# DEVELOPMENT OF A VELOCITY PROFILING DOPPLER FLOW METER FOR USE IN THE WASTEWATER COLLECTION AND TREATMENT INDUSTRY

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## ABSTRACT

A new type of Doppler flow meter, the **ADFM Velocity Profiler™**, is presented here. This new meter utilizes new signal processing techniques to measure the velocity profile, or distribution of flow velocities throughout the depth of flow, to determine the flow rate. The result is more accurate flow measurement under a greater variety of conditions. While traditional Doppler flow meters work well in smaller pipes and open channels with ideal or near-ideal flows, they can suffer from performance degradation when the channel dimensions are larger, the flows are hydraulically complex, or the speeds of the flows are very slow (< 0.25 ft/s) or very fast (> 20 ft/s). The Velocity Profiler is designed to measure flow accurately under these challenging conditions.

We present data from a number of different installations. The first are a series of controlled sites with calibrated flows. The accuracy of the Velocity Profiler was found to be within 2% of actual flow under a variety of flow conditions. The second series of tests are comparisons of the Velocity Profiler against traditional Doppler meters. The traditional meters are found to measure flow approximately 10-20% lower than the Velocity Profiler. The difference is located in a lower estimation of the average flow velocity. These differences are attributable to error sources common to the traditional Doppler systems when operated in large pipes. The final series of data are from a 9' diameter sewer interceptor which exhibits reverse flows. Data from this site are also compared to a traditional Doppler system installed at the same site. The traditional Doppler meter again measures lower flows than the Velocity Profiler because of a lower average velocity estimate. Plotting the difference between the two systems as a function of depth shows a clear tendency towards increasing underestimation of velocity, by the traditional system, with increasing depth. This is again in keeping with known possible error sources for a traditional Doppler flow meter.

## KEYWORDS

flow, Doppler, velocity, profile, wastewater, collection, treatment

## INTRODUCTION

Flow meters based on acoustic Doppler principles are widely used in the wastewater industry. However, today's acoustic Doppler flow meter technology has significant limitations in determining flow rate accurately. These limitations prompted the development of a multiple velocity-point measuring, pulsed Doppler instrument known as an ADFM Velocity Profiler™. This paper compares velocity profiling technology to present day Doppler technology and presents test results.

The Velocity Profiler was designed to meet the following goals:

1. Measure velocity accurately. The single point meter's velocity measurement limitations lead to inaccurate results.
2. Measure flow rate accurately in a wide variety of hydraulic conditions. The accuracy of single point meters under non-ideal or dynamic hydraulic conditions is not sufficient in many cases.
3. Most importantly, remove the need for a site-specific calibration of the instrument. Calibrations can be in error and dynamic flow conditions can render a calibration useless for a large portion of a meter's data record.

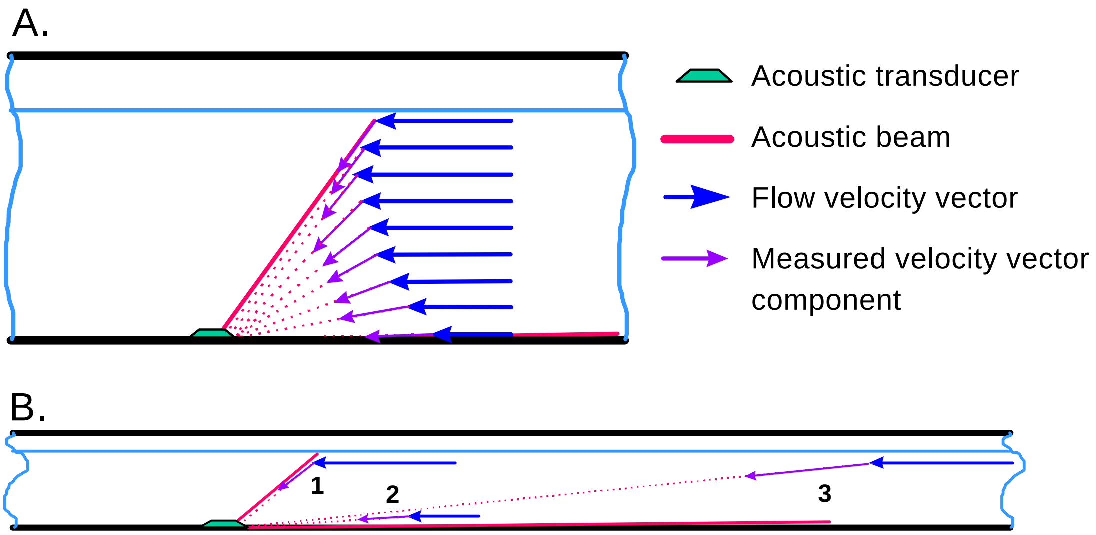
This paper will begin with the operating principles of traditional Doppler meters. Potential error sources inherent to this type of technology will be discussed. The operating principles of the Velocity Profiler are then discussed. It will be shown how the Velocity Profiler's novel approach to Doppler signal processing avoids the pitfalls of traditional Doppler systems. Data sets acquired to test the system's accuracy claims are presented, as a comparison studies between the Velocity Profiler and data from traditional Doppler systems.

## METHODOLOGY

Present day Doppler flow meters measure velocity by transmitting a continuous wave of known frequency, and analyzing the echoes backscattered from material suspended in the water to determine a Doppler frequency shift. This shift is proportional to the relative velocity between the suspended material and the transmitter. As the return signal is actually a ***spectrum*** of Doppler shifts, correct analysis of this spectrum is the key to successful Doppler signal processing.

