The Modernization of a Long-Focal Length Fringe-type Laser Velocimeter

James F. Meyers[1*], Joseph W. Lee[2], Angelo A. Cavone[3], Mark T. Fletcher[2]

1: Analytical Services & Materials, Inc. - A Part of the ROME Group, Hampton, Virginia 23666, United States
2: NASA Langley Research Center, Hampton, Virginia 23681, United States
3: Alliant Techsystems, Inc, NASA Langley Research Center, Hampton, Virginia 23681, United States
* correspondent author: james.f.meyers@nasa.gov

Abstract A long-focal length laser velocimeter constructed in the early 1980's was upgraded using current technology to improve usability, reliability and future serviceability. The original, free-space optics were replaced with a state-of-the-art fiber-optic subsystem which allowed most of the optics, including the laser, to be remote from the harsh tunnel environment. General purpose high-speed digitizers were incorporated in a standard modular data acquisition system, along with custom signal processing software executed on a desktop computer, served as the replacement for the signal processors. The resulting system increased optical sensitivity with real-time signal/data processing that produced measurement precisions exceeding those of the original system. Monte Carlo simulations, along with laboratory and wind tunnel investigations were used to determine system characteristics and measurement precision.

1. Introduction

In the early 1980s a two-component, fringe-type laser velocimeter operating in co-axial backscatter was developed and constructed to investigate flow fields about fixed wing and rotorcraft models in the NASA Langley 14- by 22-Foot Subsonic Tunnel (Hoad *et al* (1983)), Figure 1. Commercially available components were integrated with custom optics to produce a system that would measure two components of velocity at focal distances from 2.4- to 7.6-m from 1.7-micron polystyrene latex (PSL) particles. The system was mounted on a traversing mechanism capable of moving the measurement volume ±1.0-m in the streamwise and vertical directions. Additionally a pan/tilt mirror was employed to align the optical axis along any selected angle within ±30-degrees to the tunnel centerline and ±10-degrees about the horizontal plane. The measurement volume was calculated to have a diameter of 200-microns with a length of 1.0 cm at tunnel centerline.

Figure 1.- Long-focal length laser velocimeter installed in the 14-by 22-Foot Subsonic Tunnel in 1982.

While the laser velocimeter has been used as a routine measurement system over the years, it required an expert in the technology to conduct flow field measurements. Since the system was located in the plenum area surrounding the test section which had environmental characteristics similar to those found outside the building, changes in temperature and pressure due to environmental and tunnel conditions resulted in laser misalignment and hence misalignment of the optical system. The signal processors were high-speed counters with a Laser Velocimeter Autocovariance Buffer Interface (LVABI) (Clemmons (1983), Cavone *et al* (1987)) providing the data collection, storage and transfer to the controlling minicomputer. In 1991 the counters were replaced with Frequency Domain Signal Processors to improve measurement accuracy, 1-percent of reading versus 2-percent with the counters (Meyers and Murphy (1990), and Hepner (1994)).

Although its use as a measurement system has declined in the recent past due to the development and implementation of Doppler Global Velocimetry and Large-Field PIV techniques, the LV system is still relied on for measurement accuracy validation of those planar techniques. The requirement for an expert in the technology to align and operate the system along with concerns regarding the reliability of 20 to 30-year old hardware further limited its use. The NASA Subsonic Rotary Wing Project recently sponsored an effort to modernize the laser velocimeter to make it more relevant to current research requirements. The goal was to remove as many optical components as possible from the harsh environment in the plenum and replace the dedicated signal processing and data acquisition electronics with systems that could be supported in the future. Further, the system must be easier to maintain and use so that it could be aligned and operated by test engineers and technicians that are not experts in the field of laser velocimetry. The resulting system must also meet or exceed measurement accuracies and capabilities of the original laser velocimeter.

2. Approach

The characteristics of the original, free-space optical system prohibited relocating any component, including the laser, to a remote, environmentally stable location. Thus the free-space components were replaced with a state-of-the-art fiber-optic based system. The only elements retained were the 300 mm-diameter zoom lens and the 400 mm-diameter pan/tilt mirror. These two elements along with two turning mirrors and the distal end of the fiber-optic probe shown in Figure 2 (pan/tilt mirror not shown) would be the only major optical components subjected to the environment in the tunnel plenum area. Alignment tools and jigs were incorporated in the system to easily establish proper optical alignment. A laser beam power monitor, also shown in Figure 2, was added to the system. The monitor incorporates four photo-diodes and is positioned behind the final turning mirror to provide the necessary feedback that would allow minor alignment adjustments to be made remotely during wind tunnel operation when personnel are prohibited from being in the plenum area. The laser, color splitting optics, receiver system, and proximal end of the fiber-optic probe shown in Figure 3 would be housed in a laboratory-type environment adjacent to the tunnel plenum.

