Lab 5: Boundary Layer Transition Detection with Temperature Sensitive Paint

Innovative Scientific Solutions, Inc.

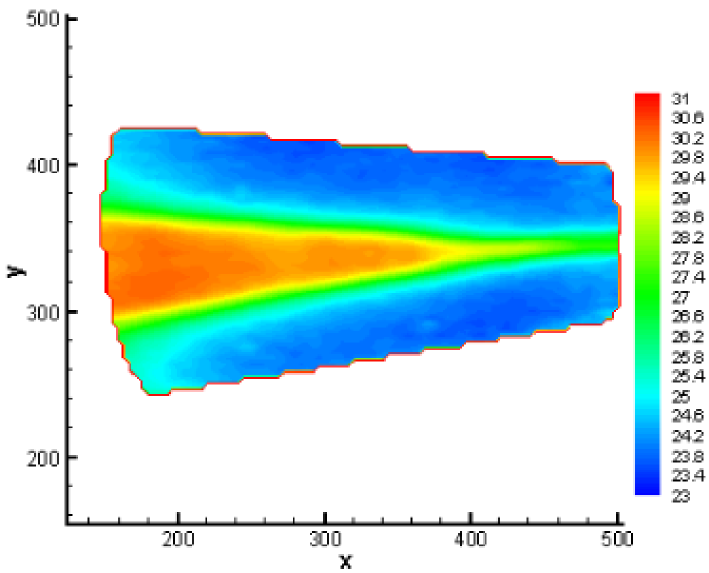
7610 McEwen Road

Dayton, OH 45459

innssi.com

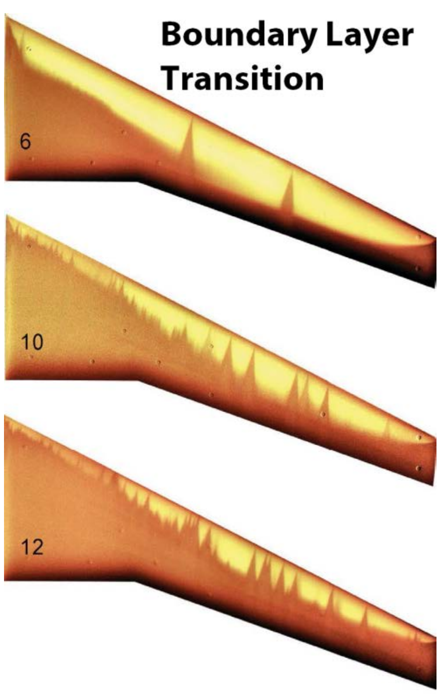
(937)-630-3012

Applications



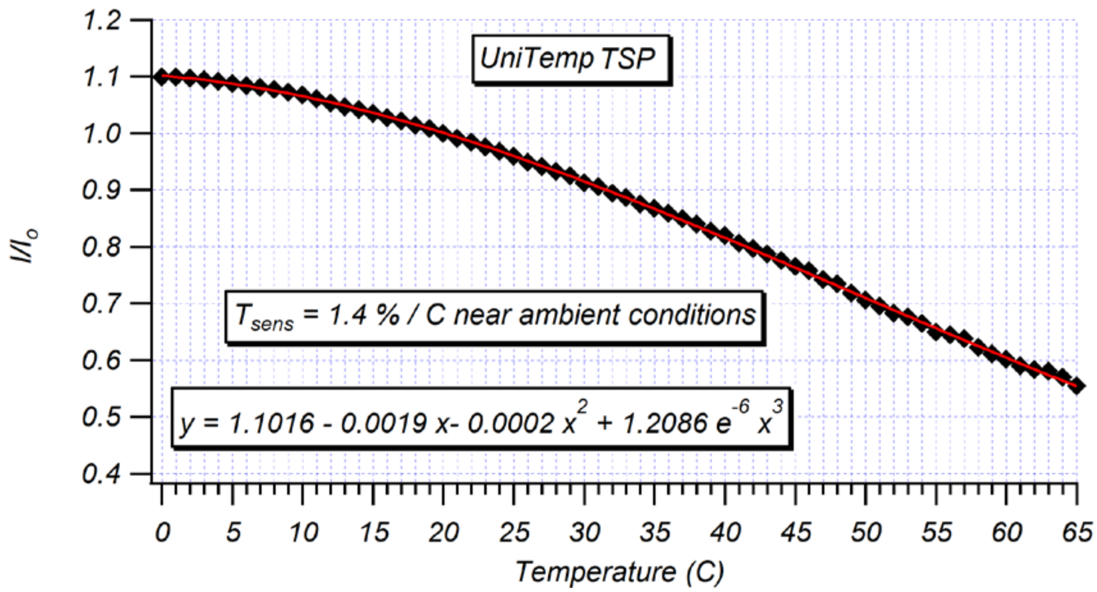
One of the first uses of TSP was for the detection of boundary layer transition. This has been demonstrated by several teams including NAL, DLR and NASA. In this application, the heat flux at the surface, and therefore the surface temperature, is a function of the local heat transfer coefficient. As the heat transfer coefficient is substantially larger for a turbulent boundary layer as compared to a laminar boundary layer, a sharp increment in the surface temperature is indicative of transition. The image shows the evolution of the surface temperature of a 5 degree cone in the Mach 6 Ludwig tube at Purdue University. A small transition bump is located just upstream of the field of view. Note the wedge of high surface temperature located behind the transition bump.

