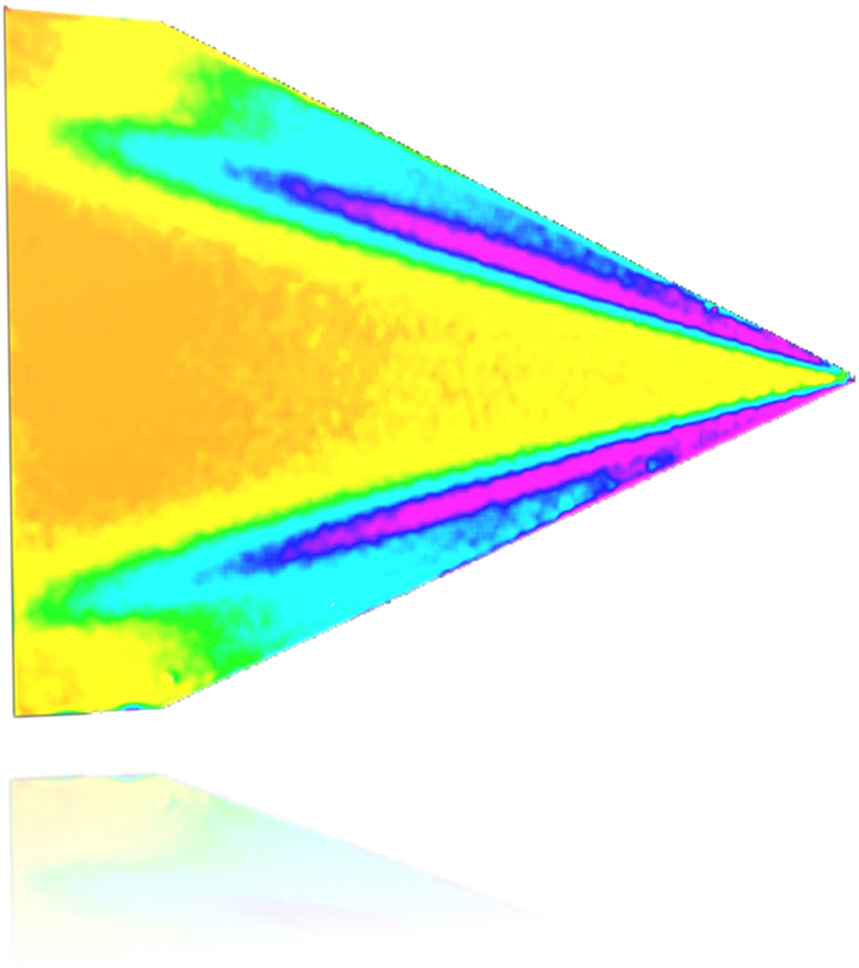
INNOVATIVE SCIENTIFIC SOLUTIONS, INC

LAB 3: LOW-SPEED DELTA WING



Steve Palluconi

7610 McEwen Road

Dayton, OH 45459

innssi.com

(937)-630-3012

Introduction

A wind tunnel is an important tool for aerodynamic research where PSP can provide data not available from pressure taps or balances. Many objects such as aircraft and automobile models are subject to wind tunnel testing and these can be painted with PSP to show pressure gradients and boundary layer transitions over the body.

Hardware

The PSP-CCD-C scientific CCD camera from is used in conjunction with an LM2X-DM-400 LED lamp. The LED lamp illuminates the test object, exciting the luminescent probe in the paint, and the emission from the probe is then captured by the camera through a 530 nm long-pass filter. As in the previous labs, the laptop connects to the camera to acquire data through ProAcquire and then reduces data in OMS-Lite. Refer to the ProAcquire user manual and hardware user manuals for detailed instruction on each.

Figure 1: PSP-CCD-C CCD Camera

Figure 2: LM2X-DM 400 nm LED Lamp

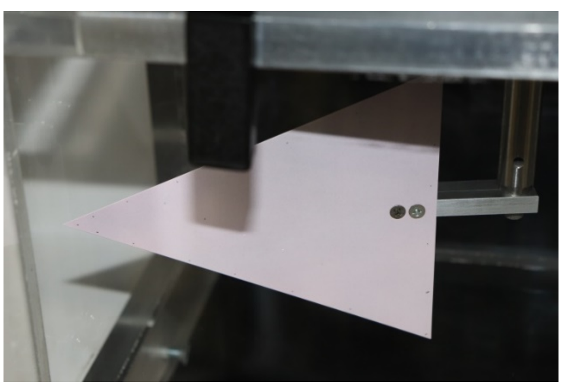


Figure 3: Delta test object

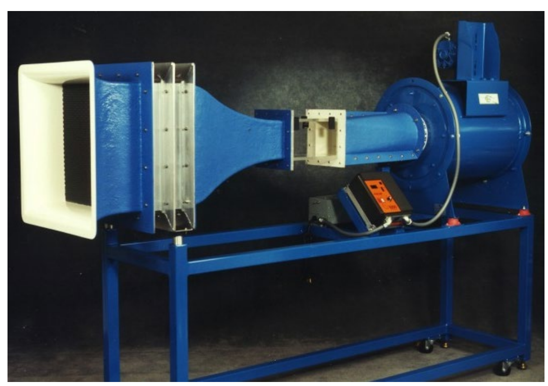


Figure 4: Wind Tunnel

A small delta wing is used inside the test window of a low-speed wind tunnel. This can be painted with either BinaryFIB® or Binary UniCoat pressure sensitive paint for this demonstration. Be sure to account for all power supplies and cables. Once all of the equipment is accounted for, it is time to set up the experiment. Users should complete Labs 1 and 2, which cover basic hardware and software setup and use, before beginning this exercise.

The PSG-3 pulse delay generator can also be used as the master timer if one was purchased.

Experimental Setup

The camera and LED lamp should be mounted so that they are rigid and do not move when the wind tunnel is being run. This will help to eliminate inaccuracies in the data. The camera and LED lamp should be positioned near the test window so that the camera can focus on the test object and the LED lamp can uniformly illuminate the surface as shown in Figure 5. Attach all power supplies to the camera, LED lamp, and the computer. More details of experimental setup and data acquisition are explained in Lab 2.

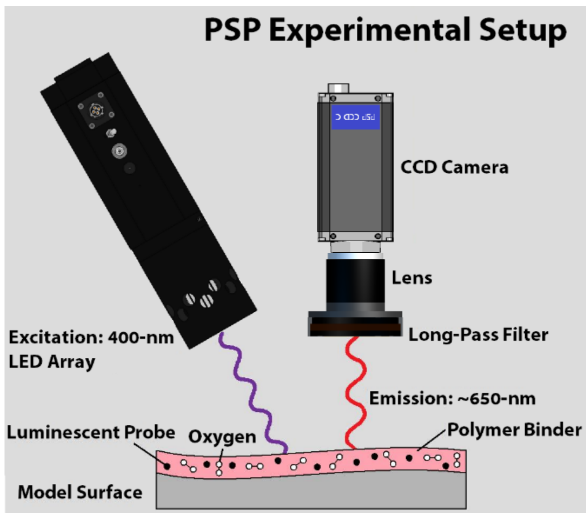
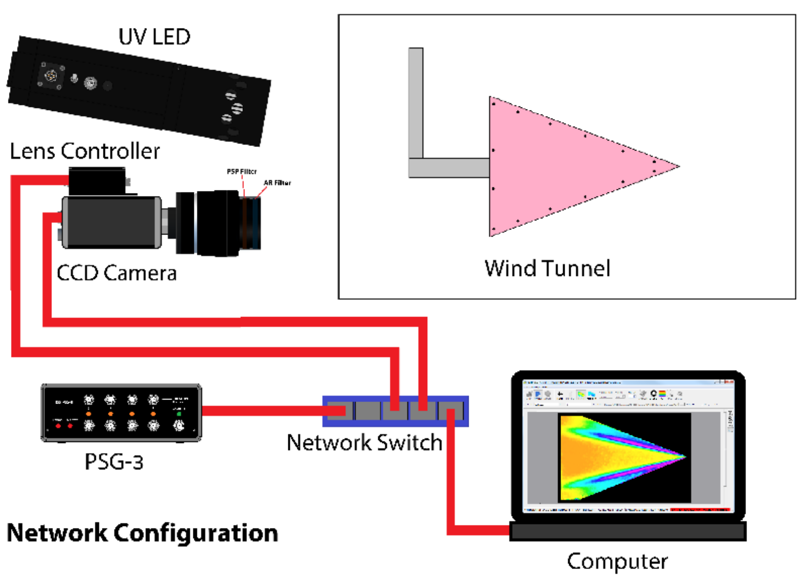


Figure 5: Experimental Setup

The wind tunnel has a test section window where the test object is to be placed. Mount the test object so that it is in the center of the test section. The angle at which the delta plane encounters the flow can be adjusted to the user's liking.



