interrogation spot size (image window area), the correlation function only has the particle displacement peak and noise peaks. The autocorrelation zero velocity peak is caused by particle images correlating with themselves. In 1-frame cross-correlation—when the image windows do *not* overlap—there are no particle images correlating with themselves, so the zero velocity peak is not produced. With non-overlapping 1-frame cross-correlation, the order of the particles is known, the first particle images are in image window 1 and the second particle image are in image window 2. Since there is no ambiguity in which particles came first, the anti-velocity peak is not present in the correlation. By eliminating these two strong peaks, that do *not* contain velocity information, the signal-to-noise ratio is increased.

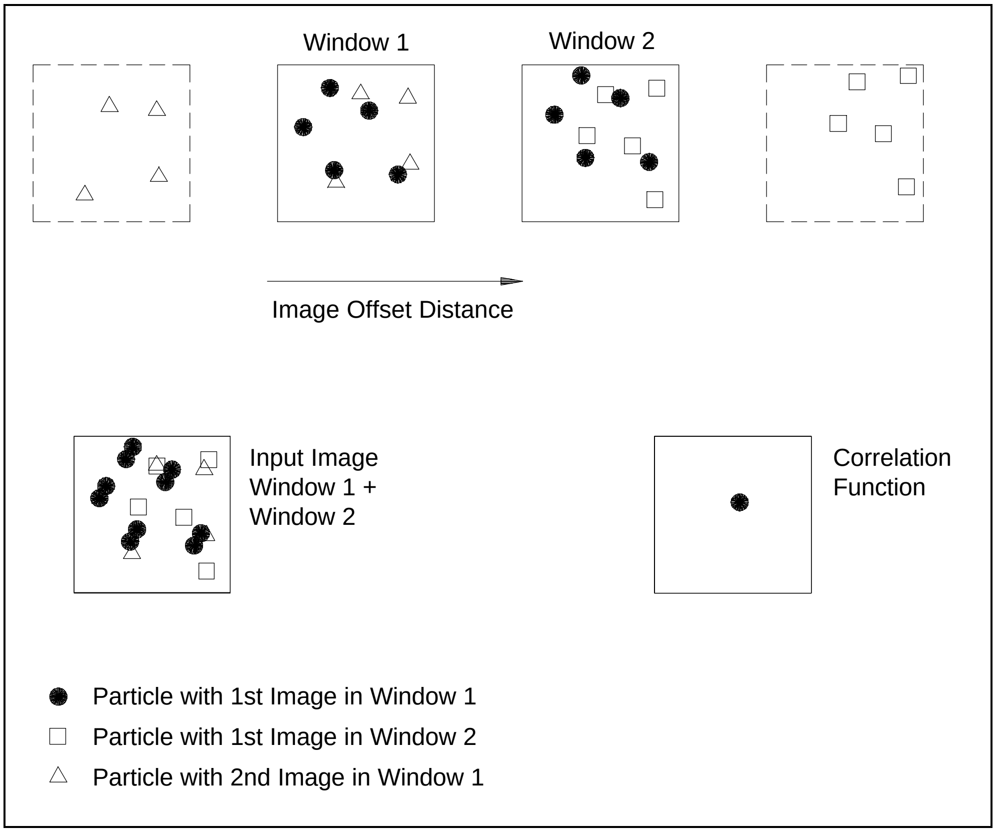

Figure 2-5
1-Frame Cross-Correlation Image Windows

In Figure 2-5, image window 1 has the images of particles that were in image window 1 for the first pulse of light, and the images of particles that were in a different image window and moved into image window 1 for the second pulse of light. Image window 2 also has two sets of particles, the same set of particles in image window 1 which captured at the second and particles that were in image window 2 for the first pulse. These particles, that are in image window 1 for the first pulse and in image window 2 for the second pulse, can be seen to have a particle image displacement in the input window where the first and second image windows are added and displayed. The other particle images do *not* have a consistent displacement. The particles that are in image window 1 for the first pulse and image window 2 for the second pulse contribute the velocity peak in the correlation window. The other particle images just contribute to noise peaks.

Overlapping 1-Frame Cross-correlation Windows

When the image shift distance is less than the image window size, zero velocity and anti-velocity peaks are in the correlation. The overlapping image window 1-frame cross-correlation looks like the autocorrelation function with the zero peak displaced by the window offset, and forward velocity peak is also stronger than the reverse velocity peak. The peak search area depends on the window offset and the correlation is performed in the largest half plane determined from the second window offsets. The directions are relative to the zero peak location.

Peak Search Area Table

| X Offset | > | Y Offset |
X Offset   +   Right
X Offset   -   Left
| X Offset | < | Y Offset |
Y Offset   +   Up
Y Offset   -   -   Down
X Offset = 0   Y Offset = 0   Flow Direction Input

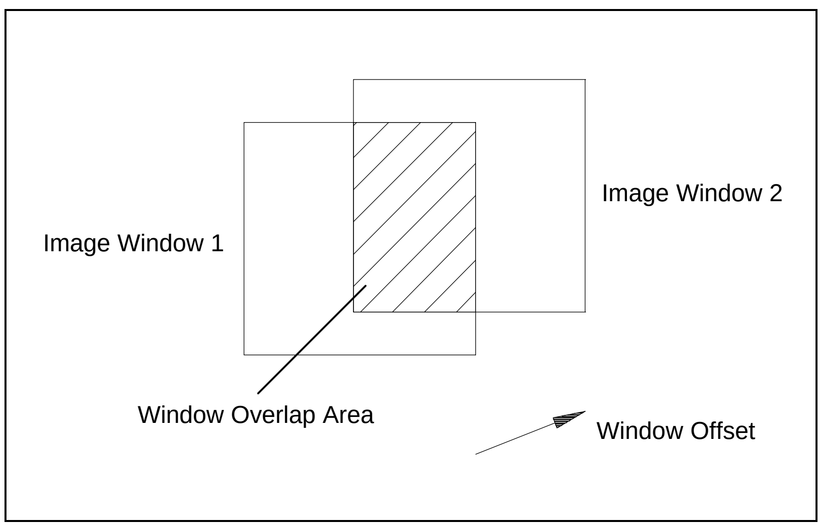

Figure 2-6
1-Frame Cross-correlation Window Overlap

The peaks produced by a particle image pair processed with overlapping window 1-frame cross-correlation depend on the locations of the particle images relative to the window overlap area. Particle image pairs with both first and second images in the window overlap area produce the three peaks found in the autocorrelations: zero velocity, velocity, and anti-velocity peaks. These peaks are displaced from the center of the correlation by the window offset distance. Particles with one image in the window overlap area will contribute to the zero-velocity peak and the velocity peak. The velocity peak for these particles is from the pairing of a first particle image in the non-overlapping area of image 1 with a second particle image in the overlapping area of window 2, or the first particle image in the overlapping area of window 1 with the second particle image in the non-overlapping area of window 2. Particle image pairs that move from the non-overlapping window area of window 1 to the non-overlapping area of window 2, contribute only to the velocity peak. The velocity peak is stronger than the anti-velocity peak because there are more particle images contributing to it. The zero-velocity peak is at the known window offset distance and is blacked out before the peak search.

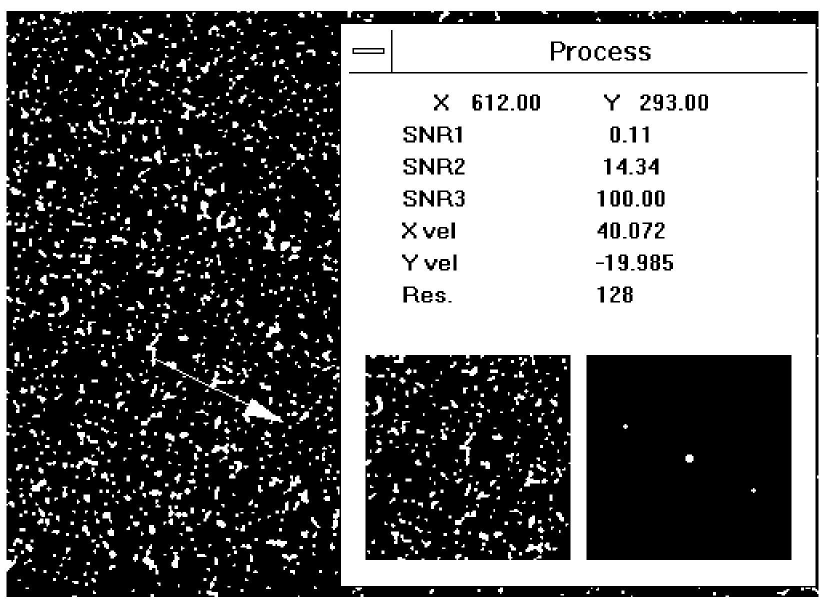

Figure 2-7
Autocorrelation

This autocorrelation result for particle displacements of 40, -20 pixels requires a 128-pixel resolution interrogation spot to get a valid result. This correlation could also be computed using 1-frame cross-correlation with an X Offset = 0, Y Offset = 0.

