

Professional Analyst, Flight Path Shadow Graph Edition

User Manual

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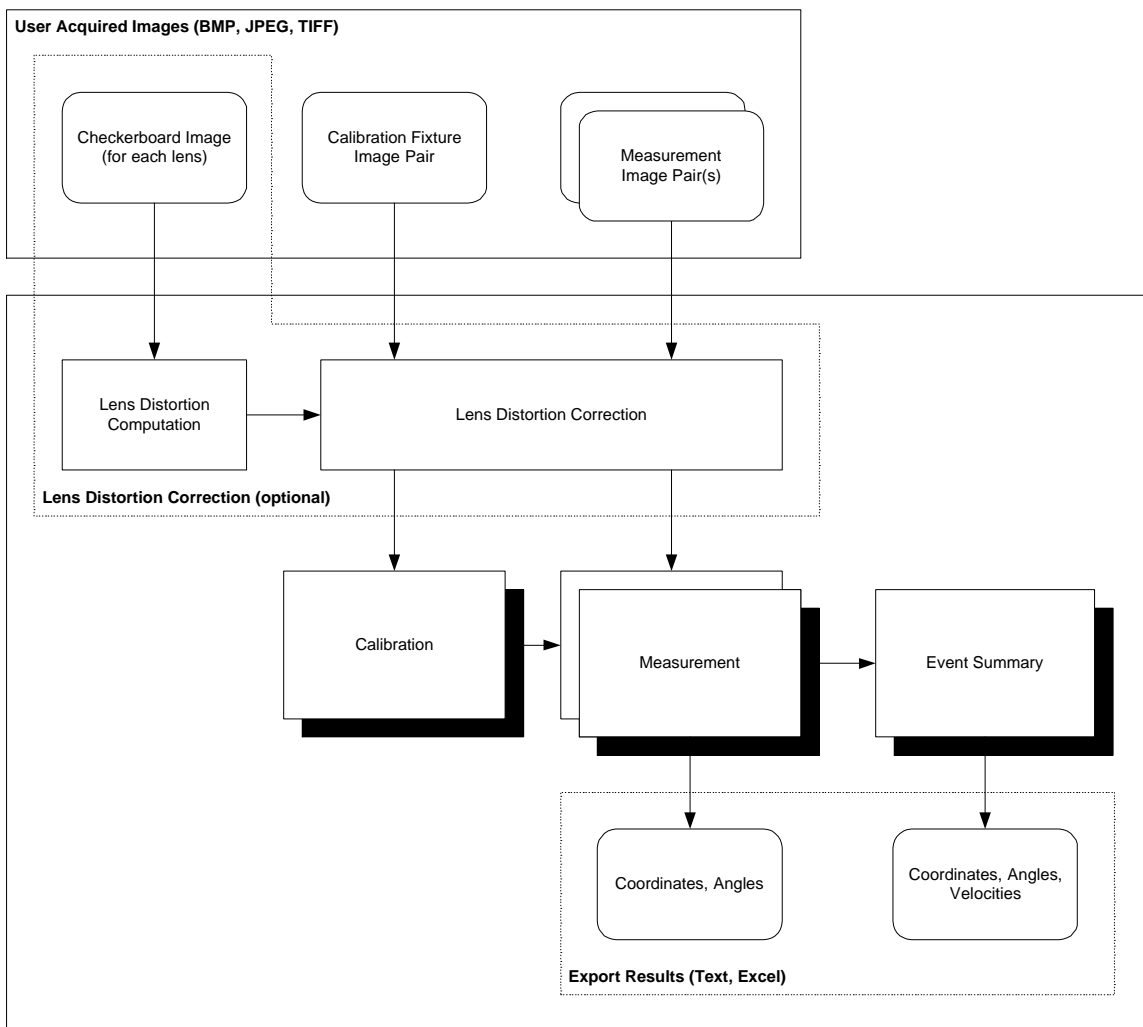
Overview

The Professional Analyst, Flight Path Shadow Graph Edition software can provide accurate 3-D measurements of points and angles using simultaneously acquired images from a pair of cameras. This document describes the application interface, the calibration and measurement procedure, and the data export capabilities of the software.

For more information on the technical background of this software and a discussion of the accuracy and sources of error, please refer to the *Professional Analyst, Flight Path Shadow Graph Edition, Brief Technical Overview* document.

Application

The application has three main document types: Calibration, Measurement, and Event Summary. The Calibration document uses images of a calibration fixture taken by a pair of cameras and computes a calibration for each camera. The resulting calibration pair is used by the Measurement document to do precise measurements on a pair of images from an event. A sequence of Measurement documents is used to construct an Event Summary document that compares the results from each of the Measurement documents to produce a summary of the event. Each of these document types will be explained in more detail in the later sections.



In addition to the Calibration and Measurement images, an optional Lens Distortion Correction tool is provided for removing radial lens distortion from images. If distortion is present in your lenses, then images of a checkerboard target should be taken using each

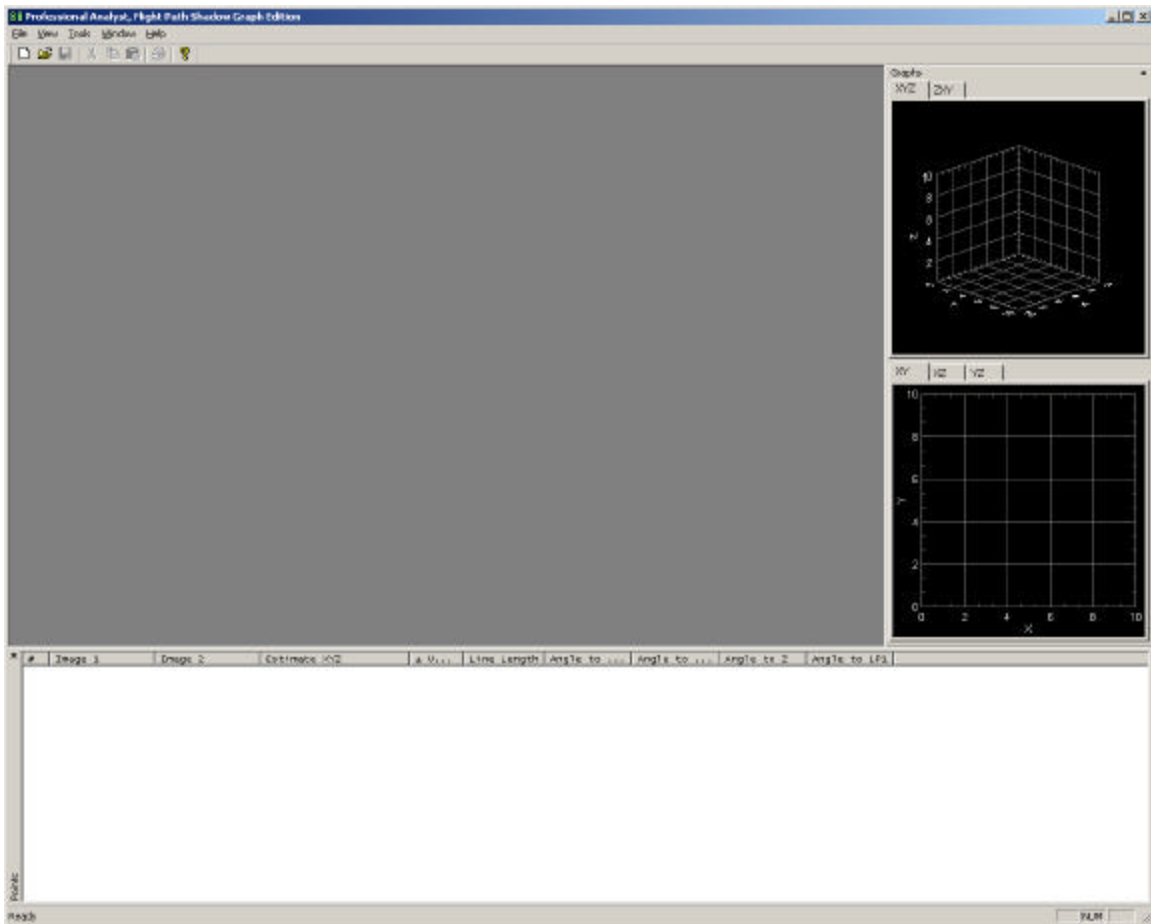
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lens and the resulting lens distortion correction computed. See the Appendix for more details on Lens Distortion Correction.

Application Windows

The main application window has three primary sections: the main desktop area where documents appear, the Graph windows, typically docked on the right, and the Points List, typically docked on the bottom.



The Graphs dialog contains a set of 3D graphs and a set of 2D graphs. The 3D graph can be rotated by clicking and dragging the left mouse button. To pan the 3D and 2D graphs, hold the **Shift** key while clicking and dragging the left mouse button. To zoom the 3D and 2D graphs, hold the **Alt** key while clicking and dragging the left mouse button. If your mouse is equipped with a wheel button, the wheel can also be used to zoom the graph windows. Additional options are available in the context menu by clicking the right mouse button over the graphs.

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
The Points List provides information about all selected points for the Calibration and Measurement Documents and it provides information about the Measurement Line Pairs for the Event Summary Documents.

Document windows typically have controls on the right and images on the left. The images can be panned and zoomed using the same controls as the graphs. **Shift** + left mouse button for panning, and **Alt** + left mouse button for zooming. The mouse wheel also controls zooming. When using the mouse wheel to zoom, the image will zoom in/out on the currently selected point. This allows the user to very quickly zoom in and out on a particular feature. Click where you would like to zoom, then use the mouse wheel. The application will automatically center the current selected point.

Document windows will have a toolbar across the top of each window. The document toolbar typically contains some or all of the following controls. Many of the items below have separate settings for the top and bottom views. Click on the view that you wish to change the settings for and then click on the desired toolbar button. A green box in the upper right corner of each view indicates which view is currently active.

 Toggle Side Panel

Switch the side panel between a small toolbar version and the full size version.

 Image Settings


Adjust image settings such as brightness, contrast, gamma, etc.. This control has separate settings for the top and bottom views.

 Locate Point Settings

Adjust parameters for the automatic location of points for Calibration Documents. This feature will be discussed later in this document. This control has separate settings for the top and bottom views.

 Define World Reference Frame

Define the transformation to the world reference frame for Calibration Documents. This feature will be discussed later in this document.

 Define Reference Markers

Define location of reference markers. These markers are used to perform approximate compensation for small camera motions.

 Enable Midpoint Finder

Enable the midpoint finder tool. This tool allows you to click and drag two endpoints of a line in the image. The program will draw a marker that indicates the center of the line. The program will also draw a circle through the two endpoints and centered on the center of the line. To hide the midpoint finder tool, click anywhere in the image, but do not drag.

 Enable Reticle

Show or hide the reticle (cross-hairs) in the view. This control has separate settings for the top and bottom views.

 Enable Rulers

Show or hide rulers along the edges of the view. This control has separate settings for the top and bottom views.

 Show Point Labels

Show point labels (numbers) next to each point in the view. This control has separate settings for the top and bottom views.

 Flip Vertical

Flip the image vertically. This control has separate settings for the top and bottom views.

 Flip Horizontal

Flip the image horizontally. This control has separate settings for the top and bottom views.

 View Actual Size


Resize the displayed image so that it is shown at the actual resolution of the image. This control has separate settings for the top and bottom view.

 Fit in Window

Resize the displayed image so that the complete image is shown in the view. This control has separate settings for the top and bottom view.

 Pan Mode

Set the mouse mode to pan mode so that all left click and drag mouse operations will pan the image. This control has separate settings for the top and bottom views.

 Zoom Mode

Set the mouse mode to zoom mode so that all left click and drag mouse operations will zoom the image. This control has separate settings for the top and bottom views.

Typical Test Scenario

A typical test scenario has multiple steps. The first step is camera calibration. During calibration, you prepare the cameras to be able to perform precise measurements by determining properties of the cameras. This is typically done by capturing images of a calibration fixture and then analyzing these images to produce a calibration file. The next step is to run the actual projectile tests to conduct measurements. During measurement, images of the projectile are captured by the calibrated cameras. These measurement images, combined with the calibration from the cameras, are then used to produce 3D measurements of points on the projectile.

The calibration step only needs to be performed as necessary. If none of the cameras have been moved or changed since the last calibration, then the previous calibration should be satisfactory. The uncertainty in the measurements can be used to determine if a

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new calibration is required. If the uncertainty exceeds a desired limit, then a new calibration must be performed.

If there are multiple camera stations located along the firing path, then calibration and measurement must be performed for each station. The measurements from each of the camera stations are then combined to produce an event summary. An event summary is a collection of measurements from multiple camera stations for a single firing event. The event summary computes additional information by comparing the results from each of the measurements, such as velocity and angular velocity.

Calibration

In order to perform accurate measurements using the camera system, a calibration must first be performed. This calibration computes necessary information about the properties and location of each camera. If any of the cameras are moved or changed after calibration, then a new calibration must be performed.

Calibration is performed by capturing images of special *calibration fixtures* that have fiducial markers at precisely known locations. These images can then be analyzed and the properties of the camera systems can be determined.

If your test setup has multiple stations, a world reference frame must be defined in order to compare results from one station to another. Multiple techniques for defining a world reference frame are discussed in a later section of this document.

