ISSI

INNOVATIVE SCIENTIFIC SOLUTIONS, INC

Lab 2: PSP Data Acquisition and Processing

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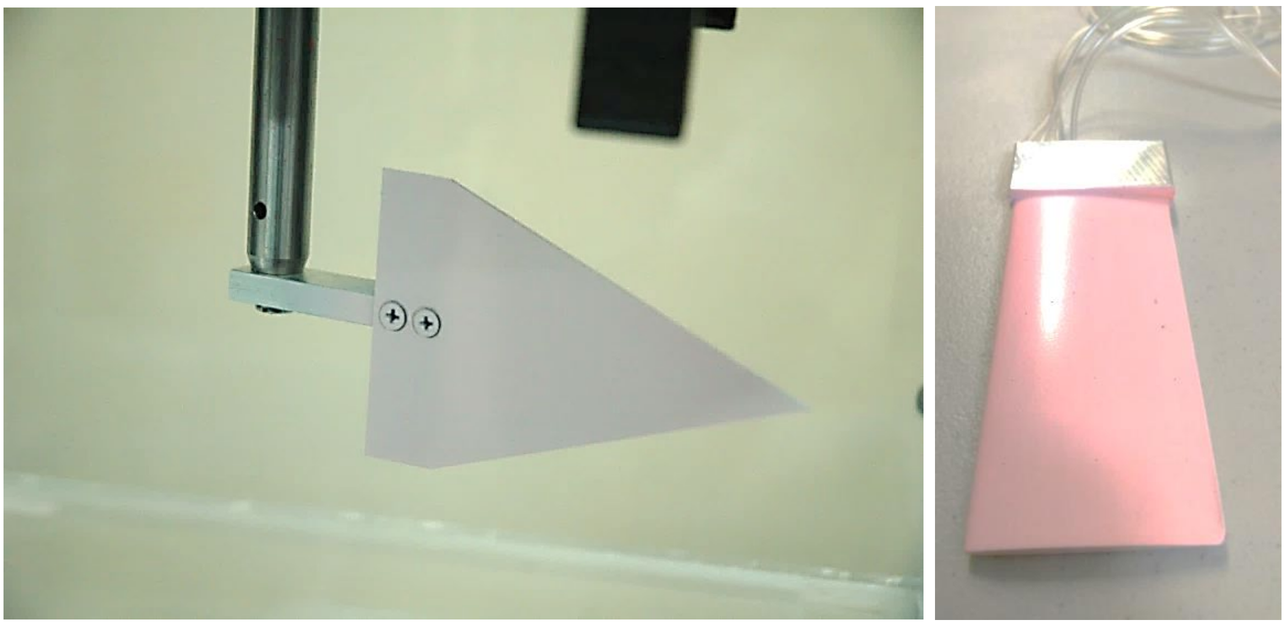
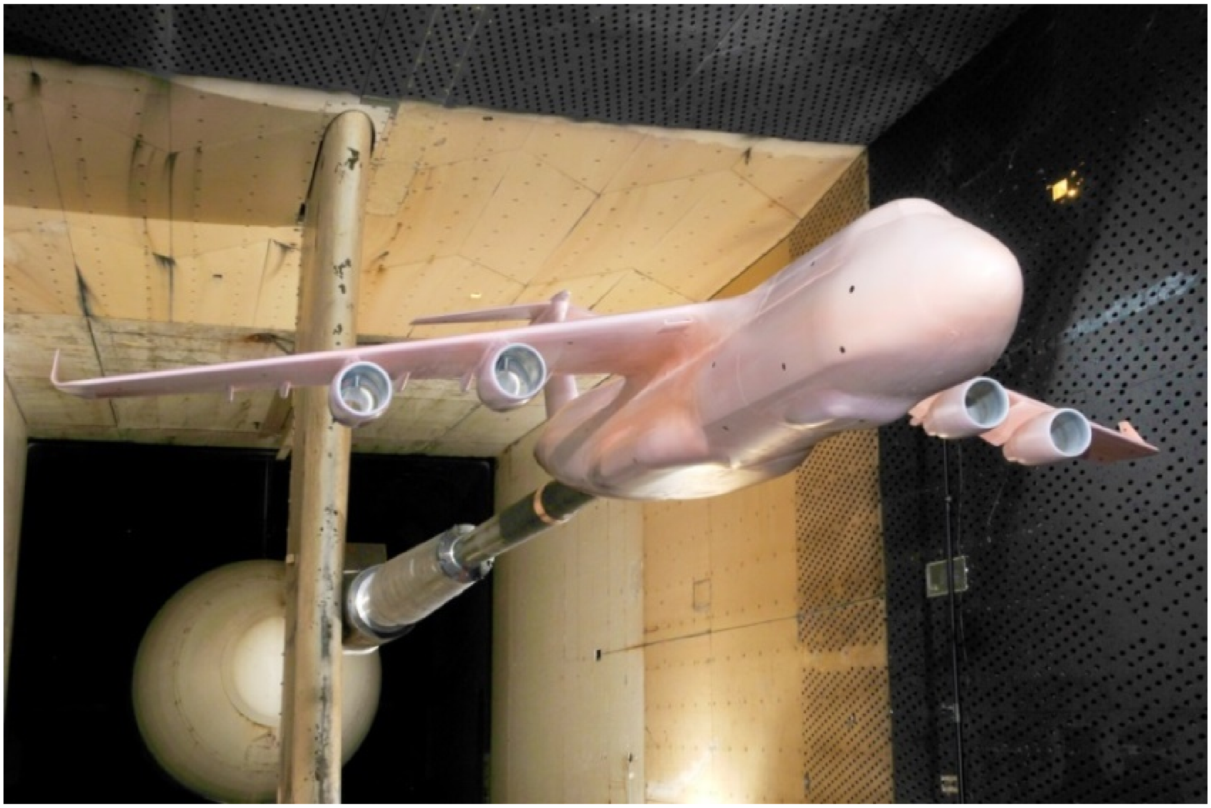
Pressure Sensitive Paint

Pressure sensitive paints (PSP) are optical sensors for surface pressure measurements. Traditional techniques for measuring surface pressure on models are limited to point measurements and to geometries where there is enough space to install them. Installation and instrumentation of a model with pressure taps and transducers is often costly due to the machining requirements and the sensors themselves. PSP is not limited by model geometry. It can measure pressure on model surfaces at every visible point with superior spatial resolution. Much like a paint coating, PSP is applied to a surface using an HVLP paint gun or airbrush.

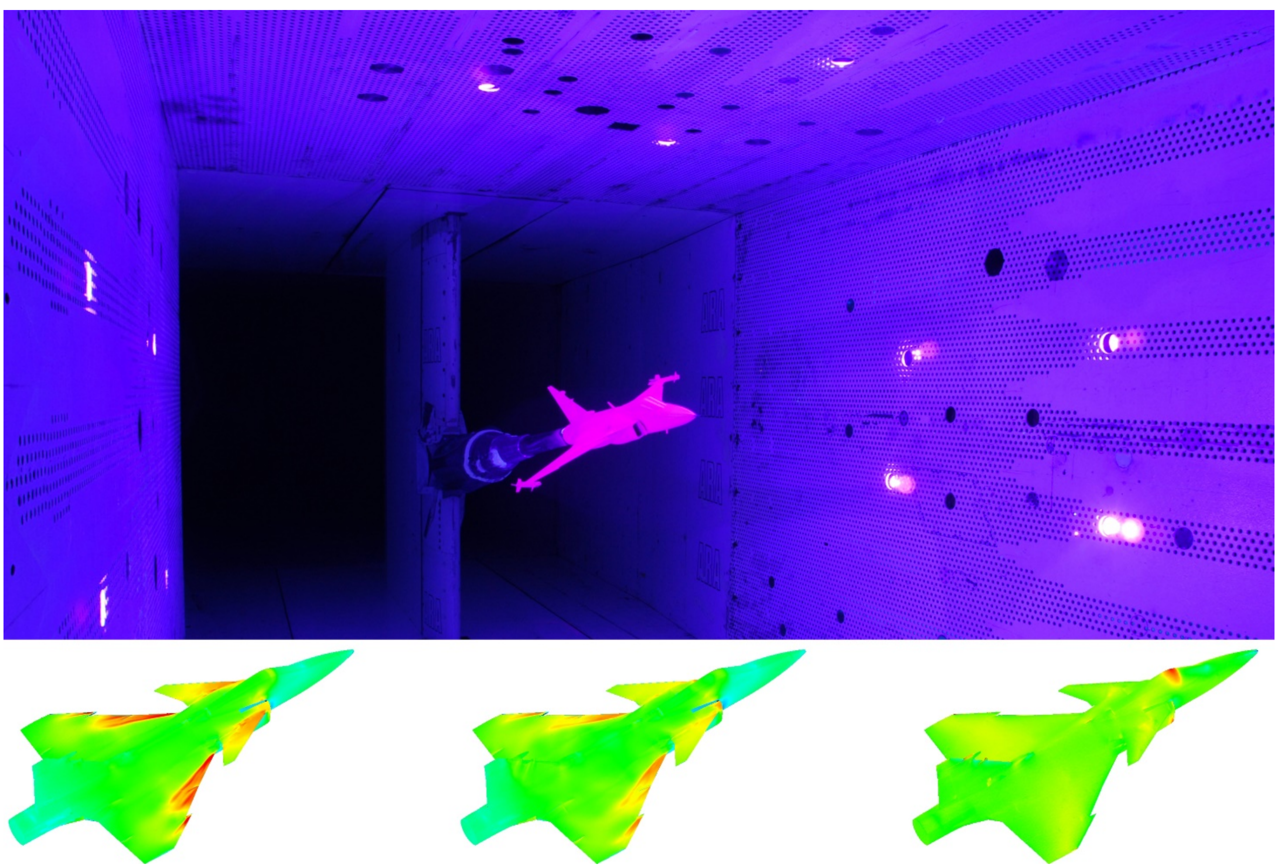


Models Painted with PSP - Left: Delta Wing Mounted in a Wind Tunnel, Right: NACA 0012 model

Most often, PSP is used in wind tunnel research as a validation tool for computational fluid dynamics (CFD) models of certain flow conditions over a model of an aircraft. Wind tunnels from small, academic low-speed wind tunnels to large scale transonic research wind tunnels and hypersonic wind tunnels have utilized PSP for model testing and validation for over 20 years. Today, PSP continues to be a valuable resource in government and commercial testing of aircraft, helicopter, automotive, high-speed train, bridge and architectural models and their components. PSP is also utilized as a tool for film-cooling effectiveness measurements in gas turbine engine blade design.



