Investigation of Particle Sampling Bias in the Shear Flow Field Downstream of a Backward Facing Step

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Abstract

The flow field about a backward facing step was investigated to determine the characteristics of particle sampling bias in the various flow phenomena. The investigation used the calculation of the velocity:data rate correlation coefficient as a measure of statistical dependence and thus the degree of velocity bias. While the investigation found negligible dependence within the *free stream* region, increased dependence was found within the boundary and shear layers. Full classic correction techniques over-compensated the data since the dependence was weak, even in the boundary layer and shear regions. The paper emphasizes the necessity to determine the degree of particle sampling bias for each measurement ensemble and not use generalized assumptions to correct the data. Further, it recommends the calculation of the velocity:data rate correlation coefficient become a standard statistical calculation in the analysis of all laser velocimeter data.

Introduction

The inability to perfectly measure a physical process can be attributed to the lack of precision and accuracy of the measuring device and the affect of external influences on the overall accuracy of the measurement. Early instrumentation systems suffered from such poor precision, external influences were generally ignored. The advent of

analog-to-digital converters helped the precision by reducing the sources of variability error inherent to analog systems to just the sensor. The converters, however, added new problems by measuring a process only at discrete times requiring statistical estimates of that process, continuous tracking no longer possible. With the increased precision, external influences now became important, especially the added influence of the digital sampling. Mathematicians tell us there is no influence on the measurement statistics if the sampling is independent of the physical process. Thus one may obtain quality measurements by uniformly sampling a process because the driving digital clock is independent of the process being sampled. The mathematicians further tell us that uniform sampling is not required, any clock with independent statistics will do, e.g., random walk, Gaussian, Poisson, etc.

During the advent of laser velocimetry, analog measuring techniques such as spectrum analyzers and frequency lock loops were used to measure the near continuous signals obtained from water flows. The digital frequency tracker was developed by using an analog-to-digital converter to sample the output from the frequency discriminator in a frequency lock loop. The increased control of the feedback loop by digital circuits operating on digital signals increased measurement precision and even reduced the requirement of near continuous input signals. The next logical step was to remove the frequency lock loop and directly digitize the individual signal burst obtained from a single particle passing through the laser velocimeter sample volume. Extensive studies of particle passage statistics indicated that their arrivals obeyed Poisson statistics regardless of the average rate. Remembering that the mathematicians stated that Poisson statistics were an independent sampling process, researchers placed their laser velocimeters in air flows and reduced their seeding rates to tolerable levels with full confidence that this new technique was the panacea of measurement techniques.

In 1973 McLaughlin and Tiedermann (1973) of Oklahoma State University noticed their mean velocity measurements of a turbulent boundary layer were consistently higher than theory predicted. Seeking to determine the cause of this discrepancy, they reasoned that a uniformly seeded volume would yield a greater number of particle passages per unit time through the sample volume as the velocity increased. Since the number of measurements of the higher velocities in the turbulent flow would be greater than the number from lower velocities, the statistical velocity mean would be weighted toward the higher velocities. Applying a weighting function of inverse velocity to the statistical calculations, their measurements agreed much closer to theory.

Now convinced that mathematicians should be barred from the real world, researchers began to apply the inverse velocity correction to all laser velocimetry data. It wasn't long before correction schemes were being developed faster than researchers could digest them. Techniques such as two-dimensional weighting, true velocity magnitude weighting, residence time weighting, and time averaging were being developed as the *true* correction scheme. The only universally accepted truth was that all laser velocimeter data was in error and needed correcting.

Back to the Basics

Stevenson, Thompson, and Roesler (1982) from Purdue University reasoned that if a particle was present every time the signal processor was ready to make a measurement, true unbiased measurements could be made. This resulted in a uniform sampling process much the same as obtained from digital frequency tracker measurements of water flows. Using a low speed, turbulent air flow and varying the seeding rate from 100 to 20,000 particle passages per second, a seeding limited sampling to processor limited sampling transition was made. The arithmetic averages of the measured ensembles as a function of data rate are shown in Figure 1. These results show a clear change in velocity from high to low as the data rate increased. Unfortunately, this data was used to *validate* the two-dimensional correction scheme ignoring the influence of statistical mathematics.

In 1984 Meyers and Wilkinson (1984) from NASA - Langley Research Center were tasked to prove that the laser velocimeter could be used to make turbulence intensity measurements of flow fields with acceptable accuracy. The test was conducted in the jet from a fully developed turbulent pipe flow using an orthogonal three component laser velocimeter with a hot wire placed 2 mm downstream of the sample volume to serve as the measurement standard. The hot wire was calibrated in the particle laden (0.5 micron polystyrene) flow against the laser velocimeter mean velocity measurements. The hot wire output was digitized with each measurement converted to velocity through a spline fit calibration curve with the resulting ensemble statistically analyzed in the manner used for the laser velocimeter data. The 15 m/s flow was seeded sufficiently to yield an average data rate of 2,000 samples per second. True velocity vector measurements by the three component laser velocimeter operating in full coincidence indicated an on-axis flow with small angular scatter until the entrained region was reached where the flow deviated slightly outward and the scatter increased to approximately ±10 degrees. The local turbulence intensity at this point was in excess of 30 percent. Thus the flow was one dimensional through the operating envelope of the hot wire. With the

test conditions well defined, comparative testing began. Radial scans were made at several downstream locations from the exit of the jet. The local turbulence intensity values compared well within the core region of the jet, but deviated greatly in the entrained region, Figures 2 and 3. Attempting to improve the comparative measurements, the one-dimensional weighting factor was applied to the laser velocimeter data, Figures 2 and 3. Curiously, the comparisons within the core became worse while the comparisons in the entrained regions improved. This trend continued in all radial scans.

Although it may seem that the Purdue and NASA investigations are totally unrelated, they both point toward the fundamental statistical mathematics which define the phenomenon known as *velocity bias*. The Purdue investigation measured the flow in the shear region downstream of a backward facing step. This flow is composed of two parts: flow from above the step and flow recirculated within the separation zone. One would expect the flow from above the step to be approximately free stream with consistent seeding while the recirculation flow would be slower with less seeding. This flow field would yield measurements fitting the classic description of velocity bias even though the cause is far from the basic assumption of uniform spatial seeding. The jet flow exhibits similar properties in the entrained region where fast, heavily seeded air from the pipe mixes with slow, lightly seeded entrained air. Again the classic description of velocity bias without uniform seeding. Since the correction procedure works, should we really care about the reason?

But the correction doesn't work. Consider the data when the signal processor was saturated in the Purdue investigation and the worsening comparison when the correction was applied to the data from the core of the jet. Remember the mathematicians said that independent samples of a process does not modify the ensemble statistics. The saturated signal processor is a classic case of uniform sampling, thus insuring independence of the sampling from the process being measured. Therefore the velocity measurements to the right in Figure 1 are indeed correct. The measurements of the flow in the core region of the jet were made at a rate far from saturation of the signal processor and thus obeyed Poisson statistics. Since the particles were added 66 pipe diameters upstream of the jet, full mixing should yield a uniform spatial distribution within the fully developed turbulent flow. Why doesn't the correction work? Maybe the mathematicians were correct after all. A calculation of the statistical correlation coefficient between the measured velocity and the data rate would show their degree of dependence. The standard correlation coefficient between any two processes is defined by equation 1:

$$C = \frac{<U - u_i><R - r_i>}{\sigma_u \ \sigma_r}$$

(1)

where in this case U is the statistical mean velocity from the selected measurement ensemble and u_i is the ith velocity during the shortest period of time considered to be independent from other times. This is typically referred to as the flow correlation time. R is defined as the statistical mean data rate during the acquisition of the selected measurement ensemble and r_i is the data rate during the ith flow correlation time. The simultaneous measurement of velocity with the hot wire provided the data necessary to determine the flow correlation time for each measurement ensemble in the radial scan. The velocity time history obtained with the laser velocimeter was divided into flow correlation times and the instantaneous velocities and rates calculated. Applying these values to equation 1 and normalizing by the standard deviations of velocity and data rate, the correlation coefficients were determined. The resulting coefficients, plotted in Figure 4, indicate an independent sampling process in the center of the flow since the coefficients are near zero, and a dependence in the entrained region since the coefficients are greater than zero. Therefore the measurements within the core of the flow are indeed independent and the statistics should not be corrected whereas the measurements within the entrained flow are not independent and their statistics should be modified.

The Correction Schemes Continue

The Purdue and NASA investigations clearly illustrate that the simple correction schemes previously proposed are not applicable because they are based on the general assumption of uniform spatial seeding. These two investigations illustrate that this assumption is not generally valid and even when it is, the sampling may still be independent and thus not requiring correction. These investigations indicate that any correcting scheme must be based only on characteristics contained within the measurement ensemble being processed.

The first approach to be based only on the ensemble characteristics was the sample and hold processing technique developed by Dimotakis (1976) (backward step algorithm) and Edwards and Jensen (1983) (forward step algorithm). This technique develops a continuous velocity time history by holding a velocity measurement until the next velocity measurement is made in the manner of a sample and hold circuit. This velocity time history is then uniformly sampled at an arbitrary rate to develop the flow statistics. By uniformly sampling the time history, the particle arrival statistics are nullified and the

resulting measurement statistics are correct. While not requiring the extremely high data rates as the saturated signal processor approach, the sample and hold method should have a data rate ≥10 measurements per flow correlation time to fully describe the velocity time history. Since the required data rate is dependent on the flow correlation time at each point in the flow, a method needs to be developed to estimate the correlation time either during data acquisition or from the acquired data ensemble.

