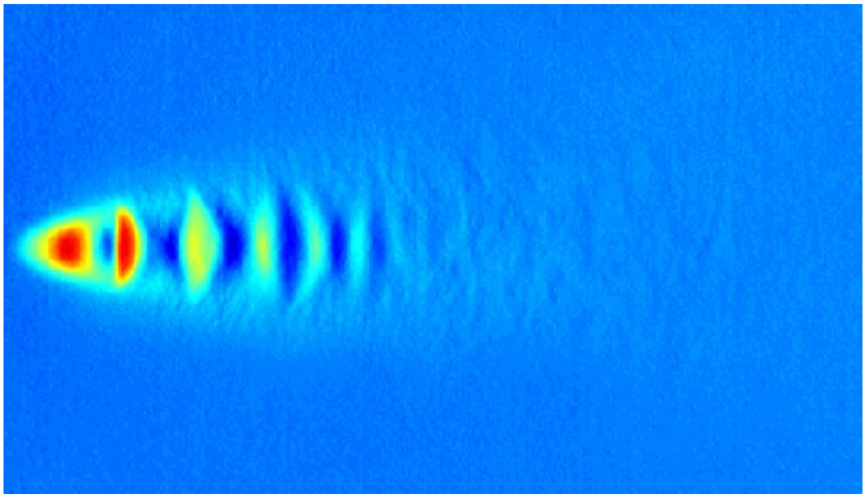
INNOVATIVE SCIENTIFIC SOLUTIONS, INC

Lab 1: Introduction to OMS-Lite



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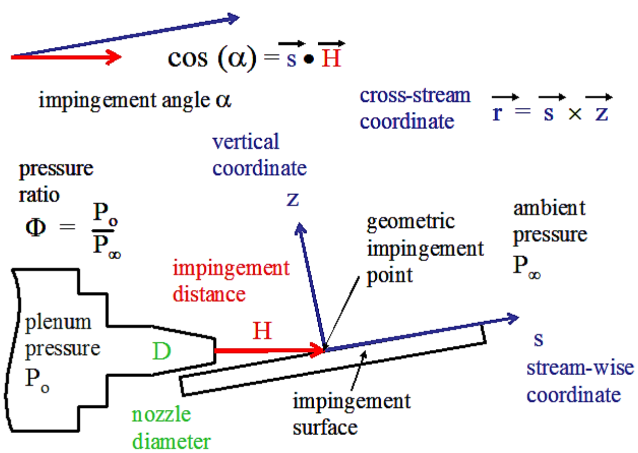
Introduction

This example is designed to introduce the most basic concepts of Pressure Sensitive Paint (PSP) data reduction using OMS-Lite. The example files are located in the [*Lab 1\Lab_1 data files*] directory. We will introduce the experimental setup and data acquisition followed by data reduction.

Experimental Setup

A schematic of the experimental setup for the inclined impinging jet is shown in Figure 1. The physical parameters of interest are the geometric impingement distance (H) the impingement angle (α), and jet pressure ratio (Φ). The distance along the major axis of the jet from the center of the jet nozzle to the geometric impingement



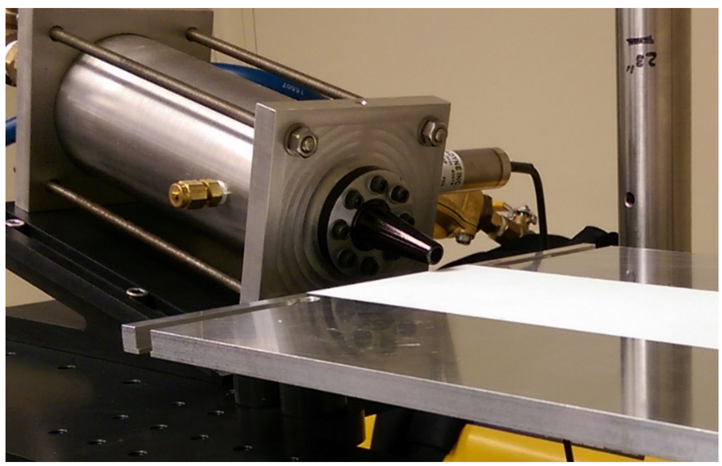


Figure 1: Geometry & Nomenclature for the Inclined Impinging Jet

point (GIP) is the impingement distance (H). The GIP is defined as the intersection of the jet axis with the impingement surface. The impingement distance (H) is set at four jet diameters for this experiment. The impingement angle (α) is defined as the angle between the major axis of the jet and the surface of the impingement plate. The impingement angle (α) is set to fifteen degrees. Finally, the pressure ratio (Φ) is defined as the ratio of the jet plenum pressure to the ambient pressure (P_o/P_∞). The pressure ratio (Φ) is 3.03, this results in a sonic under-expanded jet for the converging nozzle that we are using. Upon exit from the nozzle, the flow expands and accelerates to super-sonic speeds. The resulting shocks and expansion fans will interact with the impingement surface and create a complex pressure distribution that will be investigated using the PSP.

Data Acquisition

A schematic of the PSP experimental setup is shown in Figure 2. The PSP layer is applied to the surface of the impingement plate using a HVLP painting gun. The paint is excited using light from a UV LED module (ISSI LM2X-DM-400). The luminescent intensity from the paint on the model surface is optically filtered using a 610 nm long-pass filter (Figure 3) to block the excitation light from entering the camera lens. Images of the painted impingement surface are captured using a scientific CCD camera. These images are stored digitally and will be processed using OMS-Lite to determine the pressure distribution.

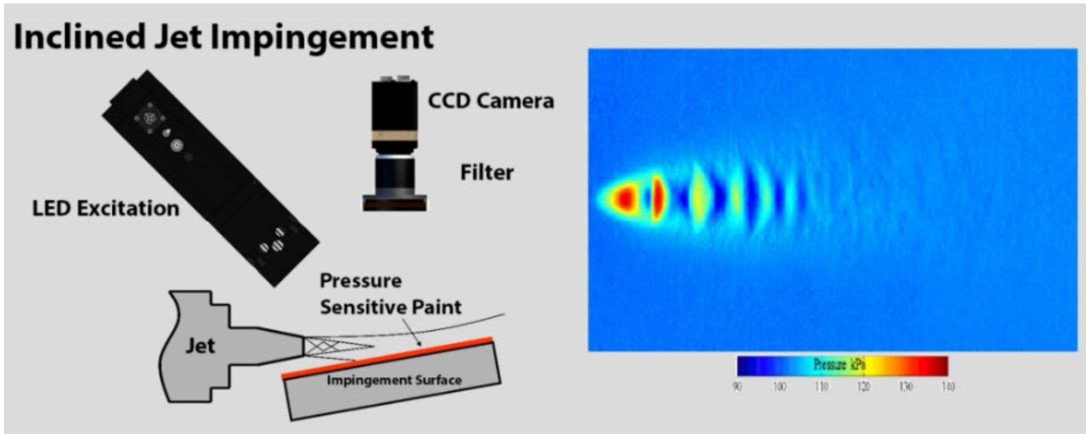


Figure 2: Impinging Jet Experimental Setup

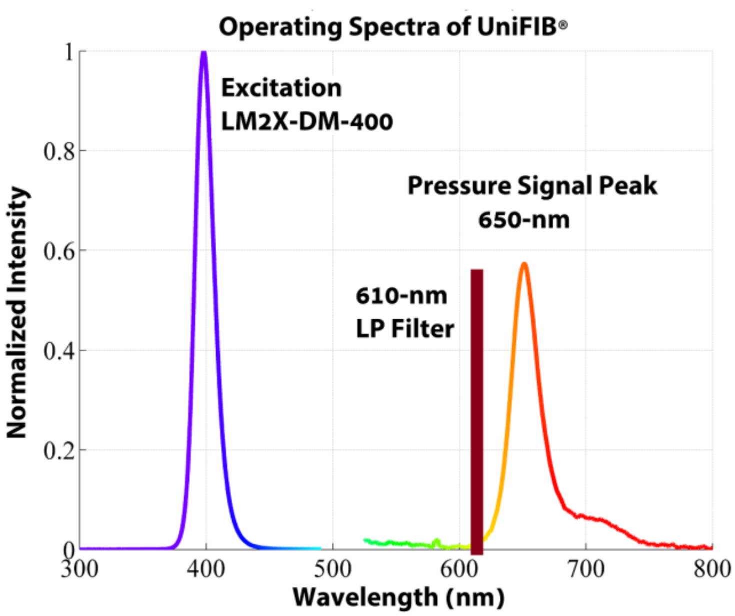


Figure 3: UniFIB® Spectra and Long-Pass Filter

The data acquisition method used in this example is known as radiometric acquisition. Radiometric acquisition, either single-channel or binary, refers to the acquisition method where data is acquired by taking a series of images at a known reference condition as well as on-condition or when the model is aerodynamically loaded. This is the most commonly used method in recent years. The radiometric approach is used for both single and dual luminophore PSPs.