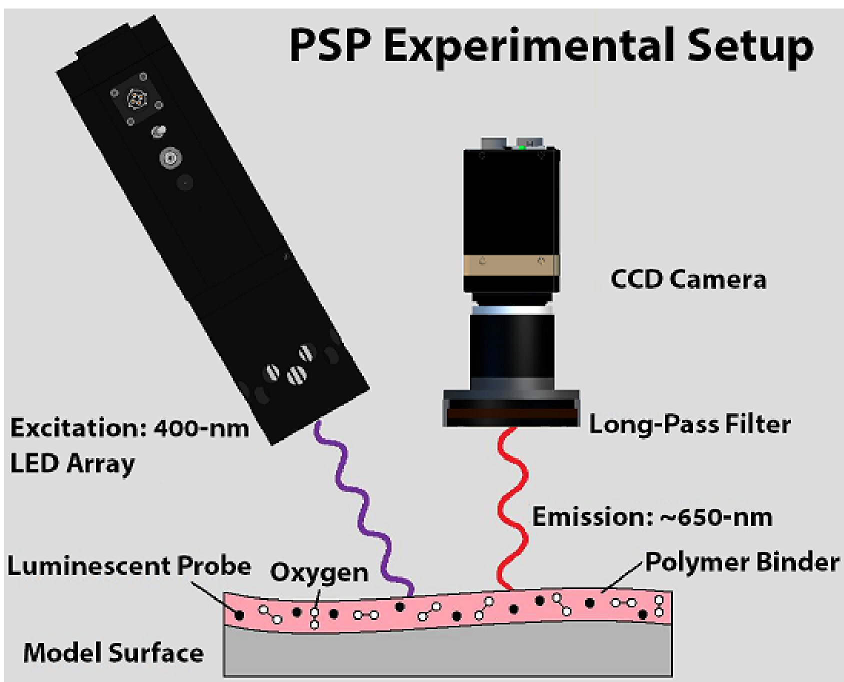
A C-5M Super Galaxy Model Painted with Pressure Sensitive Paint (U.S. Air Force Photo)



A PSP Test at the Aircraft Research Association Transonic Wind Tunnel of the Saab Gripen Model

How Does PSP Work?

A typical PSP is composed of an oxygen-sensitive fluorescent molecule embedded in an oxygen permeable binder. The PSP method is based on the sensitivity of certain luminescent molecules to the presence of oxygen. After application, the PSP is excited with a high-intensity LED, typically a UV 400-nm source. When a luminescent molecule within the PSP absorbs a photon from the LED, it transitions to an excited singlet energy state. The molecule then recovers to the ground state by the emission of a photon of a longer wavelength (red-shifted). When oxygen can interact with the molecule, the transition to the ground state is non-radiative. This process is known as oxygen quenching. The rate at which these two processes compete is dependent on the partial pressure of oxygen at the PSP surface. A higher oxygen quenching rate results in a lower intensity of light emitted from the PSP layer whereas lower oxygen quenching rates results in a higher intensity of light emitted. The result is an output from a model surface of varying intensities based on the local oxygen concentration which is directly correlated to the local barometric pressure. The output from the PSP is recorded with a sensitive scientific camera through a long-pass filter.



A Typical PSP Experimental Setup

After the images are captured with the camera, they are stored for post-processing. Images are converted from images of intensity variations to images of pressure using a previously determined calibration of the same paint type. From there, false color maps are applied to better visualize the pressure gradients on the model surface. Data can be plotted and compared to pressure taps if present. Typical PSP test are within 5% of the pressure tap data.

Introduction

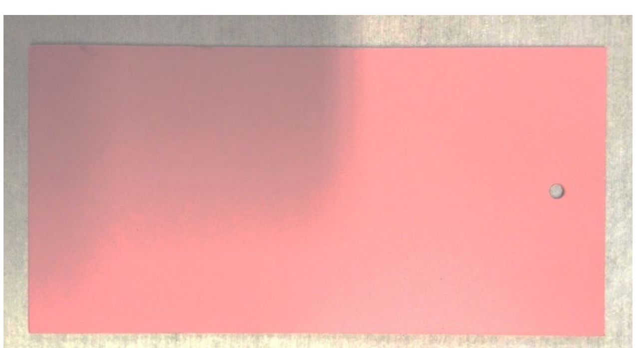
Two programs are used to gather and analyze the pressure sensitive paint data. ProAcquire is used to capture images and export them for analysis and OMS-Lite is used to process the images and display pressure measurements. This experiment will introduce the experimental setup and cover the data acquisition and data reduction process. Refer to the ProAcquire user manual and hardware user manuals for detailed instruction on each.

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 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. A small aluminum sample was painted with PSP. A pulse delay generator is used to synchronize the LED output and camera acquisition.

PSP-CCD-C Color CCD Camera

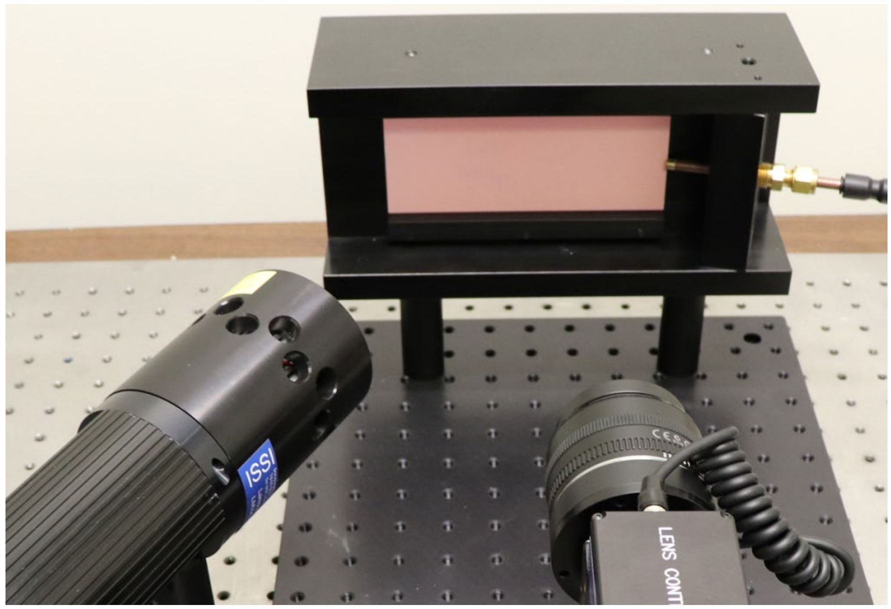
LM2X-DM-400 UV LED Lamp Module



Aluminum Test Model Painted with PSP

PSG-3 Pulse Delay Generator

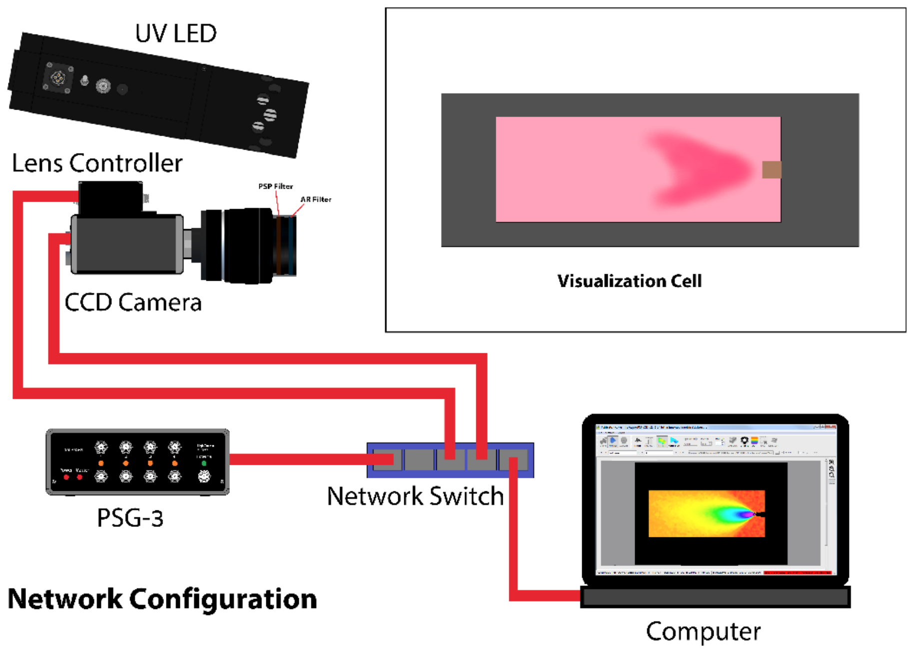
Experimental Setup



In this example, a flat plate was painted with FIB Basecoat and UniFIB® pressure sensitive paint and mounted on a PSP demo system. Compressed nitrogen gas was connected to the nozzle on the PSP demo system. This creates an area of very low oxygen concentration when impinging on the surface, which creates a strong intensity gradient on the excited PSP layer. Quantitative data is not the requirement for this exercise, understanding how PSP works and the data acquisition process is the goal. In place of the PSP demo system and nitrogen jet (if your lab does not have this setup), a simple can of keyboard duster spray can be used to create the same effect on a PSP sample. Blank samples are included which can be painted and tested for practice.

