The Development of Ultrasonic Meter Performance Diagnostic Methods Velocity Profile Ratios

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Abstract

Check meters are commonly used by calibration facilities to monitor system performance. Check meters at the CEESI Iowa Natural Gas High Flow Facility have been installed in two different configurations: permanently installed check meters upstream of the customer meters and check meters installed downstream of the customer meters in variable configurations. The data from two 12” ultrasonic check meters normally placed downstream of customer meters will be examined to investigate the effect of velocity profile on the performance of ultrasonic flowmeters.

Statement of Objective

CEESI has been operating a natural gas calibration facility since March 1999. The facility utilizes pipeline gas in a bypass mode. The system uses turbine meters as standards and both turbines and ultrasonic flowmeters as check meters. The performance of the check meters is monitored through the use of Statistical Process Control (SPC) models which in turn provide the system operators with system stability and performance information. Two ultrasonic check meters have been selected for discussion in the present work. A large database of ultrasonic meter performance information has been accumulated for these meters over a three year period. An ongoing effort is underway to organize and analyze these data for the benefit of the natural gas industry. This paper is a continuation of earlier work (1)(5).

The current work is significant for two reasons. The first is that the two meters are “state of the art” meters. That is, both meters represent the current models sold by two different manufacturers. The second reason is that these meters have been exposed to a wide range of velocity profiles over a three year period. The digital data produced over this period will provide users of ultrasonic flowmeters information about installation effects that has not been previously available.

Discussion of “error”

The AGA9 [3] definition of meter “error” is the difference between velocity values reported by the meter and calculated from the laboratory standard. The ISO VIM [4] states:

> "The error concept can be used when there is a single reference quantity value to refer to, which occurs if a calibration is made by means of measurement standard of negligible measurement uncertainty."

Current day ultrasonic meter calibration processes are characterized by meters exhibiting long term random effects that are smaller than the uncertainties of the laboratories. It is suggested that the use of the term "error" does not meet the ISO VIM definition. This paper will use the term "offset" to represent the difference in velocity values.

Velocity Profile Ratio

Velocity profile ratio was recognized as a diagnostic tool several years ago. The meters used for this study are 4 path chordal meters. The calculation of velocity profile ratio for the two meters is shown below.

$$Profile\ Ratio = \frac{V_b + V_c}{V_a + V_d} \qquad \text{[Eq. 1]}$$

where:

V is the velocity reported for an individual chord

a,b,c,d are the chord identifiers

Velocity profile ratio values are monitored and compared to baseline profile ratio values. The baseline values are established at a calibration facility if the meter is calibrated and are also established when the meter is placed in service. Slight variations in velocity profile ratio are interpreted as an indication of buildup of dirt or "pipe rouge" while large variations may indicate the presence of a foreign object in the vicinity of the meter or flow conditioner.

Some gas companies have established threshold values of variation in velocity profile ratio. If the variation in velocity profile ratio exceeds the threshold value the meter is inspected or transducers are removed and cleaned. There is little data to base these threshold values on.

SPC12A and SPC12B

The two meters used for this study were obtained from different manufacturers. Both meters are of the chordal design. While one meter has transducers that are slightly recessed from the pipe wall the other has transducers that protrude slightly into the flow. Both meters provide Modbus interfaces which were used to collect a full set of measured and diagnostic values.

The two 12" SPC meters are always placed downstream and in series with the MUT in the 16" test section. The length of 12" piping upstream of the two 12" SPC meters varies a bit due to the length requirements of the MUT. Flow conditioners are occasionally placed in the line upstream of the SPC meters.

SPC12A

SPC12A was initially installed in the CEESI Iowa facility as an R&D meter. In March 2005 the electronics and transducers were replaced and the meter was put into service as a check meter. The period of time covered by the analysis of this meter is from October 2007 to the present. The present analysis are based on 5400 data points obtained over a velocity range of 3 to 112 ft/sec. The range of MUT inside diameters varied from 3.6 to 12 inches.

SPC12B

SPC12B has been installed in the CEESI Iowa facility since 2006. The period of time covered by this analysis is from March 2009 to the present. The present analysis are based on 9000 data points obtained over a range of 4.5 to 136 ft/sec. The range of MUT inside diameters varied from 2 to 12 inches.

SPC12B has a reduced bore diameter. The inlet diameter is 11.938" and the meter bore diameter is 10.645". The inlet and exit wall surfaces have been beveled to provide a transition from the inlet and exit pipe diameters to the reduced bore diameter. The measured gas velocity at the meter is higher than the gas velocity in the adjacent piping.

SPC12B utilizes a Reynolds number based algorithm to calculate the velocity profile at low velocities. It is not known when the ultrasonic flowmeter begins using this algorithm.

Figures

Six types of plots will be shown for each of the three check meters. The figures are:

1. Meter Offset Data with performance bands
2. Mean Deviation (Performance) also referred to as "Between"
3. Standard Deviation (Performance) also referred to as "Within"
4. Reported Profile Ratios
5. Representative (10 - 20 ft/sec) Offset as a function of Velocity Profile Ratio
6. Slopes of Meter Offset Data plotted as a function of Velocity Profile Ratio

The plots of meter offset data with performance bands show data residuals with bands at 95% intervals. A curve fit of meter offset as a function of velocity was used to calculate the residual of each data point. The "residual" is the difference between a data point and the curve fit. Residuals are indicated as circles and the solid lines represent a statistical interval that contains 95% of the data. The plot shows that the random variations increase with decreasing velocity which is common for most measuring instruments. This effect is often referred to as "percent of full scale effects". The curve fit of meter offset and velocity was performed using data in the early part of the time period shown for each meter.

The statistical interval width is $\pm 2s_c$ where s is a standard deviation expressed in percent. Frequently S_c can be defined by an equation of the form:

$$S_c = a + (b/v) \times 100\% \qquad \text{[Eq. 2]}$$

where v is velocity. Traditionally the coefficients “a” and “b” are selected until the interval appears to contain 95% of the data, a methodology more qualitative than quantitative. A better method of quantifying meter performance has been used in this study.