$$I(P,T) = \frac{F(P_{on}, T_{on})\, h\, n\, L}{F(P_{off}, T_{off})\, h\, n\, L} = \frac{F(P_{on}, T_{on})}{F(P_{off}, T_{off})}$$

Single-luminophore PSP

Three images were acquired during the data acquisition procedure (seen in Figure 4). The first image is a background image (***Jet15_BG.tif***). This is taken to compensate for any ambient light present. The background image is just that, the background or backdrop of the camera's view during data acquisition. The background image is subtracted from the wind-off and wind-on images to remove any signals that are not from the PSP itself. The background image is taken with the LED turned OFF.

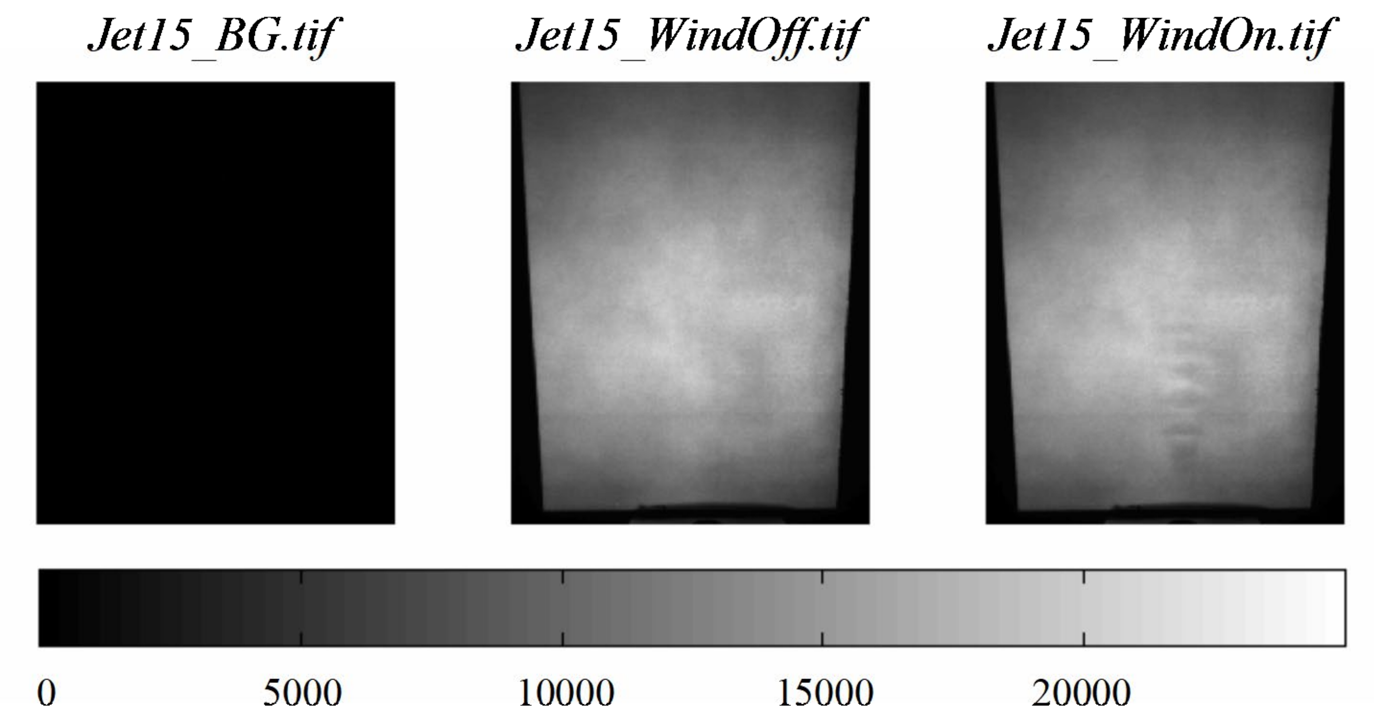


Figure 4: Raw images for impinging jet

The next image taken is the wind-off image (***Jet15_WindOff.tif***). This image is taken of the test object (flat plate) but with the impinging jet off but the LED turned ON. The final image taken is the wind-on image (***Jet15_WindOn.tif***). This image is taken of the test object with the jet turned ON and LED ON. Camera and lens settings were not adjusted between each image set acquired and the camera position was fixed. This should be the case for any PSP acquisition as changing the camera exposure time or lens aperture will look like an intensity change in the paint response which would be correlated to a pressure change. This will be covered further in later examples.

Data Processing

At its most basic, the data reduction procedure for PSP involves removing the background image from each of the wind-off and wind-on images and then calculating the ratio of the wind-off / wind-on images and finally converting this ratio to pressure using a calibration that relates this ratio to pressure values. For practical implementation of PSP, several other image processing steps are often required. These steps can include compensating for the background lighting, image alignment, filtering, calibration, temperature correction, and resection. We will first process the data using a simple ratio and introduce OMS-Lite and the image display tools.

To create a new project, open the OMS-Lite program. The window in Figure 5 will open to start a new project.

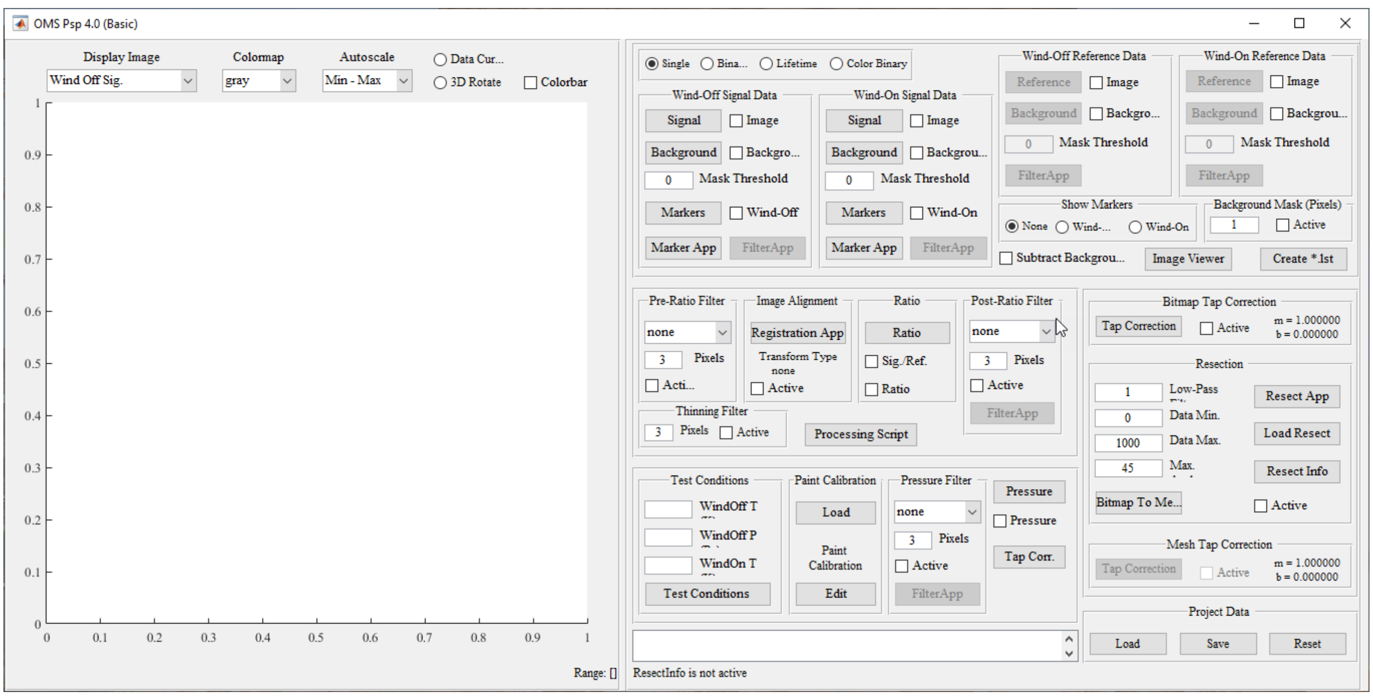
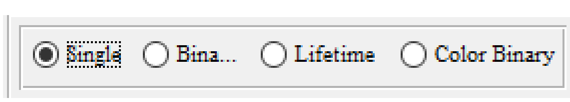