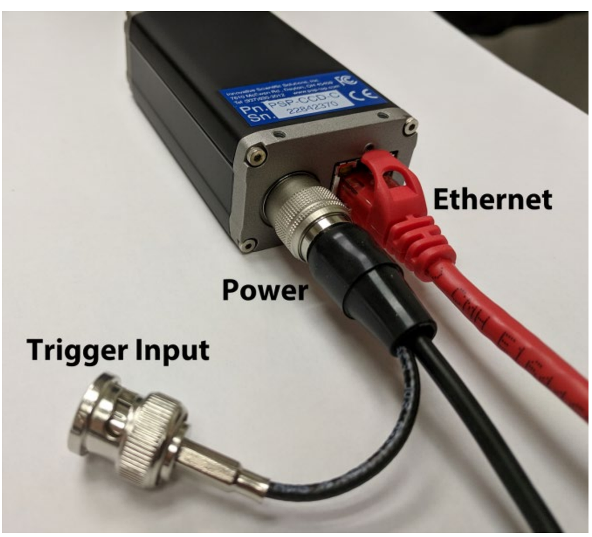
A clean and open workspace will be needed to set up the experiment. Proper mounting bracketsand a sturdy workbench should be used to prevent the model and equipment from being moved or disturbed during data aqcuisition. Any movement in equipment or the model can result in innaccurate data. The camera and LED lamp should be mounted so that they are rigid and do not move when the data acquisition begins. This will help to eliminate inaccuracies in the data caused by model shifting. The camera and LED lamp should be positioned near the test object so that the camera can focus on the painted surface and the LED lamp can uniformly illuminate the surface as shown below. The camera should be placed normal to the PSP surface or as close as is possible. The LED should be positioned such that it has a different angle of incidence to the PSP surface than the camera to avoid direct reflection into the camera. The test object will need to be placed at the appropriate distance from the camera so that it is easily focused in the lens. If a lens controller was purchased with the system, it can be used for fast and accurate focusing.

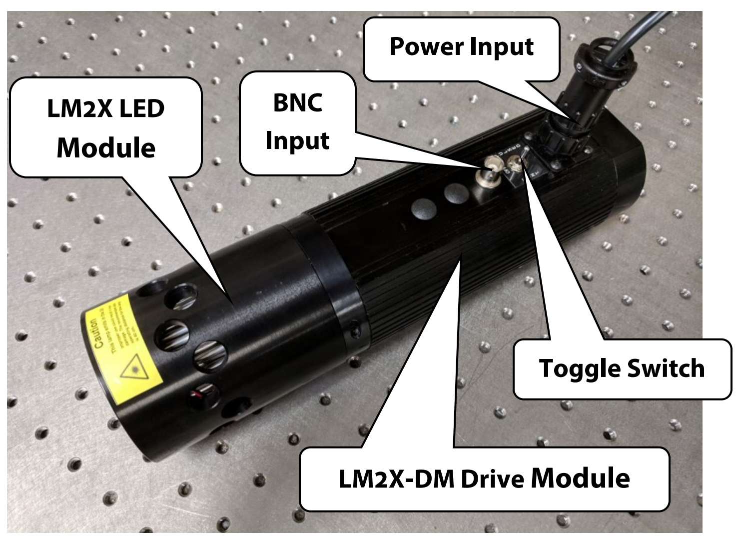
Attach all power supplies to the camera, LED lamp, and the computer. All devices communicate with the computer via a local network through an Ethernet switch. Once all licenses are installed, all devices should connect once software is open.



Network Configuration

Plug the power supplies into power outlets. The noise from the fans on the lamp and the LEDs from the Ethernet connection on the CCD camera will assure they are powered on. The CCD camera connects to a computer with the OMS ProAcquire software to capture and record desired images.





CCD Camera Connections **LED Power Supply Connection**

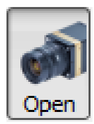
It is necessary to take images under three conditions to produce accurate, uncompromised pressure measurements. The three images that will be captured are a *background* image, a *wind-off* image, and a *wind-*

on image. Factors that can compromise data are excess noise or illumination, such as ambient light in the test area from light sources other than the LED lamp. Before beginning setup, check to assure that all of the necessary equipment is present.

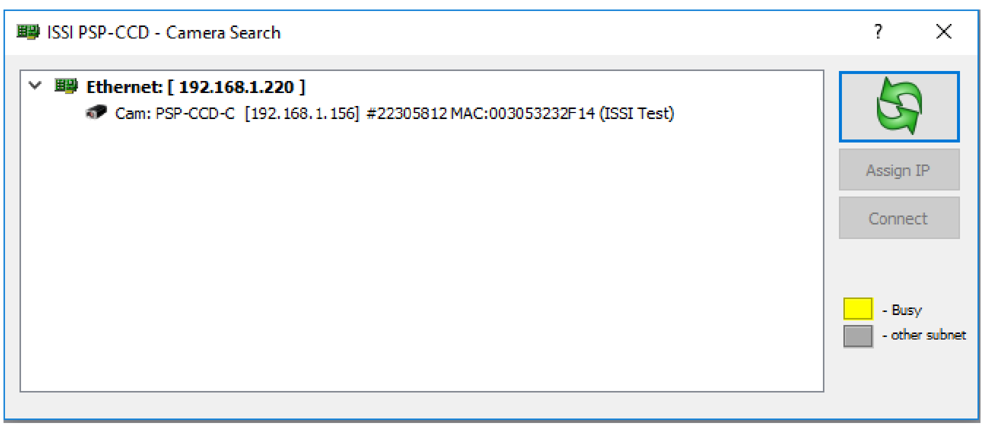
Data Acquisition

ProAcquire is the software package used with the PSP-CCD cameras. For full details on operation of ProAcquire, refer to the user manual. ProAcquire is made to be a simple and effective interface for the user that is directly compatible in output file format with ISSI OMS post processing software.

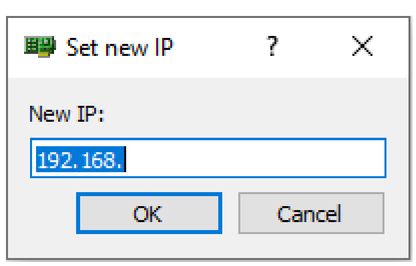
Opening the software will open the main page of the software. At this point, the software will be inactive since no camera has been selected.

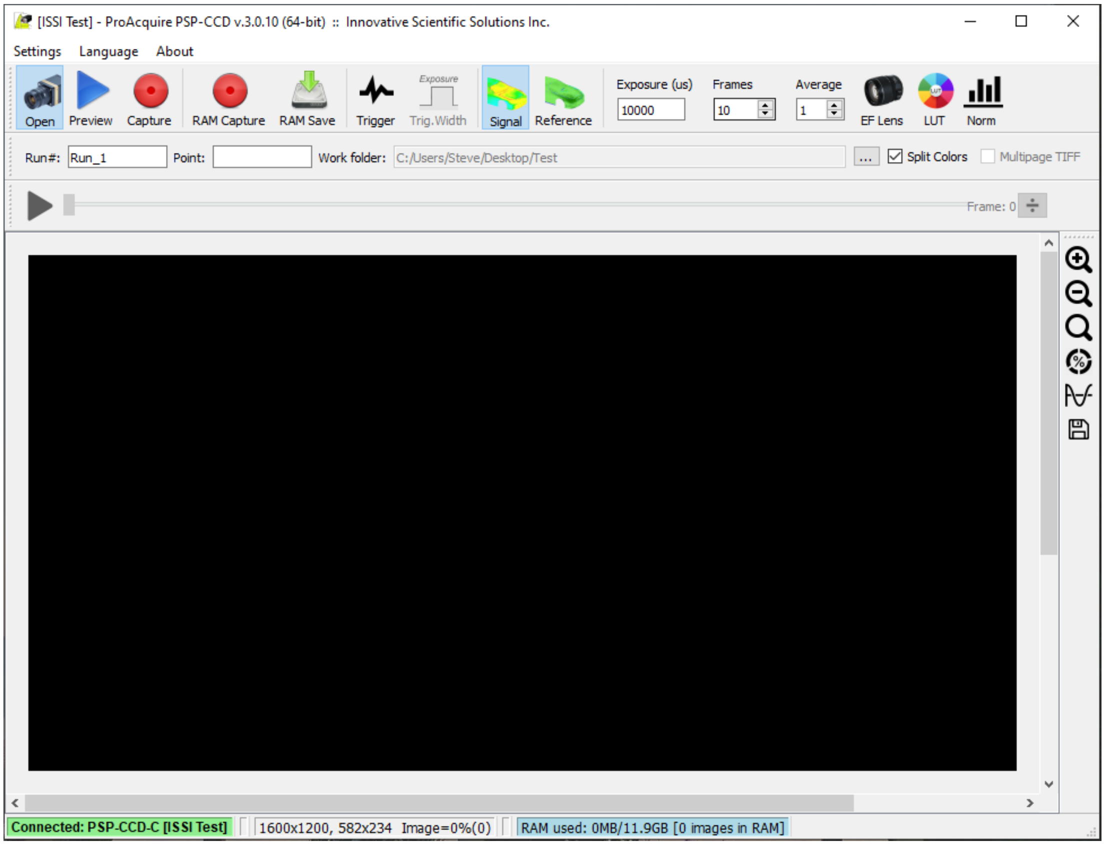
To connect to a camera, press the ***Open*** button: 

This will show all connected cameras with their IP addresses and serial numbers.