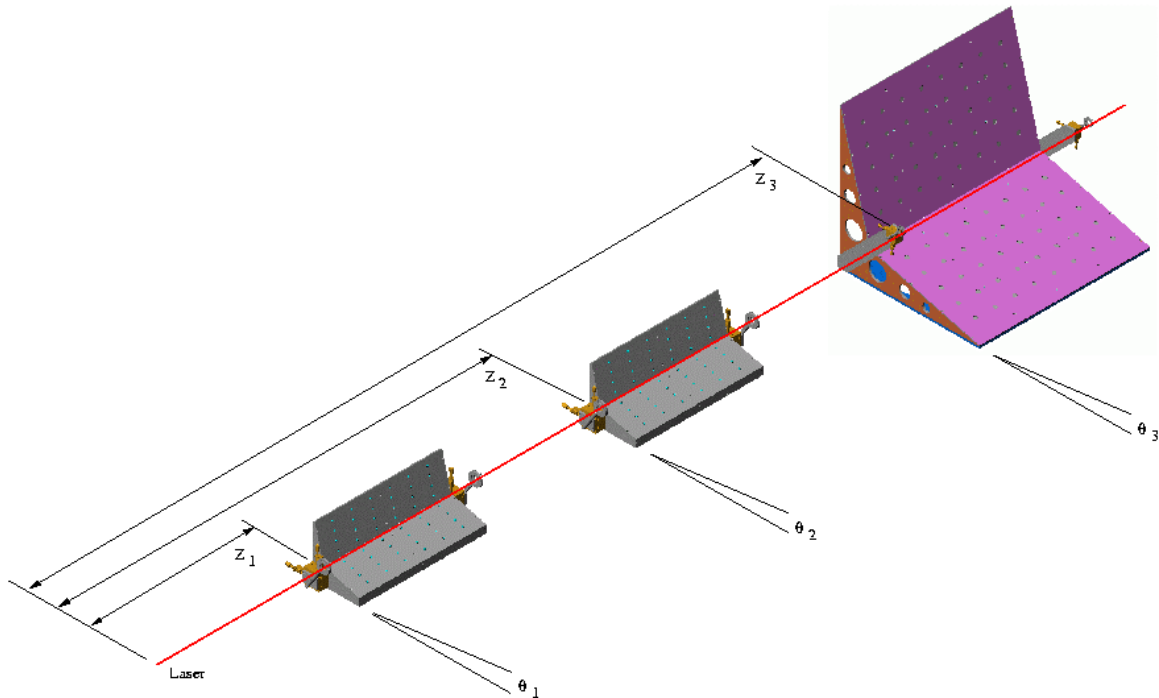
The recommended technique is to ensure alignment of multiple calibration fixtures using adjustable irises. A typical calibration procedure for an event with multiple stations:

1. An optical alignment device (e.g. a laser or theodolite) should be used to ensure alignment of each calibration fixture relative to the firing path. Place the alignment device next to the gun barrel and shine it down the expected path of the projectile.
2. Place the calibration fixture in the center of the field of view of each camera, roughly aligned to the path of the projectile (within $\pm 6-7$ mm). The entire calibration fixture (including irises) should be completely visible in both camera views.
3. Adjust the position of the irises on the ends of the calibration fixture using the fine adjustment screws so that the laser passes through the exact center of both irises when they are closed. If the alignment device cannot be centered on the irises, then shift the whole calibration fixture so that the alignment device can be centered in the irises.
4. Measure the distance from the gun barrel to the first iris on each calibration fixture. This will be the *Z Coordinate of the First Point* for each fixture. This value is used to help define the world reference frame.

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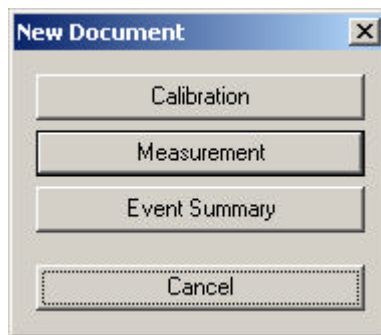
5. Measure the angle of each calibration fixture in the direction perpendicular to the path of the projectile. This will be the *Base Angle* for each fixture. This value is used to help define the world reference frame.
6. Capture images of each calibration fixture from each camera.

An example of the alignment of multiple fixture designs using a laser is shown below. Your fixtures may not appear like the ones shown below, however, they must have some common elements, such as the adjustable irises that are visible by both cameras in each station.



The resulting images are then used to create *Calibration Documents* for each camera pair.

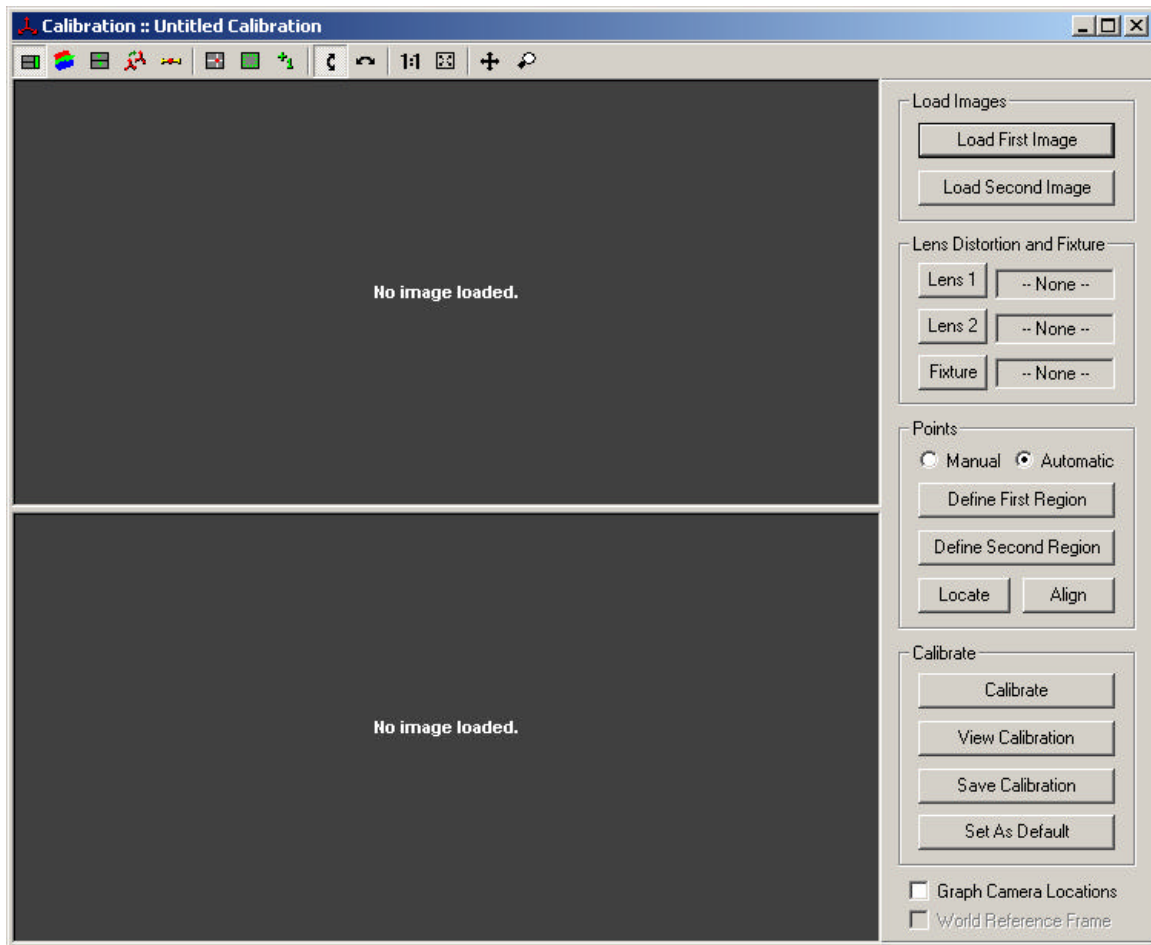
A Calibration Document is created by selecting **File** → **New**.



Then select **Calibration**. An empty calibration document will appear.

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All controls are located on the top toolbar and on the left panel of the Calibration Document window. The toolbar controls were described earlier in this document.

The standard procedure for calibrating cameras is as follows:

1. Load the first calibration image by clicking on the **Load First Image** button and select the correct image file (BMP, TIFF, or JPEG). This image should be from the left camera when looking down the flight path towards the target.
2. Load the second calibration image by clicking on the **Load Second Image** button and select the correct image file. This image should be from the right camera when looking down the flight path towards the target.
3. If the lenses that are being used require distortion correction, load the appropriate lens coefficient files using the **Lens 1** button or the **Lens 2** button for the first and second images respectively. The lens coefficient files (*.lens) should be generated using the Lens Distortion Correction Tool described in the Appendix.
4. Load the fixture information file for the specific calibration fixture that is being used. The fixture file (*.fixt) should have been generated from theodolite measurements. The fixture file contains information about the location of the

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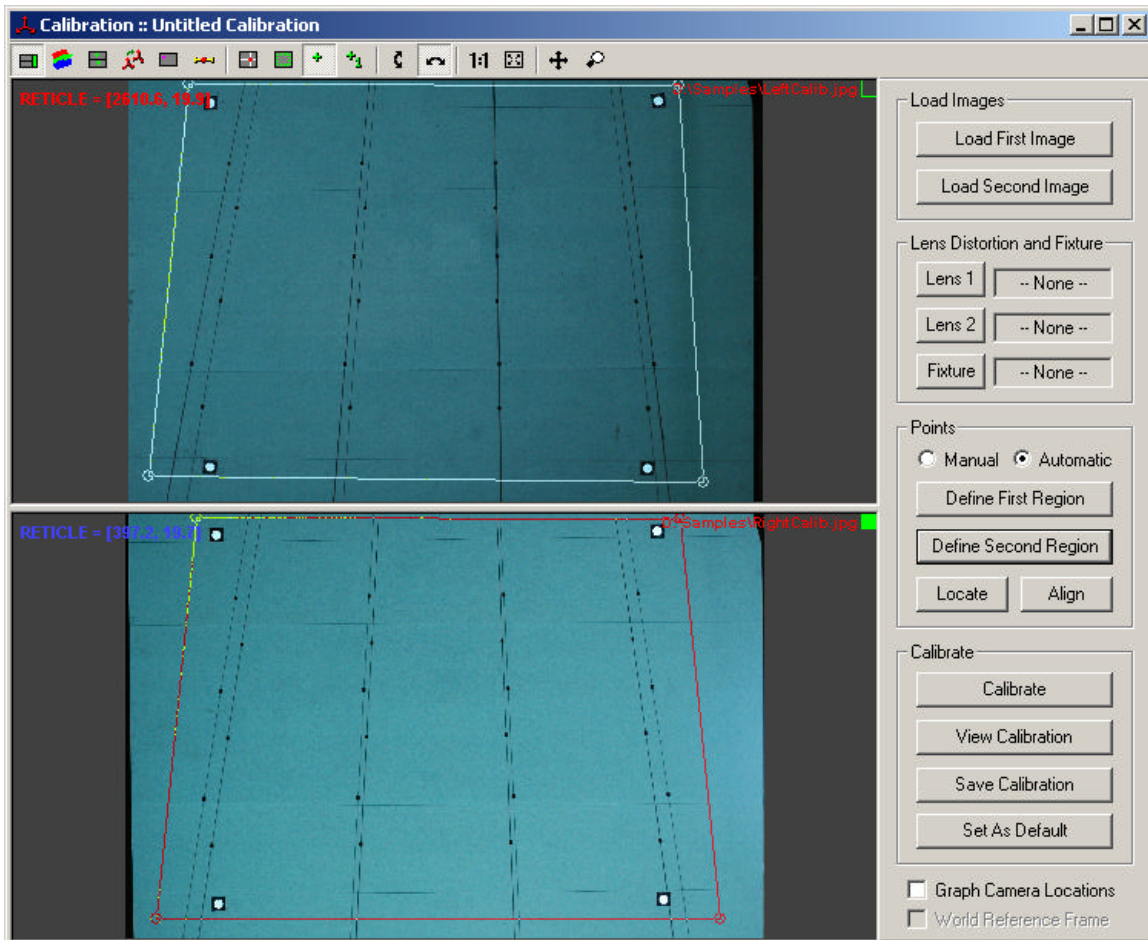
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fixture points and the default units of measure. The method for generating a fixture file from theodolite measurements is discussed in the next section.

5. Now the fixture points need to be identified in the top and bottom images. There are multiple options for locating the fixture points. It can be done manually or automatically.

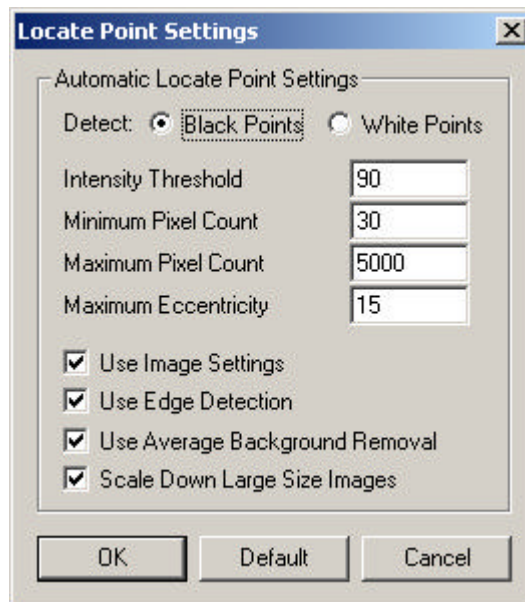
To locate points automatically:

- Select **Automatic** in the Points section of the right panel.
- Define a region around all the fixture points in the top image by clicking on **Define First Region**. Then click the left mouse button at the four corners of the polygon containing all the fixture points. Make sure that you include all fixture points. If you make a mistake, click on **Define First Region** again and redraw the region.
- Define a region around all the fixture points in the bottom image by clicking on **Define Second Region**. Then click the left mouse button at the four corners of the polygon containing all the fixture points in the bottom image.
- Click on **Locate** to automatically locate fixture points in both images.



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- If the automatic location of points fails, there are parameters that can be adjusted to change the behavior of the automatic location scheme.
 - i. Click on the **Locate Point Settings** icon on the toolbar, or right-click on the top or bottom image and select **Locate Point Settings** from the drop down menu.