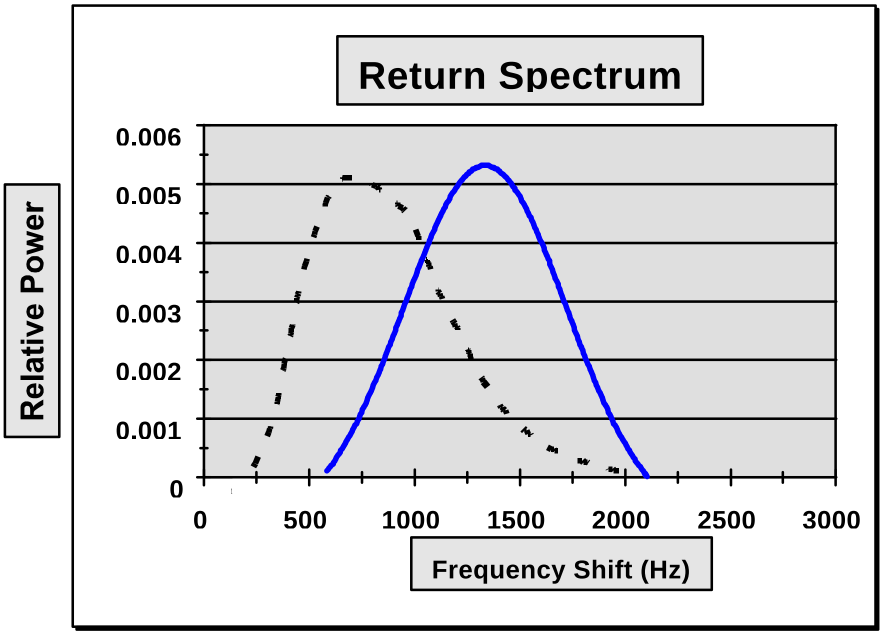
Two factors influence the return signal spectrum's shape. The first is related to the angular width of the transmitted acoustic beam. The Doppler shift magnitude is proportional to the velocity ***component*** along the direction between the receiver and the suspended material. Therefore, the spatial relationship between the suspended material and the receiver affects the return signal spectrum. The larger the acoustic transmitter/receiver beam width, the larger the range of spatial relationships, and the greater the return signal spectrum's width. Figure 1.A. shows the range of spatial relationships between the transmitter/receiver and the velocity vectors in the flow. The second factor is range bias. Suspended particles close to the receiver contribute more energy to the spectrum than particles farther away. In figure 1.B. it is seen that returns from flow vectors 1 and 2 will have greater power than the return from vector 3. However, the Doppler shifts from vectors 1 and 2 are much smaller than that of vector 3. Average velocity determined from a calculation of the power spectrum's first moment will result in an value biased towards flows near the receiver.

Figure 1. A. Origin of spectral broadening of the return signal due to a wide acoustic beam. B. Origin of range bias errors.



Typical single point Doppler flow meters determine the average velocity of a flow from a large ensonified volume, requiring wide acoustic beam widths and long transmit times, and making them susceptible to the errors outlined above. Figure 2 shows the effect these errors have on the return spectrum. The solid line is the desired spectrum, and the dotted line is the actual received spectrum. A calculation of first moment to determine the return spectrums average frequency will result in an underestimation of the average velocity. Methods that measure peak Doppler shift are an improvement, although they still suffer from the same problem - determining the frequency shift from an altered spectrum. Also, these methods depend on a finite signal to noise ration (S/N). Signals measured at finite S/N will always have the true peak Doppler shift submerged in noise.

Figure 2. Degradation of return signal spectrum due to spectral broadening and range bias.



The results of the above velocity measurement also need to be interpreted, with respect to the hydraulic conditions of the installation site, to generate a flow rate value. This is where site-specific calibrations, and their potential errors, come into play. These calibrations are empirical in nature, and are often done for only a few flow conditions. If the flow conditions change (e.g., from free flow to backwater conditions) the flow pattern can change significantly invalidating any assumptions made during calibration.

## THE RANGE-GATED DOPPLER FLOW METER TECHNIQUE

The Velocity Profiler transducer assembly consists of four piezoelectric transducer elements that emit short acoustic pulses (called ***pings***) into the water. The system range-gates the return signal, measuring velocity in many small volumes (called ***bins***) which are regularly spaced throughout the water column. Figure 3 shows the placement of the bins in the depth of flow, which are represented by the small black circles. The velocity in each volume is measured independently, so that an independent velocity profile for each beam is obtained.

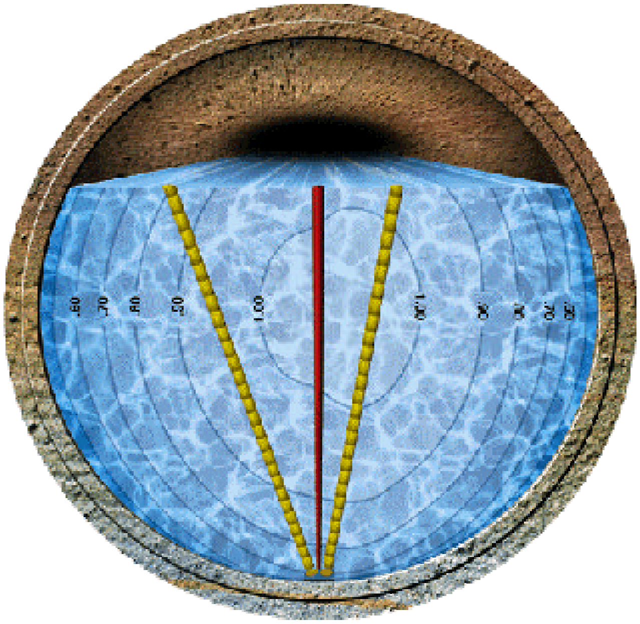
The narrow beams minimize errors related to beam width. Since the acoustic pulses are very short, and the velocity is measured in small bins, range bias is virtually eliminated. A single bin is typically a cylinder 4 cm in diameter and 5 cm long. In a 2 m deep flow there can be as many are 40 discrete bins for every beam. Thus we have an accurate measure of the velocity distribution within a pipe or channel, both vertically and transversely.