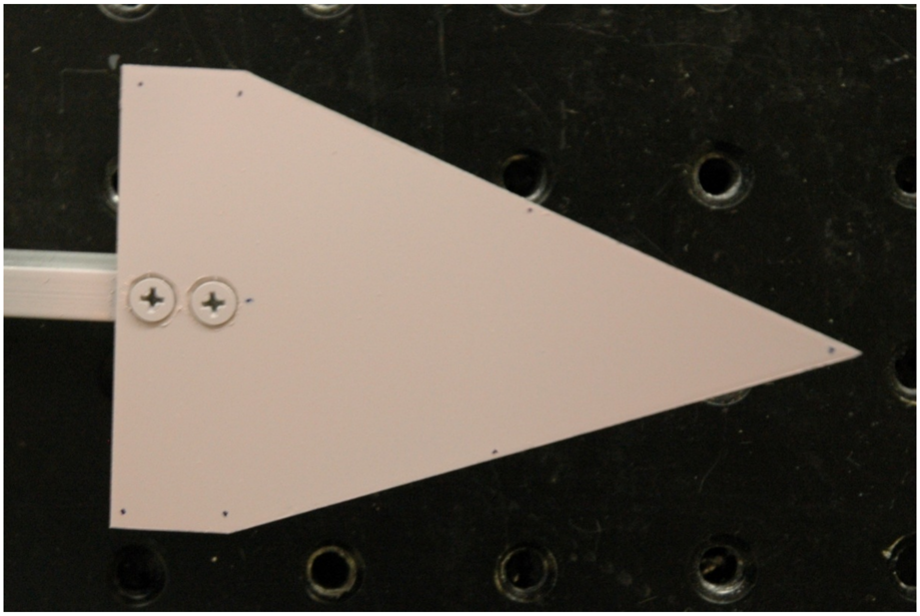


Figure 6: Markers on Painted Model

In wind tunnel tests where the test body is likely to move or deflect during data acquisition, it is necessary to use markers for image alignment. Markers can be physically placed on the test object by simply marking the painted surface with a marker or pen. This will show up on the wind-off and wind-on images as an area with little illumination since the paint is not visible. The user can use these reference points to create their markers. Figure 6 shows an example of markers placed on the test object prior to data acquisition. As discussed in the image alignment section below, the number of markers is important for the movement correction process. For this exercise 8 markers is sufficient.

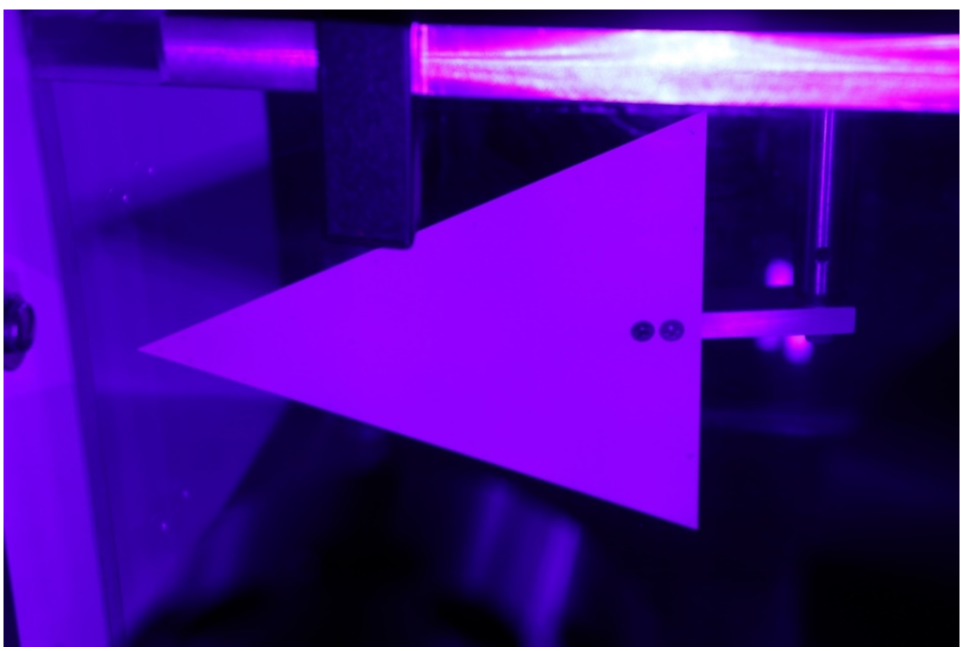
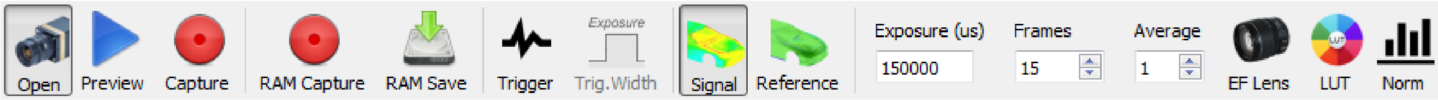
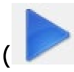
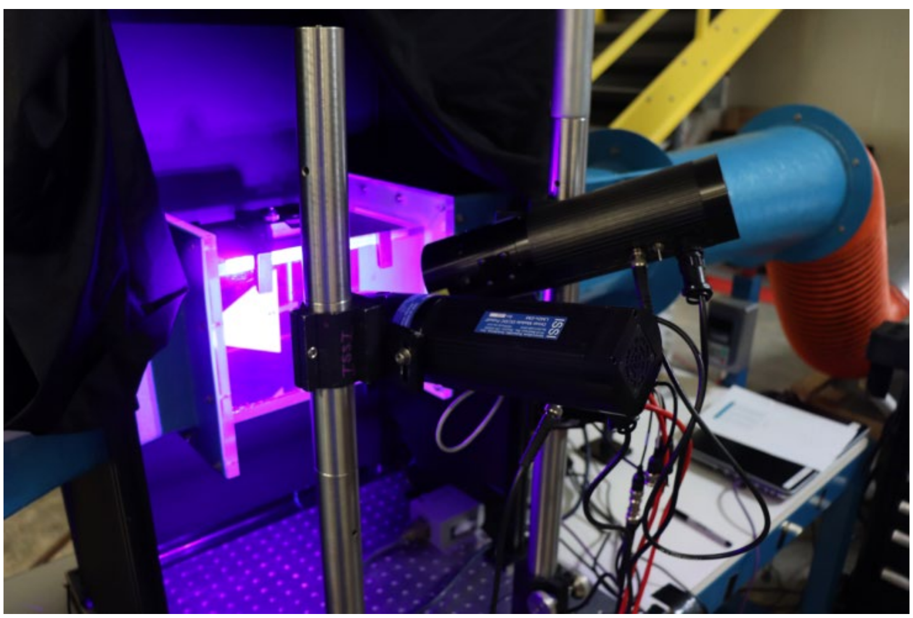


Figure 7: Wind tunnel test section

Data Acquisition



In ProAcquire (), use the live preview () to view the image seen by the camera and adjust the camera's focus so that the image in the preview is clear. Be sure to turn off or block any light sources to avoid noise in your data before data acquisition begins. Place the delta at a slight angle of attack (15-20 degrees) and mount securely in the test section. Capture the background image with the room lighting and the LED lamp turned off. Save the background image as *background.tif* in a new folder where all images will be stored. Create a new file each time a new image with different settings is captured by pressing the  icon in the upper left area of ProAcquire next to the file path description. We will demonstrate the frame average function and its improvement to the signal-to-noise ratio. Capture the wind-off images with the wind tunnel off. Set the frames to average to 4 and the exposure to a level where the image is not saturated. Turn the LED lamp on and allow it to stabilize before taking data. Capture wind-off images for frame averages of 4, 16, and 64 and save them each accordingly (Example: *wind_off_XXXms_Xfr.tif*). It is good practice to include some detail in the file name so it is easier to decipher later on when reducing the data.



Start the wind tunnel and let stabilize for a 1-2 minutes. Capture a wind-on image at chosen conditions using 4 frames averaged and save it as a name that will reference these conditions (Example: *wind_on_XXXms_Xmps_Xfr.tif*). Repeat this process while holding the airspeed steady and the exposure time constant while increasing the frames to average to 16, and 64. We will compare these later to see the advantages of averaging more frames. Once all images are captured, gradually slow down the airspeed of the wind tunnel and power off. All images for data reduction should now be acquired and saved.

Data Reduction

Reducing the data into an image of pressure involves taking the ratio of the wind-off / wind-on images and then calibrating the image to relate the ratio to pressure. Create a new project in OMS Lite using the PSP Single channel option. Select the folder that the data files taken are saved in. Save the project as ***low_speed_delta.pspproj***. In the GUI for the Single Channel tab in OMS Lite, load the wind-off, wind-on, and background images for the case of 4 frames averaged at 30 m/s. While selecting from the list of images at these conditions, you will notice that there are two images saved for each data point taken (Figure 8). The Bayer filter of the PSP-CCD-C (see quantum efficiency for PSP-CCD-C) matches the spectral emission of BinaryFIB® PSP, making it an ideal match for the paint. The images acquired by the color camera are split into the different color planes of the Bayer mask by use of the ***Split Colors*** function. This will split the array into red, green and blue signal. The red image is what is called the pressure sensitive image because the pressure sensitive emission is captured here. The green image is referred to as the reference image because it captures the signal of the pressure in-sensitive reference. The blue is unused.

This split gives the final images ¼ the resolution of the full array. However, this allows acquisition of the pressure sensitive and reference image on the same camera frame. The camera will only save a red and green image noted with _p (pressure sensitive) and _r (reference).

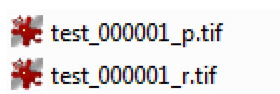
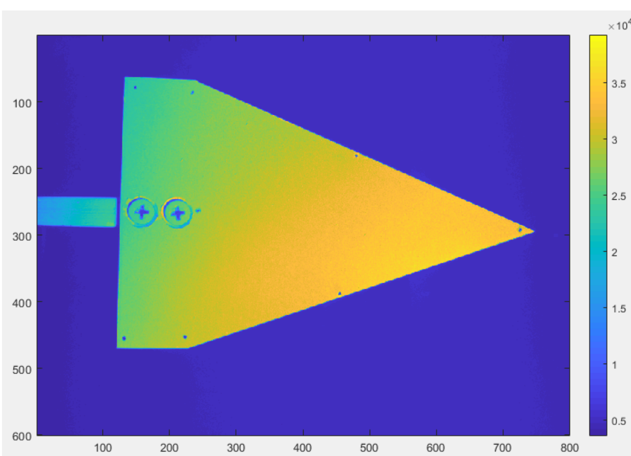


Figure 8: Locating the signal channel

Notice in Figures 11 and 12 below, the difference in intensity on the right hand toolbar and in the color of the images.