Figure 5: OMS-Lite Main Window

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



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.

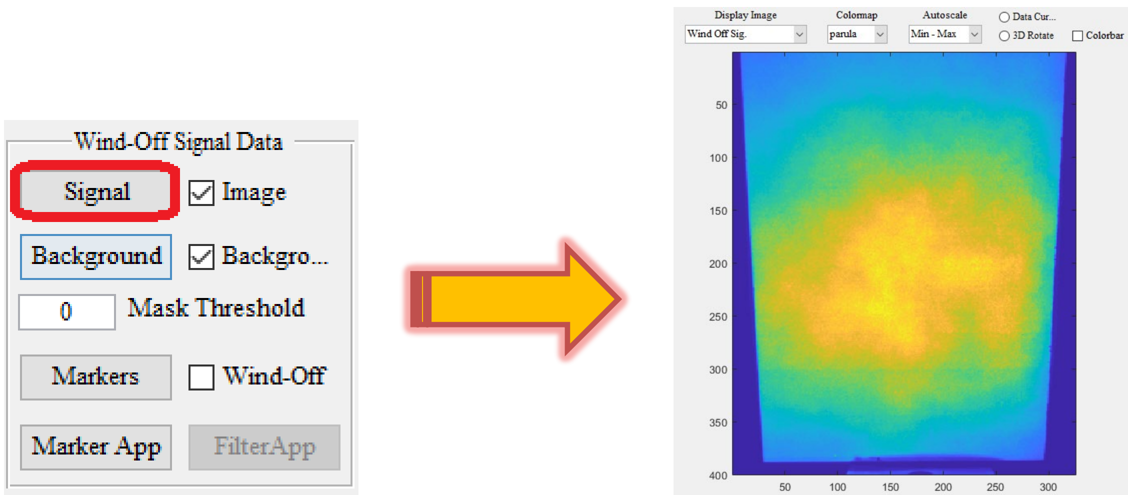


Figure 6: Loading an Image

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.

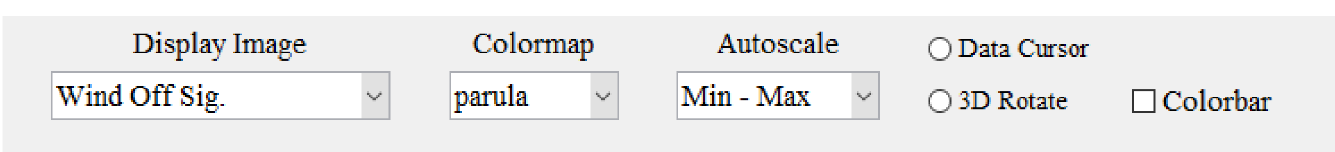
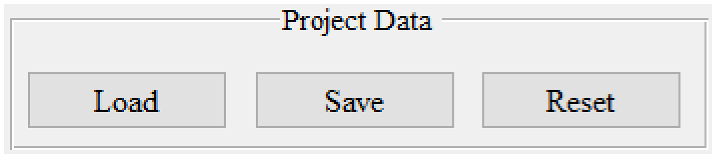


Figure 7: Image Toolbar

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.

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.

Removing Image Background

Areas of the image which are not painted sections of the model will need to be removed from the images. This is done using a 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. 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.

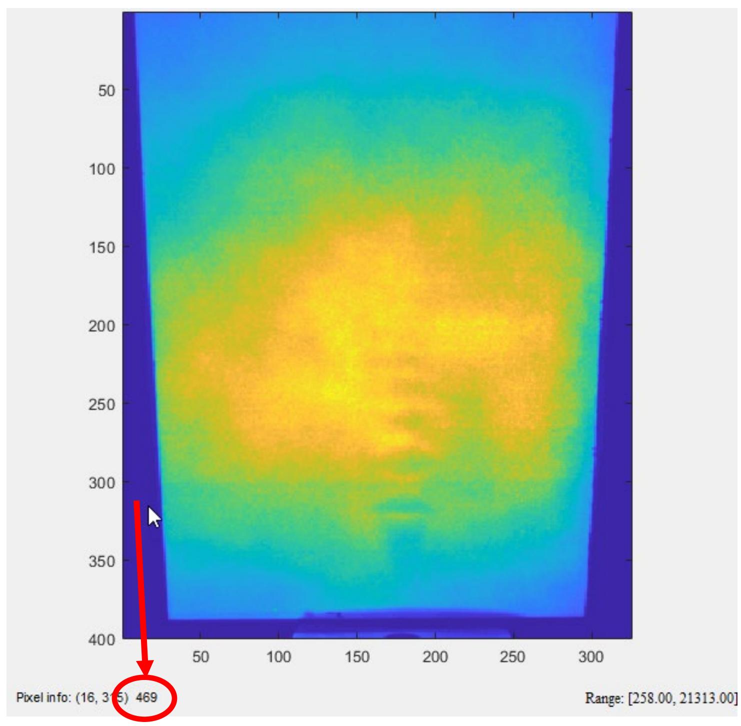
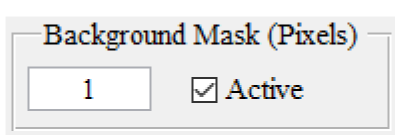


Figure 8: Sampling the Image Background



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 1000 for both the wind-off and wind-on images. This is above the background signal level shown in the image in Figure 8.

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.

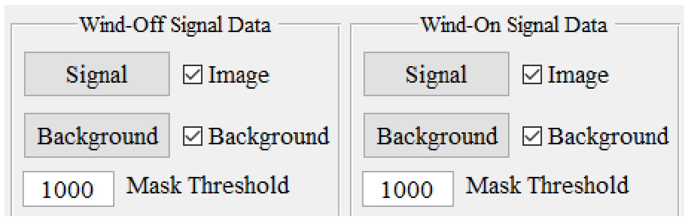


Figure 9: Mask Threshold

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).

A value of 1 will not remove any additional background past what the ***Mask Threshold*** will remove. Increasing the number will remove more of the background not removed by the image threshold. This tool is useful if there is a reflection on an area away from the painted surface. It acts as a type of thinning filter, biasing areas at or near background levels without removing useful portions of the image.