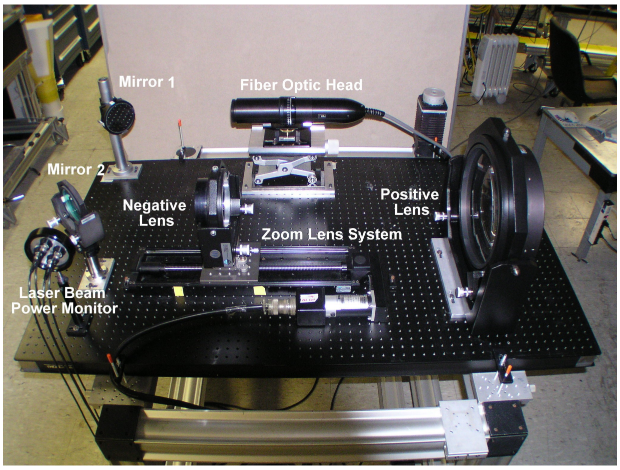

Figure 2.- Distal probe and zoom lens – section of the laser velocimeter located in the plenum.

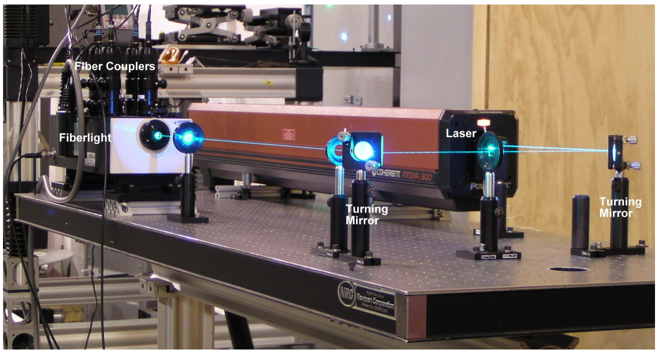

Figure 3.- Section of the laser velocimeter to be located in a laboratory environment (laser, color/beam splitting optics, photomultipliers, directing optics and fiber-optic couplers).

The concern that a failure in the signal processors, which contained components that were no longer available, would put wind tunnel testing at risk necessitated the replacement of the processors with equipment that could be supported both now and in the foreseeable future. The obvious approach would be to replace the processors and LVABI with current state-of-the-art laser velocimeter signal processors and data acquisition units. However, with the rapid advance in electronics, in a few years these processors may no longer be supported and wind tunnel testing would again be at risk.

An alternative approach based on the the method first used by Griskey *et al* (1975) was implemented. This method utilized off-the-shelf general purpose high-speed digitizers and data acquisition systems that were available at that time, along with a minicomputer to perform the signal/ data processing. While Griskey demonstrated the power of digitizing each signal burst and then Fourier transforming the captured burst to determine the signal frequency, his equipment was far too slow for production testing. Equipment is now readily available which has the speed and capacity for production testing so this approach provides a cost effective method that may even give measurement accuracies exceeding those obtained with specialized hardware developed for laser velocimetry applications. The resulting configuration for data acquisition and signal/data processing based on this method is shown in Figure 4. Since general

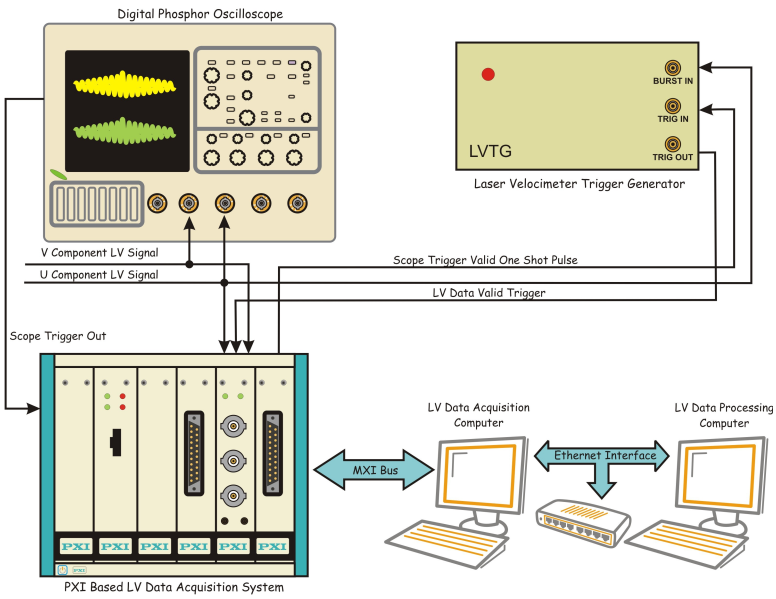

Figure 4.- Data Acquisition / Signal/Data Processing system hardware interconnection diagram.

purpose hardware used for acquisition is controlled by custom software operating in the LabVIEW environment and the signal/data processing is accomplished using software executed on standard personal computers, this approach should be easily supported in the future.