If it is assumed that the flow velocity remains near a given value during the flow correlation time, a method for estimating that correlation time can be developed as follows. Divide the velocity range of the selected data ensemble into ten velocity bins and overlay these bins on the velocity time history. Based on the assumption, velocity measurements made within a flow correlation time should remain in the same velocity bin, whereas measurements in successive flow correlation times probably will be in other bins. Thus an estimate of the flow correlation time may be obtained by calculating the average residence time for the flow velocity to remain within a bin. Testing this technique using data from the turbulent jet indicated that the average residence times were approximately 20 percent of the correlation times obtained from the hot wire. The required data rate can now be determined for the sample and hold technique.

Instead of adjusting the particle generator, it may be easier to use the flow correlation time and the knowledge that measurements in successive correlation times are independent to develop a new technique to insure statistical independence of the data. A single velocity measurement within a correlation time should represent the flow velocity during that time and additional measurements give an indication of the particle arrival rate statistics for that velocity. Thus a second interrogation of the velocity time history can yield an ensemble of independent velocity measurements and the particle arrival rate as a function of flow velocity. The method, developed by Edwards and Meyers (1984), begins by incrementing the velocity bin corresponding to the first particle velocity measurement. The time history is then interrogated for one flow correlation time following that measurement and the number of measurements determined regardless of their velocity. The velocity bin corresponding to the first particle velocity measurement in the arrival rate histogram is incremented by this number. The particle velocity measurement following the flow correlation time then becomes the first particle and the above procedure repeated, Meyers (1988). The process continues throughout the velocity time history generating a velocity histogram of independent measurements and a particle arrival rate histogram. The particle arrival rate histogram is then normalized by the velocity histogram to

yield the average number of particle arrivals as a function of velocity. If classic velocity bias were present, the particle arrival rate histogram would be a linear function rising with increased velocity. This would also correspond to a positive correlation coefficient between velocity and data rate. If the measurements were truly independent such as a uniform sampling, the particle arrival rate histogram would be a horizontal line and the correlation coefficient would be zero. If the slower flow in a mixing region was the heavier seeded, the particle arrival rate histogram would be a linear function decreasing with increased velocity and the correlation coefficient would be negative. Finally normalizing the velocity histogram by the particle arrival histogram yields a velocity histogram with all particle arrival rate biases removed.

Comparisons of differences between the original velocity measurements, one-dimensional correction, and histogram data processing with the hot wire measurements along a radial scan of the pipe flow jet, shown in Figure 3, indicate their relative merits. The corresponding correlation coefficients between velocity and data rate, shown in Figure 4, indicate the degree of velocity bias present in each measurement ensemble. Clearly the histogram data processing method maintains the best overall comparison with the hot wire data. It would be interesting to make these comparisons on the data obtained from the Purdue University tests shown in Figure 1, but the data no longer exists in raw form. Therefore a backward facing step has been constructed and the flow field remeasured.

Experimental Apparatus

The backward facing step facility, illustrated in Figure 5 and shown in Figure 6, is a suction facility with air being pulled through a single screen and honeycomb followed by four additional screens down a flat section 16 step heights long to a step expansion of 2:1 and an aspect ratio of 12:1. The inlet flow had a free stream velocity of 4.5 m/s and a turbulence intensity, measured by hot wire of 1.2 percent. The Reynolds number was 650 based on the momentum thickness of the boundary layer at the step. The Reynolds number based on step height was 22,200 and the displacement thickness of the boundary layer at the step was 0.35 step height. The 0.8 micron polystyrene seed particles were injected via atomization of a 50:50 mixture of ethanol and water in the air being pulled into the facility. Oscilloscope observations of the signal bursts indicated only monodisperse particles were passing through the measurement volume.

The laser velocimeter, shown in Figure 6, was a four component system using a single Argon ion laser. The 488.0 nm line was selected and input to fiber optics and transmitted to a single component system located just downstream of the final screen. This fixed system measured the velocity along the centerline of the facility and provided the reference free stream velocity and data rate measurements and baseline particle arrival statistics. The remaining three components using the 514.5 nm, 496.5 nm, and 476.5 nm lines comprised the measurement system. The measurement system, illustrated in Figure 7, used orthogonal transmission optics rotated 45 degrees to obtain direct three component measurements through a single window. A single optical receiver, using chromatic filtering for component separation, located perpendicular to the facility collects the scattered light. The focal length was 0.5 m with f8.5 collecting optics yielding a spherical sample volume 100 microns in diameter. High-speed burst counters processed the signals from the three measurement components. An LVABI data acquisition system, Cavone, Sterlina, Clemmons, and Meyers (1987) acquires the digital measurements from the three counters and passes the data ensembles to a minicomputer for final data processing and storage. The free stream component is processed by a burst counter in free run mode with direct input to the microcomputer used to monitor the tunnel parameters. The free stream results are passed to the minicomputer upon demand when the measurement ensembles are obtained.

Measurements

A detailed vertical traverse was conducted three step heights downstream of the step. The velocity statistics were computed using arithmetic statistics, the histogram method developed by Edwards and Meyers (1984), the one-dimensional bias correction developed by McLaughlin and Tiederman (1973), and a three-dimensional bias correction to account for the full velocity vector. The detailed velocity scan was made with the three laser velocimeter components in full coincidence and the velocity vector of each particle determined. This provided the velocity vector magnitudes required for the three-dimensional correction. As shown in Figure 8, the determination of the mean velocity profile using the basic statistics and the histogram method track closely. The one-dimensional correction caused the velocities to deviate considerably behind the step whereas the three-dimensional correction moved the velocities closer to the basic statistics. The standard deviations of velocity normalized by the free stream velocity accentuates the differences between the basic statistics and the one-dimensional correction and three- dimensional correction, Figure 9. Since the histogram method continues to track the basic statistics, the correlation coefficient between velocity and data rate is

expected to be small. The correlation coefficient, plotted in Figure 10, is indeed small with the maximum magnitude of 0.16 whereas the coefficient for the pipe flow data was up to a value of 0.3, Figure 4. However, the trend of the data is interesting. The correlation increases to a peak in the free shear layer where the heavily seeded high speed flow is mixing with the lightly seeded recirculating flow. The correlation then decreases to a negative peak in the shear region between the recirculation and the boundary layer indicating the slower boundary layer contains the greater number of particles. The flow correlation time, plotted in Figure 11, is constant above the step then makes a smooth transition to a value three times longer behind the step. A marked increase in correlation time is then seen within the boundary layer behind the step.

An overall view of the flow field was made by measuring the velocities over a 0.5-inch grid from 1-inch upstream to 24-inches downstream of the step. The laser velocimeter was run in non-coincidence mode to increase the data rate especially in the separated region behind the step. The basic statistics, the histogram method, and 1-dimensional bias correction results are shown for the mean velocity in Figures 12-14 respectively and Figures 15-17 respectively for the standard deviations normalized by the local mean velocity. Again the basic statistics and the histogram method have comparable results whereas the 1-dimensional bias corrected data deviates considerably from them, especially behind the step.

The velocity:data rate correlation coefficient map is shown in Figure 18. If the correlation coefficients nine inches downstream of the step are compared to the corresponding data in Figure 10, one notices major differences between the two data sets. Apparently the recirculation zone has gained significant numbers of particles, reversing the previous trends. A repeat of the vertical scan which yielded the data for Figure 10, was performed with the same instrumentation settings used for the flow field mapping. A comparison of these two scans in Figure 19 show similar results above the step, however the trends behind the step have opposite phases. This indicates that the heaviest particle concentration was within the recirculation zone. In reality this apparent change in the particle distribution is attributed to instrumentation settings. During the first scan, the reset time was adjusted from the normal 75 μsec to 300 μsec when the measurement volume was in the recirculation region. During the flow field mapping, the reset time was held at 75 μsec for all measurement locations. When the mean velocity slowed in the shear regions, the short reset time allowed the high-speed burst counters to obtain two or more measurements from the same Bragg-shifted signal burst. These extra measurements had no effect on the resulting velocity statistics because

the correlation was so low, however they did cause the 180 degree phase shift in the correlation data. These results clearly show the sensitivity of the velocity:data rate correlation to changes in the experiment, in this case the instrumentation settings.

Summary

Two flow fields, a jet from a turbulent pipe flow and the flow about a backward facing step, have been investigated using a laser velocimeter. The resulting data was analyzed using classic statistical methods with and without standard velocity bias corrections, and using the method of Edwards and Meyers to obtain independent samples from the acquired data ensemble for statistical analysis. The data was also tested for the basic assumption of velocity and data rate dependence. The results indicate little if any dependence and therefore little bias in regions considered free stream. In the entrained regions (jet flow) and shear regions (backward facing step) some dependence was found. This dependence was both positive and negative and could be changed by instrumentation settings. Therefore these changes indicate the importance of determining the degree of velocity bias if present, contained within each measurement ensemble, based on that ensemble and not generalized assumptions. Further, the calculation of the correlation coefficient between velocity and data rate should be routinely calculated to determine the degree and direction of any bias which may be present.