Each time the Velocity Profiler pings, it collects the velocity data. This data will have a random error associated with it, due to the inherent spectral width of the transmitted pulse and the nature of "cloud scattering", the scattering of the pulse off of the suspended material. As this error is random, it can be reduced by averaging many pings together into an ensemble. The ensemble standard deviation of a velocity measurement is the single ping standard deviation, divided by the square root of the number of pings averaged together. Typically, the averaging of 400 pings takes only a few minutes. In this way, it is possible to get extremely precise estimates of velocity at a fairly rapid rate.

In addition to velocity data, a fifth transducer measures the water level. This fifth acoustic beam is directed towards the surface and is represented in the figure by the gray column. By range-gating the returns of this vertical beam, the distance to the surface is accurately measured.

The velocity data from each bin is entered into a data-adaptive algorithm which generates a mathematical description of the 2D velocity structure; the flow pattern or velocity profile, represented by the dotted circles within the depth of flow. Known hydraulic functions are fit to the real data to interpolate velocities throughout the entire depth of flow. The 2D velocity distribution is integrated over the cross-sectional area to determine the flow rate.

Figure 3. Representation of the Velocity Profiler's method of operation.



Doppler technology applied in this way results in a flow meter that is less susceptible to measurement error for most flow conditions. It does not require site-specific calibration for accurate flow rate measurement. An accurate description of velocity distribution throughout the pipe is computed directly from discrete velocity measurements.

## RESULTS

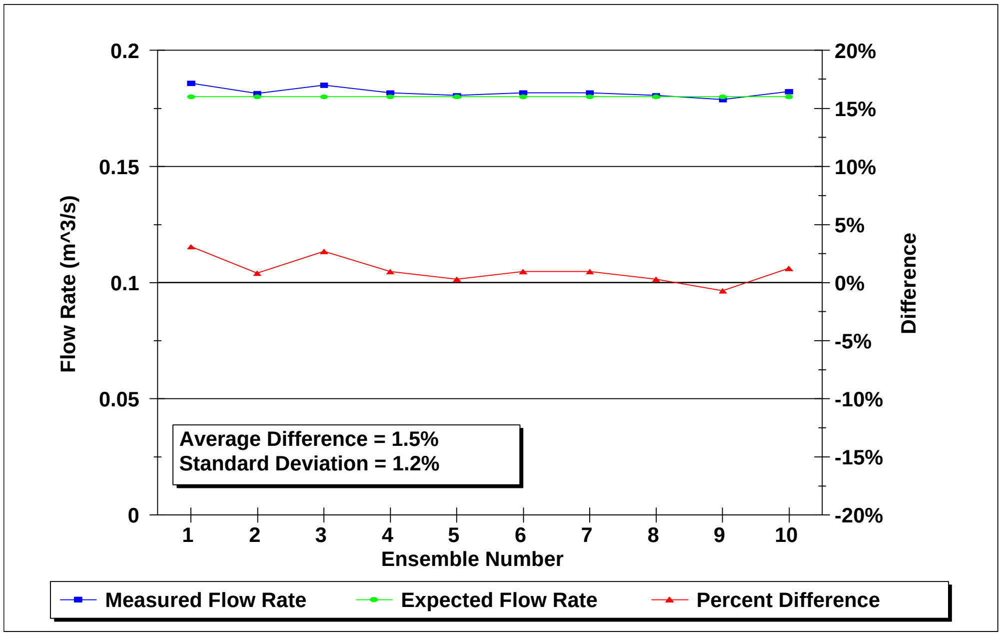
The Velocity Profiler has been tested under both controlled and field conditions. The first three data sets presented here are from laboratory tests in which the Velocity Profiler's accuracy was examined.

### CONTROLLED TESTS

The first data set shows data collected in a 600 mm wide rectangular channel located at the Australian Water Technologies (AWT) offices in Sydney, Australia. The flume's water supply line is fitted with a magnetic flow meter, NATA certified to an accuracy of 0.25%. There was no site-specific calibration of the system. The Velocity Profiler was simply placed in the middle of the channel, on the bottom, and turned on.

Figure 4 is of data collected during the test. Measured Flow Rate (square markers) refers to data collected by the Velocity Profiler. Expected Flow Rate (round markers) refers to data from the magnetic flow meter on the supply line. Also displayed is the percentage difference (triangular markers. The difference is referenced to the "true" value of flow measured by the magnetic flow meter. The average difference between the two meters is 1.5%, with a standard deviation of 1.2%.