3. Performance Predictions

Although the above approach is attractive in several ways, there are numerous questions that must be answered before it can be accepted for use in a production wind tunnel. These questions are as follows: Can the fiber-optic based laser velocimeter provide the signal amplitudes/quality of the original system?; What signal conditioning electronics are required?; How long a burst record length is needed to obtain the same accuracy as the previous approach?; What is the most accurate method to measure signal frequency?; How long does it take to process the captured signals?; Can real-time data processing be performed?; and others. In order to obtain insight into the answers to these questions, the Monte Carlo simulation of a fringe-type laser velocimeter (Meyers and Walsh (1974), Meyers and Murphy (1990)) was modified to simulate the measurement of a synthetic flow using a laser velocimeter with the characteristics of the proposed system. As with any simulation, its value lies with its ability to accurately model the process being simulated, which in this case, is a signal burst generated by a particle passing through the measurement volume. Two signal bursts, one from a particle passing through the center and the other passing through the edge of the measurement volume, were captured with an analog storage oscilloscope in 1977, Figure 5. The captured signals were part of a study to validate the hypothesis by Mayo (1975) that signal bursts were a triply stochastic Poisson process. Photon pile-up can be clearly seen in the first signal burst along with its decay to photon limited amplitudes as the particle leaves the measurement volume. The second burst is entirely photon limited. The insight provided by this study led to the modification of the original simulation program (Meyers and Walsh (1974)) to obey Poisson statistics. The program was also modified to account for the complex electro-magnetic interactions of the two scattered wave fronts as a particle passes through the overlapping laser beams as described by Adrian and Earley (1975). The ability of the simulation to model both classic and photon-resolved signals is shown in Figure 6.

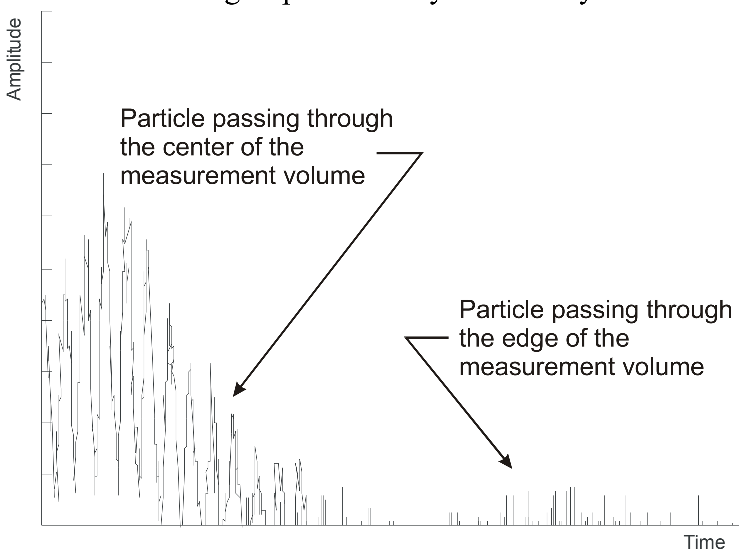

Figure 5.- Captured signal bursts from particles passing through the center and edge of a laser velocimeter measurement volume.