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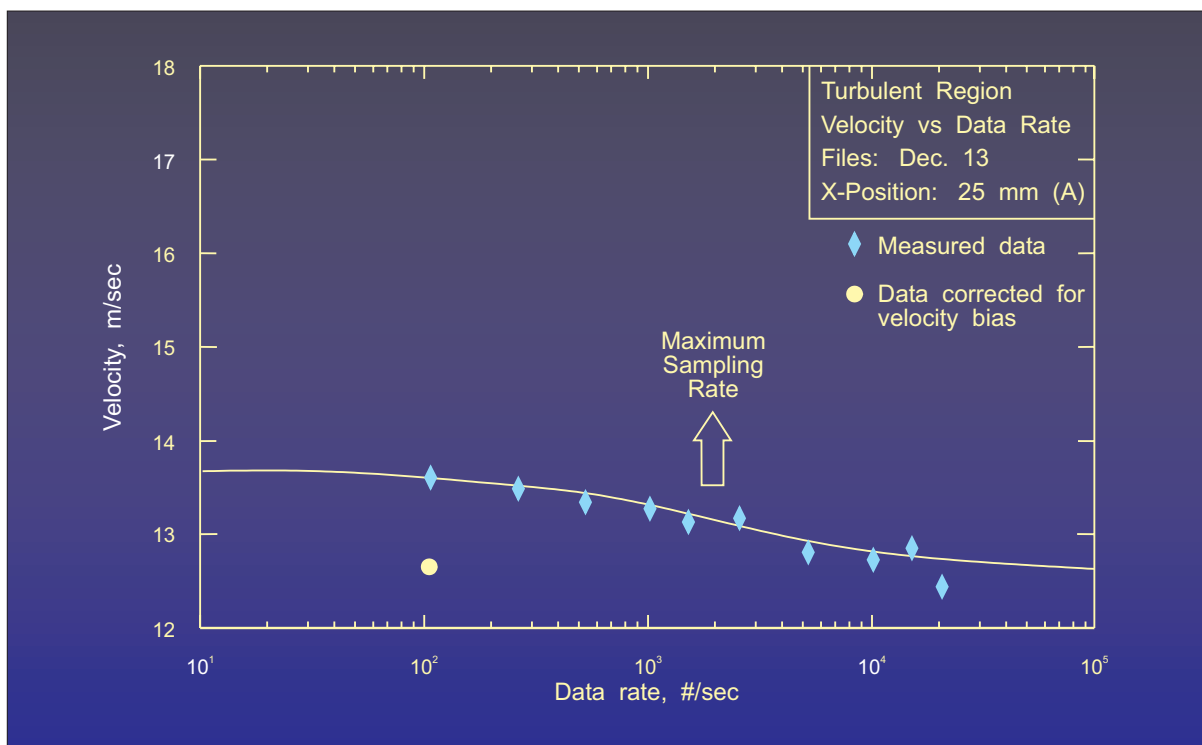
Figure 1.- Mean velocity as a function of data rate in the shear layer downstream of a backward facing step, Stevenson, Thompson, and Roesler (1982).
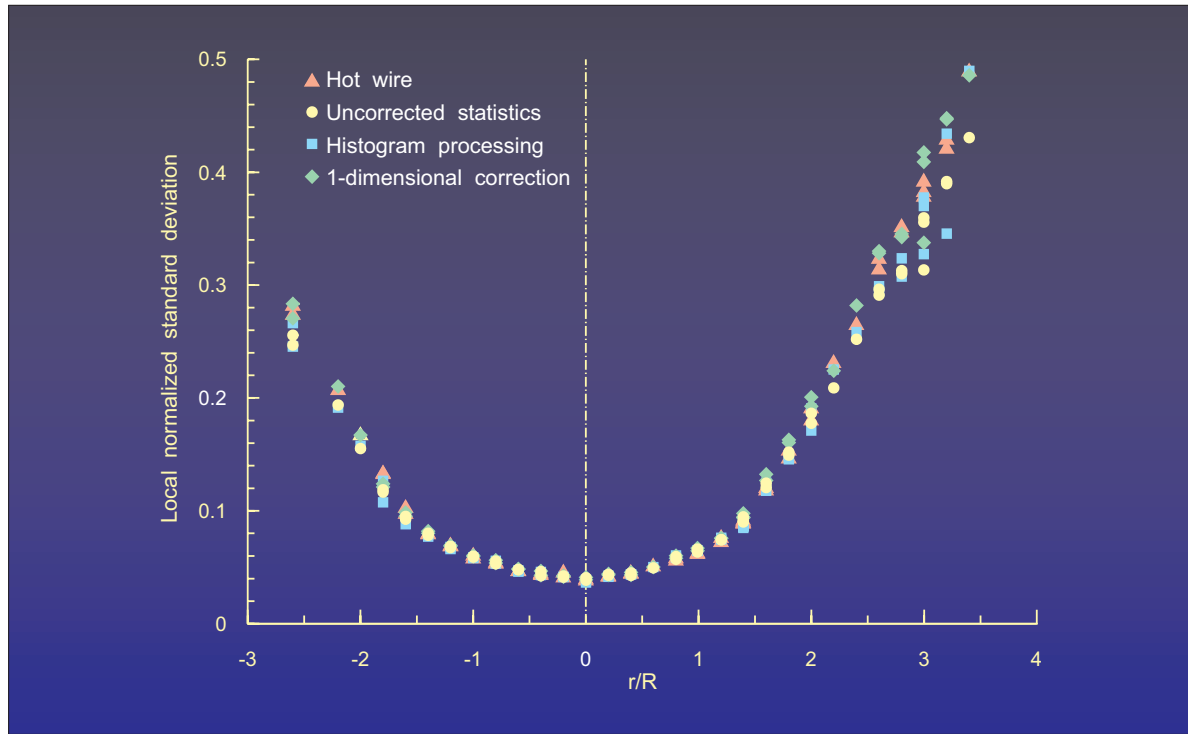
Figure 2.- Standard deviation of velocity normalized by the local mean velocity along a radial scan six pipe diameters downstream from the exit of a fully developed turbulent pipe flow.
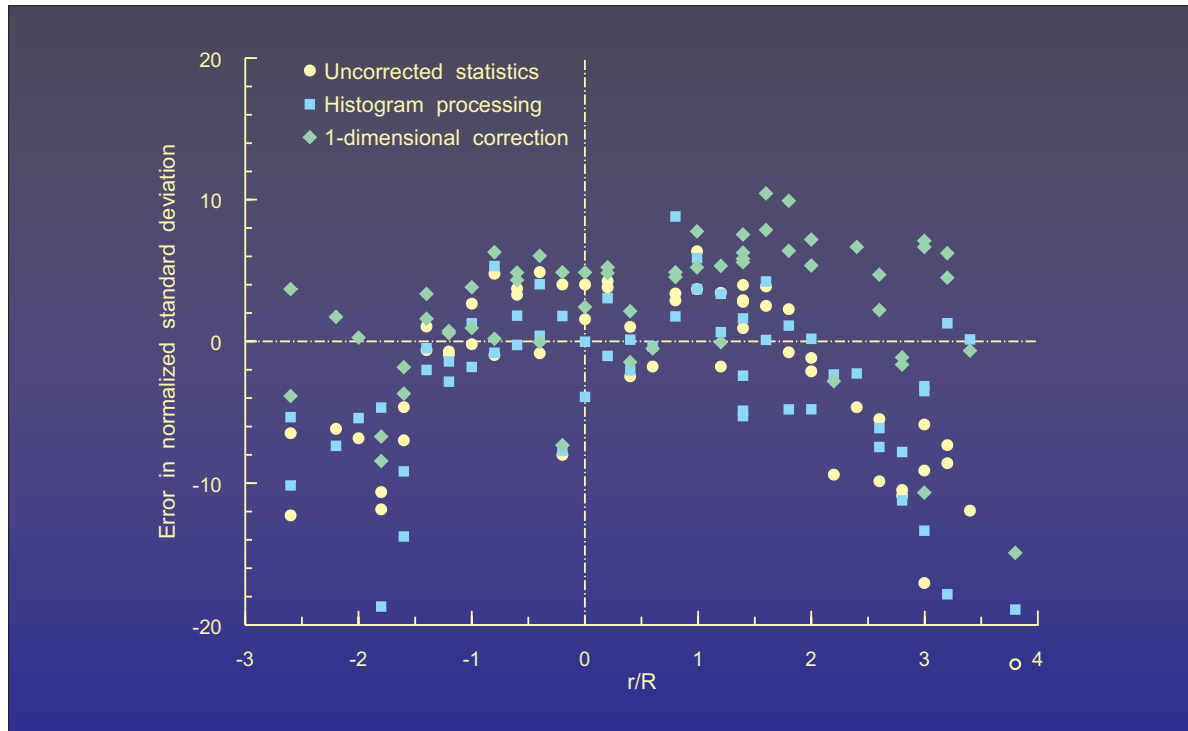
Figure 3.- Difference between normalized standard deviations of velocity simultaneously measured by a laser velocimeter and a hot wire normalized by the hot wire measurements.