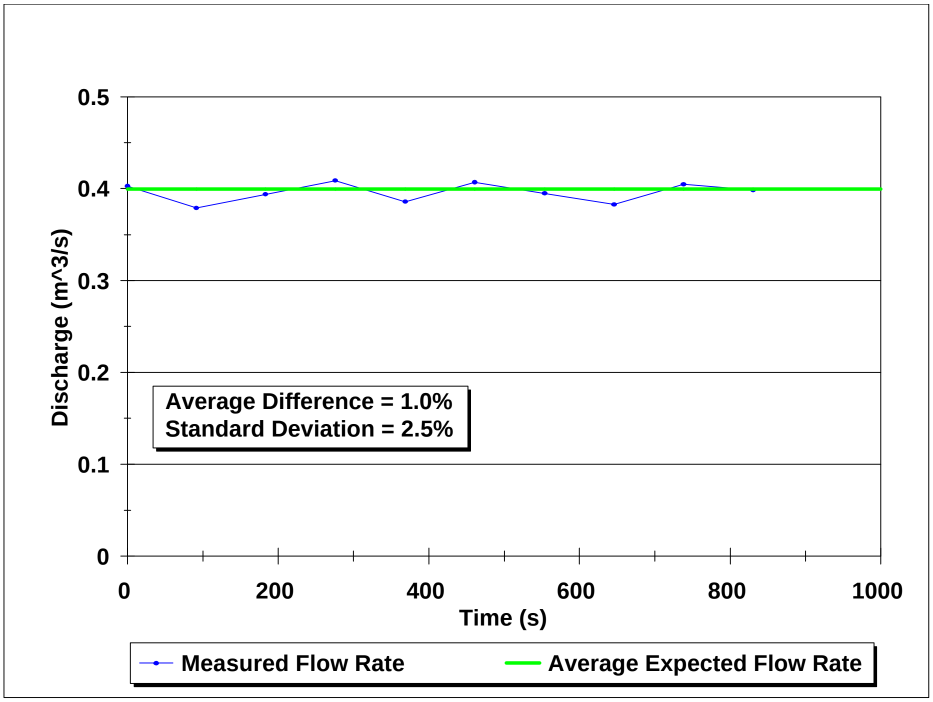
Figure 4. Velocity Profiler data collected in a 600 mm wide channel.



The next data set was collected at the River Hydraulics and Hydrology Section of the Civil Engineering Research Institute of the Hokkaido Development Bureau in Japan. The tests were conducted in a 1000 mm wide rectangular flume. The flume's water supply came from a 800 mm pipe fitted with a magnetic flow meter to measure the flow rate. This meter was calibrated to an accuracy of 0.5%. The Velocity Profiler was placed on the channel bottom, in the middle, and no calibration was performed.

Figure 5 shows a plot of 10 ensembles of Velocity Profiler data collected with the initial setup. Measured Flow Rate refers to data collected by the Velocity Profiler and Average Expected Flow Rate refers to readings by the mag meter. The averaged difference between the Velocity Profiler and the mag meter is 1.2%. The standard deviation of the flow rate measurements collected by the Velocity Profiler is 1.5%.

Figure 5. Velocity Profiler data collected in a 1000 mm wide rectangular channel



Note to the reader. The following data sets were collected in association with municipal and federal agencies located in the US. As these agencies use imperial units of measurement, the following data sets will be presented in these units.

The third data set to be presented comes from tests conducted at the Bureau of Reclamation's Water Resources Research Laboratory in Denver, Colorado. The Velocity Profiler was tested in two sites at the lab - a 4 ft wide flume and a 12 ft wide rectangular channel. In both lab sites, the system was installed on the bottom of the channel, in the center of the channel. No in-situ calibration or rating was performed.

Venturi meters were used to measure flows in both sites. The flows were determined using a mercury manometer to measure the differential pressure across the venturi. This manometer was read several times during the above tests. Once set up, the flow was held constant through the control of an active feedback circuit. The laboratory venturi meter was calibrated prior to the Velocity Profiler demonstration. A weigh tank facility was used to calibrate the venturi meter and the uncertainty in the venturi flow measurement was within ± 0.8 % of the weigh tank measurements for flow rate.

Figure 6 shows the test results from the 4 ft flume, with flow rate and depth plotted as a function of time. The round symbols are the Velocity Profiler flow data, the squares are the spot readings of the lab's venturi meter, and the triangles are Velocity Profiler depth readings. The Velocity Profiler data correlates very well with the venturi meter readings.

At the beginning of the record, there is some scatter to the Velocity Profiler data, as the level in the flume had just been set and the depth of the system was still equilibrating. After the first few points, the flow rate readings (and depth readings, which are not shown) become steady. The Velocity Profiler average of flow rate during the initial depth of flow of 4 ft (after depth equilibration) is 6.86 $ft^3$/s, compared to 6.98 $ft^3$/s for the manometer readings during the same time period; a difference of -1.72%.

We also see a change in the Velocity Profiler flow measurement after the level is increased to 7 ft at around 10:00 a.m. The Velocity Profiler is now over predicting the flow by around 5%. This is because one of the beams is intersecting the wall of the flume at about 5.5 ft from the bottom. Consequently, the beam is reflected back towards the middle of the flow where the velocities are larger than they are near the wall. This falsely raises the average velocity of this beam pair, raising the estimate of flow rate.

The spacing on the x-axis is irregular as several sampling intervals were used. The intervals are different as some of the Velocity Profiler's measurement parameters, such as bin size and the number of individual measurements within a sampling interval, were varied. The changes were selected so that they did not affect the overall accuracy of the flow rate measurement.

