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Assessment of Secondary Pitot Probe Locations on a Small UAS

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May 2024

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Abstract

Urban Air Mobility (UAM) and Advanced Air Mobility (AAM) have been at the forefront of many aeronautical discussions because of the potential revolutionary improvement to urban transportation. In this study, a representative Research Aircraft for eVTOL Enabling techNologies, Sub-scale Wind Tunnel Flight Test (RAVEN SWFT) nosecone was placed inside the NASA Langley Research Center's 12-Foot Low-Speed Wind Tunnel with a pitot-static assembly installed. The study aimed to determine a suitable location and orientation of the pitot-static assembly on the nose of the vehicle, which consists of two airspeed sensors: one for the flight controller and one for data collection. The dynamic pressure was varied from 0.5 to 5 psf for each test point. Additionally, three different offset distances from the center boom and three different angles for the flight controller pitot tube were tested. The data from both of the pitot tube assemblies were compared to the wind tunnel and the Aeroprobe pitot tube. The results show that the flight controller pitot tube performs better when it is placed further away from the nosecone, regardless of the angle. The results also show that the angle does not affect the accuracy of the pitot tube when the vehicle yaws or pitches regardless of the mounting angle and location. The study provides useful insights for the design of the airspeed measurement systems on small Uncrewed Aerial Systems (sUAS), which can be applied to other UAM and AAM applications.

Contents

Acronyms

AAM	Advanced Air Mobility
eVTOL	electric Vertical TakeOff and Landing
LaRC	NASA Langley Research Center
RAVEN	Research Aircraft for eVTOL Enabling techNologies
STDV	Standard Deviation
sUAS	small Uncrewed Aerial System
SWFT	Sub-scale Wind Tunnel Flight Test
TTT	Transformational Tools and Technologies
UAM	Urban Air Mobility
UAS	Uncrewed Aerial System
VTOL	Vertical TakeOff and Landing

Nomenclature

β	angle of side-slip
ρ	air density
P	pressure
psf	pound per square foot
q	dynamic pressure
T	temperature
v_∞	free-stream velocity

1 Introduction

Urban Air Mobility (UAM) and Advanced Air Mobility (AAM) have been at the forefront of many aeronautical discussions because of the implications of adopting them to enhance urban transportation. The theory behind UAM and AAM is to have a conventional or electric Vertical Takeoff and Landing (VTOL) vehicle transport a passenger or cargo without the delays of current transportation within a shorter distance than current commercial transportation routes. The Research Aircraft for eVTOL Enabling techNologies, Sub-scale Wind Tunnel Flight Test (RAVEN)(SWFT) vehicle has been designed to help continue the advancement of the UAM and AAM industry. The RAVEN SWFT project was designed as a sub-scale control system test bed for future UAM eVTOL aircraft. To record data, and supplement the flight controller, the RAVEN SWFT vehicle has a pitot-static boom on its nose with two airspeed sensors. In this study, a representative RAVEN SWFT nosecone was placed inside the NASA Langley Research Center's (LaRC) 12-Foot Low-Speed Wind Tunnel with two pitot-static assemblies installed. For the RAVEN SWFT vehicle, two airspeed sensor systems are required. The study was designed to test the accuracy of the flight controller pitot tube in various mounting locations along the central data collection boom. One probe for data collection redundancy outside of the flight control system. The other probe is being used for sending information to the flight controller. At the time of this publication, two separate airspeed sensor system locations have yet to be well-researched for the accuracy of the recorded data. This test was designed to supplement that information for the RAVEN SWFT project and other small Uncrewed Aerial Systems (sUAS) projects at NASA. These sUAS platforms' performance and safety depend on accurate and trustworthy measurement. Precision airspeed measurement is essential for sUAS, and this study can aid the aerospace industry in designing and optimizing these systems. Examples of circumstances where this is advantageous include: environmental monitoring, fire reconnaissance, precision farming, UAM, and more.

Documentation on single-probe systems vary in use-cases and research. Though for this experiment, a flight test engineering best practices for single-probe nose mounted airspeed assemblies were used, where the probe should be a minimum of 1.5 times the fuselage diameter in front of the nose of the aircraft. [1]

2 Experiment

2.1 Test Setup

For conducting the test, the NASA LaRC 12-Foot Low-Speed Tunnel was used to mount and test the representative RAVEN SWFT nosecone and both airspeed assemblies in a controlled environment. To mount the nosecone to a straight sting in the tunnel, wooden bulkheads were created to hold a dummy balance inside to provide an adequate mounting surface that could support the assembly. These bulkheads were epoxied into place with the dummy balance installed inside the nosecone. Figure 1 labels all of the main hardware and electronics inside the RAVEN SWFT representative nosecone and their relative locations. The following figure, Figure 2, shows the entire wind tunnel assembly, showing the 3D-printed mounts and the scale of each piece relative to one another. Although all three probe offsets are displayed in this figure, only one 3D-printed offset was tested at a time. Figure 3 shows the physical nosecone and the four holes for the screw mounts on the sting in the tunnel.

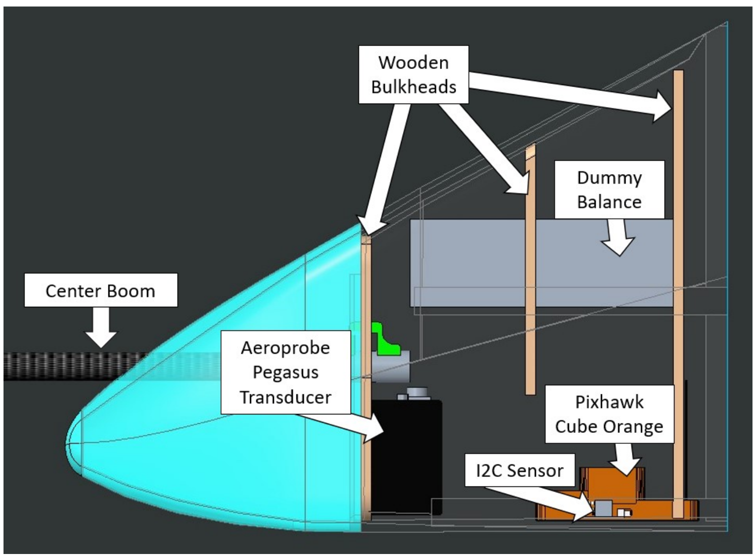


Figure 1: Internal view of the CAD model of the test assembly

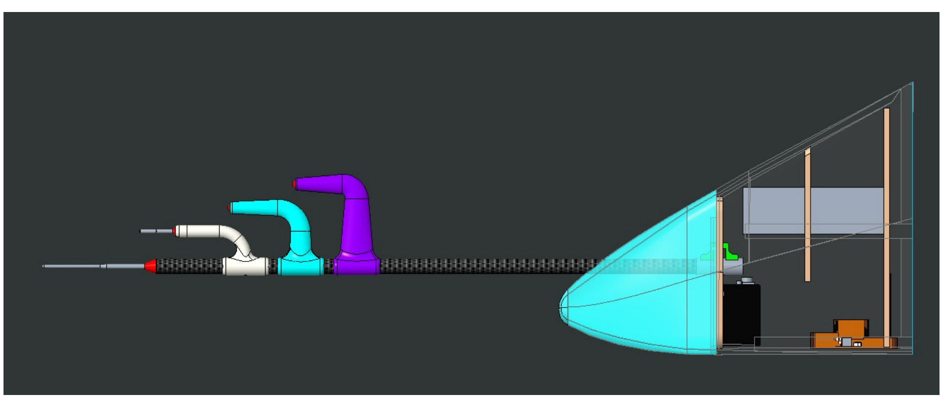


Figure 2: CAD model of the test assembly

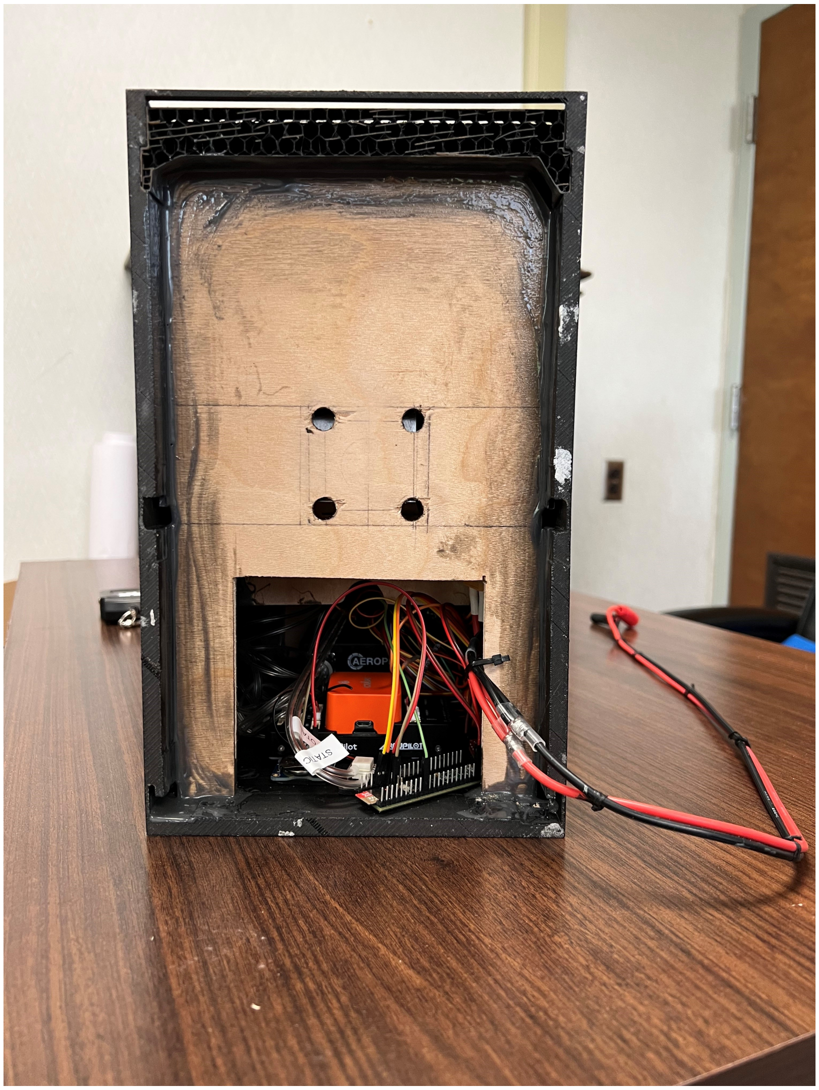


Figure 3: Full rear view of the nosecone assembly

Figure 4 below shows the backside of the nosecone assembly and displays some of the electronic components used in the test. For data collection, a Pixhawk Cube Orange was used to read and collect the data from the I2C airspeed sensor (designated as the flight controller pitot). A Teensy was used in combination with an Aeroprobe Transducer to record the data collected from the Aeroprobe sensor (designated as the data collection sensor). The I2C sensor is a 3DR/MRO MS4525DO airspeed sensor and comes with the probe, the data transducer, and some tubing.[2] The Aeroprobe sensor is a 5-hole straight probe from the Aeroprobe company. The transducer used for the Aeroprobe was the Aeroprobe Pegasus transducer with 5 inH2O and 15 psi range sensors.[3] One thing of note is that the Aeroprobe transducer and sensor combination is required to be calibrated every 12 to 24 calendar months, and the probe used in this test was past its calibration due date.[4]

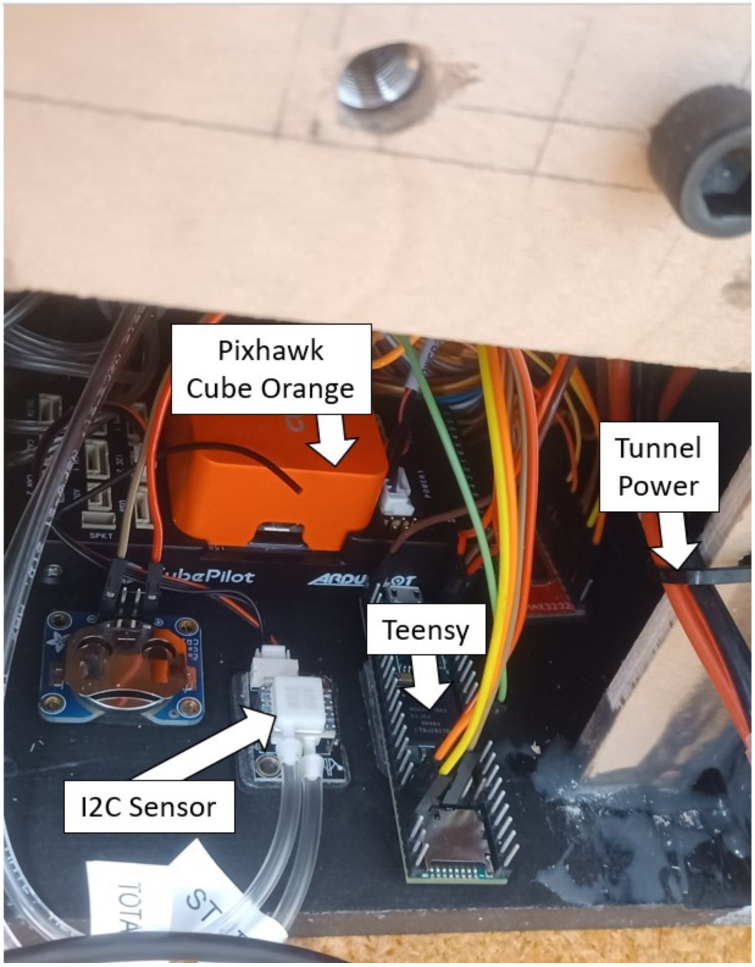
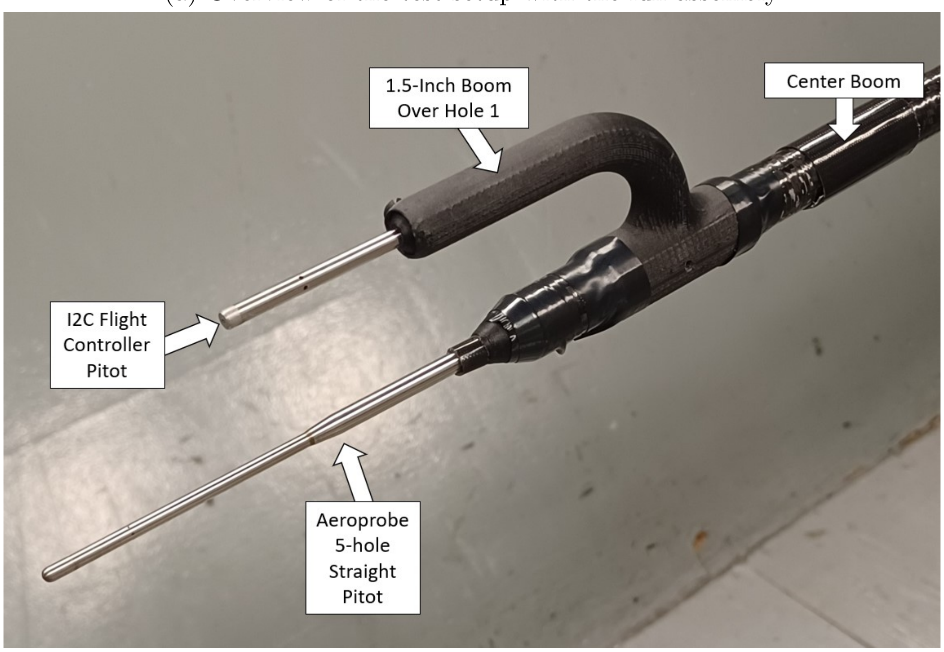


Figure 4: Back view of the nosecone assembly

The full test assembly was installed on the sting inside the wind tunnel test section with the 1.5-inch flight controller pitot sensor mount, mounted in hole number 1 horizontally (0-degree in relation to a plane parallel to the floor). This installation can be seen in Figure 5. For more information on the hole locations and mounting positions, see Section 2.3. The flight control pitot offset was designed and 3D-printed with Onyx filament from Markforged.[5] This allowed for the parts to be rapidly be prototyped and interface directly to the center data collection boom with a snapping feature to hold it in place. Electrical tape was stretched over each side of the interface between the center boom and the 3D-printed offset part to ensure that the flight controller pitot offset was mounted securely and to provide cleaner aerodynamics. Duct tape was used to cover the unused holes to prevent them from interfering with the test.

(a) Overview of the test setup with the full assembly



(b) Close-up view of the 3D-printed boom mounting

Figure 5: Wide and closeup view of the 1.5-inch boom mounted over hole 1

2.2 Generalized Procedure and Safety Notes

Prior to testing in the wind tunnel, the test's electronics were bench tested and verified to ensure that everything was working as expected. All electronics were configured such that when they are powered on they immediately start recording data on a new log file.

In order to run the test, an informal post-installation inspection was completed by the wind tunnel team. This inspection verified that all hardware for the test was secured, the test would not create any risk of damage to the wind tunnel, and the tunnel power was working correctly. The electronics were tested to ensure that the power was being routed correctly and that all electronics were still working after installation. Once the nosecone was installed, the 3D-printed 1.5-inch pitot boom was installed using the detailed procedures listed in Appendix A. Before leaving the test section, all holes and hardware were checked to ensure they were correctly taped down, installed at the correct angle, distance, size, and checked for security. Once ready, any installation materials in the test section were removed. The test section door and the operator's area door were closed when leaving. At the time of leaving the test section, the power supply was cycled to start a new log. Due to the new log file being created after every power-on, it was noted each time to help later during the data processing phase.

2.3 Test Points

The test contained 27 hardware-mounted test points, and a dynamic pressure sweep would run at each location. These dynamic pressure sweeps would record data for 30 seconds through the tunnel data system for each dynamic pressure in the test matrix. This test used the dynamic pressures of 0.5, 1, 2, 3, 4, and 5 psf. For each dynamic pressure sweep, an associated offset distance (1.5", 2.5" and 3.5") was used to separate the Pixhawk pitot and the Aeroprobe sensor. 3D-printed offsets were created to create distance between the Aeroprobe and Pixhawk sensors. These distances were measured from the center-line of the center boom and were designed to be 1.5-inches, 2.5-inches, and 3.5-inches. For each test point, the test was repeated in the three holes on the center boom. The furthest location from the nose is hole number 1, and the closest is hole number 3. These holes were cut to a distance of more than 1.5 times the fuselage diameter to work with flight test best practices.[1] The hole locations were measured starting from a line drawn on the Pixhawk pitot to the tip of the nosecone. Although these hole locations did vary, the tubing length was kept constant throughout all testing. For additional reference, Figure 6 shows the holes cut into the central boom, and the silver line to the far right of the image denotes the intersection of the boom and the nosecone. The larger silver line between holes 1 and 2 denotes the line of 1.5-times the fuselage diameter. Each boom was also tested at 3 angles per hole. Each angle is based on a plane parallel to the floor. For example 90 degrees is vertical (perpendicular to the floor plane). Figure 7 has a visual overlay of the test hardware setup to describe the mounting angles used. The pictures were not taken for data analysis purposes and therefore should only be used as an approximate representation for this paper. Finally, each offset was mounted at 3 different angles per hole (90 deg, 45 deg, and 0 deg). In order to simplify calling out each data point, the test points were simplified. For example, 1.5-1-90 is the 1.5-inch offset over hole 1, mounted at 90 degrees. The hardware test points are shown below in Tables 1, 2, and 3. In addition, three tests were run on the 2.5-inch boom for a β angle of -5 degrees. The 2.5-inch offset was tested at 3 psf and mounted at 0 degrees for this test.

Table 1: Test Matrix 1.5-inch offset

1.5-inch Boom		
Hole 1 (17.4 inches)	**Hole 2 (14.5 inches)**	**Hole 3 (11.75 inches)**
90 degrees (Vertical)	90 degrees (Vertical)	90 degrees (Vertical)
45 degrees	45 degrees	45 degrees
0 degrees (Horizontal)	0 degrees (Horizontal)	0 degrees (Horizontal)

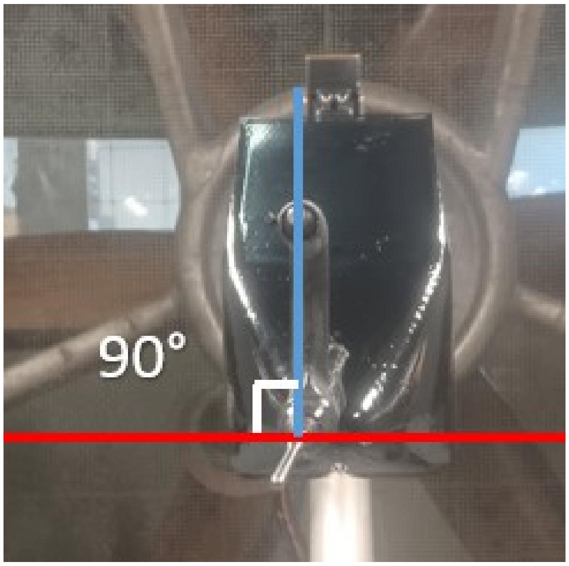
Table 2: Test Matrix 2.5-inch offset

2.5-inch Boom		
Hole 1 (17.4 inches)	**Hole 2 (14.5 inches)**	**Hole 3 (11.75 inches)**
90 degrees (Vertical)	90 degrees (Vertical)	90 degrees (Vertical)
45 degrees	45 degrees	45 degrees
0 degrees (Horizontal)	0 degrees (Horizontal)	0 degrees (Horizontal)

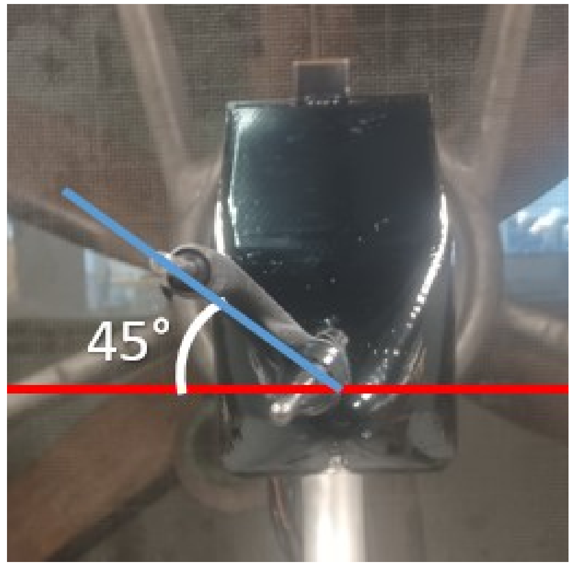
Table 3: Test Matrix 3.5-inch offset

3.5-inch Boom		
Hole 1 (17.0 inches)	**Hole 2 (14.1 inches)**	**Hole 3 (11.375 inches)**
90 degrees (Vertical)	90 degrees (Vertical)	90 degrees (Vertical)
45 degrees	45 degrees	45 degrees
0 degrees (Horizontal)	0 degrees (Horizontal)	0 degrees (Horizontal)

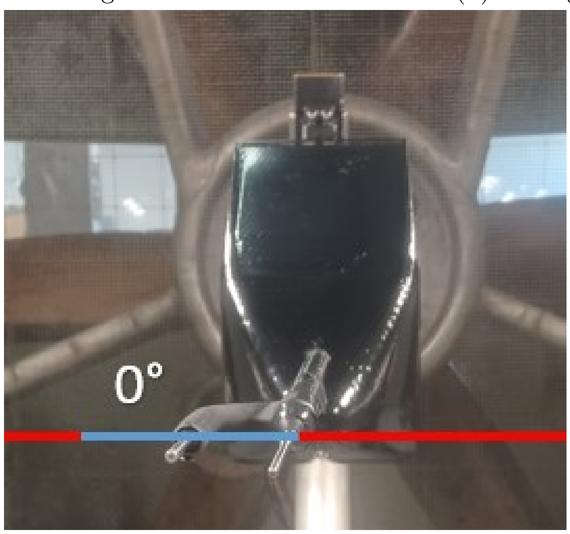
Figure 6: Picture of holes 1, 2, and 3 cut into the central boom



(a) 90-Degree Mounting



(b) 45-Degree Mounting



(c) 0-Degree Mounting

Figure 7: Visualization of Mounting Angles

3 Data Analysis

For the analysis, MATLAB was used to import, process, and display the data in the form of graphs for useful comparison. First, the raw data from the Pixhawk, Aeroprobe, and the wind tunnel needed to be converted to a similar format for comparison. For the wind tunnel data, the atmospheric pressure, temperature, and dynamic pressure were provided. This meant that both density and velocity could be calculated. The calculations below assume an ideal gas, and the temperature is the temperature recorded by the probe during the test. The equations used for density as well as the velocity are seen below in equations 1 and 2.