A camera highlighted in yellow is busy and connected to another computer running ProAcquire. If a camera is displayed in grey, its IP address does not match the local network and should be changed to match the local network. To do this, click on the camera in grey and press ***Change IP***. Once the IP address matches the local network, the text will change to black. Double-click on the camera to open.





ProAcquire Main Page

Once the features have been activated, the buttons will show color meaning the camera is connected.

A new file folder will need to be created by the user for all data to be stored. Make sure to document the location of this file folder so that it can be easily found once all data is gathered. Once the new file folder is created, the file location path will need to be opened in ProAcquire. To open a new file path, click the  icon on the toolbar. This will bring up a window so that new folder can be selected. Locate the file folder that was created and select it in the drop-down menu at the top of the window. This folder is empty and will appear that way. Type in a file name in the empty box where is says 'Run#:'. The name typed in this box will be the name of the files located in this folder during each data acquisition. Each file will have a number extension attached to it and two images (reference and signal images) will be saved during each type of data capture (background, wind-on, wind-off). It is important to know which file is the background, and which are the wind-on, and wind-off, so name them accordingly during each capture to avoid confusion.

The toolbar controls the camera acquisition parameters.

Preview will display a preview of the camera view. This can be externally triggered and will operate at the maximum repetition rate possible based on the sensor and exposure settings.

Capture will capture the prescribed number of ***Frames*** given by the user and then stop.

Trigger will start acquisition (***Preview*** or ***Capture***) once initiated by external trigger.

Trig. Width will take the pulse width of an external trigger to use for the exposure time of the camera. If selected, ***Exposure*** will be disabled.

For the color camera (PSP-CCD-C), the ***Pressure*** and ***Reference*** buttons will be enabled. This enables the user to switch the display on the screen between red (pressure) and green (reference) channels on the array.

Exposure is the exposure time of the camera (in microseconds).

Frames is the number of images the camera will capture in ***Capture*** mode.

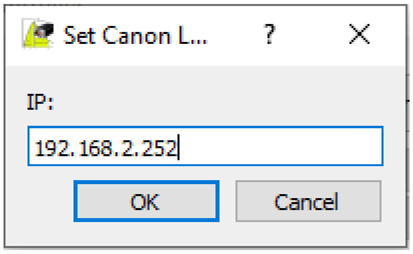
Average is the total number of frames which will be acquired (if greater than 1) when image averaging is used. The number of ***Frames*** divided by the number of ***Averages*** is the number of individual images saved, each an average of this multiplier. For example, if the number of ***Frames*** is 10 and the number of ***Averages*** is 2, 2 images will be saved, each an average of 5 frames. The ***Frames*** and ***Averages*** must be multiples of each other for this function.

Note: Average frames are always saved for the sum of the images taken whether averaging is being used or not. Each time a set of images is saved; there will also be a ***.LST*** *file with the same prefix as the images acquired. This is list file containing all images from that acquisition. Opening the list file in ProImage and then converting to a TIFF file will give the average for all images acquired in the sequence.*

Overclock will put the camera into overclocked mode, giving it a maximum frame rate of 44 fps versus the standard 35 fps. Overclocked mode is not recommended unless necessary as it creates more shot noise in the acquired images leading to lower data quality (Only available with ProAcquire version 2).

EF Lens controls the LC-2 Canon® lens controller if it is connected on the local network. Click the icon to open.

Press ***Connect Lens*** and enter the IP address of the lens controller to open communication.



The control interface will then be active so the parameters can be adjusted.

For this experiment, we will use radiometric mode which is the default mode.

Background

The first image that should be captured is the background image. This image is captured to compensate for any ambient light present. Take the background image with the LED lamp and any room lighting turned OFF. The background image is just that. The background image is subtracted from the wind-off and wind-on images to remove the effects of ambient light present in the room.

Wind-OFF

The next image to be taken is the wind-off condition image. For this condition, the painted test object should be imaged with the LED lamp turned on for several minutes to stabilize as seen below. It is important to let the LED lamp remain on for several minutes before the image is acquired so that it reaches equilibrium. To turn the LED lamp on, flip the switch by pulling up and pushing towards the side labeled **Cont**. To pulse the LED with the camera or pulse generator (via external trigger input, move the switch to **Pulsed** and connect a BNC cable between the LED and camera or PSG-3.

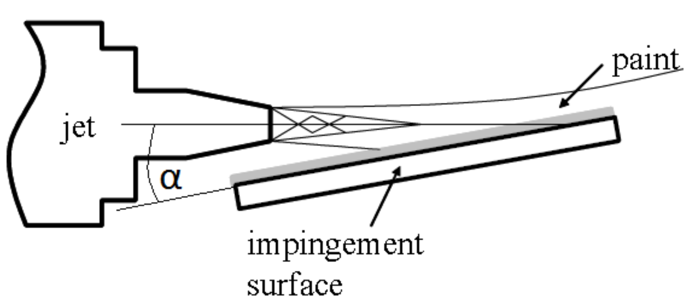
Trigger Switch on LM2X-DM LED Module

Acquiring the Wind-Off Image

The wind-off image is taken without any air flow over the test object and shows the illumination of the paint at static, ambient conditions. This image is used to remove the static conditions from the wind-on image by taking a ratio of the two images.

Wind-ON

The final image to be acquired is at the wind-on condition. For this image, a jet (can of dust-off or nitrogen) is directed towards the surface of the test object at a known angle α. Be sure the jet is held close to the surface so that a clear pressure difference is detected on the surface of the test object.



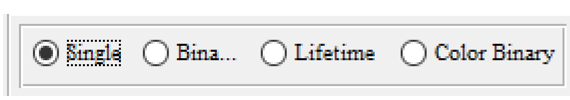
Wind-On Condition Setup

Be sure to leave the jet or dust spray on until the image has been captured (it may take a few seconds). All images needed for data processing are now acquired and stored in the folder created by the user.

Acquiring the Wind-On Image

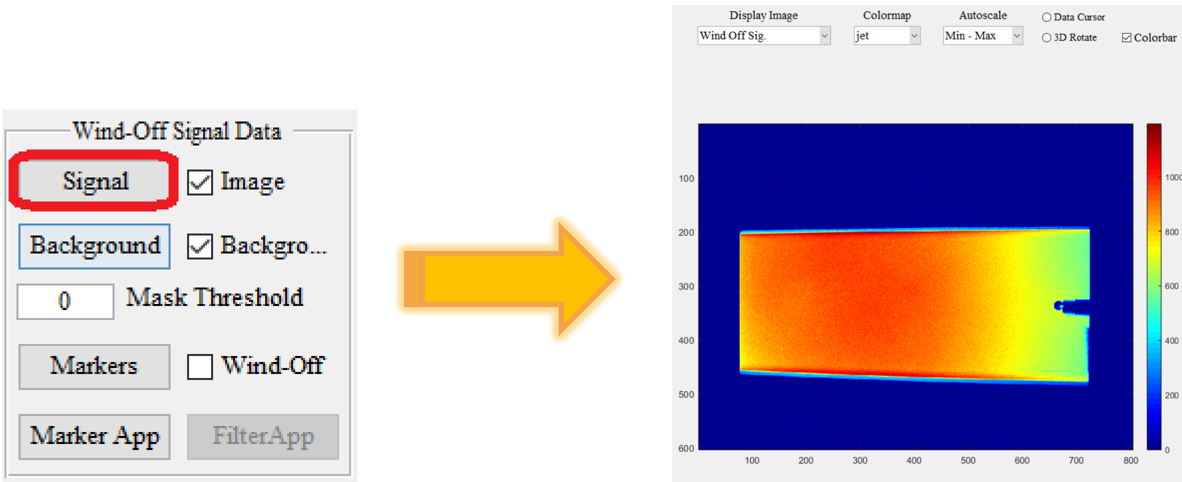
Data Processing

Begin by selecting which type of data acquisition was used to acquire the images. In this case, the method was single luminophore. Select ***Single***.



Save this project using the ***Save*** button on the main window of OMS-Lite.

Next, load images into the program. The images are provided with this example. There are two types of image names, signal and reference. Signal images are images of the pressure sensitive response and reference images are images of the reference signal or pressure insensitive response. Reference images are acquired in Binary PSP acquisition. This example is single component so we will not be loading any reference images. When ***Single*** is selected as the project type, any fields for importing reference images are disabled. Binary PSP acquisition and processing will be covered in later examples. Begin by loading the wind-off image into the project. This is done by clicking the button labeled ***Signal*** under the ***Wind-off Signal Data*** label. Navigate to the folder location where the example images are stored to load the image.



