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ANALYSIS OF FILTERING PROCESSES INFLUENCE ON PRESSURE DISTRIBUTION RESULTS OBTAINED WITH PSP TECHNIQUE

André Ribeiro de Barros Aguiar
Cayo Prado Fernandes Francisco
Universidade Federal do ABC, Avenida dos Estados, 5001 Bangú 9210-971 - Santo Andre, SP – Brasil, Telefone: (011) 44370108 Ramal: 0108
ufabc.andre@gmail.com, cayo.fernandes@gmail.com

João Batista Pessoa Falcão Filho
Ana Cristina Avelar
Jessica Jia Ling Hsu
Instituto de Aeronáutica e Espaço (IAE), Divisão de Sistemas Aeronáuticos (ALA), Pça. Marechal Eduardo Gomes, 50, CEP: 12228-904, São José dos Campos, São Paulo
jb.falcao@ig.com.br, anacristina.avelar@gmail.com, jessicajl.hsu@hotmail.com

Abstract. *Tests were performed at the TTP (Pilot Transonic Wind Tunnel) of the IAE (Institute of Aeronautics and Space) in order to analyze the pressure field surface distribution over an AGARD standard model and help certifying the tunnel reliability. The results were obtained varying the Mach number from 0.4 up to 1.1 and the pressure distribution over the model was found by the PSP (Pressure Sensitive Paint) technique. It allowed the complete determination of the pressure over the surface of the model and the results could be compared with experimental data from reliable transonic industrial installations, namely, the AEDC 16' PWT and the NAA 7' TWT wind tunnels. The PSP is a relatively new optical technique that is being aggregated to the TTP with the aim of improving the test capabilities and procedures. Therefore, as an optical instrumentation, filtering processes and its effects on the pressure distribution should be considered relevant. The present work will evaluate the effect of different filters (Gaussian, Median, Flat) and the variation of its parameters (number of iterations, filter diameter) applied at the pressure fields so as to obtain a less oscillatory, but still physically meaningful result. Afterwards, images of compressible effects, obtained with Schlieren technique, will be used in order to determine the capability of PSP technique to identify and proper localize structures as shocks and expansion waves. As the Schlieren technique does not involve any filtering process it is a suitable tool for comparison with the PSP results.*

Keywords: *PSP, Filtering, AGARD, Transonic Testing*

1. INTRODUCTION

The Pilot Transonic Wind Tunnel (TTP) of the Institute of Aeronautics and Space (IAE) is a modern installation suitable to perform many different aerodynamic tests. This aerodynamic facility is continuously driven by a main two-stage compressor of 830 kW of power. Its control subsystems settle stable flow condition in its 0.25 m high and 0.30 m wide test section, guaranteeing Mach and Reynolds number values to better represent the real scale vehicle flight conditions (Falcão Filho and Mello, 2002). Figure 1 shows part of the TTP aerodynamic circuit, with its plenum chamber open. The tunnel is completely operational but, since it is a relatively new installation, new technologies and procedures are still being integrated and special tests are needed to assess its reliability when compared with other wind tunnel installations. TTP has undergone many calibration test procedures for these purposes and this particular work presents the test campaign concerning the results of pressure distribution obtained on the surface of the AGARD (Advisory Group for Aerospace Research and Development) model installed in the TTP using PSP (Pressure Sensitive Paint) technique.

Among the most common standard models, the AGARD model is ostensibly used as an inter-laboratorial tool to compare wind tunnel performances. The model used, AGARD-C is particularly adequate for transonic tests (Goethert, 2007). The experimental data collected during the campaign was compared with data, from the scientific literature (Fromm and Leef, 1961).

This modern optical technique is based upon the relation between partial pressure of oxygen and the luminescence effect. It gives a complete surface pressure distribution over the model through a non-intrusive experimental procedure. However, this technique presents some spatial limitations when very thin wings or models with sharp corners are the object of investigation (Watkins *et al.*, 2011). While these approaches provide information on the exact pressure at a point on the model, pressure taps are limited to providing data at discrete points, thereby making it difficult to measure the surface pressures between these sites.