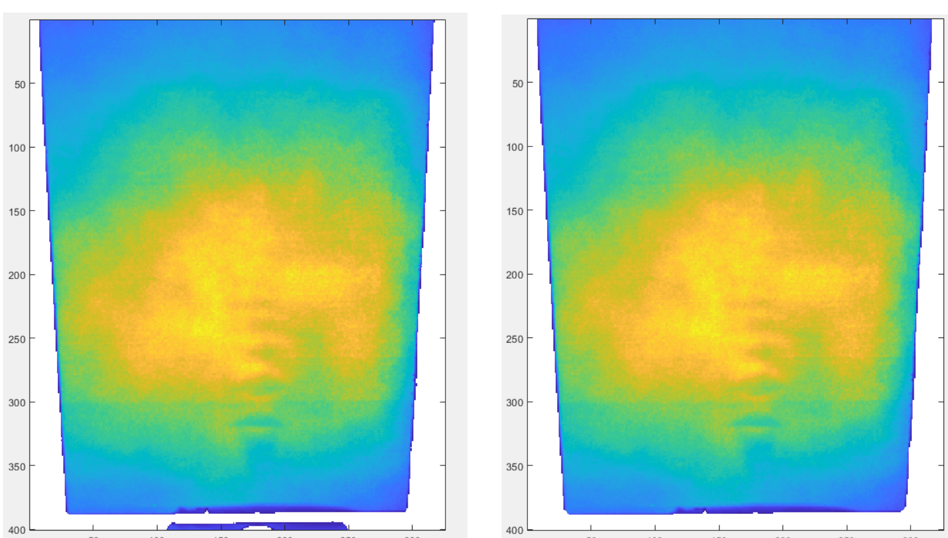


Figure 10: No Erosion Filter (Left) vs Erosion Filter (10) Applied (Right)

Markers will not be used for this example and will be covered in later examples. Markers are used to align images where a model moves between the off and on conditions.

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. 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.

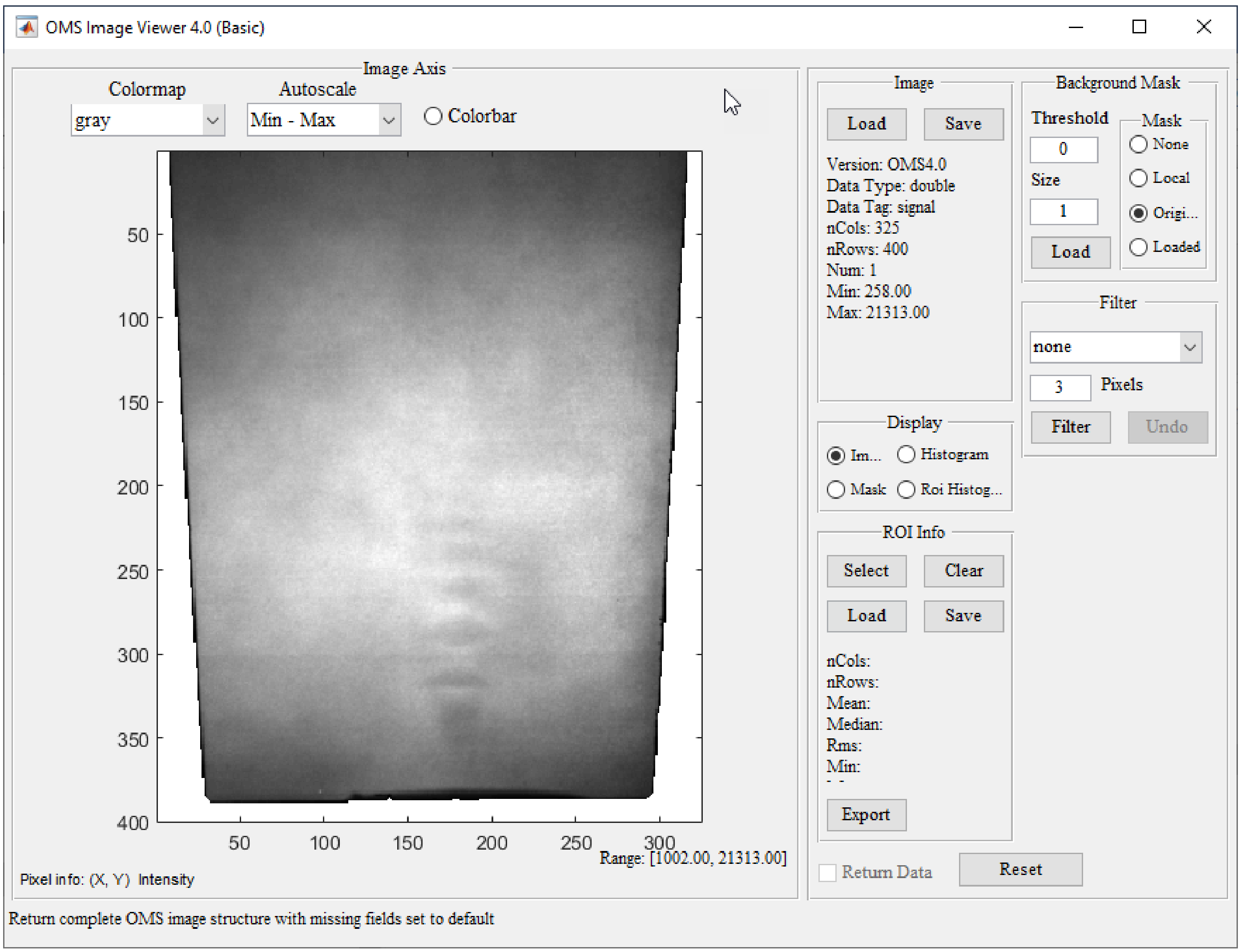


Figure 11: Image Viewer

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.

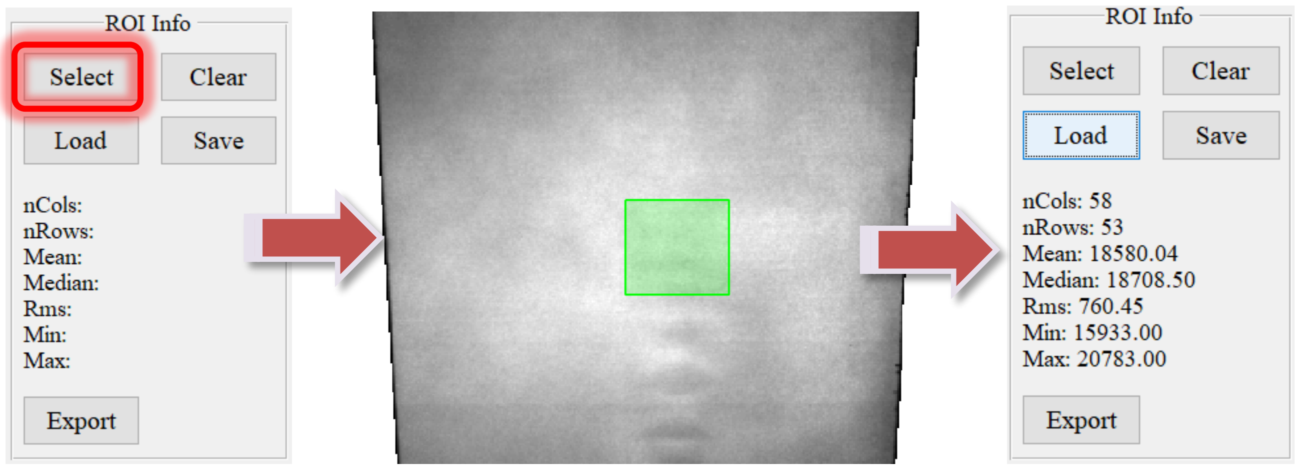
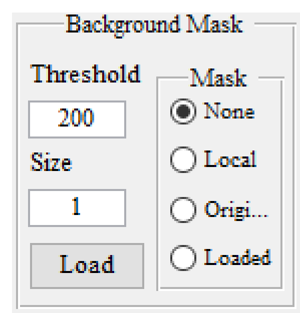


Figure 12: Using the Image Viewer ROI Tool

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.