Loading an Image

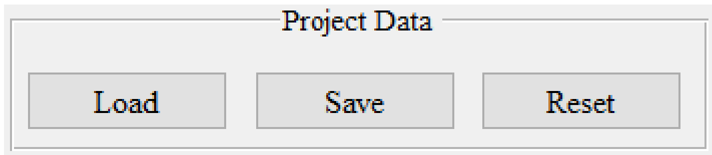
Next, load the background image by clicking ***Background*** under the ***Wind-off Signal Data*** label. Next, repeat this process but for the ***Wind-on Signal Data*** section. The same background image can be used for both wind-on and wind-off conditions. All images will be displayed in the window on the left of the user interface. The drop-down menu ***Display Image*** is used to select which image to display. Now that all raw images are loaded, we can begin data processing.

Once each image is loaded into OMS, it can be displayed within the interface. The current image can be changed by selecting another image from the ***Display Image*** pull-down menu (shown in Figure 7), including final processed images.

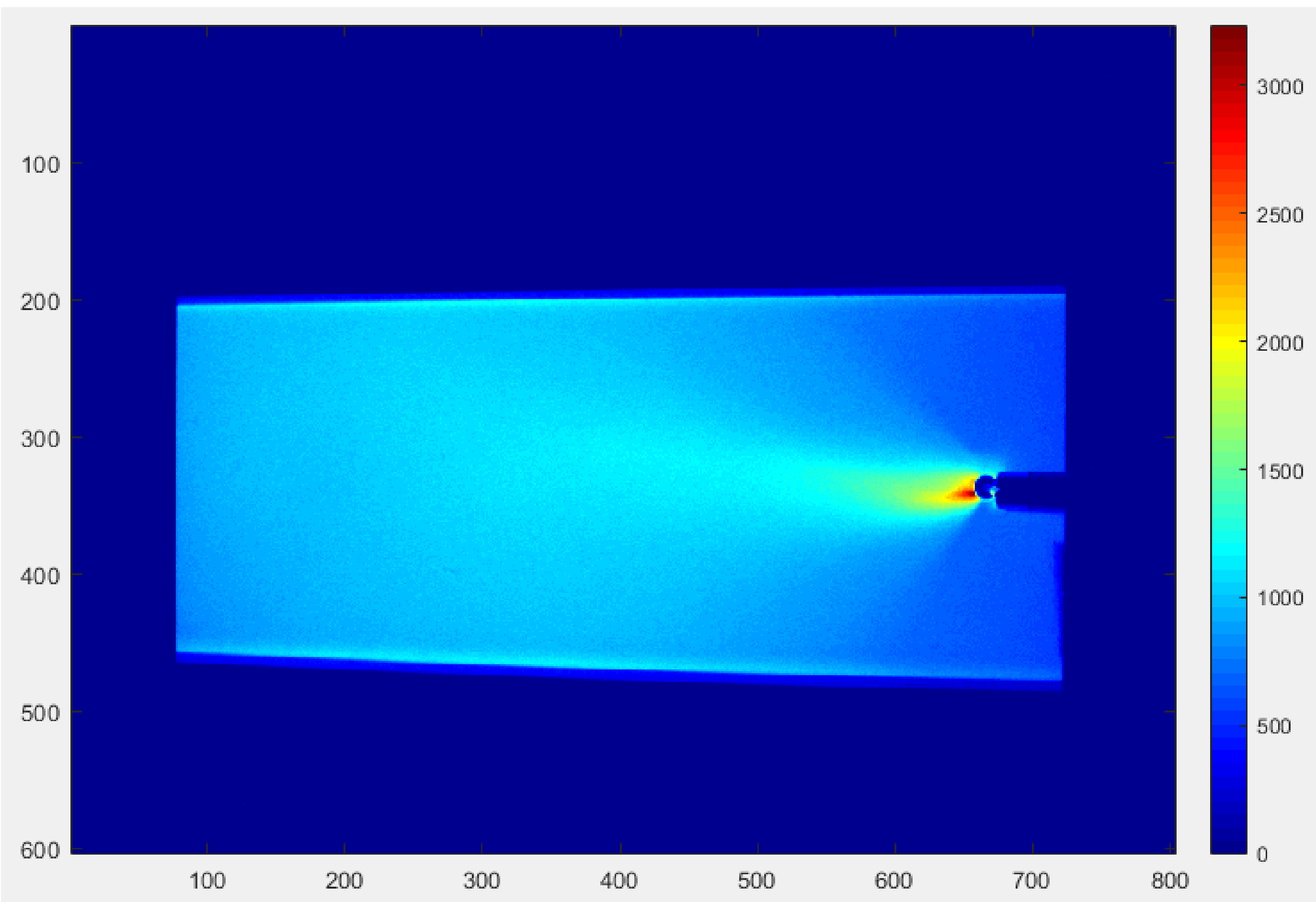
Image Toolbar

The ***Color Map*** or look-up table can be changed to more easily view gradients on the image. Using the ***Autoscale*** drop-down menu, the intensity range of the image can also be adjusted over set increments for better gradient visualization. This is most useful on data with low dynamic range. Color bars can also be added to the image to show the scale. For datasets with a 3D mesh, once applied, the data can be displayed here on the mesh and rotated. There is no 3D mesh for this example.

With all images now loaded into OMS-Lite, save the project. The ***Project Data Section*** can save, load and reset the program to remove the loaded data. Save the project in the same folder as the raw images.



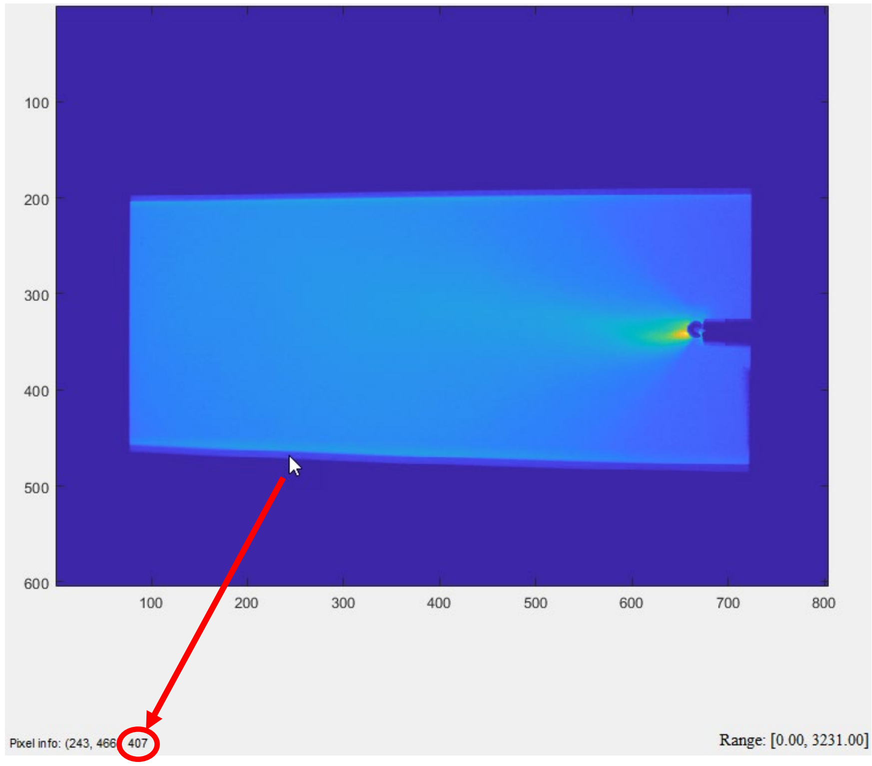
This project file will save in the file format **.pspproj**. This is native to OMS-Lite and not compatible with other processing software.



Raw Wind-On Image

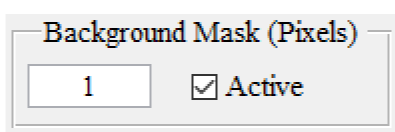
View each saved image to assure the correct images are loaded. The wind-off image will have a flat intensity field on the sample while the wind-on image will display a strong gradient.

Removing Image Background



Sampling the Image Background

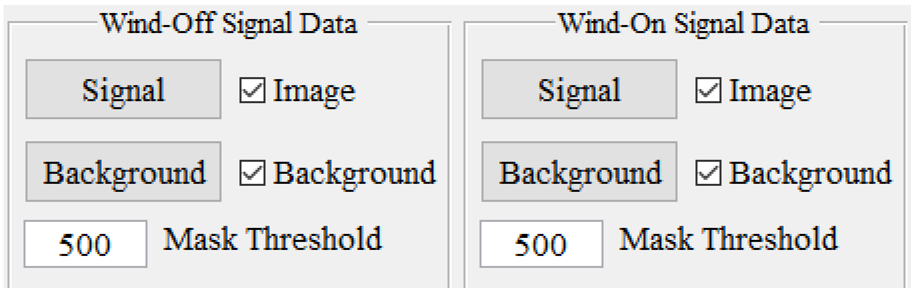
PSP measurements are based on the measurement of the luminescent intensity from the painted surface. It is not uncommon for some regions of the surface to produce substantially smaller signals than the bulk of the painted surface. This may be due to poor illumination, physical damage to the paint (chipping), or the presence of markers on the surface that are used for image alignment. If the signal level is too low in a given region, the signal to noise ratio is not sufficient to yield meaningful data. These regions should be excluded from the remainder of the data processing as they will yield inaccurate data. These areas will need to be removed from the images. Use the threshold tool to remove any pixels which are not PSP surface. The threshold tool works by setting a minimum threshold value for pixels on the image. Any pixel values below this threshold will be removed. The ***Mask Threshold*** can be set for each image in the same section in which they are loaded into OMS. Probe the image to see the signal level of non-painted sections of the image. In this case, a mask of 500 was chosen based on the signal level shown at right. The area sampled is a reflection or shadow near the edge of the painted sample which we want to exclude from the data processing. To activate the ***Mask Threshold*** and remove this background signal, check ***Active*** in the ***Background Mask*** section. This will remove the background once the ratio image is computed as well as apply the erosion filter.