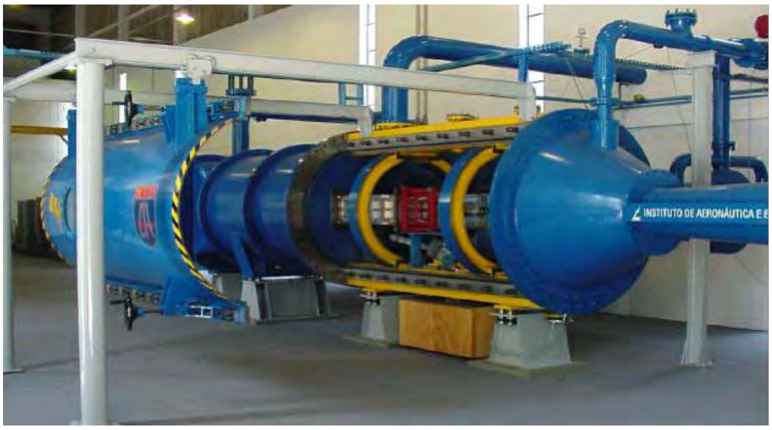

Figure 1. Pilot Transonic Wind Tunnel installation.

The experimental data collected was compared with data from the scientific literature (Fromm and Leef, 1961) presenting tests conducted in two very important industrial transonic facilities: AEDC 16’ PWT (16 Feet Propulsion Wind Tunnel from Arnold Engineering Development Center) and NAA 7’ TWT (7 Feet Trisonic Wind Tunnel from North American Aviation).

It is important to note that the PSP technique requires specific image processing after the images are taken. The images obtained possess a representative high frequency oscillation in measurements, which does not represent the physical phenomena occurring in the flow. It is necessary to apply a filtering process and, more important, understand how this process affects the results in order to accurately determine the desired information.

The software used to obtain these data is called ProImage ®, developed and provided by ISSI, in which it is possible to apply different types of corrections and filters. A complete analysis of the filtering process will be done and the results are to be expressed in terms of comparisons of data and images. The differences between different classes of filters, in which Gaussian filter is the most well-known example, will be discussed.

Afterwards, a qualitative comparison with the Schlieren technique (Tropea, 2007) will be presented. This is an important evaluation due to the nature of these two techniques: both of them are optical techniques, but the PSP requires post-processing while the Schlieren does not, it just makes compressible phenomena observable owing to density changes in the flow, being a reliable and useful tool for the localization and visualization of shocks and expansion waves.

2. METHODOLOGY

For better comparison with data from literature, the tests were conducted at Mach numbers 0.6, 0.8, 0.9 and 0.95 at zero angle of attack. The results presented in this work, however, are restricted to Mach 0.95.

Background images were previously obtained in order to correct the pressure field along the model by aligning the images and then compute their ratios, which will, ultimately, be converted to pressure using the calibration of PSP. The flow properties need to be exactly specified, so the ProImage® software can compute the variables accurately. The accurate computation of the properties from the acquired images is the main step of the process due to the ink sensitivity with respect to temperature (ISSI, 2009).

By properly determining the thermodynamic characteristics of the flow, static and dynamic pressures may be obtained through the equations below:

$$P_{static} = \frac{P_{total}}{(1+\frac{(\gamma-1)}{2}M^2)^{\frac{\gamma}{(\gamma-1)}}} \tag{1}$$

$$P_{dynamic} = \frac{1}{2}M^2\gamma\frac{P_{total}}{(1+\frac{(\gamma-1)}{2}M^2)^{\frac{\gamma}{(\gamma-1)}}} \tag{2}$$

Images have to be acquired within two wind conditions, specifically, wind on and wind off. The ‘wind off’ images will be the reference values when the Mach number equals zero. Furthermore, a series of background images without

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the presence of the model also need to be acquired. Additionally, it is important to note that the CCD camera is set to register two distinct moments: the moment before the quantum decay and the one, subsequently, after the decay.