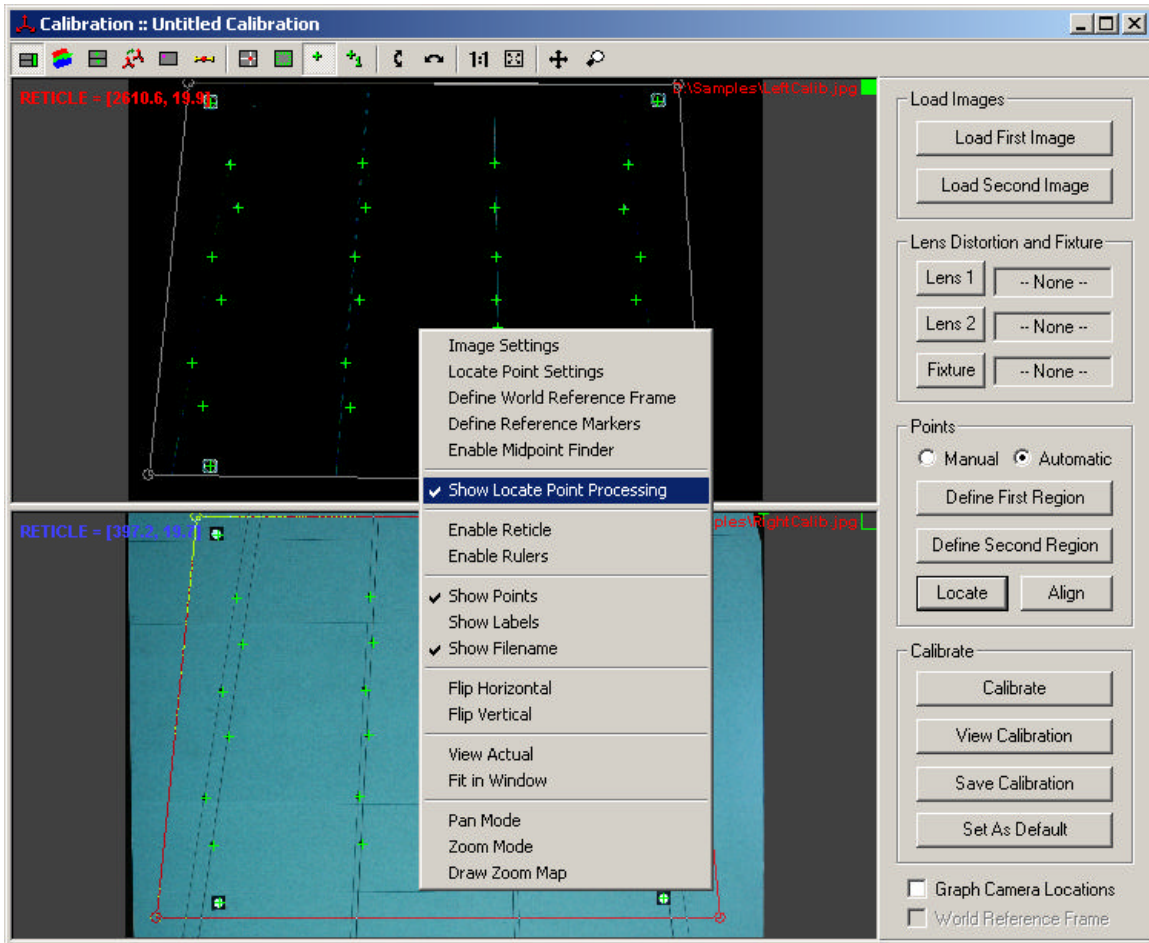


There are different settings for the top and bottom images, so if necessary, change both settings separately. For instance, if one image is darker than normal, use a lower Intensity Threshold value for that image.

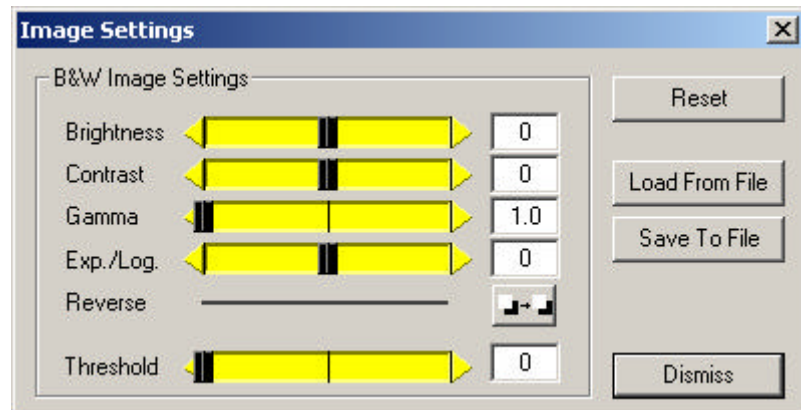
A useful tool for helping to know how to adjust the Locate Point Settings is the Show Locate Point Processing option available in the context menu of the image window. Right-click on the image and select **Show Locate Point Processing**.

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- ii. In addition, improving the contrast of the fixture points can also help in automatically locating them. You can change the image settings for the top and bottom images by clicking on the **Image Settings** icon on the toolbar, or right-click on the image and select **Image Settings** from the drop down menu.



To locate points manually:

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- Select **Manual** in the Points section of the right panel.
- Click on a point in the top image corresponding to a fixture point.
- Click on a point in the bottom image corresponding to the same fixture point.
- Click on the **Add Point** button.
- If you wish to adjust the coordinates of a point, select the point in the Points list. Click on the correct points in the top and bottom images. Then click on the **Update Point** button.

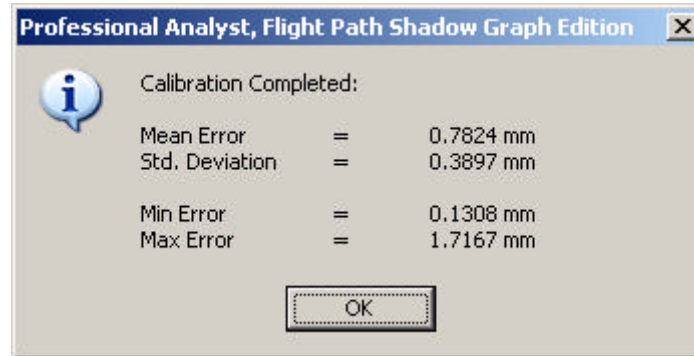
#	Image 1	Image 2	Calibration XYZ	Estimate XYZ	Error
1	288.4	188.9	-1.0, -1.0	-744.1, -222.7, 2464.8	
2	251.2	57.2	-1.0, -1.0	1289.0, -809.7, 2111.1	
3	207.0	1835.6	-1.0, -1.0	-346.0, -2792.3, 3211.1	
4	2462.1	1942.1	-1.0, -1.0	1288.0, -2799.8, 3111.1	
5	-1.0	-1.0	2878.9, 88.8	-817.9, 288.7, 2160.7	
6	-1.0	-1.0	504.5, 801.3	1282.0, 771.7, 2111.1	
7	-1.0	-1.0	2549, 1829	-223.9, 3459.4, 3111.1	
8	-1.0	-1.0	478.1, 1818.2	1288.0, 2418.8, 3111.1	
9	478.0	395.0	2459.9, 615.6	2.8, 2.3, 769.5	
10	1528.0	393.7	1047.0, 406.1	712.4, 0.7, 769.5	
11	1792.4	282.1	1212.4, 397.8	812.8, 0.4, 769.5	
12	2374.9	596.2	636.1, 589.5	913.0, 0.0, 769.5	
13	294.0	825.0	2515, 1067	2.3, 8.7, 469.5	
14	1074.1	816.1	1074, 1069	213.1, 0.4, 469.5	
15	1748.4	816.1	1236, 1031	212.1, 0.2, 469.5	
16	2423.9	827.7	550.1, 1032.0	313.1, 0.0, 469.5	
17	299.0	1246.7	2400, 1664	6.4, 8.2, 169.5	
18	1027.1	1248	1898, 1657	386.4, 0.2, 169.5	
19	1748.1	1247	1195, 1548	881.1, 0.1, 169.5	

- To remove a point, select the points to remove in the Points list. Then click on the **Remove** button.
- After you have set all the fixture points, if you wish for them to be automatically aligned to a standard grid pattern used by typical calibration fixtures, then click on the **Align** button.
- Note that since the screen reference markers are only visible in one of the two cameras, the first sets of points will either have (-1,-1) as the coordinates for Image 1 or Image 2. This indicates that these points are

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only visible in one of the two cameras. Estimated XYZ values will not be computed for these points.

6. Once all fixture points have been located, click on the **Calibrate** button.



If the calibration statistics are unsatisfactory, you must check your sources of error. Check that all points have been located properly. Check that there is no unwanted distortion introduced by the camera lenses, mirror, or other optics.

After a pair of cameras have been calibrated, you can view the results of the calibration by selecting **View Calibration**.

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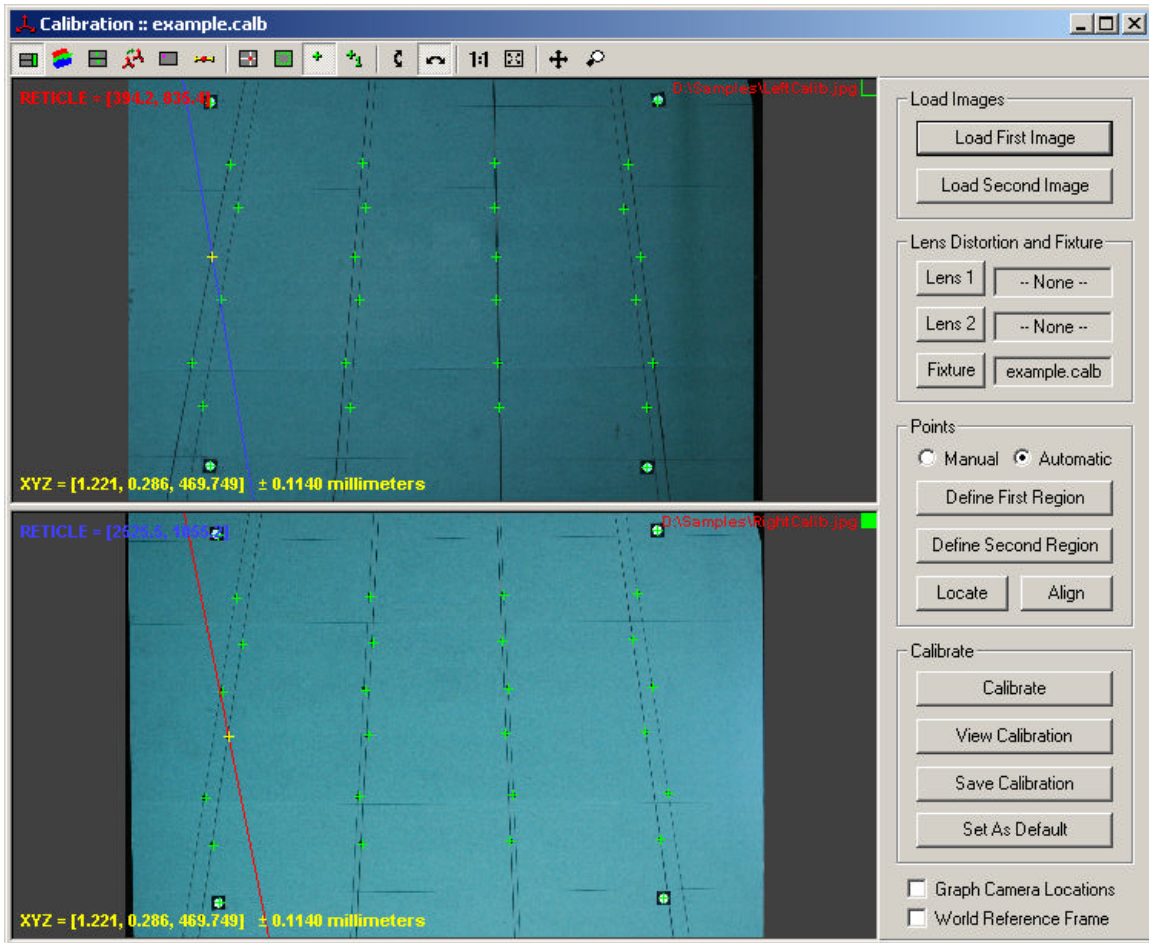
First Camera			Second Camera		
Location			Location		
537.4290	2019.8799	-1617.719	490.0275	-2170.997	-1616.022
Rotation			Rotation		
0.9998	-0.0119	0.0126	-0.9999	-0.0142	0.0011
-0.0007	0.6983	0.7159	0.0107	-0.6944	0.7195
-0.0173	-0.7158	0.6981	-0.0094	0.7195	0.6945
Translation			Translation		
-492.8738	-251.9677	2584.4433	461.0575	-349.9946	2688.8313
Center of Projection			Center of Projection		
1490.64	1027.50		1519.98	1028.56	
Axis Scale Factors			Axis Scale Factors		
6572.83	-6587.62		6581.36	-6570.45	
Calibration Statistics					
Mean Error	0.7824	Standard Deviation	0.3897		
Minimum Error	0.1308	Maximum Error	1.7167		
Units: Millimeters					
OK					

After the cameras have been calibrated, for every point that you click on in the top image, an epipolar line will be drawn in the bottom image and vice versa. The epipolar line indicates which points in the bottom image could correspond with the point that you have clicked on in the top image.

The current point in the top image is shown with a red plus symbol. The corresponding epipolar line in the bottom image is shown as a red line. The current point in the bottom image is shown with a blue plus symbol. The corresponding epipolar line in the top image is shown with a blue line.

The red plus and the blue line and the blue plus and the red line may not exactly intersect. The red and blue lines represent images of two rays coming from each camera. Since they do not exactly cross, the midpoint of the shortest distance between the two lines is shown with a yellow plus symbol in both the top and bottom views. The distance from the yellow plus to the red and blue lines is the uncertainty in the position estimate. Information along the bottom of each view indicates the 3D coordinates of the midpoint and the uncertainty associated with the 3D coordinates.