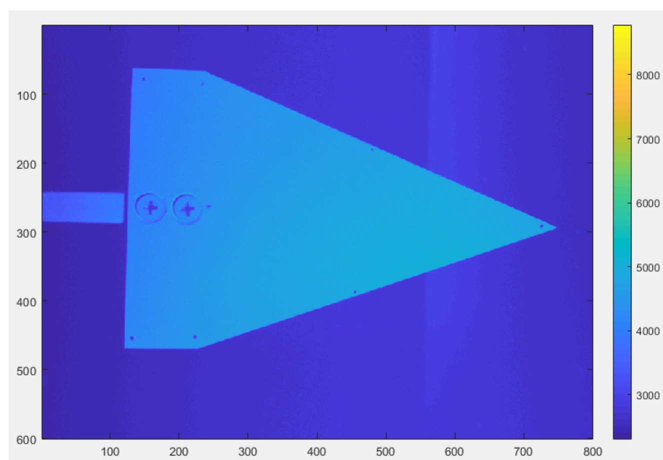


Figure 9: Signal Channel Uncorrected Image (Wind-Off), Figure 10: Reference Channel Uncorrected Image (Wind-Off)

The yellow and orange image is the signal and the blue image is the reference channel. The signal channel goes up to around 35000 counts in intensity while the reference only goes up to about 5000 counts. Once this is known for one case it will remain the same for all. The signal channel will not change from case to case; it is constant for each camera.

The same background image may be used in all cases and should be the signal channel as well. Examine the wind-off and wind-on images and set the dark threshold near to the signal level of the background of the image (colored blue in Figures 9 and 10).

<u>Process the data without filtering or aligning:</u> If we first process the data without using any of the filtering or alignment options, we can see the improvement those features provide. The image used here was the 4 frame averaged. Do not apply any of the filters or markers when creating the ratio image. Load the paint calibration file ***BinFib-B.pspcal*** and enter the test conditions for your experiment (Mach = 0.1, atmospheric temperature and pressure, dynamic pressure of ~500 Pa and $\alpha = 15$, $\beta = 0$). Compute the pressure image and adjust the paint minimum and maximum levels so that you see an image with clarity similar to Figure 11. Use this image as a reference for the filtered and aligned images to check for improvement.

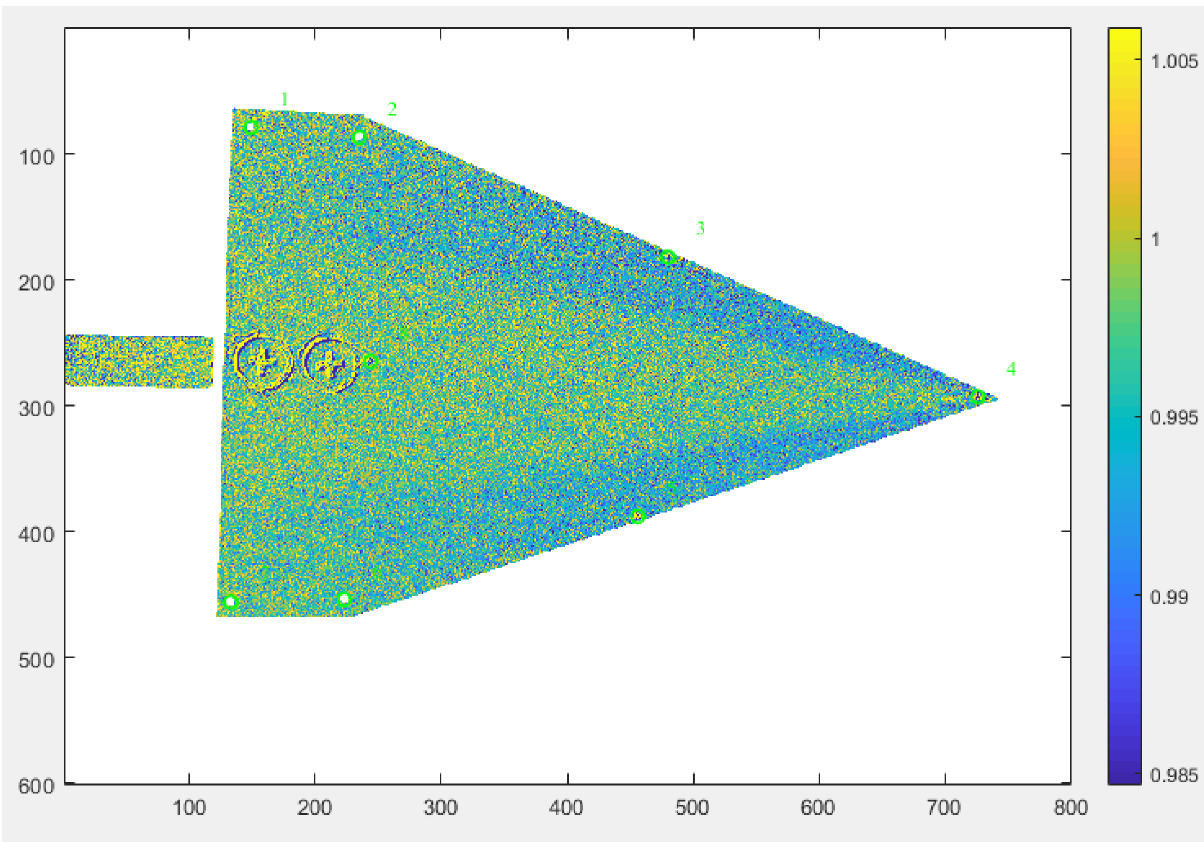


Figure 11: Unfiltered Pressure Image (4 Frame average, 30 m/s)

Registration Markers

The marker application allows the user to add, move or remove registration markers from the bitmap image. Markers are used for image registration to correct for model movement between wind-off and wind-on conditions and for pressure tap correction where pressure taps are present.

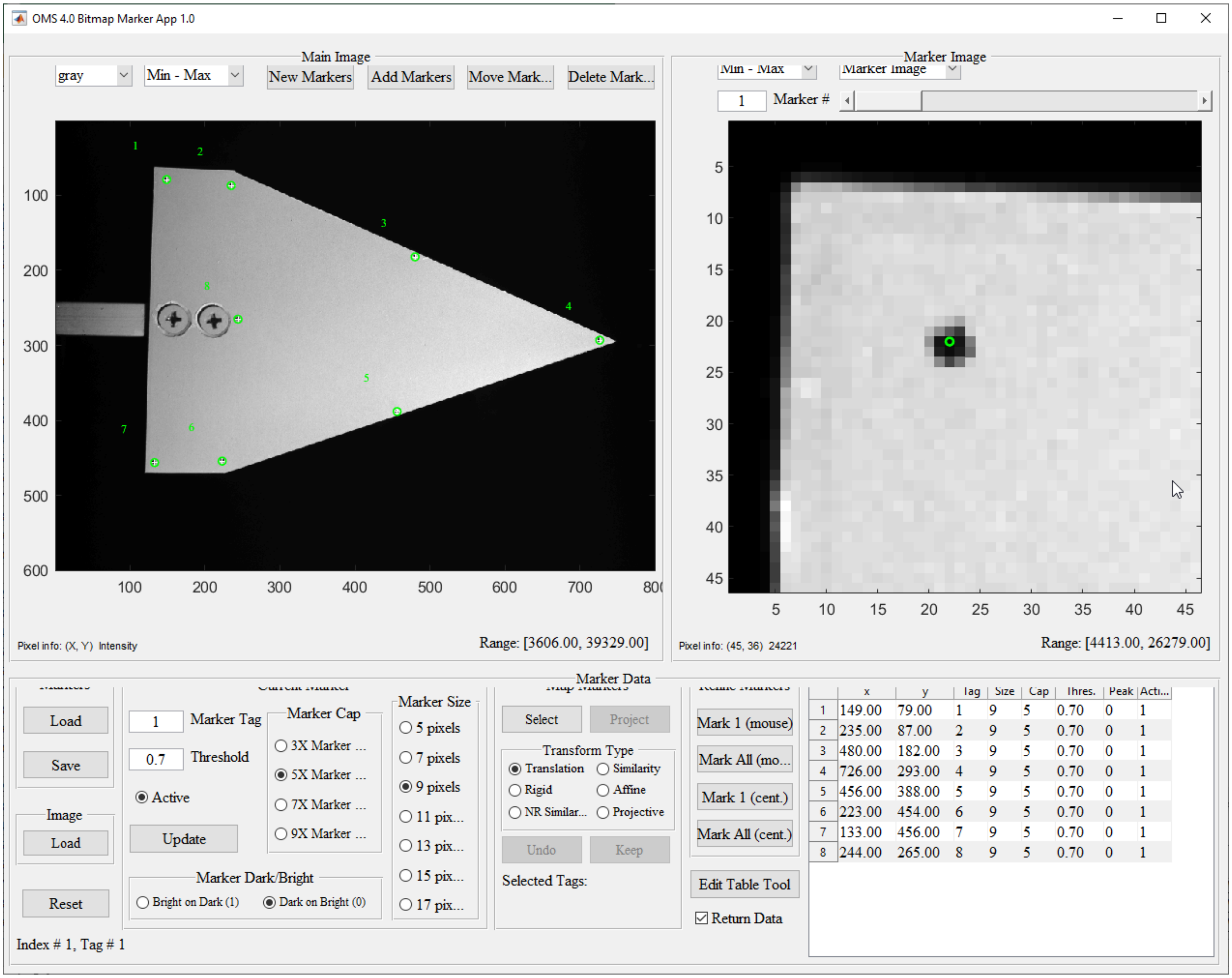


Figure 14: Marker Application

Markers

Save/Load – save and open existing markers or marker files

Image

Load – load an image into the Marker App

Reset – clear all images and markers from the Marker App

To add new markers to an image, select the **New Markers** button at the top of the screen.