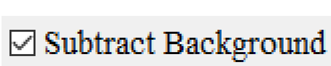


Threshold: Threshold value intensity. All pixels with intensity values lower than this number will be set to zero.

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).

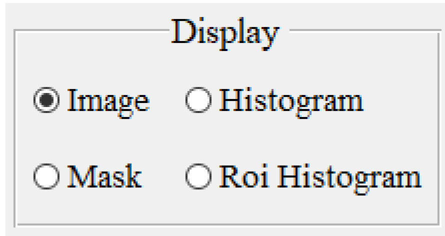
Mask: This will apply one of the threshold masks to eliminate the image background. The **Local** mask is the value listed in ***Threshold*** to the left. The **Original** mask is the mask which was applied in the main window under ***Mask Threshold***. **Loaded** will use a mask that was previously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

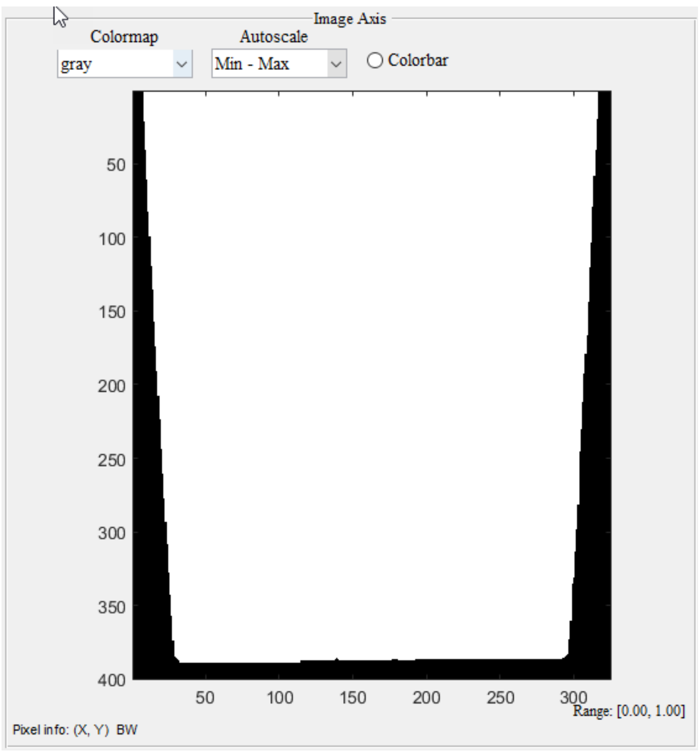


Figure 13: Image Mask

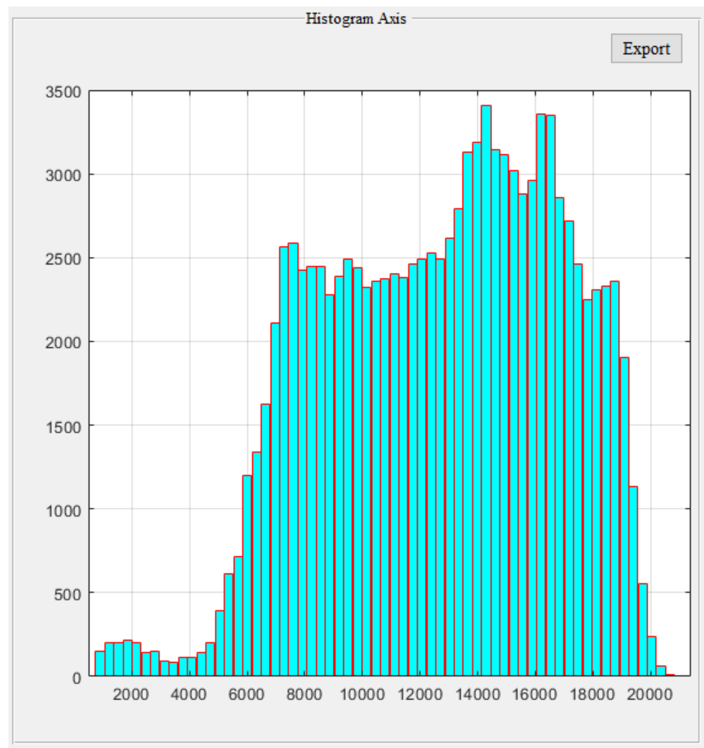
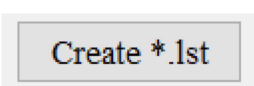


Figure 14: Histogram

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.

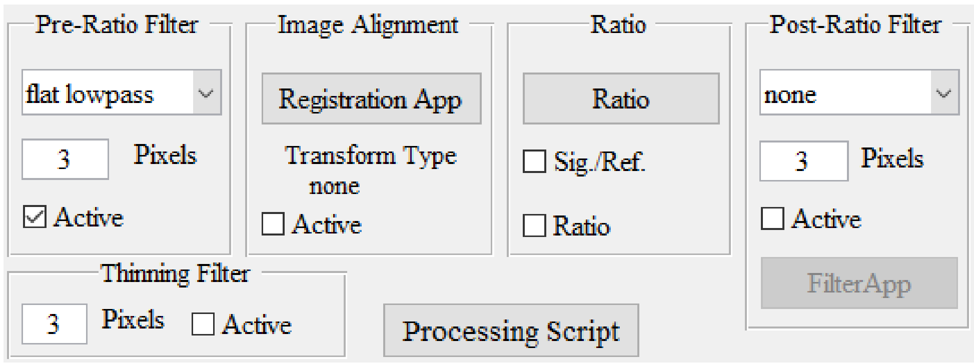
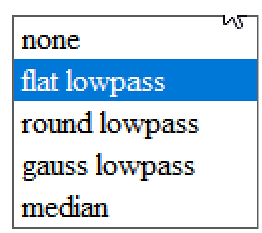


Figure 15: Filtering, Image Alignment and Ratio

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. Given that this dataset has strong pressure gradients, the signal to noise ratio is quite good for PSP and requires minimal filtering.

Filtering can be applied to the raw images and processed images. ***Pre-Ratio Filter*** 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. To test this filter, use the ***Image Viewer*** tool. A 5-pixel median filter was used in this example.

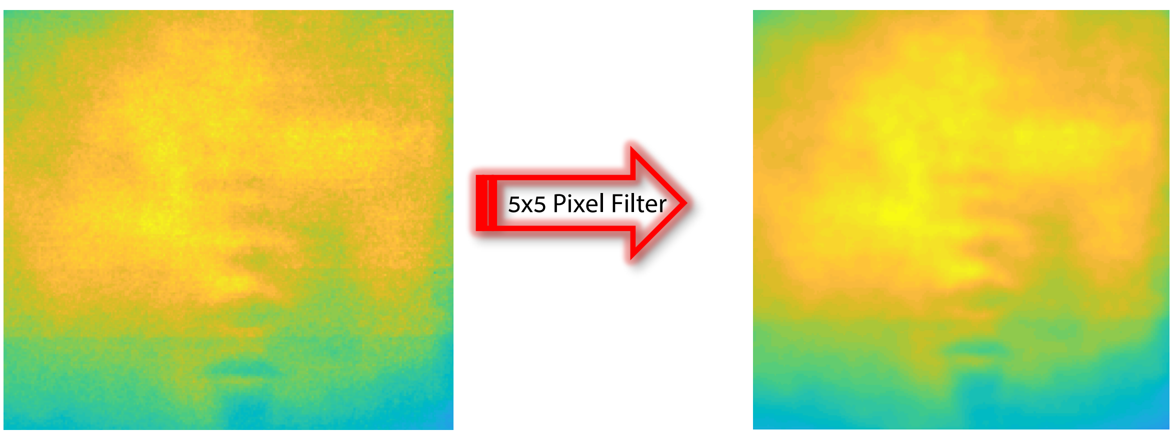
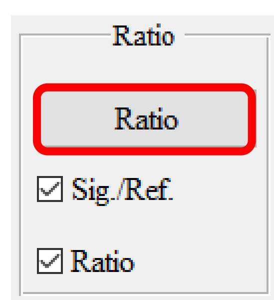


Figure 16: Pre-Ratio Filter



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.