The statistical intervals that describe meter performance have been calculated using a new approach. Two parameters are required for this analysis: meter velocity and meter offset. The analysis of the ultrasonic data begins by dividing the data set into discrete velocity intervals. Since most of the check meter data was taken at less than 30 ft/sec, the range of velocities in a velocity interval is narrow. At higher velocities, the velocity intervals were composed of data from data over a wider range. The standard deviation of the data over each velocity interval was calculated. The standard deviation values at each velocity interval are shown for both of the SPC meters in Figures 1 and 2. The standard deviation data were used to establish the “a” and “b” coefficients in equation 2. The calculated performance bands are shown for SPC12A and SPC12B in Figure 3.

SPC analysis has been utilized at CEESI to monitor ultrasonic meter and calibration system performance [2]. The meter offset data were used to develop control charts for meter performance. The meter offset residuals determined from calibration data obtained for a single MUT inside diameter are compiled and the mean and standard deviation are calculated. Two control charts containing values of meter offset mean and standard deviation plotted against time are shown for each of the check meters. The dependence of meter error on velocity prevents directly comparing results obtained at different velocities on a percent basis. The data are normalized based on the confidence interval (Eq. 1) prior to creation of control charts therefore the ordinate values in the standard deviation control charts are presented as multiples of s.

The solid lines in the mean deviation control charts are control limits calculated based on 95% confidence. The process can be stated to be operating in a state of statistical control if 95% of the data lie between the control limits. The standard deviation control charts only have one control limit because the standard deviation cannot have a negative value. Statistical control is demonstrated if 95% of the data points lie below the single control limit. Control charts are valuable in summarizing large data sets by condensing multiple data points obtained during one day into two values. The control charts allow for a quick check of how consistent the current calibration is when compared to the accumulated history.

An additional analysis method has been applied to the data in this study. The effects of meter velocity profile ratio have been examined in each of the velocity intervals used to determine the statistical performance intervals. Meter offset as a function of profile ratio was plotted for each of the velocity intervals. Plotting meter offset against meter velocity profile ratio identifies two effects that may not be revealed by the SPC models. The first is the effect of profile ratio on meter performance. The second is deviation of each data point from the curve fit. A regression analysis was performed on each of the data sets to determine the rate of change of meter performance as a function of meter velocity profile ratio at each velocity interval.

It is important to note that the check meters have not been adjusted. During the calibration of an ultrasonic flowmeter calibration factors are input into the meter registers. The calibration factors often vary with flowrate or meter velocity. A correction value corresponds to a nominally fixed velocity and, since the meter was never adjusted, the individual offset values can be expected to vary or shift up or down relative to one another.