Clicking **New Markers** will pop up a green box. Drag this box to the first marker and double-left-click the mouse to set it as a marker. **Add Markers** will add additional markers to an existing marker set. There are 8 registration markers on this dataset.

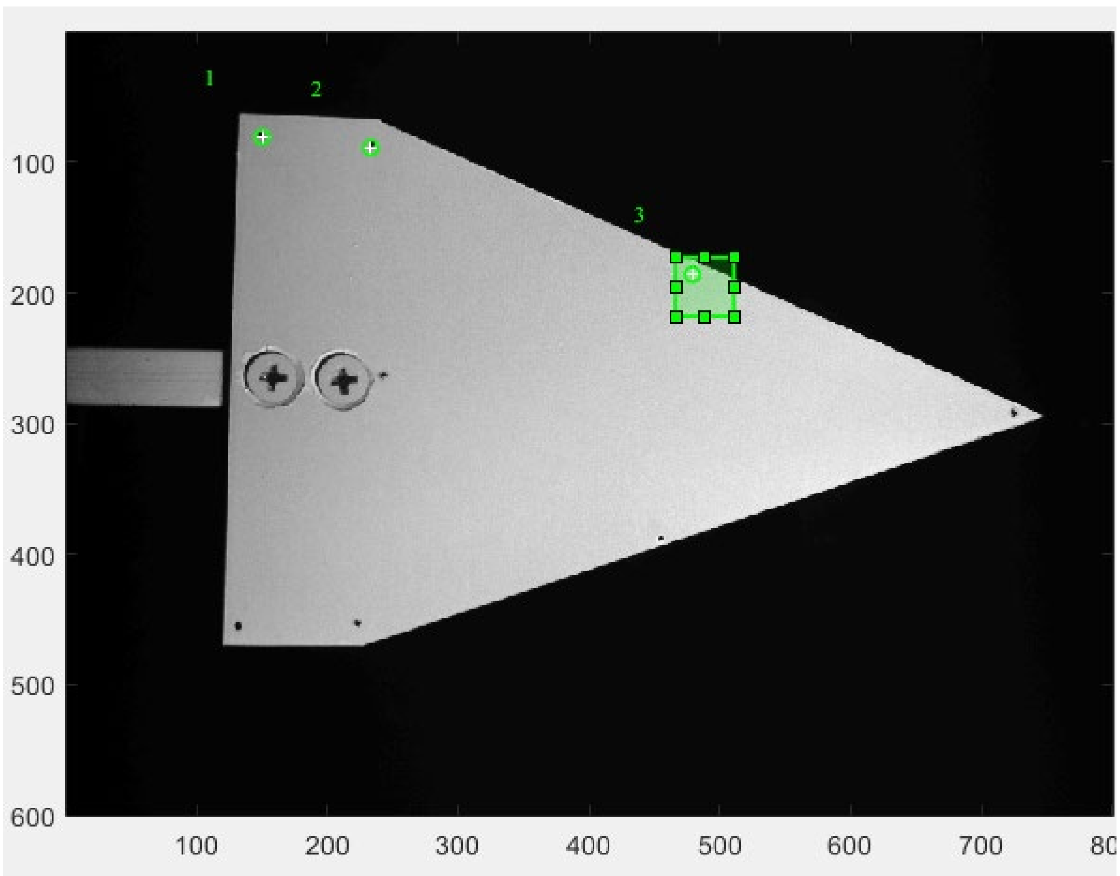
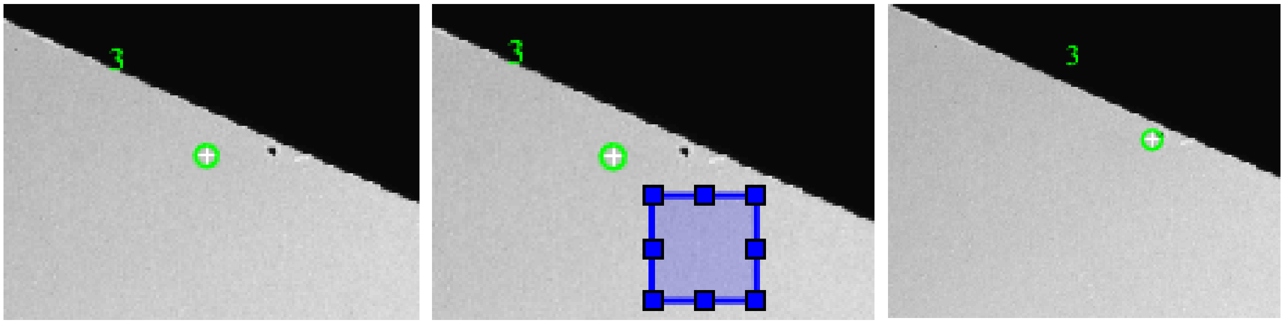
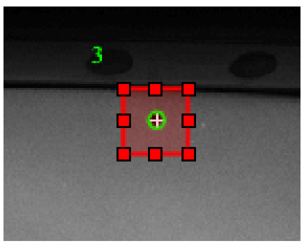


Figure 15: Adding markers to the uncorrected image

To move an existing marker, click the **Move Marker** button on the top toolbar of the main image screen. A blue box will appear. Drag the blue box over the marker to be moved. Double-click on the marker. Now a green box will appear. Drag the green box to the physical marker location where you want to place this bitmap marker. Double-click on the physical marker location. The marker will now move to the physical marker location.



To delete an existing marker, click **Delete Marker**. A red box will appear on the image. Drag this box over to the marker and double-left-click on the marker to delete it.



Current Marker

To change the current marker being viewed, use the slider or text window on the right side zoomed-in view called Marker Image.

This tool set allows for adjustment of each marker on the bitmap.

- sets the tag number of the current marker

Threshold - sets the threshold value of the current marker (0.1 to 0.9)

Marker Dark/Bright – select the marker type, dark marker on bright background or a bright marker on a dark background.

Marker Cap – selects the size of the marker selection tool window

Marker Size – size of the expectant physical marker on the bitmap

Refine Markers

Marker positions may need refinement due to non-centered placement when they were manually positioned. Marker refinement tools find the center point (peak or pit) of each marker automatically using the existing marker position and a cross-correlation algorithm to center the marker in the same position on the marker in all images. This is necessary for proper image alignment due to model movement between wind-off and wind-on conditions.

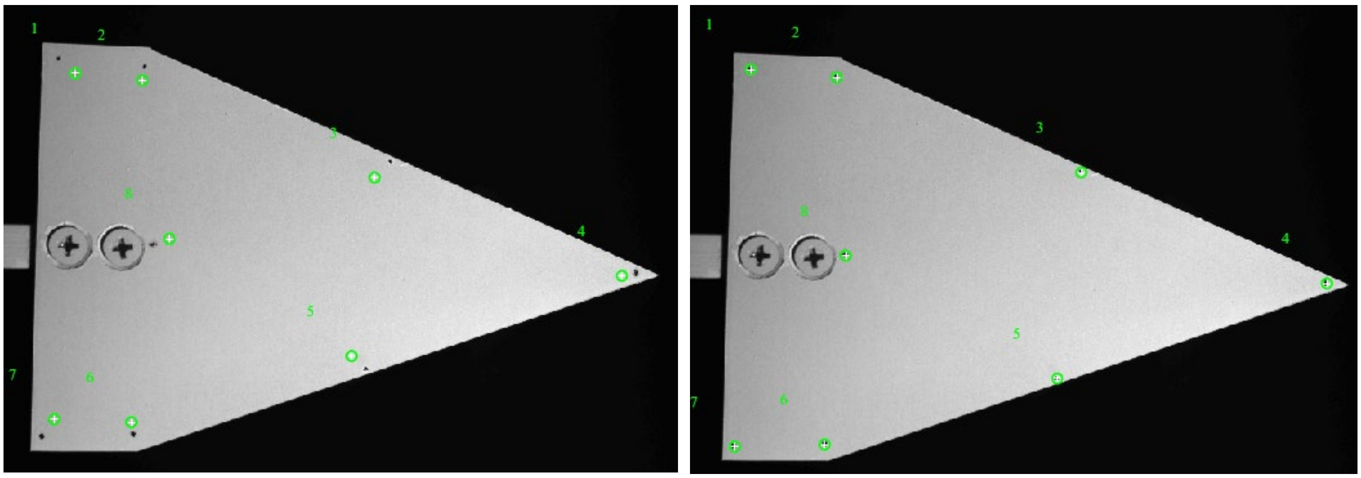


Figure 16: Markers Before (left) and After (Right) Refinement

Manual Refinement

Mark 1 (Mouse) – Refine current marker position manual using mouse. Double-left-click on the green box once it is centered around the physical marker location.

Mark All (Mouse) – refine all marker positions manually using mouse. Once selected the program will move to each marker automatically after the manual revision. Double-left-click on the green box once it is centered around the physical marker location.