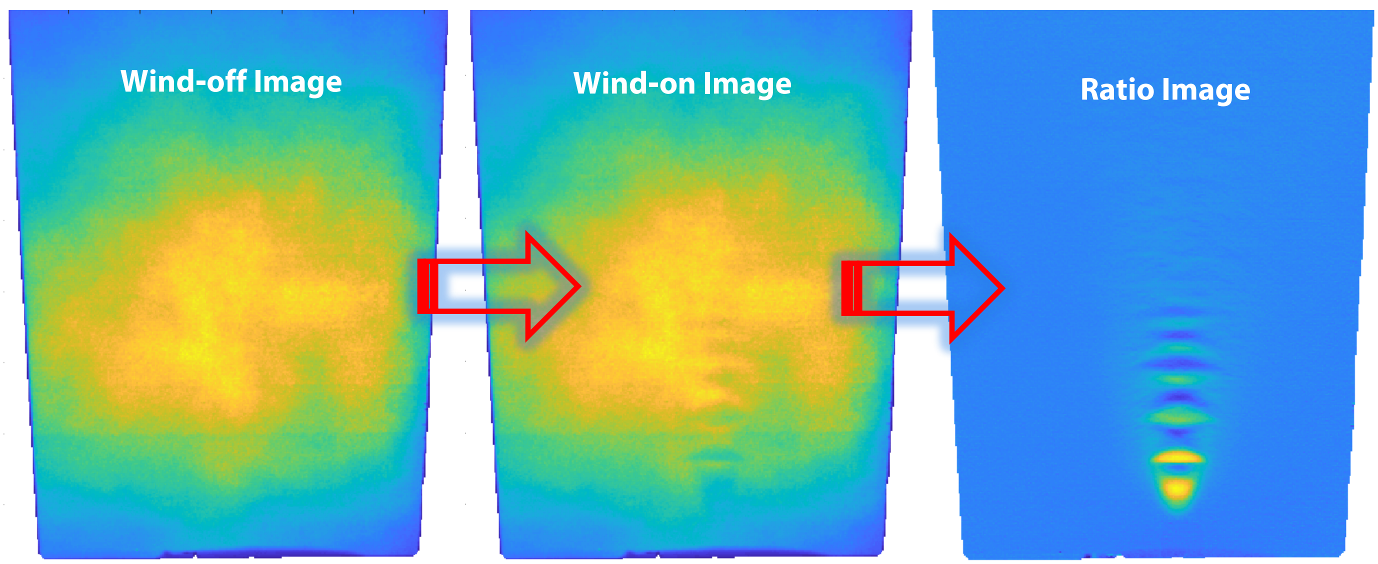


Figure 17: Computing the Ratio Image

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.

Post-Ratio Filter

Once the ratio image is computed, further filtering of the image can be applied. If there is shot noise present in the flat field (areas where the signal level did not change), it can be reduced here. To change the filter type or size, select the desired filter type from the drop-down menu and enter a pixel size (3-21) for the filter. Then click the ***Ratio*** button again to re-compute the ratio with the new post-ratio filter settings.

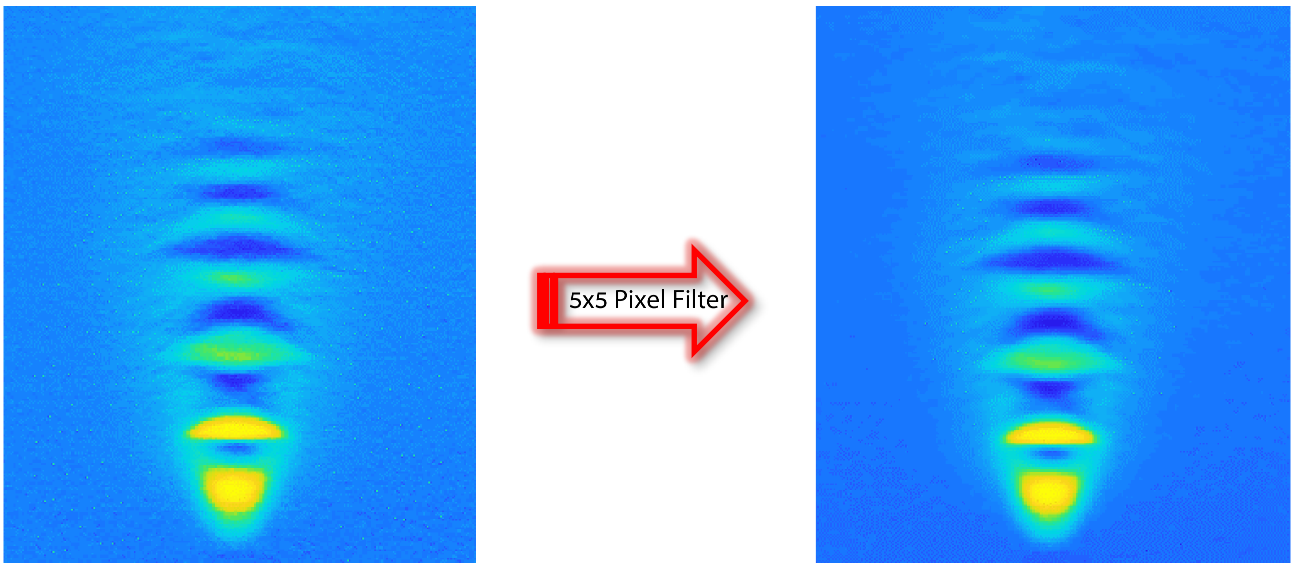


Figure 18: Post-Ratio Filter

Over-filtering of an image will result in loss of the shape of the actual pressure map at the surface. Filtering should only be done to smooth shot noise and imperfections. If the data is to be used in research, over filtering the data will produce biased or incorrect representations of the true pressure map.

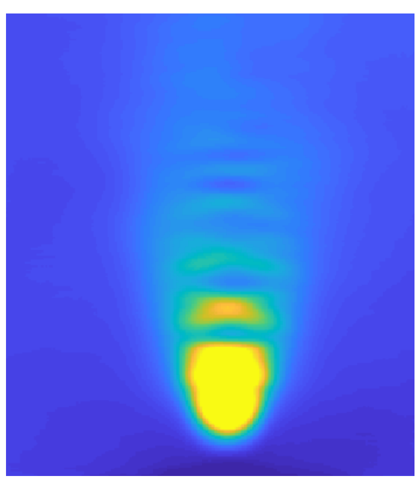


Figure 19: Over Filtering an Image Will Remove Detail from the Pressure Map

Thinning Filter

The thinning filter is a high-pass filter that will clean up the edges of the image. This filter is used to remove the edges of the active image area by the set pixel size. When there is model shift between wind-off and wind-on a border will be created even once images are aligned. This border is well above or below the actual values near those regions and needs to be removed before filtering is applied or it will propagate into the data.

Select the size of the thinning filter in pixels. This is used if there is an edge effect on the painted surface from a smoothing filter. This is typically done post conversion after the automatic conversion is computed. Thinning is not required in this example but will be shown in later examples.