Once all data are introduced, the software is able to convert the luminescent images into pressure field images and all of the filtering options are presented. It is important to understand how the filtering process affects the results since it is an interpolation process that softens the signal oscillation and may also influence the pressure gradients. For example, an excessive attenuation may be the reason for the loss of physical meaning of the final pressure coefficient results or even a weak shock wave may be missed unavoidably. Nevertheless, the non-treated optical oscillations can misrepresent the physical phenomena, once there are no oscillations of high frequency on the pressure coefficient in the analyzed experiment. For this situation, it is indispensable the use of low-pass filters, which are filters that pass low-frequency signals and attenuates signals with frequencies higher than a cutoff frequency. The cutoff, in this image context, is the filter diameter. It corresponds to minimum and maximum limits set so that the filter will exclude data that is out of the prescribed range [ProImage, 2010].

Figure 2a depicts an untreated image and Fig. 2b shows its pressure coefficient along the center line of the model. It is evident the presence of high frequency oscillations not associated with the physics of the flow being measured.

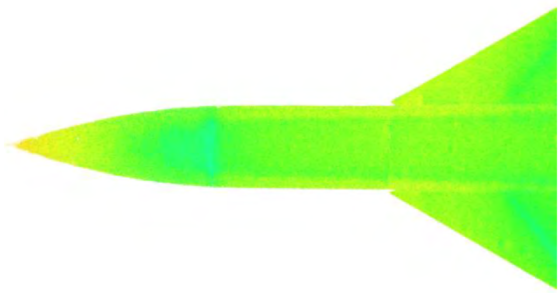

Figure 2a. AGARD-C standard model with no filtering process.

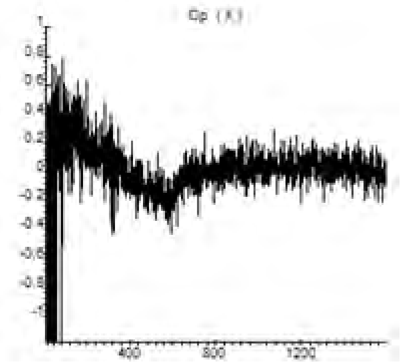

Figure 2b. Pressure coefficient along a center line of the AGARD-C standard model with no filtering process.

3. RESULTS

A filtering process must be applied in order to obtain the correct interpretation of the image results. At first, the number of iterations was fixed in order to evaluate the effect of a change in the filtering diameter. The first analysis was made using a common filtering process, which is the 2D Gaussian filter. The influence of the diameter on smoothing is depicted on Fig. 3a and Fig. 3b below. It significantly decreases the frequency of oscillations, which is the aim of the process. On the other hand, it is important to remember that the spatial resolution of the final image will be reduced by the application of this low-pass filter. Comparing the real image with the result, it is clear that the shape of the model is excessively smoothed so that it is important not to magnify its value. The size of the filter should be selected to smooth the data without compromising the spatial resolution unnecessarily.

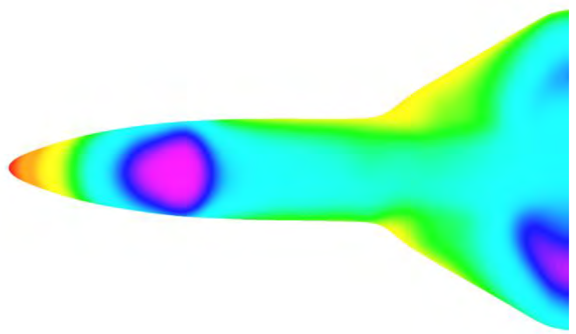

Figure 3a.Image Pressure coefficient distribution over the surface of the AGARD-C standard model after the maximum diameter was applied (99)

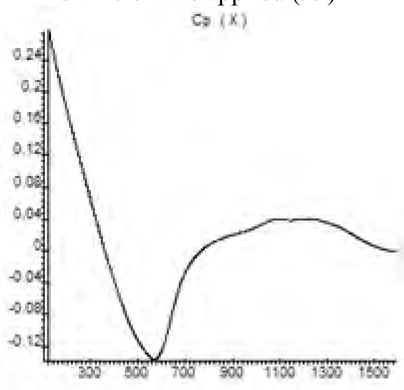

Figure 3. Results of Pressure coefficient along a center line of AGARD-C standard model after the maximum diameter was applied.