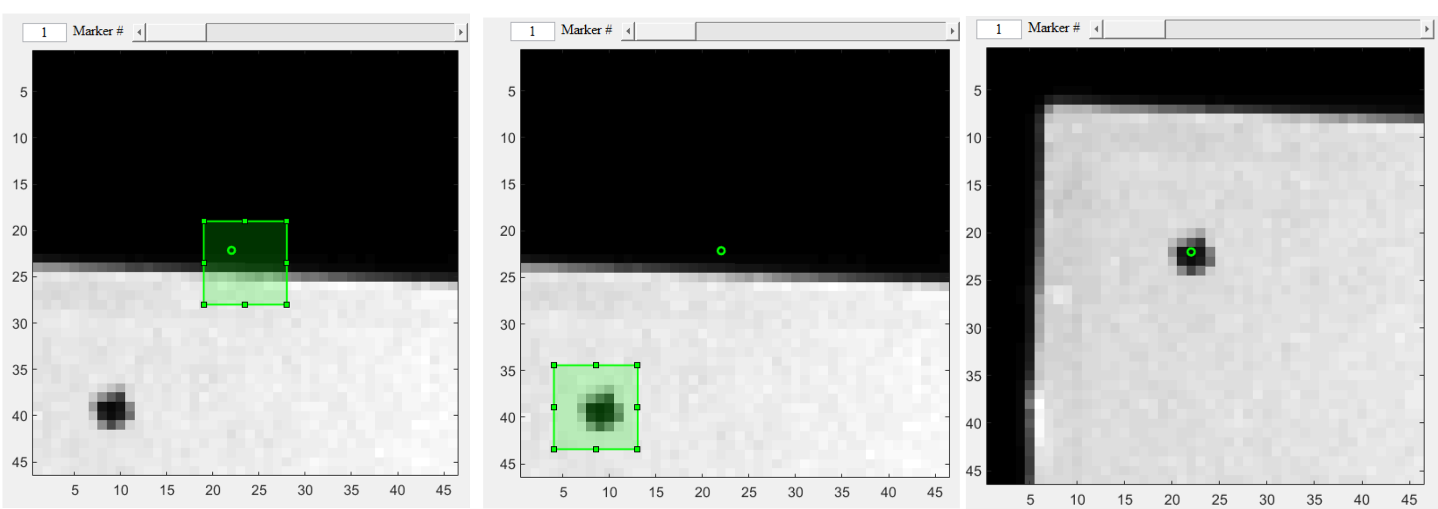


Figure 17: Marker Refinement

To exit, right click the mouse inside the green box.

Automatic Refinement

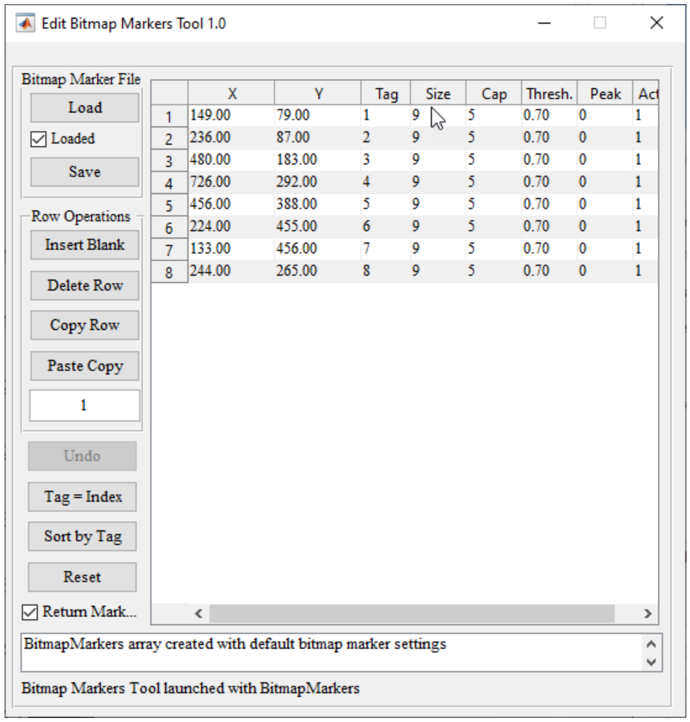
Mark 1 (Center) – refine marker position on current marker using centroid calculation.

Mark All (Center) – refine all marker positions to find the center point of each physical marker using centroid calculation. When manually marking images, it is not necessary to mark each individual image in a wind-off/wind-on set. For example, mark the wind-off image of a camera view and then save the markers corresponding to that image. Now open the wind-on image of that same camera view. Load the markers that were saved for the wind-off image. They will all be shifted from the center of the makers on the wind-on image because the model moves relative to the camera between wind-off and wind-on. Click the **Mark All (Center)** button and the marker tool will automatically revise each marker so that it is at the center point of each physical marker.

Marker Table – the marker table displays the XY location of each marker, the enumeration and the tag associated and the cap size used to select the marker. Active and inactive markers are indicated by a 1 or 0. 1 is active and 0 is inactive and will not be used for image alignment or pressure tap correction.

	x	y	Tag	Size	Cap	Thres.	Peak	Acti...
1	149.00	79.00	1	9	5	0.70	0	1
2	236.00	87.00	2	9	5	0.70	0	1
3	480.00	183.00	3	9	5	0.70	0	1
4	726.00	292.00	4	9	5	0.70	0	1
5	456.00	388.00	5	9	5	0.70	0	1
6	224.00	455.00	6	9	5	0.70	0	1
7	133.00	456.00	7	9	5	0.70	0	1
8	244.00	265.00	8	9	5	0.70	0	1

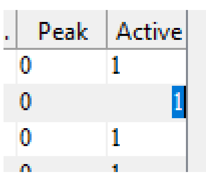
Edit Table Tool – will allow for indexing the markers to match tag enumeration to the index or allow for the tag to be changed to match existing drawings for pressure taps or markers on the model. Many times, markers are added manually using a pen and then these locations are manually or automatically selected using the marker application, paying no attention to the enumeration used by the model mesh or pressure tap map. Editing the tag number of each marker allows the user to match the tag to the physical marker it's matched with so that they have the same enumeration on the physical model and bitmap data during post-processing.



	X	Y	Tag	Size	Cap	Thresh.	Peak	Act
1	149.00	79.00	1	9	5	0.70	0	1
2	236.00	87.00	2	9	5	0.70	0	1
3	480.00	183.00	3	9	5	0.70	0	1
4	726.00	292.00	4	9	5	0.70	0	1
5	456.00	388.00	5	9	5	0.70	0	1
6	224.00	455.00	6	9	5	0.70	0	1
7	133.00	456.00	7	9	5	0.70	0	1
8	244.00	265.00	8	9	5	0.70	0	1

Figure 18: Marker Tool Table

Markers can be saved or loaded from this window. Markers can be made active or inactive in this window. Active =1, Inactive =0.



Peak	Active
0	1
0	1
0	1

Click on the number shown in the ***Active*** column for the marker you want to activate/deactivate and set type 1 or 0.

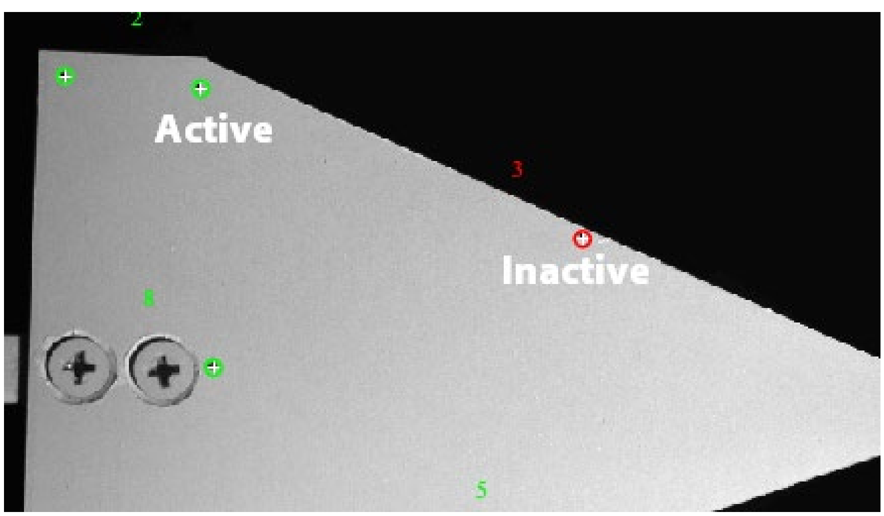


Figure 19: Active/Inactive Markers

Row Operations

Insert Blank – inserts a blank row into the marker list where values can be manually entered.

Delete Row – removes an existing row from the list

Copy Row – copies an existing row to the clipboard

Past Row – paste an existing row to the list

The text box shows which row the operation will be performed on

Undo – go back one operation

Tag=Index – sets the tag number to the index number

Sort by Tag – sort the rows based on tag number only (lowest to highest)

Reset – revert to original enumeration and arrangement

Image Alignment

The ***Registration Application*** allows you to test out different image alignment tools using the markers to optimize the alignment for the dataset. There are several options for mapping algorithms to choose from. These options correspond to the type of model movement between the fixed and moving images, anywhere from simple 2D translations to complex twisting and bending.