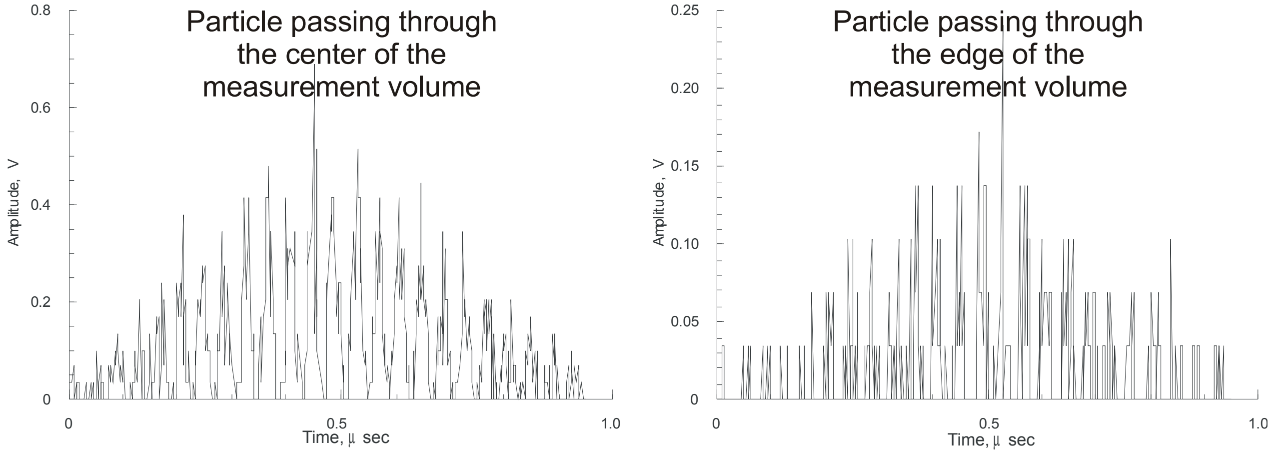

Figure 6.- Simulated signal bursts from particles passing through the center and edge of a laser velocimeter measurement volume.

The second portion of the simulation was to provide a flow field for the randomly generated particles. The velocity magnitude and horizontal and vertical flow angles are randomly selected based on Gaussian statistics set by means and standard deviations provided by the user. Each particle trajectory is randomly positioned within a vertical plane aligned along the optical centerline obeying uniform statistics in the vertical and horizontal directions. Particles whose trajectories pass inside the $1/e^3$ laser power locus within the vertical plane aligned with the optical centerline are considered selected and the U- and V-component signal bursts simulated. Since the component velocities are known for each particle, a direct comparison can be made between the *measured* velocities and the *actual* particle velocities. Thus the simulator could be used to evaluate signal processing schemes along with obtaining predicted signal bursts generated by the proposed optical system set to its various focal distances.

Based on the research reported by Meyers and Murphy (1990) and experimentally confirmed by Hepner (1994), frequency domain processing yielded the most accurate measurements of laser velocimetry signal frequencies. Additionally Fast Fourier Transforms provide a way to rapidly determine a signal frequency on a general purpose computer. Thus FFT processing was selected as the core of the signal processing algorithm. The next step was to determine the signal frequency based on the frequency spectra of each captured signal burst. The approach used during processing was not to consider the frequency spectra as a continuum, but as a series of impulses separated by the frequency resolution as determined by the length of the captured signal trace. In this view, the spectral peak containing the signal frequency is analogous to a histogram, with the amplitude of each impulse being proportional to the amount of spectral energy contained in that frequency bin. The following six methods, all based on this model, were evaluated by direct comparison, signal burst-by-signal burst, of the measured frequency with the actual signal frequency of that burst.

Peak	Frequency of the peak location
Gaussian	Peak of a Gaussian fit of the peak location ± 1 frequency bin
Histogram (3)	Evaluate the peak location ± 1 frequency bin as a weighted histogram

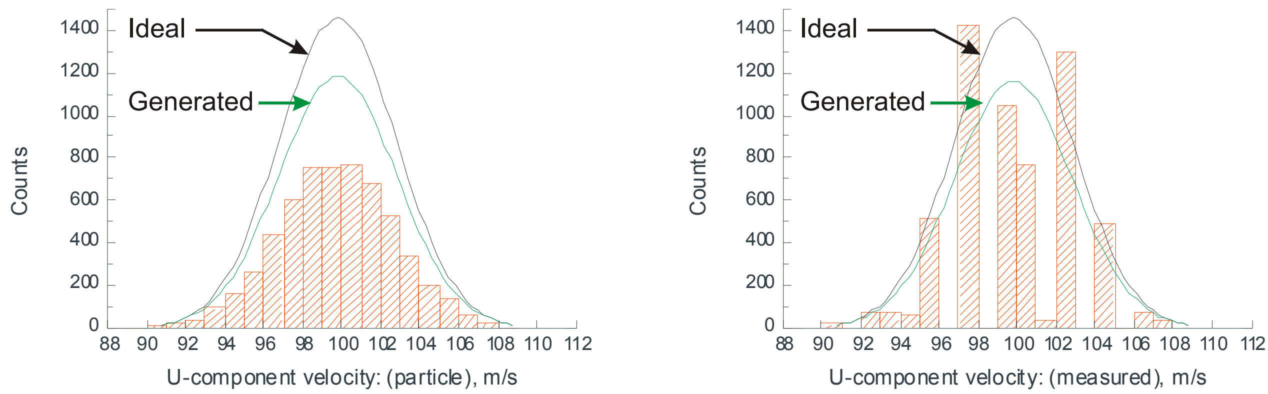

Figure 7.- U-component distributions from particles that yielded velocity measurements based on the particle velocity determined by a Gaussian fit of the peak signal frequency, total number of particles = 5,909 out of 10,000.