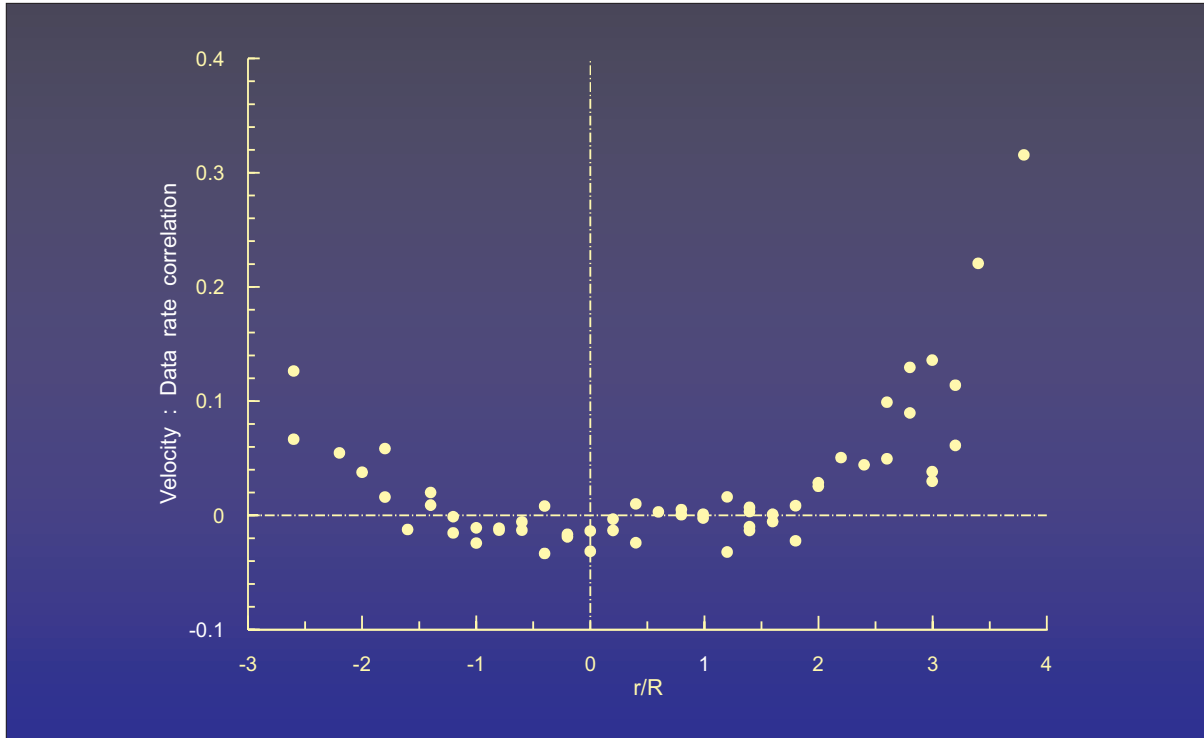
Figure 4.- Correlation coefficients between velocity and data rate along a radial scan six pipe diameters downstream from the exit of a fully developed turbulent pipe flow.
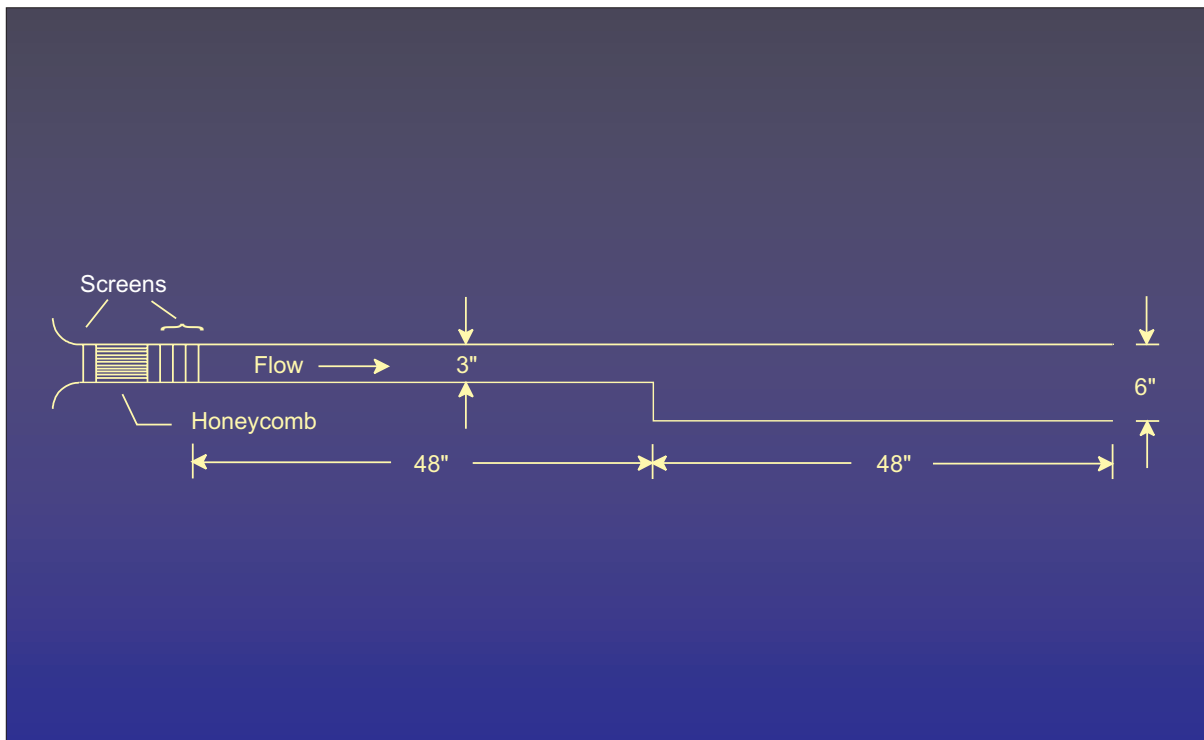
Figure 5.- Axial cross section of the backward facing step apparatus.
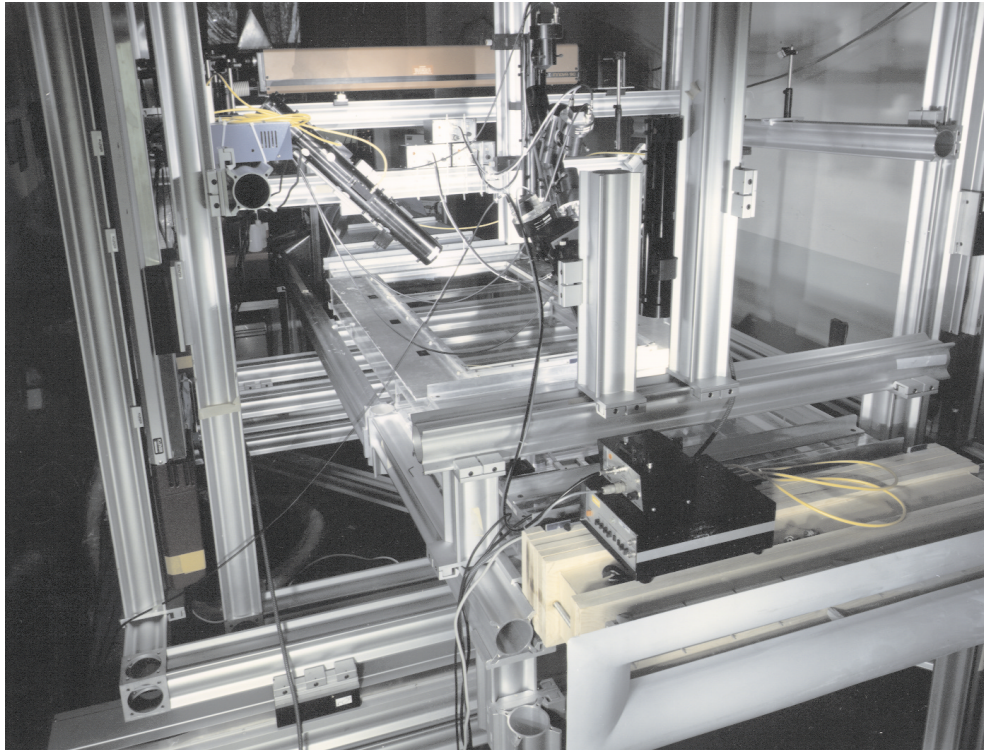
Figure 6.- The backward facing step apparatus and the four component laser velocimeter system installed on the traversing mechanism.
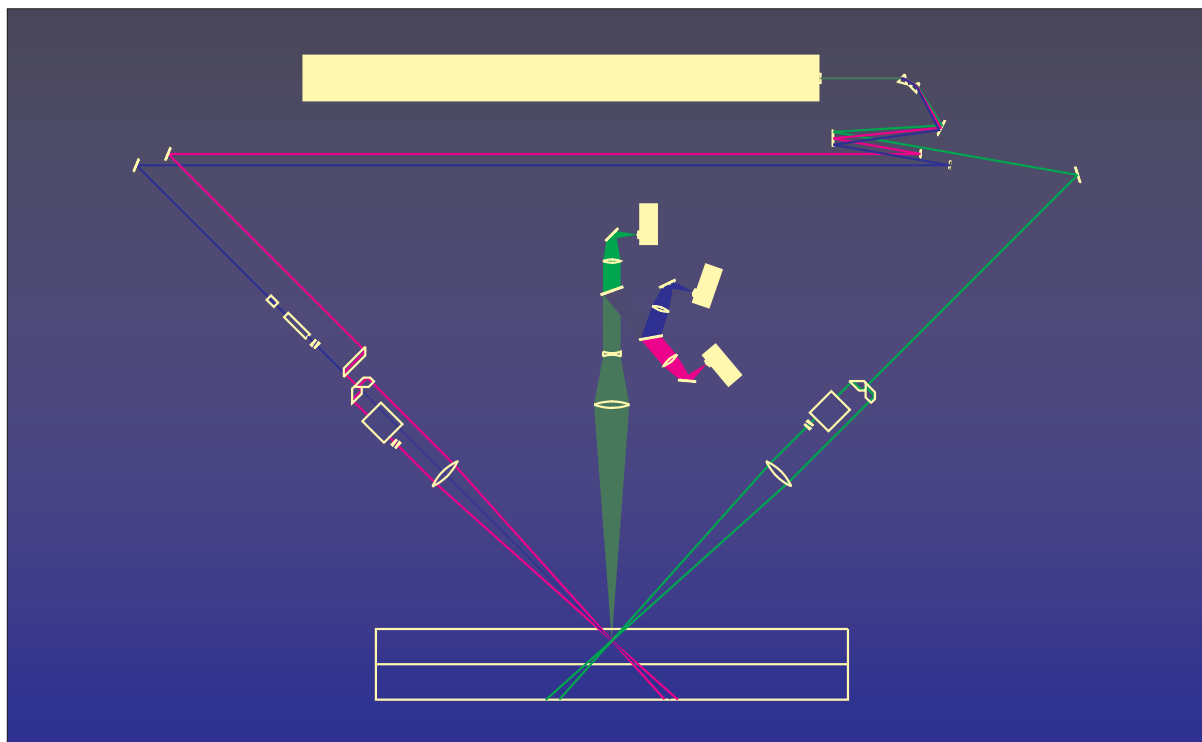
Figure 7.- Schematic of the three component laser velocimeter measurement system.
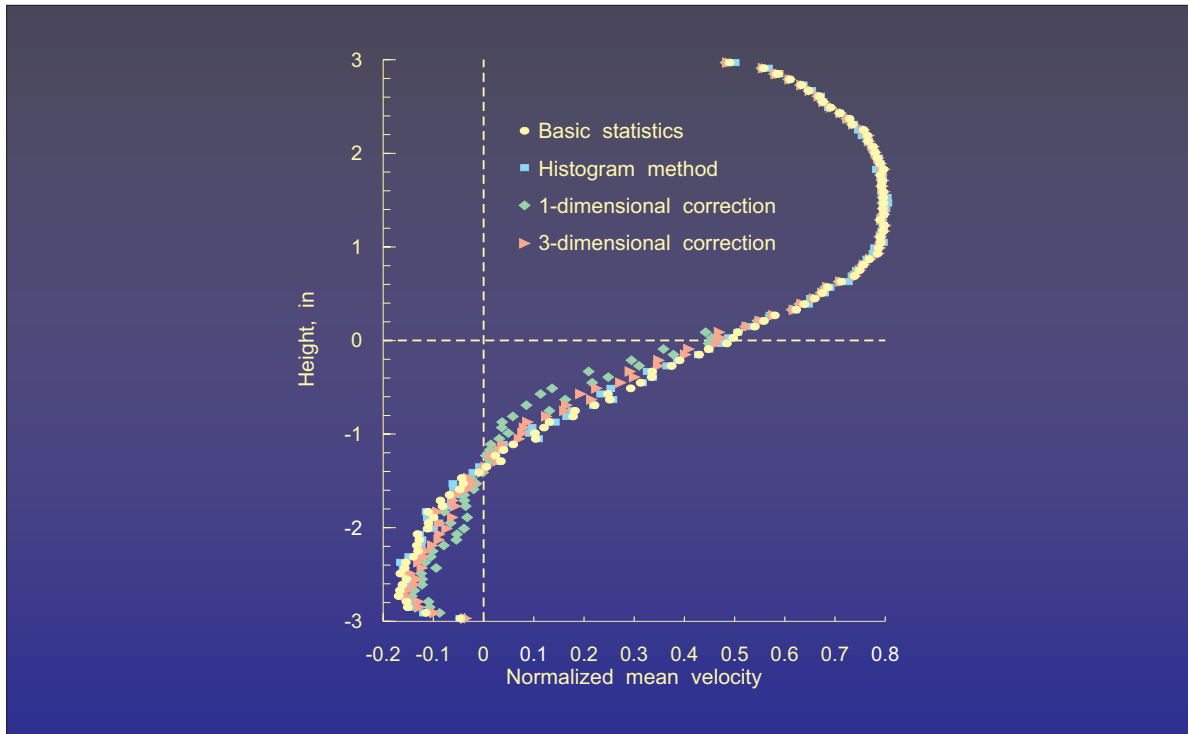