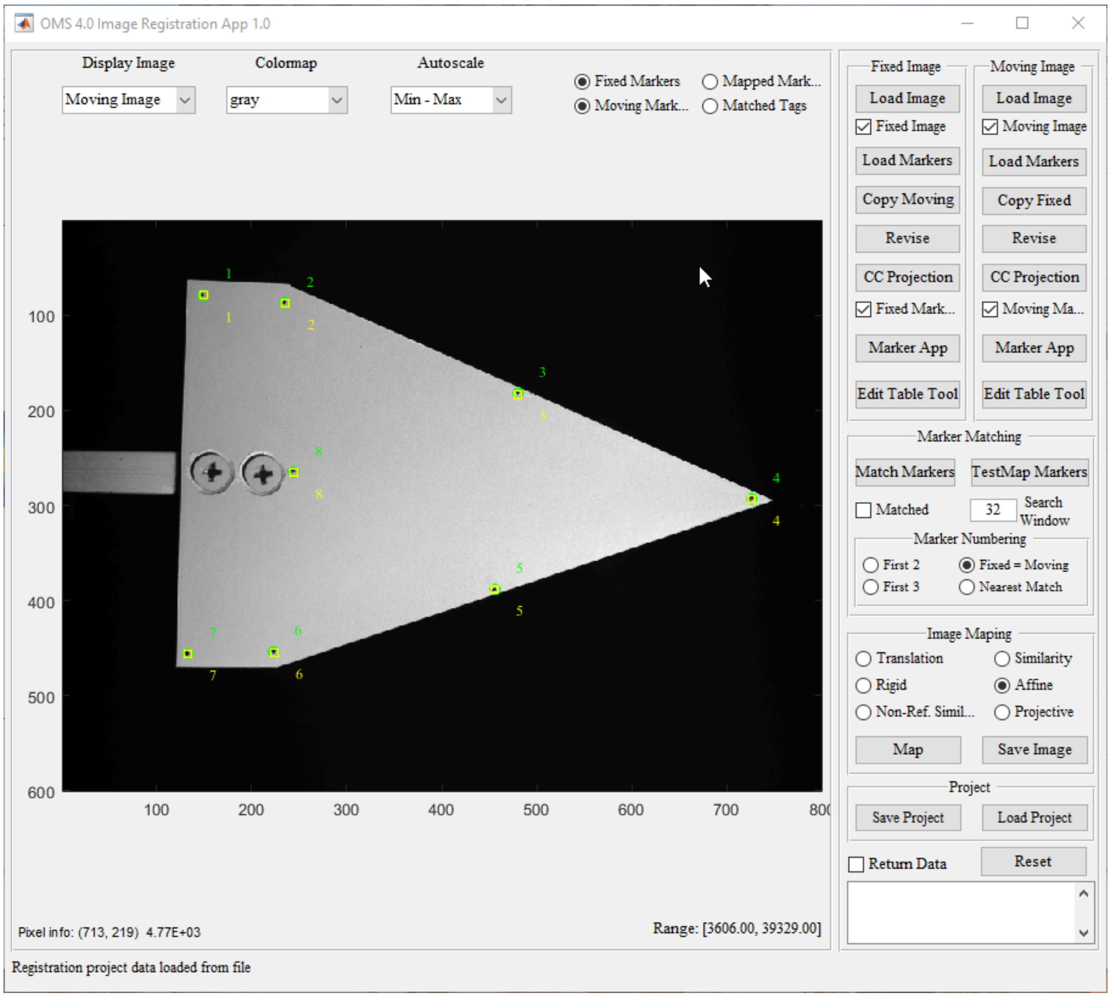


Figure 14: Registration Application

Translation: Warp moving image using translation transform based on control points. Used for 2D translational movements of the model between fixed and moving images.

Rigid: Warp moving image using rigid transform based on control points. For rigid 1D or small movements

Non-Ref Similarity: Warp moving image using non-reflective similarity transform based on control points.

Similarity: Warp moving image using similarity transform based on control points.

Affine: Warp moving image using affine transform based on control points.

Projective: Warp moving image using projective transform based on control points.

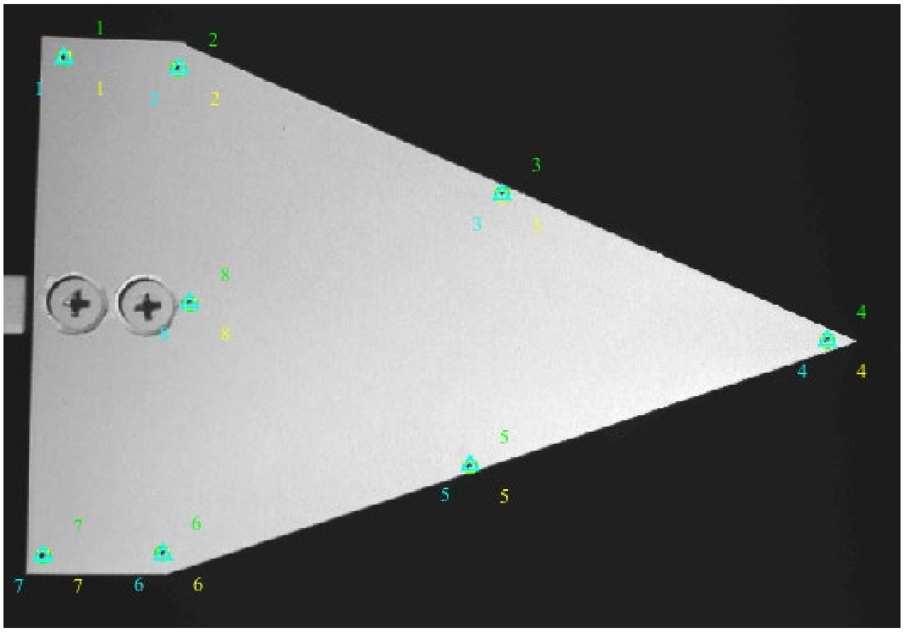
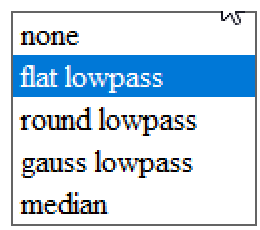


Figure 15: The Fixed-Mapped image showing the image alignment after mapping using the Registration App

For this example, an ***Affine*** image mapping was used. Marker Number of ***Fixed=Moving*** was used meaning fixed marker numbers are identical to the moving marker numbering. You will notice almost no alignment issues with this dataset as the model did not move significantly during data acquisition. Once the image has been mapped, save the mapped image and save the project from the Registration Application in the same folder where the data is stored. To load a previously saved registration project file, click ***Load Project***.

Digital Image Filtering



Digital image filtering is used to reduce shot noise, remove paint imperfections and shrink the look-up table of the image to better visualize gradients in the image. This is often necessary in PSP data processing, especially for low-speed data where the dynamic pressure is very small and gradients are closer to the noise level of the image. Shot noise is a result of the digital image acquisition and can add a speckle pattern to the image. This problem gets worse the warmer the image sensor gets. Ways to reduce or remove shot noise are to keep the sensor cooler, take a longer record of images to compute the average and to apply smoothing filters to the image in post-processing. Each time a smoothing filter is applied, the pixel to pixel variation is being reduced to produce a smoother image. Each time one is applied, the minimum and maximum (look-up table) values change. There are 4 options available for image filtering. Filter types and sizes can be tested in the ***Image Viewer*** tool before applying them to the project data.

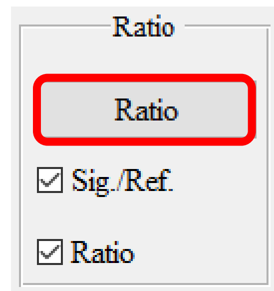
Flat Lowpass: This linear filter computes the average value of the pixels in the selected region in a square and assigns that average value to all pixels. This is also known as a box filter.

Round Lowpass: This linear filter computes the average value of the pixels in the selected region in a circle and assigns that average value to all pixels.

Gauss Lowpass: This is a non-uniform lowpass image-blurring filter which convolves the image with a 2D Gaussian function. Gaussian filters are used to blur and remove noise from images. The Gaussian filter is not effective at remove salt and pepper noise from images.

Median: A median filter is a non-linear digital filter which is used to remove noise from an image. The median filter goes through the image pixel by pixel and replaces each pixel value with the median value of the neighboring pixels. Median filters force pixels with distinct intensities to be more like their neighbors, getting rid of intensity spikes (salt and pepper noise) which distinguish them. The median filter preserves the edges of the image while removing noise.

Filter Pre-Ratio will apply the selected filter to the PSP images before any image alignment or ratio is calculated. This is used to clean up data with higher shot noise. Select the X-Y pixel size (3-21) for the filter and the filter type and make sure to click the ***Active*** box to enable this filter.



The **Post-Ratio Filter** applies one of the low pass filters to the ratio image once computed. Select from one of the lowpass filter options, select pixel size (X-Y) and check the box for **Active** to enable this filter.

Click ***Ratio*** again to recompute the ratio if you change post ratio filter or thinning filter.

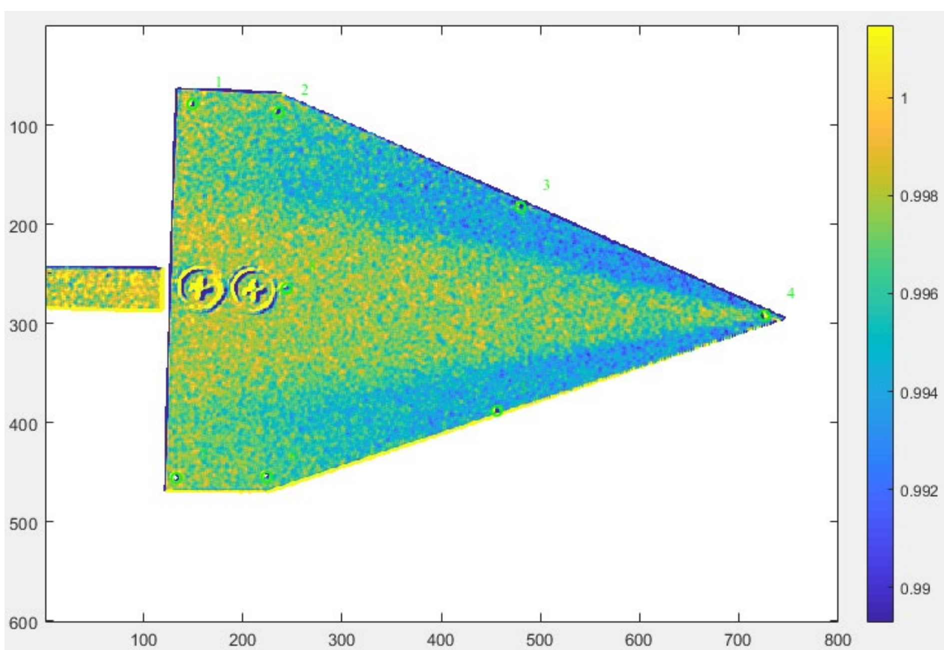


Figure 12: Ratio Image with Lowpass Filter (4 pixels)

A 4-pixel lowpass filter still leaves plenty of shot noise in the processed image. Using a larger lowpass filter size of 16 pixels gives a better visualization of the pressure gradient, reducing the image shot noise effect, shown in Figure 13.