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When you are satisfied with the calibration results, you can save the calibration to a file using the **Save Calibration** button. This will save all the calibration information to a calibration file (*.calb) that can be used by the Measurement document to perform measurements on other images taken by the same cameras.

If you would like the same calibration to be used for all newly created Measurement documents, then select the **Set As Default** button after the calibration has been saved to a file.

Fixture File Generation

Fixture files used by the calibration procedure must be generated after the wire frame has been placed between each set of screens in the test range. The XYZ location of the four reference markers on each of the screens and the four reference markers on the wire frame fixture must be measured using a theodolite (or similar device). These XYZ coordinates are in the local coordinate frame defined by the measuring device. All XYZ coordinates must be in the same coordinate frame. Therefore, if using a theodolite, the

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theodolite must remain in the same position when conducting all measurements so that all coordinates are in the same reference frame.

The input dialog for generating the fixture file for the Shadow Graph system is shown below.

Fixture File Generator

Screen Reference Markers (XYZ)

Screen	Point	X	Y	Z
Left Screen	1.	-313.9	768.7	2166.7
	2.	1182.8	771.7	2162.8
	3.	-321.9	1659.4	1280.9
	4.	1195.6	1656.8	1280.7
Right Screen	1.	-344.2	-911.7	2164.8
	2.	1189.6	-905.7	2162.8
	3.	-346	-1792.3	1280.1
	4.	1155	-1788.8	1276.2

Wire Frame Grid (XYZ) [Left Side]

Markers	Point	X	Y	Z
Markers	1.	2.8	1.7	1188.5
	2.	903.8	0	1188.8
	3.	0	0	0
	4.	900.3	0	0

Rows: 3, Columns: 4
 X Offset: 0, Y Offset: 169.5
 X Spacing: 300, Y Spacing: 300
 From File

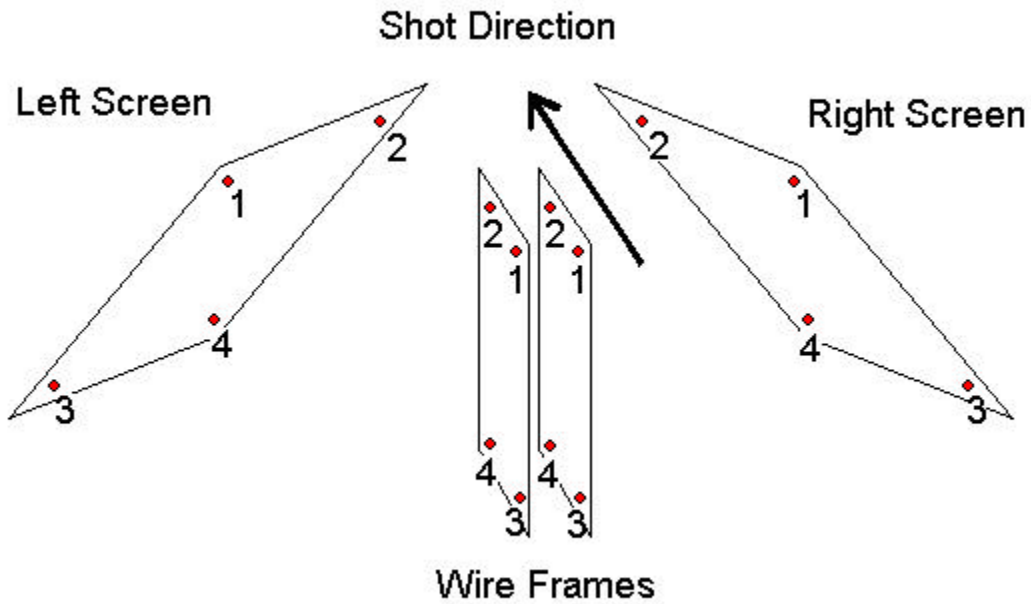
Wire Frame Grid (XYZ) [Right Side]

Markers	Point	X	Y	Z
Markers	1.	3	-135.8	1057
	2.	903.5	-136.9	1057.5
	3.	2.3	-136.5	-4
	4.	902.5	-137.2	-3.7

Rows: 3, Columns: 4
 X Offset: 0, Y Offset: 177
 X Spacing: 300, Y Spacing: 300
 From File

Save Entries Load Entries Units: Millimeters Generate Fixture File Close

The XYZ coordinates for four points on each of the screens and four points on the wire frame are required to generate the fixture file. The ordering of the four points is shown below, as seen when looking down the flight path towards the back wall of the bunker.

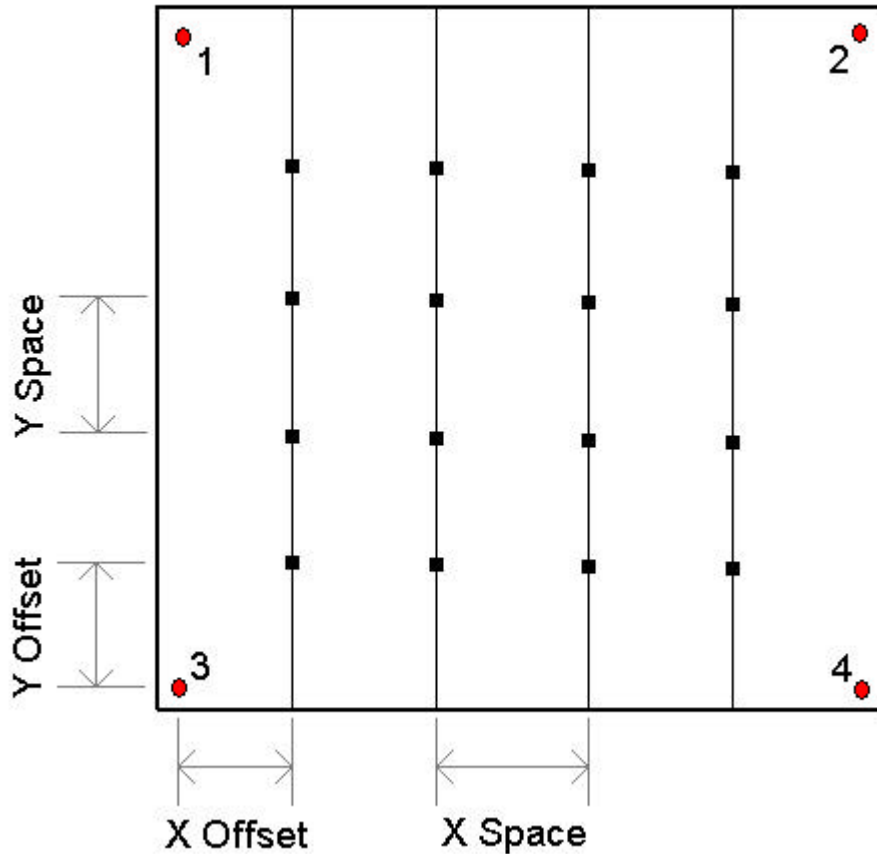


Note that the first point is always the point closest to the entry point and farthest from the target.

In addition to the four target points on each of the two wire frames (shown in red), additional offset and spacing information is required for each wire frame in order to determine the location of the wire markers relative to the corner targets.

If you are standing underneath the right screen, looking at the wire frame, the wire frame should appear as shown below.

Wire Frame



Since the wire frame should be exactly planar, we only need to determine the X and Y coordinates of each of the beads in each wire frame. The X and Y offset of the first wire bead from reference marker 3 allows us to compute the exact location of the first wire bead. Each of the wires should be equally spaced apart, and each of the beads on the wires should be equally spaced apart, creating a precise grid. Knowing the X and Y spacing will allow us to compute the location of every wire bead in the frame.

If the beads on the wire frame are not equally spaced, then the exact X and Y coordinates of each of the beads relative to reference marker 3 can be loaded from a file. The first line of the text file should specify the number of points that are contained in the file. The subsequent lines should contain the X and Y offsets from reference marker 3, separated by a comma. Z values are not required because the wire frame should be planar. To load offsets from a file, check the **From File** checkbox and select the file to use by clicking on the **Browse...** button.

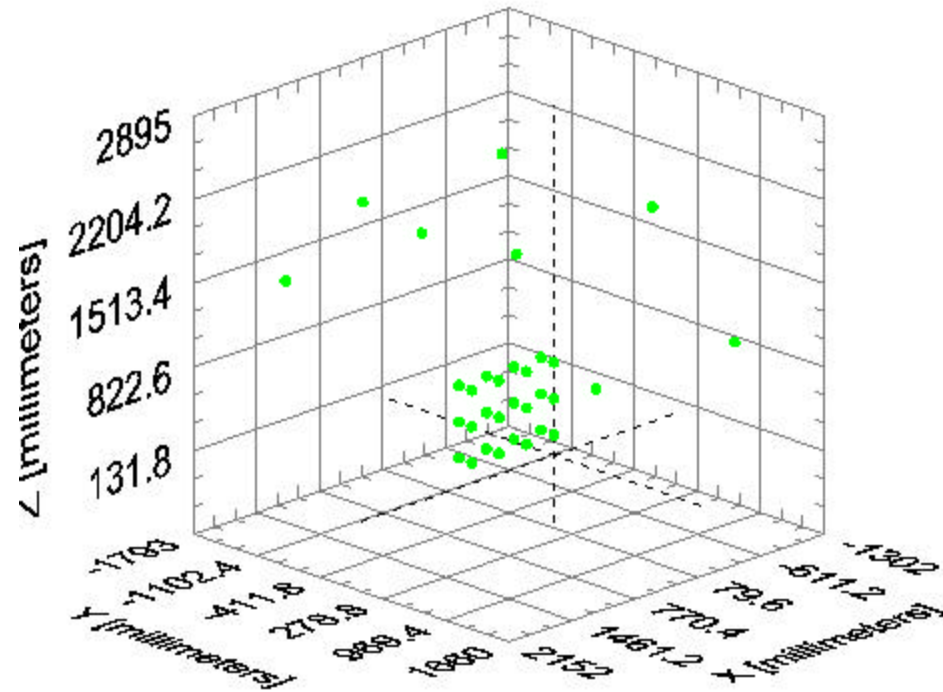
Enter the correct values for both the left and right wire frames.

When all the values are input into the Fixture File Generator dialog, you can hit the **Generate Fixture File** button and save the resulting fixture file.