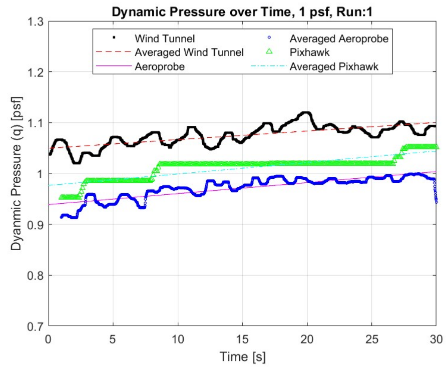
$$\rho = \frac{P_a}{RT} \tag{1}$$

$$v_\infty = \sqrt{\frac{2q}{\rho}} \tag{2}$$

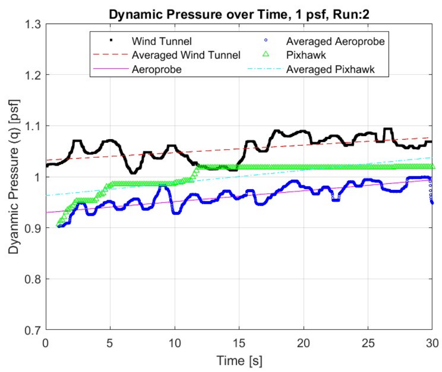
For the Aeroprobe and Pixhawk data, the air density and the dynamic pressure were the only two variables that were calculated. Note that the Aeroprobe and Pixhawk did not record temperature, so standard temperature was assumed for these calculations. Equation 3 defines dynamic pressure as:

$$q = \frac{1}{2}\rho v_\infty^2 \tag{3}$$

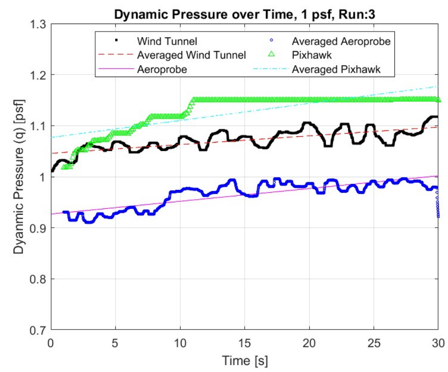
Initially the wind tunnel data, the Aeroprobe data, and the Pixhawk data were plotted next to each other in thirty second segments for baseline comparison. For the first data analysis, the data sets from each test point were visually compared to determine the best and worst of the angles. Figure 8 shows an example of one set of angle differentiation plots.



(a) 1.5-1-90



(b) 1.5-1-45



(c) 1.5-1-0

Figure 8: Angle comparison of the 1.5-inch boom over hole 1, at 1 psf

When comparing the figures to each other, the figures were assigned either a green star or a red star. A green star denotes the angle with the best performance for that specific dynamic pressure and angle. The red star on the other hand denotes the worst performance for the dynamic pressure and angle. Furthermore, error calculations were performed to assist in the selection of the highest performing angle and offset location. The error data seen in Figure 9 was used to make the final quantitative decision about whether or not the data being presented was within experimental limits. See the error analysis section 3.1 for a better description about the error calculations.

```
Error in Run: 1
Average Error =      0.064617
Absolute Error =     0.073051
Percentage Error = 7.479265
Mean Error =         0.064617
```

(a) 1.5-1-90

```
Error in Run: 2
Average Error =     0.054201
Absolute Error =    0.069326
Percentage Error = 7.197925
Mean Error =        0.054201
```

(b) 1.5-1-45

```
Error in Run: 3
Average Error =     -0.055387
Absolute Error =    0.079687
Percentage Error = 6.772904
Mean Error =        0.055387
```

(c) 1.5-1-0

Figure 9: Error data from Figure 8

It should be noted that all data was passed through MATLAB's median filter command to reduce the noise in the system.[6] Such filters are common with data that is rapidly changing to help the flight controller respond. Additionally, in flight test, a Kalman filter will be applied to help reduce error further.

3.1 Error Analysis

Comparative error between the wind tunnel and the Pixhawk was the primary method in which the data was analyzed. Figure 9 shows the errors used in the evaluation, which consisted of an average error, absolute error, percent error, and the mean error. The average error is the actual average of every error point along the curve fit. For the remainder of the errors, only the maximum error was calculated because the higher the error the less desirable the position (attempting to observe worst case scenario). These errors were then classified by each hole position, each dynamic pressure step, and placed into pitot-offset groups. For instance, figure 9(c) has the lowest maximum percentage error so it would receive a green star for being the lowest in the 1.5-1-X group. Then when compared against the remainder of the data, it would receive a tally. When this process was finished for all cases, the tallies were counted to determine which offset-angle combination had the lowest error overall.

Since the objective of this experiment was to find the mounting location for the flight controller pitot tube, airspeed over time was plotted for the specific mounting location chosen. Then by taking the bounds of all tests, error bars were created to help the control system engineers understand the variability of the sensor. An example fo these error bars is Figure 10.

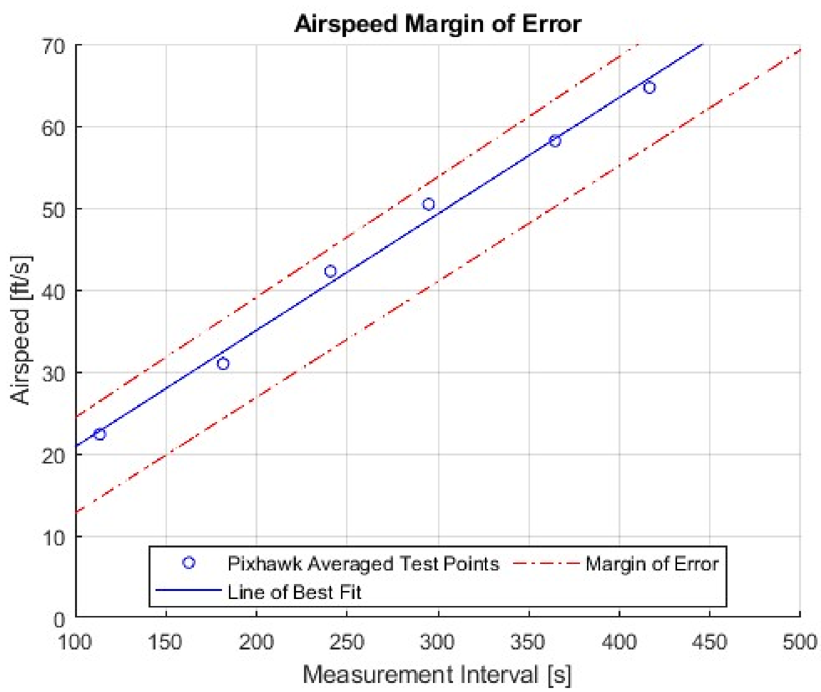


Figure 10: Airspeed Error for 1.5-1-0

In addition to the dynamic pressure graphs, an excel sheet was created to compare the percentage error data for each dynamic pressure against each offset above the center boom as well as for each mounting angle. Due to constraints, the experiment was only able to run through its 27 hardware test points once and thus creates a concern that this data might not be repeatable. Based on the data pulled from this test however, it seems that the data recording throughout was precise but not accurate. This trend is seen in Figure 11 from the Standard Deviation (STDV) % Error column and row. The data varied throughout each test point, but the standard deviation appeared consistent throughout the test.

The percent error was consistently the lowest over hole 1 when compared to the other hole positions. Hole 3 had the highest percent error over the whole test, with most percentages being over 9%. Hole 2 percent errors were on par with hole 1, but when the design of the full vehicle comes into play, best practices indicate a pitot sensor needs to be further away from the rotors.

Test Point	Max Percent Error per q						Average % Error	STDV % Error
	0.5	1	2	3	4	5		
1.5-1-90	5.49	7.48	9.87	11.91	13.59	13.79	10.36	3.37
1.5-1-45	2.88	7.20	12.07	10.27	10.63	9.27	8.72	3.29
1.5-1-0	15.94	6.77	1.66	5.39	4.82	5.90	6.75	4.83
2.5-1-90	17.69	6.61	3.22	3.58	4.42	7.27	7.13	5.42
2.5-1-45	10.60	1.68	5.96	8.63	9.34	11.27	7.91	3.57
2.5-1-0	10.10	0.78	2.87	5.17	8.64	9.44	6.17	3.83
3.5-1-90	18.71	6.06	1.33	2.83	5.03	5.96	6.65	6.19
3.5-1-45	5.52	2.90	5.87	6.31	7.78	9.85	6.37	2.33
3.5-1-0	12.17	2.41	3.61	5.47	8.48	8.97	6.85	3.68
1.5-2-90	6.73	4.25	7.30	9.30	11.31	12.96	8.64	3.19
1.5-2-45	10.48	3.20	5.53	6.91	8.62	10.50	7.54	2.89
1.5-2-0	11.91	3.10	3.91	5.82	7.63	8.92	6.88	3.29
2.5-2-90	15.98	3.16	2.61	5.31	5.76	7.73	6.76	4.88
2.5-2-45	5.53	2.57	6.15	7.81	9.71	9.67	6.91	2.74
2.5-2-0	6.16	5.91	6.46	7.45	8.73	9.52	7.37	1.48
3.5-2-90	15.48	1.54	2.83	5.51	6.49	7.96	6.64	4.93
3.5-2-45	6.65	2.28	6.31	6.62	8.58	9.62	6.68	2.52
3.5-2-0	4.42	4.17	6.41	7.80	9.03	9.76	6.93	2.34
1.5-3-90	6.95	9.30	6.96	10.40	11.43	13.23	9.71	2.50
1.5-3-45	4.58	7.45	6.12	9.17	9.51	10.67	7.92	2.29
1.5-3-0	5.26	5.79	6.64	8.33	10.14	9.89	7.68	2.09
2.5-3-90	9.86	5.34	6.53	8.91	9.03	11.04	8.45	2.13
2.5-3-45	12.56	10.59	10.10	13.81	13.66	15.24	12.66	1.99
2.5-3-0	20.89	4.91	9.55	11.36	13.54	13.12	12.23	5.27
3.5-3-90	8.47	2.39	6.69	6.56	9.57	8.45	7.02	2.55
3.5-3-45	22.59	13.10	6.84	7.71	10.55	7.21	11.33	6.01
3.5-3-0	19.41	9.21	9.02	9.61	11.33	8.46	11.17	4.15
STDV %	5.68	3.04	2.67	2.56	2.50	2.32		

Figure 11: Percent Error Comparison

On top of the previous statements, the wind tunnel data was not perfect. The pitot probe for the tunnel was located relatively close to a wall and not in the center like the testing was. The probe being tested was not perfectly centered in the tunnel as it was an estimation of zero calibrated by the sting as well as the mounting hardware. Additionally, the tunnel could not be assumed to be entirely laminar which is seen through the noise in the data from both the testing probes as well as the wind tunnel probe. Finally, as testing continued in the tunnel, the ambient temperature of the tunnel was increasing proportionally to the outside air temperature. That being said, these effects were minimized through the data processing and the error associated with it could be assumed to be negligible.

3.2 Results

As seen in Figure 12, the Pixhawk data in this specific test point, is higher than both the wind tunnel data as well as the Aeroprobe data. This figure displays the 1.5-inch boom installed over hole 1 horizontally (0 degrees). Although the data overshot the wind tunnel, it shows a favorable accuracy overall. The Pixhawk data flattens out at around 12 seconds. Flat lines like this occurred in numerous tests, thus it cannot be ruled out, though generally the trend did not continue for this long of a time-step. For the sake of this test, these apparent freezes in the data were ignored, but are being looked into for the future testing of the vehicle. The data clearly shows that being further away from the nose provides a more consistent and accurate data set. In addition, the discussion in section 3.1 discussed that hole 1 has some of the lowest percent errors. Therefore, different orientations and offset distances at the hole 1 location should be the primary interest for the team. To see all of the graphs for each test point see Appendices B, C, and D.

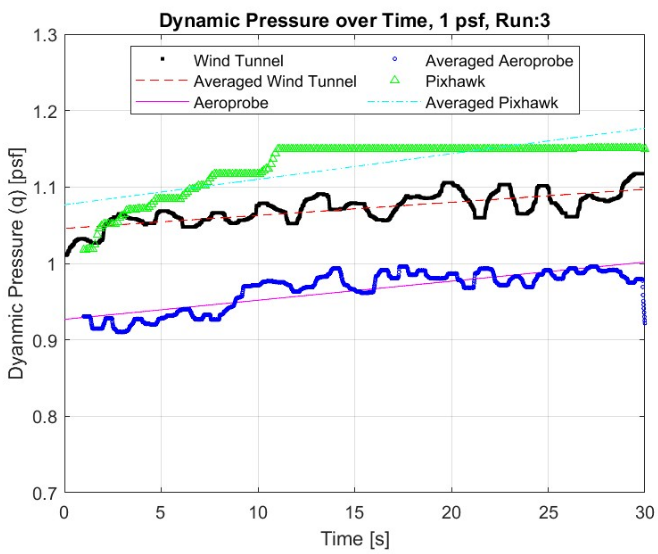
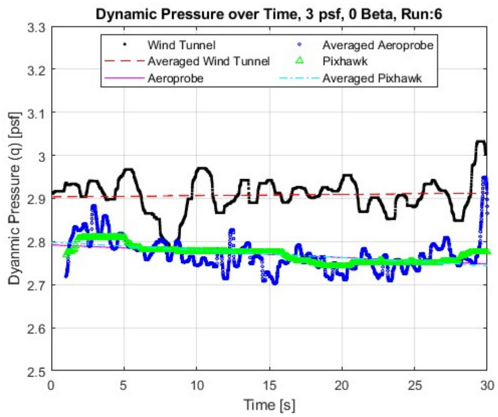
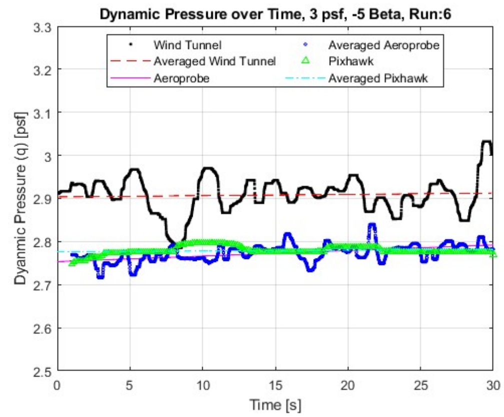


Figure 12: Comparison Data for the 1.5-inch boom over hole 1 with an angle of 0 degrees

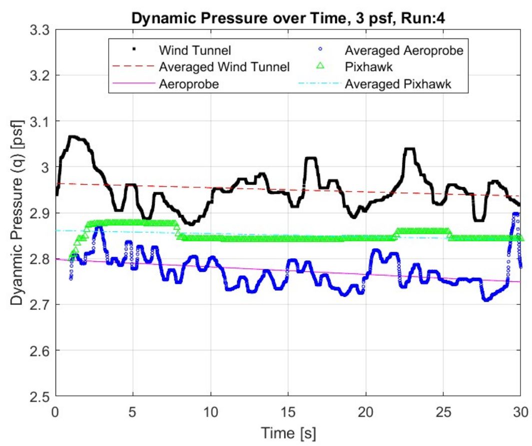
The actual mounting position during flight is another matter of consideration. The central boom may produce extra turbulence at the 0 and 45 degree mounting angle, when the vehicle yaws to the right or left while in flight. Additionally, the central boom may produce extra turbulence for the 90 or 45 degree mounting angle when the vehicle pitches up. To investigate this, the 2.5-inch boom was examined during the 3 psf dynamic pressure point and the representative test article was yawed to -5 degrees/β. Figure 13 below shows a set of plots that compare the 0 degrees/β, 0 degree mounting angle to the -5 degrees/β, 0 degree mounting angle. Figure 14 displays the error found in each test when compared to the wind tunnel. The hole 1 data shows an decrease of roughly 1.4% error between the 0 degrees/β to the -5 degrees/β. The percent error declines when the β angle is applied, but because of the small percent change it can be attributed to the variability of the data set. Therefore, the error seen is most likely negligible. That being said, the data for 2.5-1-90 at 0 degrees/β shows a decrease of roughly 1.1% from the 0 degrees mounting angle to the 90 degrees mounting angle, and approximately a 2.5% decrease from the 0 degrees with 0 degrees/β. Those percentage errors are also low in magnitude and could be considered negligible.



(a) 2.5-1-0 at 3 psf with 0 β



(b) 2.5-1-0 at 3 psf with -5 β



(c) 2.5-1-90 at 3 psf with 0 β

Figure 13: β angle data comparison between 2.5-1-0 at 0 deg β and 2.5-1-0 at -5 deg β

```
3 PSF
Error in Run: 6, Beta: 0
Average Error =     0.136641
Absolute Error =    0.167832
Percentage Error = 6.115423
Mean Error =        0.136641
```

(a) 2.5-1-0 at 3 psf with 0 β

```
3 PSF
Error in Run: 6, Beta: -5
Average Error =     0.129002
Absolute Error =    0.130729
Percentage Error = 4.699922
Mean Error =        0.129002
```

(b) 2.5-1-0 at 3 psf with -5 β

```
3 PSF
Error in Run: 4, Beta: 0
Average Error =     0.098880
Absolute Error =    0.102342
Percentage Error = 3.577153
Mean Error =        0.098880
```

(c) 2.5-1-90 at 3 psf with 0 β

Figure 14: Error Data for β Angle Movement

The decision came down to two different iterations of the probe based on the data analysis. The test points that were chosen were 3.5-1-90 and 1.5-1-0 because of their position, accuracy, and consistency. A box-whisker plot was made for each of the test points to more effectively compare the range of dynamic pressure change in order to aid in decision-making. These plots can be seen below in Figures 15 and 16. The whiskers represent the maximum and minimum values for all the data that the MATLAB "boxchart" command does not deem to be an outlier. Anything outside of 1.5 times the numbers that bound the median box are considered an outlier with this command.[7] The wind tunnel line shown on this figure denotes the average recorded wind tunnel data dynamic pressure. Ideally, the box would be lined up in the center of that line for both precision and accuracy. That being said, the 1.5-1-0 plot has a notably higher number of outliers than the 3.5-1-90 plot. The data is slightly skewed since the outliers do not affect the overall median spread since they fall outside of the 1.5 times value. However, it is also important to keep in mind that the 3.5-inch data exhibits greater consistency between those values despite the values being more tightly confined in the median box, which inflates the probability limits. It is of interest that in the 1.5-1-0 plots, the median box is consistent with the wind tunnel data at 0.5, 1, and 2 psf but it starts to decline in performance as the dynamic pressure increases. This decrease is also seen in the 3.5-1-90 plots, but the decrease is seen from 0.5 psf all the way to 5 psf. Also, when the probes are compared directly to the intended dynamic pressure value and not the recorded wind tunnel (red line in the plots), the 1.5-inch probe stayed within a 0.15 psf range of that number for all of the tested dynamic pressures.

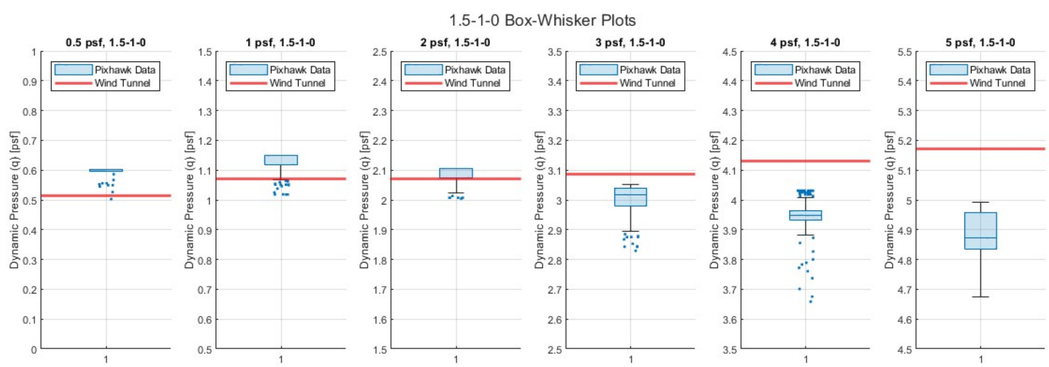


Figure 15: Box Whisker for 1.5-1-0 at All Tested Dynamic Pressures

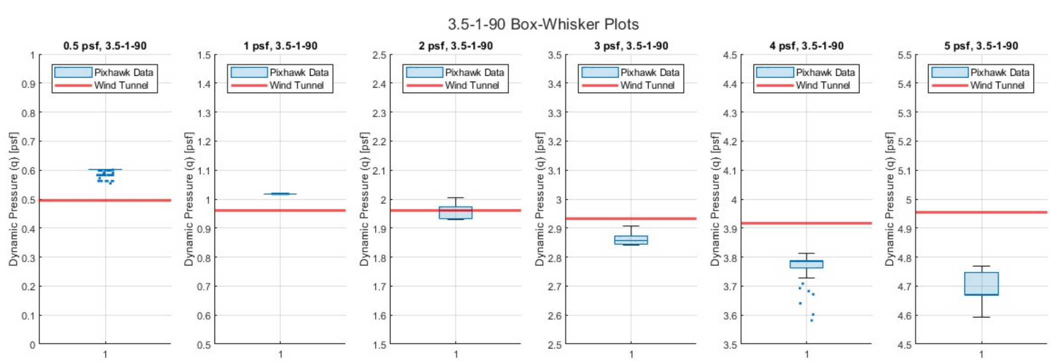


Figure 16: Box-Whisker for 3.5-1-90 at All Tested Dynamic Pressures

4 Summary

Prior to conducting a flight test, it is crucial to measure and comprehend the accuracy of the two airspeed probes mounted on the nose of the RAVEN SWFT vehicle. It was discovered that the offset should be placed as far away from the aircraft's nose as feasible, regardless of the offset angle. Furthermore, the 1.5-1-0 boom was selected because of its actual positioning in relation to the vehicle's attitude and consistency in data across the whole dynamic pressure range. Since the performance between the 1.5-1-0 probe and the 3.5-1-90 probe were similar, the team selected the 1.5-1-0 probe due to its smaller form factor and weight difference. Additionally, the results from the error, dynamic pressure, and airspeed plotting favor this probe selection. However, more testing and flight validation would be required to determine the optimal probe mounting location for this vehicle.

Additionally, the experiment shows some of the capabilities of these platforms and how well the data is measured from the relevant probes. In order to help design strategies that mitigate or offset these effects, the data offers insight into the inherent variability and uncertainty of the airspeed data. Finally, the study sheds light on a few aerodynamic factors that impact airspeed measuring systems on sUAS, including turbulence generated by a centrally located boom and the yaw/pitch angles of the craft.

In order to better understand the properties of these small pitot tubes and be able to account for the inaccuracy on a larger scale, future research on the safety and dependability of sUAS airspeed systems could mimic this work with a more calibrated airflow and repeatable test points. Optimizing mounting angles and separations from air disturbances such as rotor/prop wash or other aerodynamic influences is also important. Traditionally, pitot tubes are mounted on the wing of small aircraft but in the case of RAVEN SWFT that method is not ideal due to the propellers being installed there. Additionally, other VTOL aircraft have tilting components, which reduce the number of locations an airspeed sensor can be installed. If a probe were to be mounted on a wing, it also would affect the local laminar flow and pressure distribution on the wing surface. In some sUAS platforms, the airspeed assembly is the most important piece of the avionics because they rely on the airspeed data for their guidance algorithms. If these platforms are to continue gaining more autonomy, these airspeed sensors may need to be redundantly placed. Studies such as this are valuable to better understand airspeed sensor data being read into the flight controller and the proximity that would be acceptable for the redundant sensors.