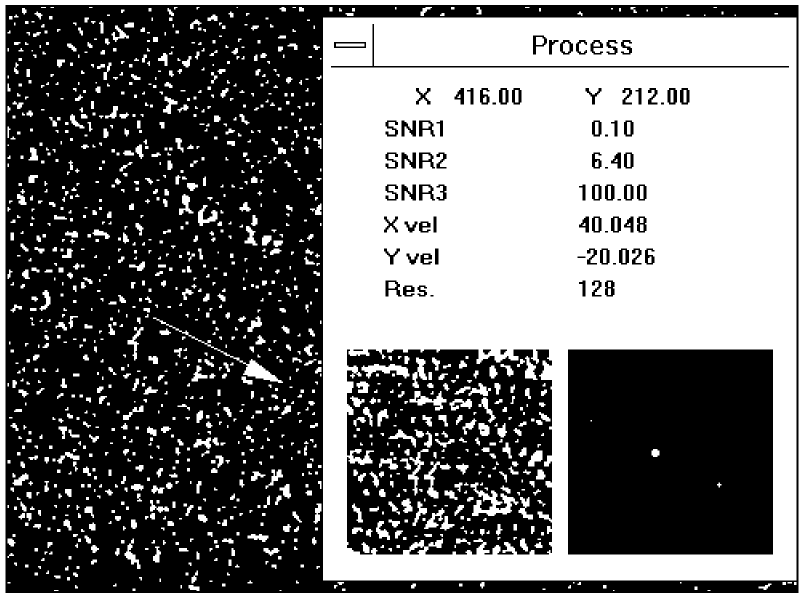

Figure 2-8
Overlapping Window Cross-correlation X Offset =10, Y Offset = 0

Figure 2-8 shows a 1-frame cross-correlation with X Offset = 10, Y Offset = 0. The interrogation spot is 128 pixels so there is a 118-pixel overlap between the first and second windows. This large overlap gives the three peaks from the autocorrelation the zero peak, the velocity peak and the anti-velocity peak. The peaks have moved 10 pixels left in the correlation due to the 10 pixel X Offset. The velocity peak is stronger than the reverse peak. In this overlapping window case the peak search is to the right of the zero velocity peak. The input window in the Status Box shows the sum of the first and second windows. The images are kept separate for processing but showed together so that you can see what is being processed.

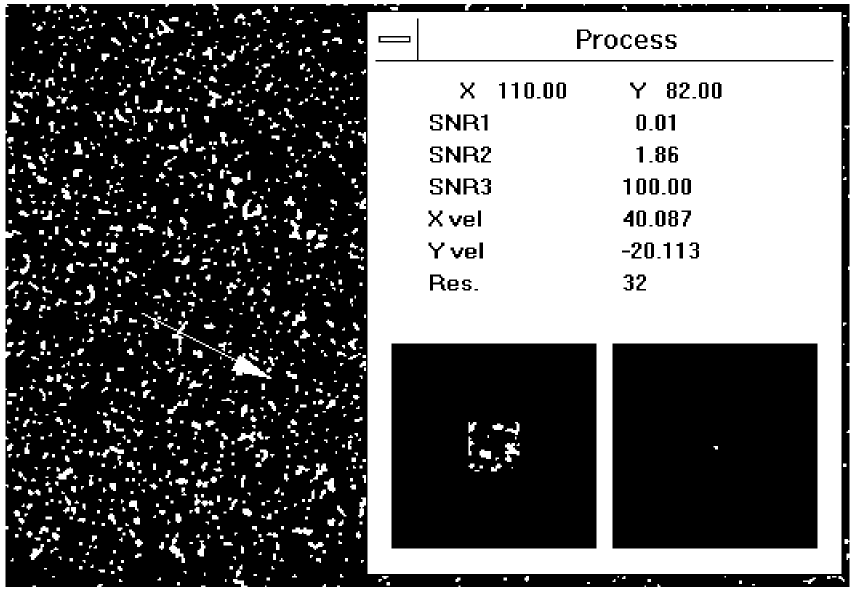

Figure 2-9
Non-Overlapping 1-Frame Cross-correlation

Figure 2-9 was processed using a window offset of X Offset = 40, Y Offset = -20. By moving the second window by the average particle image displacement, a 32-pixel resolution interrogation spot can be used. The 32-pixel windows are smaller than the 40× 20 pixel offset so the only the velocity peak is in the correlation window, the zero peak and anti-velocity peaks are not present. This illustrates one of the advantages of 1-frame cross-correlation over autocorrelation, the interrogation spot can be much smaller than used with 1-frame cross-correlation, as shown in the previous examples. This allows more velocity vectors to be extracted from the image.

When the second window is shifted by the mean pixel displacement, the correlation rules-of-thumb are modified. The required number of particle pairs is reduced. The velocity range is still limited as the velocity peak cannot go beyond one-half the way from the correlation center to the edge. This is the same one-fourth interrogation spot displacement criteria but it applies to distances from the window offset not particle image displacements.

Cross-correlation by Histogram

The processing of the 1-frame cross-correlation is done using FFT analysis. It could also be done using the particle tracking histogram approach described in detail for autocorrelation processing. In the 1-frame cross-correlation histogram all of the particle images in image window 1 are identified and their locations. A separate list of all of the particles and their locations is made for image window 2. Particles located in the image window overlap area are included on both lists. The distance from each particle in image window 1 to each particle in image window 2 is found. By plotting the particle pair locations, the particle image displacement is found as the most common displacement. If the images overlap, particles in the overlap region are in both window 1 and window 2 and correlate with themselves. Particle image pairs in the overlap region have two possible pairings—from image 1 to image 2 the displacement distance and from image 2 to image 1 the anti-velocity distance. Only the particles in this overlap region contribute to the zero peak and anti-velocity peak.

The 1-frame cross-correlation function could also be computed by making two transparencies of the image frame with clear particle images and a black background. By moving the second transparency by the window offset distance, the correlation strength in the center of the correlation is found by the light that passes through both transparencies. By moving the second transparency, the interrogation spots size over the first the displacement with the strongest correlation function can be found.

Cross-correlation By Fourier Transforms

The cross-correlation function is computed using Fast Fourier Transforms (FFTs). The FFT processing gives the same results as the histogram approach, but is more efficient with the computer. The processing sequence is a 2D FFT on window 1 and a 2D FFT on window 2. The FFT result of window 1 is multiplied by the complex conjugate of the window 2 FFT result. Computing the 2D FFT of the multiplication result and taking the modulus gives the correlation result.

2-Frame Cross-Correlation

2-frame cross-correlation uses two image frames with one pulse of light on each frame. The flow velocity is found by measuring the distance the particles have traveled from frame 1 to frame 2. With 2-frame cross-correlation, only images from laser pulse 1 are on frame 1, and only second laser pulse images are on frame 2. This complete separation of the first and second particle images allows the velocity to be measured without directional ambiguity. Image shifting is not required to resolve the directional ambiguity for 2-frame cross-correlation. Zero-velocity does not exist for 2-frame cross-correlation as with the single image frame correlation techniques. Since the particle image is recorded on two image frames, a particle with zero velocity shows up on both image frames at the same location and can be measured.

The signal-to-noise ratio of 2-frame cross-correlation is the best among all the correlation methods. This is because only first particle images are in image window 1 and only second particle images are in image window 2. There is not the overlapping of first and second particle images as with the single image frame system.

The limitation of using 2-frame cross-correlation is in the effective image capture rate, or framing rate. The particle must move less than one-fourth of the interrogation spot in the time between the first and second laser pulses. The framing rate for 35mm film cameras, and many high resolution CCD cameras, makes 2-frame cross-correlation PIV not practical. With standard RS-170, the time between frames is 33 ms, or 30 Hz. With CCIR, the time between frames is 40 ms, or 25 Hz. The time interval of 33 ms between images is only useful for very low velocity flows. To increase the effective frame rate, “frame straddling” is used. In frame straddling the laser is pulsed at the end of the first exposure period and then at the start of the second exposure period. This allows short time intervals between pulses so that high velocity flows can be measured. When frame straddling is used with a 30-Hz camera, two image frames are required for each measurement and the flow sampling rate is 15 Hz. For the best results, a camera that can capture a picture and then move the image into memory and start integrating the next image frame quickly is desired. The movement of charge between the photosensitive pixels and memory must be very fast for high-speed 2-frame cross-correlation. The time it takes from the end of one exposure period and the start of the next exposure period determines the maximum flow velocity that can be measured. The time it takes to readout the image from the CCD to the computer determines the frame rate or how frequently the flow can be sampled.

This power spectrum result from the 2D FFT is a *computed* Young's Fringe pattern, the particle image displacements in the frequency domain. In many early PIV analysis systems, the Young's Fringe was optically obtained using a HeNe laser to illuminate a PIV transparency. This processing technique was used primarily because less computing power was available at that time. With Young's Fringe patterns as the input image only, a single 2D FFT is computed to get the autocorrelation. An inverse 2D FFT and power spectrum on the Young's Fringe pattern produces the autocorrelation.

The power spectrum is computed from the sum of the squares of the real and imaginary components. The square root of the computed power spectrum should be used to get the same scaling factors for the peak intensities to compare the direction correlation techniques with FFT correlation. Calculating the square root of the computer power spectrum is skipped to save processing time. It does not affect which peak is selected as the displacement peak, but it does change the relative peak intensities and the signal-to-noise ratio numbers.

One difference between processing the data using direct correlation methods and FFT correlation processing method is aliasing. With particle tracking histogram technique, the maximum displacement is the full interrogation spot size. With the correlation by convolution the maximum displacement is limited to the displacements checked. In both these cases if the displacement is too large the particle pair peak is unlikely to be measured. With FFT autocorrelation displacements, from two particle image diameters up to half the interrogation spot are measured correctly. Displacements between half to the full spot size are measured in the wrong location.