Figure 6. Velocity Profiler data collected in a 4 ft. flume at the Bureau of Reclamations laboratories in Denver, Colorado.

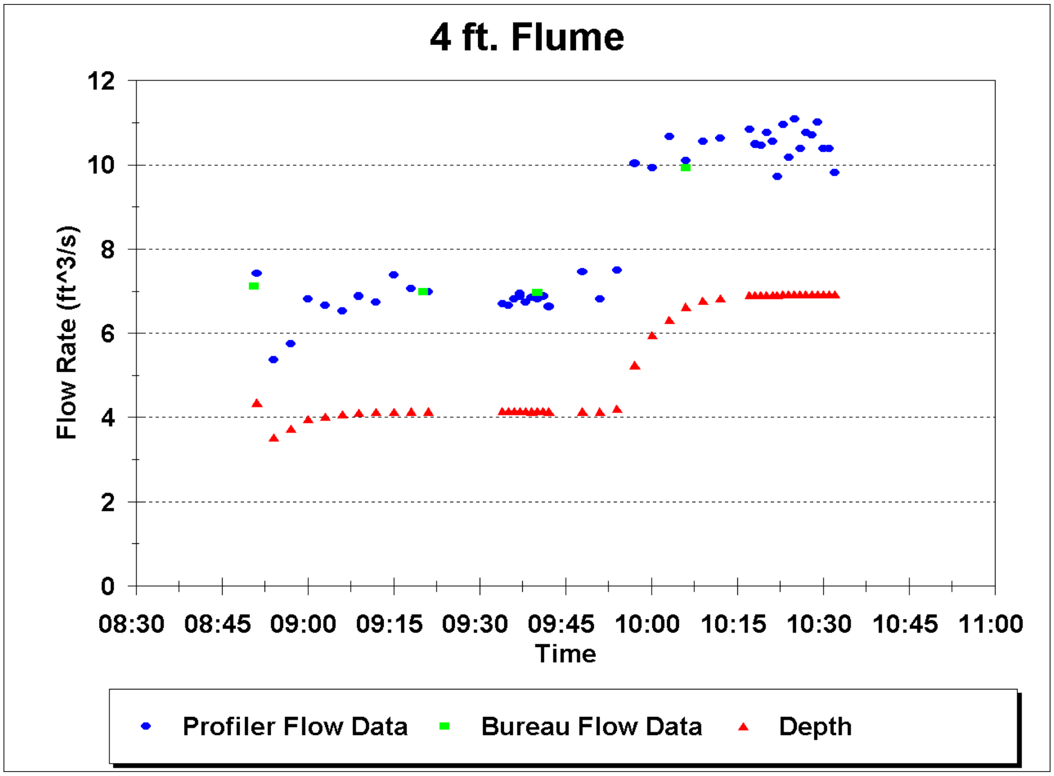


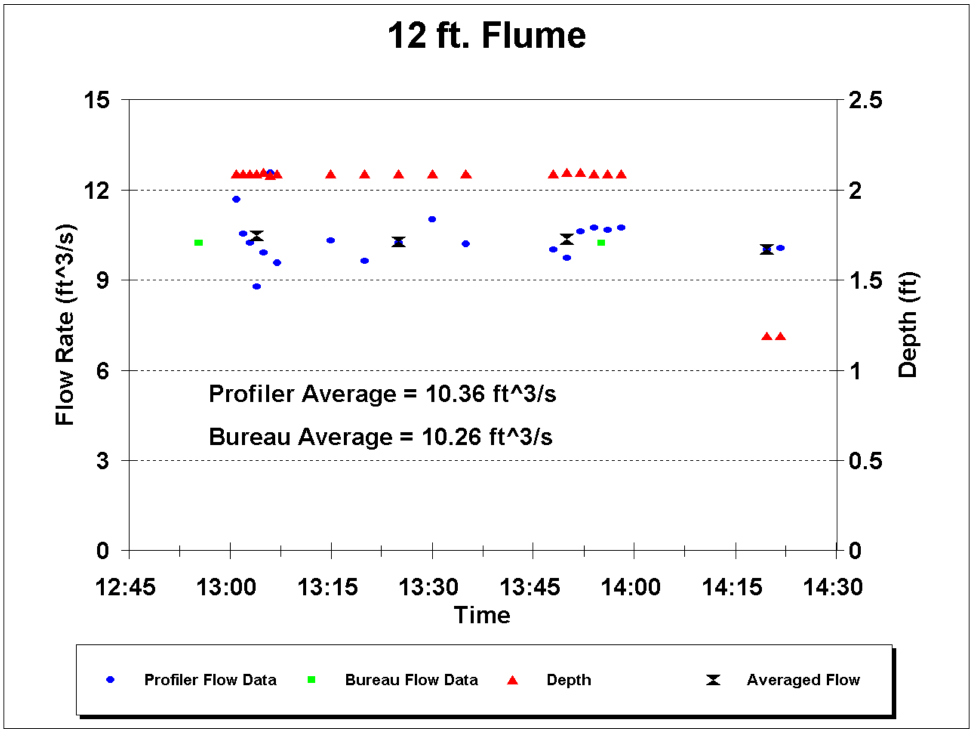
Figure 7 shows the results from several test runs in the 12 ft channel. The round symbols are the Velocity Profiler data, the squares are the spot readings of the lab's venturi meter, and the triangles are velocity Profiler depth readings. Again, the Velocity Profiler data were averaged over different sampling intervals.