Introduction



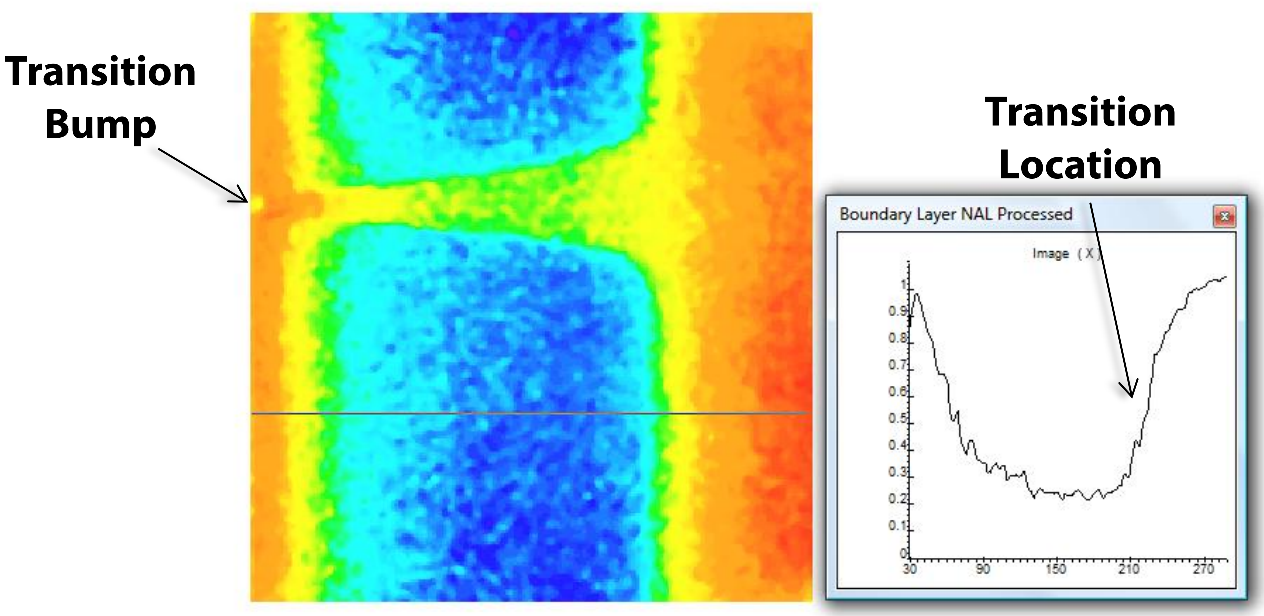
Traditional measurement techniques for acquiring surface temperature distributions on models have utilized embedded arrays of thermocouples and RTD's. This requires significant construction and setup time while producing data with limited spatial resolution. An alternative approach is to use temperature sensitive paint (TSP) to measure surface temperature. The advantages of temperature sensitive paint include non-intrusive measurements and high spatial resolution when compared to conventional measurement techniques. Image based temperature measurements using TSP are accomplished by coating the model surface with the paint and illuminating the surface with light of the appropriate wavelength. The luminescence from the surface is recorded using a CCD camera through a long-pass filter to separate the luminescent signal from the excitation light. The luminescence from the TSP is a function of the local temperature, and therefore, each pixel on the camera acts as a thermocouple.

The photo-physical process governing the operation of a TSP is outlined here. We combine a luminescent molecule and a polymer binder. Generally, we prefer a binder that is impermeable to oxygen. The molecule is excited by the absorption of a photon. From the excited state the molecule has several competing relaxation paths. The path of interest for TSP is known as thermal quenching, a non-radiative decay mechanism. This deactivation results in a system where the luminescent intensity from the molecule is a function of the temperature to which the molecule is exposed. To determine this intensity versus temperature relationship, a sample of the TSP is placed in a calibration chamber. The sample is exposed to a series of temperatures and the luminescent intensity of the sample is recorded. Each intensity is normalized by the intensity at a reference condition and plotted versus temperature. (U. Fey, 2003)



Typical TSP Calibration

Convective heat transfer is much higher in turbulent flow than laminar flow. TSP can be used to examine surface temperature variations between these laminar and turbulent regions. In low speed wind tunnel tests like we will demonstrate, the model is either heated or cooled to increase the temperature gradient across the transition line.



Detection of boundary layer transition using TSP

The TSP measurements give the time evolution of the temperature distribution across the model. From here, the heat flux can be calculated can be calculated from a heat transfer model. Transition is identified where a sharp increase from low to high heat transfer is observed. (T. Liu, 1997)

Hardware

Like the previous lab, this experiment is run in a low-speed wind tunnel to investigate the pressure gradients over a NACA 0012 airfoil using the PSP system. The NACA 0012 is a well-known and well-studied symmetrical airfoil.

The PSP-CCD-C or PSP-CCD-M scientific CCD camera from is used in conjunction with an LM2X-DM-400 LED lamp. While 460-nm is the optimal excitation wavelength for UniTemp TSP, the 400-nm LED can still be used. 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 550-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: Aluminum NACA Wing Model)

Figure 4: Wind Tunnel

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 caused by intensity variations from excess vibrations. 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 Labs 2 and 3.