Displacements larger than half the spot are in an aliased position in the autocorrelation. With these large displacements, the peak moves back towards the center. The true displacement is the distance to the edge of the autocorrelation plus the distance from the edge to the peak. The peak location is measured as the distance from the center to the peak not the true distance. Because of the danger of aliasing, the autocorrelation is not searched to the edges for peaks. With the outer ⅛ of the autocorrelation not searched displacements from ⅜ to ⅝ the spot are not allowed. This leaves only displacements from ⅝ to 1 spot that can be measured in an alias position. You must take care to set up the processing parameters so that these very large displacements do not happen.

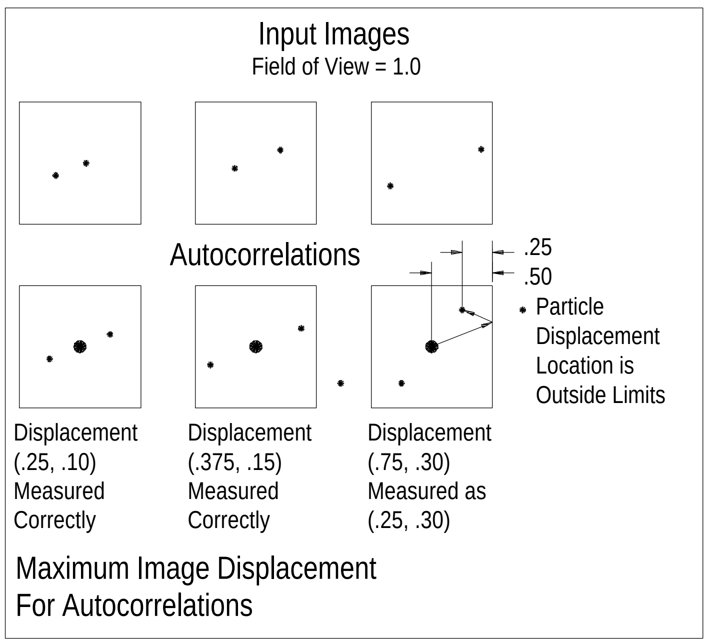

Figure 2-10
Demonstrating the Maximum Image Displacement and Aliasing

Rules-of-Thumb for Autocorrelation PIV Analysis

This section gives some guidelines for optimizing your experiment for best PIV results. To get the best results from a PIV experiment, the image capture and the interrogation must match the flow. Typically, the parameters that you can set to optimize the measurement are: the time between laser pulses (dT); image shifting; interrogation spot size; photograph magnification; lightsheet dimensions; seed particle and seed concentration. With these parameters in mind, the following rules were developed.*

- ❑ Rule 1: Interrogation spot size should be small enough so that one vector describes the flow within that spot.
- ❑ Rule 2: There should be more than ten particle image pairs per interrogation spot.
- ❑ Rule 3: Maximum in plane displacements should be less than ¼ of the interrogation spot size.
- ❑ Rule 4: Maximum out of plane displacement should be less than ¼ of the lightsheet thickness.
- ❑ Rule 5: Minimum in-plane displacement should be two particle-image diameters.
- ❑ Rule 6: Exposure must be large enough to clearly show the particles.

Rule 1: Interrogation-Spot Size Should be Small Enough For One Vector to Describe Flow for That Spot

This puts a limitation on the velocity gradient in an interrogation spot. If the velocity gradient is too large then the displacement peak becomes larger in area with a lower peak height, leading to the likelihood of measuring noise. Figure 2-11 shows how measurement errors can occur because of too large velocity gradients.

*The PIV rules of thumb were developed by Keane and Adrian in *Optimization of particle image velocimeters. Part 1: Double pulsed systems* Measurement Science and Technology 1 (1990). This paper included Rules 1 through 5, TSI added Rule 6.

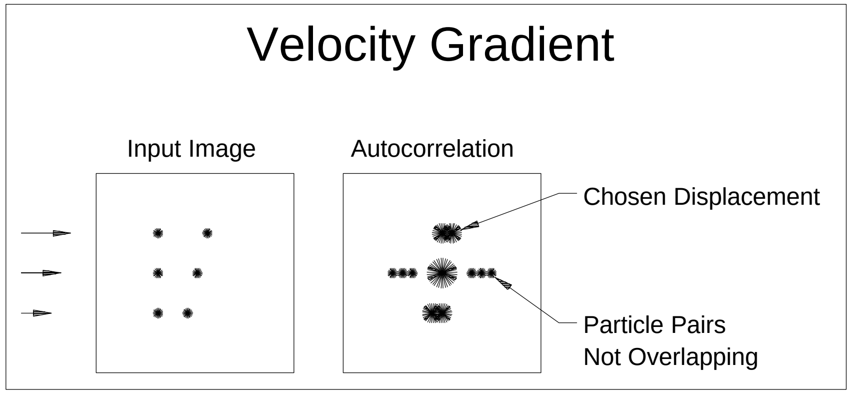

Figure 2-11
Velocity Gradient Error

Correlation produces the average velocity over the interrogation spot. The larger the spot, the more the averaging that takes place. To see the fine flow details, small spots are required. However, the minimum spot size is determined by Rule 2.

Rule 2: Should Have More than Ten Particle Image Pairs Per Interrogation Spot

The percentage of correct velocity measurements as a function of number of particle pairs has been established by Keane and Adrian. Their results are shown in Figure 2-12. These results show that the percentage of correct velocity measurements correlates strongly with the number of particle image pairs in the spot. (This work also takes lost pairs, and Rules 3 and 4 into account.) As the concentration increases beyond one per spot, the percentage of valid measurements increases. This is because many pairs of particle images contribute to the displacement peak. The noise peaks caused by the correlation of the images of different particles decrease relative to the displacement peak. The loss of some pairs is tolerable because many others pairs are still creating the displacement peak.

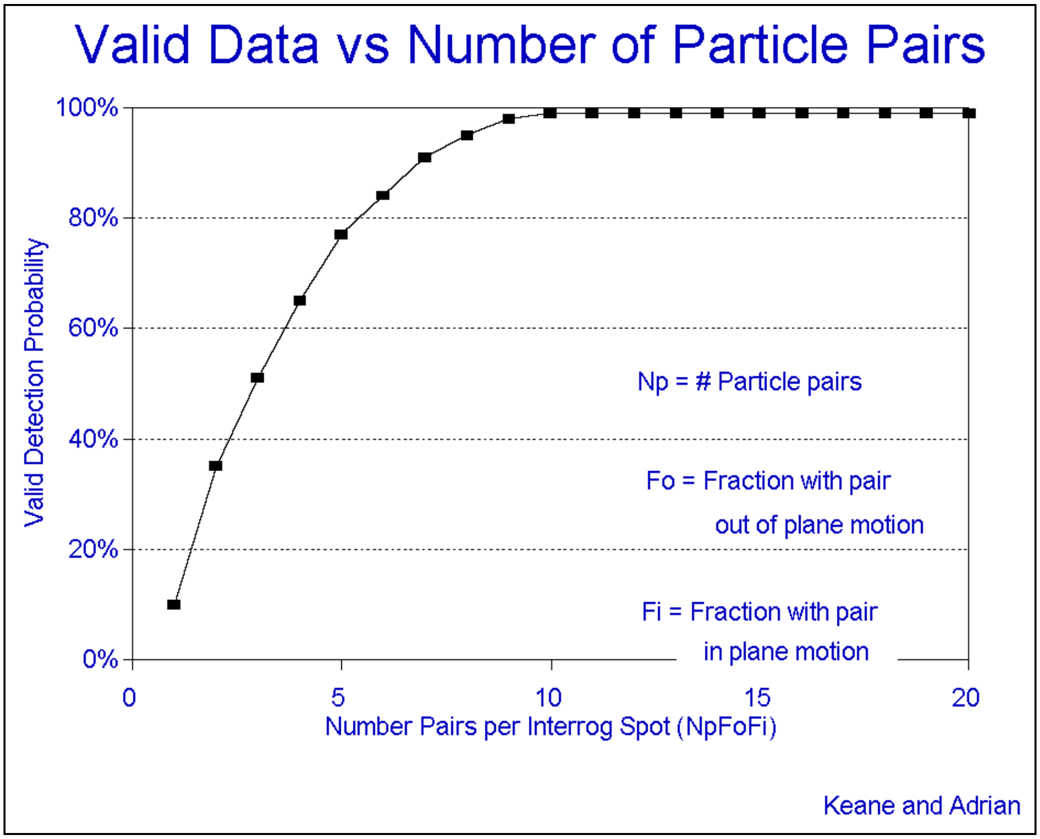

Figure 2-12
Correlation of Correct Velocity Measurements with the Number of Particle Images

Particle image concentrations with an average of one per interrogation spot produce the most erroneous measurements. This is because there is a high probability of having two pairs, or one and a half pairs or two half pairs in the interrogation spot. With two pairs of particles of equal size, the correlation for the distance between the two particles is as strong as the distance between the first and second image. With two pairs of particles of equal size, the wrong measurement is made fifty-percent of the time. With these low concentrations, a single particle that crosses the interrogation spot boundary can cause wrong measurements to be made. Figure 2-13 illustrates these errors for low particle-image concentration images.