Acknowledgments

This research has been carried out at the NASA Langley Research Center, supported by the Aeronautics Systems Engineering branch. The authors are grateful to the Transformational Tools and Technologies (TTT) Project which funded this study as a part of a subset of the RAVEN SWFT project. Also, the authors would like to thank Matthew Gray who helped get the study moving forward by implementing his expertise in electronics and provided the data acquisition for this study. Finally, the authors would like to thank the team at the NASA Langley Research Center, 12-Foot Low-Speed Wind Tunnel for the operations and troubleshooting expertise throughout this study.

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Appendix A

Procedure

1. Install 1.5-inch pitot boom over hole 1
   (a) Be careful and ensure that tubing is not bent, pinched, or otherwise impeded.
      i. Use the created wire/string with a weight to pull the tubing through the pitot tube. Ensure you have pulled it through enough to see which tube goes onto the sensor.
         A. You may need to use the spring to help force the nut down through the pitot tube.
      ii. Once the sensor is attached to the tubing, carefully pull the tubing back using the other two holes as well as the back hatch.
2. Match the line on the pitot to the front of the holder.
   (a) Tighten holder screw
3. Tape off holes 2 and 3
4. Rotate the small boom until it is **perfectly vertical**
   (a) Tape in place using electrical tape to create a smooth transition between center boom and flight controller boom.
5. Measure distance between the line on the sensor and the beginning of the nosecone (Marked on the centet boom)
   (a) Record that number
6. Verify the test section is clear of FOD (Foreign Object Debris) and that everything is strapped down tight
7. Take a few photos of the assembly (Focus on the pitot end, get one straight line down the boom, and one isometric view of the whole rig in the tunnel)
8. 8. Once verified, close the test section door, turn on the power output to the assembly, and note the log number associated with that test.
   (a) Leave the tunnel. Ensure that the operators area door is closed.
9. Run wind tunnel for dynamic pressures from 0.5 to 5.
   (a) The operator will run the tunnel up to the correct dynamic pressure, once stabilized hit the take data button on the computer.
      i. This will run the tunnel data recording for 30 seconds.
      ii. When the computer beeps, the operator will move to the next dynamic pressure.
      iii. Repeat step 8a for all dynamic pressures
      iv. Once all data has been taken, right click on the end test point button, then click save at the bottom. Record the wind tunnel test number for the previous test and the next one.

Note: **** If anything looks unstable or something is wrong, stop all operations until problem can be solved and fixed. ****

10. Once the tunnel has been turned off and the fan is no longer spinning, you can enter the tunnel.
11. Turn off tunnel power and note that from that point on a new log file is created on the Pixhawk
12. Temporarily remove the tape holding the flight controller boom in place.

13. Rotate the controller boom **45 degrees** to vehicle right of the center axis.
    (a) Be careful and ensure that tubing is not bent, pinched, or otherwise impeded.
    (b) Tape in place using electrical tape to create a smooth transition between the center boom and the 3D-printed one.
14. **Repeat steps 5 - 12**
15. Temporarily remove the tape holding the small boom in place.
16. Rotate the 3D-printed boom **90 degrees** to vehicle right of the center axis.
    (a) Be careful and ensure that tubing is not bent, pinched, or otherwise impeded.
    (b) Tape in place using electrical tape to create a smooth transition between the center boom and the 3D-printed one.
17. **Repeat steps 5 - 12**

2.5-inch probe

18. Carefully remove the tape from the 3D-printed boom.
19. Remove the pitot holder screw from the 1.5-inch boom and install it loose onto the 2.5-inch boom.
20. Gently pull on the tubing to create enough slack to remove the sensor from the tubing.
    (a) Keep the pitot holder on the pitot, it will help to protect the pitot while making the change.
21. Remove the 1.5-inch boom.
22. Expose the tubing in holes 2 and 3 to be able to pull on the tubing carefully to help pull the tubing through the 2.5-inch boom.
23. Install 2.5-inch pitot boom over **hole 1**.
    (a) Be careful and ensure that tubing is not bent, pinched, or otherwise impeded.
        i. Use the created wire/string with a weight to pull the tubing through the pitot tube. Ensure you have pulled it through enough to see which tube goes onto the sensor.
            A. You may need to use the spring to help force the nut down through the pitot tube.
        ii. Once the sensor is attached to the tubing, carefully pull the tubing back using the other two holes as well as the back hatch.
24. Match the line on the pitot to the front of the holder.
    (a) Tighten holder screw.
25. Tape off holes 2 and 3 again
26. Rotate the small boom until it is **perfectly vertical**
    (a) Tape in place using electrical tape to create a smooth transition between center boom and flight controller boom.
27. Measure distance between the line on the sensor and the beginning of the nosecone (Marked on the center boom)
    (a) Record that number
28. Verify the test section is clear of FOD and that everything is strapped down tight
29. Take a few photos of the assembly (Focus on the pitot end, get one straight line down the boom, and one isometric view of the whole rig in the tunnel)
30. 8. Once verified, close the test section door, turn on the power output to the assembly, and note the log number associated with that test.
    (a) Leave the tunnel. Ensure that the operators area door is closed.

31. Run wind tunnel for dynamic pressures from 0.5 to 5.
    (a) The operator will run the tunnel up to the correct dynamic pressure, once stabilized hit the take data button on the computer.
        i. This will run the tunnel data recording for 30 seconds.
        ii. When the computer beeps, the operator will move to the next dynamic pressure.
        iii. Repeat step 8a for all dynamic pressures
        iv. Once all data has been taken, right click on the end test point button, then click save at the bottom. Record the wind tunnel test number for the previous test and the next one.

Note: **** If anything looks unstable or something is wrong, stop all operations until problem can be solved and fixed. ****

32. Once the tunnel has been turned off and the fan is no longer spinning, you can enter the tunnel
33. Turn off tunnel power and note that from that point on a new log file is created on the Pixhawk
34. Temporarily remove the tape holding the flight controller boom in place.
35. Rotate the controller boom **45 degrees** to vehicle right of the center axis.
    (a) Be careful and ensure that tubing is not bent, pinched, or otherwise impeded.
    (b) Tape in place using electrical tape to create a smooth transition between the center boom and the 3D-printed one.
36. **Repeat steps 25 - 33**
37. Temporarily remove the tape holding the small boom in place.
38. Rotate the 3D-printed boom **90 degrees** to vehicle right of the center axis.
    (a) Be careful and ensure that tubing is not bent, pinched, or otherwise impeded.
    (b) Tape in place using electrical tape to create a smooth transition between the center boom and the 3D-printed one.
39. **Repeat steps 25 - 33**
40. **Repeat the above procedures for switching between the 2.5-inch and 3.5-inch as well as the 3.5-inch back to the 1.5-inch booms. Also repeat these steps for holes numbered 2 and 3.**

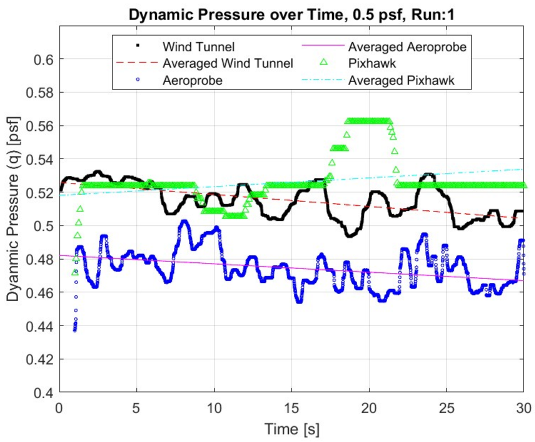
Hole 2 and 3:

41. Repeat all procedures from above taping off the respective holes that are not in use. Follow the same procedure and order for installing and removing the flight controller, 3D-printed booms.