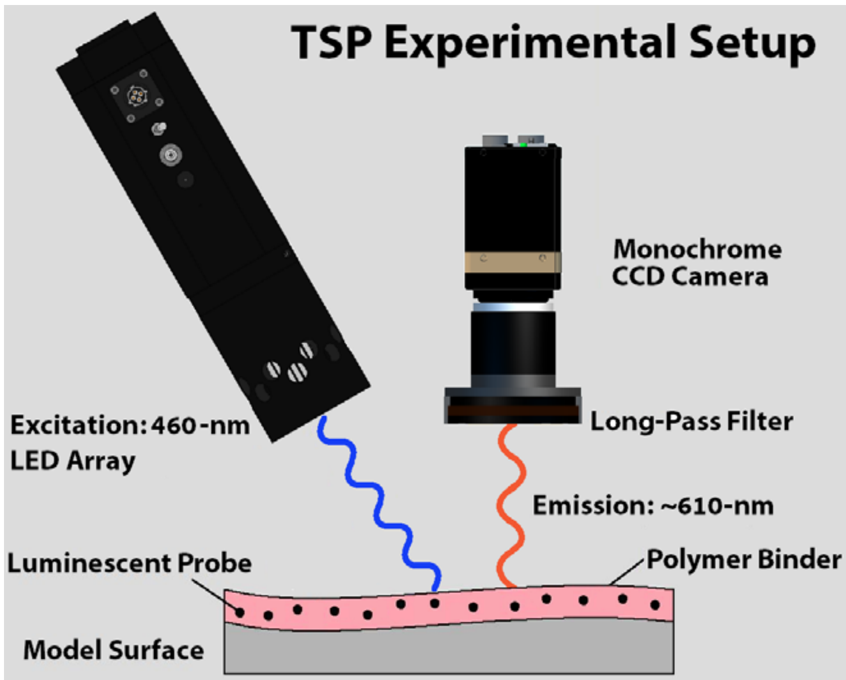


Figure 5: Experimental Setup

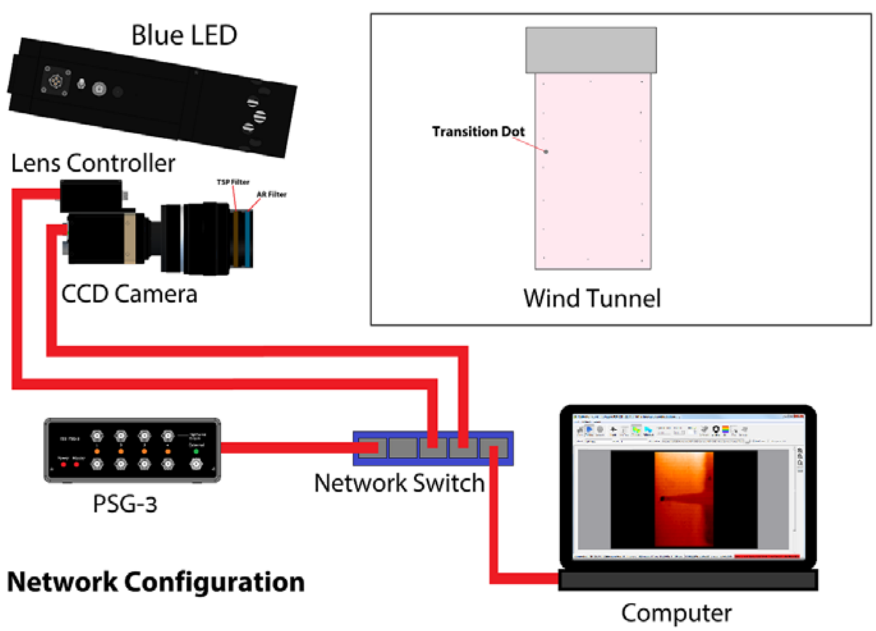


Figure 6: System Networking

In wind tunnel tests where the test body is likely to bend or rotate during data acquisition, it is sometimes necessary to use markers for image alignment. Markers can be physically placed on the test object by simply marking the painted surface with a pen. This will show up on the wind-off and wind-on images as an area with little to no illumination since the paint is not visible.

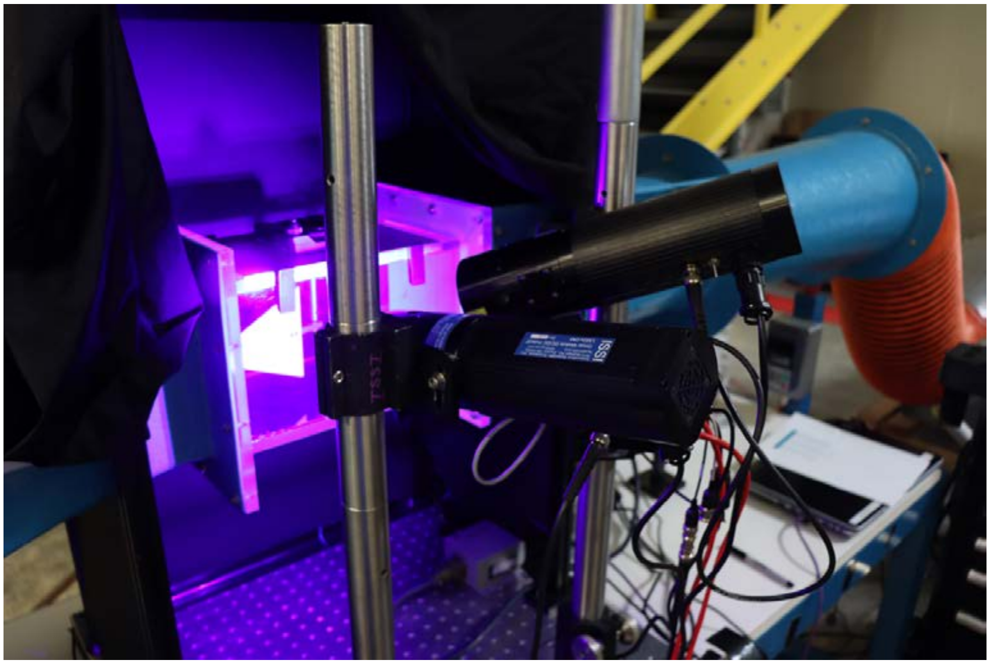


Figure 7: Setup in Wind Tunnel Test Section

The most effective way to generate a temperature gradient is to coat the model in an insulating surface and then preheat or pre-cool the model before running. For this experiment, the NACA wing was coating in a Mylar® adhesive coating. A glue dot was then added near the leading edge of the suction surface of the wing.

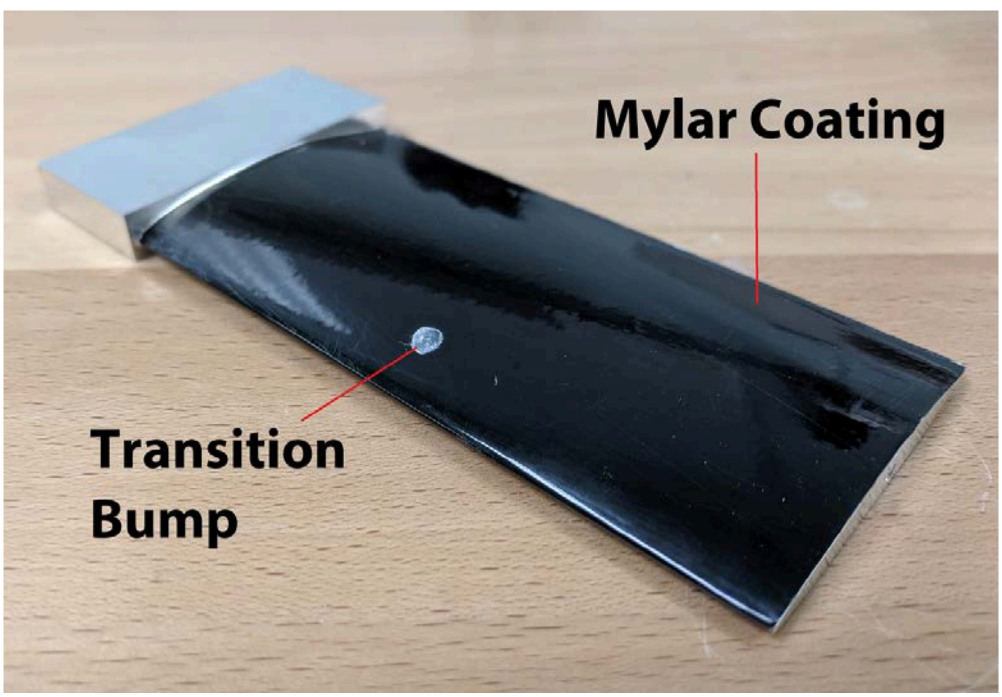


Figure 8: Wing Model with Mylar Coating and Transition Bump

After drying, the TSP was applied over the entire surface. Allow 5-10 minutes for the paint to dry before installing the model into the test section for testing.