Figure 8.- Mean velocity measurements normalized by the free stream velocity upstream of the step along a vertical traverse, three step heights downstream of the backward facing step.
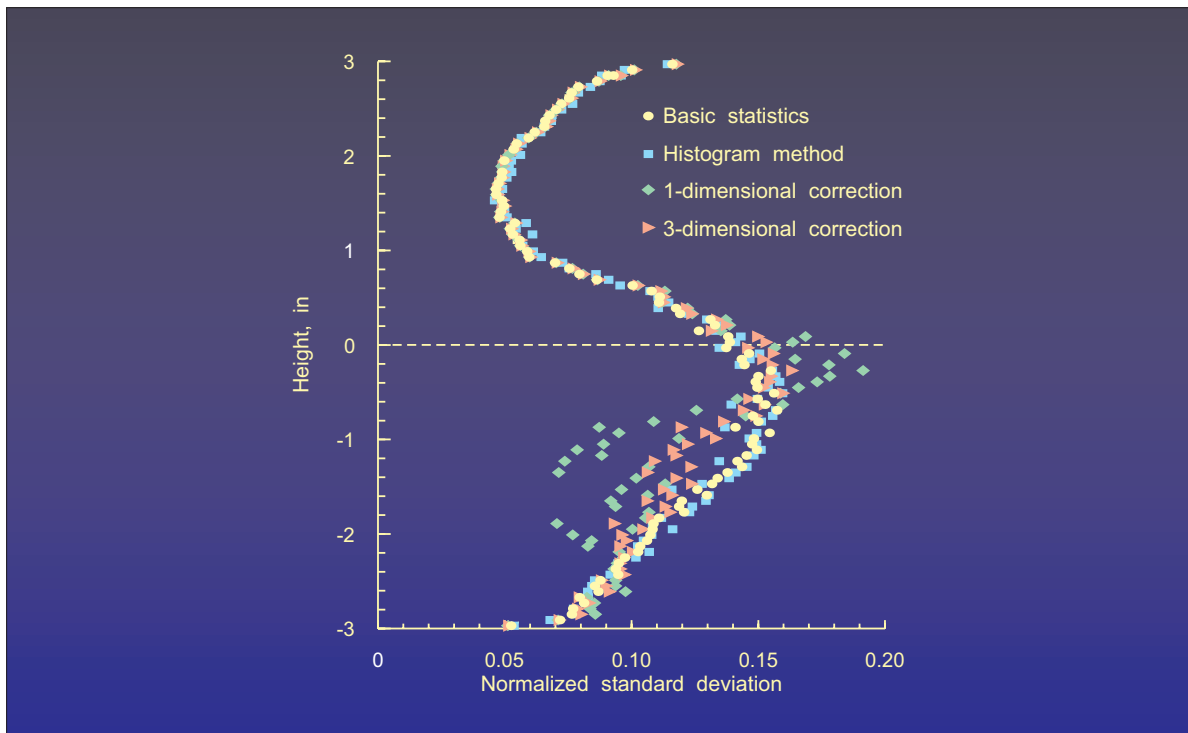
Figure 9.- Standard deviations of velocity normalized by the free stream velocity upstream of the step along a vertical traverse, three step heights downstream of the backward facing step.
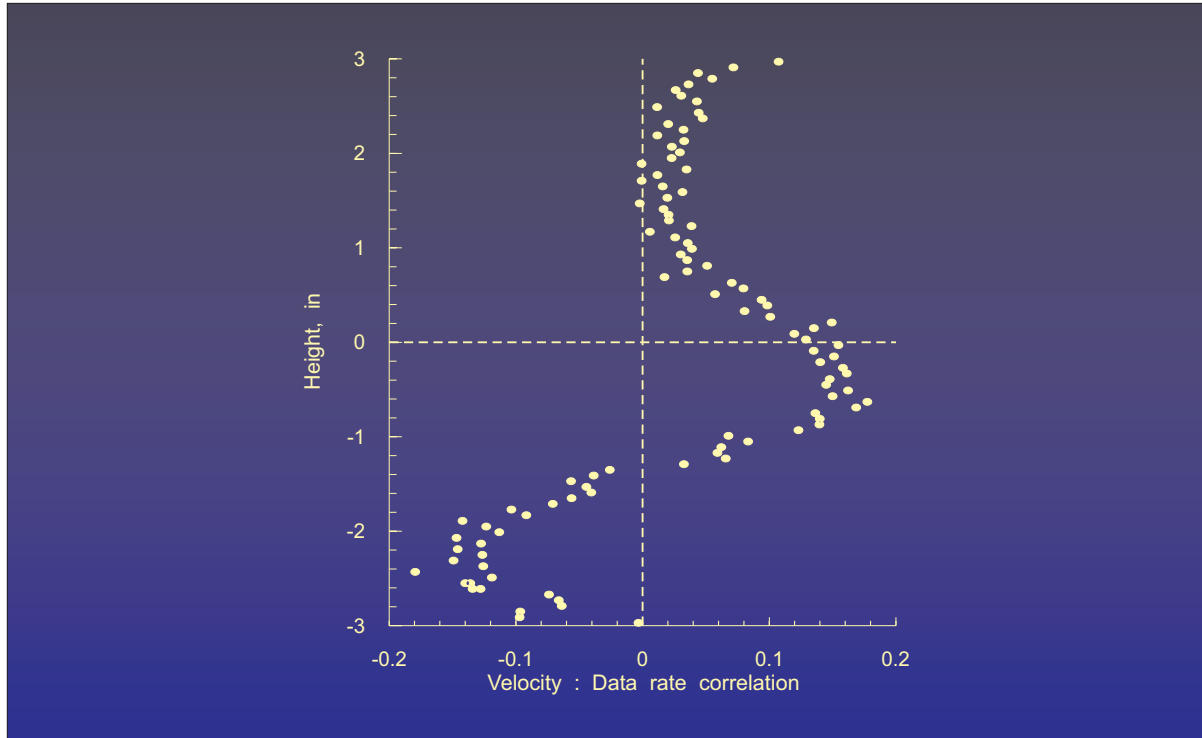
Figure 10.- Velocity:data rate correlation coefficients along a vertical traverse, three step heights downstream of the backward facing step.
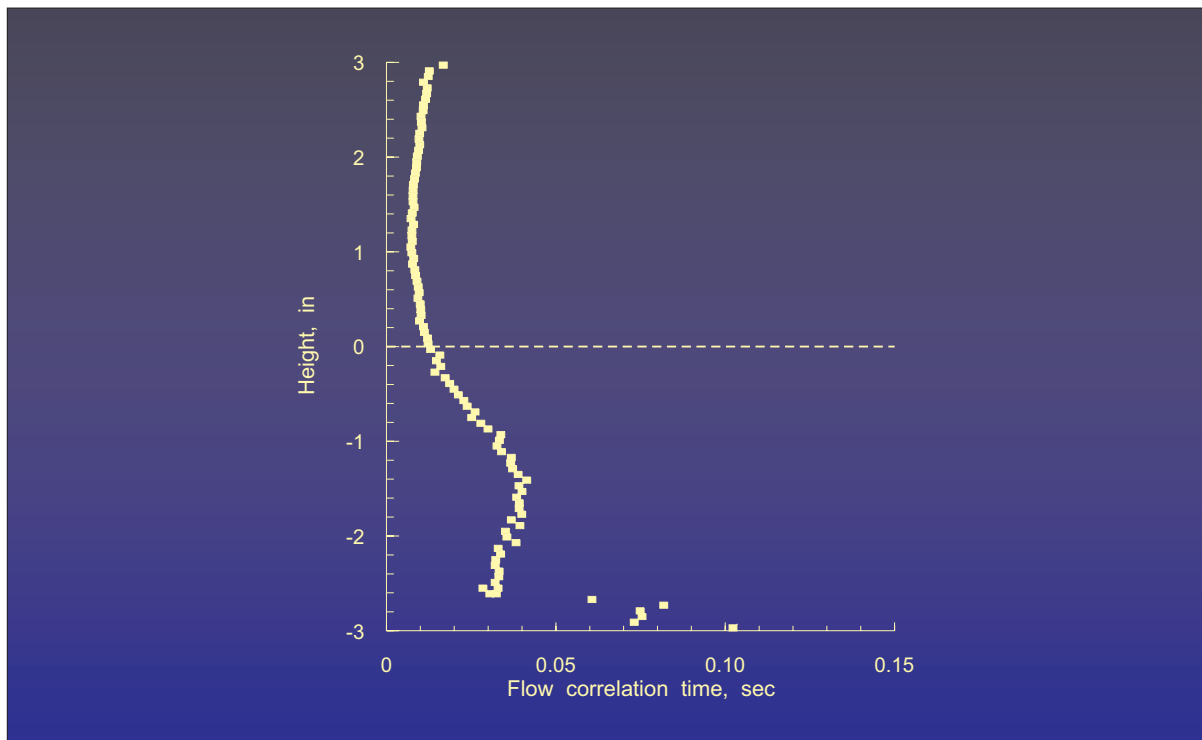
Figure 11.- Flow correlation time measurements along a vertical traverse, three step heights downstream of the backward facing step.