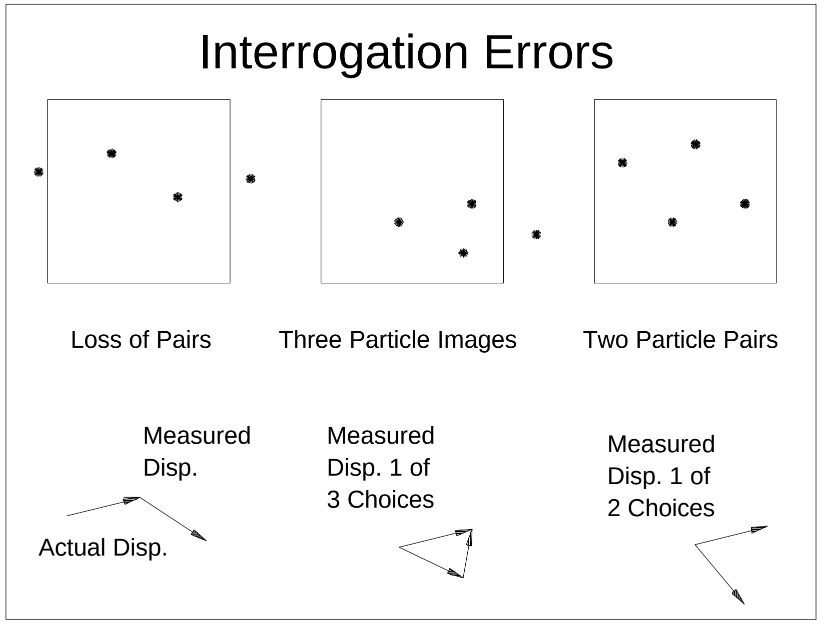

Figure 2-13
Interrogation Errors

The percentage of correct velocity measurements increases with decreasing particle image concentrations-from an average of one pair per spot down to very low concentrations. This is because where a pair of particles is found, it is unlikely that a second particle will also be in the spot to cause confusion about the correct pairing. A velocity measurement is only possible where a pair of particles is found so very low seeding concentration pictures produce sparse vector fields. If the goal of the experiment is to measure the flow on a high resolution grid, low seeding concentrations must be avoided. This increasing correct vectors with decreasing particle concentrations assumes that the processor is set to reject areas with very low signals and that it can distinguish between the gray scale variations in background light and the particle images.

Effective seeding can be increased by increasing the interrogation spot size. With a larger interrogation spot there are more pairs per spot. When you increase the spot make sure that you are not violating the velocity gradient requirement of Rule 1. Decreasing the interrogation spot gives more velocity vectors with the same interrogation spot overlap. For high-resolution work and for investigating small flow structures, you should select small interrogation spots.

Rule 3: Maximum In-Plane Displacements Should Be Less than One-Fourth Interrogation Spot Size

This maximum displacement is a compromise between two parameters: Large displacements for the best percent of reading accuracy and small displacements to minimize lost pairs.

As explained before, the velocity is measured by finding the location of the particle displacement peak. The location of the peak is measured with centroid or curve fit to a fraction of a pixel. The accuracy of the PIV measurement is a percent of full scale, or a number of pixels. The peak location error is the same wherever it is located, near the center zero velocity peak or near the edge. With large displacements the peak location error is a smaller percent of reading than small displacement peaks. The absolute maximum displacement that gives the correct displacement is half the interrogation spot. If large displacements are used, the FFT aliases, the peak location, and the measured peak give the wrong velocity.

Lost pairs refers to particles that are inside the interrogation spot for only one laser pulse. In-plane motion causes particles to move across the spot border. Fast moving particles are more likely to lose a pair than the slow particles. Lost pairs creates a velocity bias towards slow velocity flow. The lost pair estimation is given in Rule 4.

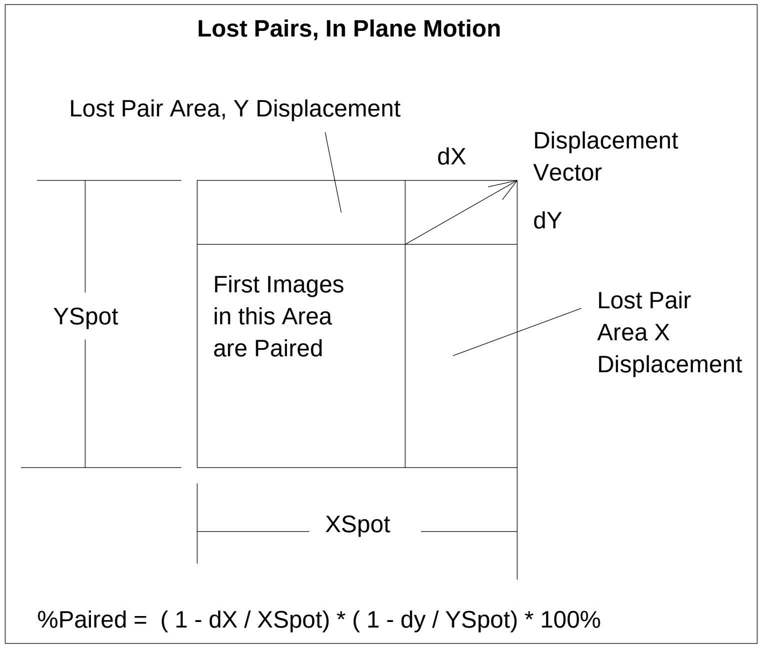

Figure 2-14
Lost Pairs

The compromise between these two objectives is ¼ spot displacement, to give good pairing and to use the accuracy of the system.

Rule 4: Maximum Out-of-Plane Displacement Should be Less Than One-Fourth of Lightsheet Thickness

This rule is established to keep the lost pairs (due to out-of-plane motion) to an acceptable level. In many experiments the lightsheet is about 1 mm thick and the interrogation spot is 1 mm× 1 mm. With this 1 mm cube measurement volume, the restrictions on out-of-plane displacement is no greater than the in-plane displacement. With both in-plane and out-of-plane displacements considered, the estimated percentage of particles with pairs in the interrogation spot is:

Percentage Paired = (1–dX/Xspot) * (1–dY/YSpot) * (1–dZ/Thick) * 100%

where

Percentage Paired = Percent of particles with a pair in the interrogation spot
dX = Particle image displacement in X direction
dY = Particle image displacement in Y direction
dZ = Particle image displacement is Z direction, out of plane motion
XSpot = Interrogation spot size in X direction
YSpot = Interrogation spot size in Y direction
Thick = Lightsheet thickness

When the maximum one-fourth interrogation spot and lightsheet thickness image displacement is used, an average of 42% of the particle images are paired. The seeding concentration must be increased for the lost pairs to get the same results. With one-fourth spot displacements in all three directions then the required seeding concentration is ten pairs per spot divided by the .42 paired, which is equal to 24 pairs per spot.

Rule 5: Minimum In Plane Displacement Should Be Two Particle Image Diameters

If the particle image displacement is less than two particle image diameters, the image would be one elliptical particle image instead of two particle images. The autocorrelation zero peak and displacement peaks must be separated to accurately measure the centroid of the displacement peak. If the peaks overlap, the centroid will include some of the zero peak and bias the measurement towards zero displacement.

Figures 2-15 and 2-16 show the autocorrelation at two points in a turbulent flow. The displacement at the first spot is about two particle-image diameters. In the autocorrelation, the displacement peak has separated from the central zero peak. This point gives a good velocity measurement.

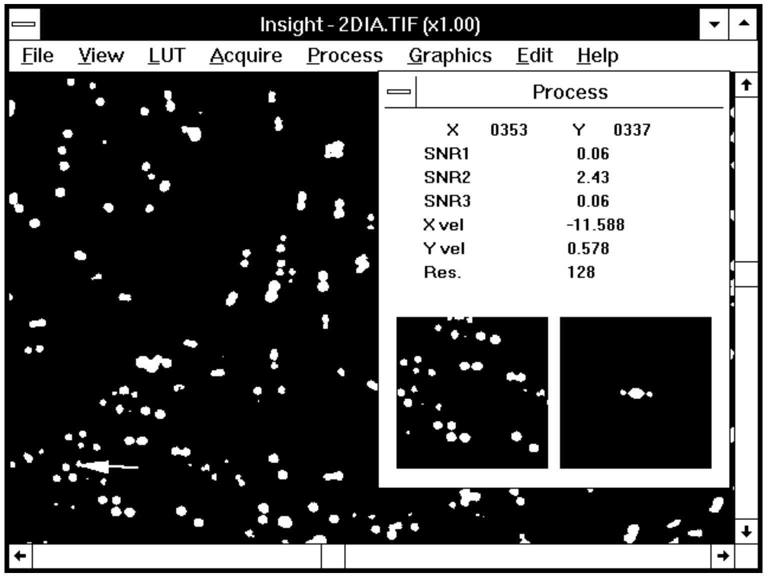

Figure 2-15
Autocorrelation at Two Points in a Turbulent Flow

Figure 2-16 shows an interrogation spot with about one particle-image diameter displacement. Here the displacement peak is connected to the central zero peak producing a single oval central peak. When the displacement peak blends into the zero peak, velocity measurement error occurs. In this case the measured velocity is the distance between particles and not the particle image displacement.