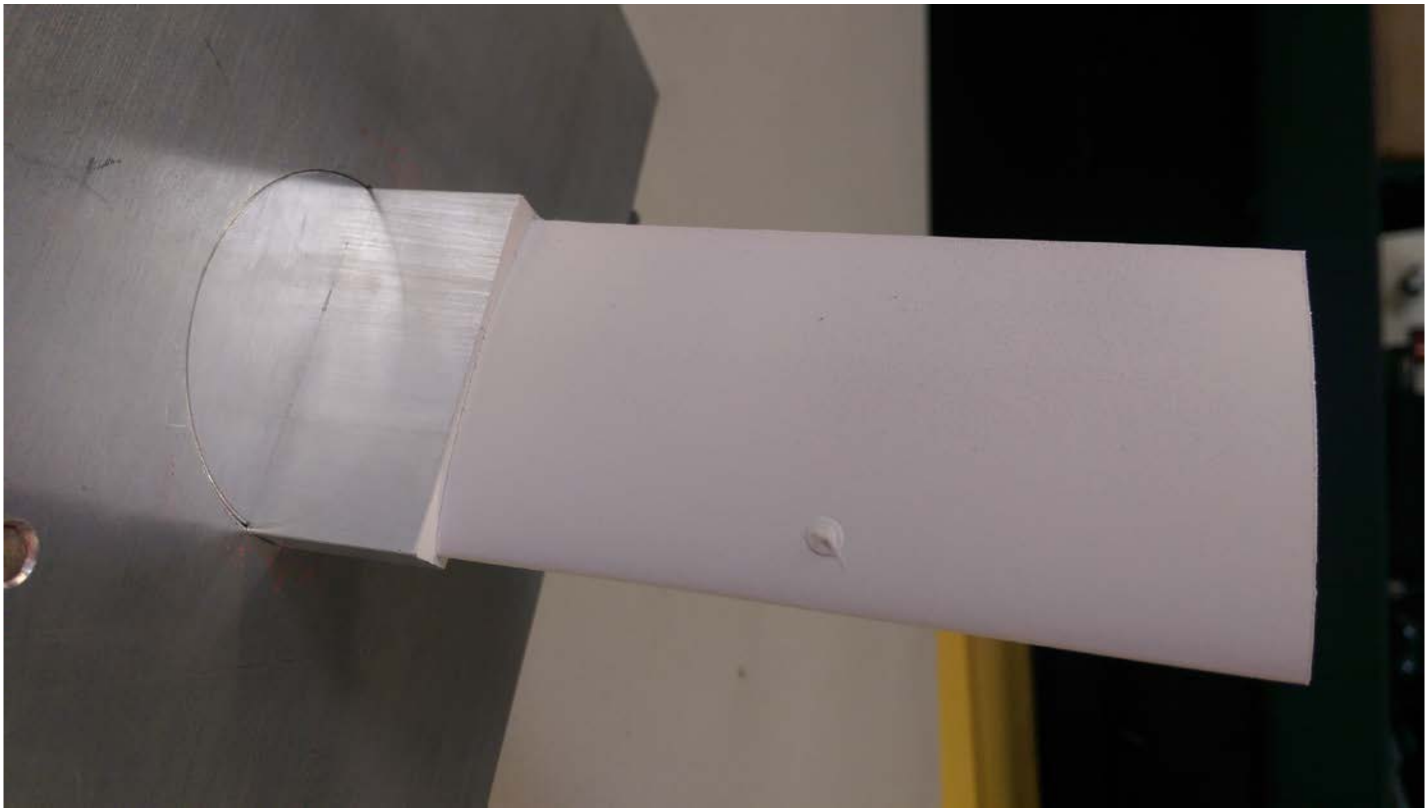
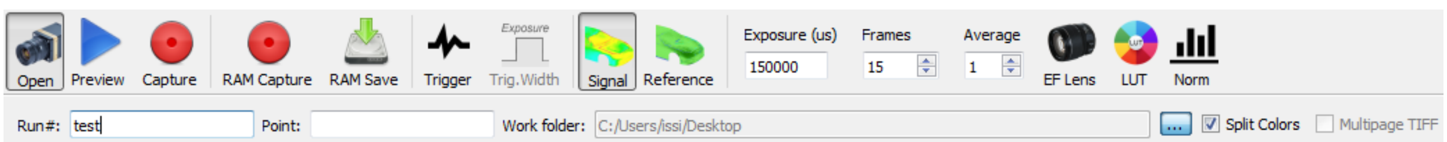
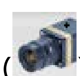
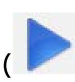


Figure 9: Wing Model After TSP is Applied

Data Acquisition



Install the model into the wind tunnel test section. Align the camera and LED for optimum illumination of the surface. Open ProAcquire () and use the live preview () to view the image seen by the camera and adjust the focus so that the image in the preview is clear. Focus the camera lens either manual or by use of the EF Lens Controller if one was purchased with the system. Save the lens focus position or lock down the focus ring of the manual lens. Create a new file each time a new image with different settings is captured by pressing the  icon in the lower toolbar of ProAcquire next to the ***Work Folder*** description. Keep ***Split Colors*** checked for color cameras as the red channel used for TSP will still need to be separated. Be sure to turn off or block any light sources to avoid noise in the data before data acquisition begins. With the model installed in the wind tunnel mounting fixture, heat the model for several minutes with a heat gun. Record the model temperature on the TSP surface and place the model back into the test section. If it is easier, the model may be removed from the test section and heated separately before being re-installed. A small oven could also be used to heat the model.

With the LED(s) on and the model re-installed and heated, capture wind-off images (*wind-off.tif*). Do not average the wind-on images as the temperature evolution from the heat transfer gradient will change as data is recorded. Turn on the wind tunnel and set it to the desired airspeed and allow it to stabilize. Once the tunnel is up to speed the data acquisition can begin. Capture a series of 100 images or more (*wind-on.tif*). The images used in this example were acquired at 60 m/s. The model was preheated to ~80 degrees Celsius before installing into the wind tunnel.

After the wind-off and wind-on data are collected, capture the background image with the room lighting and the LED lamp turned off. Save the background image (*background.tif)* in the same work folder where all images for this experiment will be stored.

It is important not to saturate the image by over-exposing it. Check the signal level on the image in ProAcquire before data acquisition begins.

Data Reduction

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 and green signals. If using the PSP-CCD-M, do not check ***Split Colors***. The TSP response will be captured only in the red channel. See the spectral response of UniTemp below in Figure 10.