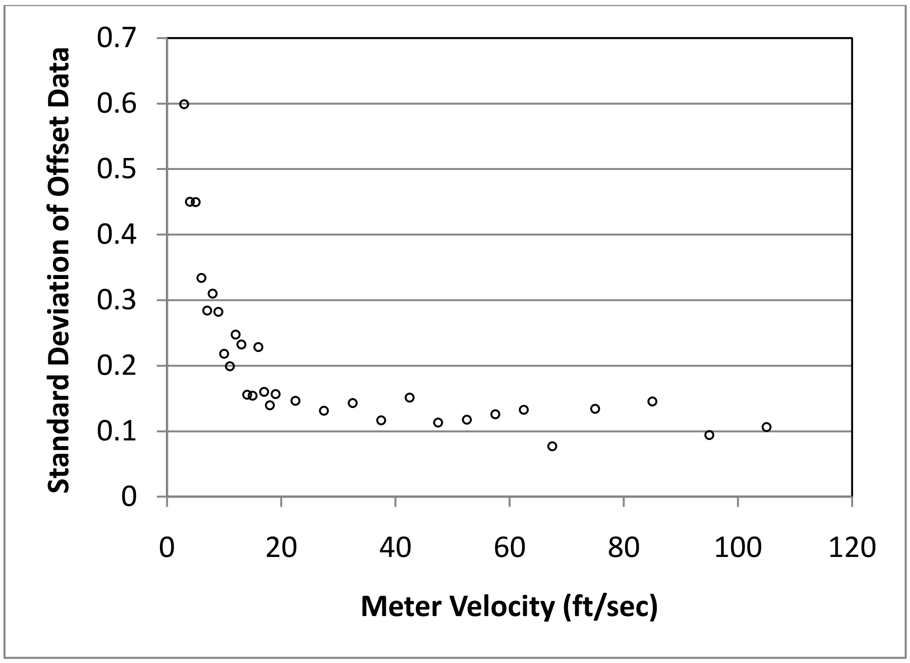

Figure 1. SPC12A Standard Deviation Values for Discrete Velocity Intervals

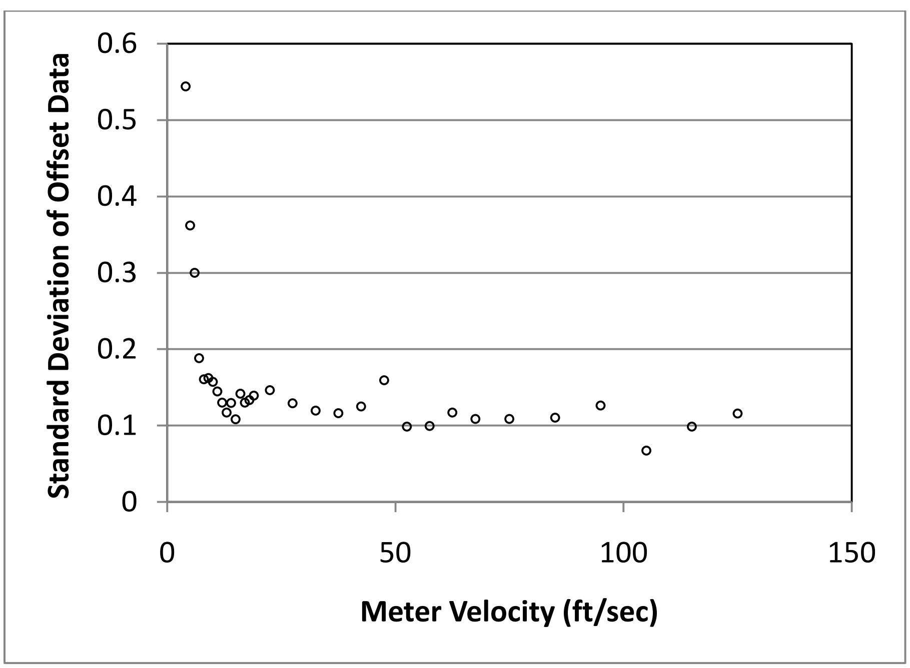

Figure 2. SPC12B Standard Deviation Values for Discrete Velocity Intervals

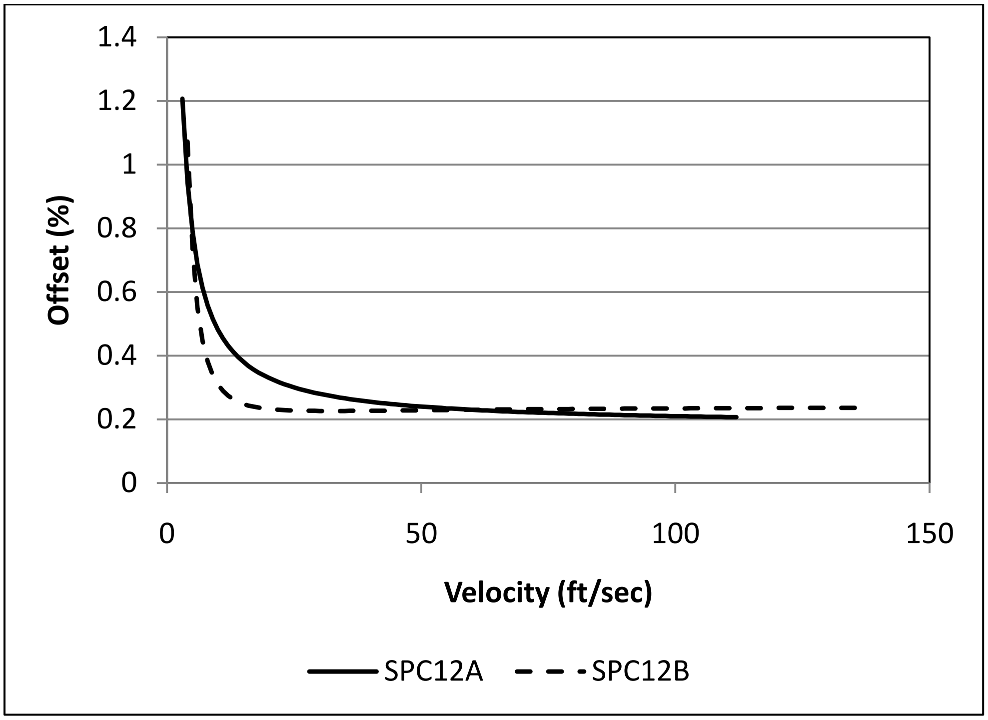

Figure 3. Performance Bands for SPC12A and SPC12B

SPC12A Figures

Figure 4: Meter Offset Data with performance bands

The even distribution of the data within the interval bands is an indication of consistent performance over time. At the highest velocity the performance bands are at ±0.21%. There are groupings of data outside the bands but this is not unexpected due to the variations in upstream conditions.

Figures 5 and 6: SPC Plots – Mean Deviation and Standard Deviation

The gap in Figures 5 and 6 shows the meter was not in service for approximately 6 months. The meter then saw intermittent use from late 2008 till March 2009. Figures 5 and 6 indicate that the performance of SPC12A was consistent over time.

Figure 7: Relationship Between Velocity Profile and Upstream Meter Diameter

If a small line size expands to a larger line size a high velocity profile value is expected. The data in Figure 7 illustrate a trend of decreasing velocity profile ratio with decreasing upstream pipe diameter which indicates that the behavior of the flow is the opposite of what is expected. That is, the highest velocity profile values are measured when the upstream meter has the same inside diameter as the SPC meter. The range of velocity profile values is approximately 0.1 for all the upstream pipe diameter conditions. The data in Figure 7 are grouped tightly and show a distinct trend in the variation of velocity profile ratio values.

Figure 8: Meter Offset Variation Due to Changes in Velocity Profile

Meter offset values are shown for a velocity range of 10 to 20 ft/sec. The meter offset decreases with larger values of profile ratio. The overall change in meter performance with the observed velocity profile ratio variation may be as high as 1.0%. The data are grouped tightly and show a distinct trend.

Figure 9: Rate of Change of Meter Offset with Velocity Profile

Regression analysis was performed on each of the velocity ranges. The slopes of the regression lines are shown in Figure 6. The data all have negative values with the exception of one point. The data points from 0 to 60 ft/sec form a curve but above 60 ft/sec the data exhibits scatter. The average rate of change value is -1.5 with a maximum value of -3.5.

SPC12A Summary

Figures 4, 5, and 6 all indicate that the meter performance was stable and consistent over the time interval being examined for this study. The velocity profile ratio values are grouped tightly with a well defined trend with upstream pipe diameter. The velocity range shown in Figure 8 was for 10 to 20 ft/sec. The 10 to 20 ft/sec velocity range was selected because it represented the behavior at higher velocities very well. At lower velocities the behavior was less coherent. Figure 9 shows that as velocity profile ratio increases the ultrasonic meter will tend to under register flow. The rate of under registration is more pronounced at lower velocities which would indicate more stable velocity profiles at higher velocities.

SPC12B Figures

Figure 10: Meter Offset Data with performance bands

The even distribution of the data within the interval bands is an indication of consistent performance over time. The trending of the data indicates a higher order polynomial may produce a better fit to the meter offset data. At the highest velocity the performance bands are at ±0.20%.

Figures 11 and 12: SPC Plots – Mean Deviation and Standard Deviation

The bands in Figure 11 show a slight change in meter performance changes in mid 2009. The variation is not large but seems consistent with a gradual increase in the bands throughout the time interval under consideration. Figure 12 indicates consistent standard deviation values over the time interval under consideration.

Figure 13: Relationship Between Velocity Profile and Upstream Meter Diameter

Figure 13 reveals two distinct trends in velocity profile ratio. The trend seen in SPC12A, low profile ratio values with small upstream diameter, is apparent. Another distinct trend is also visible in the plot, profile ratio values that do not appear to be affected by upstream meter diameter. The range of velocity profile values is approximately 0.08 for all the upstream pipe diameter conditions. The small range of velocity profile ratio values may be a result of the reduced meter body bore.