To remove the background based on the ***Mask Threshold*** settings, right-click elsewhere in the main window or press enter on your keyboard. Unchecking the ***Active*** box will add the background back to the image.

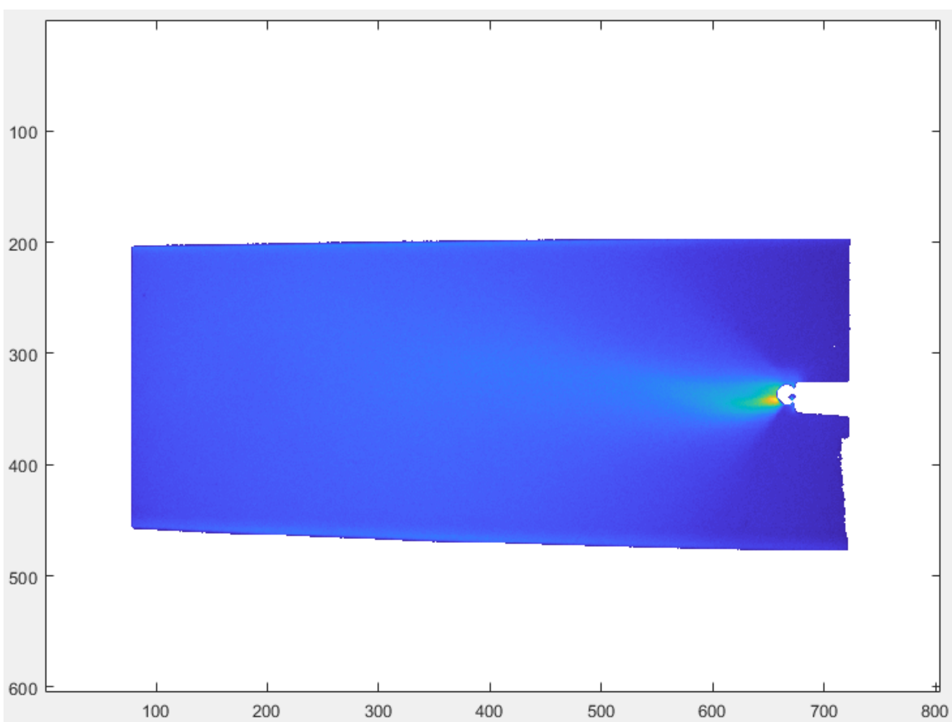
Set the ***Mask Threshold*** for each image to 500 for both the wind-off and wind-on images.

OMS-Lite will set all pixels which fall below the mask threshold to zero. This will effectively erase the background level pixels from view, leaving only the pixels where PSP signal is imaged. PSP signal levels will be well above signal levels of anything left in the background of the image if all reflective surfaces are properly masked.



Mask Threshold for this Dataset

In some cases, LED reflections off of surfaces will be well above the background mask threshold. The ***Background Mask*** is an image erosion tool which is used to remove areas like reflections around the image which were not removed by the mask threshold. The value for ***Background Mask*** can be set from 1-15. This will smooth rough edges of the active area (not set to background by the threshold). In this case, the default value of 1 can be left because there are no reflections that the ***Mask Threshold*** did not sufficiently remove.



Background Removed from Wind-On Image using Mask Threshold

Image Viewer

The Image Viewer tool is used to assess the image statistics like min/max, RMS and histogram. Data can be saved and exported to a CSV file for later use. Final processed images can also be exported in JPEG or TIF format. Filters and threshold values can also be tested here without affecting the original images in the project file. Consider this a test area for background masks and image filtering as well as the place to export your data.

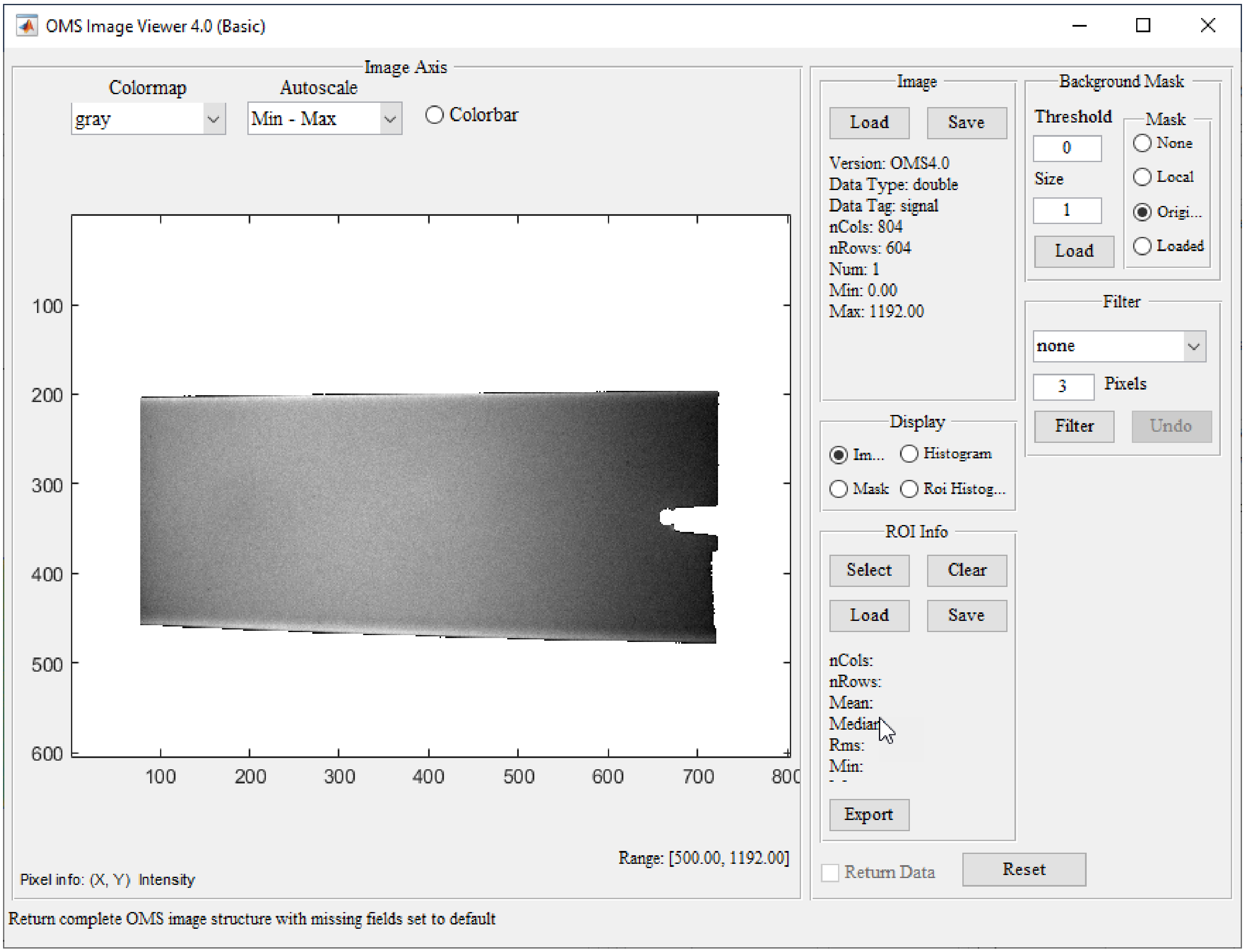
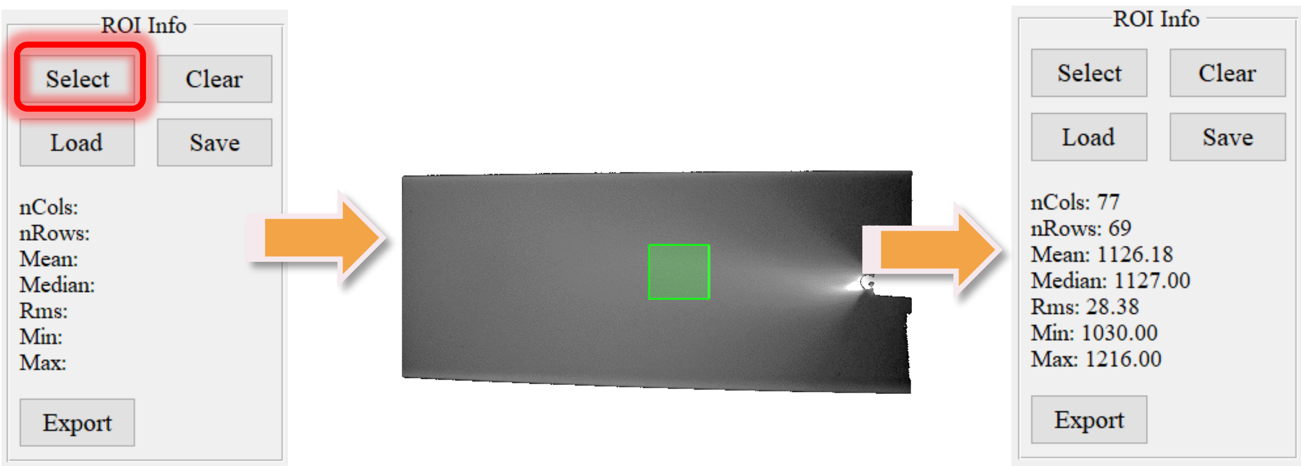


Image Viewer

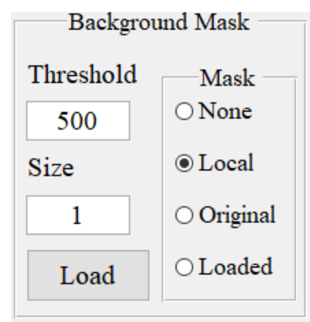
Load/Save an image from the ***Image*** toolbar. This displays software and image information like the image resolution, minimum and maximum intensity values. Any changes made to the image can be saved from here.