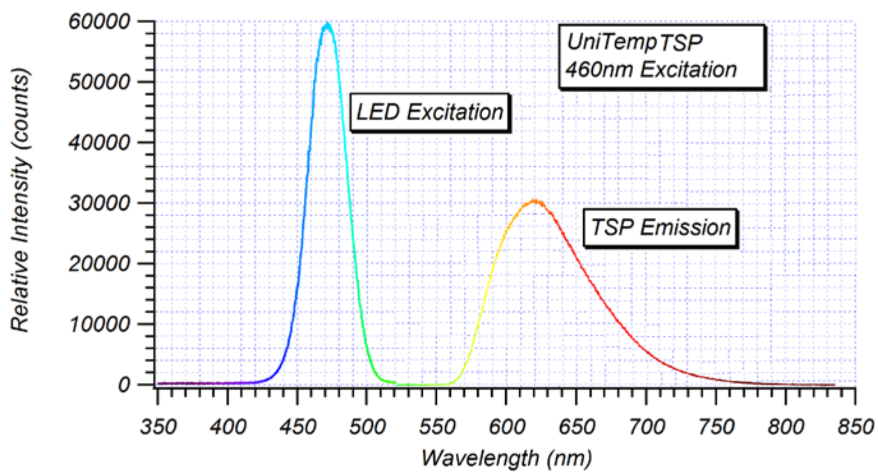


Figure 10: Spectral Response of UniTemp TSP

For TSP measurements, the green and blue channels of the color camera are unused. This split gives the final images ¼ the resolution of the full array. If higher resolution is desired, a monochrome camera can be used, taking advantage of the full resolution of the sensor. The camera will only save a red and green image noted with the suffix _p (signal) and _r (reference). The _p images will be the only images used for TSP processing.

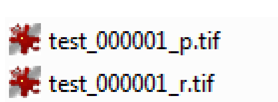
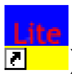


Figure 11: Locating the Signal Channel

If the monochrome PSP-CCD-M was used, there will be no suffix on the images since they are monochromatic.

Reducing the data into an image of temperature involves taking the ratio of the wind-off / wind-on images and then converting the image to temperature with a previous calibration. Create a new project in OMS Lite (

) using the PSP Single Channel option. There is no TSP channel option so the PSP processor can be used. Select the folder that the data files taken are saved in. Save the project as *NACA_TSP.ims*.

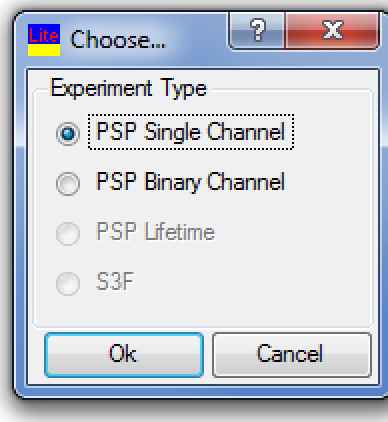


Figure 12: Single-Channel Processing

In the GUI for the Single Channel tab in OMS-Lite, load the wind-off, wind-on, and background images. The wind-on image should be an image taken some time after the tunnel start to visualize the temperature gradient caused by the increased convective heat transfer from the turbulent boundary layer.

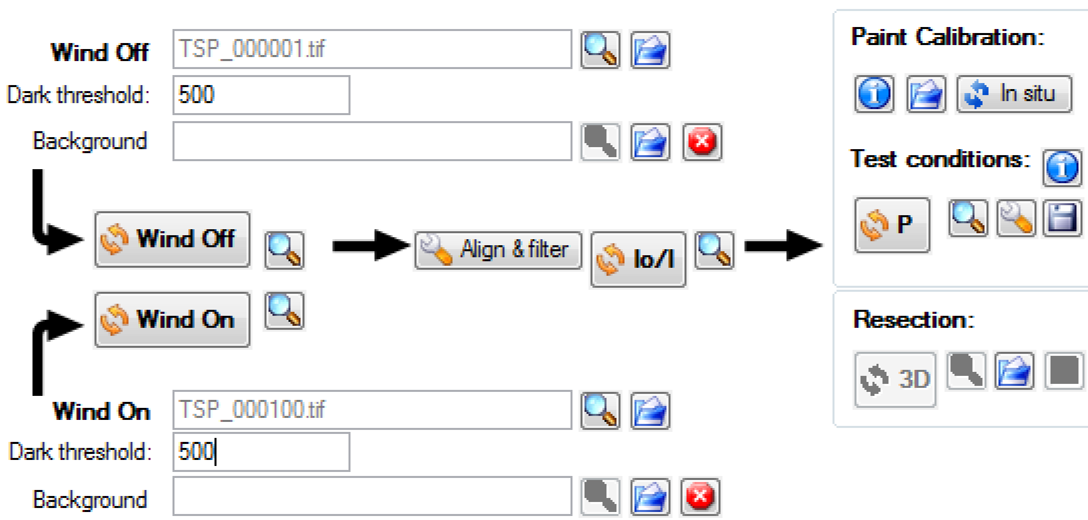


Figure 13: Single-Channel Interface

A dark threshold should be set to remove the background (non-painted areas of the image) from the image. Set the dark threshold just above the maximum value of the non-painted area seen on the image. See Figure 14 where the dark threshold is determined. After calculating the corrected off and on images, the background level signal (anything below the threshold value) will be removed from the image before further processing.

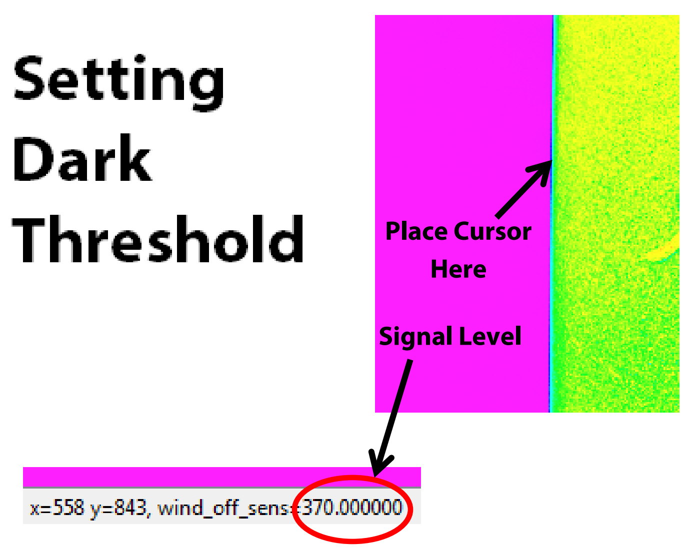


Figure 14: Dark Threshold

Once the dark threshold is set, calculate the wind-off and wind-on corrected images using the icons:

The corrected images will have the dark threshold set to what was input and the background image subtracted if one was acquired.