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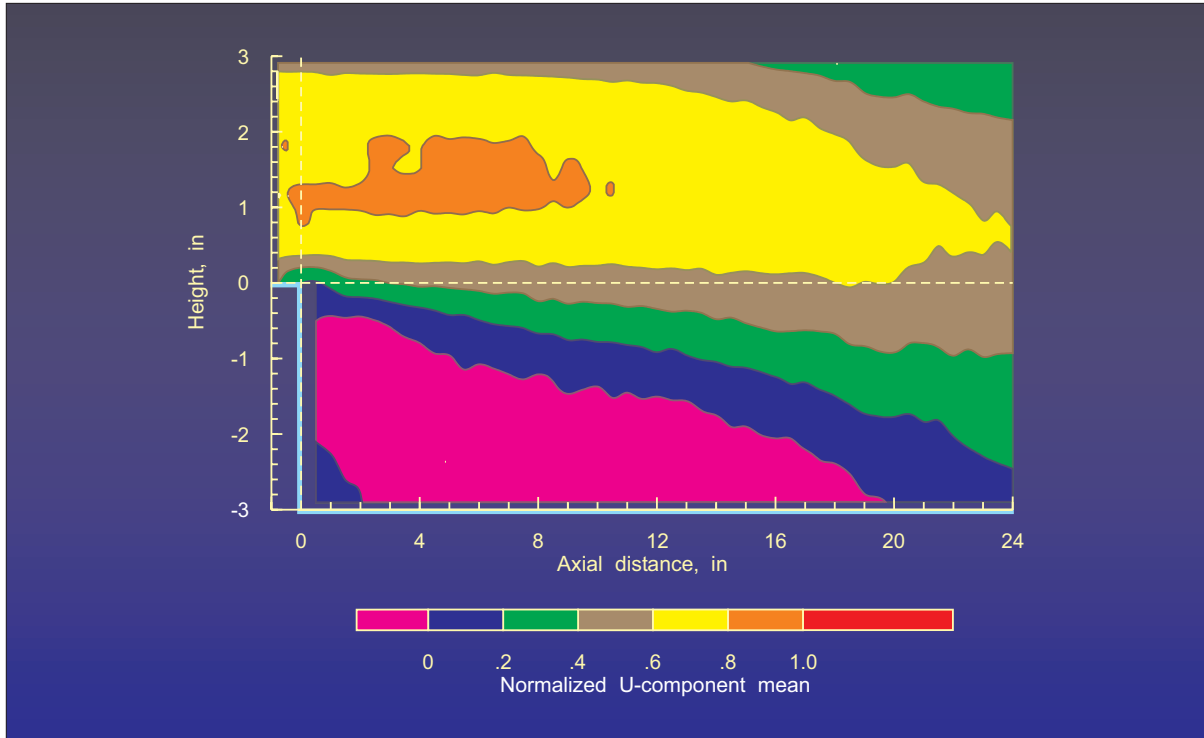
Figure 12.- Mean velocity flow field map about the backward facing step using basic statistical data processing.
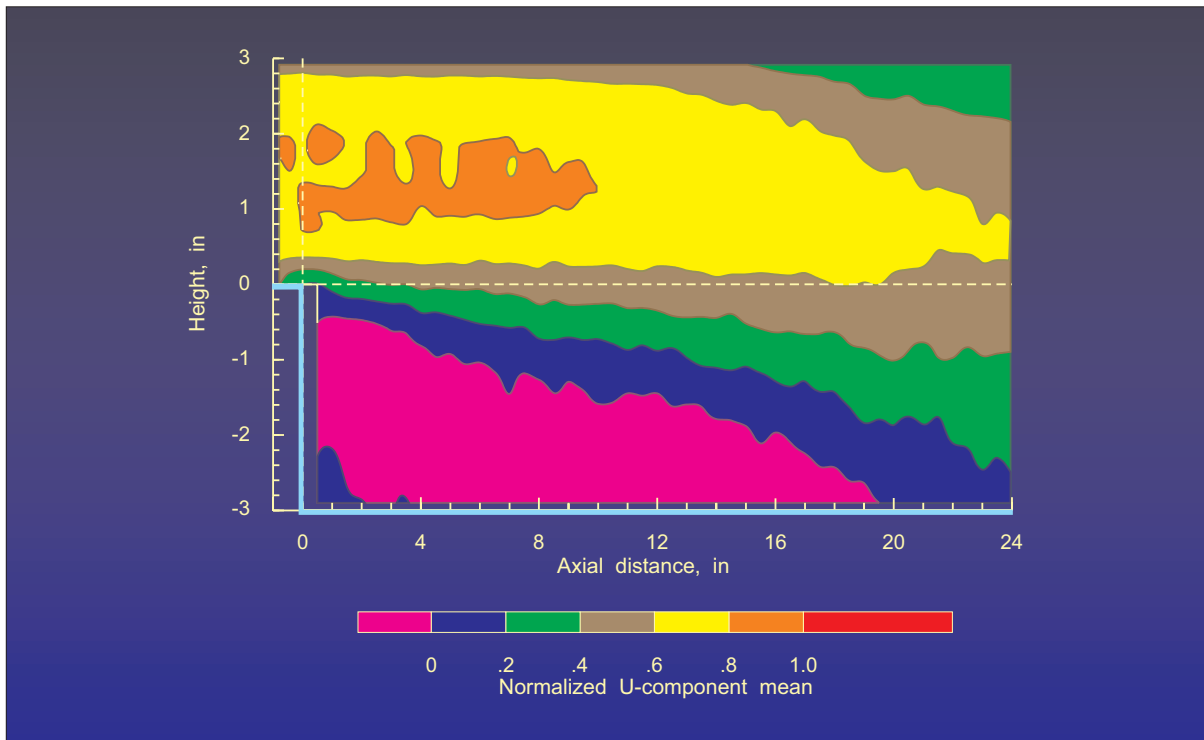
Figure 13.- Mean velocity flow field map about the backward facing step using the histogram method of data processing, Edwards and Meyers (1984).
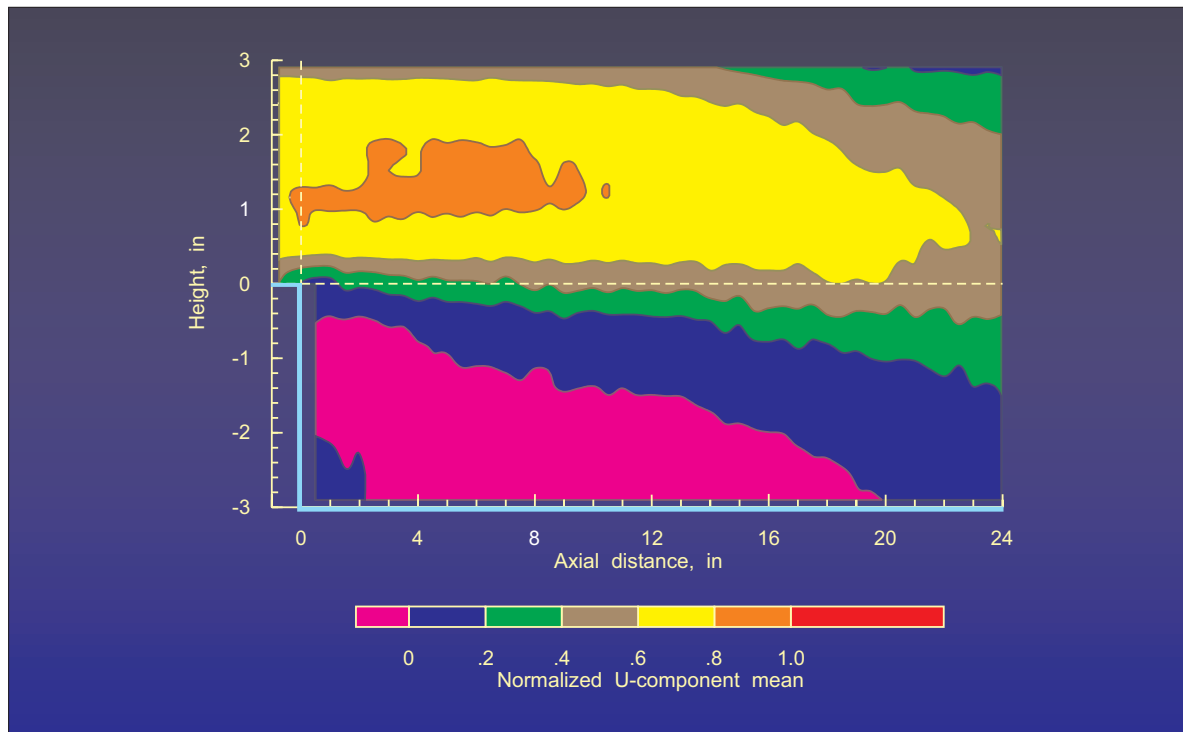
Figure 14.- Mean velocity flow field map about the backward facing step with the basic statistical data corrected using the classic 1-dimensional velocity bias correction technique, McLaughlin and Tiedermann (1973).
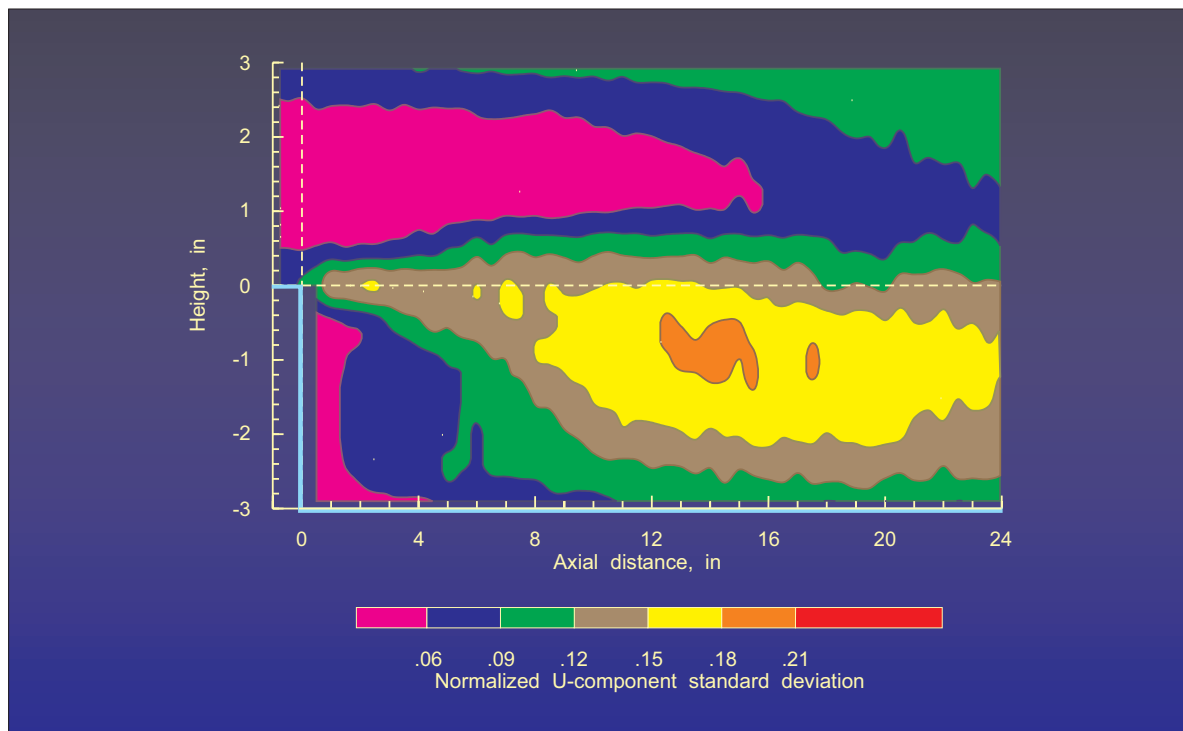