After a coherent diameter was chosen, the number of iterations can be changed, so that it is possible to understand its effects and also investigate the computational cost of the filtering process. The number of iterations and the filter diameter are not the only parameters that can be varied; it is also possible to choose the filtering type. The software provides three options of low-pass filter options of filtering, which are the Gaussian, Flat and Median filter. The process was repeated for all of the three filters and the one which was best suited for the phenomena was carefully chosen.

The flat filtering was tested with no success. Figure 4 compares four different numbers of iterations (5, 10, 20, 50) but the results shows that the Flat filtering does not change the effect of high oscillations. The profiles are essentially the same.

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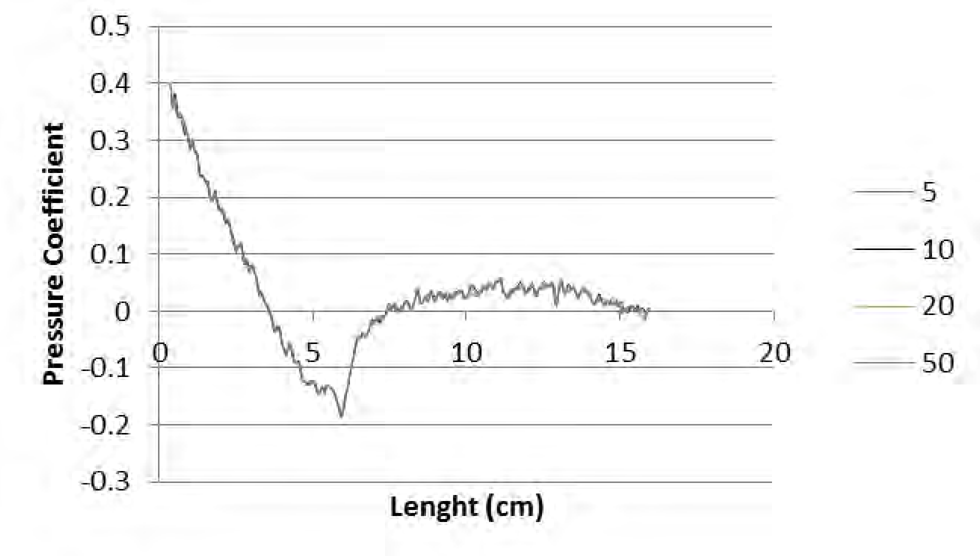

Figure 4. Comparison different numbers of iterations for the Flat filtering.

The Median filtering, which is done by obtaining the median value of two adjacent pixels, does not affect the result as expected and, besides, for more than 2 iterations, the software diverges leading to no result at all. Figure 5a and Fig. 5b are images obtained from the software and they show a comparison between two different diameters (3 and 50) of the Median filtering, both for two iterations.

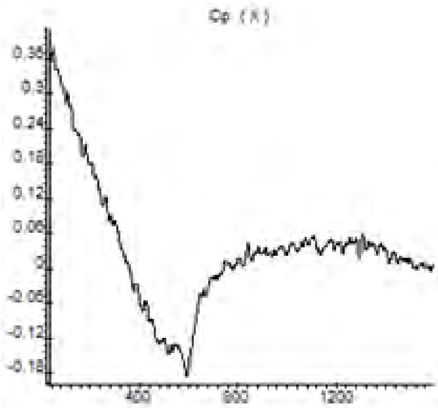

Figure 5a. Pressure coefficient filtered with diameter of 3

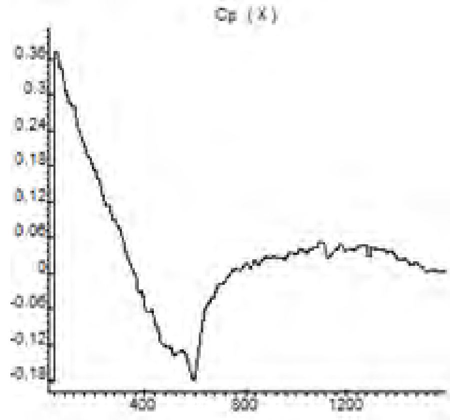

Figure 5b Comparison of Pressure coefficient filtered with diameter of 50.