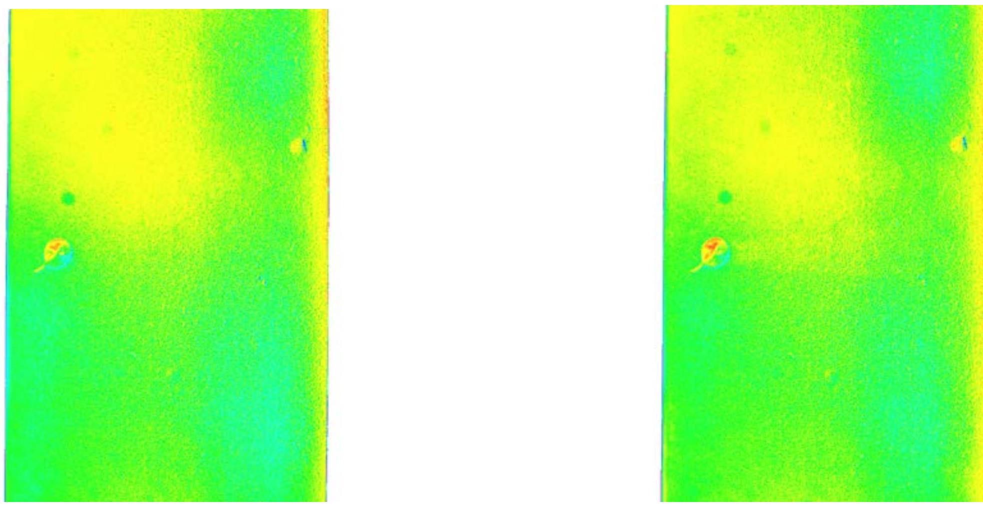


Figure 15: Left: Wind-off Image, Right: Wind-on Image

The boundary layer transition is already detectable behind the glue dot in the raw wind-on image. Next, the intensity ratio will be computed. Before this is done, the align and filtering tool needs to be utilized to set the parameters of the alignment and filtering. Since this model did not have resection markers, QPED (a cross-correlation algorithm) will be used to align the wind-off and wind-on images. Use the default QPED settings. If markers are present, the Box Size represents the X by Y size box around which the alignment algorithm will search for the associate marker on each image to do an alignment. Fix First should be left at 0. Order defines the order of the polynomial fit for the alignment algorithm. As a general rule, 0 and 1st order fits are used for 1- and 2-D model shifting while 2nd and 3rd order are for more complex twisting and bending. Generally, we recommend using 0 or 1st order alignments.

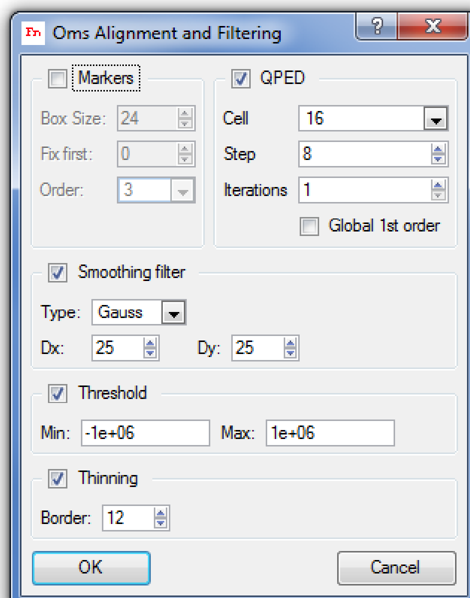


Figure 16: Alignment & Filtering Tool

A smoothing filter can be used to improve the signal to noise ratio of the TSP data. For this example a 25 px by 25 px Gauss filter was used. The threshold level can be left at default levels since the background level was previously removed. Thinning is used to trim the active area (where there is paint on the model) of the image. There is going to be some shifting of the model between off and on. This typically leads to an small alignment error of 1-2 pixels which appears as a line around the model in the image. As larger low-pass filters are applied, this line is magnified. The larger the filter used, the larger the thinning needs to be.

Once the alignment and filtering parameters are set, calculate the ratio image using 

. This will calculate the wind-off (Io) over wind-on (I) ratio. This image is purely an intensity ratio with no calibration yet applied. The intensity ratio will however, provide a detailed map of the effect of the temperature gradient on the surface.

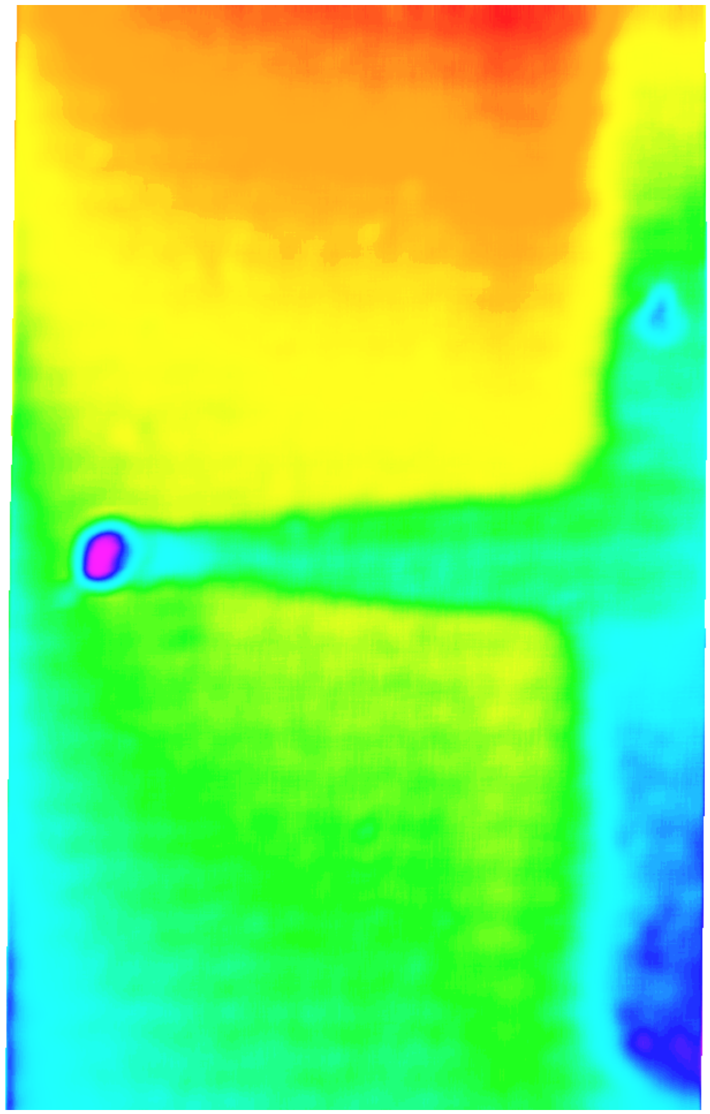


Figure 17: Intensity Ratio

After the ratio image is computed, the paint calibration file should be loaded. For TSP, a modified calibration file will be used. The "pressure" entered in the calibration file is not pressure but temperature. The program for PSP processing is being used to compute temperature using this modified calibration file. Load the calibration file by clicking the folder icon shown in Figure 18.