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```
% units: millimeters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%      Calibration File for Shadow Graph Fixture
%
%      AUTOMATICALLY GENERATED FILE - DO NOT MODIFY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% number of points
32
% cartesian points
% right screen
-344.2, -911.7, 2164.8
1189.6, -905.7, 2162.8
-346, -1792.3, 1280.1
1155, -1788.8, 1276.2
% left screen
-313.9, 768.7, 2166.7
1182.8, 771.7, 2162.8
-321.9, 1659.4, 1280.9
1195.6, 1656.8, 1280.7
% wire frame (left)
1.81287, 1.10067, 769.497
301.812, 0.734126, 769.498
601.812, 0.367644, 769.498
901.811, 0.00122332, 769.498
1.1061, 0.671558, 469.498
301.106, 0.447917, 469.498
601.105, 0.224313, 469.499
901.105, 0.000746391, 469.499
0.399325, 0.242448, 169.499
300.399, 0.161708, 169.499
600.399, 0.080982, 169.5
900.399, 0.000269464, 169.5
% wire frame (right)
2.81296, -135.987, 773.5
302.813, -136.318, 773.6
602.812, -136.649, 773.7
902.812, -136.98, 773.8
2.61503, -136.185, 473.5
302.615, -136.478, 473.6
602.615, -136.771, 473.7
902.614, -137.065, 473.8
2.41711, -136.383, 173.5
302.417, -136.638, 173.6
602.417, -136.894, 173.7
902.417, -137.15, 173.8
```

The fixture file can then be loaded into a new Calibration document.



World Reference Frame

The coordinate frame of the calibration is the coordinate frame that is used by the calibration fixture file that was loaded. All the coordinates in the fixture file are referenced from the local origin for a particular station. In order to compare information from one pair of cameras to another pair of cameras or X-Ray systems, the coordinates need to be referenced to some mutual world reference frame. All coordinates can then be transformed from the local calibration fixture reference frame to the world reference frame.

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A tool is provided to help define the transformation between the calibration fixture and world reference frame. You can access this tool by selecting the **Define World Reference Frame** button on the toolbar, or by right clicking in the image and selecting **Define World Reference Frame**.

There are three methods for entering information about the world reference frame. You can directly type in the rotation and translation matrix used to transform calibration coordinates to world coordinates. Or you can select two points that lie on the world reference frame Z-axis and supply the Z coordinate of the first point and the base angle of the fixture. Or you can specify the distances and coordinates to a set of fixed points from the origin of the local coordinate frame.

Define World Reference Frame

Rotation and Translation ($X_w = R * X_c + T_w$)

Rotation (R)

1	0	0
0	1	0
0	0	1

Translation (T_w)

0	0	0
---	---	---

Units: Undefined

Direct Entry | Two Points on Z-Axis | Distances to Fixed Points

Manual Entry of Rotation and Translation

Rotation (R)

1	0	0
0	1	0
0	0	1

Translation (T_w)

0	0	0
---	---	---

Units: Undefined

OK Cancel Apply

Direct Entry

For the first method, if the rotation matrix and translation vector are known, simply enter them into the appropriate boxes and hit **Apply** or **OK**.

Two Points on Z-Axis

For the second method, the standard calibration fixture should be equipped with two adjustable irises, one on each side of the fixture. If the fixture does not have these irises, then you must use one of the other methods for determining the transformation to the world reference frame.

The calibration fixture should have been positioned so that the irises are aligned with the flight path and are visible in both camera views. To define the world reference frame:

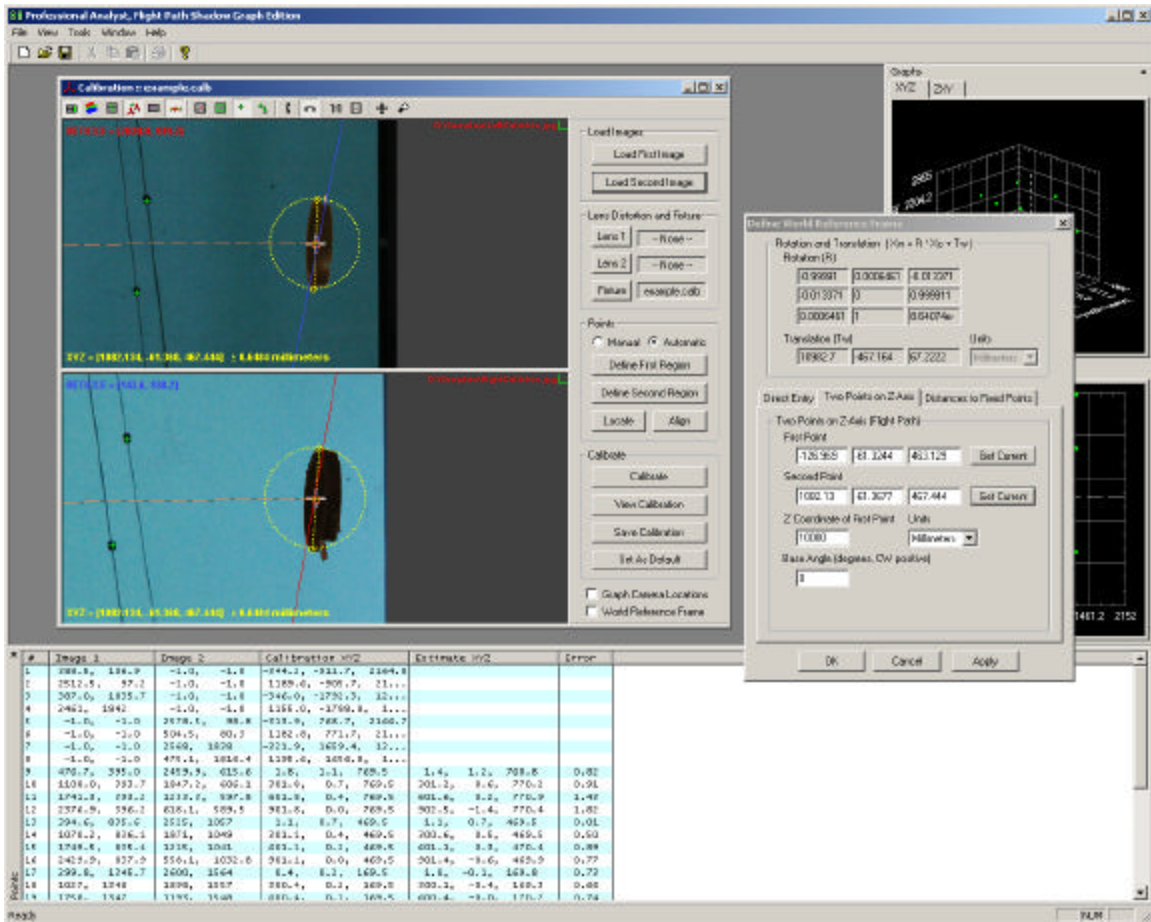
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1. The system should have been calibrated already, as described earlier.
2. Click on the center of the left iris in the top and bottom views of the calibration document window. Check the uncertainty in the coordinates to make sure that a suitable point has been chosen.
3. Click on **Get Current** for the **First Point** in the Define World Reference Frame dialog. An orange box should appear in the calibration document window to indicate the first point.
4. Click on the center of the right iris in the top and bottom views of the calibration document window. Check the uncertainty in the coordinates to make sure that a suitable point has been chosen.
5. Click on **Get Current** for the **Second Point** in the Define World Reference Frame dialog. An orange box should appear in the calibration document window to indicate the second point and a dotted line should be drawn between the first and second points.
6. Enter in the **Z Coordinate of the First Point** and the units of the Z coordinate. This should have been measured when the calibration fixtures were being aligned.
7. Enter in the **Base Angle** in degrees. This should have been measured when the calibration fixtures were being aligned.
8. Hit **Apply** and the equivalent rotation and translation will be computed and applied.

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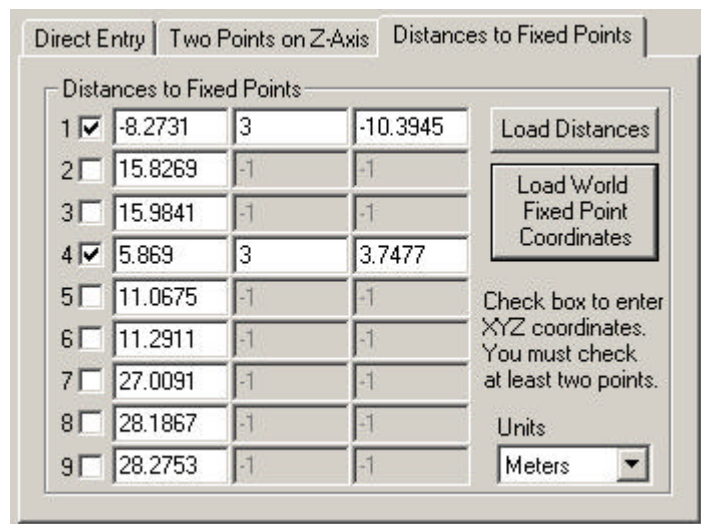
Note that the first point should be the point closest to the entry point of the projectile. In the

Distances to Fixed Points

The rotation and translation from the local coordinate frame to the world reference frame can be determined by knowing the XYZ coordinates of two fixed points combined with the distances to at least two other fixed points.

The distances are used to determine the translation. The XYZ coordinates are used to determine the rotation.

The exact coordinates of the fixed points in the world



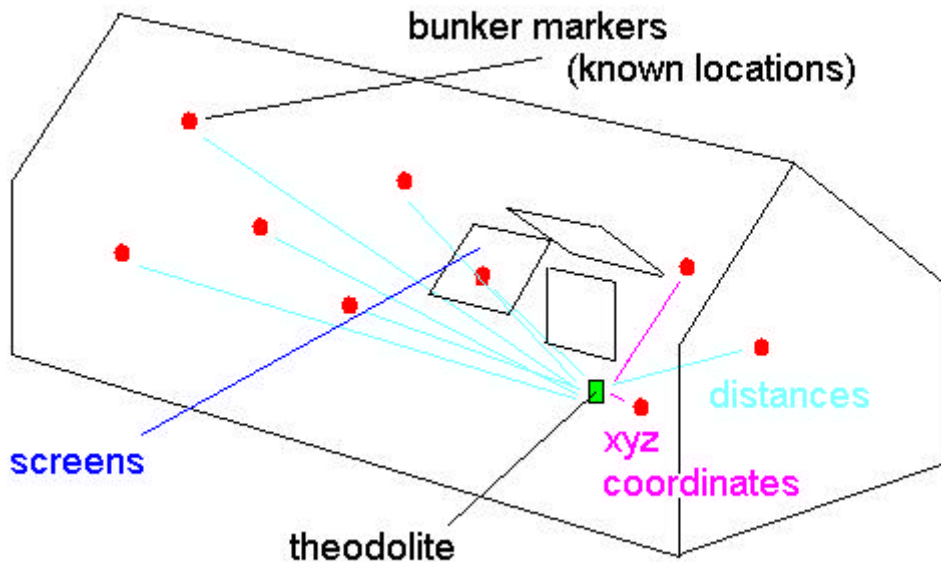
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reference frame must be known. These coordinates should be placed into a text file. The first line of the text file should indicate the number of fixed points. Each subsequent line should contain the XYZ coordinates separated by commas for each of the fixed points. To load the file containing the fixed point coordinates, click on the **Load World Fixed Point Coordinates** button. Shown below is an example with five fixed point coordinates.