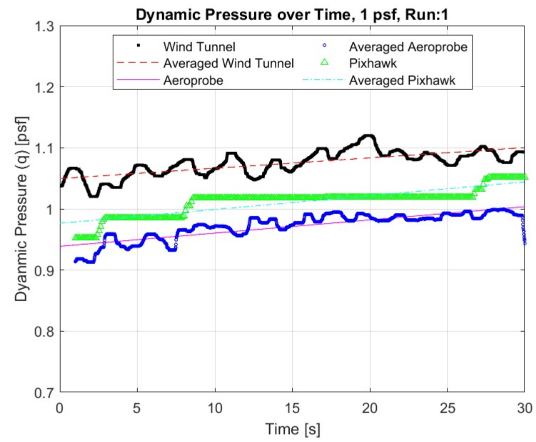
Appendix B

Dynamic Pressure over Time Plots: Hole 1

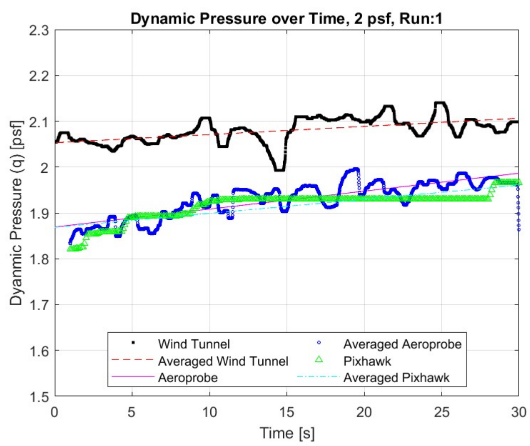
B.1 1.5-1-90



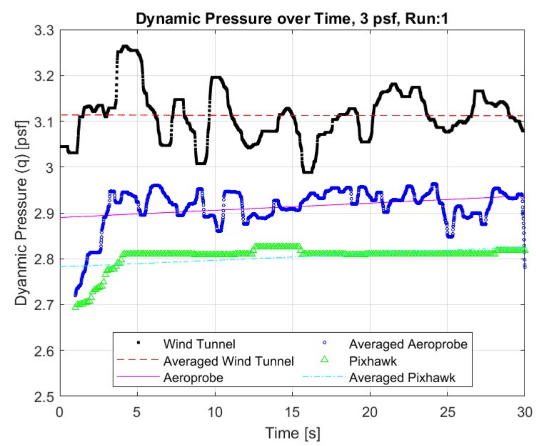
(a) 1.5-1-90 at 0.5 psf



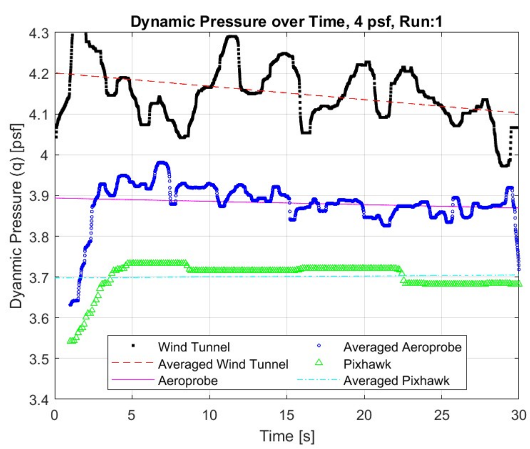
(b) 1.5-1-90 at 1 psf



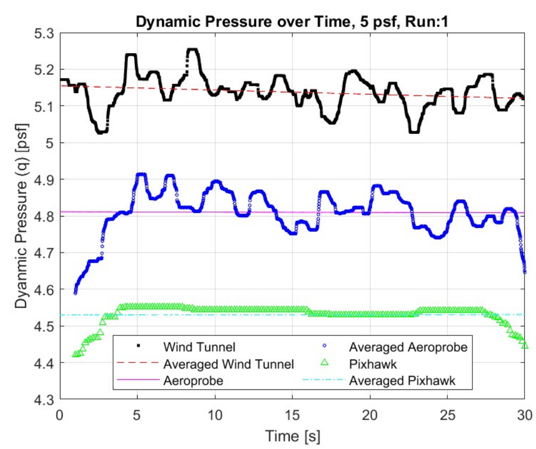
(c) 1.5-1-90 at 2 psf



(d) 1.5-1-90 at 3 psf



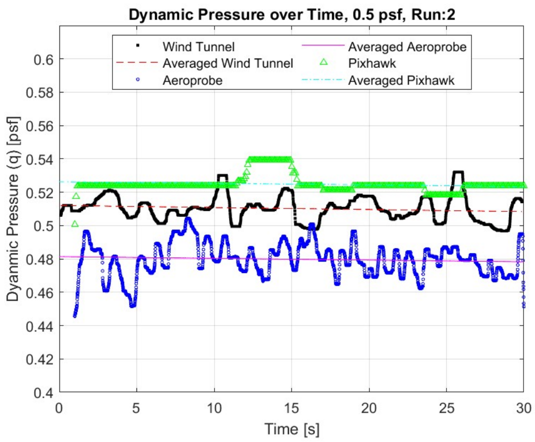
(e) 1.5-1-90 at 4 psf



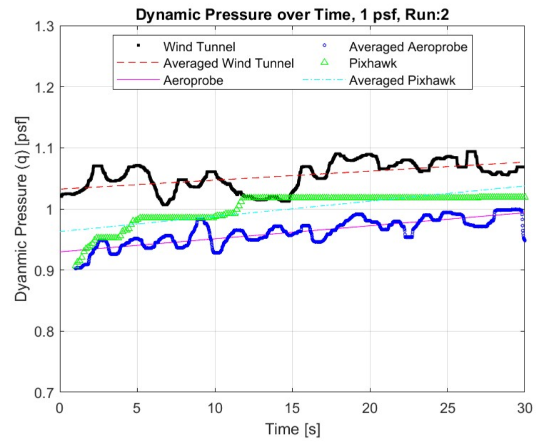
(f) 1.5-1-90 at 5 psf

Figure B1: 1.5-1-90

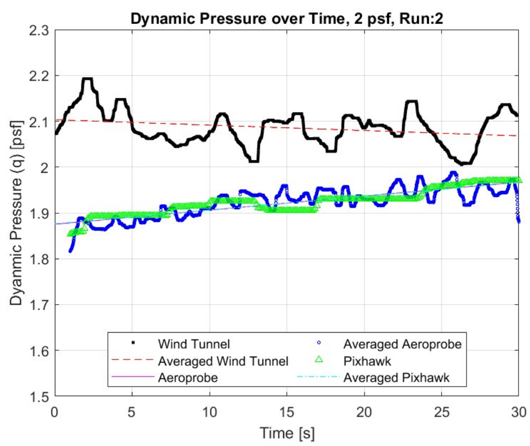
B.2 1.5-1-45



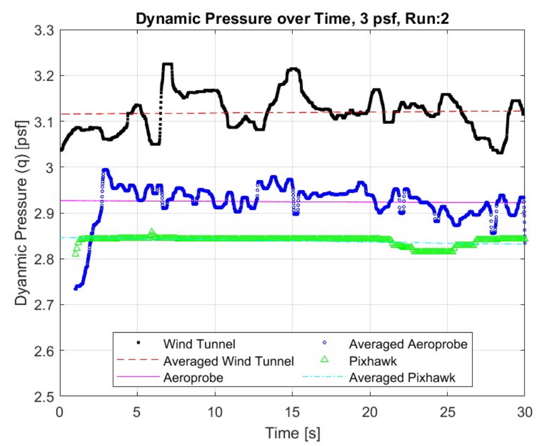
(a) 1.5-1-45 at 0.5 psf



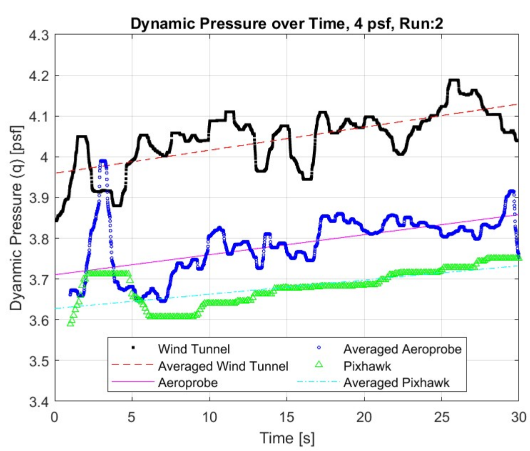
(b) 1.5-1-45 at 1 psf



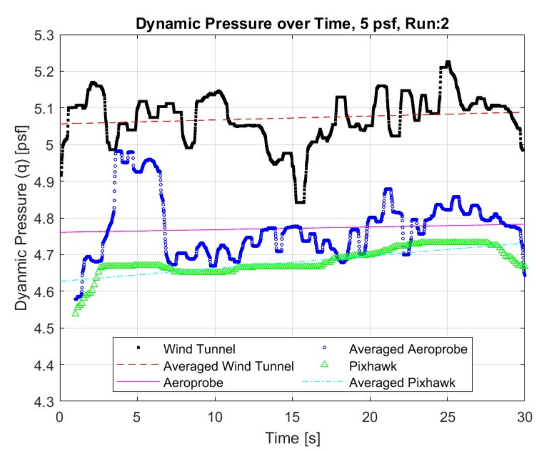
(c) 1.5-1-45 at 2 psf



(d) 1.5-1-45 at 3 psf



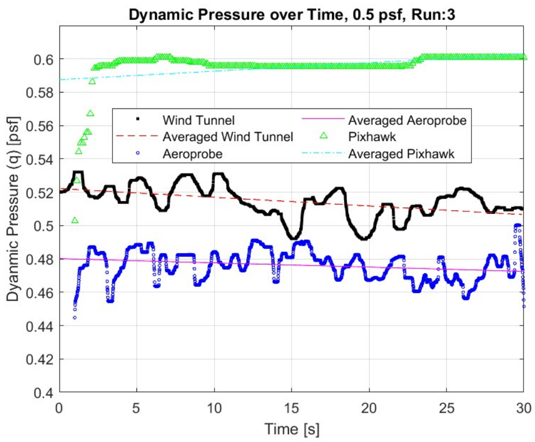
(e) 1.5-1-45 at 4 psf



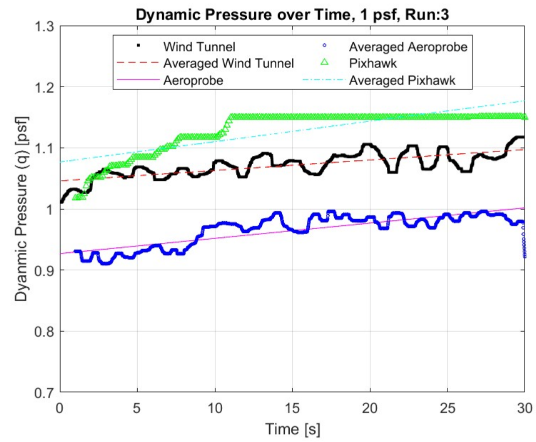
(f) 1.5-1-45 at 5 psf

Figure B2: 1.5-1-45

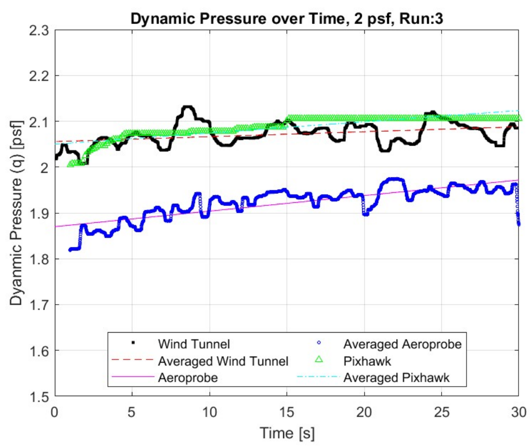
B.3 1.5-1-0



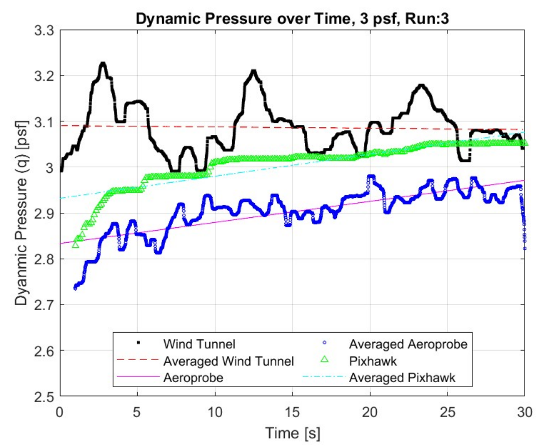
(a) 1.5-1-0 at 0.5 psf



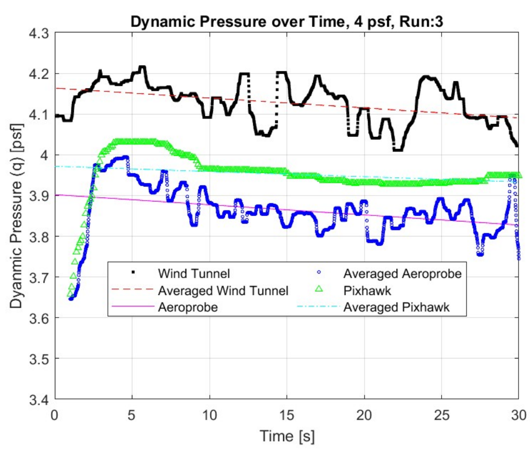
(b) 1.5-1-0 at 1 psf



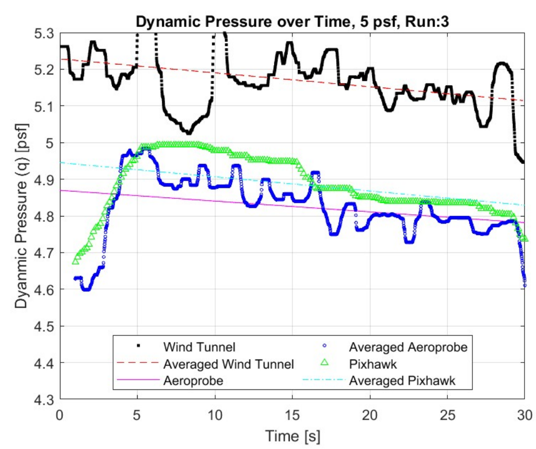
(c) 1.5-1-0 at 2 psf



(d) 1.5-1-0 at 3 psf



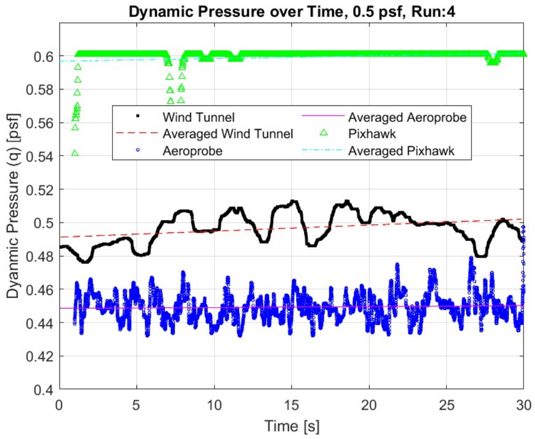
(e) 1.5-1-0 at 4 psf



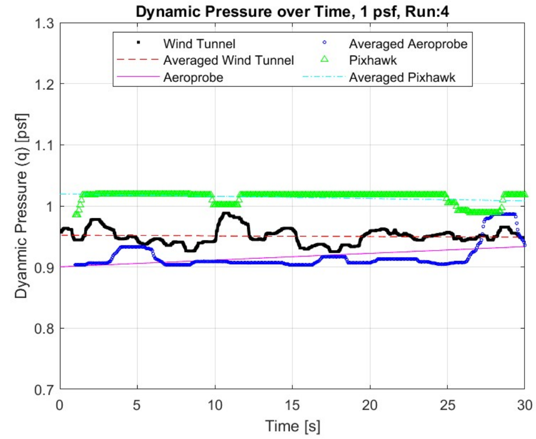
(f) 1.5-1-0 at 5 psf

Figure B3: 1.5-1-0

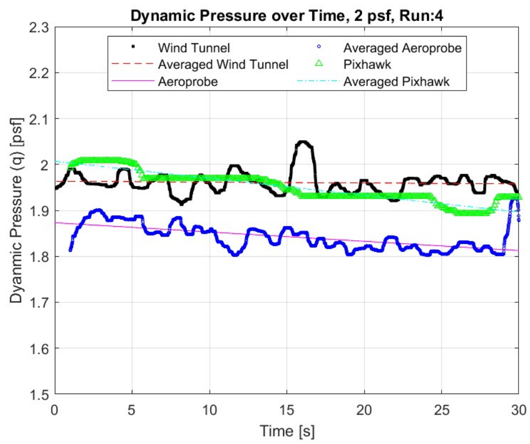
B.4 2.5-1-90



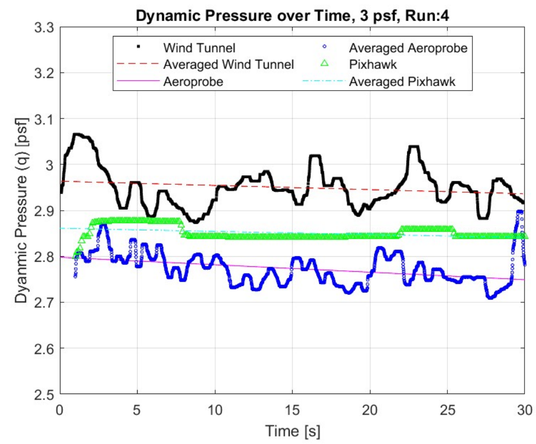
(a) 2.5-1-90 at 0.5 psf



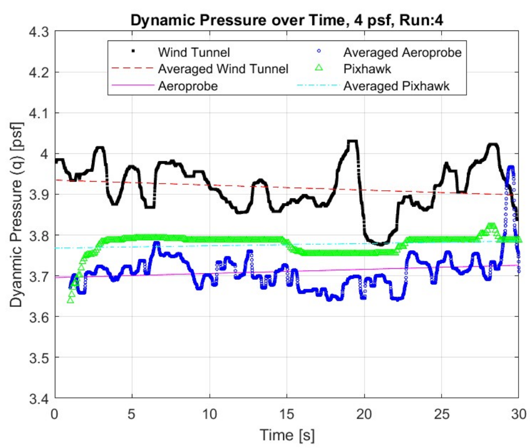
(b) 2.5-1-90 at 1 psf



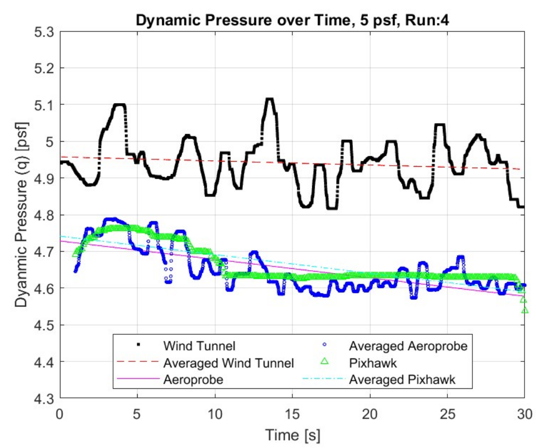
(c) 2.5-1-90 at 2 psf



(d) 2.5-1-90 at 3 psf



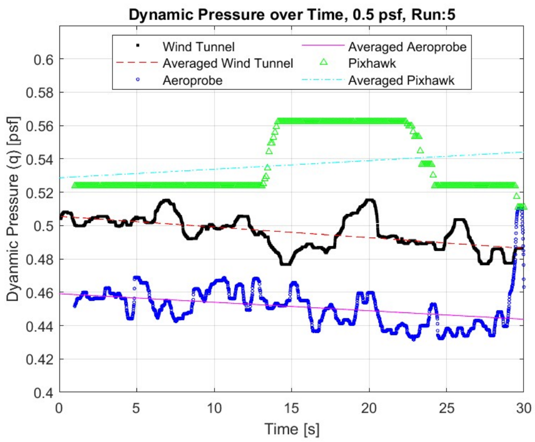
(e) 2.5-1-90 at 4 psf



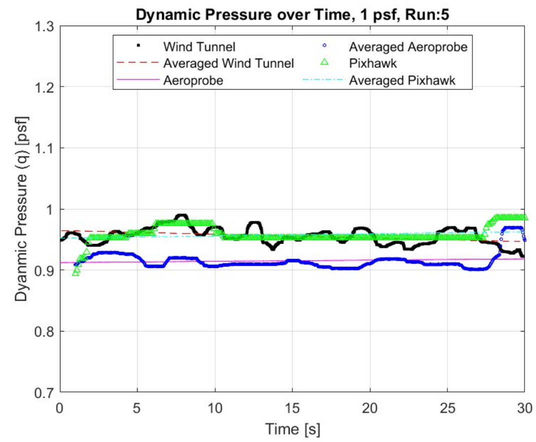
(f) 2.5-1-90 at 5 psf

Figure B4: 2.5-1-90

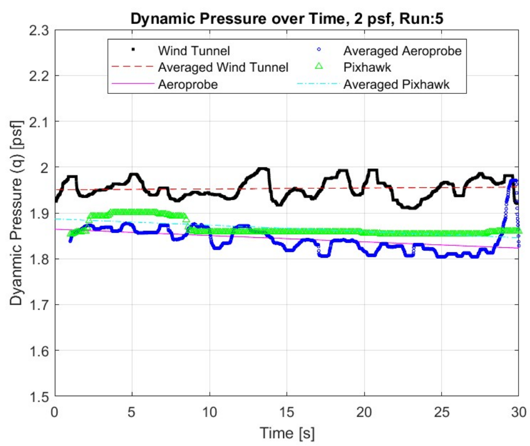
B.5 2.5-1-45



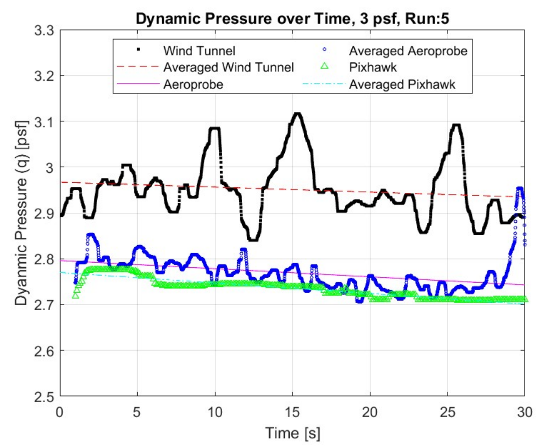
(a) 2.5-1-45 at 0.5 psf



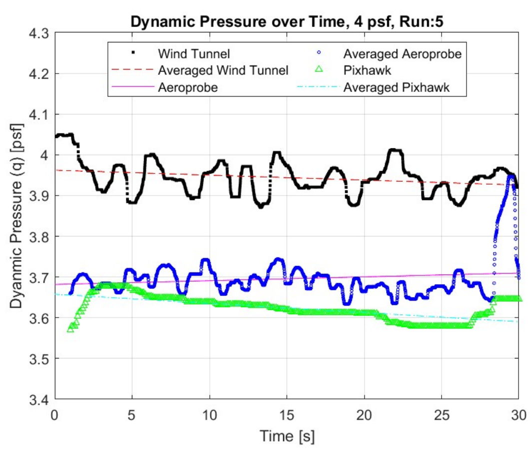
(b) 2.5-1-45 at 1 psf



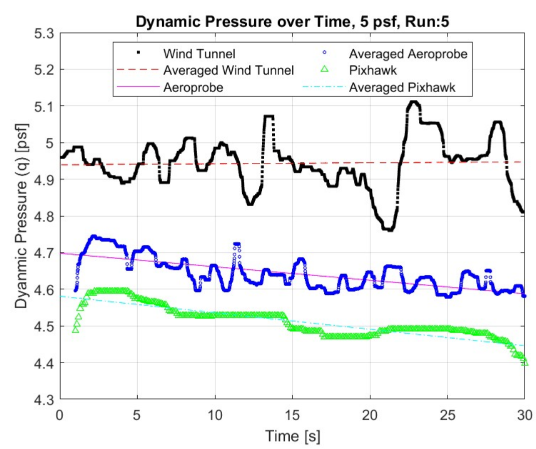
(c) 2.5-1-45 at 2 psf



(d) 2.5-1-45 at 3 psf



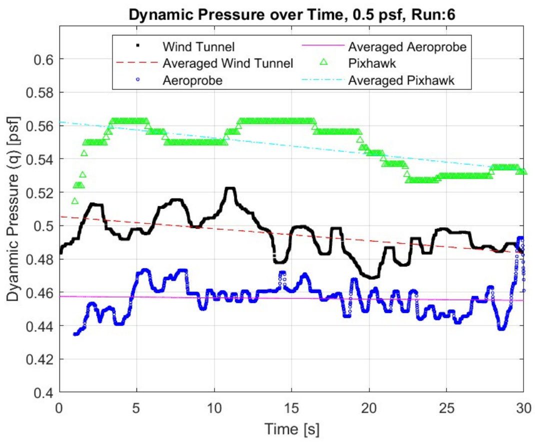
(e) 2.5-1-45 at 4 psf



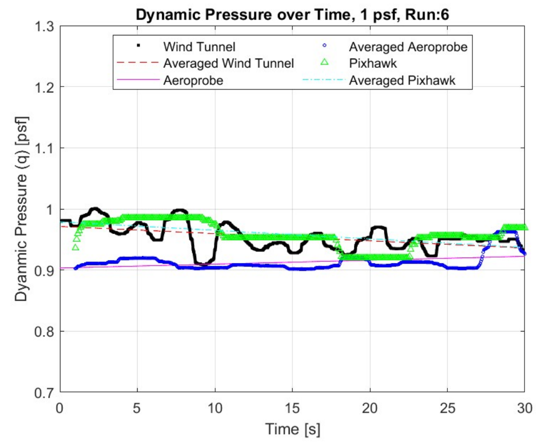
(f) 2.5-1-45 at 5 psf

Figure B5: 2.5-1-45

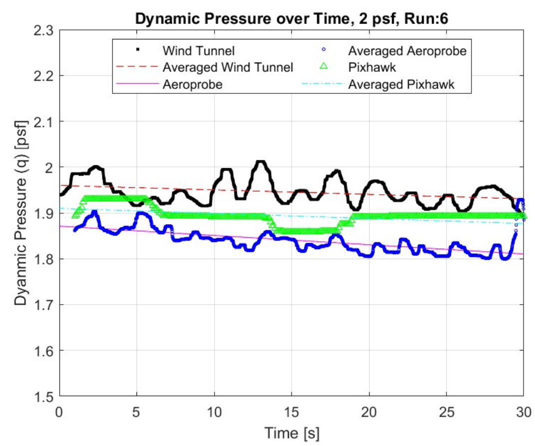
B.6 2.5-1-0



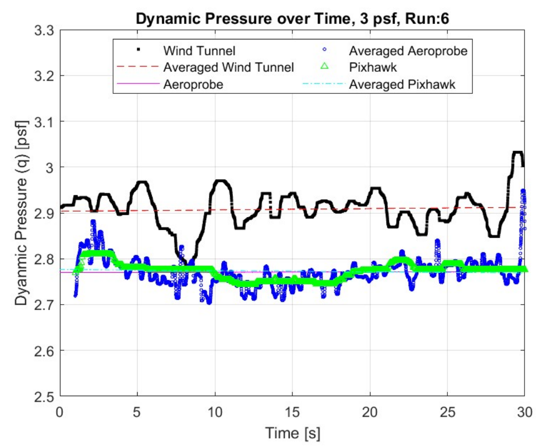
(a) 2.5-1-0 at 0.5 psf



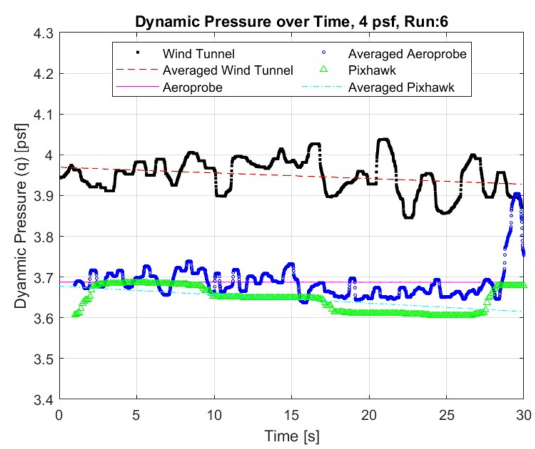