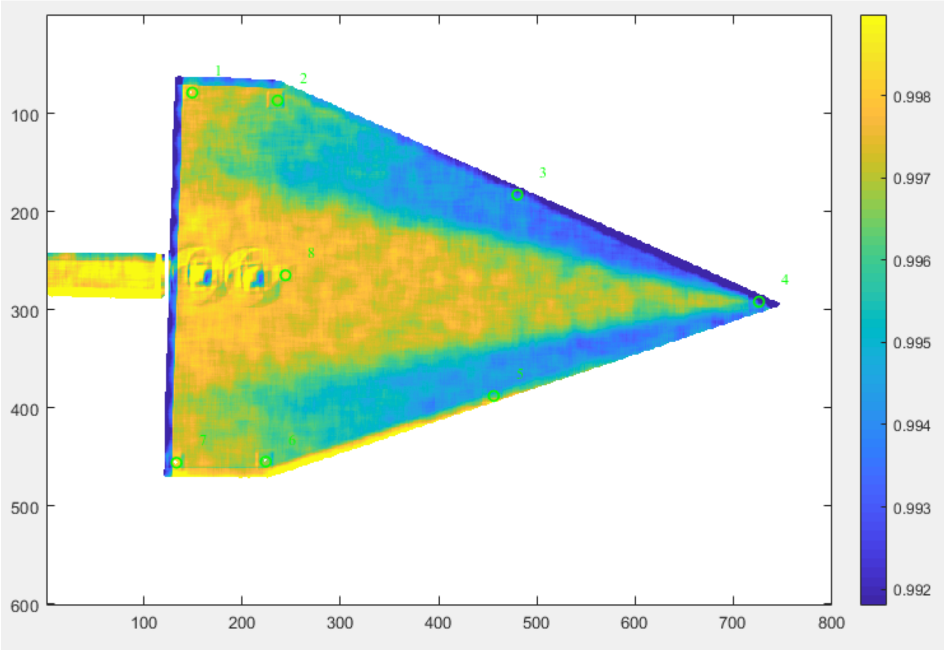


Figure 13: Ratio Image with Low-Pass Filter (16 pixels, 16 frames)

Repeat the same process for the higher frame averaged images to see the effects of the low-pass filter.

The ***Thinning Filter*** is used to remove the edges of the active image area. When computing a ratio, there are often edge effects from small alignment errors or poor signal level. These will show as dark or bright borders (see Figure 16) around the active area of the image. It is preferable to remove these areas before applying smoothing filters so they do not affect the PSP data. Choose the appropriate size for the dataset you are working with. For this dataset, a 7-pixel thinning filter was used.

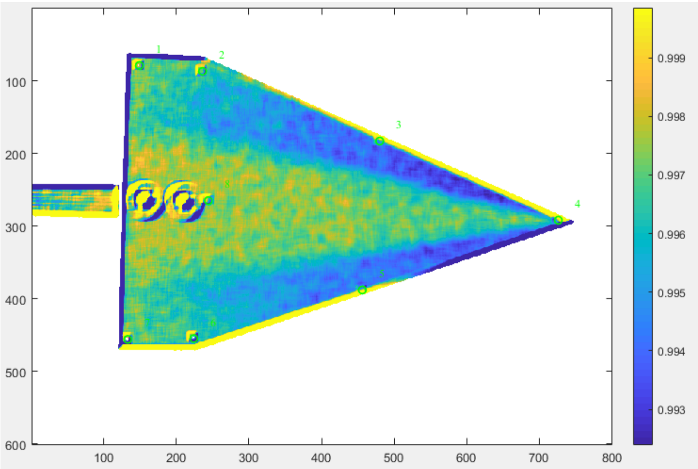


Figure 16: Ratio image *without* thinning filter applied

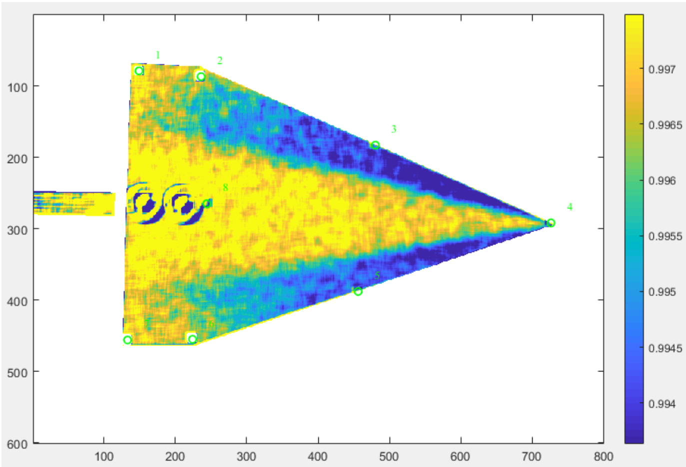


Figure 17: Ratio image *with* 7-pixel thinning filter applied

Processing Script

The processing script condenses all image processing functions into one window so that they can be saved and used on additional datasets. If you are processing a batch of single images individually, this script can be loaded into each project file rather than re-entering all parameters each time. The script for this dataset is shown in Figure 18.

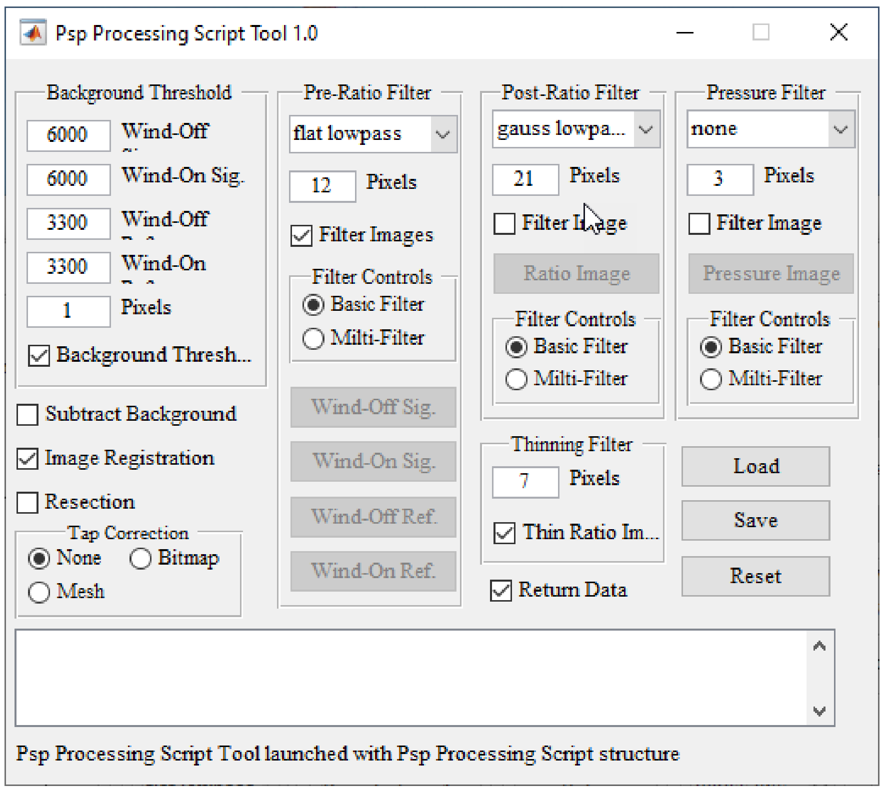
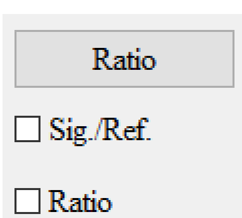


Figure 18: Processing Script for Delta Wing Project

To save the script to use for other datasets, click ***Save***. The script will be saved with the file format **.pspscript**.

Image Ratio

When all filters and alignment tools have been decided for the dataset, the image ratio can be computed.



To compute the wind-off/wind-on image ratio, click the Ratio button. This will also compute all filtering and alignment functions stored in the processing script. The image ratio will next be converted to pressure.

Conversion to Pressure

Enter the test conditions for the wind tunnel when the data was acquired. This test was performed at ambient conditions in a low-speed wind tunnel. The test conditions for this dataset are shown in the test conditions tool table in Figure 19.