ROI Info can export data to a CSV file. Begin by selecting an ROI by clicking **Select**. A green selection box will appear on the image. Drag the box to position and pull from a corner to resize to cover the desired ROI. To save the ROI for later use, click **Save** and the ROI will be saved as a **.IMGROI** file native to OMS 4. Click **Export** to save the data to a CSV file for later use.



Using the Image Viewer ROI Tool

The ***Background Mask*** toolbar is used to apply background threshold masks to the image. The threshold for intensity cutoff is set here. This is all for display purposes. No changes will be made unless the image is saved from here.

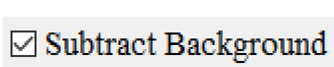


Threshold: Threshold value intensity. All pixels with intensity values lower than this number will be set to zero.

Size: This is the size of the image erosion filter. This filter will smooth rough edges of the active area (not set to background by the threshold).

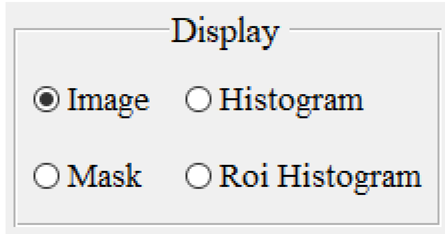
Mask: This will apply one of the threshold masks to eliminate the image background. The **Local** mask is the value listed in ***Threshold*** to the left. The **Original** mask is the mask which was applied in the main window under ***Mask Threshold***. **Loaded** will use a mask that was previously saved and loaded into the ***Image Viewer***.

Once the background mask and threshold have been decided and the filter size and type optimized, exit the image viewer and continue on to process the images.



Checking the box next to ***Subtract Background*** will subtract the background image for each of the loaded PSP/TSP images. This will remove any effects of room lighting that were present during data acquisition.

The ***Display*** settings allow for displaying the image, the mask and the histogram of the image.



The image mask shows the borders of the active image area versus the background. ***Histogram*** shows a distribution of the numerical intensity values of the image. ***ROI Histogram*** shows the histogram of the selected ROI.

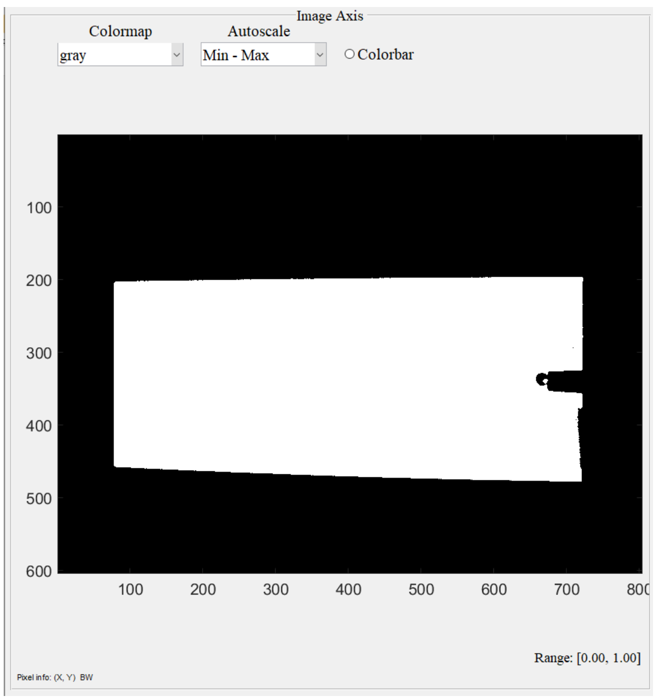
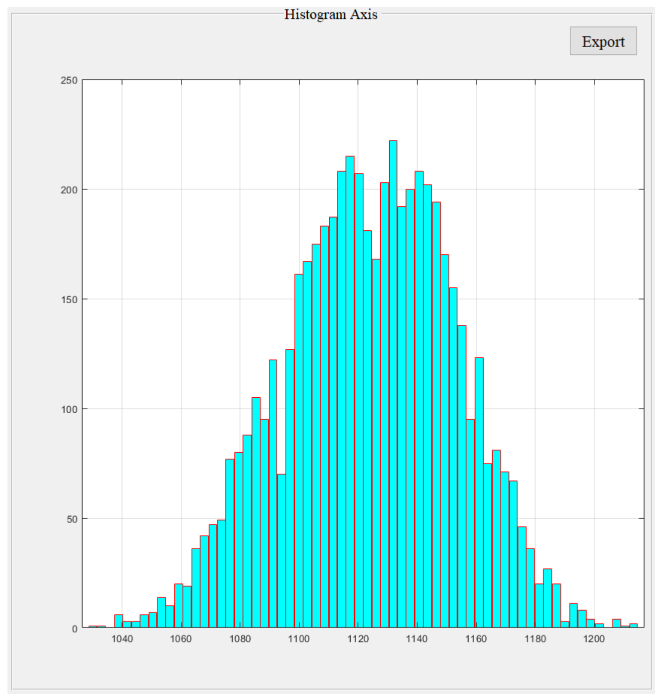
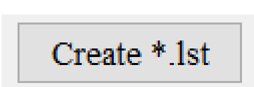


Image Mask



ROI Histogram

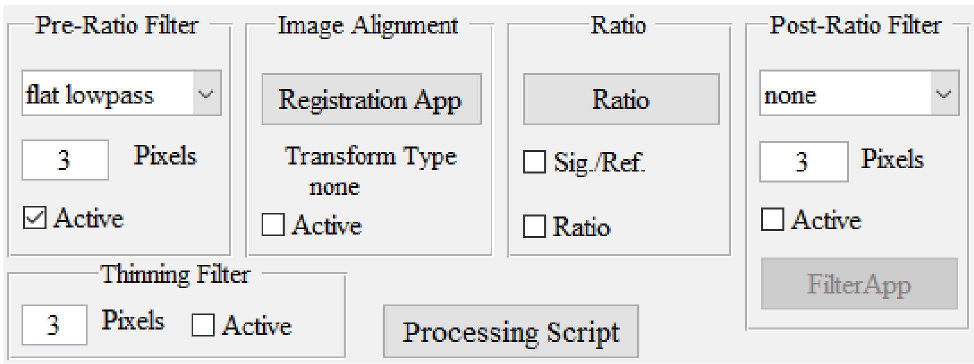
Create List File



A list file is a text-based file which is a compiled list of select image files. When a list file is loaded, it is displayed as an average of the images contained in the list file itself. Select multiple images to create a list file. This will be saved as a text file with the extension **.lst**.

Image Processing

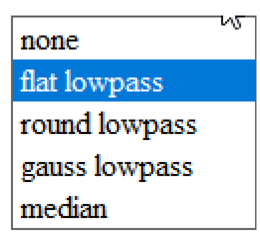
Once all images and markers have been loaded and added to the project file, image processing is performed to create calibrated pressure maps from raw bitmap images. Lowpass filtering, image alignment and image ratios must be performed before images are converted to pressure or other values.



Filtering, Image Alignment and Ratio

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 in OMS Lite.



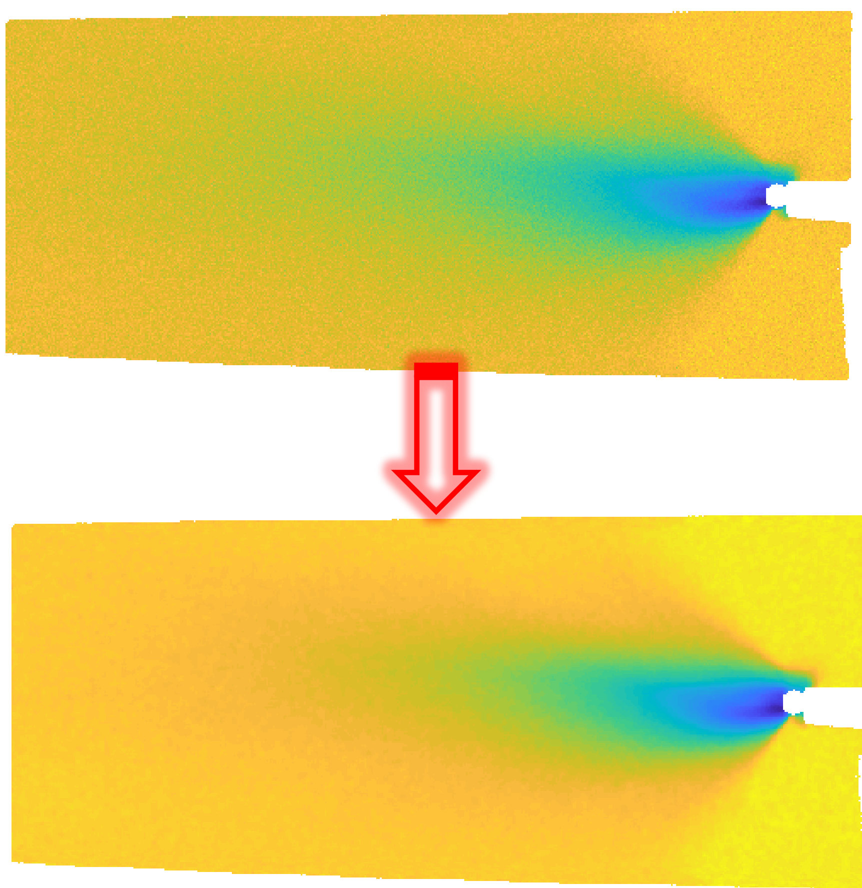
Flat Lowpass: This linear filter computes the average value of the pixels in the selected region in a square and assigns that average value to all pixels. This is also known as a box filter.