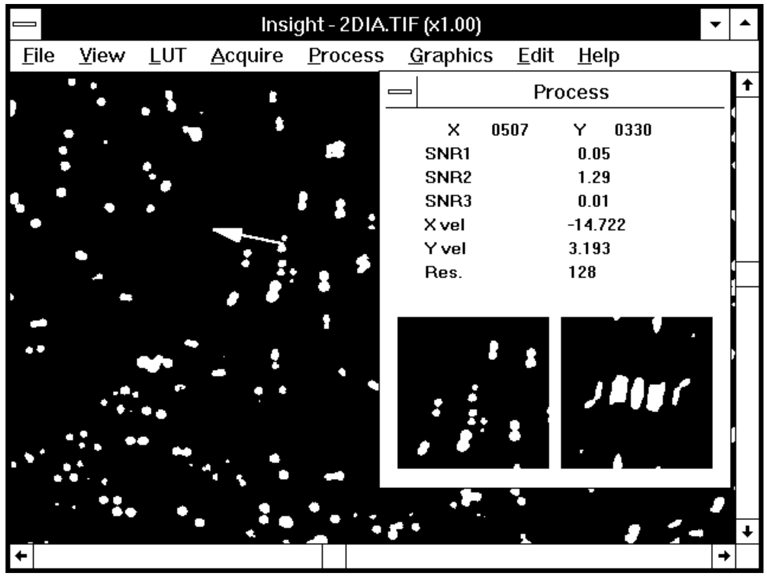

Figure 2-16
An Interrogation Spot with One Particle-Image Diameter Displacement

Rule 6: Exposure Should be Large Enough To Show Particles

There are many factors that determine the exposure. These are:

- Laser energy
- Lightsheet dimensions
- Camera Focal length number
- Photograph magnification
- Film Speed and resolution
- Particle size, and
- Particle material

The PIVCALC program uses all the above experimental parameters, except particle scattering parameters, to compute the lightsheet intensity and camera exposure.

Regarding particle scattering, particle size and material determine the scattered light power in the image of each particle. The particle scattering is in the Mie regime for most PIV applications. Mie scattering is complex and the scattered energy varies greatly with scattering direction, particle size, and particle index of refection. The complexity of Mie scattering makes it difficult to make general statements about how much exposure is required for a given experiment. In most applications through trial and error, you can find the correct exposure.

It is difficult to quantify the parameters that affect exposure and come up with a clear recommendation. Generally, you can use a 5-Watt Argon Ion laser for water flows that have low velocities. Use a Nd:YAG laser for higher velocity flows, especially air flows with micron -sized seed particles.

CHAPTER 3
Image Shifting

This chapter discusses image shifting and how it can be used to resolve directional ambiguity.

As mentioned in the Analysis chapter, the autocorrelation function produces two displacement peaks for each particle image pair. These are of equal strength and 180° apart. The forward peak is the distance from the first image to the second and the reverse peak is the distance from the second image to the first. When there are no flow reversals the correct peak is found by selecting the peak search half-plane: left, right, up, down. However, when there are flow reversals, no single search half plane is correct for the entire flow. Directional ambiguity is thus a problem with autocorrelation processing.

This problem is illustrated (Figure 3-1) in the analysis of a rotating solid body with an up flow direction. On the left half of the wheel, the arrows point to the right and on right, half the arrows point left. This is because when the displacement peak crosses the vertical line the reverse peak is chosen. In this example the image could be processed correctly by choosing a right flow direction, but if the lower half of the wheel was imaged a similar error would occur. Image shifting offers the solution to this problem.

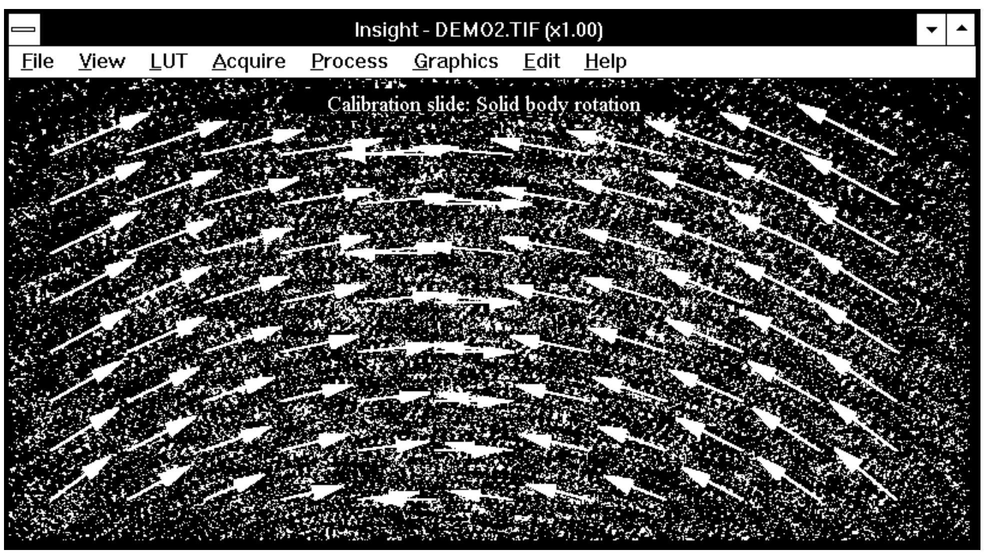

Figure 3-1
Flow Analysis of a Rotating Solid Body

How Image Shifting Is Used

Mirror image shifting uses a rotating mirror that is placed between the lightsheet and the camera. The mirror rotates in the time between laser pulses and adds the image shift velocity to the flow velocity. The short duration of the laser flash effectively freezes the mirror at two angular positions. The first pulse is taken with the mirror at one position and the second pulse after the mirror has rotated. An object in the flow with no velocity is recorded in two locations. The distance between the two images of a stationary object is the image shift distance. This displacement is added to the displacement due to the particle images movement. When the image shift displacement is larger than the largest flow reversal displacement, all correct displacement peaks may be found in a single search half-plane. The peak is at a distance equal to the velocity displacement plus the image shift displacement. By subtracting the image shift displacement from the measured peak location, you can find the displacement due to flow.

Selecting Image Shift Direction and Magnitude

When selecting image shift direction, keep in mind that the image shift is usually provided in one direction only. It is helpful to look at the range of displacements that can be measured with from the autocorrelation function. When the autocorrelation function is searched for displacement peaks only one half is searched. This is because the autocorrelation function is symmetrical and searching the other half plane gives a peak with negative displacement, directional ambiguity. Also, the edges of the autocorrelation are not searched because peaks too close to the edge are likely to go off the edge and aliasing may occur.

Using the autocorrelation target zone (Figure 3-2) is helpful in deciding the direction and magnitude of the image shift. For the best measurements, all of the particle image displacements should be inside the white autocorrelation target zone. There are four target zones possible one for each flow direction-up, down left, right. and the INSIGHT software measures the particle image displacements which is the vector sum of the displacement due to motion and image shift displacement. The image shift displacement is a translation of the particle displacement across the autocorrelation, as shown in Figure 3-3.

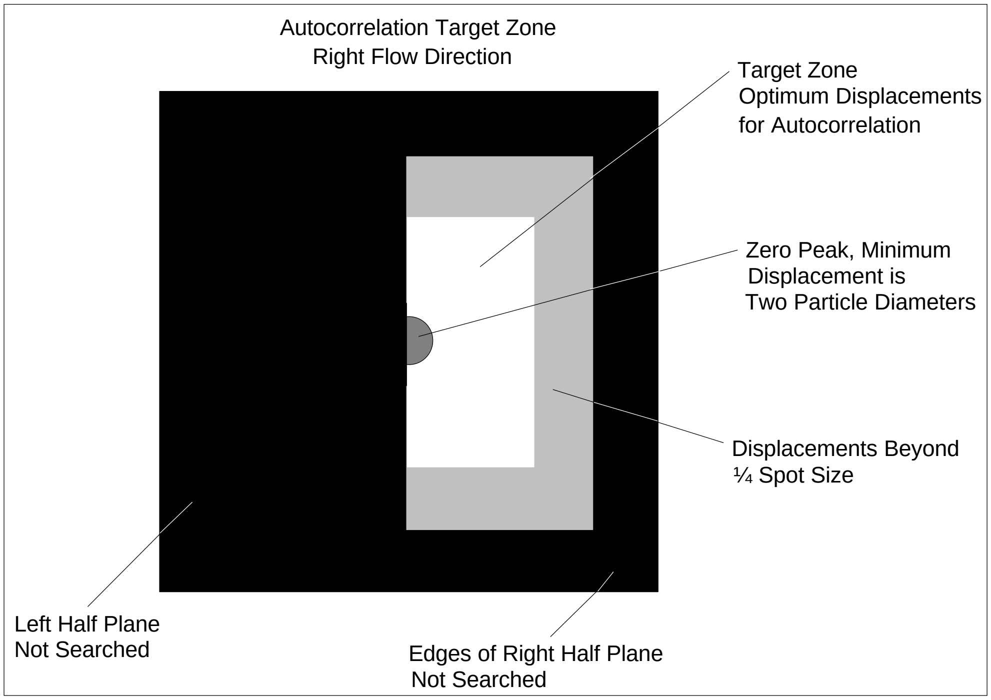

Figure 3-2
Autocorrelation Target Zone

To make successful measurements without directional ambiguity all of the particle image displacements must fall within the peak search area. In flows without reversals, image shifting is not necessary. However, when there are flow reversals some of the forward displacement peaks may be in the right half plane and some in the left. By using image shifting and selecting the correct interrogation spot size and dT, the range of particle image displacements can be made to fit into the peak search area.