(b) 2.5-1-0 at 1 psf



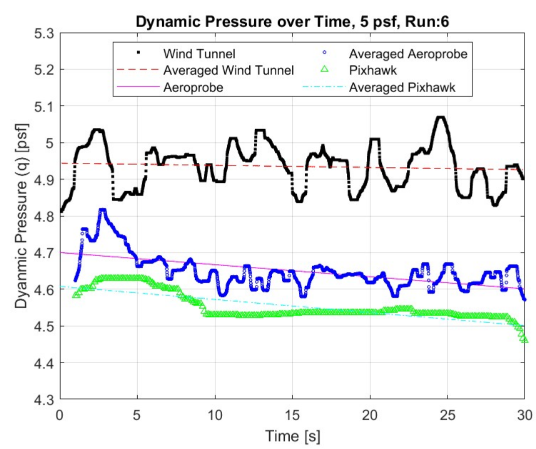
(c) 2.5-1-0 at 2 psf



(d) 2.5-1-0 at 3 psf



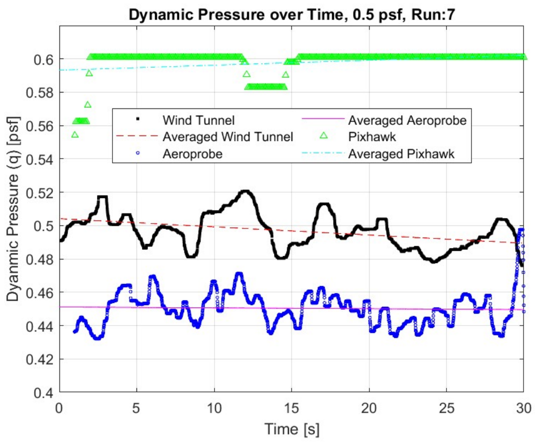
(e) 2.5-1-0 at 4 psf



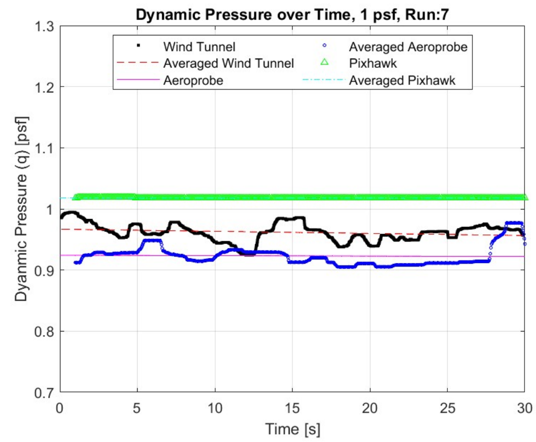
(f) 2.5-1-0 at 5 psf

Figure B6: 2.5-1-0

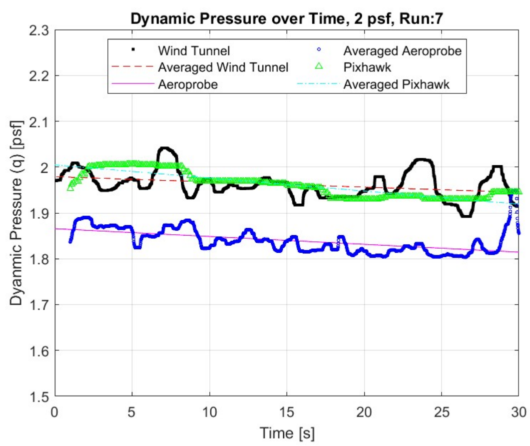
B.7 3.5-1-90



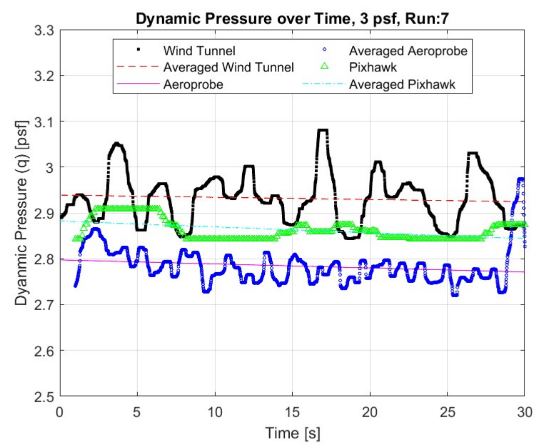
(a) 3.5-1-90 at 0.5 psf



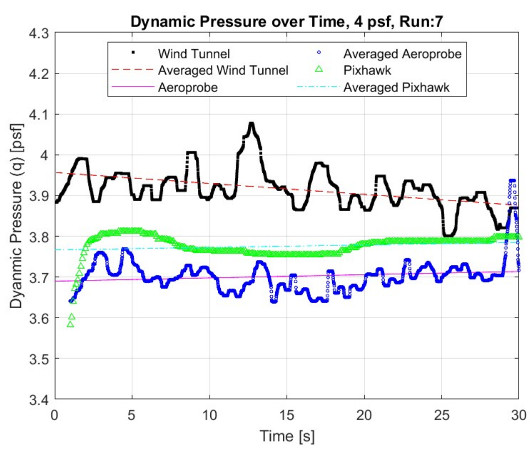
(b) 3.5-1-90 at 1 psf



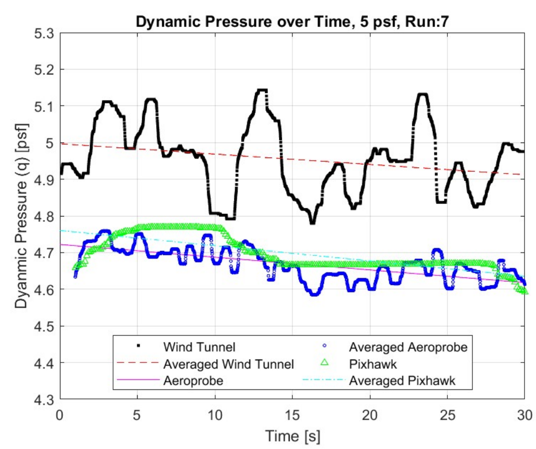
(c) 3.5-1-90 at 2 psf



(d) 3.5-1-90 at 3 psf



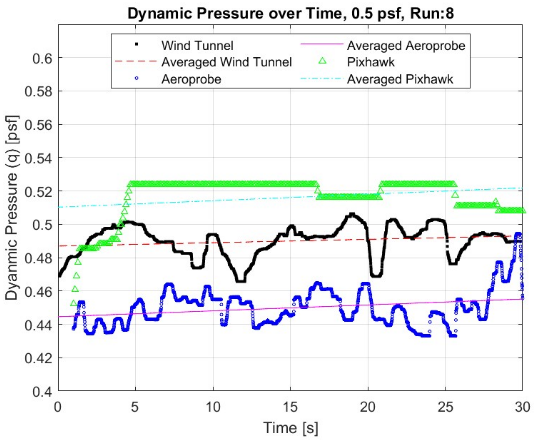
(e) 3.5-1-90 at 4 psf



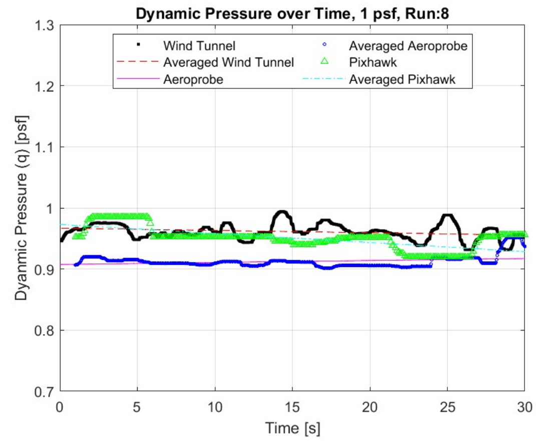
(f) 3.5-1-90 at 5 psf

Figure B7: 3.5-1-90

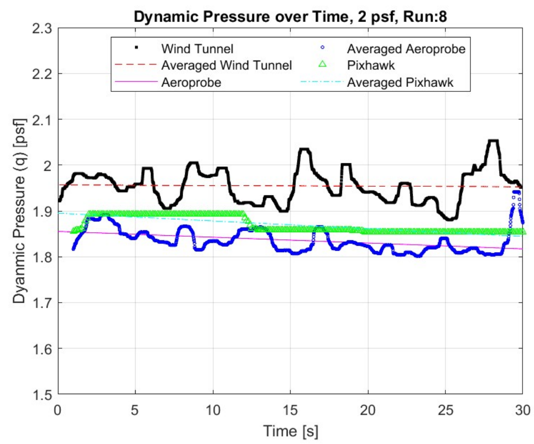
B.8 3.5-1-45



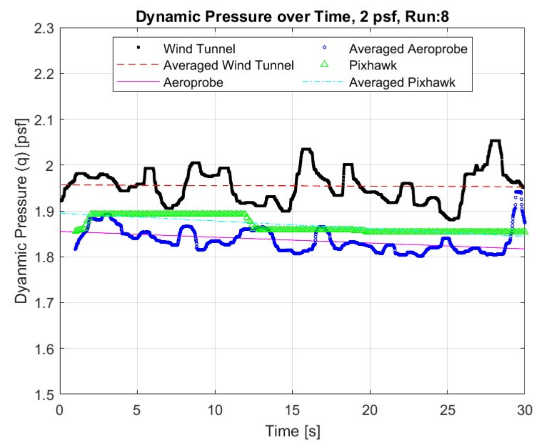
(a) 3.5-1-45 at 0.5 psf



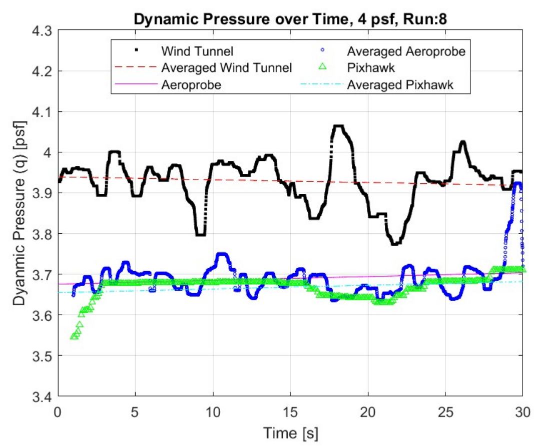
(b) 3.5-1-45 at 1 psf



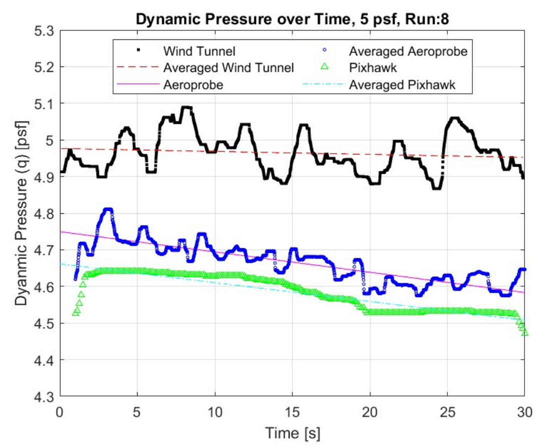
(c) 3.5-1-45 at 2 psf



(d) 3.5-1-45 at 3 psf



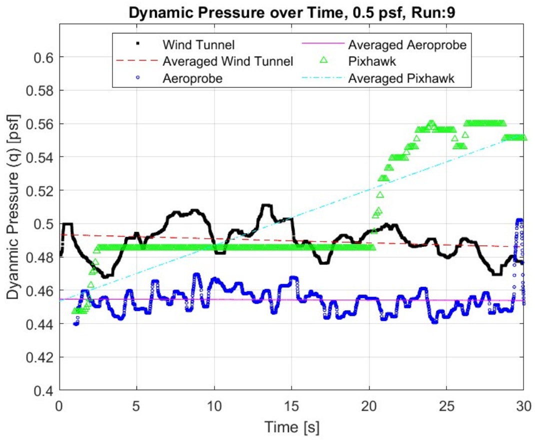
(e) 3.5-1-45 at 4 psf



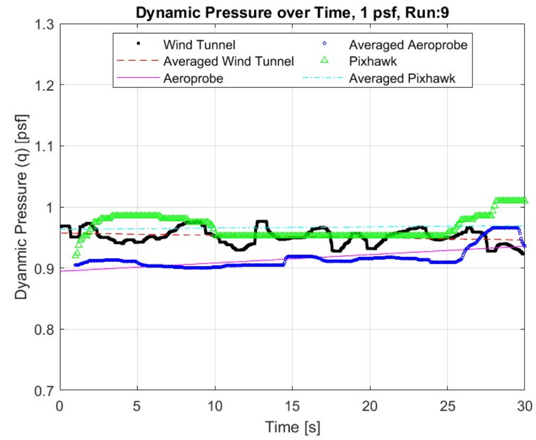
(f) 3.5-1-45 at 5 psf

Figure B8: 3.5-1-45

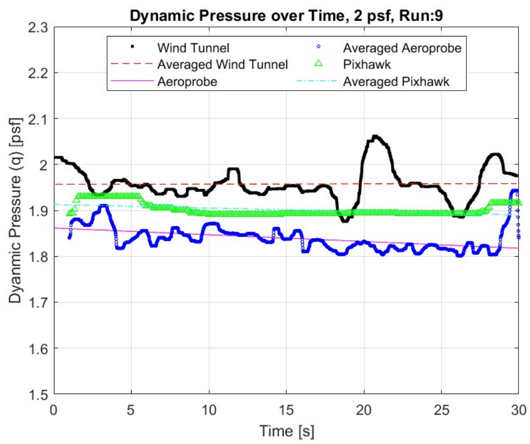
B.9 3.5-1-0



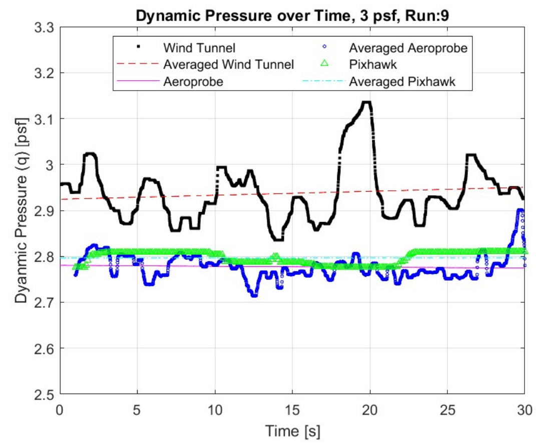
(a) 3.5-1-0 at 0.5 psf



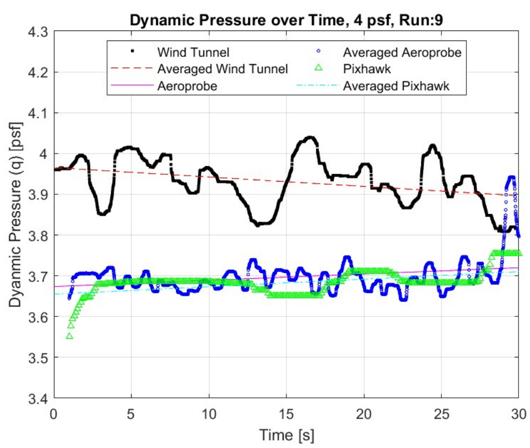
(b) 3.5-1-0 at 1 psf



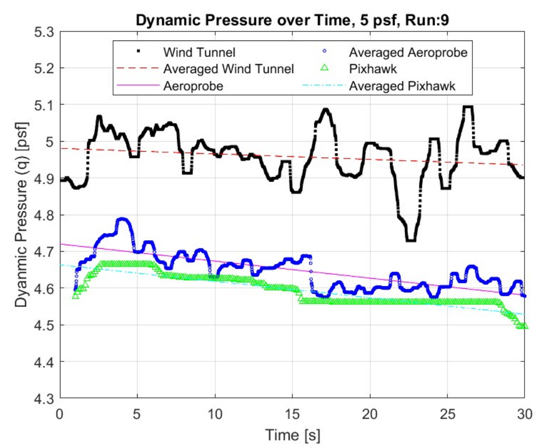
(c) 3.5-1-0 at 2 psf



(d) 3.5-1-0 at 3 psf



(e) 3.5-1-0 at 4 psf



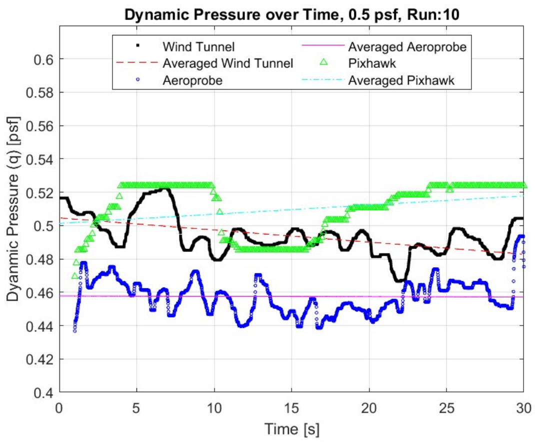
(f) 3.5-1-0 at 5 psf

Figure B9: 3.5-1-0

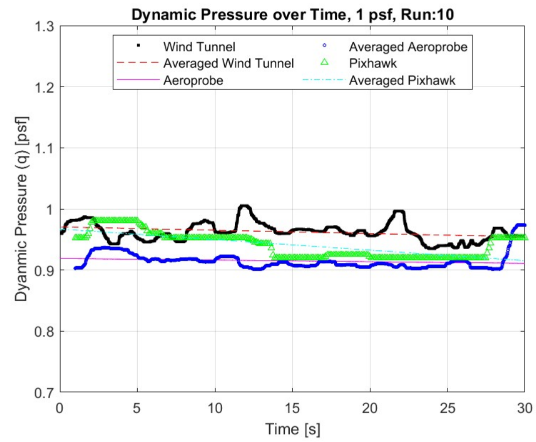
Appendix C

Dynamic Pressure over Time Plots: Hole 2

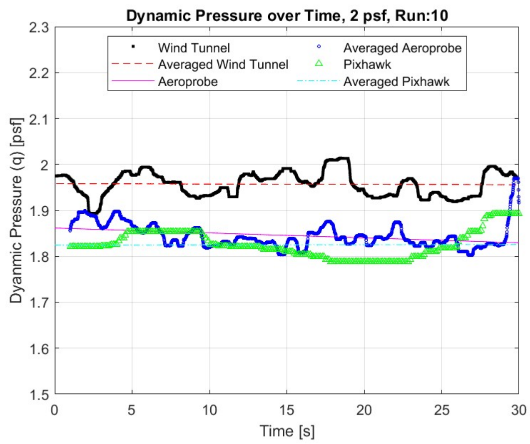
C.1 1.5-2-90



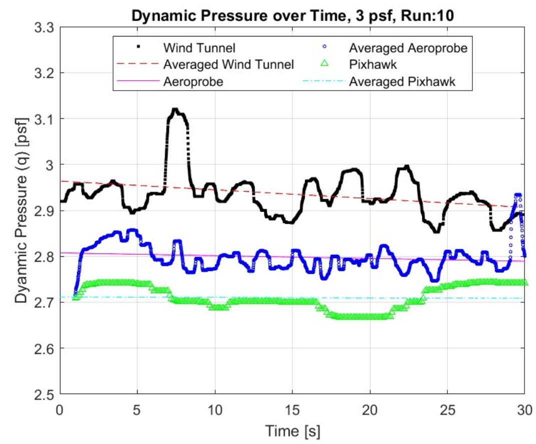
(a) 1.5-2-90 at 0.5 psf



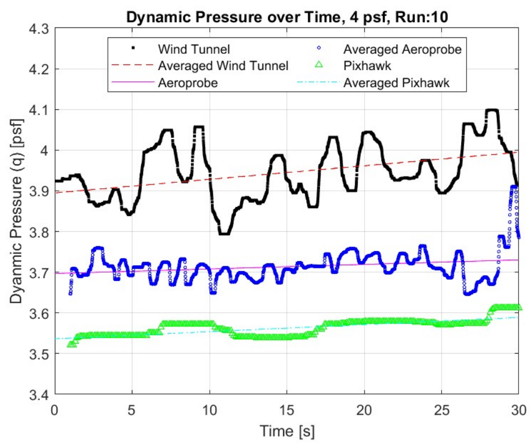
(b) 1.5-2-90 at 1 psf



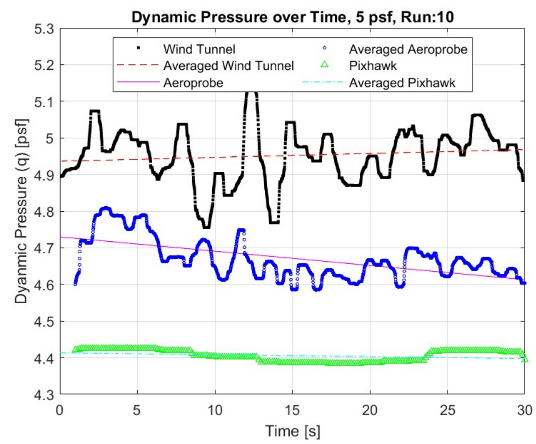
(c) 1.5-2-90 at 2 psf



(d) 1.5-2-90 at 3 psf



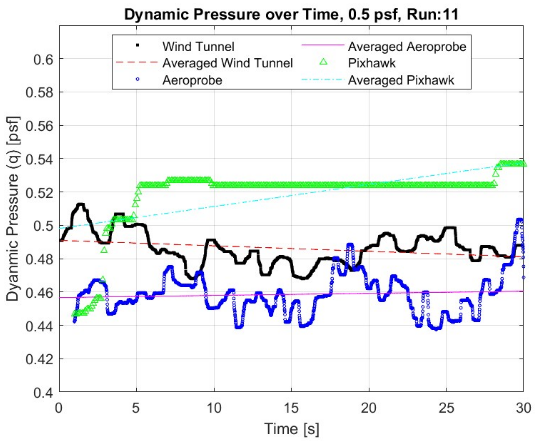
(e) 1.5-2-90 at 4 psf



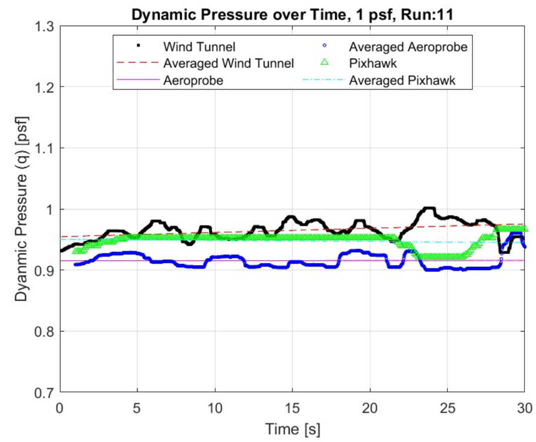
(f) 1.5-2-90 at 5 psf

Figure C1: 1.5-2-90

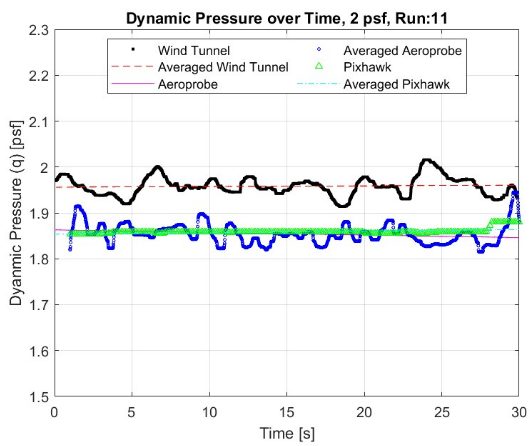
C.2 1.5-2-45



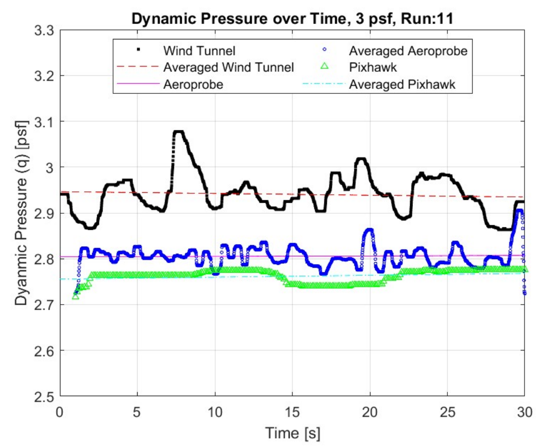
(a) 1.5-1-45 at 0.5 psf



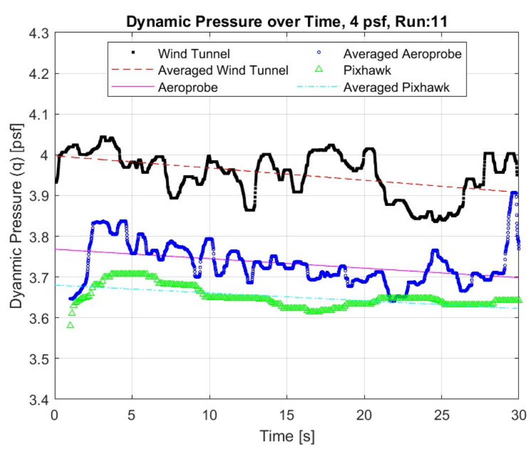
(b) 1.5-1-45 at 1 psf



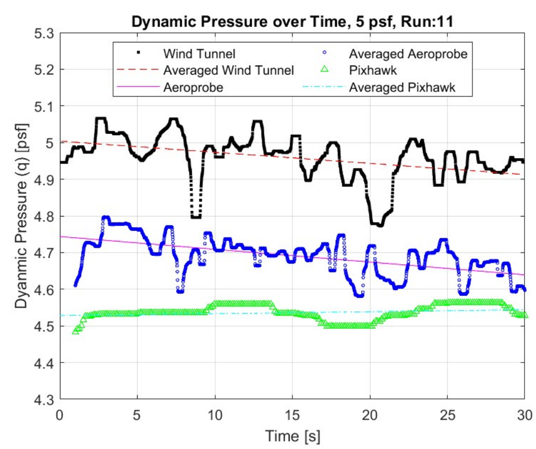
(c) 1.5-1-45 at 2 psf



(d) 1.5-1-45 at 3 psf



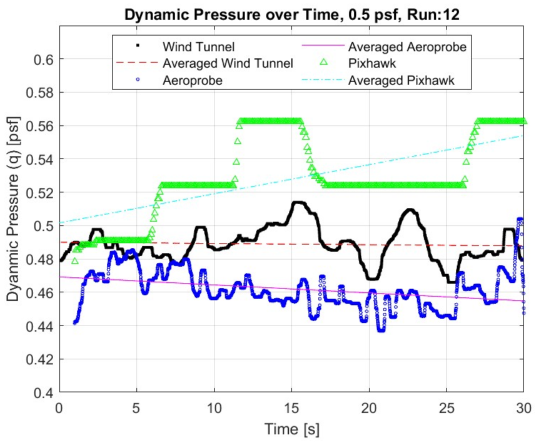
(e) 1.5-1-45 at 4 psf