These first processes of filtering are based on smoothing the image itself while the final filtering is an interpolation of the properties, which is the reason why it is important not to magnify the use of the last one. The final filtering has a great impact on the curve profile.

After a detailed comparison of the filtered images, a final filtering was applied and the pressure mapping treated images were compared to the refractive images provided by the Schlieren technique. Figure 6 represents the final result after all the filtering processes using a filter diameter of 20 with 20 iterations for both filtering and final filtering. It is important to highlight there is an edge effect due to lightning reflection so that the corners of the model do not represent a trustful spatial distribution. This effect could also be lessened by adjusting the CCD camera focus appropriately. Thus, the pressure coefficients were obtained from a center line along the axis of the model. The filtered pressure coefficient represents, though, consistently the flow properties.

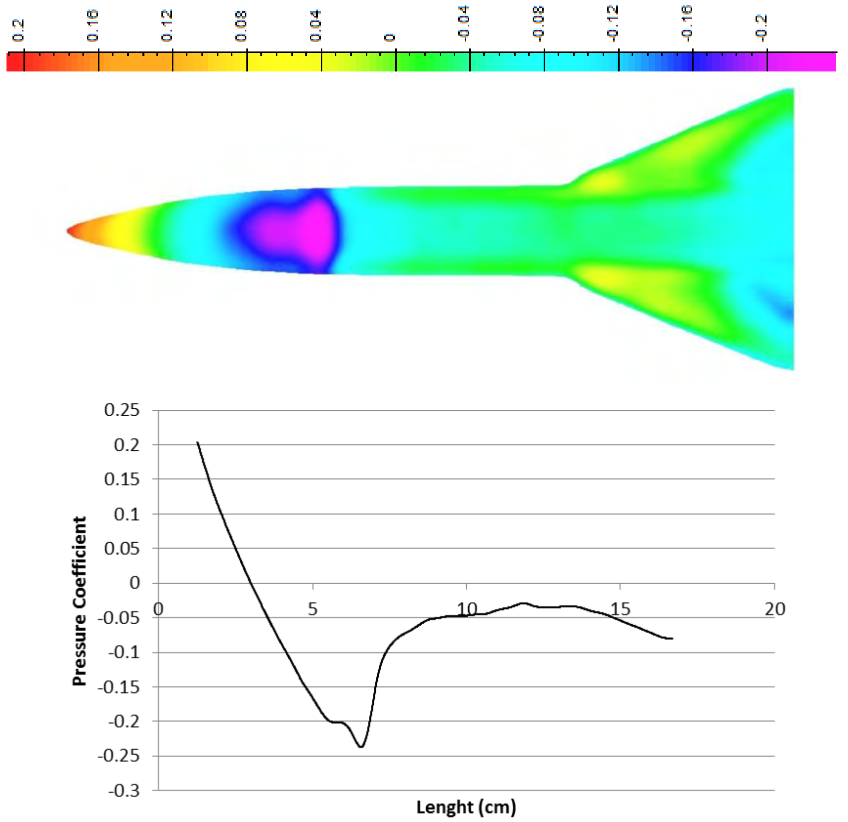

Figure 6. Final result for Mach 0.95 with the pressure coefficient as a function of its length.

The computational cost of the filtering processes was also verified in order to help reaching a cost-effective computational approach. An analysis based on the variation of the filter diameter reveals a relation in which the time increases quadratically with the filter diameter as depicted by Fig. 7 (for a fixed value of 1 iteration). All of the computational analysis of this work is based on investigations made on a personal computer with the following characteristics: Intel® Core™ i5 processor, 4.00 GB of RAM and 32-bit system.