The first seven Velocity Profiler measurements were collected with an averaging interval of 1 minute. The average of these seven measurements is 10.48 ft$^3$/s. The venturi reading was 10.26 ft$^3$/s and this flow remained constant for the remainder of the test. The next five measurements were collected with an averaging interval of 5 minutes. The average of these five measurements is 10.29 ft$^3$/s. The next six measurements were collected with an averaging interval of 2 minutes, an their average is 10.43 ft$^3$/s.

This test demonstrates how the Velocity Profiler's measurements become more precise as the number of measurements averaged together is increased. The ability to average hundreds of individual flow measurements over a short period results in a very precise flow measurement. This is further illustrated by comparing the average of all eighteen Velocity Profiler measurements with the two venturi meter readings. This average is 0.97% different from the venturi meter average.

It is interesting to note that the final two Velocity Profiler readings on this plot were acquired at a depth of flow of 1.2 ft. This measurement was made with a width to depth aspect ratio of 10:1. The average value of these readings is 10.07 $ft^3/s$, a difference of -1.85% from the venturi meter readings. This demonstrates the Velocity Profiler's unique capability to measure flows in wide, shallow channels.

Figure 7. Velocity Profiler data collected in a 12 ft. rectangular channel at the Bureau of Reclamations laboratories in Denver, Colorado.



## COMPARISON TESTS

In the following data sets, the Velocity Profiler is compared against traditional Doppler systems. In these tests, the instruments are mounted at the same site and the flow rate data are compared for value and consistency.

Figure 8 is a comparison of Velocity Profiler flow rate data to two traditional Doppler type devices. All three systems were mounted in the same place in a 66 inch diameter sewer. Although the systems all correlate fairly well during low flow conditions, there is a large difference in flow rate estimation during high flows. Comparison of the depth data showed that all 3 instruments measured the same depths to within approximately 1%. Comparison of average velocity data, however, shows that the continuous wave Doppler devices correlate well with each other, but the Velocity Profiler™ average velocity values averaged 10-12% greater. This difference becomes more pronounced as the depth increases, which follows from the previous discussion of error sources in wide beam, continuous wave Doppler meters.

It should also be noted that the data from the traditional Doppler meters contains a greater degree of spread. This is due to the greater standard deviation of the velocity measurement that these systems will have. Averaging a number of measurements together will quiet this noise down, but this will also result in a loss of temporal resolution.

Figure 8. Comparison between Velocity Profiler flow rate data and two standard Doppler devices.

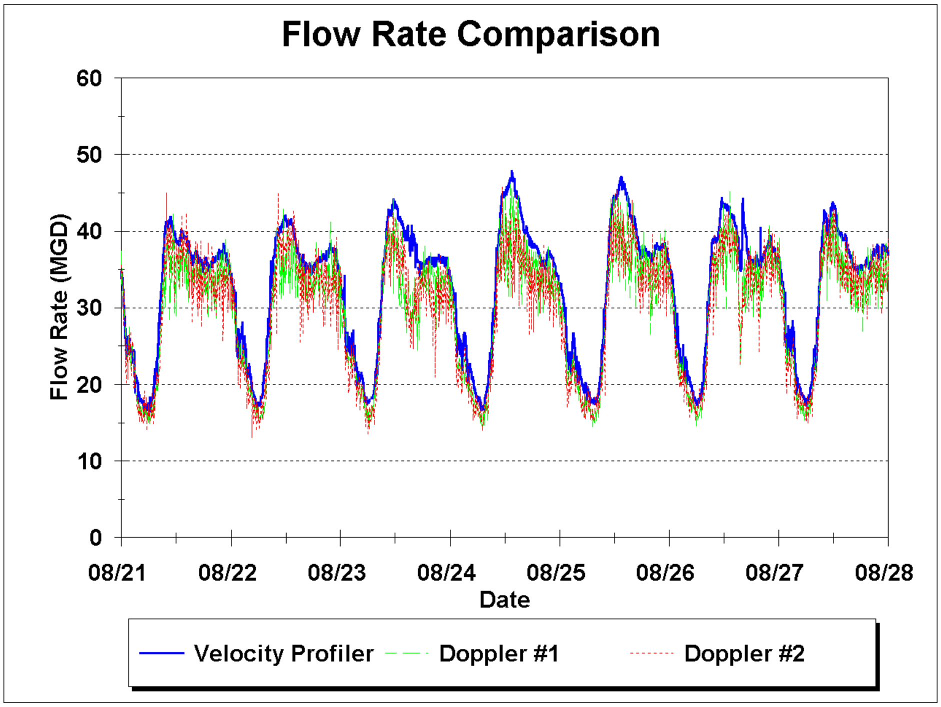
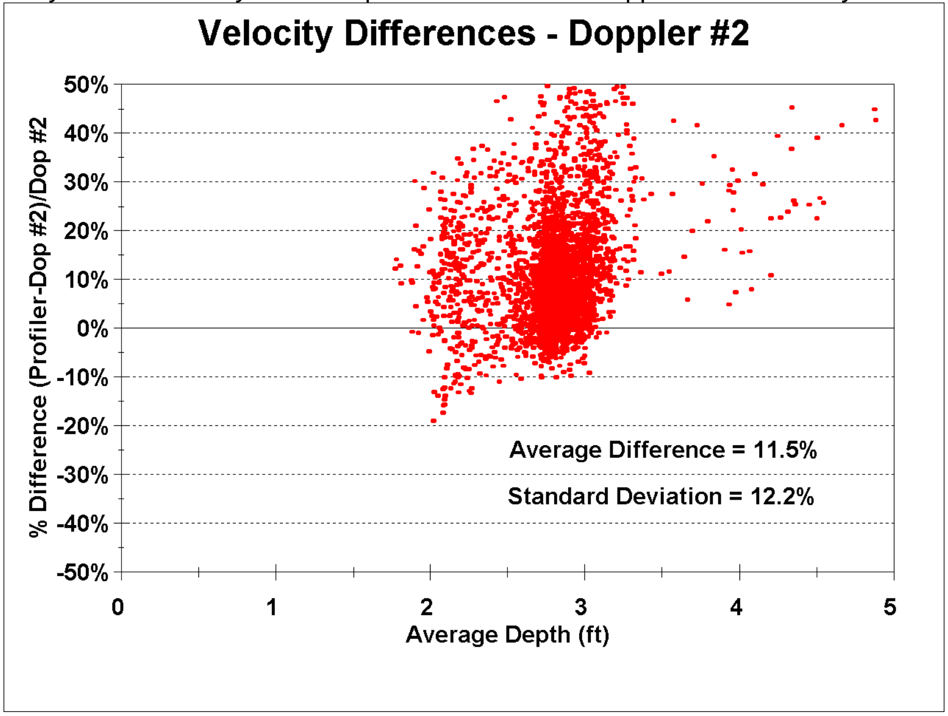