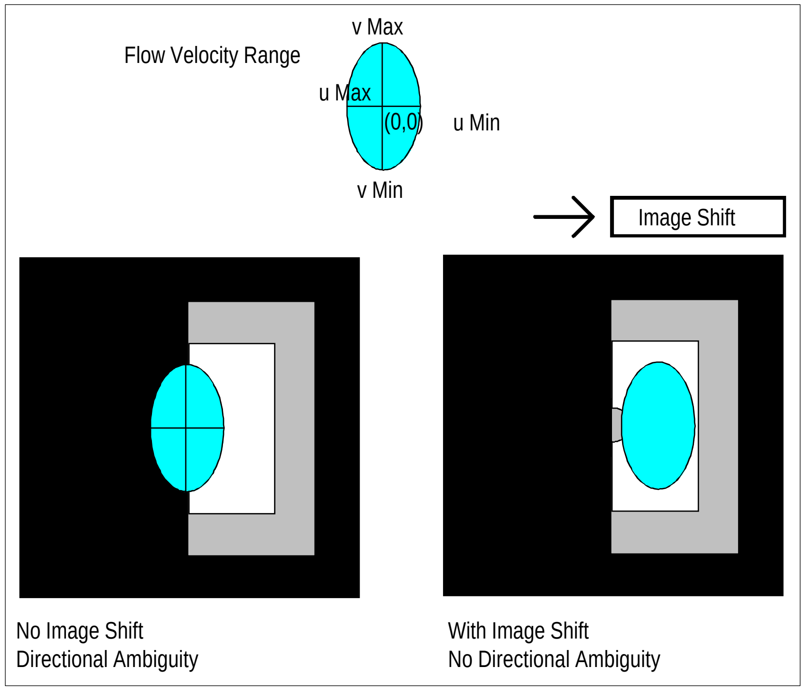

Figure 3-3
Displacement Range

The figure shows that after the image shifting, the displacement peaks are inside the selected search half plane. If the range of velocities is not symmetrical try to choose the shift direction that will best fill the search area.

CHAPTER 4
Post Processing

Post Processing refers to the analysis of the velocity vector field after the vectors have been extracted from the PIV image. Post processing consists of two basic functions—vector editing, and computing flow properties.

Vector editing is necessary because some wrong peaks may be chosen as the velocity peak. In vector fields with 1,000 points, ninety-nine percent correct vectors still gives 10 wrong vectors. During the image processing the signal-to-noise ratio at each spot must pass the threshold values to be considered a valid peak. Usually these thresholds are set to filter out most of the bad points, but if the thresholds are too high to filter out all the bad points, many good points are also eliminated.

In post processing, the vectors are compared against the neighboring vectors. Vectors that vary by more than the validation tolerance from the neighborhood average, are removed. This neighborhood check enforces continuity on the flow. Places that are left empty can be filled in by interpolating the neighboring vectors to get the best estimate of the velocity at that point.

After the vector has been validated and the missing points filled in, the properties of the flow can be computed. Measuring the flow properties like vorticity from the accurate vector field data is one the key reasons for performing PIV measurements. The post processing module computes vorticity, strain rates, and the velocity magnitude. These parameters can be displayed by color coding the arrows or by contour displays.

CHAPTER 5

Synchronization

As mentioned earlier, the Synchronizer provides the timing and sequencing of events to take a PIV photograph. Having all of the components working together is critical if you want to have each photograph capture a good PIV image. Each of the components requires some time to operate and only by sequencing them all properly you can get a good photograph.

There are however, a couple cases where sequencing the operation of the equipment by a Synchronizer is not really necessary. One such case in when you are using an argon ion laser that is operating in the continuous pulse mode. Here, synchronization is not necessary because since the laser is always pulsing, the camera can capture the image at any time. The number of pulses depends on the camera's shutter speed. For instance, if the laser is pulsing with 1 ms between pulses and the camera shutter is set for 1/30 sec, 33 ms exposure then camera records about 33 pulses. However, since image shifting cannot be used, determining flow direction is not possible.

The other case, though not very common where synchronization is not necessary is when you are measuring very low-speed flows using a video camera. For instance, if you are using the Model RS-170 system with 30 frames per second image capture rate, and the particle is not moving very much within the $\frac{1}{30}$ second, then the laser lightsheet does not have to be pulsed and by cross correlating two frames, maybe several camera frames apart, the velocities can be measured.

However, in cases where the laser is being double pulsed or image shifting is being used, you have to ensure that all the parts are working together. The following sections describe the timing sequence for all the PIV components.

Timing Requirements for PIV Components

The following discusses the timing requirements for each PIV component.

Lasers

The timing requirements for Nd:YAG lasers are different from the Argon-ion lasers.

Nd:YAG Lasers

Nd:YAG lasers require two signals to create a laser pulse; the first one triggers the flashlamp and the second signal opens the Q-Switch that pulses the laser. With single, double pulsed lasers, the second pulse is created by Q-Switching the other Marx bank in the laser. With dual, Nd:YAG laser systems, each laser receives a flashlamp and Q-Switch signal. The delay time from flashlamp to Q-Switch is usually 150 to 200 µs.

Argon-Ion Lasers

Argon-ion lasers are pulsed with the Model 620010 Beam Modulator. The Beam Modulator does not have any delay time between the triggering signal and the pulsing of the laser.

Cameras

The PIV system can operate with a variety of cameras. Cameras with external triggers and mechanical shutters such as 35mm and KODAK™ MEGAPLUS™ cameras are triggered by the Synchronizer to start the exposure. When the mechanical shutter is fully open the camera signals the Synchronizer camera shutter feedback to flash the laser.

Other externally-triggered cameras without a flash synchronization can also be used with the Synchronizer. The Synchronizer triggers the camera and then waits for the programmed Pulse Delay Time before firing the laser.

Free running Model RS-170 or CCIR CCD cameras can be used as the timing master for the Synchronizer. The analog video output from the 25 or 30 frame per second is passed through the Synchronizer. The Start of Frame signal is stripped out of the analog video and used to start an image capture sequence.

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Image Shifter

When image shifting is used the laser must be synchronized with the mirror position. For the Model 610050 in Single Sweep mode the mirror waits at the starting position for a trigger signal from the Synchronizer. It then starts its rotation. When the mirror gets to the trigger position it signals the Synchronizer to fire the laser.

Without Image Shifting

The sequence of events for capturing a series of frames with out image shifting is:

1. Synchronizer triggers the camera to start exposure
2. Camera starts exposure and triggers the Synchronizer that the shutter is open with the flash sync output.
3. Synchronizer sends fire signals to the laser for the first pulse.
4. Synchronizer waits the selected pulse separation time
5. Synchronizer sends signals for the second pulse of light.
6. The camera shutter closes at the end of the exposure time.
7. Camera winds the film to the next frame or outputs the video data.
8. Repeat the sequence for the number of frame to capture. The camera must be ready for the next exposure trigger before the frame rate time or an error will occur.

With Image Shifting

The sequence of events for capturing a series of frames with out image shifting is:

1. Synchronizer triggers the camera to start exposure
2. Camera starts exposure and triggers the Synchronizer that the shutter is open with the flash sync output.
3. Synchronizer triggers the mirror image shifter to start rotation
4. When mirror is in position shift electronics trigger Synchronizer.
5. Synchronizer sends fire signals to the laser for the first pulse.

6. Synchronizer waits the selected pulse separation time
7. Synchronizer sends signals for the second pulse of light.
8. The camera shutter closes at the end of the exposure time.
9. Camera winds the film to the next frame or outputs the video data.
10. Repeat the sequence for the number of frame to capture. The camera must be ready for the next exposure trigger before the frame rate time or an error will occur.

CHAPTER 6

Lasers, Lightsheet Optics, and Other Light Sources

This chapter discusses the different aspects of illuminating a flow.

In a PIV experiment, lasers are used to produce the high-energy pulsed lightsheet for taking PIV photographs of small particle images. TSI has developed the PIV system using three types of lasers: Argon Ion laser, Single, Double Pulsed Nd:YAG laser and Dual Nd:YAG laser.

Argon Ion Lasers

Argon Ion lasers can be used for PIV applications, particularly in applications involving low-velocity water flows.

The Argon Ion laser is a continuous wave (CW) laser with wavelengths of 476 nm to 514 nm, (violet to green). Water-cooled argon lasers have powers from 1 watt to 20 watts with 5 watt power most commonly used. Since the output beam is continuous, to take PIV images the beam is pulsed by using the LASERPULSE Beam Modulator. The Beam Modulator is attached to the LASERPULSE Synchronizer which controls the pulsing. The output beam from the Beam Modulator is the first-order diffracted beam from a Bragg cell. When the Synchronizer sends the Beam Modulator a 40 MHz drive signal, the beam is on and when the 40 MHz drive signal is off, the lightsheet is off. Using the Bragg cell allows you to program the pulse separation time and pulse duration and to synchronize the pulse with the mirror image shifter.

The pulse energy of an argon-ion system depends on the pulse separation time and the pulse duty cycle. These parameters determine the length of time the laser is on. The pulse energy is the laser power multiplied by the pulse duration. Pulse energy values of under 1 mJ are typical for argon systems. This limits the applications of argon imaging systems to water flows under 2.5 m/s.

Nd:YAG Lasers

Frequency doubled Q-Switched Nd:YAG lasers produce short duration (10 ns) high energy (50 mJ to 1000 mJ) pulses of light green (532 nm). The pulse energy is high enough to illuminate sub-micron particles in air. The pulse duration is short enough to freeze the motion of super-sonic flows. This make the Nd:YAG laser well suited for PIV applications.