Figure 14: Meter Offset Variation Due to Changes in Velocity Profile

Meter offset values are shown for a velocity range of 10 to 20 ft/sec. The data are grouped tightly and show a distinct trend.

Figure 15: Rate of Change of Meter Offset with Velocity Profile

The rate of change in meter performance as velocity profile ratio changes varies linearly through the velocity range of the ultrasonic meter. The values are positive at low velocities and negative at high velocities. The meter performance appears to be unaffected by variations in velocity profile ratio at a velocity of approximately 40 ft/sec. The maximum values of approximately -5 appear at the highest meter velocities.

SPC12B Summary

Figures 10, 11, and 12 indicate stable meter performance over the time interval under consideration. The slight increase seen in the mean deviation bands in Figure 11 may be due to the regression analysis performed on the offset data. The velocity profile ratio values show two distinct trends as the upstream pipe diameter varies. These trends are visible even though the overall variation in velocity profile ratio values is smaller than for SPC12A. The velocity range shown in Figure 14 was for 10 to 20 ft/sec. The 10 to 20 ft/sec range was selected for consistency between the two meters in this analysis. The variation of meter offset with changes in velocity profile ratio shown in Figure 14 show a clear trend. The trending of meter offset data with variations in meter velocity profile ratio was clear through the entire range of the meter. The reduced bore of the meter is seen as the mechanism that produced the clear trending through the range of velocities being considered. The sensitivity of SPC12B performance to variations in meter velocity profile is relatively high at the higher meter velocities.

Conclusions

An improved method of developing performance bands used to describe ultrasonic flowmeter performance has been demonstrated. The accurate description of meter performance will improve the quality of CEESI's statistical process control system.

A relationship between ultrasonic meter velocity profile ratio and meter offset has been found for the two 12" ultrasonic flowmeters used at the CEESI Iowa Natural Gas High Flow Facility. This relationship can be used to establish limits on allowable ultrasonic flowmeter velocity profile variation. The two meters, from different manufacturers, are more sensitive to variations in meter profile velocity ratio at different regions in their velocity range. SPC12A is more sensitive to variations in velocity profile ratio at low velocities while SPC12B is more sensitive to variations in velocity profile ratio at high velocities.

References

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5. Kegel, T., Johansen, W., "The Development of Ultrasonic Meter Performance Diagnostic Methods", 7th International Symposium on Fluid Flow Measurement, August 2009.