Histogram (5)	Evaluate the peak location ± 2 frequency bins as a weighted histogram
Half Power	Evaluate the spectral peak as a weighted histogram with the frequency limits set by a threshold equal to half of the peak amplitude
True Half Power	Evaluate the spectral peak as a weighted histogram with the frequency limits set by an interpolation to exactly half of the peak amplitude

The simulator was set to a mean velocity magnitude of 100.0 m/s with a standard deviation of 3.0 m/s, and a mean vertical flow angle of 0.0 degrees with a standard deviation of 4.0 degrees. A single data ensemble of 10,000 signal bursts was processed by each method. The signal bursts were Bragg shifted by 40 MHz and sampled at a rate of 1.0 GHz for a sample length of 10.0 μsec providing an FFT sample length of 8192. All six methods yielded mean errors of approximately 0.11 m/s (0.025% of reading (40 MHz (Bragg) + 11.5 MHz (Doppler)). As expected the Peak and Gaussian methods produced the highest standard deviations of measurement error, 0.157% and

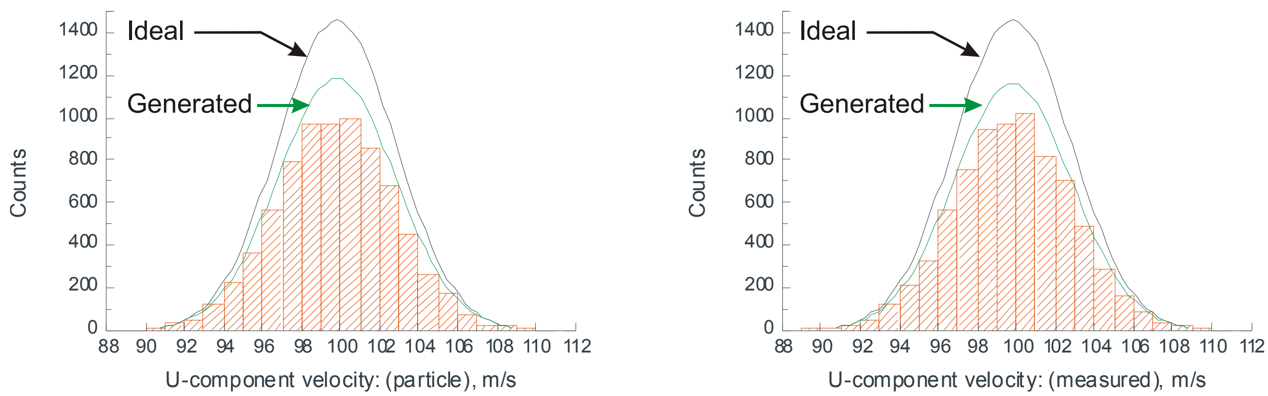

Figure 8.- U-component distributions from particles that yielded velocity measurements based on the particle velocity determined by a 5-bin histogram weighted average of the peak signal frequency, total number of particles = 7,633 out of 10,000.

0.11% of reading respectively. The other methods produced standard deviations of measurement error at approximately 0.07% of reading. While these measurement precisions all surpassed the original system's capabilities, due to the long sample length (8192 vs 256 (frequency domain processor) vs 2 (high-speed counter)), the true precision can be seen by comparing the measured U-component velocity histogram with the actual particle velocity histogram. As shown in Figure 7, the classic Gaussian estimation produced significant differences in the histogram, whereas the Histogram (5) method produced the most accurate results, Figure 8. Additionally, the Histogram (5) method accepted 7,633 signal bursts whereas the Gaussian method accepted only 5,909.

While the precisions obtained using this approach were quite impressive, the simulation also showed that the accuracy was not. If the flow velocity was oscillating in a sinusoidal manner and all data was collected during the first half of an oscillation, the measurement precision might be excellent, but the measurement accuracy was not. Thus there should be a feedback mechanism to let the user know when the measurement ensemble is sufficient to have reached statistical stationarity, and thus contain a complete sample of the flow characteristics at that measurement location. This feedback should be available with ANY instrument. Consider a method that