The Nd:YAG laser uses a flashlamp to produce the energy that is converted into the laser beam. The flashlamp can fire at about 10 Hz. To get the required short times between pulses either two Nd:YAG lasers or a Double Pulsed Nd:YAG laser can be used.

Two Nd: YAG Lasers

With two laser configuration, one laser is fired then the other. This allows any pulse separation from very short to long with the full power of each laser. The beams from the two lasers are combined into a collinear beam. Several Nd:YAG laser manufactures make PIV laser systems with two laser cavities and beam combination optics built into a single box. The TSI Model 610010 Beam Combination Optics can be used to combine the laser beams from two Continuum Surelite Nd:YAG lasers.

Double Pulsed Nd:YAG

An alternative to using two Nd:YAG lasers is the double pulsed Nd:YAG laser. The double pulsed Nd:YAG laser fires the Q-Switch twice during a single flashlamp discharge. The double pulsed laser has the advantage of being easier to align than a two laser system. The Q-Switch delay time must be set with the time between pulses (ΔT) to get two equal energy pulses. A double pulsed laser can produce two pulses with about ⅓ the single pulse energy of the laser single pulsed. The pulse energy is a function of the time between pulses with the energy declining with increase time between pulses. The maximum time between pulses with a double pulsed laser is about 200 µs. This makes the double pulsed laser appropriate for flows with velocities of 1 m/s and higher.

Other Light Sources

Lasers are used for most PIV systems because they can create collimated beams of high intensity light. The beam collimation allows the laser beam to form a well-defined lightsheet. Other light sources such as strobe lights or 35mm camera flash lamps could be used if they produce a pulse of light that is bright enough to expose the particles and if they can be controlled to form the lightsheet.

Strobe lights and 35mm camera flash lamps can be used in flows with large particles since large particles may not need much illumination and these light sources may be bright enough. However, since these light sources cannot create a thin lightsheet, they can be used only where thicker areas are to be illuminated. These light sources can also be used in experiments where large particles are part of the flow being studied and tracer particles are not being added.

Other Types of Lasers

This section briefly describes other kinds of lasers that can be used in PIV applications.

Ruby

Ruby lasers are available with high pulse energies of around 1J per pulse. One problem with this type of laser is that photographic film is not very sensitive to the red 694 nm wavelength. Film may have as much as ten times more sensitivity to the green, 532 nm wavelength of the Nd:YAG compared to the ruby light. However, the lack of film sensitivity is not be a factor if you use a CCD video camera. The pulse repetition rate is about 1 pulse per minute. The ruby laser is double pulsed for PIV.

Copper Vapor

Copper vapor lasers pulse at rates of about 20 kHz. The pulse energy is about 5 mJ per pulse with green light.

Lightsheet Optics

The flow in a PIV experiment is illuminated with a pulsed laser lightsheet. Typically, a collimated laser beam is transmitted through a cylindrical lens to diverge the beam in the height direction and a spherical lens is used to control the thickness of the lightsheet. The camera usually is focused near the lightsheet waist, at the focal length of the spherical lens.

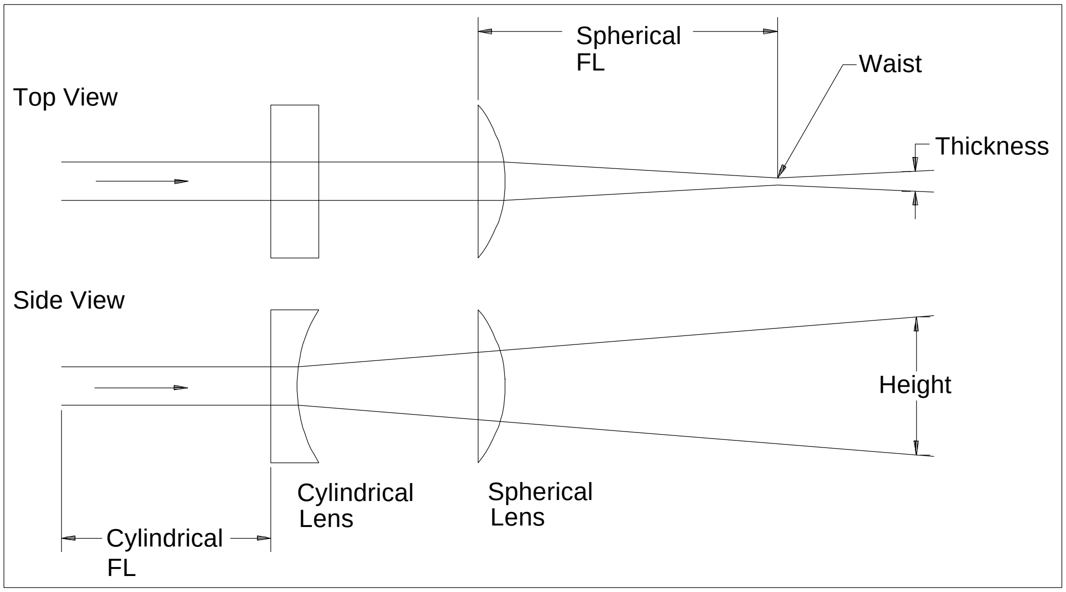

Figure 6-1
Lightsheet Optics

The cylindrical lens has a negative focal length and diverges the beam. Small focal lengths diverge the lightsheet faster than longer focal lengths. The focal length of the spherical lens is much longer than the cylindrical lens making the selection of the spherical and cylindrical lenses independent of each other. The spherical lens is selected to provide the proper-sized lightsheet thickness where the photograph will be taken. The cylindrical lens is selected to give the proper lightsheet height at that point.

When selecting the lightsheet dimensions keep in mind that the larger the cross sectional area, the lower is the light intensity and to expose the particles, the light intensity must be high enough. The photograph can be taken anywhere along the lightsheet, but usually the best place is at the focal distance of the spherical lens-near the lightsheet thickness waist, where the lightsheet is the thinnest.

When selecting the lightsheet dimensions you must also consider the variation in the beam intensity over the photograph area. The typical problem comes when, to get the thinnest lightsheet, a short focal length spherical lens is used. Since the thickness divergence is larger for short focal-length lenses, there may be a large difference in intensity due to the lightsheet thickness.

CHAPTER 7

Image Capture and Digitization

This chapter discusses various aspects of image capturing.

The image of the particle in the flow may be recorded with either a photographic film camera or with 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 captured on film and developed. The negatives are digitized and the digital image is then analyzed by the computer. With a video camera system, the CCD camera converts light energy into electrical energy and sends an electrical image to the Frame Grabber in the computer. The electrical signal can be digitized either by the Frame Grabber or in the camera. The Frame Grabber in the computer reads the camera image in and passes the information to the computer system for processing. The processing for the film and video camera images is same. The advantage of using film is that the image is recorded with higher resolution allowing the maximum number of velocity vectors with the highest accuracy while the advantage of using CCD image capture is that the vector field is available on-line. In the future the resolution issue may not be a factor when CCD cameras with resolution greater than 35mm film cameras become less expensive.

RS-170 and CCIR CCD Cameras

RS-170 is the black and white TV standard in countries with 60 Hz electricity. CCIR is the black and white TV standard used in countries with 50 Hz electricity. The CCD cameras are about the same except for the timing and resolution.

Both RS-170 and CCIR cameras have interlaced output. A video frame is composed of two fields-odd and even. First the even field is read out then the odd field. The TV standards define the readout of the image how the camera captures the image, varies from camera to camera. A few cameras expose all of the CCD pixels simultaneously and then read back the image so the frame digitized by the Frame Grabber does not show any interlacing affects. Most CCD cameras expose the even lines and read them out then expose the odd lines and read them out, or integrate the image from the time each pixel is read until the next time it is read. This can create a problem for capturing PIV images where we need to image small, moving particles. Interlacing problems can be seen in the INSIGHT software when zoomed in, each pixel is visible as a square box. If the image is interlaced, a particle shows up as a few bright pixels above a row of black pixels above some bright pixels above a row of black pixels. The bright lines are those exposed while a particle was present and illuminated by the lightsheet, and the dark lines while no particle was there or when the lightsheet was off.

With the RS-170 and CCIR cameras, the image is digitized according to the resolution specified by the Frame Grabber, not by the number of pixels that the camera CCD has. The digitized resolution of the RS-170 signal is 640×480 pixels and the CCIR resolution is 758×572. These resolutions give square pixels for standard 4:3 aspect ratio CCD sensors.

High Resolution CCD Camera

Most high resolution and scientific CCD cameras do not use interlacing. All of the pixels are exposed at the same time. This progressive scanning removes some of the difficulty in using RS-170 and CCIR CCD cameras. The Model Frame Grabber used can be connected to a wide variety of CCD cameras. A special software driver is required for each camera. At this time KODAK MEGAPLUS series of camera including the MEGAPLUS 1.4, 4.2 and XHF are supported by the INSIGHT software.

Large and Medium Format Film Cameras

Large and medium format film offer greater image capture resolution than 35mm film. The film has a constant resolution per mm so that using larger film areas allows a large format camera to capture a large field of view with the same resolution as a 35mm camera. Medium format camera uses roll film like regular 35mm cameras. A standard format camera uses film 6 cm high with common format sizes of 4.5 cm × 6 cm, 6 cm × 6 cm, and 6 cm × 9 cm. A large format camera such as the 4 in. × 5 in. format, uses sheet film.