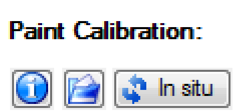


Figure 18: Load Paint Calibration

Next, the test conditions should be entered as in Figure 19. Again, since the pressure tools are being utilized to process temperature data, the pressure conditions will actually be read in as temperature. The ***Wind-off P*** should be set to the temperature of the model when it was first placed into the wind tunnel after heating. The ***Static P*** should be set to the ambient temperature. The Wind-off T and Wind-on T should be set to the same respectively.

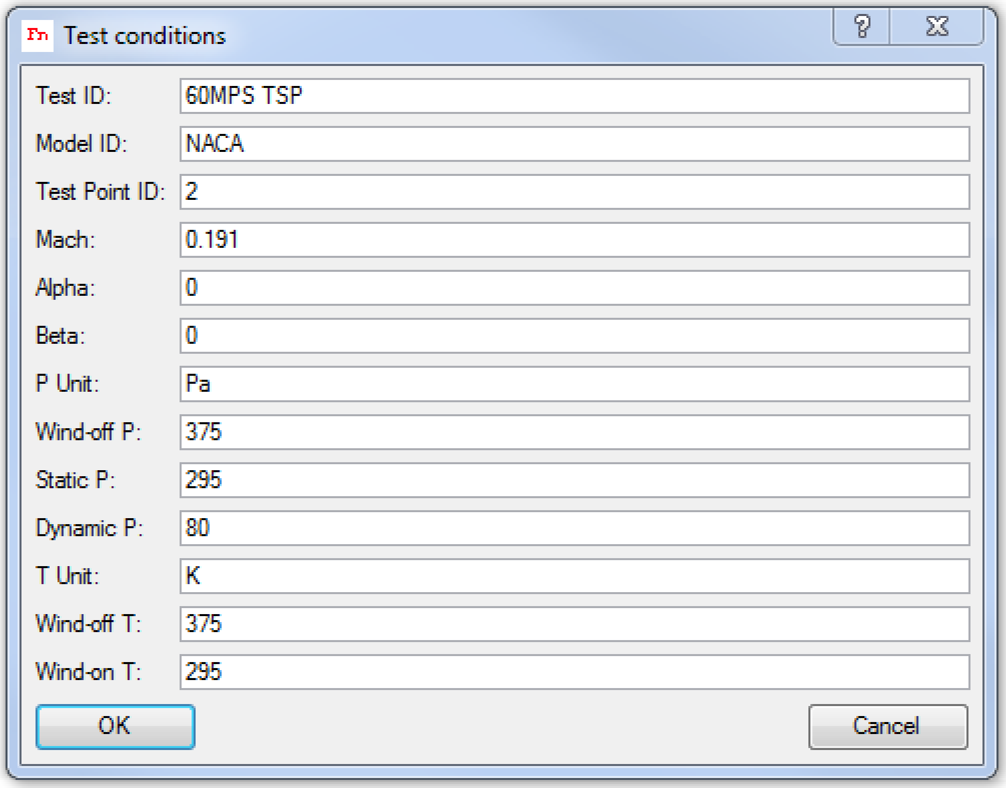


Figure 19: Test Conditions

Once the test conditions are entered, the images can be converted to temperature.

The temperature will be displayed in the legend in degrees Kelvin (K). As expected, due to the turbulent boundary layer caused by the glue dot, the temperature behind it is lower than the rest of the wing at the same chord length. This is due to the increased heat transfer from the turbulent boundary layer, cooling the surface. If the model was cooled below ambient temperature prior to testing, this area would increase in temperature behind the glue dot as shown in the example data from cryogenic TSP tests earlier. The boundary layer can also be observed going from laminar to turbulent near the trailing edge of the wing.