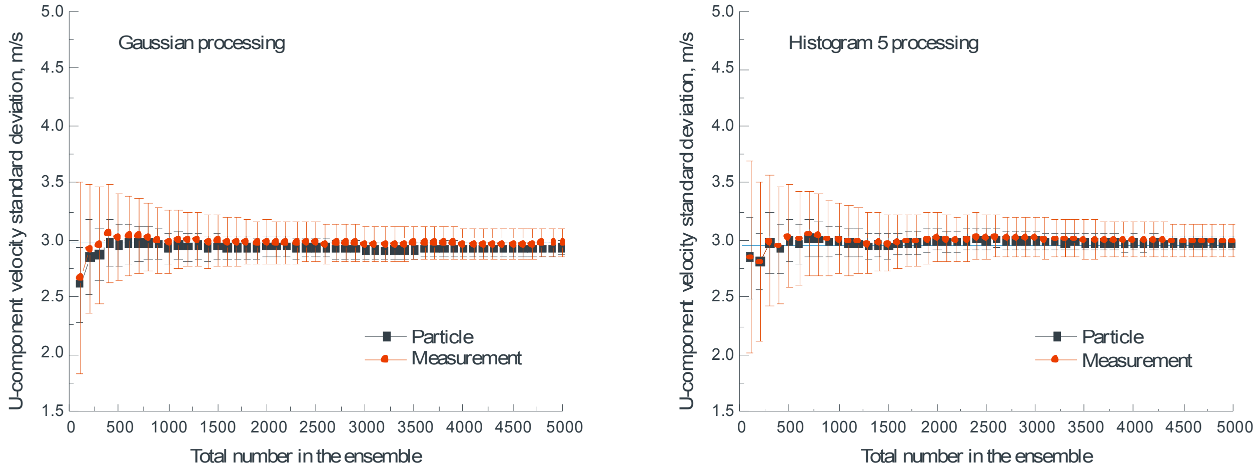

Figure 9.- Statistical convergence of the U-component standard deviation based on Gaussian and Histogram (5) processing.

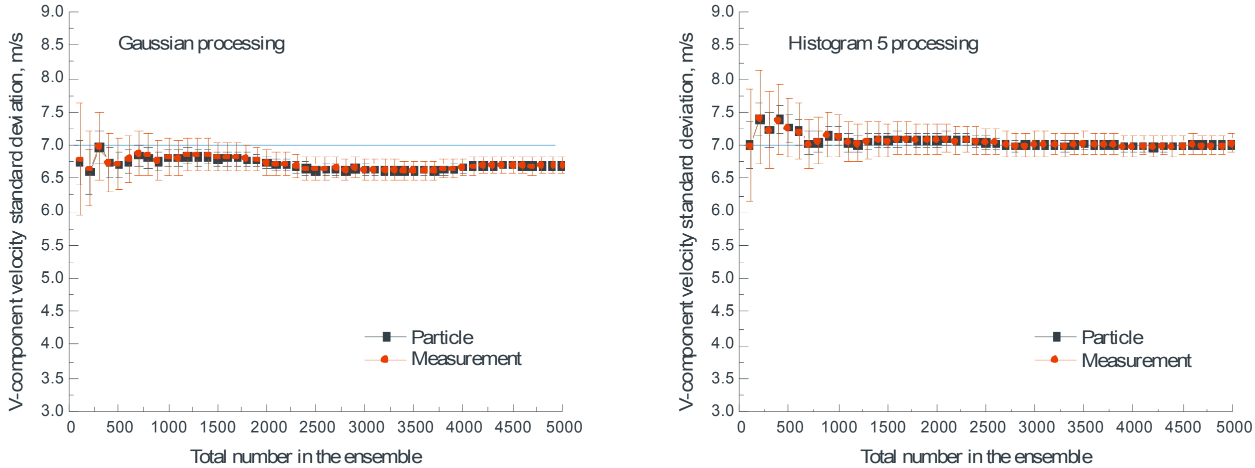

Figure 10.- Statistical convergence of the V-component standard deviation based on Gaussian and Histogram (5) processing.

computes the mean and standard deviation of the first 100 measurements, followed by computing the statistics of an ensemble containing the first 100 and the next 100, followed by an ensemble of the first 100, second 100, and the third 100, etc., as an indicator. For example, the U-component standard deviations (along with corresponding statistical uncertainty error bars) of particle velocity, along with measurements obtained using the Gaussian and Histogram (5) processing methods, are shown as a function of ensemble size in Figure 9. Both processing methods appear to reach statistical stationarity of the input U-component standard deviation of 3.0 m/s, in about 1000 measurements, with the measurement statistics faithfully tracking the actual velocity statistics. However, the V-component results, Figure 10, show that the Gaussian method produced a significant error by not reaching the input V-component standard deviation of 7.0 m/s even though it matched the convergence of the accepted particle velocity standard deviations, whereas the Histogram (5) method produced accurate measurements at approximately the same number needed for the U-component.