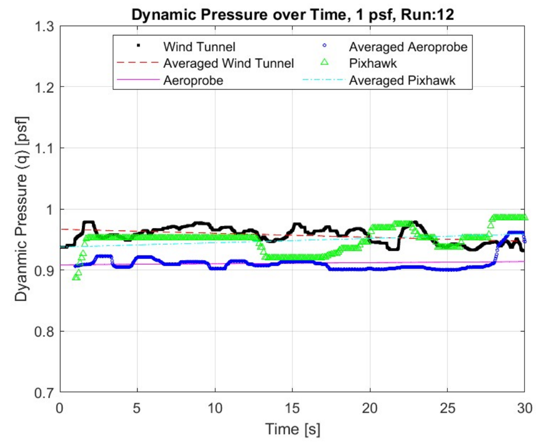
(f) 1.5-1-45 at 5 psf

Figure C2: 1.5-2-45

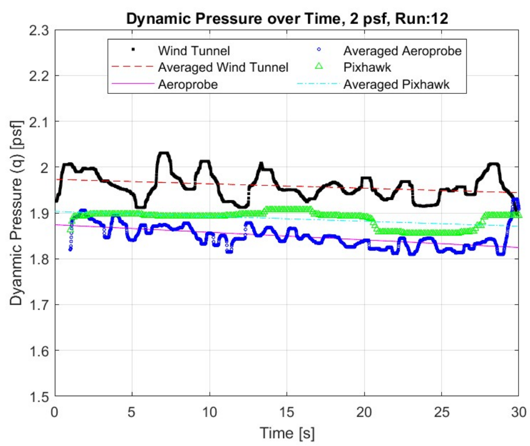
C.3 1.5-2-0



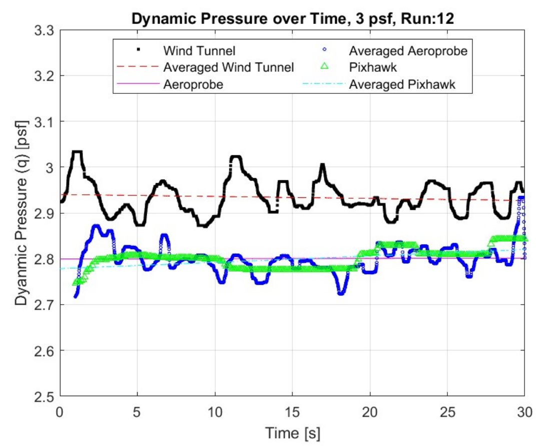
(a) 1.5-2-0 at 0.5 psf



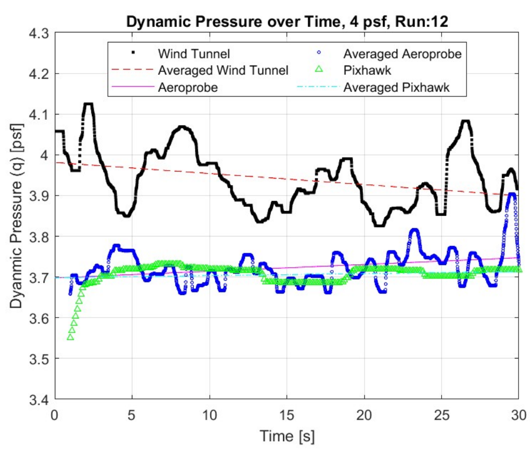
(b) 1.5-2-0 at 1 psf



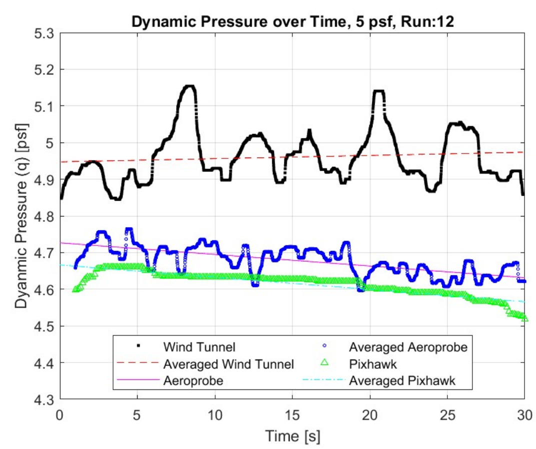
(c) 1.5-2-0 at 2 psf



(d) 1.5-2-0 at 3 psf



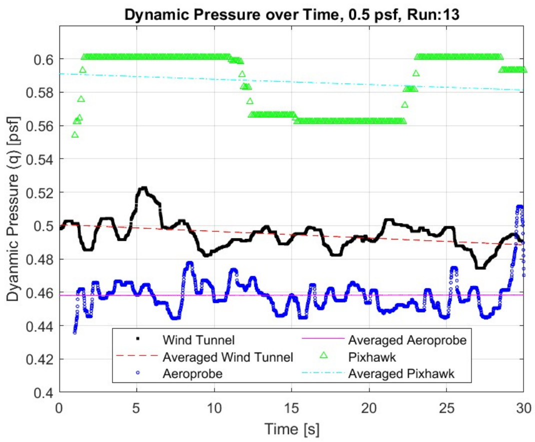
(e) 1.5-2-0 at 4 psf



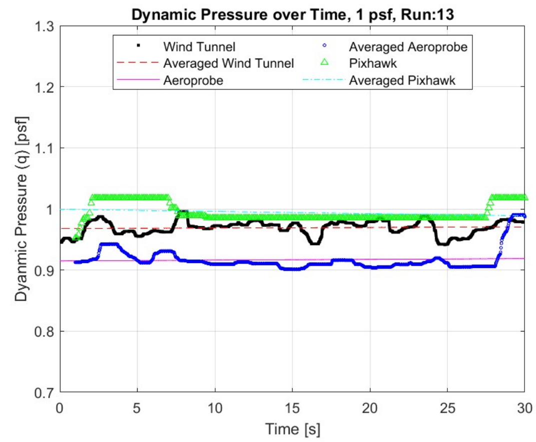
(f) 1.5-2-0 at 5 psf

Figure C3: 1.5-2-0

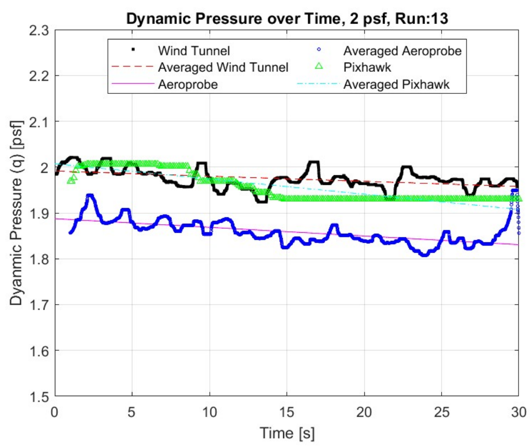
C.4 2.5-2-90



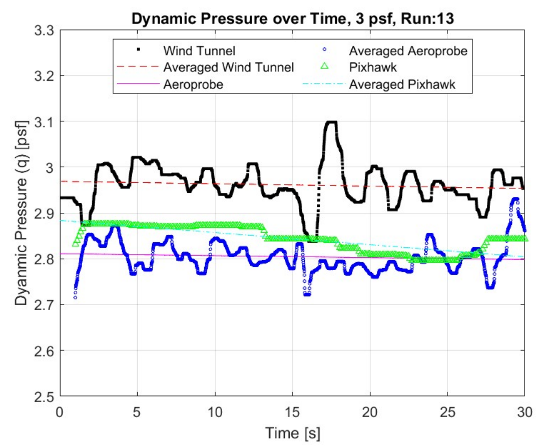
(a) 2.5-2-90 at 0.5 psf



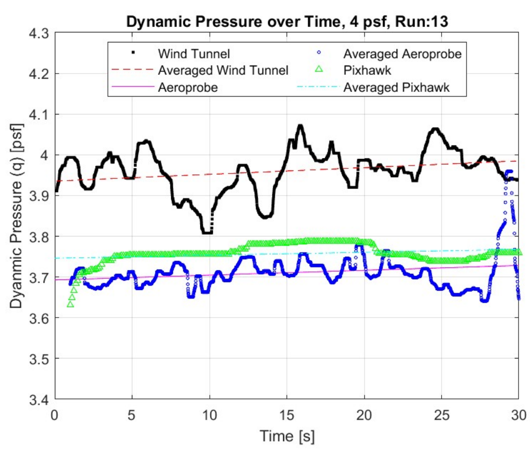
(b) 2.5-2-90 at 1 psf



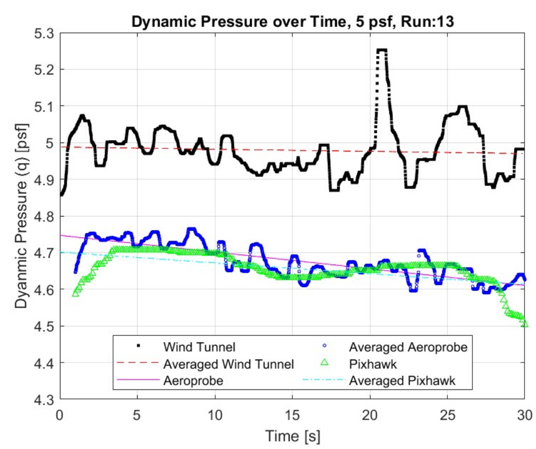
(c) 2.5-2-90 at 2 psf



(d) 2.5-2-90 at 3 psf



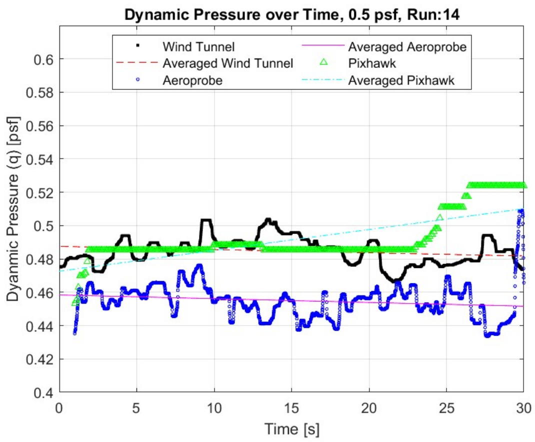
(e) 2.5-2-90 at 4 psf



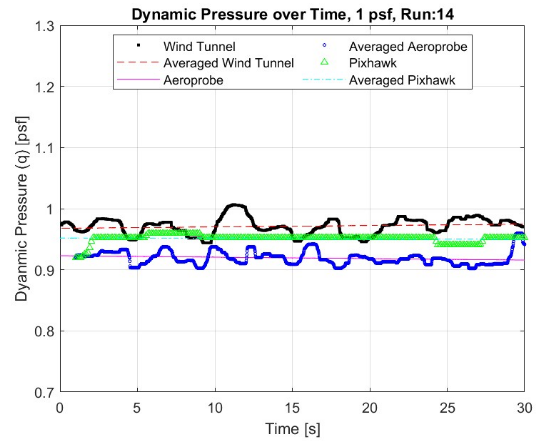
(f) 2.5-2-90 at 5 psf

Figure C4: 2.5-2-90

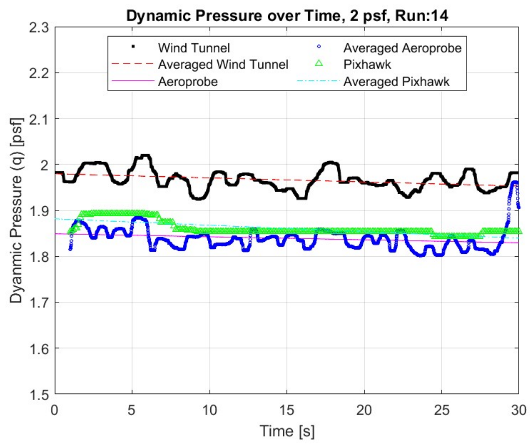
C.5 2.5-2-45



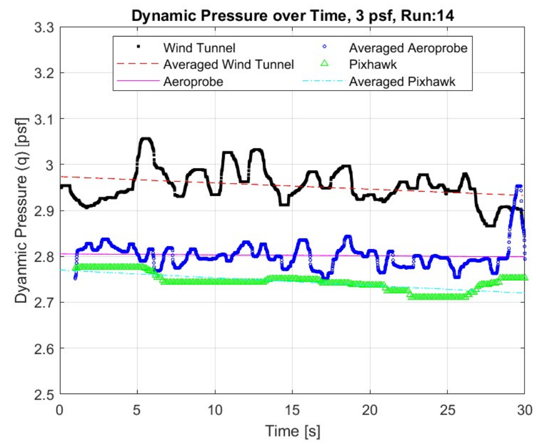
(a) 2.5-2-45 at 0.5 psf



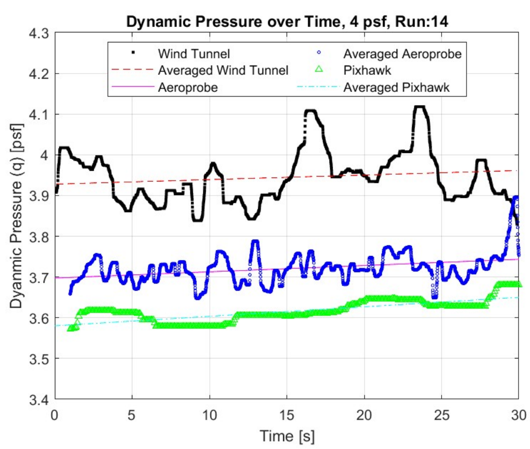
(b) 2.5-2-45 at 1 psf



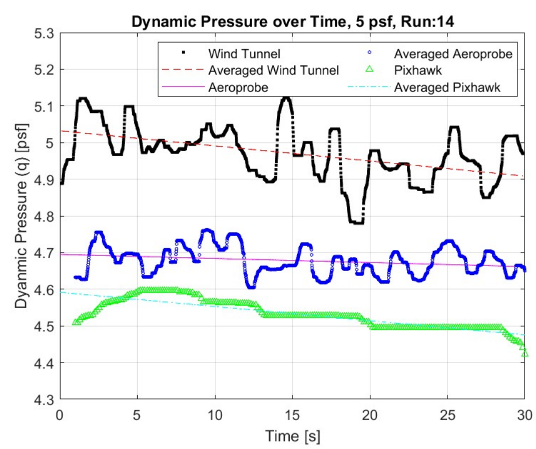
(c) 2.5-2-45 at 2 psf



(d) 2.5-2-45 at 3 psf



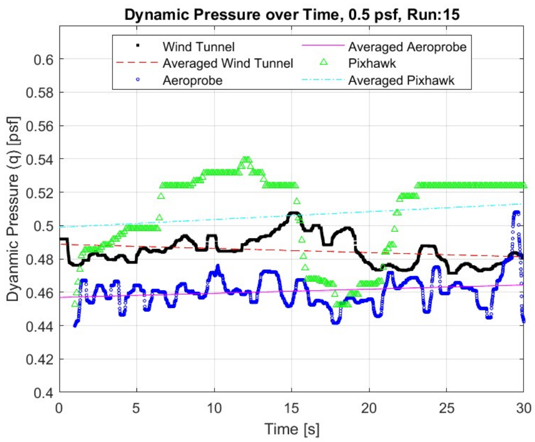
(e) 2.5-2-45 at 4 psf



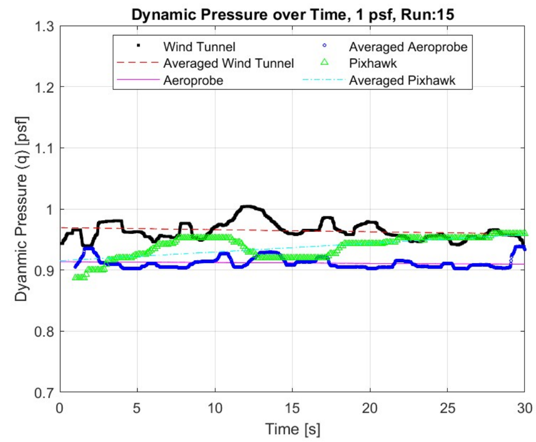
(f) 2.5-2-45 at 5 psf

Figure C5: 2.5-2-45

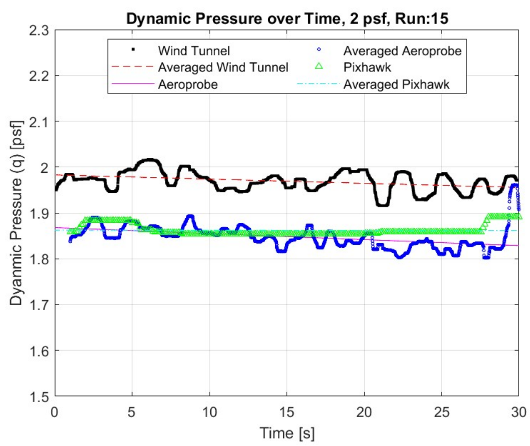
C.6 2.5-2-0



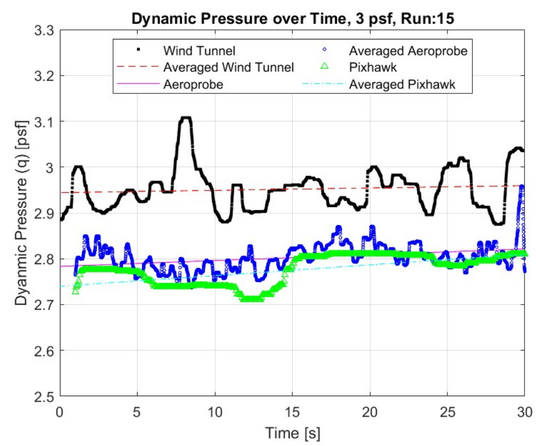
(a) 2.5-2-0 at 0.5 psf



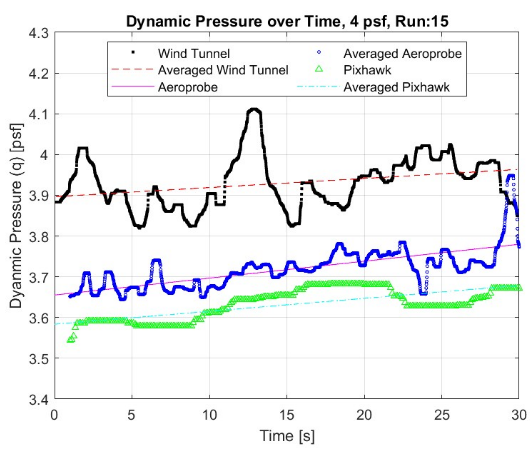
(b) 2.5-2-0 at 1 psf



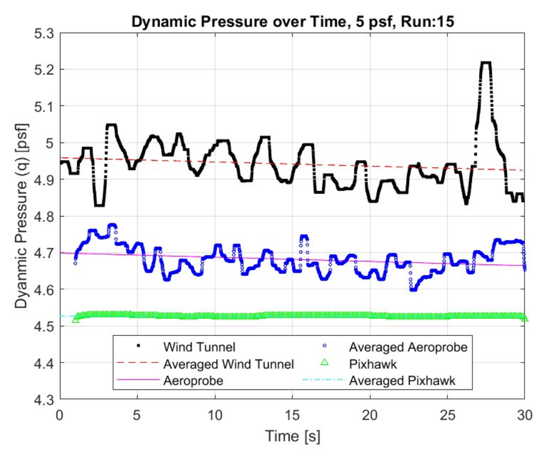
(c) 2.5-2-0 at 2 psf



(d) 2.5-2-0 at 3 psf



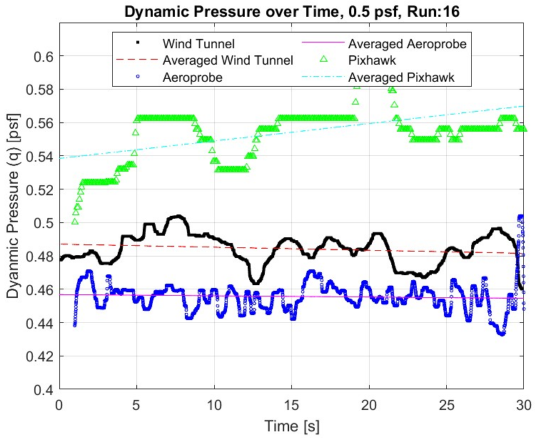
(e) 2.5-2-0 at 4 psf



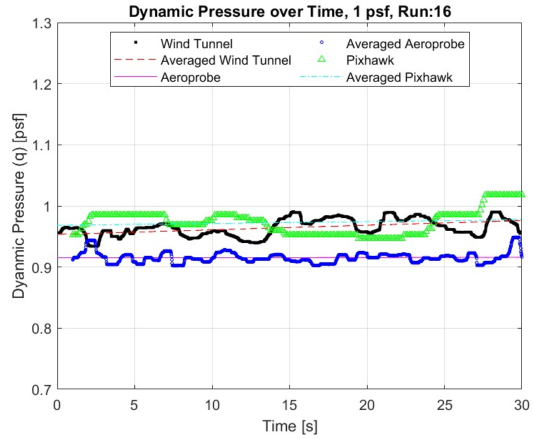
(f) 2.5-2-0 at 5 psf

Figure C6: 2.5-2-0

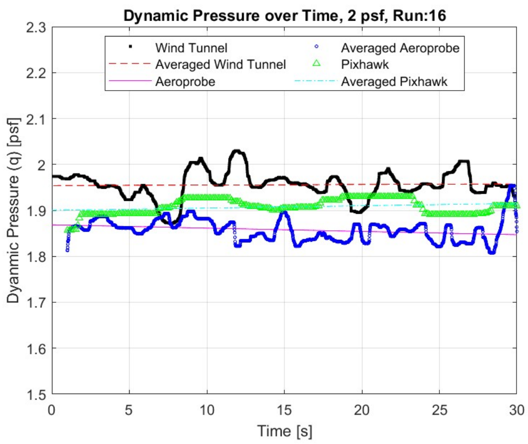
C.7 3.5-2-90



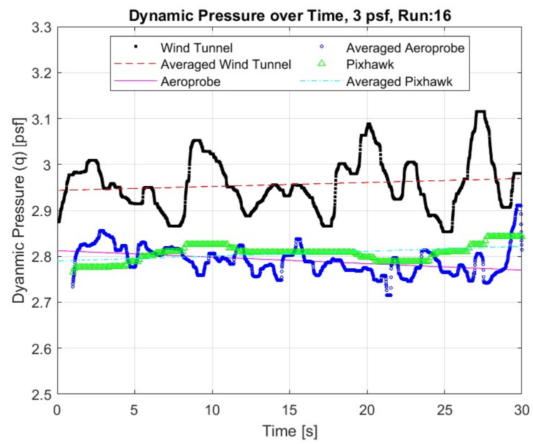
(a) 3.5-2-90 at 0.5 psf



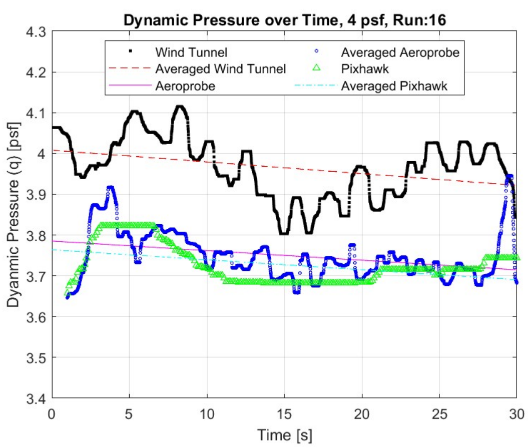
(b) 3.5-2-90 at 1 psf



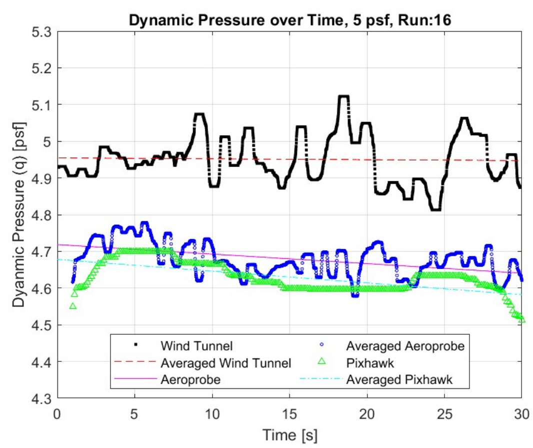
(c) 3.5-2-90 at 2 psf



(d) 3.5-2-90 at 3 psf



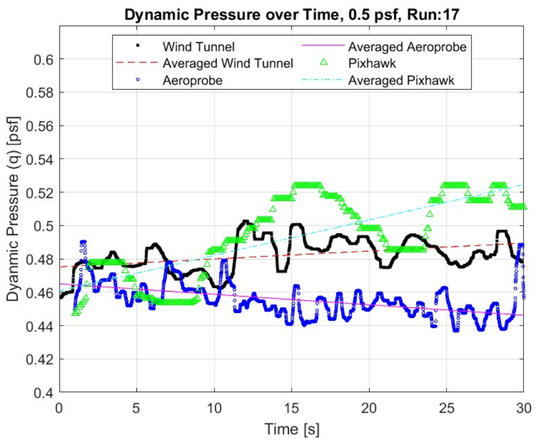
(e) 3.5-2-90 at 4 psf



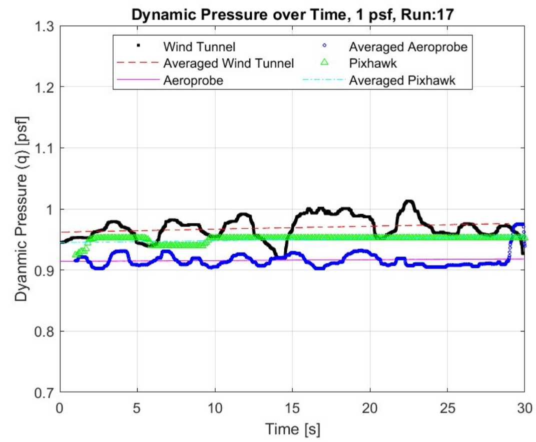
(f) 3.5-2-90 at 5 psf

Figure C7: 3.5-2-90

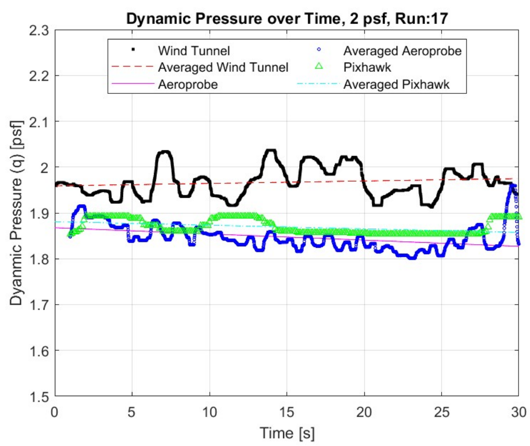
C.8 3.5-2-45



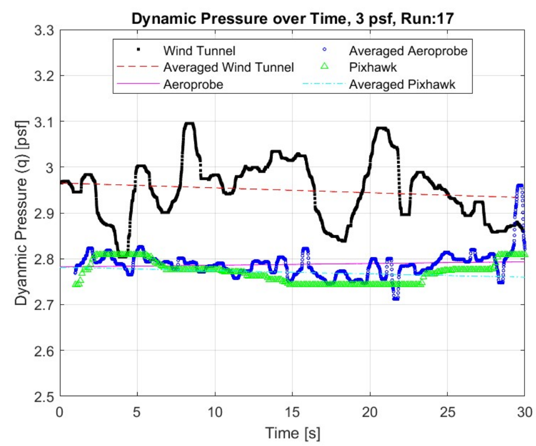
(a) 3.5-2-45 at 0.5 psf



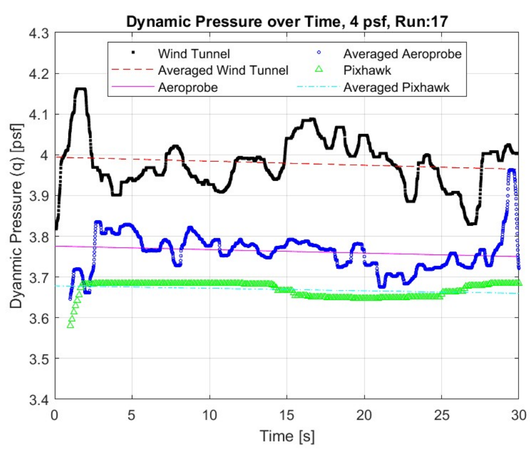