Figure 9 is a plot of the ratio of the difference between average velocity measurements of the Velocity Profiler and Doppler #2, to Doppler #2 as a function of depth of flow. The average difference is about 11.5%, with a trend toward increasing difference with increasing depth.

Figure 9. Velocity Profiler velocity data compared to traditional Doppler meter velocity data.



The velocity difference data between the Velocity Profiler and Doppler #1 was similar to Figure 9.

Figure 10 is a comparison of Velocity Profiler flow rate data to a traditional Doppler meter. The two instruments were mounted in a 108 inch diameter sewer. Again the systems all correlate fairly well during low flow conditions, but there is a large difference in flow rate estimation during high flows. Comparison of the depth data showed that both instruments measured the same depths to within approximately 1%. Comparison of average velocity data, however, shows that the Velocity Profiler average velocity values averaged 10.6% greater than the traditional Doppler meter. Again, this difference becomes more pronounced as the depth increases.

It is also interesting to note that there were flow reversals during this measurement period. Traditional Doppler meters can measure reverse flows, if they are setup properly when installed. The traditional meter is able to resolve the reverse flows, but was unable to measure velocities between zero and approximately ± 0.35 ft/s.

Figure 10. Comparison between Velocity Profiler flow rate data and a traditional Doppler meter.

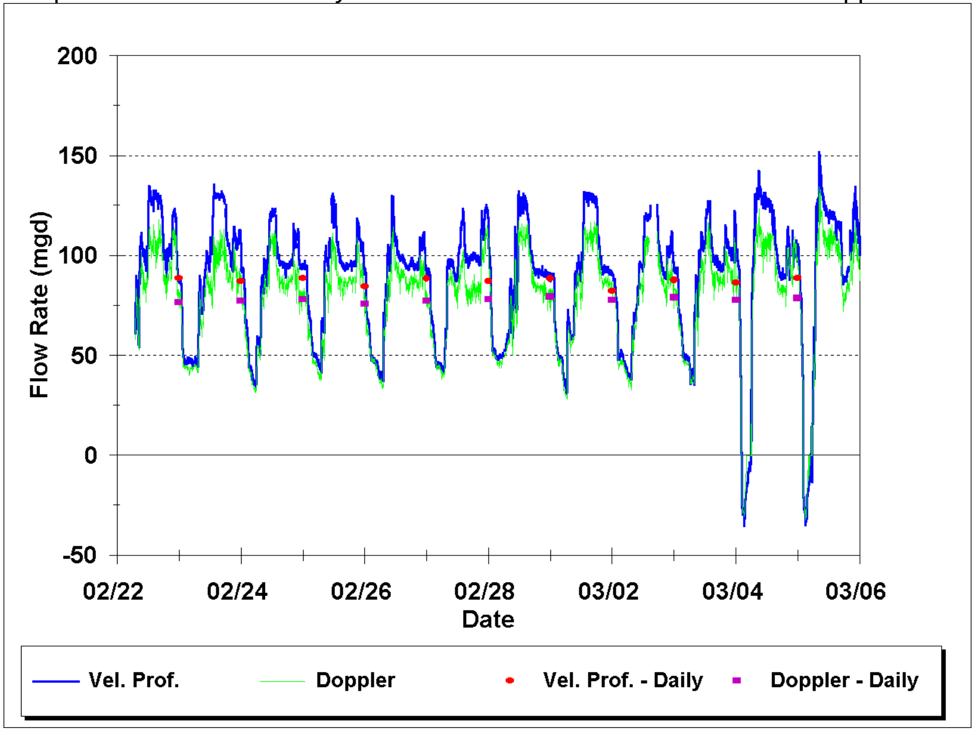
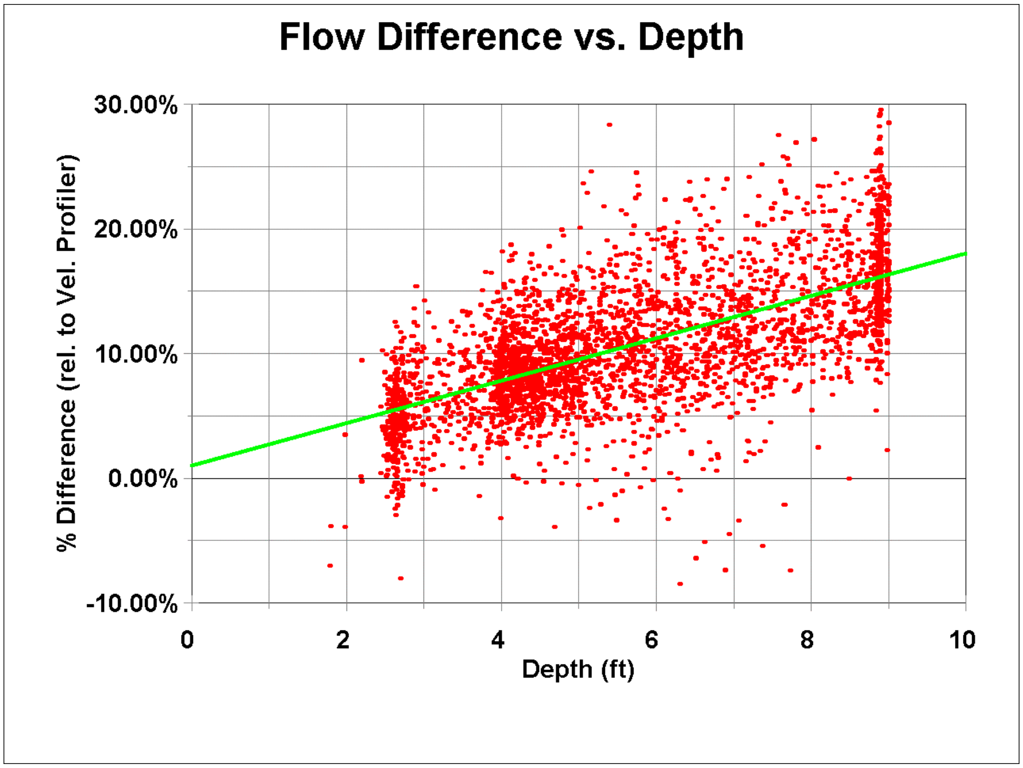