```
5
890.7, 3681.9, -2177.4
328.3, -3544.6, -1927.6
16203.1, 3734.9, -1378.4
16221.9, 3731.1, -2191.9
15598.3, -3493.4, -1428.7
```

For each of the fixed points, you must either enter a distance or XYZ coordinates. To enter XYZ coordinates, check the checkbox next to the appropriate fixed point number. You must check at least two points. These values can also be loaded from a text file. The first line of the text file should indicate how many distances or XYZ coordinates are contained in the file. For each subsequent line, if there is only a single value, it is read as a distance, if there are three values separated by commas, they are read as the XYZ coordinates. To load values from a file, click on the **Load Distances** button.

A sample layout of bunker fixed points is shown below. The theodolite is used to measure the XYZ coordinates to at least two of the points (typically the closest points) and the distances to the remaining points.



When you have entered all the distances and coordinates and have loaded the fixed points coordinates file, click on **Apply** to compute the rotation and translation.

Using the World Reference Frame

Once the world reference frame has been defined, the coordinates of all points can be displayed in either the local calibration reference frame or the world reference frame. You can select which frame to display in by checking the **World Reference Frame** checkbox in the side control panel. When displaying coordinates in the world reference frame, the graphs will label the axes as X_w , Y_w , and Z_w .

The world reference frame must be defined for each calibration if you want to compare the measurements from one camera pair to another camera pair. For example, the Event Summary document, that is described later, compares the results from multiple measurement documents to compute velocity and angular velocity. In order to compare these results, all the coordinates must be transformed into the same reference frame (the world reference frame).

Reference Markers

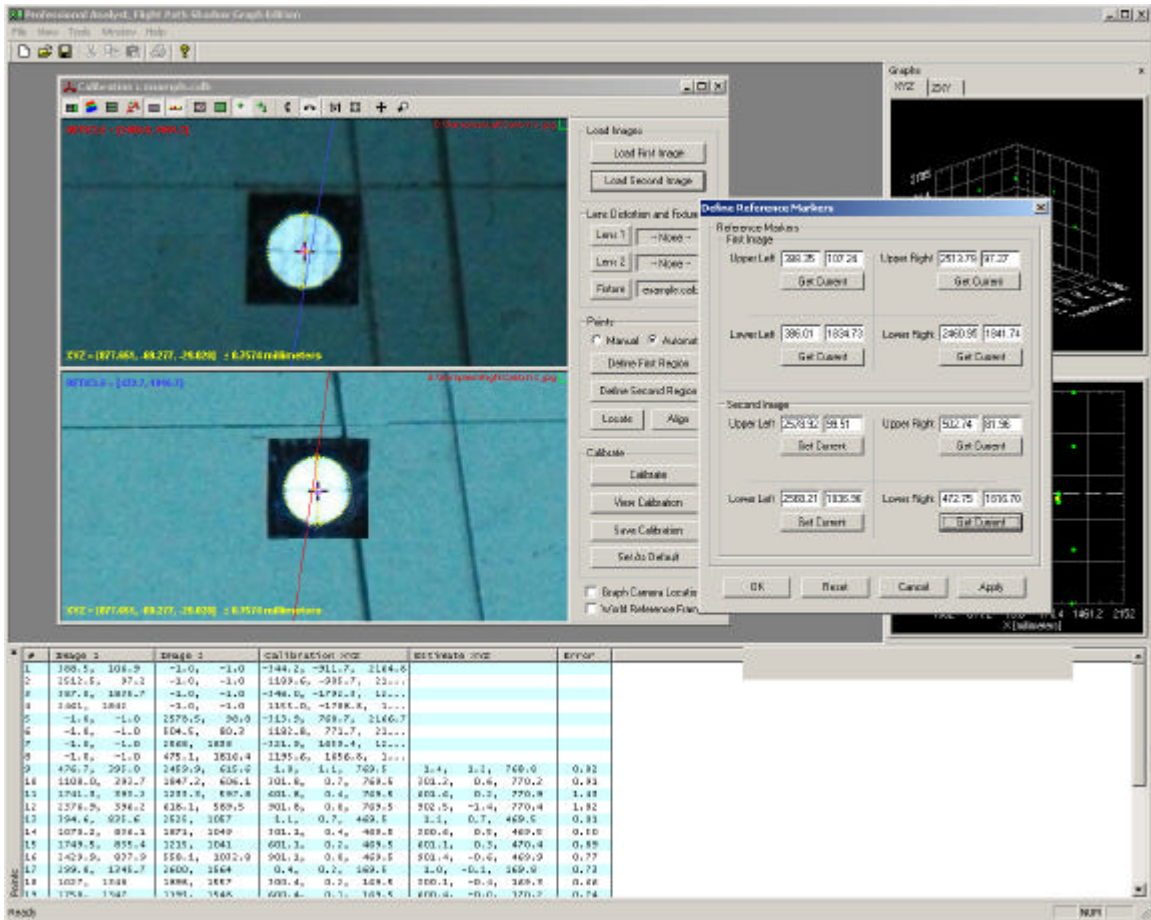
In order to approximately compensate for small camera motions between calibration and measurement, reference markers can be placed in the field of view of both cameras. This is not required. Only use this technique if you find that your cameras have moved since the last calibration and you are unable to re-calibrate. This technique is only approximate and it is highly recommended that you re-calibrate if possible.

There should be reference marks located in all four corners of each camera image. The compensation algorithm will compute the necessary transformation to ensure that the reference marks in the measurement images exactly overlap the reference marks in the calibration images.

You must identify and store the location of each of the reference marks for each calibration. Click on the **Define Reference Markers** button on the toolbar. Click on each of the reference markers in the first and second image and click on the appropriate **Get Current** button for each mark.

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After all eight reference markers have been located, hit **Apply**. The location of these markers will be saved with the calibration information when the calibration is saved. These values will be used during measurement to try to compensate for any movement of the cameras between shots.

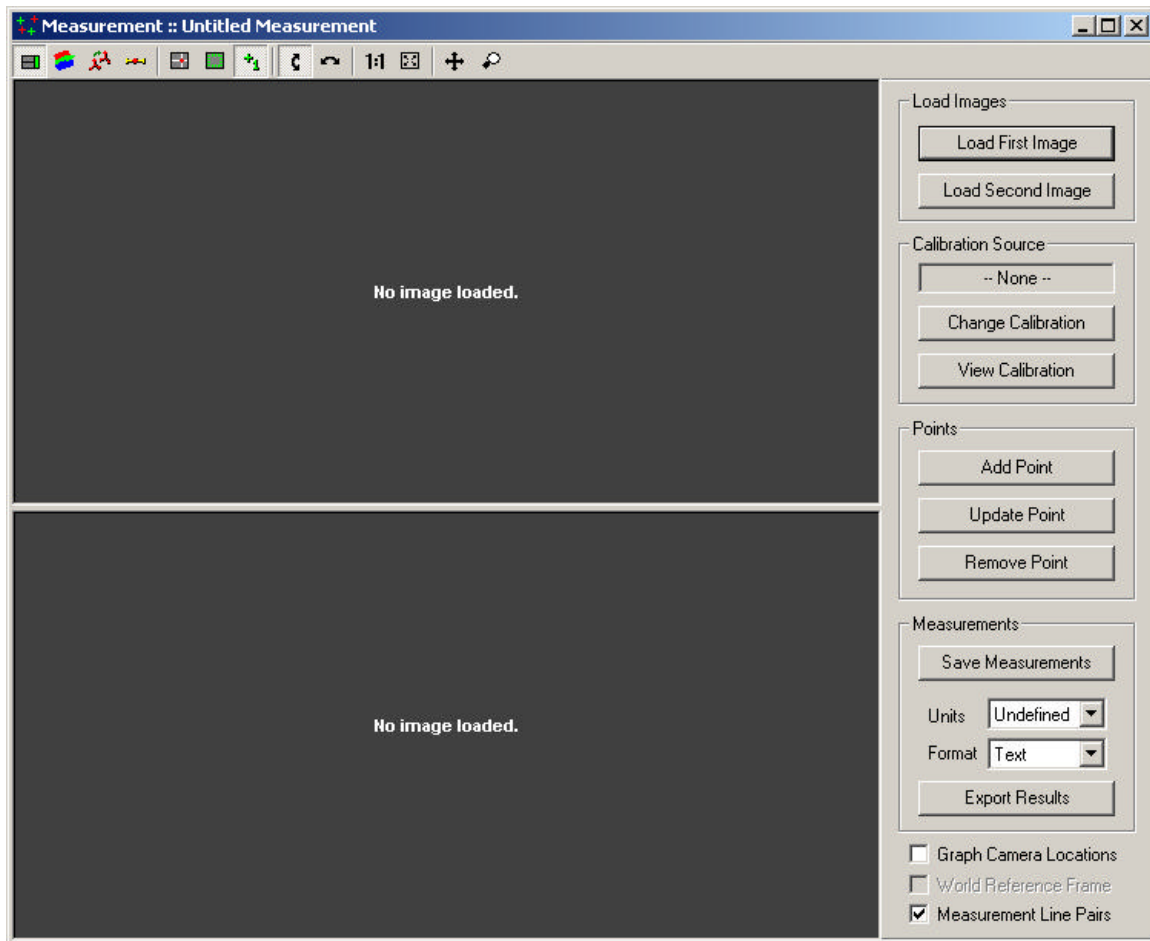
Measurement

After a calibration has been completed and a test has been conducted. The resulting images from the test can be used to perform measurements.

A Measurement Document is created by selecting **File** → **New**. Then select **Measurement**.

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All the controls are located on the toolbar or on the panel on the right. The toolbar controls were described earlier in this document.

A pair of images from an actual test should be loaded into the Measurement document. An image from the top camera should be loaded using the **Load First Image** button. An image from the side camera should be loaded using the **Load Second Image** button.

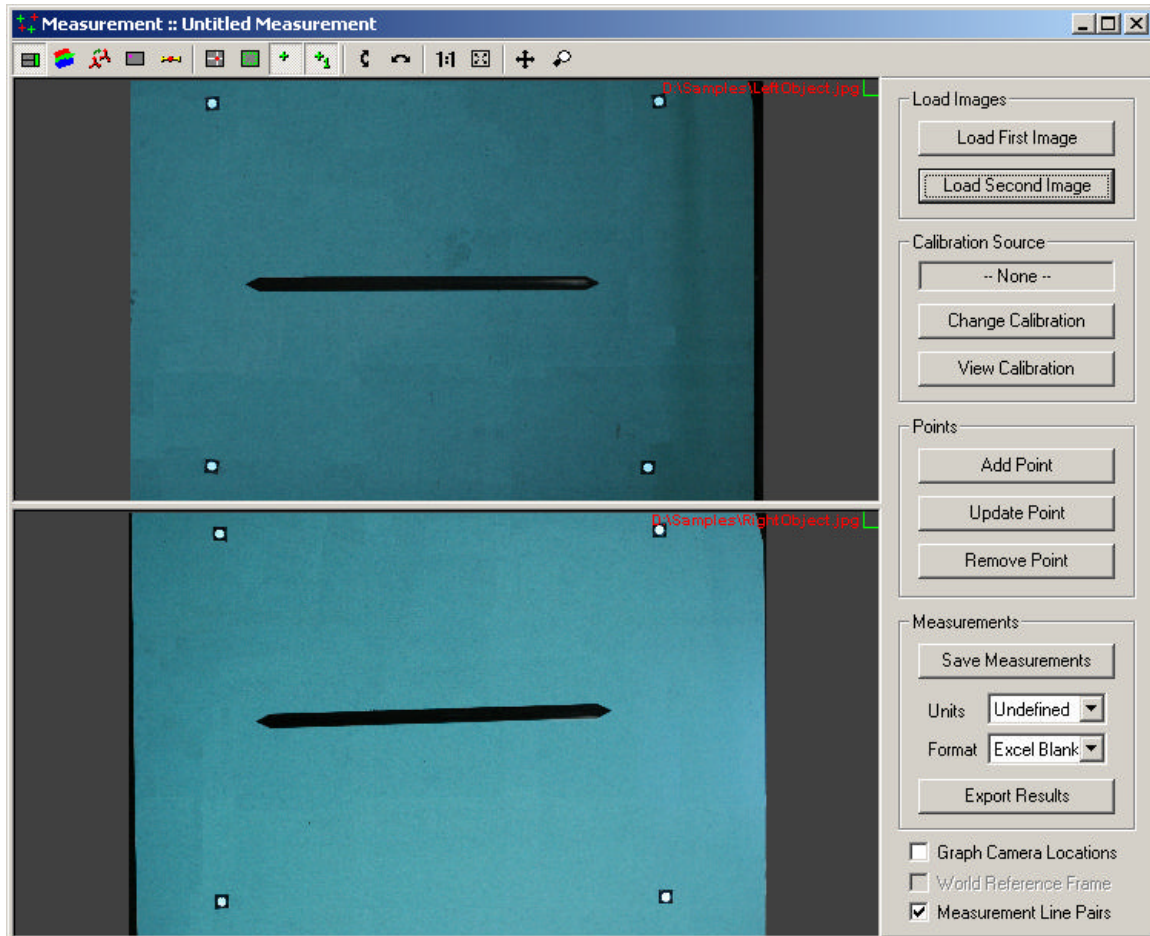
To perform measurements, a calibration must have already been performed for the cameras being used. If a default calibration had been set, the default calibration is automatically loaded. If a default has not been set, then a calibration must be loaded by using the **Change Calibration** button.

When a calibration is loaded, any lens distortion information is also automatically loaded and applied. See the Appendix for more information on lens distortion correction.

The units of measure and the world reference frame transformation are also loaded from the calibration file. The units of measure that are displayed can be changed by changing the units in the panel on the right. The world reference frame transformation can be viewed or modified using the toolbar button or the right-click context menu.

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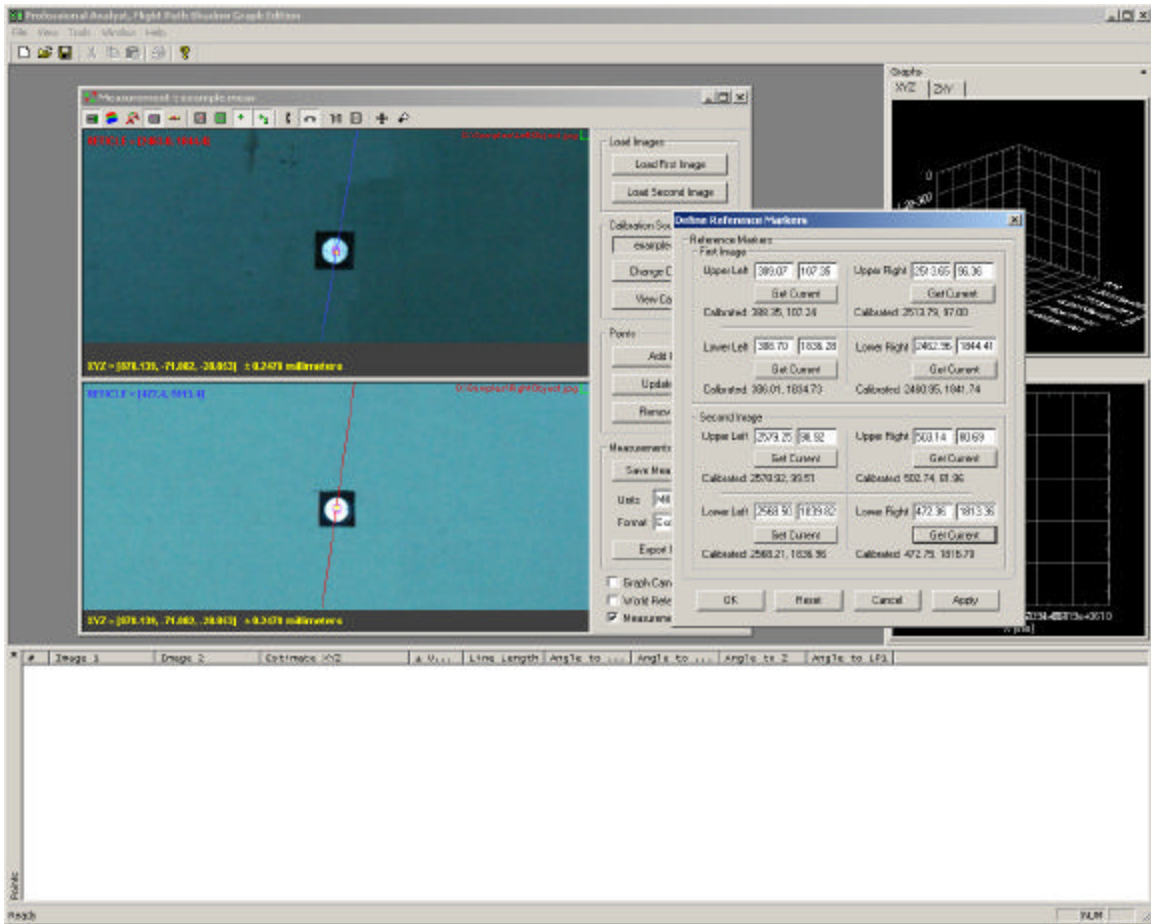
If you would like to review the calibration information, select the **View Calibration** button.

After loading the calibration, if you are using the reference marker correction scheme, you must locate the reference markers. If the cameras have not moved since you have calibrated, then you should not have to use the reference marker correction scheme and you can skip this step.

To define the reference markers, click on the **Define Reference Markers** button on the toolbar. Locate each of the reference markers and click on the **Get Current** button for each marker.

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After all reference markers have been located, click on **Apply**. Each image will then be transformed so that the reference marks in the measurement images (blue) exactly overlap the location of the marks in the calibration images (purple).