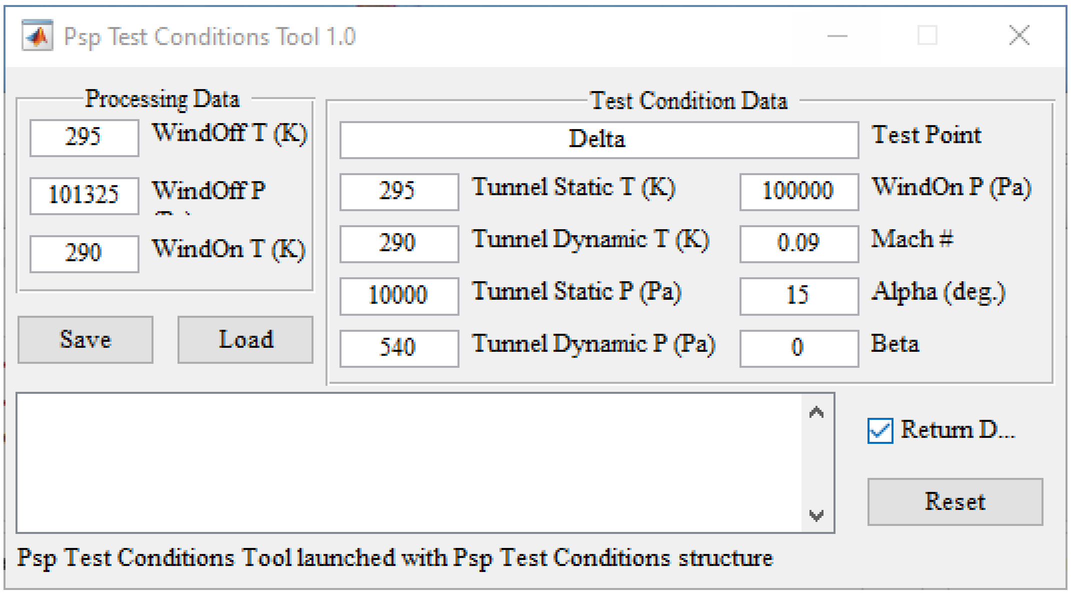
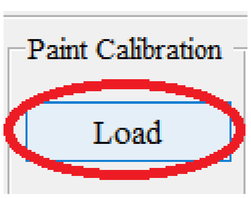


Figure 19: Test Conditions for Delta Wing

Paint Calibration

The paint calibration tool within OMS 4.0 is used to load a previously saved calibration file into the project file. This calibration file is used to convert the intensity ratio to pressure, Cp or temperature values. This tool also features all the calibration post-processing tools used to create and edit a calibration from a dataset.

Use the ***BinaryFIB-B.pspcal*** file for this dataset.



Once the paint calibration has been loaded into the project file and the test conditions entered, the ratio image can be converted to pressure or temperature values. Prior to conversion to pressure, a digital image filter can be applied to the pressure image. In the ***Pressure Filter*** section, choose the filter type (same as outlined above in the ***Image Processing*** section) and size. Check the ***Active*** box to enable the filter upon conversion to pressure.

Process the data and use filter sizes that will give the largest improvement to the pressure gradient in the image. In this case, the computer pressure image is applied a final 12-pixel Gauss lowpass filter.

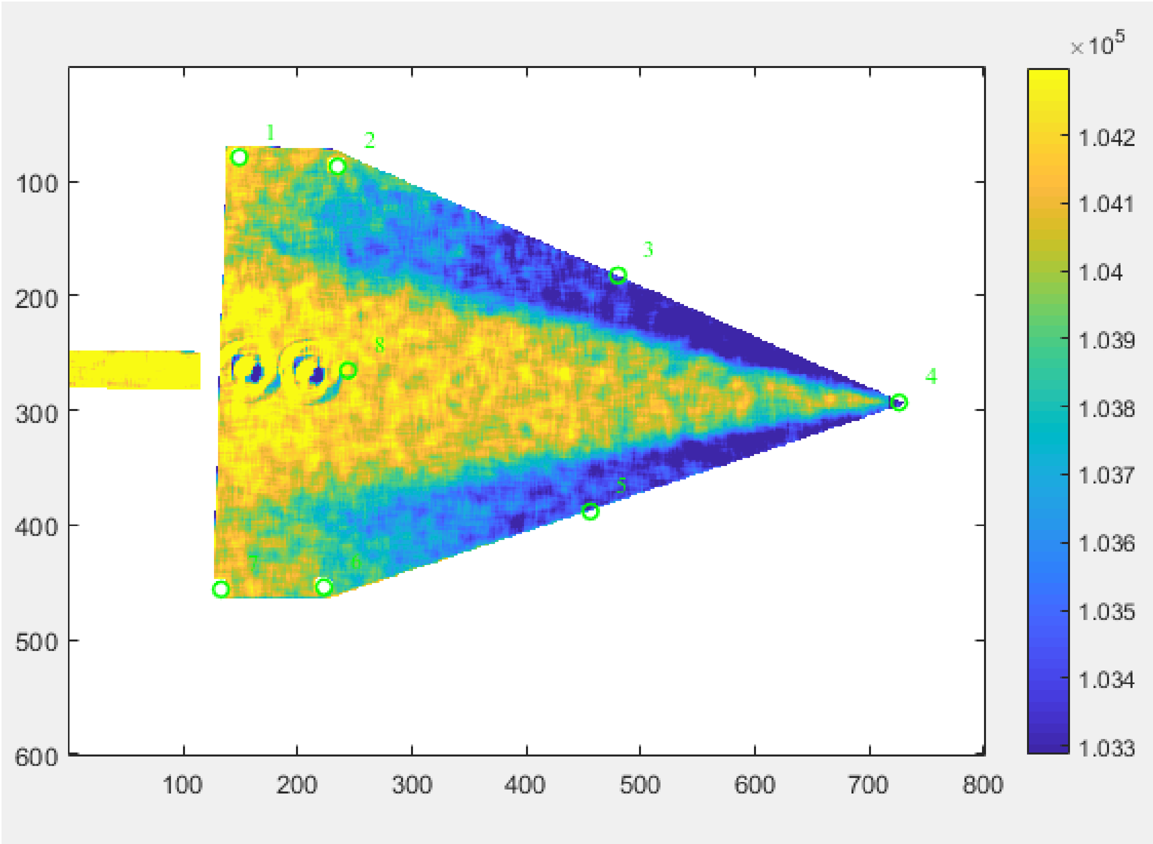


Figure 20: Final Filtered & Aligned Pressure Image

The pressure gradient is very evident in Figure 20, the filtered pressure image. You can also now observe effects that were not as clear in the unfiltered image. Notice the vortex that is now visible along the edge of the wing. Compare this computation to the known model (Figure 21 and 22) of a delta wing and you will see that the PSP system accurately captures the vortices along the edges. The rotation of the vortices at the edges produces the lower pressure seen on the pressure map. The tighter the rotation of the vortex, the lower the pressure on the surface. As the vortex makes its way down the wing, it unwinds a bit, increasing in diameter until it dissipates and breaks down. Notice the vortex start to break down (Figure 20 and 22) near the trailing edge.

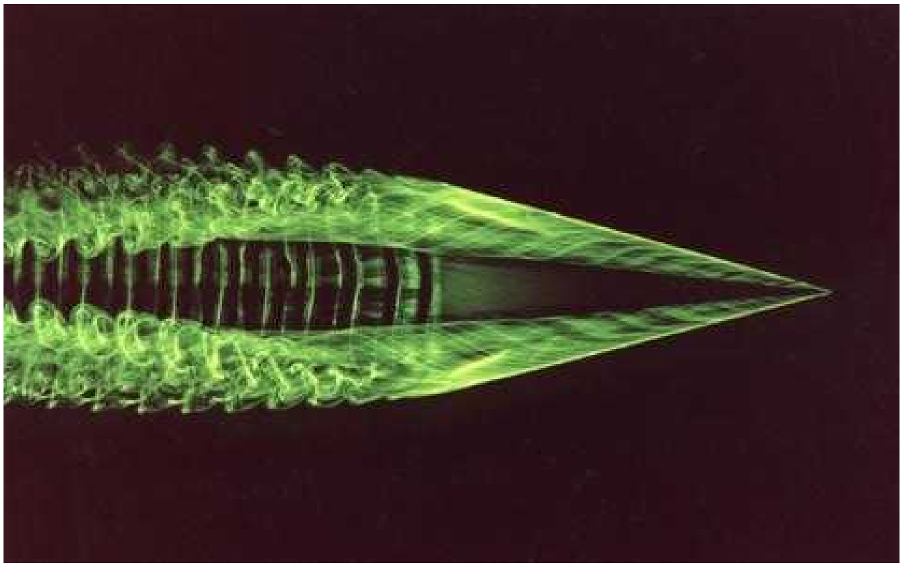


Figure 21: Flow visualization over a delta (Courtesy: Professor Charles Williamson, Cornell University)

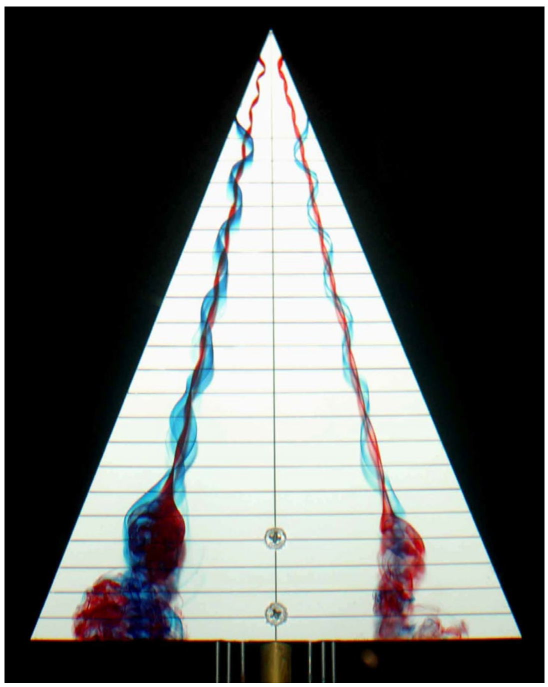


Figure 22: Vortex breakdown visualization (Courtesy: Professor T.T. Lim, National University of Singapore)