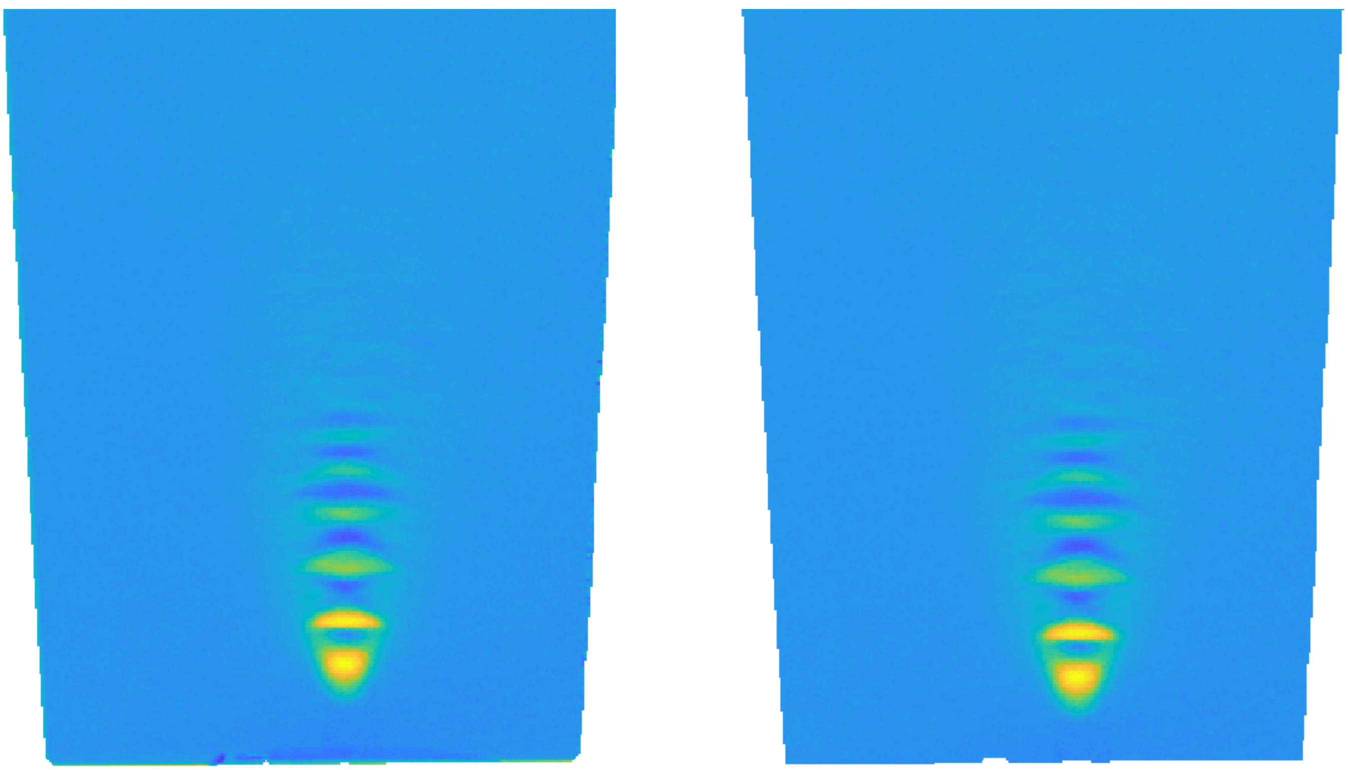


Figure 20: Thinning Filter: No Thinning Filter (Left), Thinning Filter (10 Pixels) Applied (Right)

The thinning filter will be applied to the ratio image when the ratio is computed, clicking the Ratio button.

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.

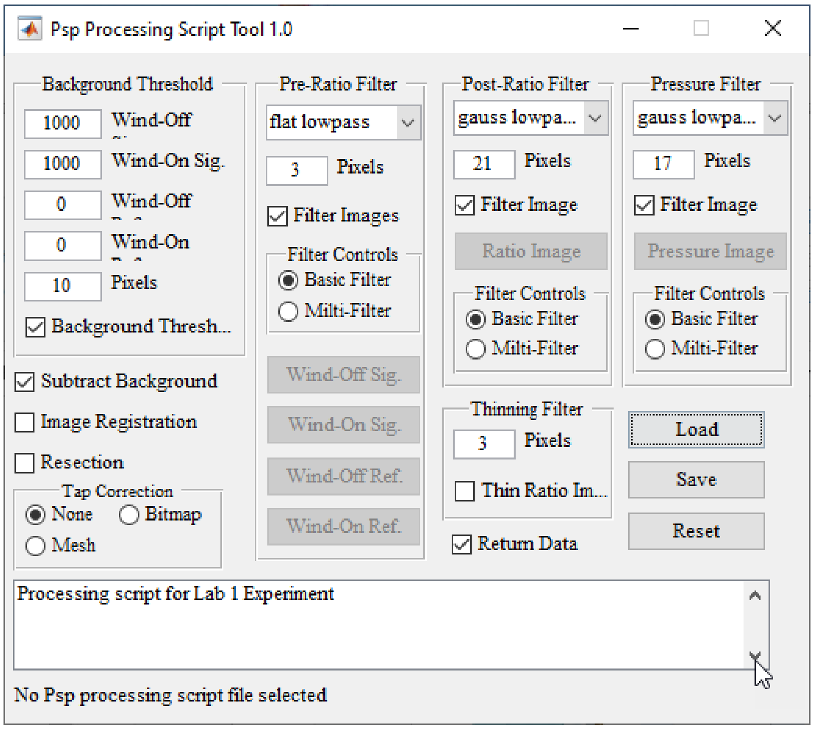


Figure 21: Processing Script Window

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

Test Conditions

To convert the ratio to pressure, it is necessary to enter the conditions that existed when the images were acquired. The tool for editing this information is opened by selecting the ***Test Conditions*** button from the section of the same name. The Wind-off pressure (102,042.8 Pa for this experiment) and Wind-off temperature (297 K for this experiment) are entered in the appropriate fields. For a single component PSP, it is necessary to enter the temperature of the model at the wind-on condition (297 K for this experiment). There is also space to add information such as the static and dynamic pressure; this information can be used to compute pressure coefficients. Information that is used to identify a specific test and test configuration may also be stored in the project file to facilitate analysis at a later date. Use all test conditions shown in Figure 22 for this experiment. Enter the test conditions for the inclined impinging jet experiment as shown. To save as a separate file to load into other projects, click ***Save***. Check the box next to Return Data to have the test condition data automatically loaded into the project file.

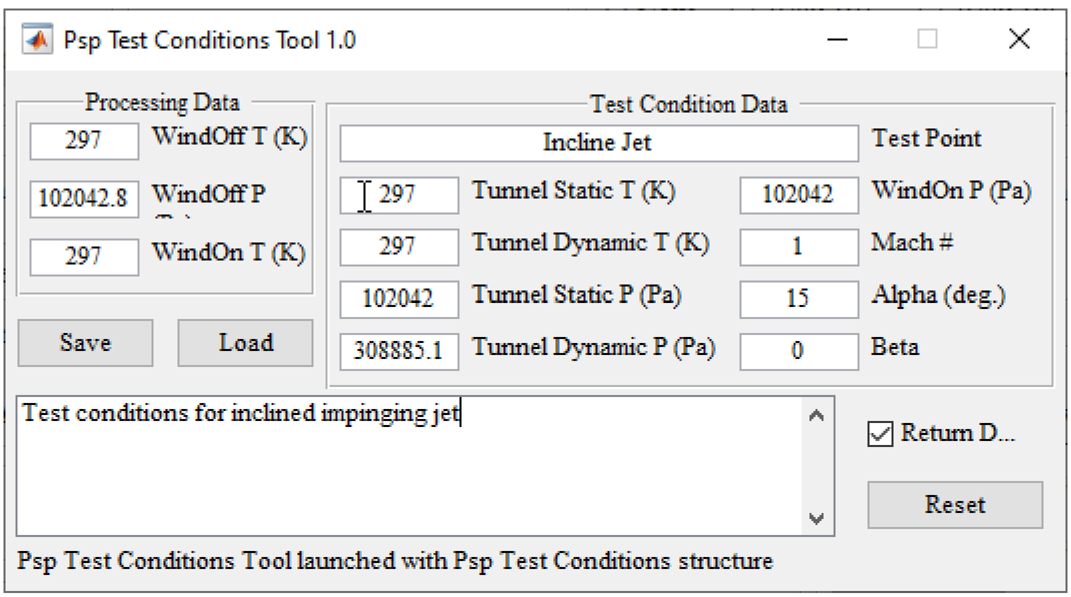
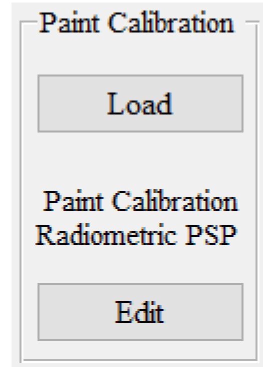