Measurements can either be the 3D location of a single point, or the 3D locations of the end points of a *Line Pair*. A line pair is a grouping of two sequential measurement points (points 1 and 2, 3 and 4, 5 and 6, ...).

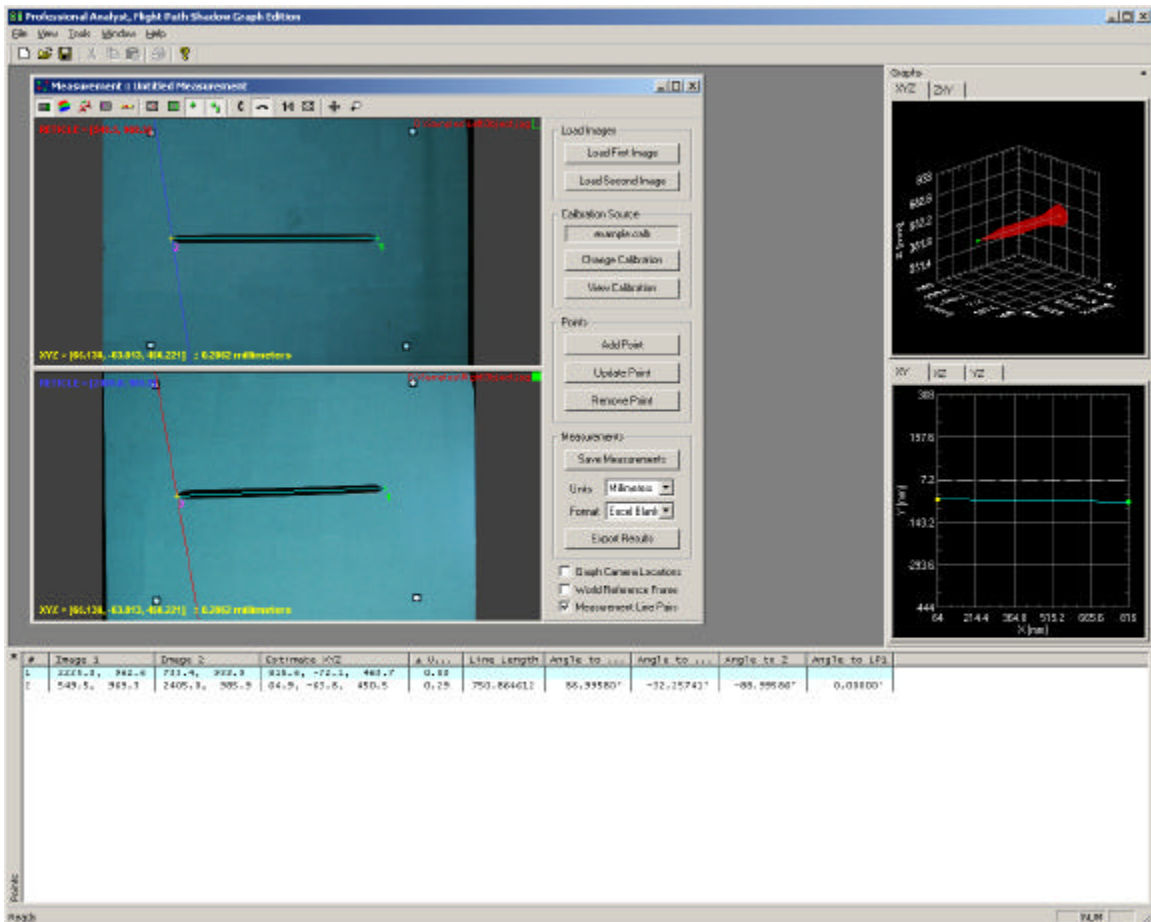
Each Measurement document can display information as single point measurements or as line pairs. To change the display, click on **Measurement Line Pairs** checkbox in the right hand panel. When the Measurement document is set to show information as line pairs, additional orientation and length information is computed for each line pair and displayed in the Points listing. In addition, the first point in a line pair is shown in green and the second point in a line pair is shown in magenta. The connecting line is shown in cyan.

Typical steps to perform a measurement:

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1. Click on a feature point in the top image. Zoom in using the mouse wheel to accurately select a feature point. The mouse wheel will zoom in/out on the currently selected point. It is always a good idea to zoom in on a feature point to ensure that you have selected the proper point.
2. Click on the corresponding feature point in the bottom image. Zoom in using the mouse wheel to accurately select a feature point. Verify that the uncertainty in the resulting image coordinates is acceptable. The uncertainty is shown on the bottom of each view. The red, blue, and yellow points and lines should be near one another in both images.
3. If you are satisfied with the feature points and uncertainty, click on **Add Point**.
4. If you would like to update the coordinates of a point, select the point in the Points list. Click on the correct feature point in the top and bottom image, then click **Update Point**.
5. To remove a point, select the point in the Points list and then click on **Remove Point**.

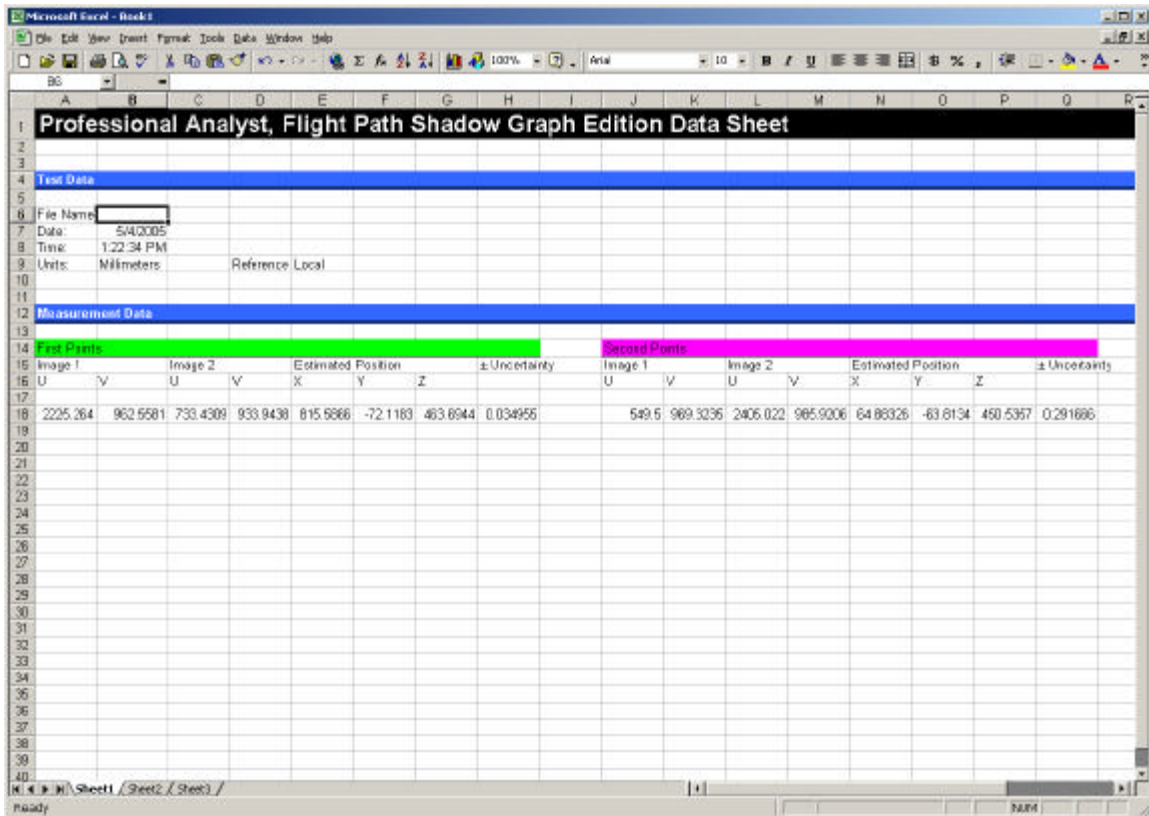


When you have selected all the points of interest, you can save your measurement results to a file. This will save the calibration information and measurement information to a measurement file (*.meas).

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Note that the measurement file contains a copy of the calibration information. Once it is saved to the measurement file, the measurement does not use the original calibration file. If you make any changes to the original calibration file, you must reload the calibration into the measurement document using the **Change Calibration** button in order to apply the changes.

You can also export the measurement results to a Text document or to an Excel spreadsheet. First select the units and the export format and then hit the **Export Results** button. Here is a sample of the export results in Excel format. The sections are color coded to correspond to the first and second points in the line pairs and the line information for each pair.



Professional Analyst, Flight Path Shadow Graph Edition Data Sheet																	
Test Data																	
File Name																	
Date	5/4/2005																
Time	1:22:34 PM																
Units	Millimeters			Reference Local													
Measurement Data																	
First Points							Second Points										
Image 1		Image 2		Estimated Position			± Uncertainty		Image 1		Image 2		Estimated Position			± Uncertainty	
U	V	U	V	X	Y	Z			U	V	U	V	X	Y	Z		
2225.264	962.6581	733.4309	933.9438	815.6866	-72.1183	463.6944	0.034955		549.5	989.3236	2406.022	985.9206	64.86326	-63.6134	450.5357	0.291696	

If the same calculations are always done in Excel, the export feature can also be told to use an existing Excel file as a template for the export results. This template can contain formulas, graphs, or any other Excel elements. Select **Excel Template** as the **Format** type before exporting. Then select the Excel file to use as a template.

Event Summary

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After you have created a set of Measurement documents for one event, you can combine these all in one Event Summary Document. An Event Summary document loads a set of Measurement documents and displays a summary of all the measurements contained in each of the Measurement documents.

An Event Summary Document is created by selecting **File → New**. Then select **Event Summary**.

	Time (sec)	File Name				
Meas 1	<input type="text"/>	<input type="text"/>	Load	Edit	Reload	Remove
Meas 2	<input type="text"/>	<input type="text"/>	Load	Edit	Reload	Remove
Meas 3	<input type="text"/>	<input type="text"/>	Load	Edit	Reload	Remove
Meas 4	<input type="text"/>	<input type="text"/>	Load	Edit	Reload	Remove
Meas 5	<input type="text"/>	<input type="text"/>	Load	Edit	Reload	Remove
Meas 6	<input type="text"/>	<input type="text"/>	Load	Edit	Reload	Remove
Meas 7	<input type="text"/>	<input type="text"/>	Load	Edit	Reload	Remove
Meas 8	<input type="text"/>	<input type="text"/>	Load	Edit	Reload	Remove
Meas 9	<input type="text"/>	<input type="text"/>	Load	Edit	Reload	Remove
Meas 10	<input type="text"/>	<input type="text"/>	Load	Edit	Reload	Remove
Meas 11	<input type="text"/>	<input type="text"/>	Load	Edit	Reload	Remove
Meas 12	<input type="text"/>	<input type="text"/>	Load	Edit	Reload	Remove
Meas 13	<input type="text"/>	<input type="text"/>	Load	Edit	Reload	Remove
Meas 14	<input type="text"/>	<input type="text"/>	Load	Edit	Reload	Remove
Meas 15	<input type="text"/>	<input type="text"/>	Load	Edit	Reload	Remove
Meas 16	<input type="text"/>	<input type="text"/>	Load	Edit	Reload	Remove

Center of Gravity, Distance From Penetrator Tip

Display

Load each measurement document by clicking on the corresponding **Load** button. For each measurement document, you must specify the time associated with that measurement. This allows the application to compute velocity information between measurements.

Up to sixteen (16) measurement documents can be combined into an event summary. After you have loaded all the measurement documents, you can save the event summary