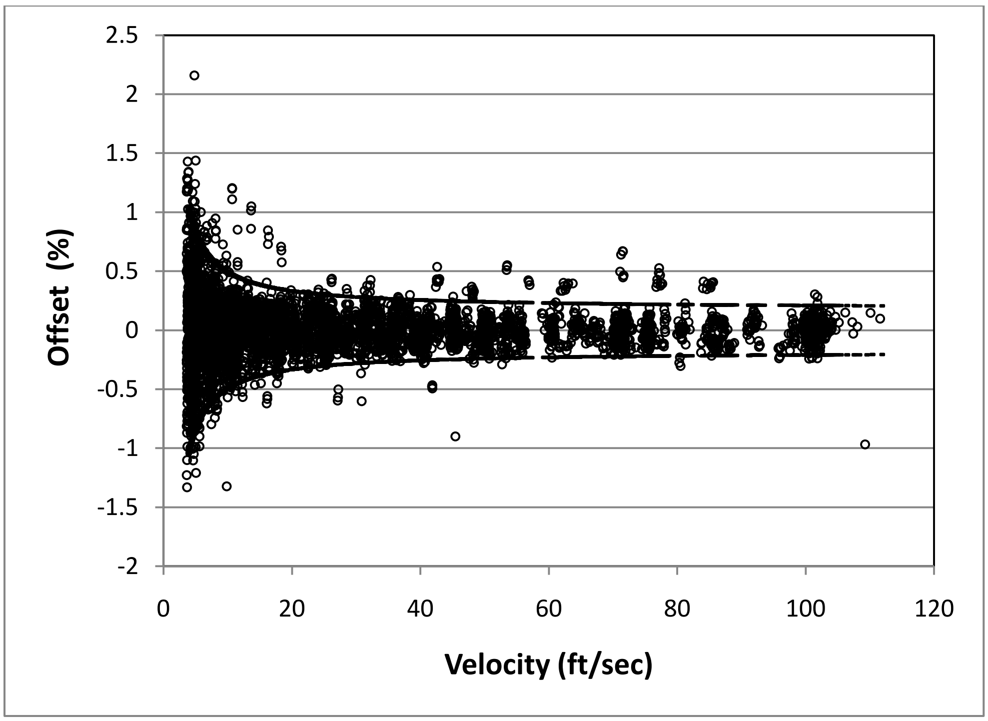

Figure 4. SPC12A Offset Data and Performance Bands

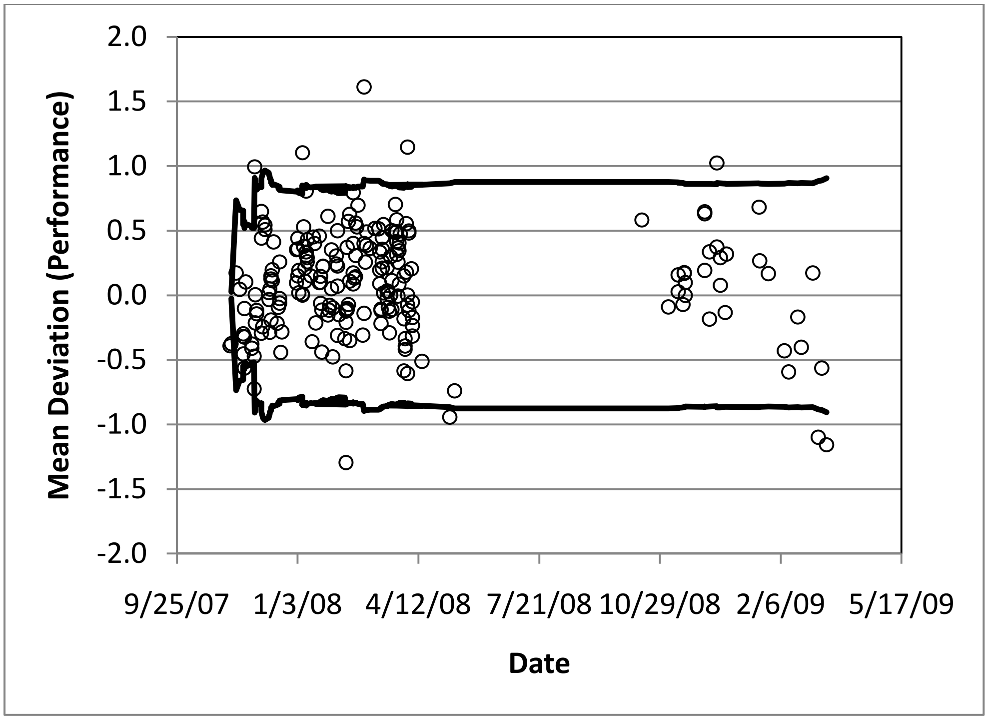

Figure 5. SPC12A Mean Deviation Plot

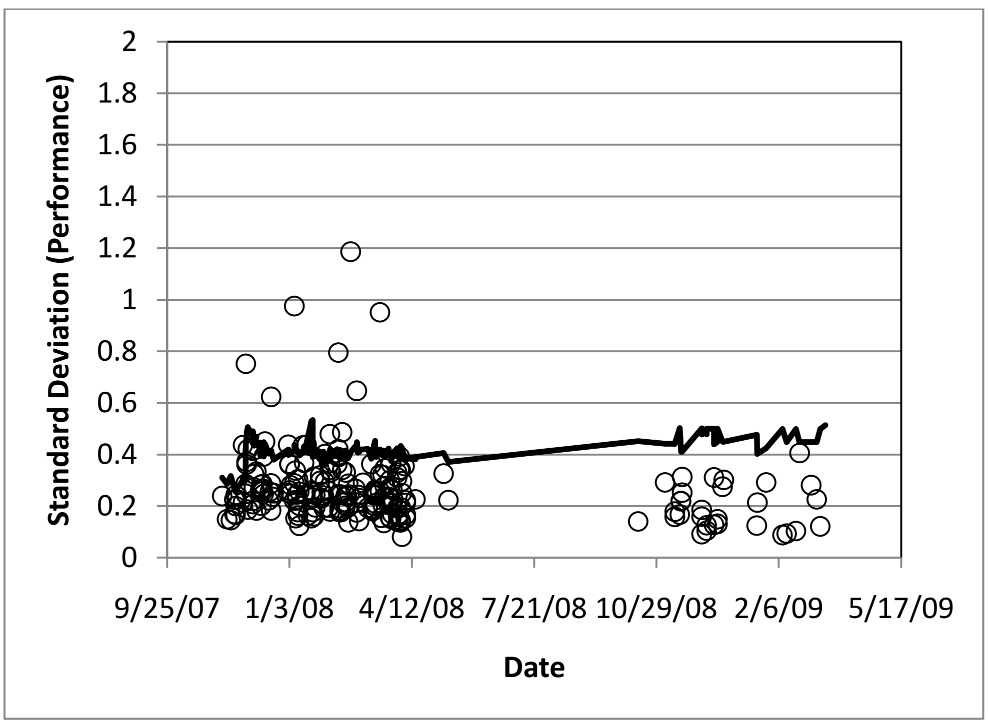

Figure 6. SPC12A Standard Deviation Data

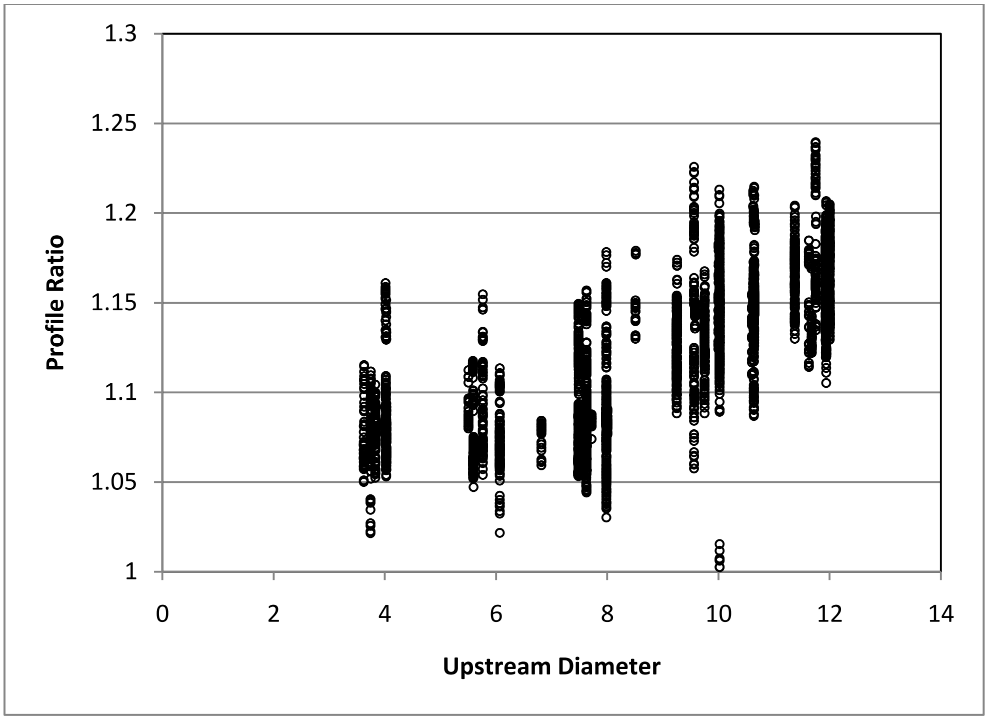

Figure 7. SPC12A Relationship Between Velocity Profile Ratio and Upstream Meter Diameter