(b) 3.5-2-45 at 1 psf



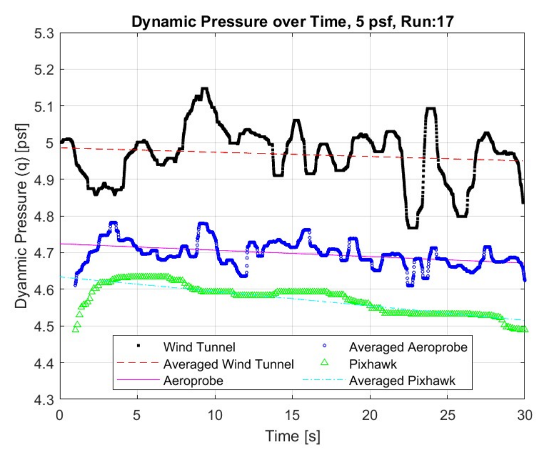
(c) 3.5-2-45 at 2 psf



(d) 3.5-2-45 at 3 psf



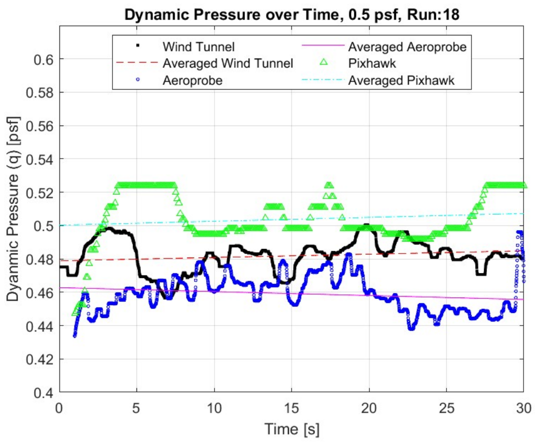
(e) 3.5-2-45 at 4 psf



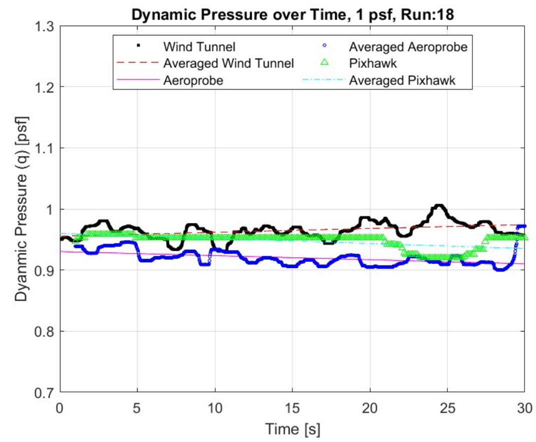
(f) 3.5-2-45 at 5 psf

Figure C8: 3.5-2-45

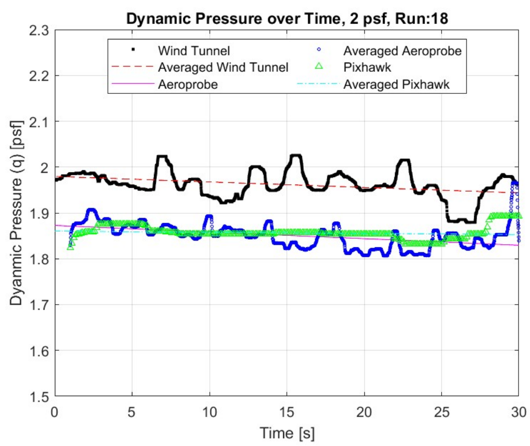
C.9 3.5-2-0



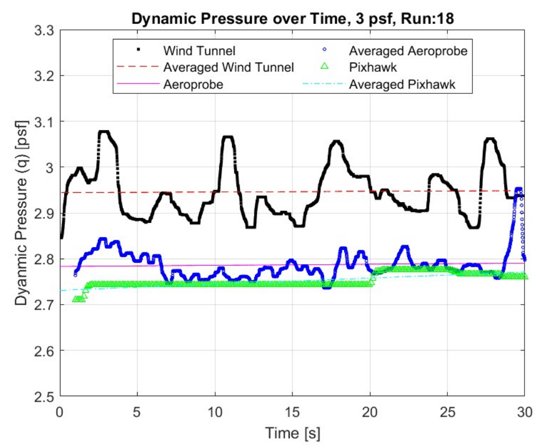
(a) 3.5-2-0 at 0.5 psf



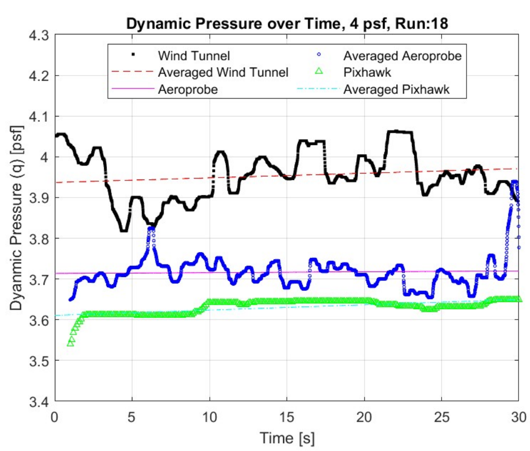
(b) 3.5-2-0 at 1 psf



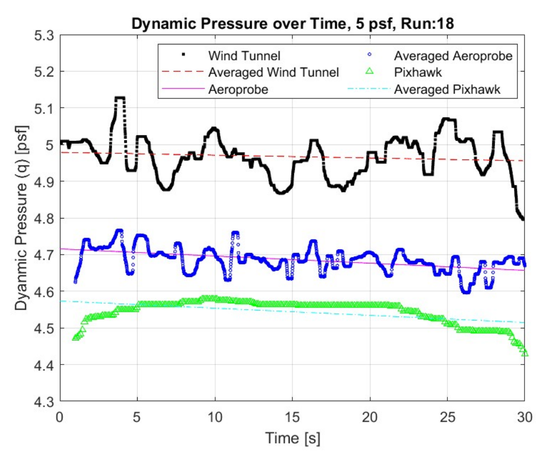
(c) 3.5-2-0 at 2 psf



(d) 3.5-2-0 at 3 psf



(e) 3.5-2-0 at 4 psf



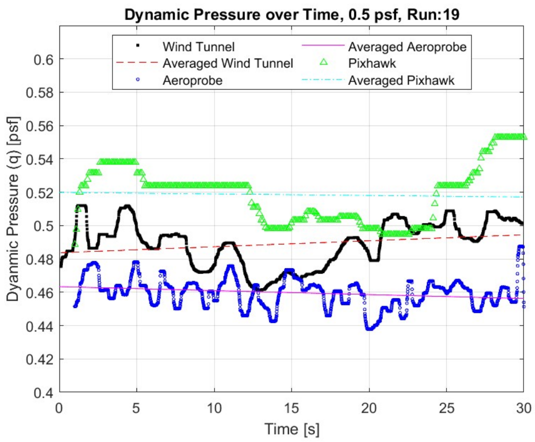
(f) 3.5-2-0 at 5 psf

Figure C9: 3.5-2-0

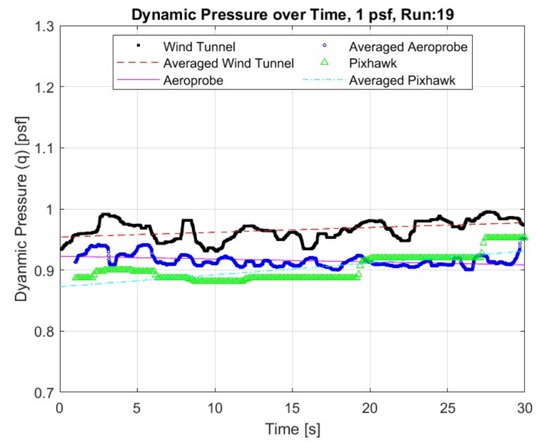
Appendix D

Dynamic Pressure over Time Plots: Hole 3

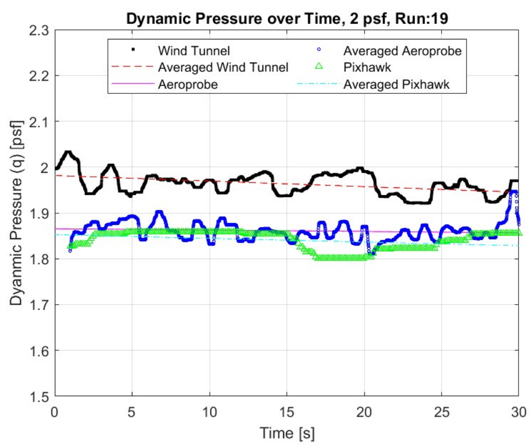
D.1 1.5-3-90



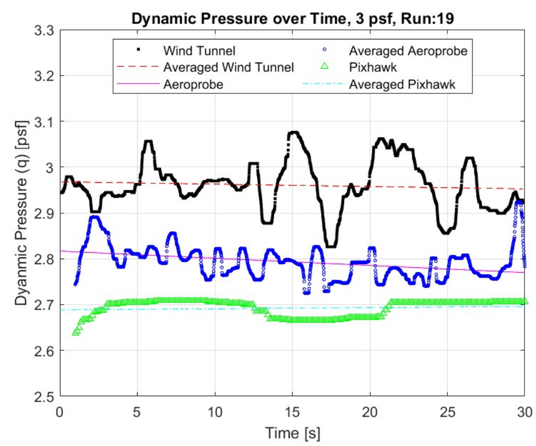
(a) 1.5-3-90 at 0.5 psf



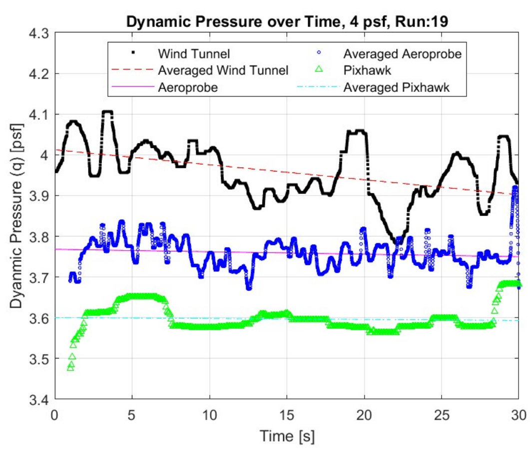
(b) 1.5-3-90 at 1 psf



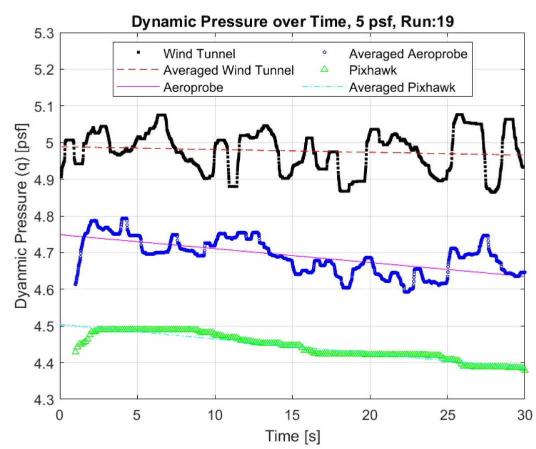
(c) 1.5-3-90 at 2 psf



(d) 1.5-3-90 at 3 psf



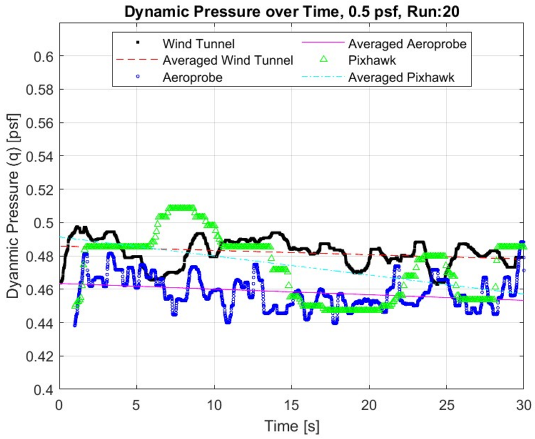
(e) 1.5-3-90 at 4 psf



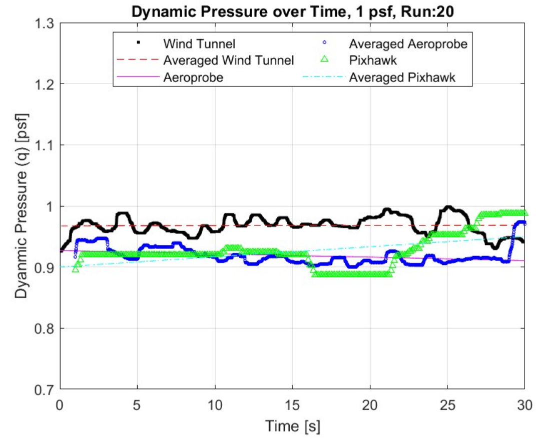
(f) 1.5-3-90 at 5 psf

Figure D1: 1.5-3-90

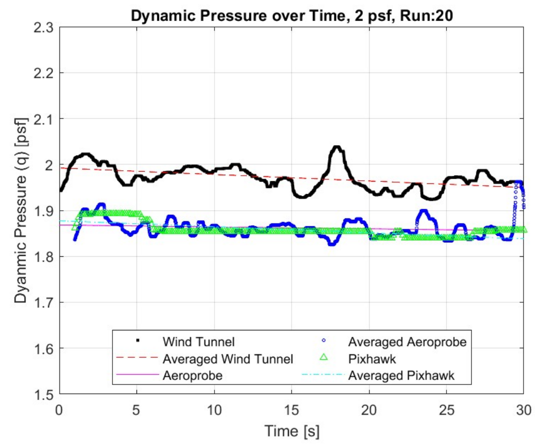
D.2 1.5-3-45



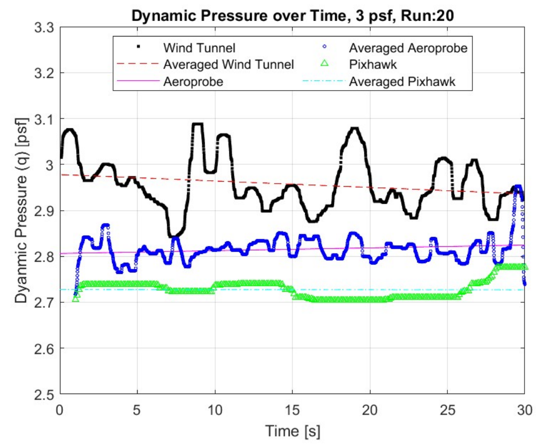
(a) 1.5-3-45 at 0.5 psf



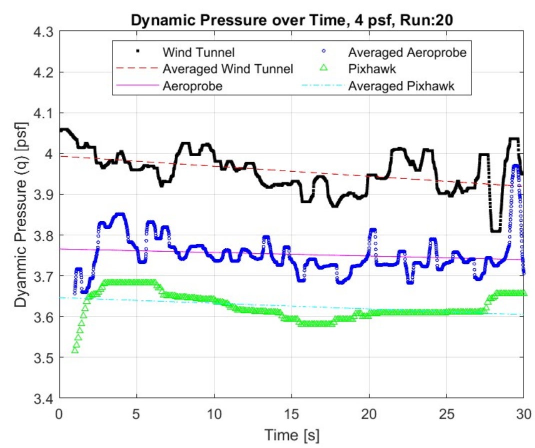
(b) 1.5-3-45 at 1 psf



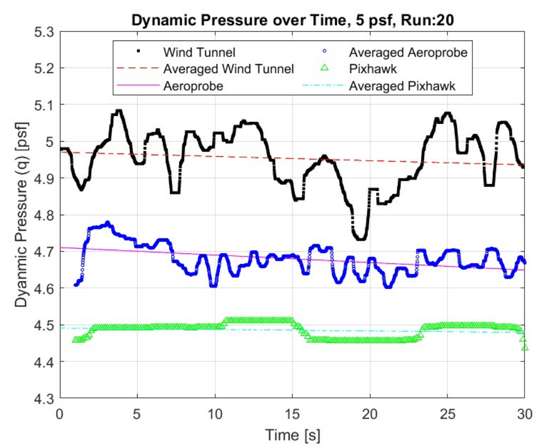
(c) 1.5-3-45 at 2 psf



(d) 1.5-3-45 at 3 psf



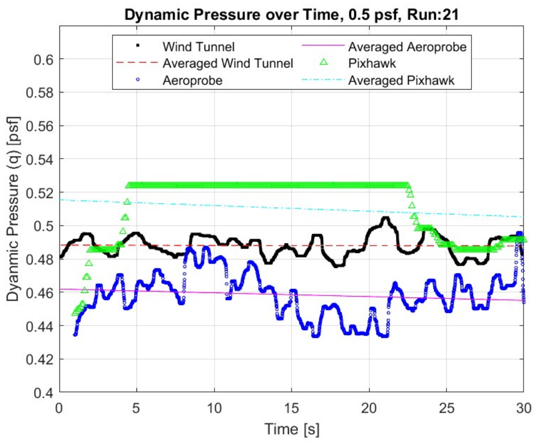
(e) 1.5-3-45 at 4 psf



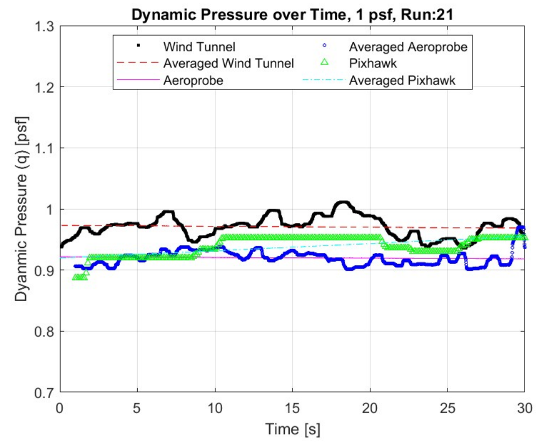
(f) 1.5-3-45 at 5 psf

Figure D2: 1.5-3-45

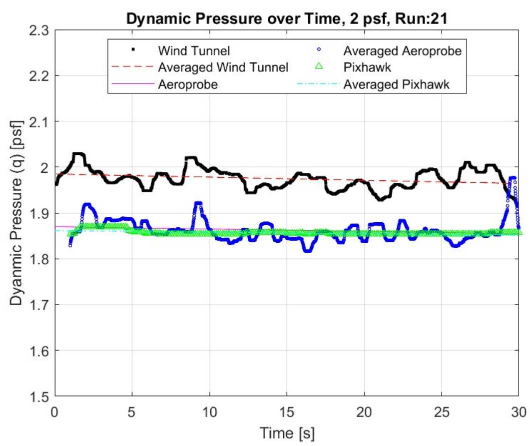
D.3 1.5-3-0



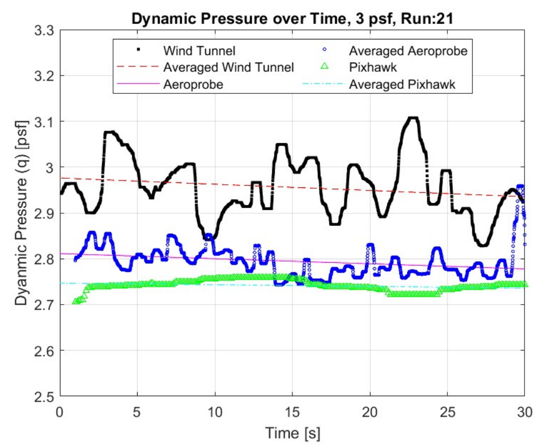
(a) 1.5-3-0 at 0.5 psf



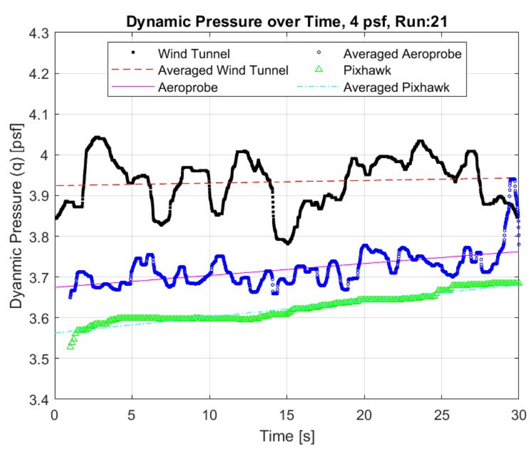
(b) 1.5-3-0 at 1 psf



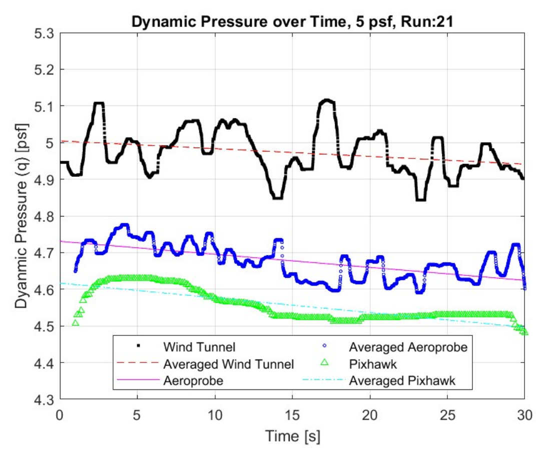
(c) 1.5-3-0 at 2 psf



(d) 1.5-3-0 at 3 psf



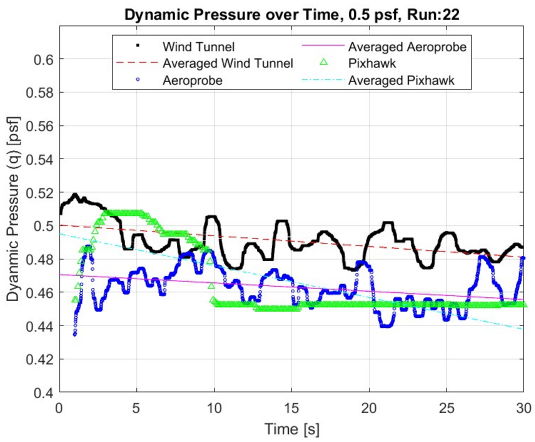
(e) 1.5-3-0 at 4 psf



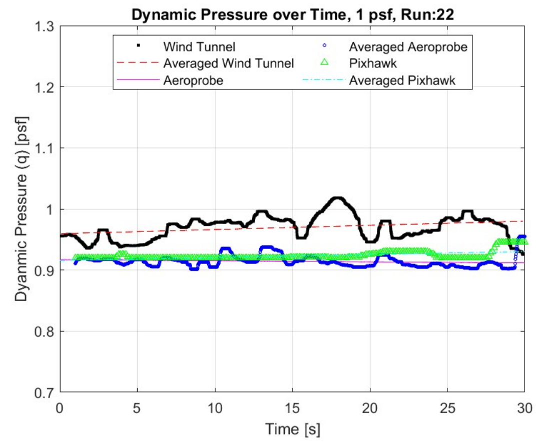
(f) 1.5-3-0 at 5 psf

Figure D3: 1.5-3-0

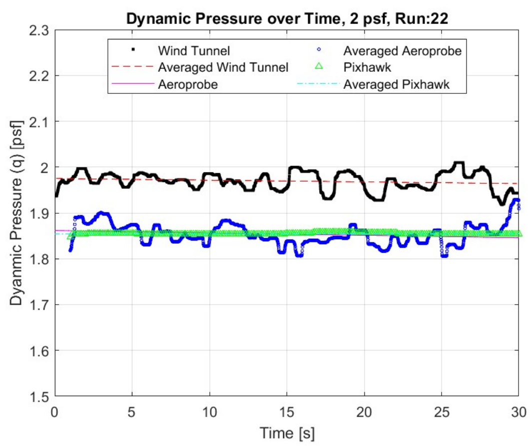
D.4 2.5-3-90



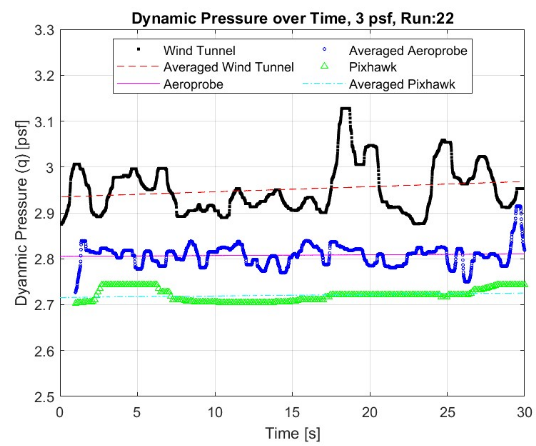
(a) 2.5-3-90 at 0.5 psf



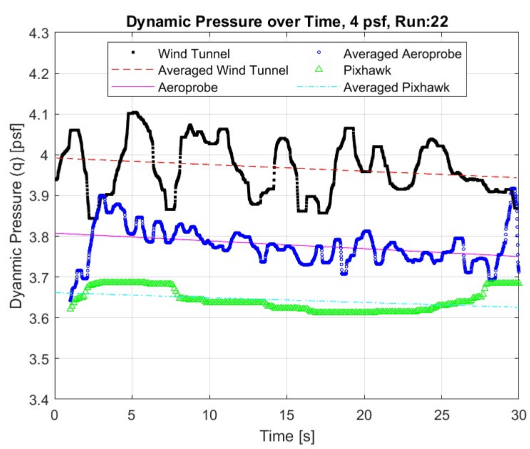
(b) 2.5-3-90 at 1 psf



(c) 2.5-3-90 at 2 psf



(d) 2.5-3-90 at 3 psf



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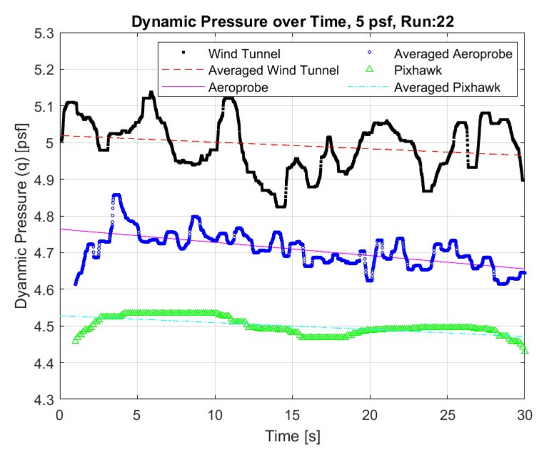
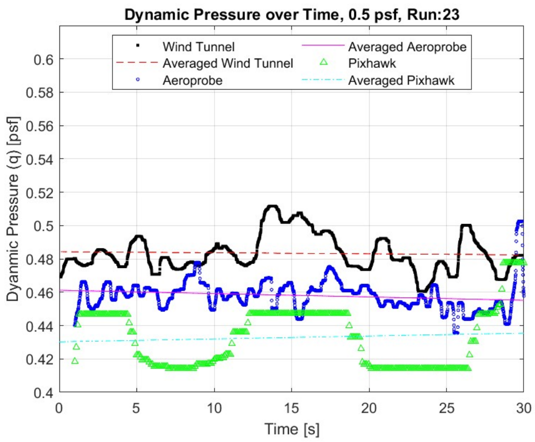