Figure 15.- Flow field map of standard deviation of velocity normalized by the local mean velocity about the backward facing step using basic statistical data processing.
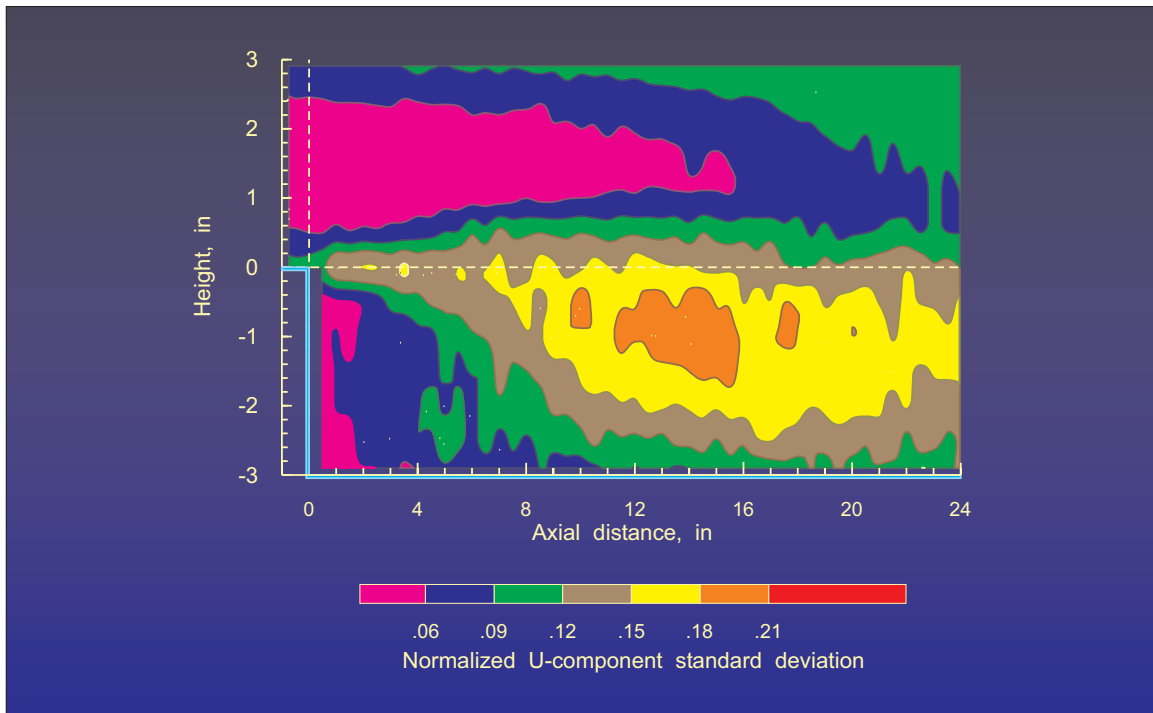
Figure 16.- Flow field map of standard deviation of velocity normalized by the local mean velocity about the backward facing step using the histogram method of data processing, Edwards and Meyers (1984).
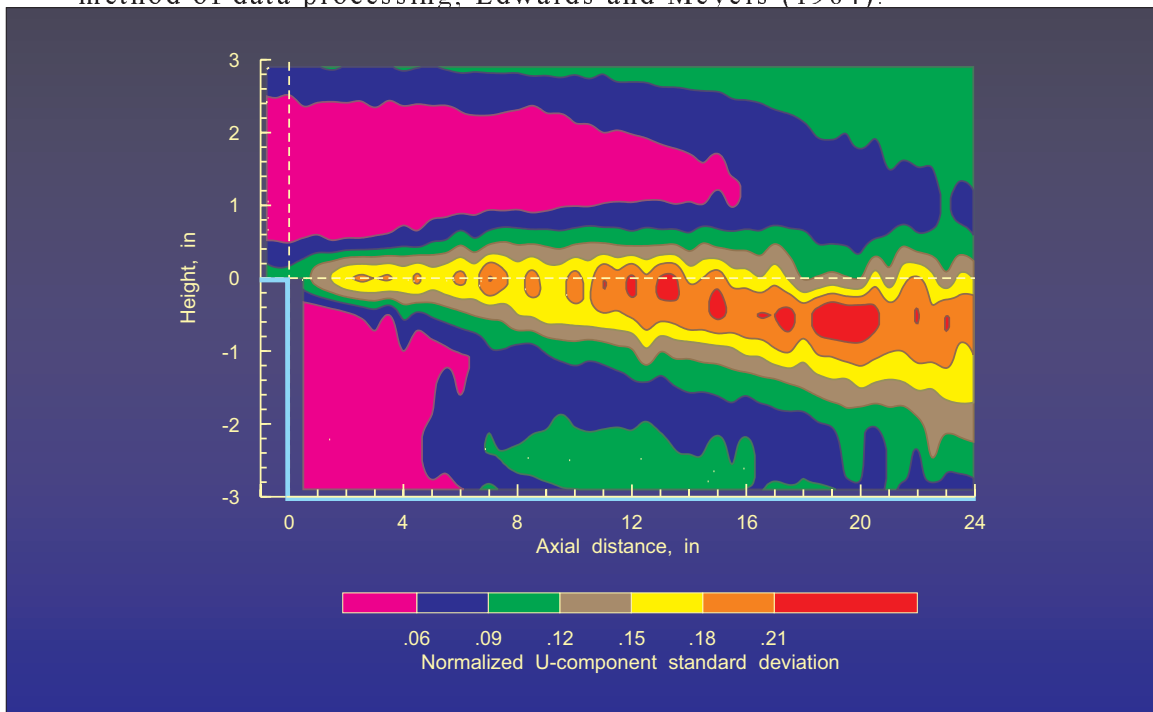