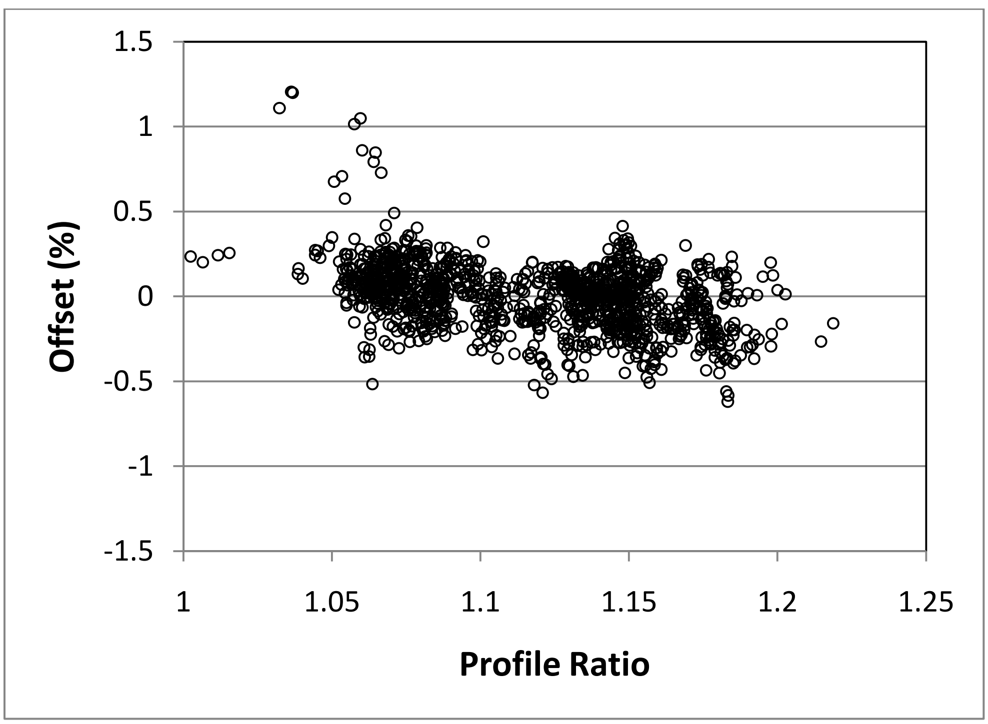

Figure 8. SPC12A Meter Offset Variation Due to Changes in Velocity Profile (10-20 ft/sec)

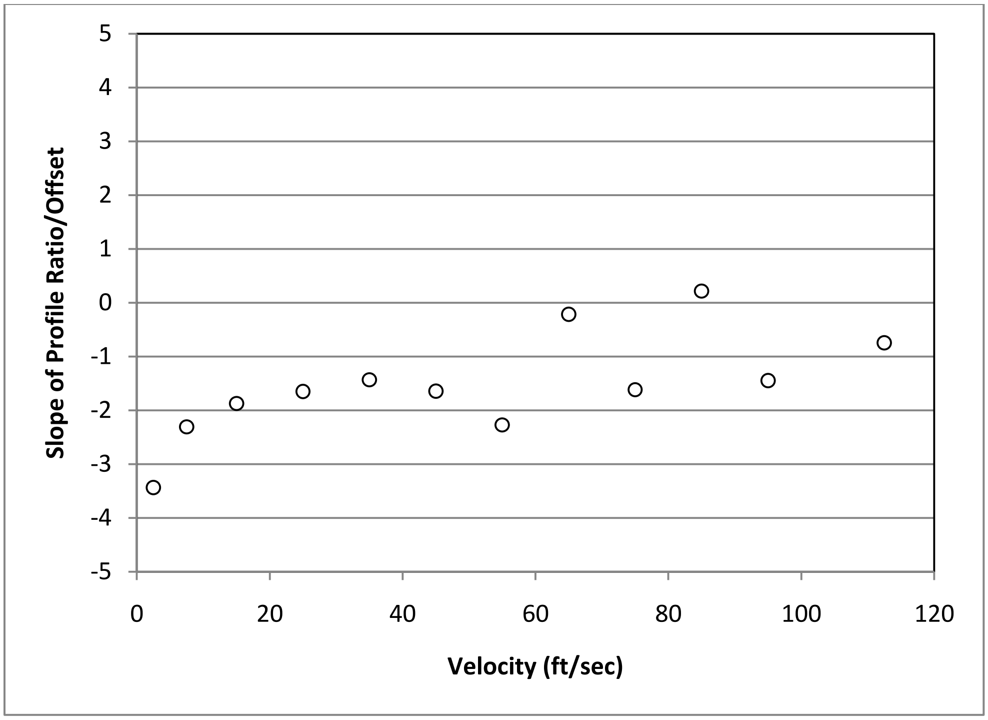

Figure 9. SPC12A Rate of Change of Meter Offset with Meter Velocity Profile Ratio