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information by clicking on the **Save** button. All the time and measurement document information will be saved to an event summary file (*.esum).

If you wish to make changes to a measurement document, you can hit the **Edit** button next to the measurement document file name. After you have finished making changes and have saved the measurement document, you must hit the **Reload** button so that the new changes are loaded by the event summary.

The Points listing will display information about each line pair contained in each measurement document. Which quantity is displayed is controlled by the **Display** drop down control in the Event Summary document window.

If you would like to display the coordinates for the center of gravity, you must supply the distance from the projectile tip (first point of a line pair) to the center of gravity. If a negative value is entered, the distance is measured from the projectile tail (second point of a line pair).

Time (sec)	File Name	Load	Edit	Reload	Remove
Meas 1	D:\Samples\sample 1.nes				
Meas 2	D:\Samples\sample 2.nes				
Meas 3	D:\Samples\sample 3.nes				
Meas 4	D:\Samples\sample 4.nes				
Meas 5	D:\Samples\sample 5.nes				
Meas 6	D:\Samples\sample 6.nes				
Meas 7					
Meas 8					
Meas 9					
Meas 10					
Meas 11					
Meas 12					
Meas 13					
Meas 14					
Meas 15					

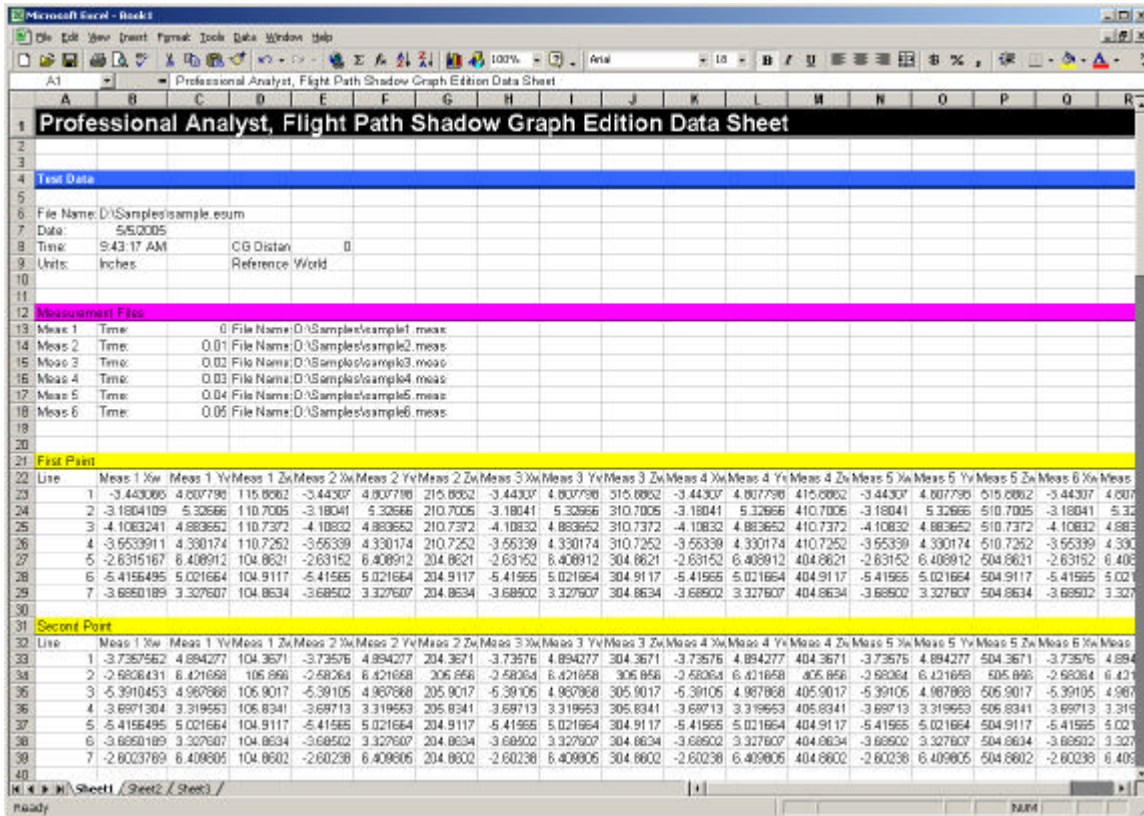
Line	Meas 1	Meas 2	Meas 3	Meas 4	Meas 5	Meas 6	Displayed	Units
1	-2, 3, 228	-2, 3, 228	-2, 3, 228	-2, 3, 228	-2, 3, 228	-2, 3, 228	First Point	Inches
2	-2, 3, 233	-2, 3, 233	-2, 3, 233	-2, 3, 233	-2, 3, 233	-2, 3, 233	First Point	Inches
3	-4, 4, 211	-4, 4, 211	-4, 4, 211	-4, 4, 211	-4, 4, 211	-4, 4, 211	First Point	Inches
4	-4, 4, 211	-4, 4, 211	-4, 4, 211	-4, 4, 211	-4, 4, 211	-4, 4, 211	First Point	Inches
5	-2, 4, 208	-2, 4, 208	-2, 4, 208	-2, 4, 208	-2, 4, 208	-2, 4, 208	First Point	Inches
6	-2, 4, 205	-2, 4, 205	-2, 4, 205	-2, 4, 205	-2, 4, 205	-2, 4, 205	First Point	Inches
7	-4, 3, 206	-4, 3, 206	-4, 3, 206	-4, 3, 206	-4, 3, 206	-4, 3, 206	First Point	Inches

The Event Summary results can also be exported to a Text document or to an Excel Spreadsheet.

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Select the units and the export format and then hit the **Export** button. This will export all available information about the measurement line pairs. The current display setting is not used during export. All possible display values are exported simultaneously.



If the same calculations are always done in Excel, the export feature can also be told to use an existing Excel file as a template for the export results. This template can contain formulas, graphs, or any other Excel elements. Select **Excel Template** as the **Format** type before exporting. Then select the Excel file to use as a template.

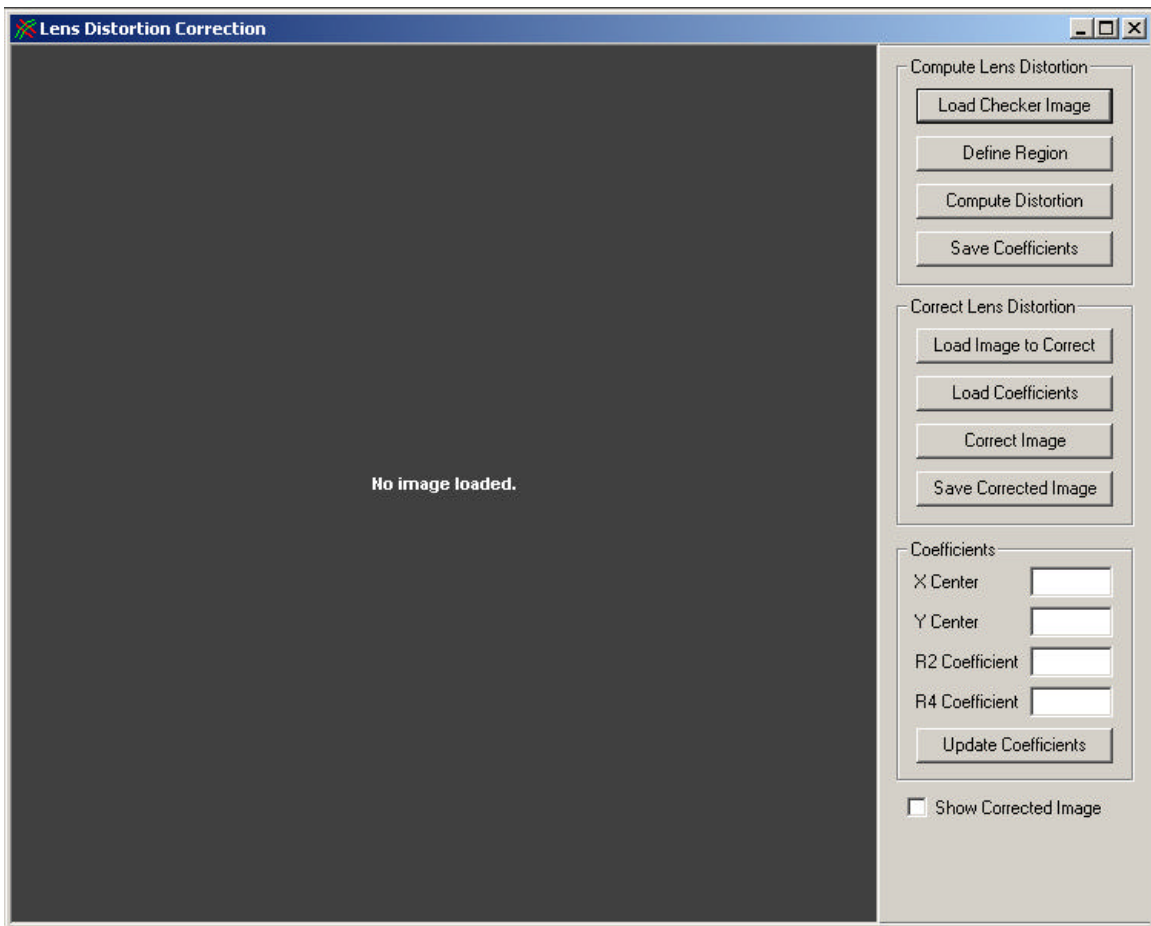
All the information is exported into the template file in Excel, with any calculations or graphs being automatically populated.

Appendix

Lens Distortion Correction

A tool is provided to help compensate for radial lens distortion. Select **Tools → Lens Distortion Correction** from the main menu..

For each lens that will be used, an image of a checkerboard pattern should be acquired. This image can be loaded into the Lens Distortion Correction window to compute whether or not distortion correction is necessary. The lens distortion correction tool will compute coefficients to compensate for radial distortion (barrel or pincushion).

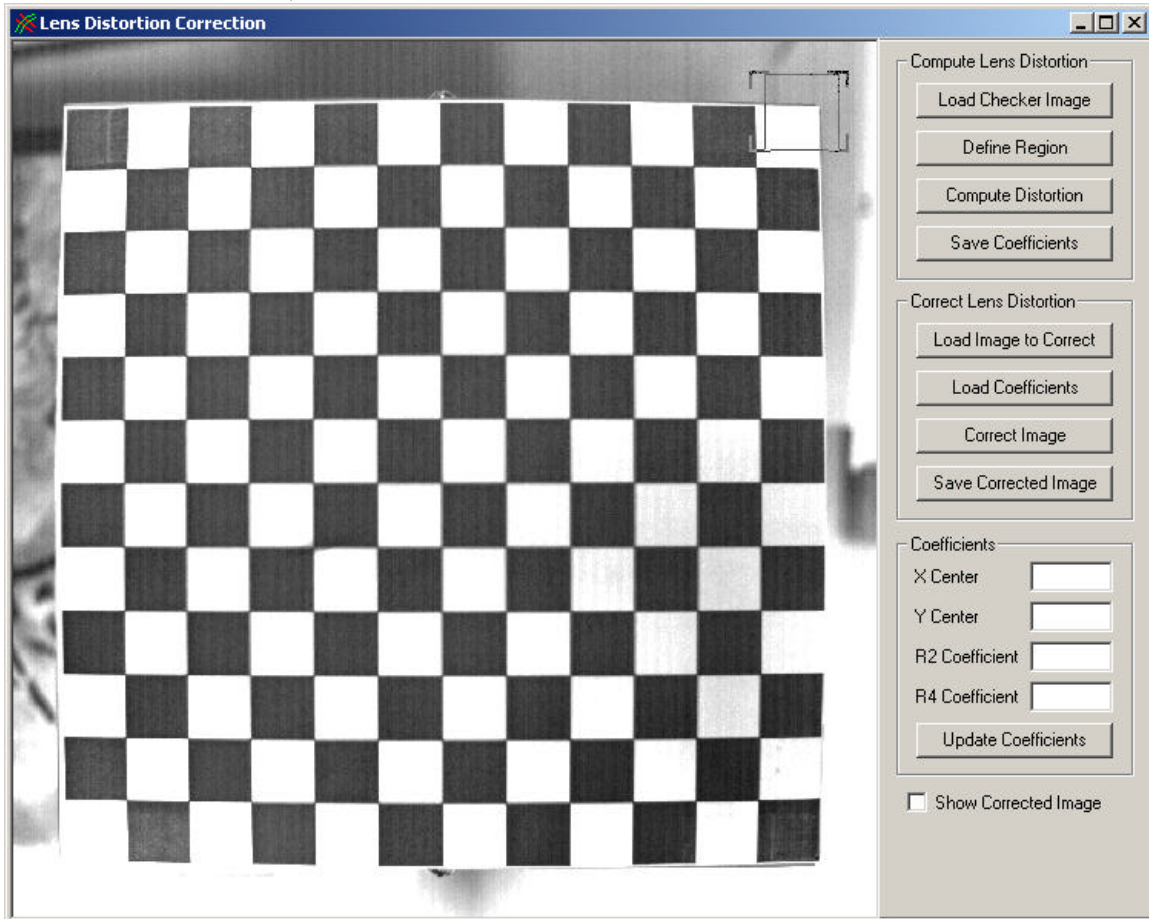


To compute lens distortion coefficients:

1. Capture an image of a checkerboard pattern using the camera and lens that will be used in testing.

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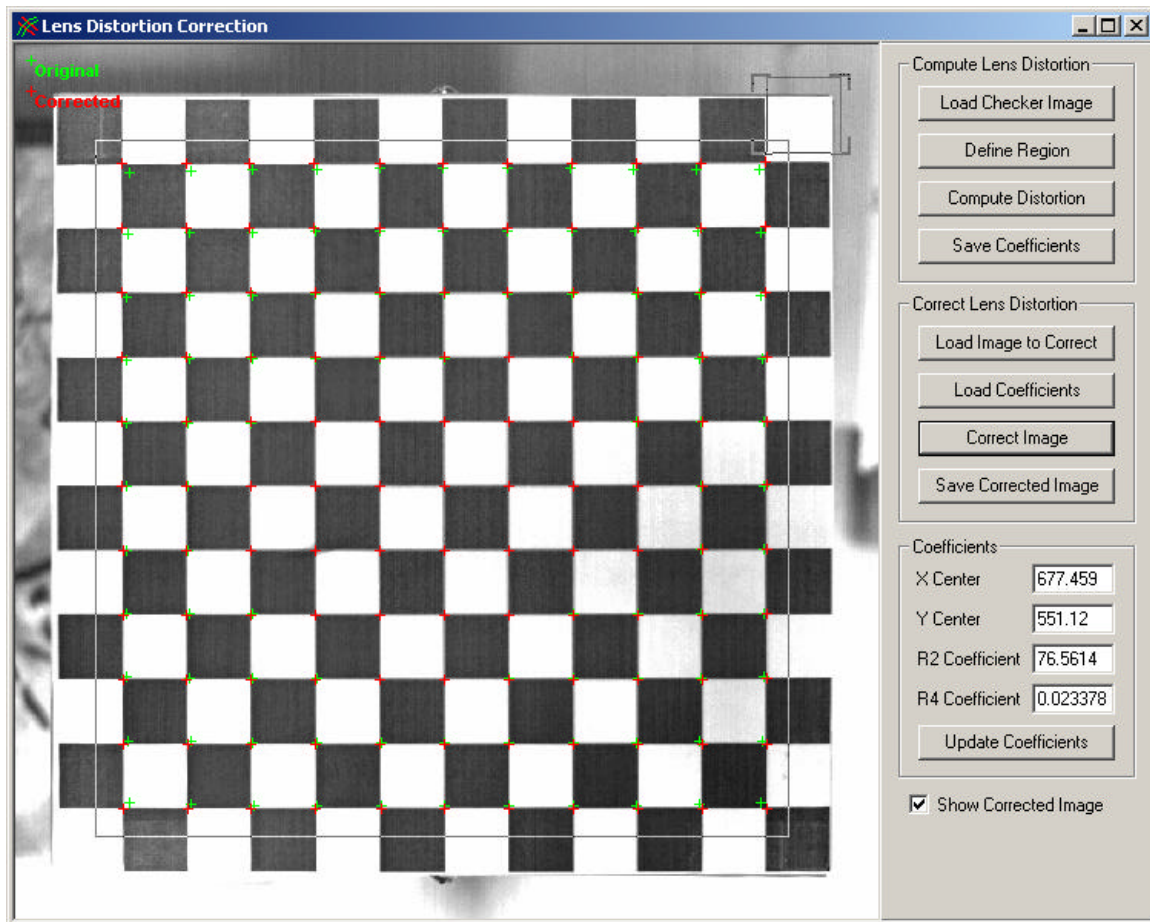
2. Click on **Load Checker Image** and select the checkerboard image file (BMP, TIFF, or JPEG).



3. Click on **Define Region** and click the left mouse button and drag a rectangle around the inside of the checker pattern. Make sure that the rectangle is inside the last set of checkerboard squares. Do not draw the region outside the entire checkerboard pattern, it must be inside the checkerboard pattern.
4. If you would like to redraw the region, click on **Define Region** again and redraw the rectangle.
5. Click on **Compute Distortion**. The distortion coefficients will be computed. If you wish to view the corrected image, you can hit the **Correct Image** button.
6. Click on **Save Coefficients** to save the distortion coefficients to a lens coefficients file (*.lens) that can be used by Calibration Documents.

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The **Correct Lens Distortion** options are provided only for verification of removal of distortion and as a tool for recovering undistorted images. These options can be used to correct other images and save the corrected versions if desired. This is not necessary since the application will automatically correct images on-the-fly if lens distortion coefficients are set.

Do not use corrected images for measurement if the lens distortion coefficients are also specified. This will result in the correction being applied twice and the resulting measurements will be distorted.

If you wish to correct an image:

1. Load the image to correct by clicking on **Load Image to Correct**.
2. Load lens distortion coefficients to use in correction. These should have been saved using the **Compute Lens Distortion** buttons to create a lens coefficient file (*.lens).
3. Click on **Correct Image**.
4. You can switch between viewing the original and corrected image by clicking on the **Show Corrected Image** checkbox at the bottom of the control panel.

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5. If you wish to save the corrected image, click on **Save Corrected Image**. It is recommended that you save to a different filename so that you do not overwrite the original image.