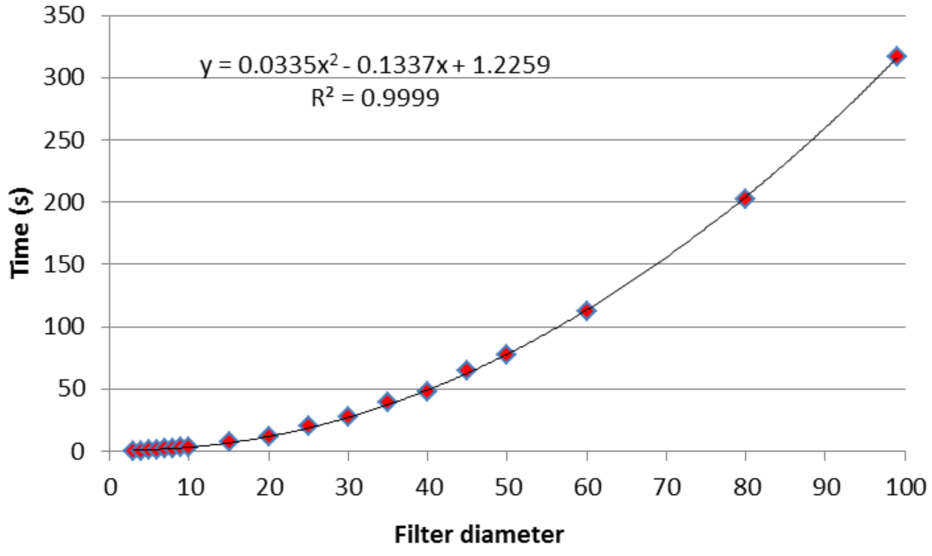

Figure 7. Correlation between the computational time and the size of the filter.

Also, as expected, the time increases linearly with the number of iterations in each filtering (for a fixed value of 1 diameter) as can be noticed on Fig. 8.

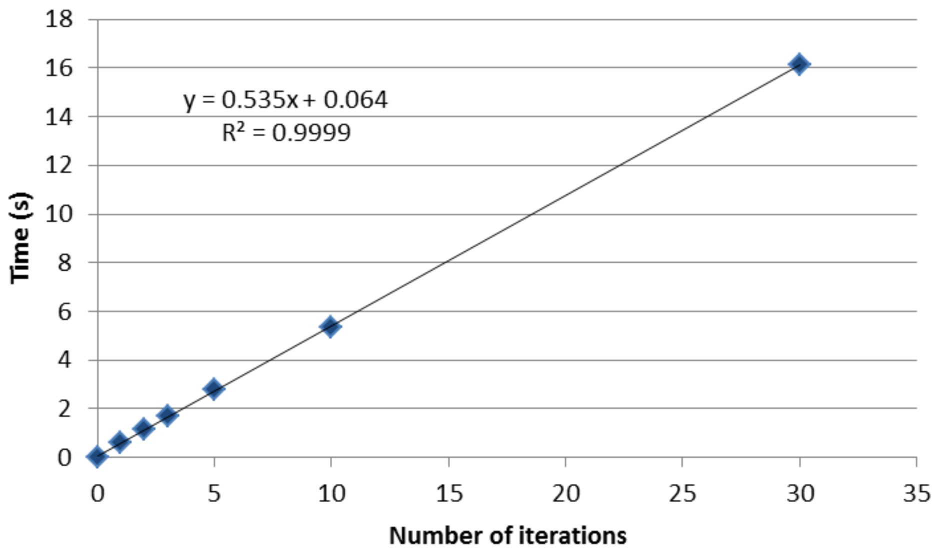

Figure 8. Correlation between the computational time and the number of iterations.