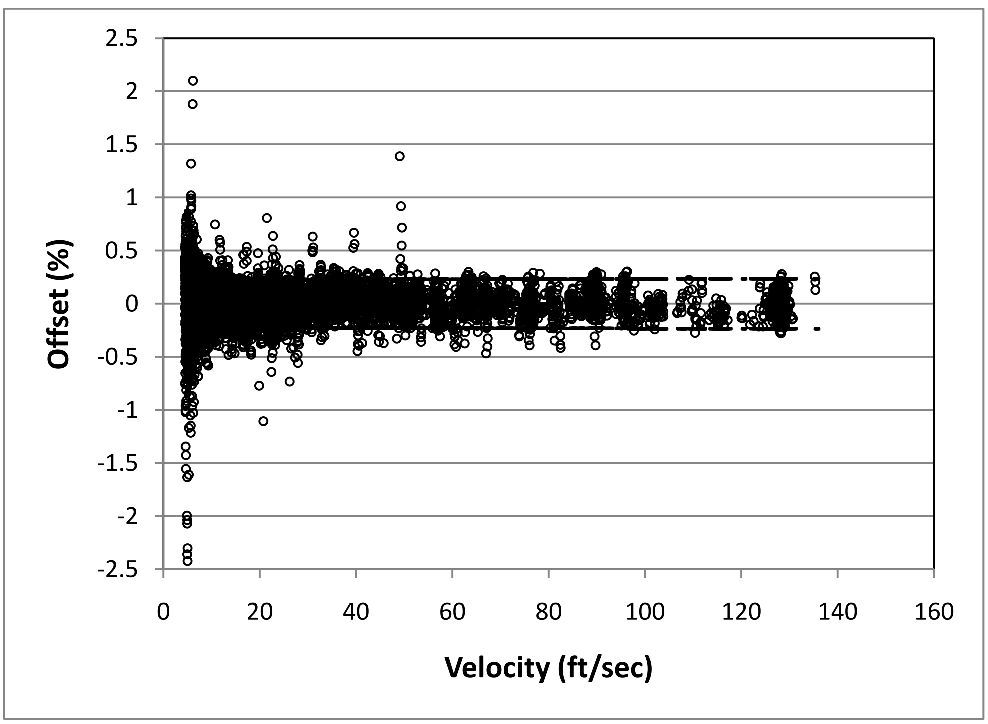

Figure 10. SPC12B Offset Data and Performance Bands

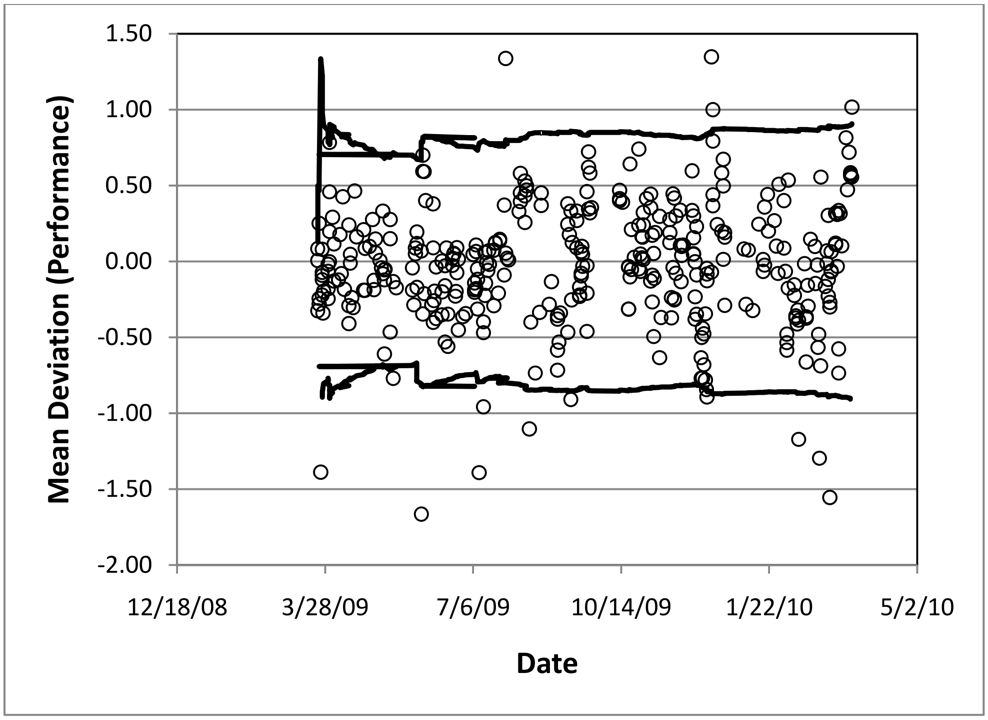

Figure 11. SPC12B Mean Deviation Plot

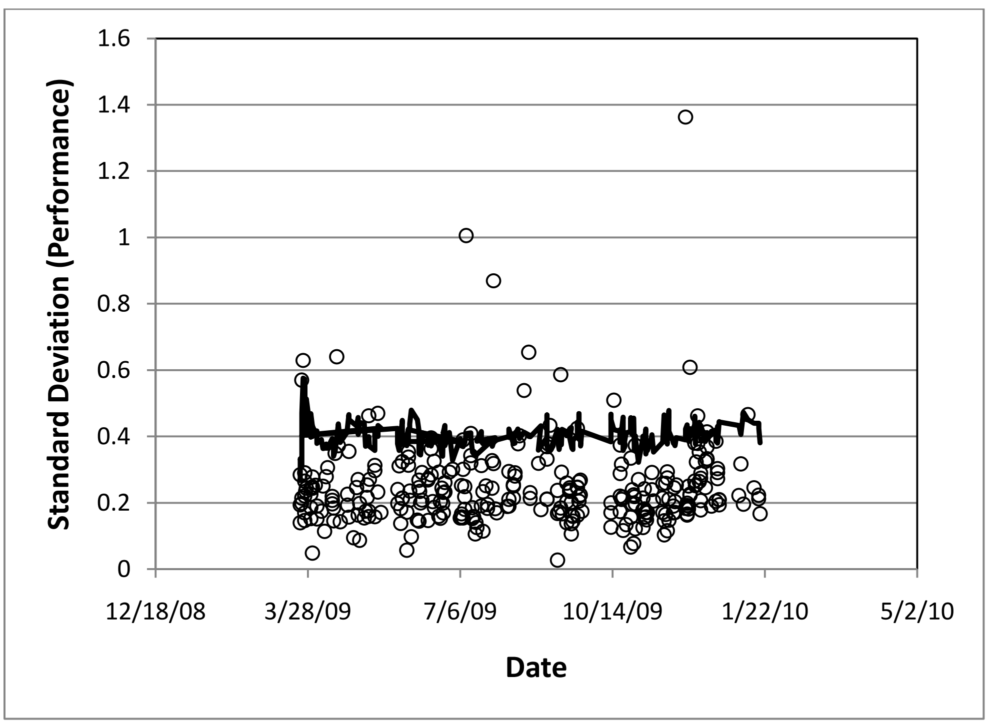

Figure 12. SPC12B Standard Deviation Data

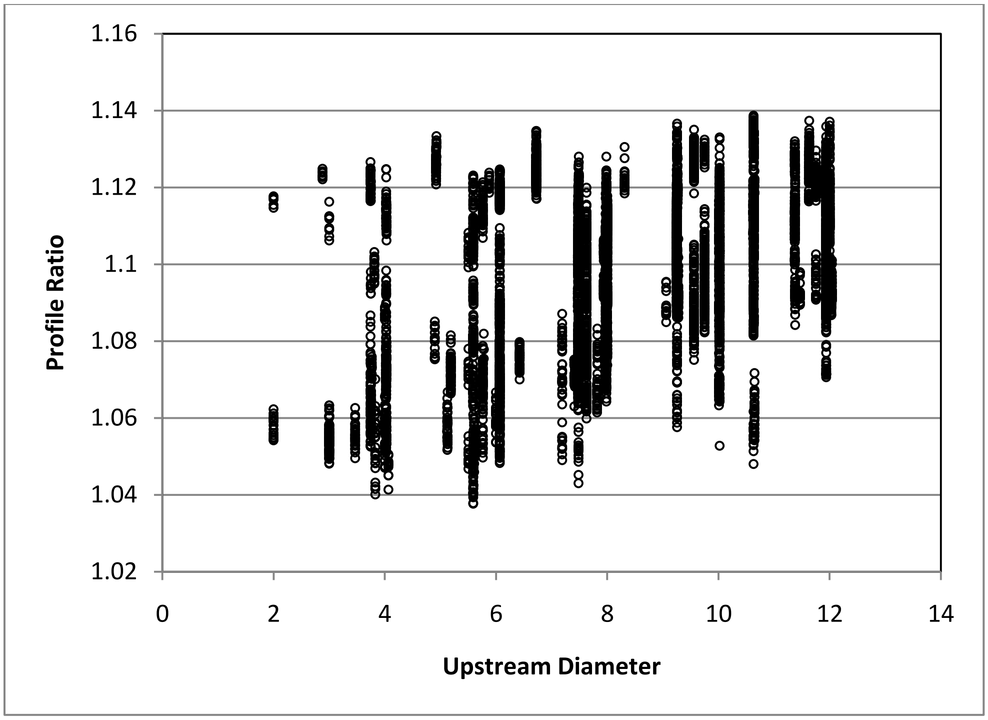