Figure 17.- Flow field map of standard deviation of velocity normalized by the local mean velocity about the backward facing step with the basic statistical data corrected using the classic 1-dimensional velocity bias correction technique, McLaughlin and Tiedermann (1973).
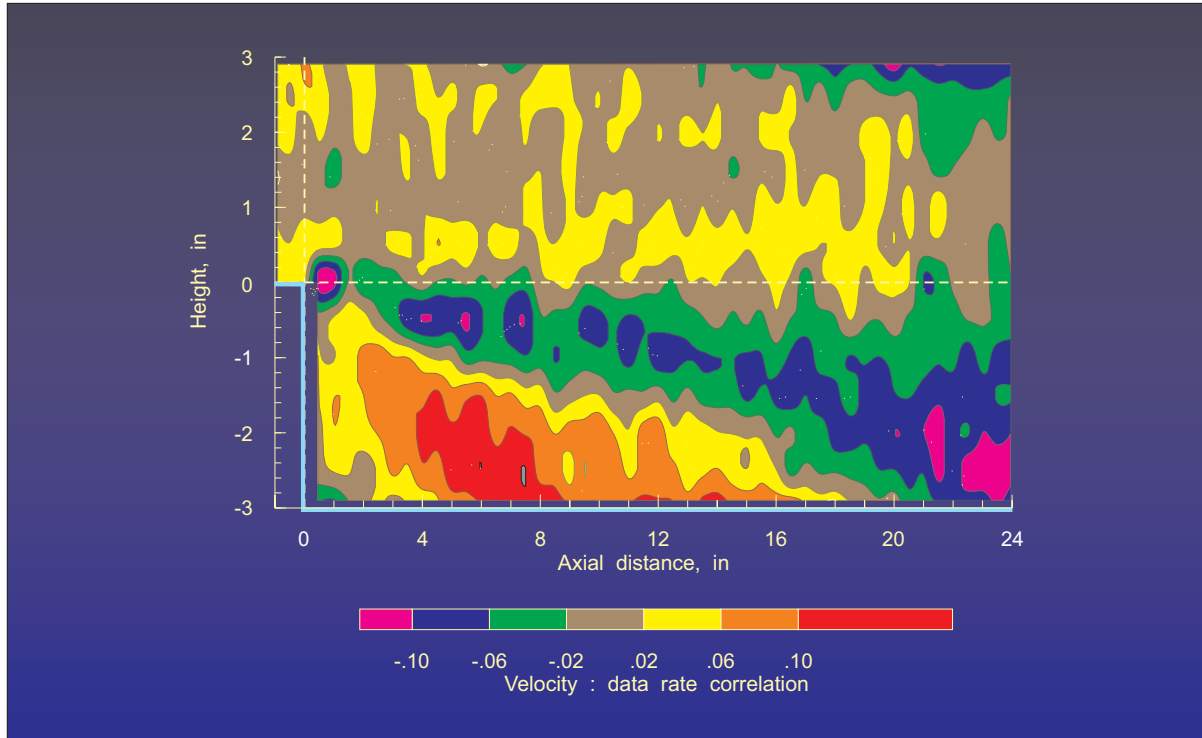
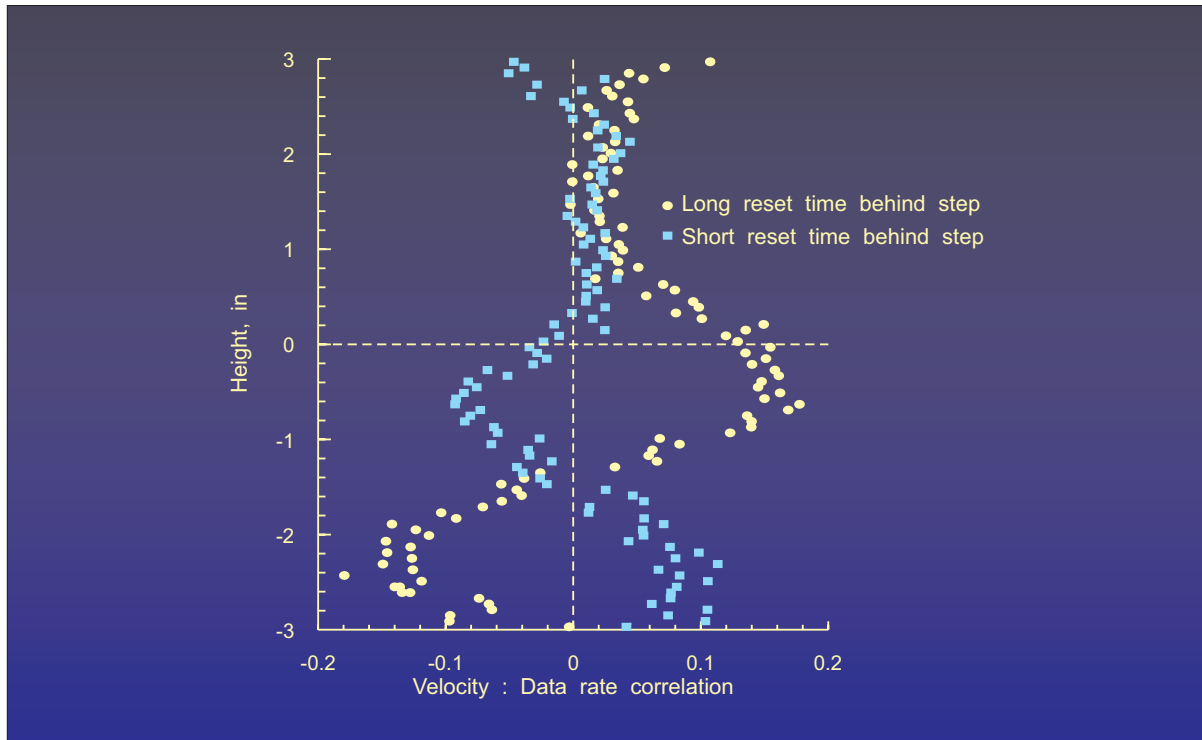Figure 18.- Map of the velocity:data rate correlation coefficients about the backward facing step.

Figure 19.- Comparison of velocity:data rate correlation coefficients along a vertical traverse three step heights downstream of the backward facing step.