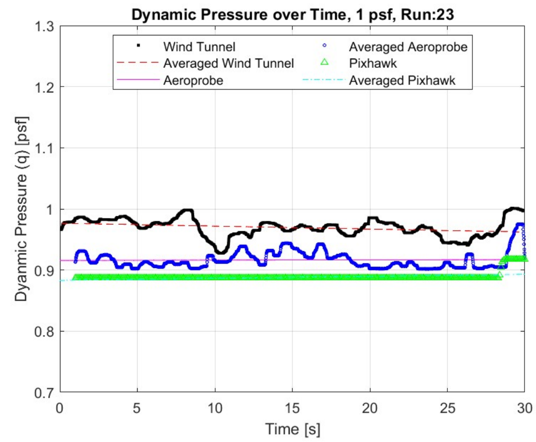
(f) 2.5-3-90 at 5 psf

Figure D4: 2.5-3-90

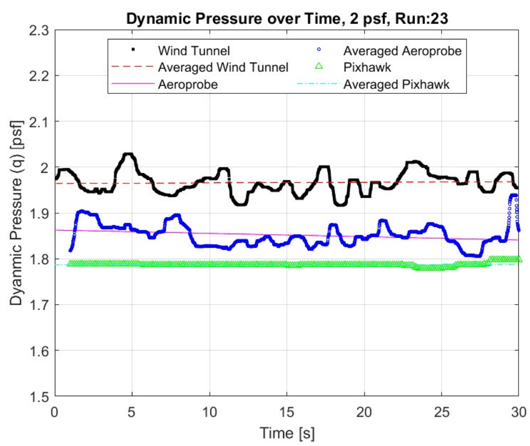
D.5 2.5-3-45



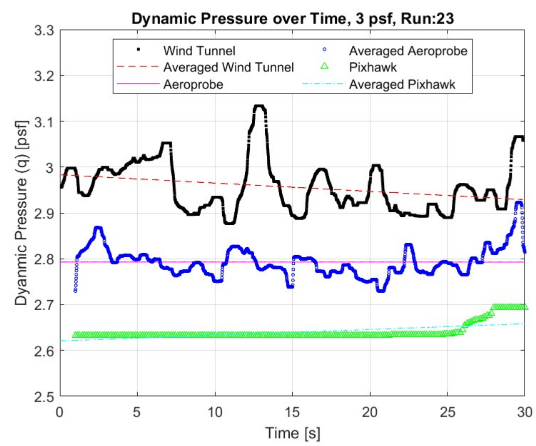
(a) 2.5-3-45 at 0.5 psf



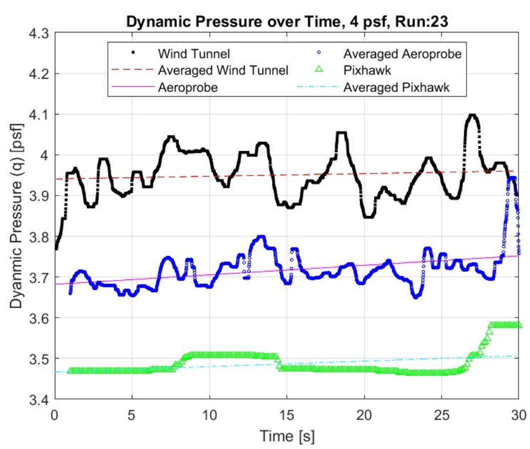
(b) 2.5-3-45 at 1 psf



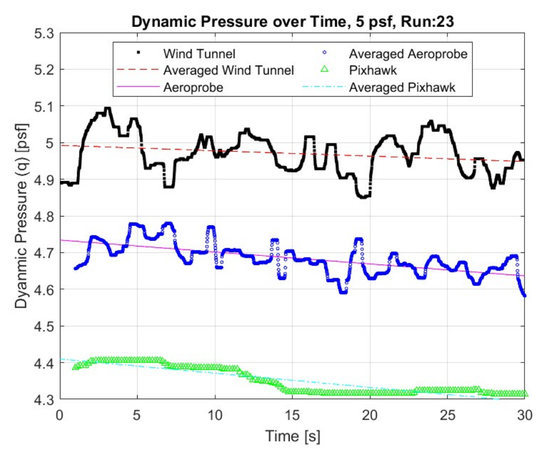
(c) 2.5-3-45 at 2 psf



(d) 2.5-3-45 at 3 psf



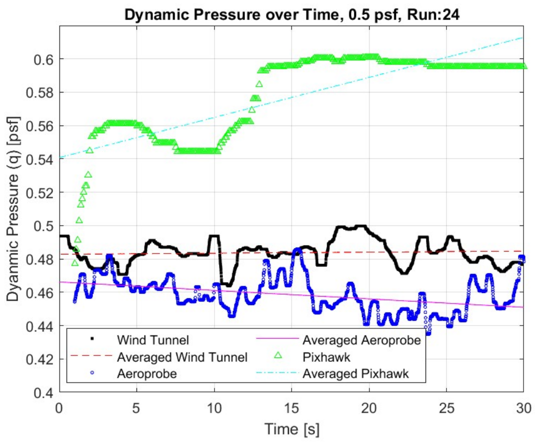
(e) 2.5-3-45 at 4 psf



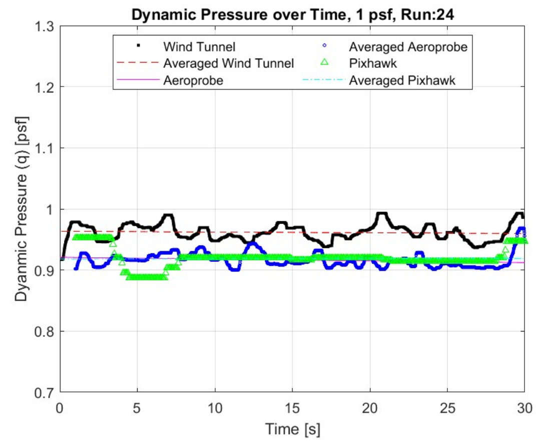
(f) 2.5-3-45 at 5 psf

Figure D5: 2.5-3-45

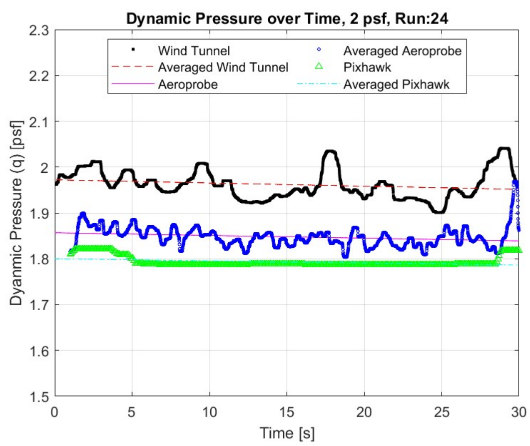
D.6 2.5-3-0



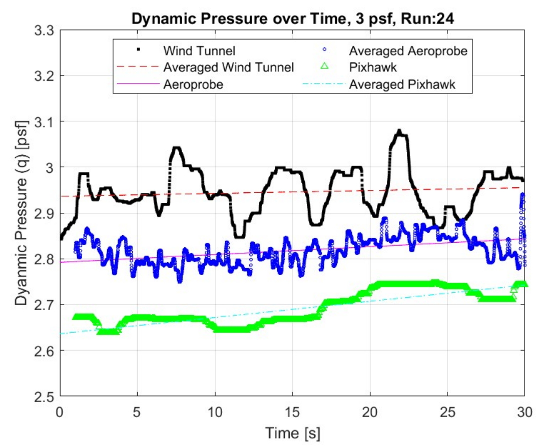
(a) 2.5-3-0 at 0.5 psf



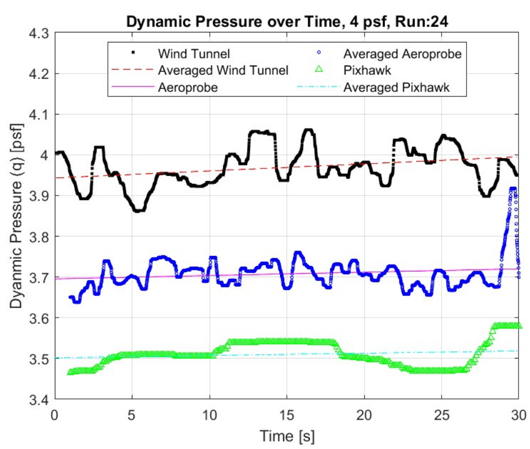
(b) 2.5-3-0 at 1 psf



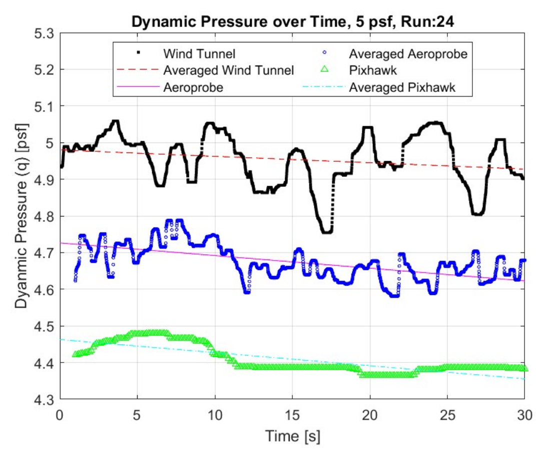
(c) 2.5-3-0 at 2 psf



(d) 2.5-3-0 at 3 psf



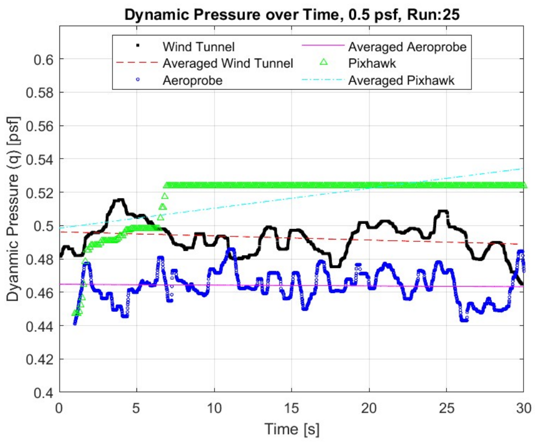
(e) 2.5-3-0 at 4 psf



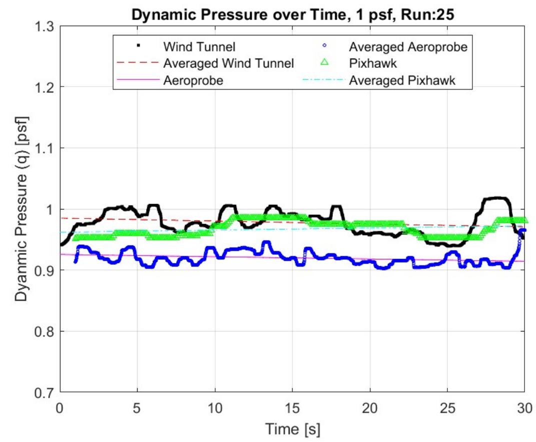
(f) 2.5-3-0 at 5 psf

Figure D6: 2.5-3-0

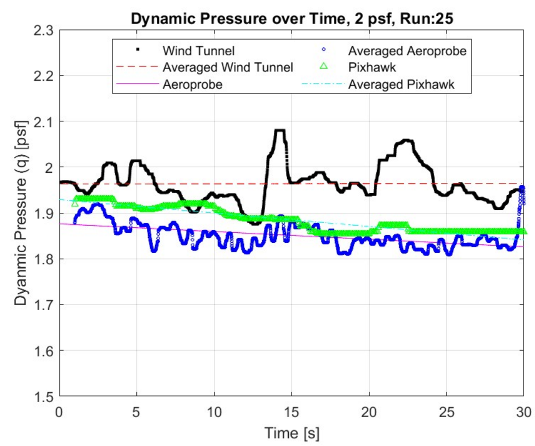
D.7 3.5-3-90



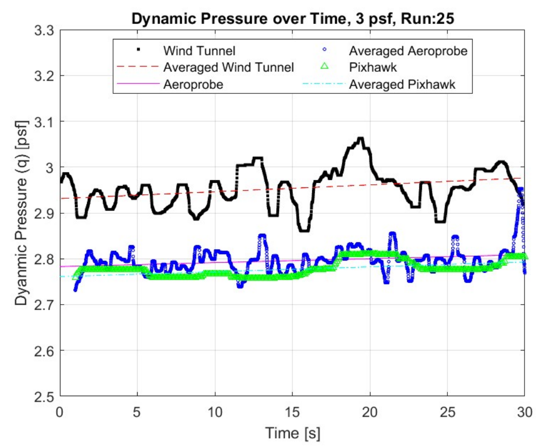
(a) 3.5-3-90 at 0.5 psf



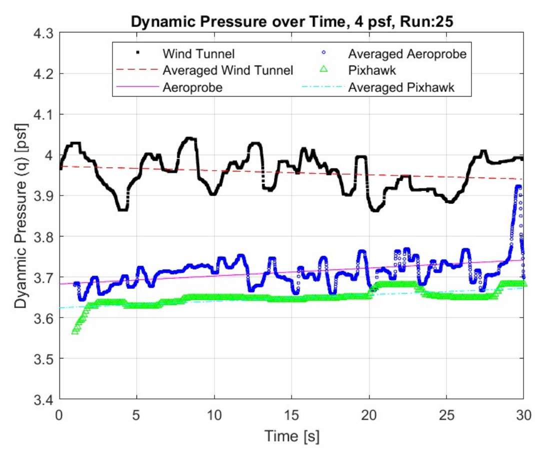
(b) 3.5-3-90 at 1 psf



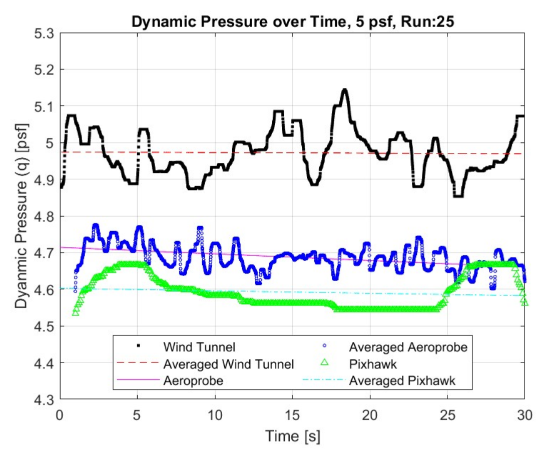
(c) 3.5-3-90 at 2 psf



(d) 3.5-3-90 at 3 psf



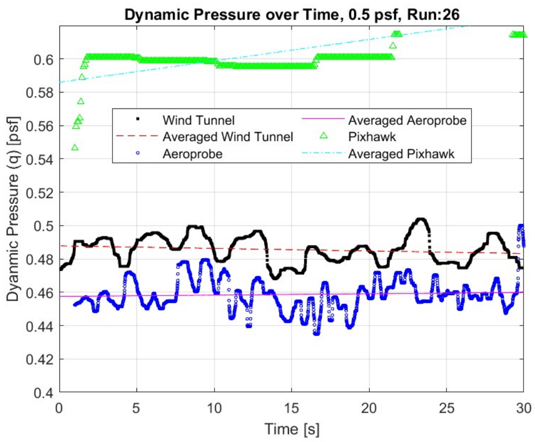
(e) 3.5-3-90 at 4 psf



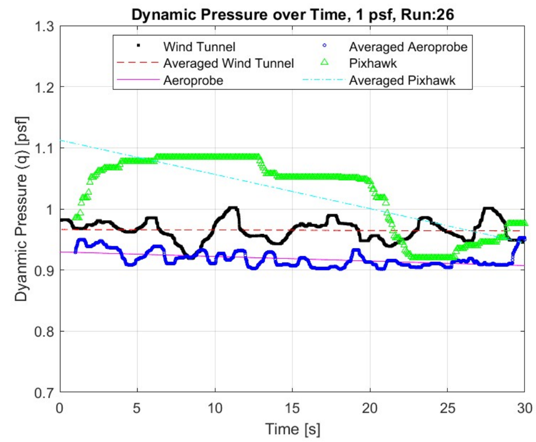
(f) 3.5-3-90 at 5 psf

Figure D7: 3.5-3-90

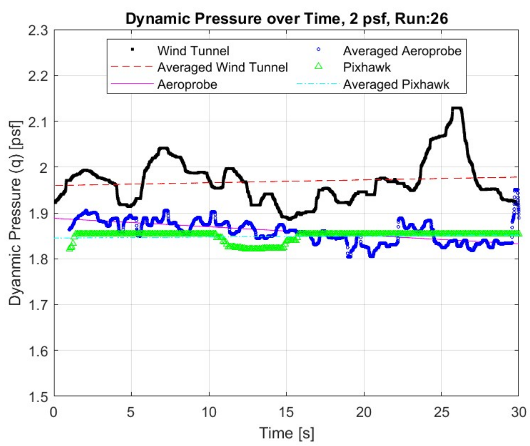
D.8 3.5-3-45



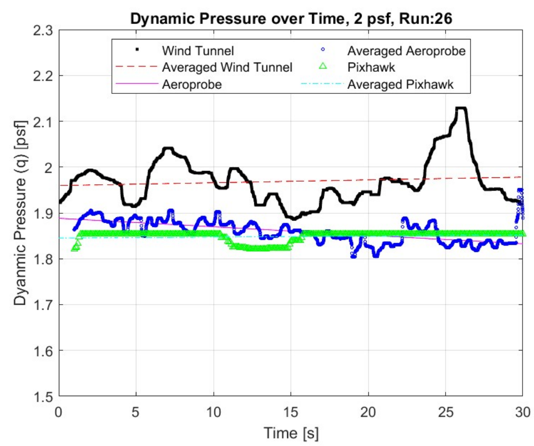
(a) 3.5-3-45 at 0.5 psf



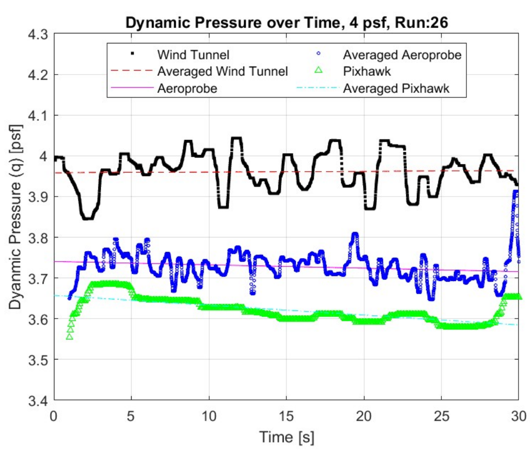
(b) 3.5-3-45 at 1 psf



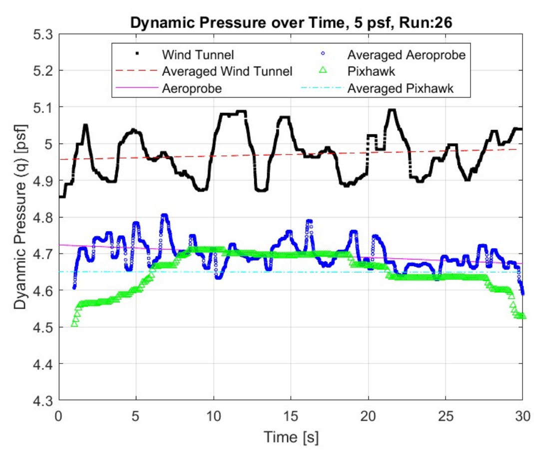
(c) 3.5-3-45 at 2 psf



(d) 3.5-3-45 at 3 psf



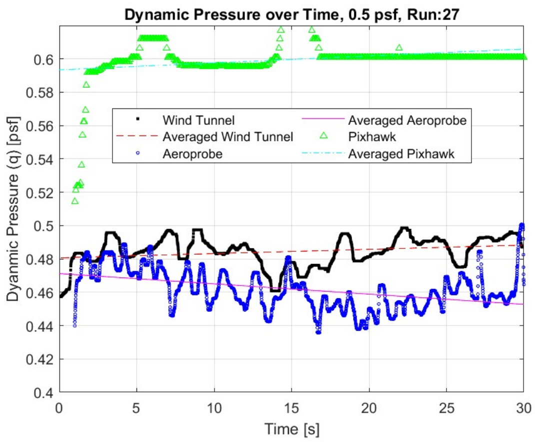
(e) 3.5-3-45 at 4 psf



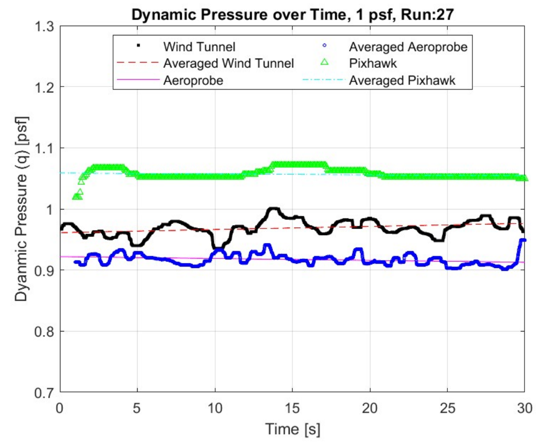
(f) 3.5-3-45 at 5 psf

Figure D8: 3.5-3-45

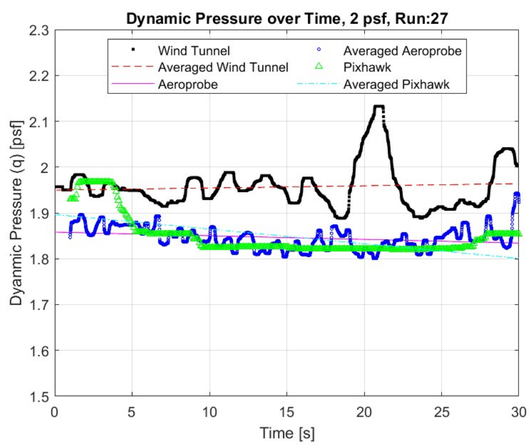
D.9 3.5-3-0



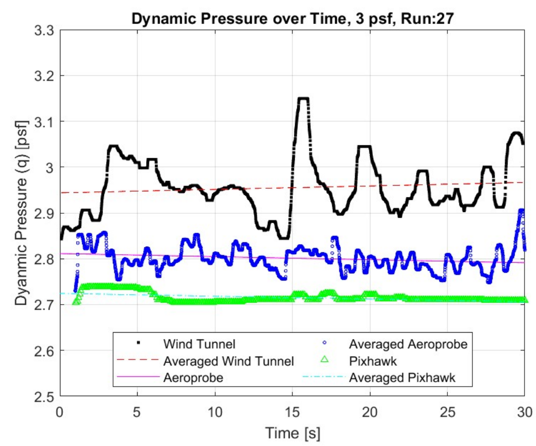
(a) 3.5-3-0 at 0.5 psf



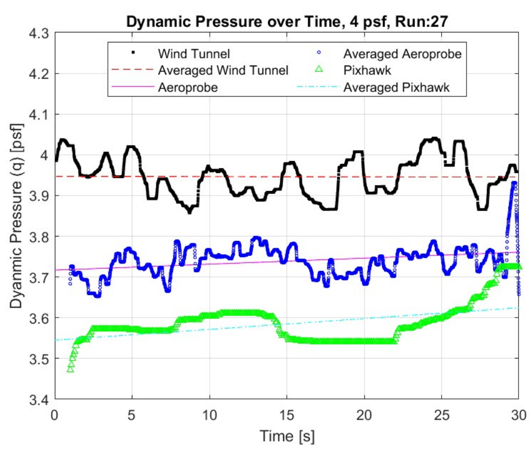
(b) 3.5-3-0 at 1 psf



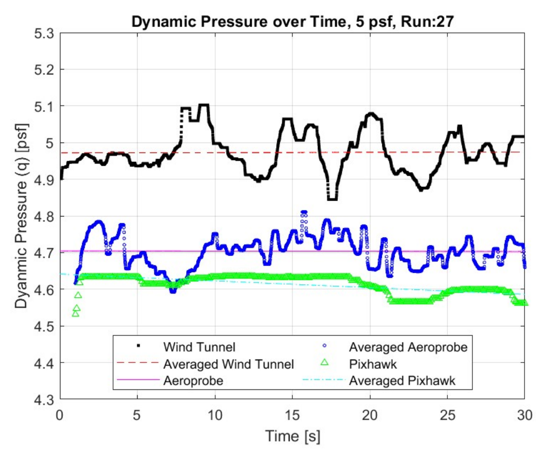
(c) 3.5-3-0 at 2 psf



(d) 3.5-3-0 at 3 psf



(e) 3.5-3-0 at 4 psf



(f) 3.5-3-0 at 5 psf

Figure D9: 3.5-3-0