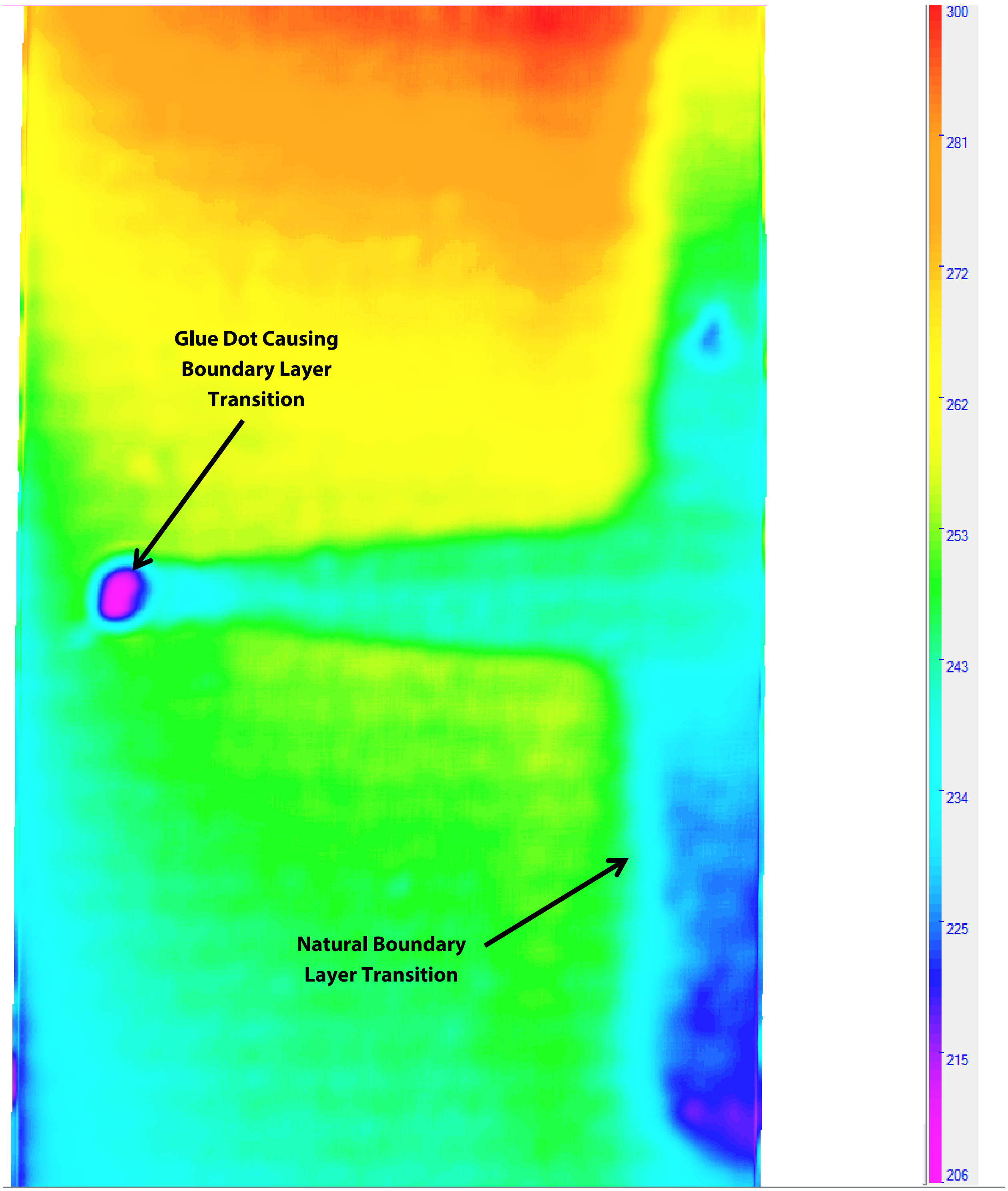


Figure 20: Temperature Field Showing Boundary Layer Transition

The processed temperature image can be probed for further investigation. The graphing tool in the toolbar will allow a line to be drawn across the image to graphically show the temperature gradient along that line. The temperature drop behind the glue dot can be shown graphically as well as the temperature profile of along the chord. This data can be saved to a text file to be compared with CFD or thermocouple data.

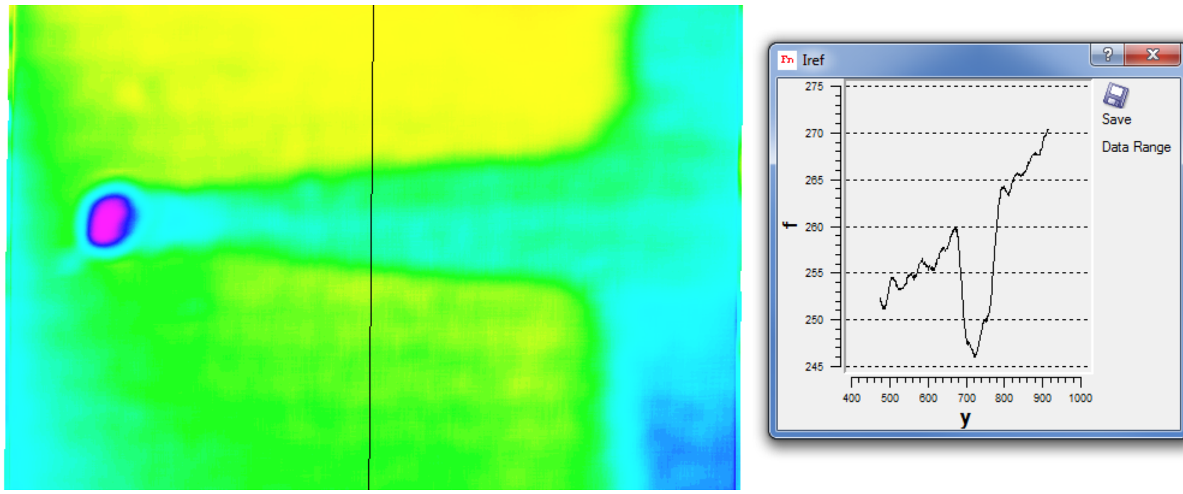


Figure 21: Boundary Layer Transition from Glue Dot

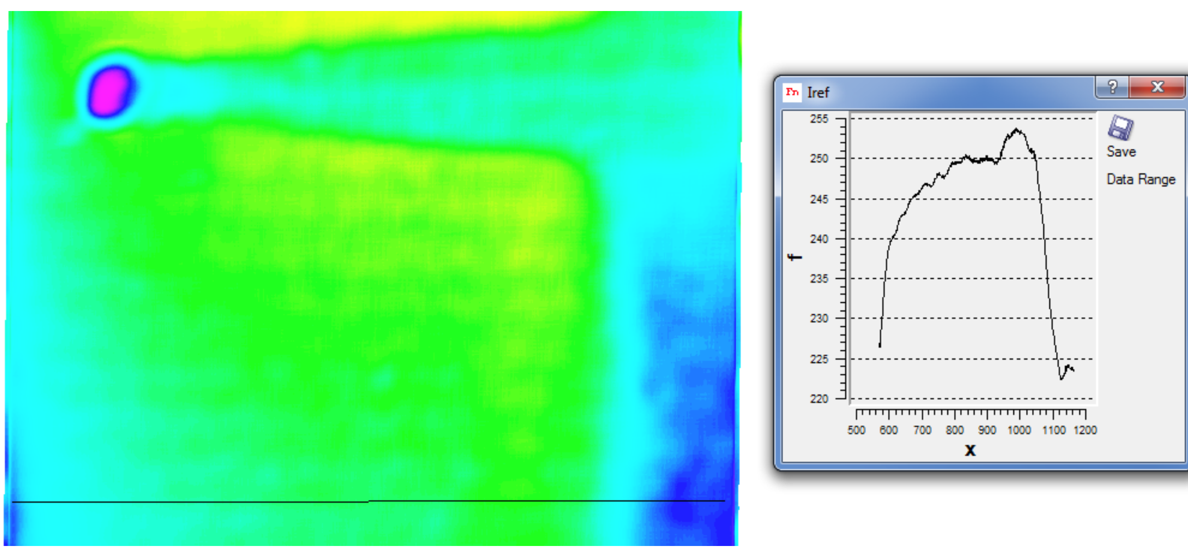
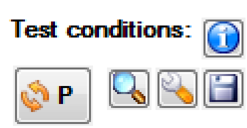


Figure 22: Boundary Layer Transition Along Chord

To save the final processed images, click the disk icon shown at right.



Works Cited

T. Liu, J. S. (n.d.). Applications of Temperature and Pressure Sensitive Paints.

U. Fey, R. H. (n.d.). Transition Detection by Temperature Sensitive Paint at Cryogenic Temperatures in the European Transonic Wind Tunnel (ETW).