Figure 11 is a plot of the ratio of the difference in flow rate between the two meters to the Velocity Profiler's reading, as a function of depth. The regression line (dark line) was not forced through a y-intercept of zero, and intercepted the axis at approximately 1%. The line has a value of 16.3% at the maximum depth of 9 ft. It is interesting to note that differences of 20-30% are quite common past a depth of 5 ft or so, and that virtually all data points have a difference of at least 10% at maximum depth.

Figure 11. Ratio of the difference in flow rates between the two meters to the Velocity Profiler reading as a function of depth.



## DISCUSSION

In the Controlled Tests the Velocity Profiler was found to accurately measure flow to within 2% of actual flow, with the actual flow being measured by calibrated instruments. This accuracy was achieved without any special installation considerations; often the system was simply laid on the floor of the channel, without any type of in-situ calibration or rating. The required installation time was only as long as it took to mount the system in the desired position. After this, the instrument was started and data acquisition began immediately.

The root of the Velocity Profiler's capability lies in the abundance of data collected, and the precision and accuracy of the data. With the measurement of many individual velocity points, a much better picture of a flows hydraulic condition is obtained. This allows us to get a much better estimate of the flow rate, without the need for ideal conditions or in-situ calibrations.

In the Comparison Tests against traditional Doppler meters, the Velocity Profiler was found to measure higher velocities, and therefore higher flow rates. In all cases it was demonstrated that this difference had a depth of flow dependence; the differences increased with increasing depth of flow. This is in keeping with the known potential error sources for continuous wave Doppler meters. It is safe to say that as pipe or channel dimensions increase, these errors will become more pronounced.

In the final data set, it was observed that the traditional Doppler meter was unable to resolve slow flows (on the order of 0.3 ft/s or less). This is most likely due to the presence of a notch filter in their signal processing. A continuous wave meter transmits signal during the entire measurement period (hence the name, continuous wave). The transmitted frequency must be filtered out of the received signal, otherwise it would swamp any signal received from the water. Since this transmitted signal also corresponds to zero Doppler, and therefore zero velocity, these meters are unable to resolve zero Doppler. The filter is meant to be designed such that only a small area around zero Doppler is affected. However, in the field environment this usually translates to a "dead zone" around zero velocity of approximately ± 0.2-0.4 ft/s, depending on the conditions and the actual meter being used. Slow flows are difficult for traditional Doppler systems to measure.

Since a Velocity Profiler uses pulse Doppler technology, zero and near-zero velocities are recognized equally well with larger velocities. In a pulse Doppler system, the same transducer element is used for transmit and receive. Therefore, all the signal being sensed by the receiver is signal coming from the water column. This method does require that the transducer have a small amount of downtime between transmit and the receiving and processing of signal. This downtime is typically less than 80 µs, the time it takes sound to travel through 5 cm of water and back.

## CONCLUSIONS

In summary, the ADFM Velocity Profiler™ was developed to bring new capability to flow measurement - accurate flow measurement without the limitations of traditional Doppler meters. The above data demonstrate the significant benefits of the ADFM Velocity Profiler™:

- Flow rate measurement accuracy on the order of 2% .
- No in-situ calibration is required.
- No interpretation of measured results required.
- Velocity profiling™ method estimates average velocity accurately over a wide variety of physical and hydraulic conditions.
- Site selection is much less critical.