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.

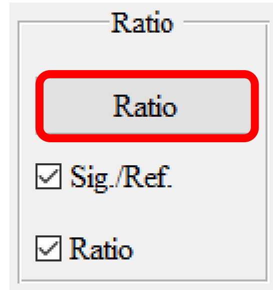
Gauss Lowpass: This is a non-uniform lowpass image-blurring filter which convolves the image with a 2D Gaussian function. Gaussian filters are used to blur and remove noise from images. The Gaussian filter is not effective at remove salt and pepper noise from images.

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.

For this exercise, we will use a flat lowpass filter of 5 pixels for the Pre-Filter Ratio and a Gaussian filter of 5 pixels for the Post-Filter Ratio. Given the large intensity gradient created by the nitrogen jet, minimal filtering is needed.



5 Pixel Filter Applied to Ratio Image (Flat Lowpass: 5 (Pre), Gaussian: 5 (Post))



To change the pre-filter type or size in the project file, select a new type and size and then click the ***Ratio*** button in the ***Ratio*** section. When a filter is applied, the image lookup table will auto-scale to the new minimum and maximum intensity values on the image.

Since no registration marks are present for the experiment, we will skip the ***Image Alignment*** toolbox. This will be covered in later examples.

Image Ratio

The ratio toolbox computes the wind-off / wind-on ratio of the images in the project file. The background images are subtracted from each of the wind-off and wind-on images before the ratio is computed. The ratio image represents the intensity ratio which normalizes the dataset. Pressure gradients between the wind-off and wind-on conditions will be more apparent once the intensity ratio is computed. Any areas of the model surface which do not change in pressure are now represented with a value of 1 and areas where pressure changes did occur are deviate in either direction from 1. This ratio is later used to convert the intensity ratio into pressure values using a calibration. Check each box for the ***Ratio*** to be computed. To apply a post-ratio filter to the project data, compute the image ratio.

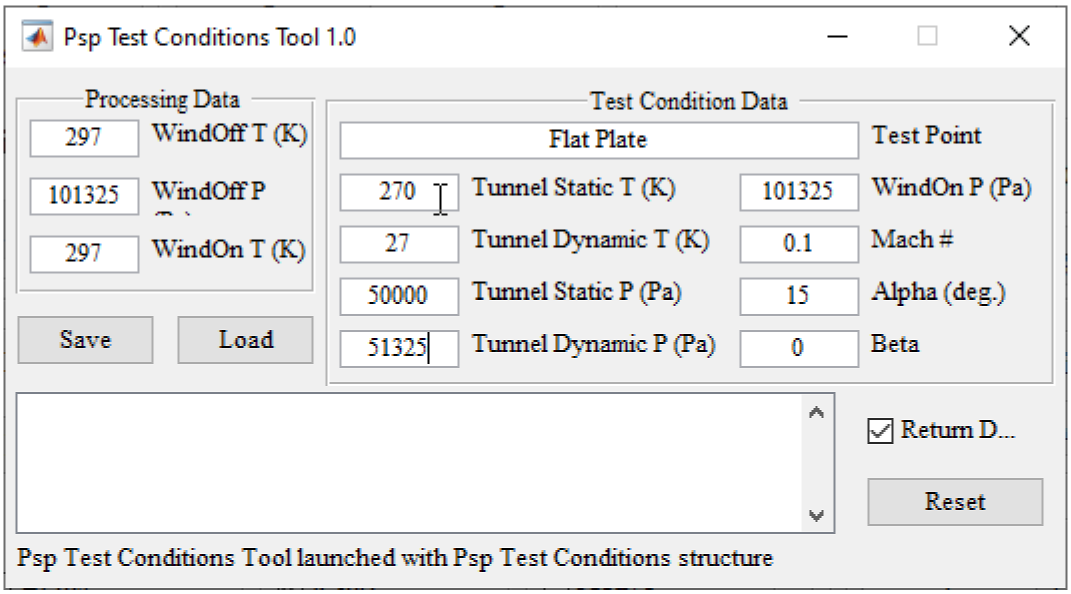
Computing the Ratio Image

Once the image ratio is computed, smoothing filters can be applied to reduce shot noise so that the lookup table can be shrunk to better show the pressure distribution.

A thinning filter can also be applied from the image filtering and alignment section. The thinning filter will be applied (when active) once the ratio is computed. No thinning filter is needed in this dataset since there is no image misalignment.

Conversion to Pressure

The final step of the data reduction is to convert the ratio image to pressure. This is done using and an a-priori calibration. Begin by entering the test conditions for the experimental setup. The test conditions below can be used for this dataset. Once the data is input for test conditions, it will automatically be stored in the project file if the ***Return Data*** box is checked.



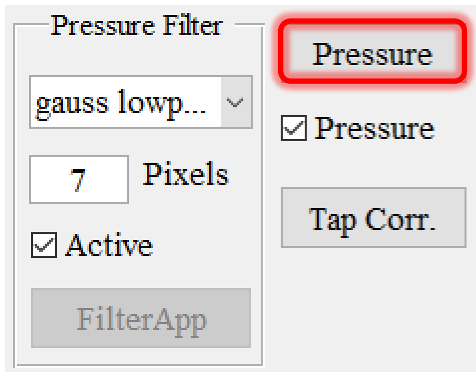
Test Conditions Window

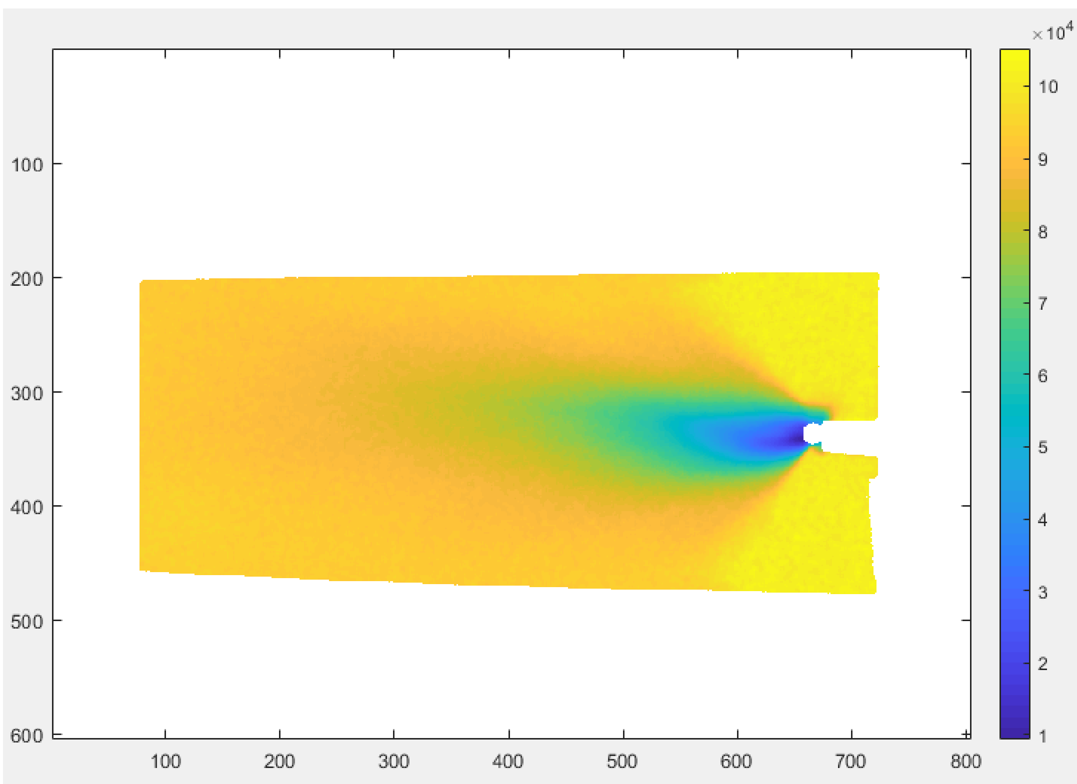
The paint calibration can be loaded automatically by clicking ***Load*** in the ***Paint Calibration*** section.

For this test, UniFIB® PSP was used. Load the calibration **UniFIB.pspcal** from the dataset.

Conversion to Pressure

Now that the test conditions have been entered, the image can be converted to pressure. Prior to the final conversion to pressure, the converted pressure image can be further filtered. For this dataset, a 7-pixel Gaussian filter was used. To convert to pressure, click the ***Pressure*** button as shown.





Final Processed Pressure Image

The reason the area of high pressure appears as an area of low pressure is because the PSP is sensitive to the partial pressure of oxygen. Since the oxygen was pushed away during wind-on conditions by the dust-off (not oxygen), it appears as an area of low pressure. This result is an example of adiabatic film cooling which is commonly studied using PSP. A later example will shown this technique in more detail.