From these simulations, the Histogram (5) approach was selected as the best overall method to complete the signal/data processing software. The software program will determine the U- and V-component signal burst frequencies, determine the interarrival times between bursts, and compute the U- and V-component velocities, velocity magnitudes, and flow angles for 10,000 captured signal bursts along with computing all coincident and non-coincident statistics in approximately 20 seconds. This processing time was sufficient to be considered as real time, thus it was not necessary to reduce the 8192 signal burst record length, even though about 60-percent of the processing time was required to transfer the captured signal bursts from the disk drive to memory. The program statistics are presented to the user in tabulated form on the screen, along with statistical convergence plots (mean and standard deviation), and histogram plots of U- and V-component velocities, velocity magnitude and flow angle. A log file is also maintained containing this information along with the velocity/flow angle for every particle measured. Finally, the captured signal burst records, along with auxiliary data (e.g., conditional sampling data, free stream conditions, etc.), are stored on hard drive for later study.

4. Working Toward the Real World

A series of laboratory investigations using a 50 m/s flow from a 50 mm diameter jet were conducted to determine the performance characteristics of the optical system. During the course of these investigations, the size of the PSL particles was reduced to 1.0-micron, and focal distances from 3.0- to 8.3-meters yielded signals that were successfully processed. Although the signal levels were reduced by a factor of three, as compared to the 1.7-micron PSL particles, the levels and signal-to-noise ratios were sufficient for accurate measurements. The only signal conditioning found necessary was the removal of the pedestal by the electronics contained in the commercial fiber-optic based sub-system. The inclusion of an electronic frequency down-mixer, typically used to increase measurement accuracy, actually reduced measurement precision, and thus was not incorporated. The measurement volume size (150-microns in diameter, 5.0 mm long at a focal distance of 4.6-m, sufficient to reach the tunnel centerline from the plenum area) was determined

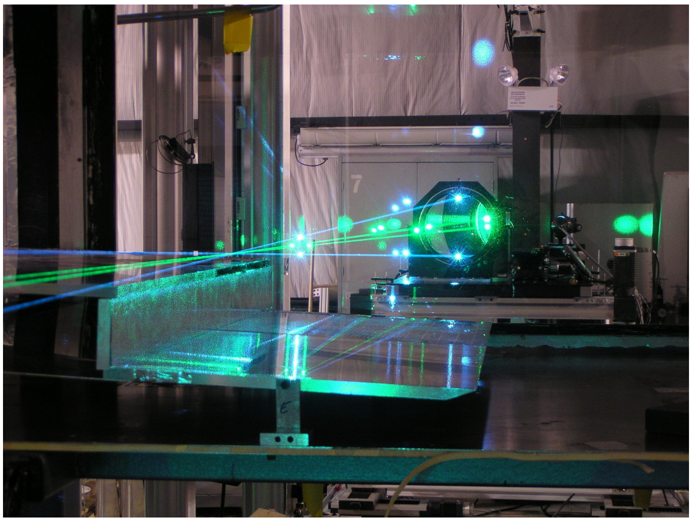

Figure 11.- Laser velocimeter installed in the research tunnel with the backward-facing model.

based on signal strength as a function of the axial location of a spinning 0.13-mm diameter wire. In addition the effects of direct backscatter flare from various surface treatments were investigated. This involved moving a test surface along and normal to the optical centerline until the noise caused by laser flare from the surface prohibited the signal processing software from obtaining velocity measurements from 1.0-micron particles passing through the measurement volume. The surface treatment with the best results, Aeroglaze®*, yielded a minimal approach distance from the center of the measurement volume of 50 mm at a focal distance of 3 m, and 250 mm at a focal distance of 6.8 m. Aeroglaze® is a polyurethane coating with a flat black finish designed for aerospace applications.

After the system characterization was completed in the laboratory, the laser velocimeter was installed in a low speed research wind tunnel with a 0.71- by 1.02-m by 3.05-m long test section, Figure 11. Two backward facing step models were tested with one having a step height of 38 mm and the other 89 mm. The tunnel was set to a free stream velocity of 45 m/s. The laser velocimeter was operated at a focal distance of 4.5-m (limited by the available space adjacent to the test section). The 38-mm step height model, test conditions and measurement grid were identical to those employed during a previous investigation in the same facility using Laser Induced Thermal Acoustics (LITA) (Hart *et al* (2000)). The comparison of the velocity measurements obtained using a particle based technique with those from a molecular based technique yielded expected and unexpected results. The mean velocity profiles had acceptable comparisons considering the differences in the techniques and the more than ten years between the two investigations, Figure 12. The profiles showed good agreement in the free stream and in the recirculating area, but in the shear region the laser velocimetry data shows evidence of the expected particle sampling bias toward the higher velocities of free stream. The standard deviations, though similar through the free stream and shear regions, deviated greatly within the recirculation region. One would expect a higher standard deviation in the shear region than observed by LITA because of sampling bias. Conversely, it would be expected that the standard deviation would be very low in the recirculation region because little turbulence is produced, as indicated by the LITA measurements. Thus it appears that the particles are being affected by aerodynamic forces not evident in the molecular flow measurements in this region. Although the physics governing LITA differs from laser