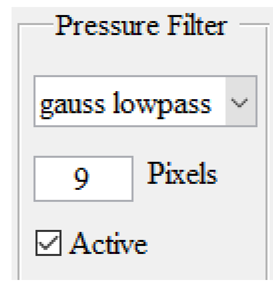
Figure 22: Test Conditions

Paint Calibration



With the calibration file loaded and the test conditions entered the paint calibration can be loaded. Click the ***Load*** button and locate the file **UniFIB.pspcal** in the work folder where the images and project are stored. Calibration files can be edited or created from this toolbox as well but that will be covered in a later example.

Pressure Filter



Once the ratio image is converted to pressure, further filtering of the image can be applied. If there is still shot noise present in the flat field (areas where the pressure did not change), it can be also be reduced here. To change the filter type or size, select the desired filter type from the drop-down menu and enter a pixel size (3-21) for the filter. Check the ***Active*** box. Click the ***Pressure*** button again to re-compute the ratio with the new post-ratio filter settings. A 9-pixel gaussian filter was used in this example.

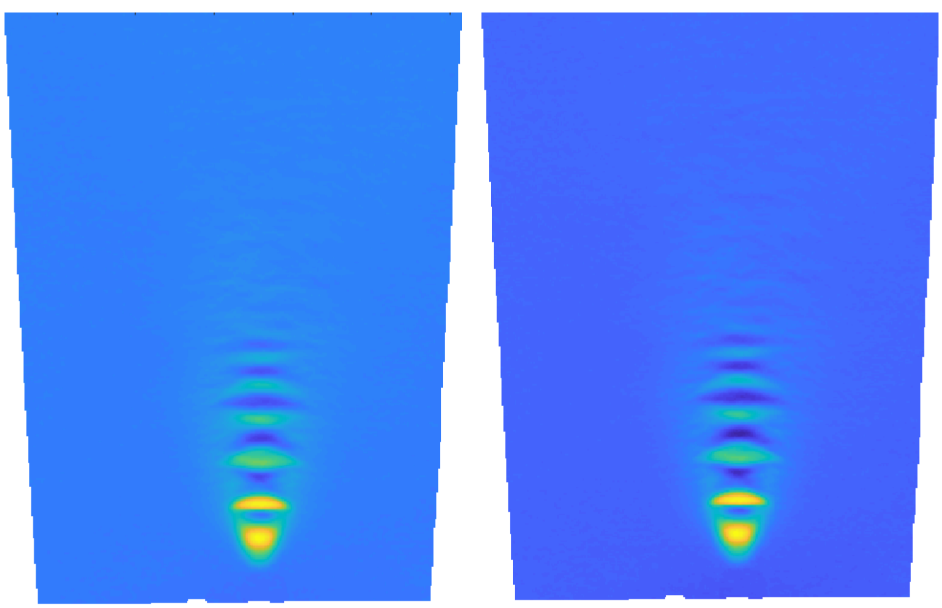


Figure 23: No Pressure Filter Applied (Left), Pressure Filter Applied (Right)

Convert to Pressure

Now the ratio image is ready to be converted to pressure using the entered test conditions and calibration.

The ***Colorbar*** can be activated now to show the lookup table, matching pressure to colors on the image. Units are displayed in Pa ($1x10^5$).

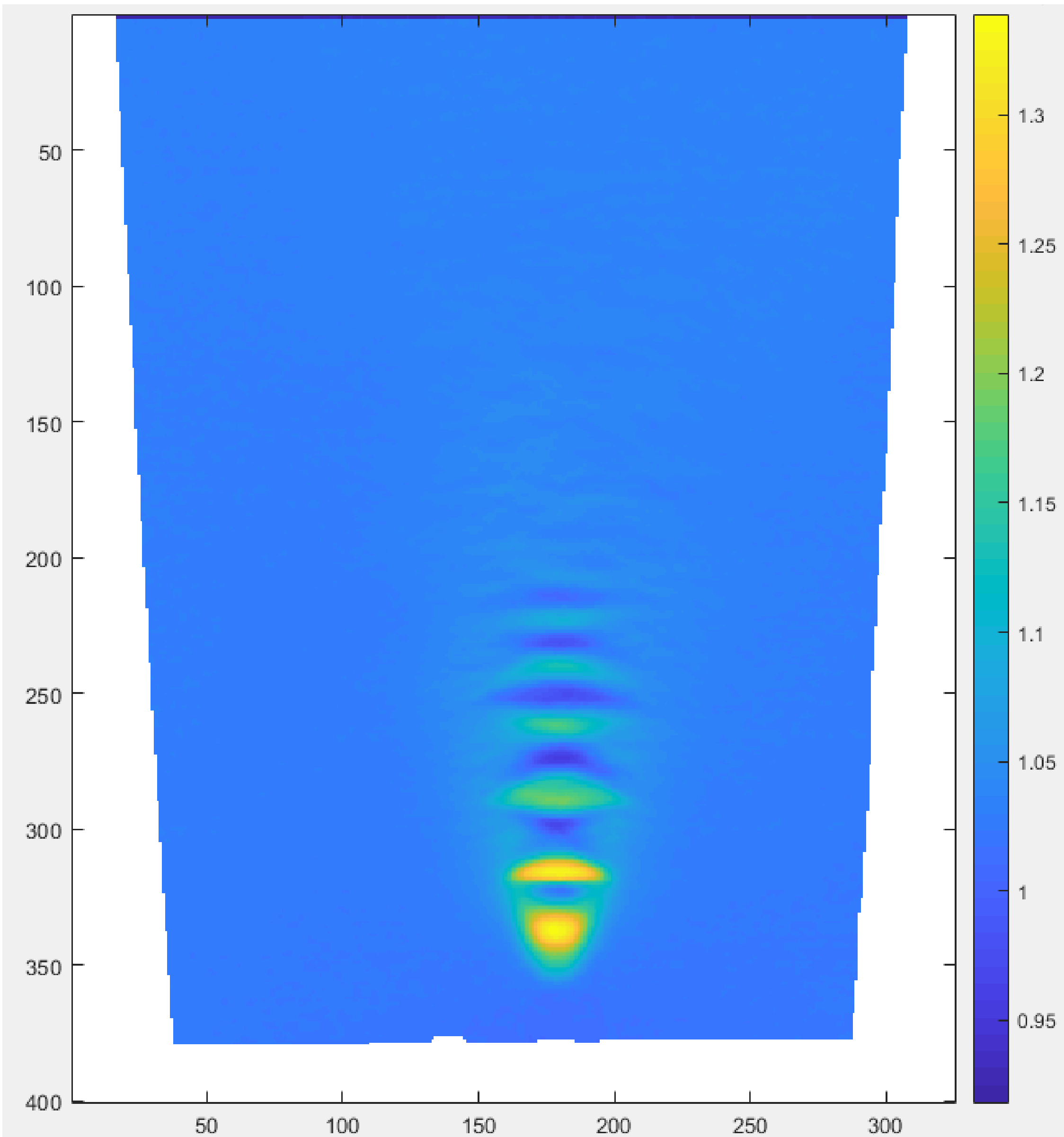


Figure 24: Pressure Field for Inclined Impinging Jet

Other functions like the Bitmap Tap Correction tool and Resection tools will be covered in later examples.