The TSI FLOWPORTRAIT Film Analysis system was designed to work with large and medium format film. The FLOWPORTRAIT can be operated with PIVINTER the TSI PIV analysis program for DOS only.

Table 7-1 shows a comparison of the cameras supported by INSIGHT for Windows software.

Table 7-1
Specifications for Cameras Supported by the INSIGHT Software

Image Sensor	Horizontal Sensor Size (mm)	Vertical Sensor Size (mm)	Horizontal number of pixels	Vertical number of pixels	Pixel size Square µm
½" RS-170	6.45	4.8	640	480	10.0
½" CCIR	6.45	4.8	768	572	8.4
⅔" CCD	8.8	6.6	640	480	13.8
⅔" CCD	8.8	6.6	768	572	11.5
MEGAPLUS 1.4	8.98	7.04	1317	1035	6.8
MEGAPLUS 4.2	18.4	18.4	2025	2030	9.0
MEGAPLUS XHF	9.1	9.2	1008	1018	9.0
35mm Slide Scanner	36	24	2592 maximum	3888 maximum	9.4
4x5" Film	125	100			

35mm Film Cameras

35mm film cameras offer a good compromise because they are easy to use, are low cost and provide high resolution images.
The 35mm film is processed and the negatives mounted in slide mounts. These negatives are then digitized using a 35mm slide scanner with up to 2700 pixels per inch, 106 pixels per mm.

Lens Aperture

When taking PIV photographs and setting the camera , the lens aperture has an effect on three parameters:

- ❑ Diffraction limited spot size
- ❑ Depth of field, and
- ❑ Illumination.

Since PIV photography is done using high magnification of small particle images, all of these parameters assume more importance than in typical photography.

Diffraction Limited Spot Size

The size of the particle image recorded on film or the CCD sensor is a combination of the image size with image magnification and the diffraction limited spot size.

Note: *This section assumes that a high quality lens is being used as designed.*

The image size of a sub-micron particle is determined by the diffraction limited spot size of the lens aperture. The formula for the spot diameter to the first dark ring is:

$$\text{Diff Spot} = 2.44 * \lambda * F/\#$$

where:

Diff Spot = Diffraction limited spot size diameter to first dark ring
λ = Laser Wavelength
F/# = Lens Aperture, (aperture diameter focal length)

Table 7-2
Diffraction Limited Spot Diameter Vs. F/#, 532 nm

F/#	Spot Diameter µm
2.8	3.6
4	5.2
5.6	7.3
8	10.4
11	14.3
16	20.8
22	28.6
32	41.5

The actual image size is a combination of the diffraction limited spot size, plus the blur due to the aberrations in the lens at the selected aperture, plus the resolution of the recording media. Keep in mind that good quality 35mm camera lenses record about 25 µm spots on KODAK Technical Panchromatic film and that you need a 50 µm-particle image displacement for image separation.

Depth of Field

Depth of field is the range of distances through which objects may extend yet still remain well focused and form an acceptable image. In PIV imaging since we need to capture the images of very small particles, these particles need to be well focused to produce good results. High magnification and large lens apertures both decrease the depth of field, but are required to get the needed image in most cases.

PIV images must be captured with as large an aperture as possible that can give an adequate depth of field. For instance, for a lens with 105 mm focal length and set for 1:1 magnification the depth of field is less than 1 mm. If the lightsheet is 1 mm thick this leaves no room for any misalignment in the camera and to increase the depth of field the lens aperture must be reduced.

The depth of field, as we mentioned before, is the distance from the object closest to the camera to the object furthest from the camera that is "well" focused. Defining well focused is somewhat arbitrary. To compute the depth of field the acceptable blur is defined as the maximum size a point object is focused to and still "in focus." For film the acceptable blur is usually between 10 µm and 40 µm. For CCD cameras the blur would be a function of the pixel size.

The depth of field formula is:

$$DOF = 2 * D^2 * \beta / A$$

where

DOF = Depth of field
D = Object distance
A = Lens aperture (mm) (fl/F#)
B = Acceptable blur size on film or CCD
β = Angular blur (B/Img D)
ImgD = Image distance

This formula shows that the depth of field is inversely proportional to the lens aperture and proportional to the f-stop number. Table 7-3 shows the depth of field for a Nikon 60 mm micro Nikor lens at a range of lens apertures and magnifications.

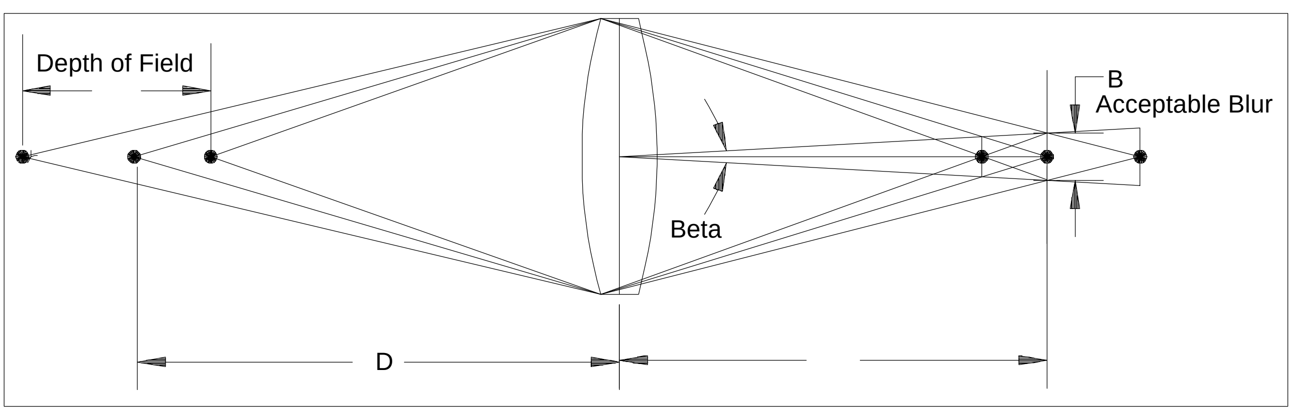

Figure 7-1
Depth of Field

Table 7-3
Depth of Field Vs Magnification and F# for 60 mm Micro Nikkor Camera*

Focus Distance mm	1/Mag	F/4	F/5.6	F/8	F/11	F/16	F/22	F/32
219	1	1	1	1	1	1	1	1
220	1.1	1	1	1	1	1	1	1
250	1.9	1	1	1	1	1	3	3
300	2.8	1	2	3	4	5	8	11
350	3.7	3	4	5	8	11	16	21
400	4.6	5	7	9	13	18	26	37
500	6.3	9	13	18	26	37	53	65
700	9.7	23	32	47	65	93	132	189

Illumination

The amount of light scattered off particles that will expose the film or the CCD sensor is determined by the lens aperture for a given photograph magnification and lens. The collection area is proportional to

$$1/(F/\#)^2$$

For macro photography, the amount of light collected by the lens is indicated by the f-stop (F#) setting on the lens. This setting is for objects at infinity distance. In most applications, you don't know the required exposure well enough to determine the difference between the effective and infinity f-stop number and may need trial exposures to find the minimum acceptable exposure. To correct for the reduced light collected at small object distances, you can use the effective f-stop number. Use the following equation to calculate the effective f-stop number.

$$Fe = (1 + Mag) * F$$

where

Fe = Effective F/#
F = F/# at infinity object distance
Mag = Image Magnification

*Reproduced from the Micro Nikkor Specification Sheet

CHAPTER 8
Seeding

This chapter discusses the importance of seeding.

To measure the velocity of a fluid without disturbing it, you need to use optical techniques such as PIV. However, air and water are transparent fluids that need tracer particles added to them to reveal the fluid motion.

The tracer particle selection criteria are:

- Particles must be small enough to follow the flow.
- Particles must scatter enough light to be detected.
- Particle concentration must be high enough to give reliable velocity measurements.

Since the two criteria, of having small particles to follow the flow and large particles to scatter light conflict, some compromise must be made.

Common choices for seeding air flows are olive oil droplets with 1 to 3 micron diameters, and fog with 1 to 10 micron diameters. Water flows are typically slower flows and since water is more dense, larger particles may be used. Polycrystalline particles (30 micron) and Pine Pollen (50 micron) have been used with some success. Phosphorescent particles are sometimes used because they radiate at a different wavelength than they absorb allowing background light to be filtered, making the particles more visible. Many other seed particles have been used for PIV measurements. The best choice of seed particle depends on the conditions of the experiment.

As mentioned in the preceding sections, for autocorrelation processing 10 particle pairs per interrogation spot are desired to give very high reliable data. This is a high seeding concentration for most experiments.

CHAPTER 9

Optimizing the Experiment

This chapter takes a quick look at how to optimize an experiment.

To optimize a PIV experiment you need to know the velocity range of the flow. However, in practice PIV measurements are made with not many known variables and using an iterative process to determine the velocity range. First, the experiment is set up so that some measurements are possible. Then the lightsheet parameters and camera magnification values are adjusted so that the particle images are exposed and then the time between pulses is selected so that some particle pairs are visible and then some measurements are made.

Next, image shifting is added. To begin with, you may use a large amount of image shift and a short time between pulses (dT) to find the actual velocity range. Once you know the velocity range the parameters can be optimized according to the rules of thumb. With video measurements this process goes much faster than with film because you get immediate results. In many cases it is best to make the measurements first with video and when the measurements are being made switch to film for the final results.