* www.lord.com/products-and-solutions/coatings/product.xml/611

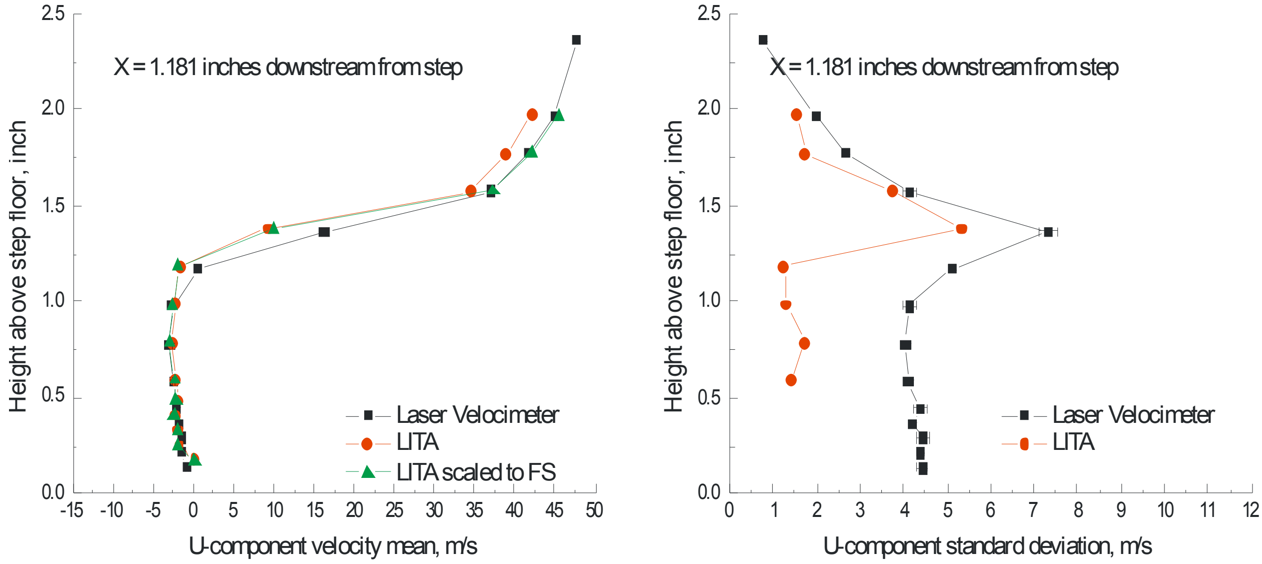

Figure 12.- Vertical U-component velocity profiles 0.8 step heights downstream of the 38-mm backward-facing step obtained with the laser velocimeter and earlier LITA measurements.

velocimetry, the optical configuration, the data acquisition hardware/software implementation, and signal/data processing methodologies/software were nearly identical, thus reinforcing the thought that particle motion was being affected. Further, the standard deviation characteristics shown in Figure 12 remained throughout the flow field downstream of the backward facing step for both step heights.

5. Concluding Remarks

A long-focal length laser velocimeter constructed over 30-years ago has been modernized with state-of-the-art fiber-optic components, general purpose high-speed digitizers incorporated in a standard modular data acquisition sub-system with custom data acquisition control software operating within the LabVIEW environment, and custom signal/data processing software executing on a standard desktop personal computer. System performance exceeded the original laser velocimeter capabilities with regard to focal distance, minimum particle size, and measurement precision, yet still maintained real time signal processing capabilities. Additionally, real-time data processing affords the user with final results during a flow field investigation that would provide insight into the flow characteristics as the investigation continued. Monte Carlo simulations along with laboratory and wind tunnel testing found that measurement precision was better than 0.1-percent, but measurement accuracy was ultimately dependent on whether sufficient signal bursts were acquired to faithfully describe the flow velocity statistics contingent on the attainment of statistical stationarity conditions within the measurement ensemble. Additionally, wind tunnel investigations of the flow downstream of backward facing steps have shown excellent agreement with measurements of mean velocity obtained with LITA, including the expected sampling bias characteristics within the shear region. However, comparisons of the standard deviation show large differences in the separation region. The cause of these differences is unknown and will require further study.

6. Acknowledgement

Valuable contributions to this work through the transfer of LITA understanding and raw wind tunnel data by Greg C. Herring is gratefully acknowledged.

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