A final filter diameter of 20 with 20 iterations leads to a reasonably time of about 128 seconds. The final comparison with the Schlieren technique is depicted below by Fig. 9. The Schlieren technique is a powerful method of accurately identifying the shock wave location. The comparison of the images exposes the strong correlation between the shock wave positioning on the Schlieren image with the low pressure (emphasized by the purple color) of the PSP result. An important fact is that the PSP technique not only reveals the exact location of the shock wave but it also depicts all of its development. It is possible, from PSP, to recognize the favorable pressure gradient producing the expansion of the wave. It may, or may not be an advantage, depending on the request.

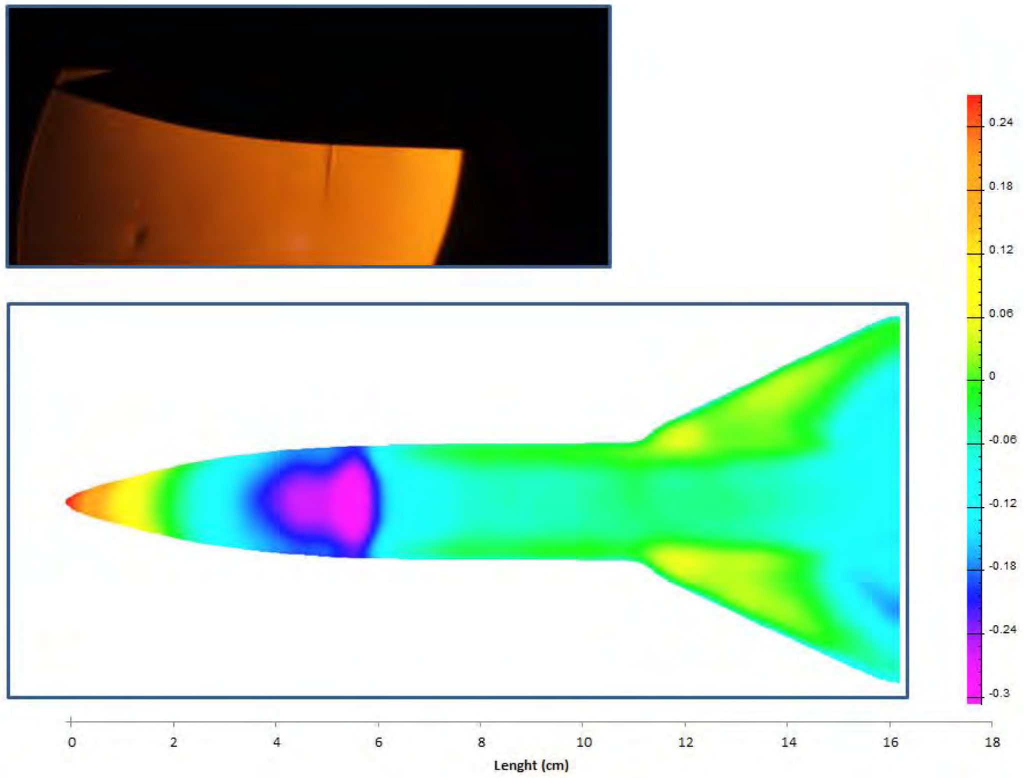

Figure 9. Comparison with the Schlieren technique for Mach 0.95.

4. CONCLUSIONS

From the results obtained, it can be noticed that the PSP technique is a reliable tool for improving the understanding of flow phenomena. Despite of its irregularities, it gives a much more comprehensive outcome than the pressure obtained with pressure ports and, allied with its precision, the PSP can be a powerful visualizing tool.

The filtering processes have to be taken carefully in order to not compromise the physical phenomena. An image with a lack of proper filtering may not represent the aspects of the flow. Within the three existing possibilities of filtering, the best results were obtained with the most known 2D Gaussian filter. The image processing used by the software is rather difficult to understand, which is why it is also important to think of alternative methods to the improvement of the results, for example, by using wavelet based methods in order to try to achieve a better result.

The Schlieren technique was an important tool to analyze the effects of filtering on an image using optical equipment and more comparisons for higher Mach numbers shall be made in order to assess its reliability. Not only the understanding of the filtering process is important but also the effects of flow variables in the experiments, such as temperature and it will also be further analyzed.

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