Figure 13. SPC12B Relationship Between Velocity Profile Ratio and Upstream Meter Diameter

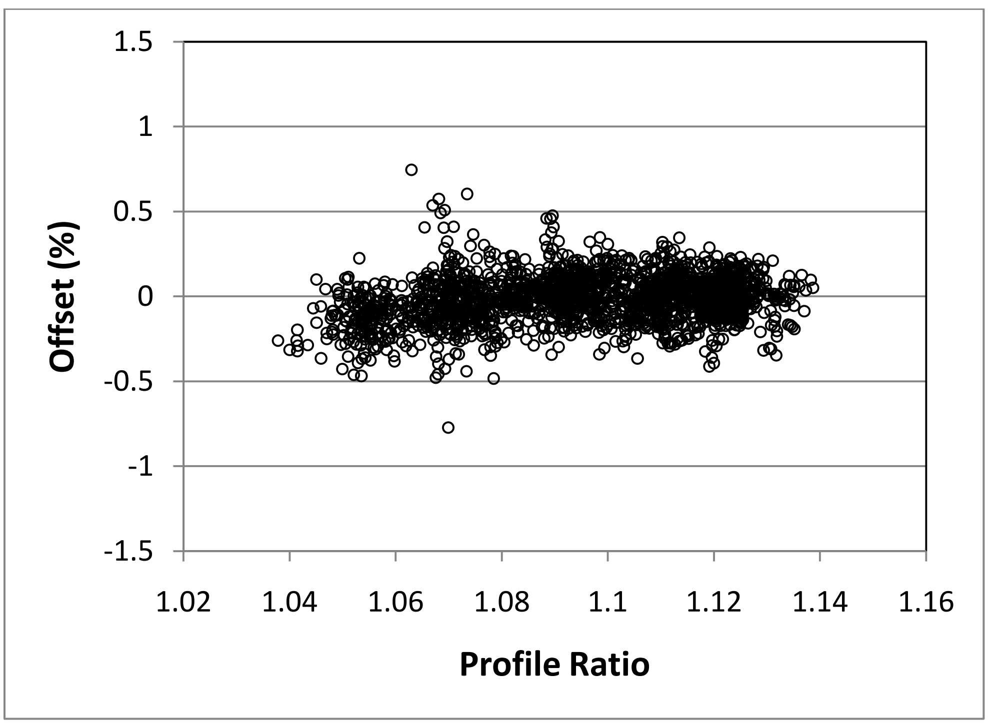

Figure 14. SPC12B Meter Offset Variation Due to Changes in Velocity Profile (10-20 ft/sec)

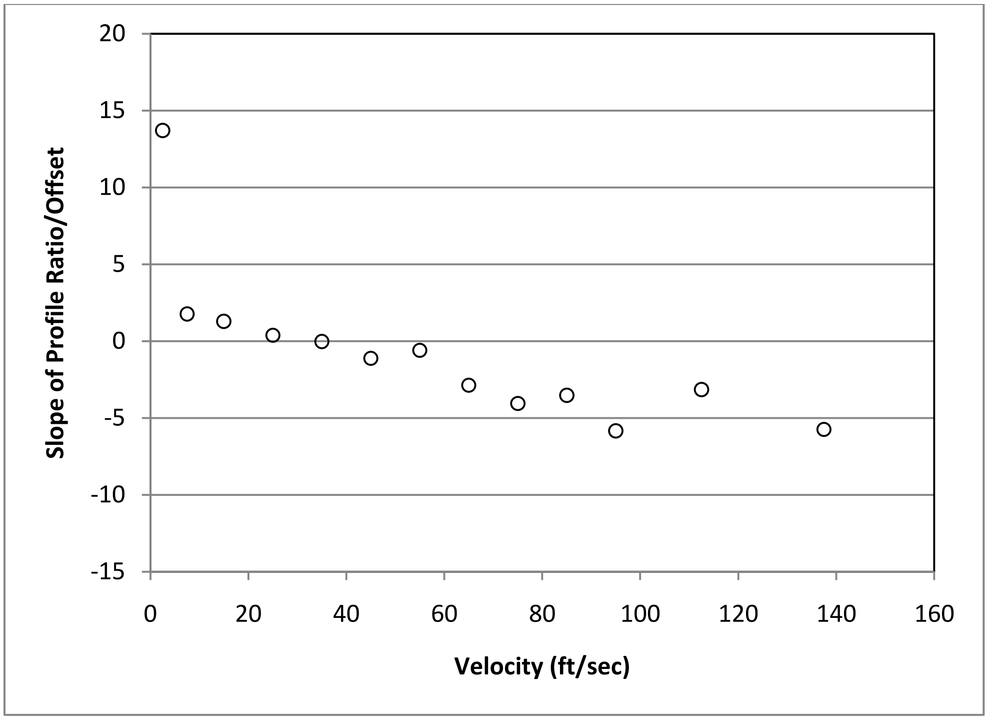

Figure 15. SPC12B Rate of Change of Meter Offset with Meter Velocity Profile Ratio