New Velocity Profiling Flow Measurement Technology for Accurate Water Management

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Introduction

Key to the successful management of water resources is accurate understanding of the flow quantity. Unfortunately, measurement of flow in an open channel is often costly, manpower intensive, and the performance limitations of the available technology may lead to inaccurate results. A new flow measurement approach, utilizing pulse Doppler signal processing, was developed to allow accurate measurement of flow rates in open channels and pipes even when the flows contain slow velocities or other complicated hydraulic conditions. The new meter derived from this technology is known as the ADFM Velocity Profiler (ADFM)

Laboratory tests of the ADFM, were conducted at the Bureau of Reclamation's Water Resources Research Laboratory in Denver, CO. Subsequent field tests of the instrument were conducted in the San Luis Drain near Los Banos, CA., and more recently in the Arizona Canal in near Phoenix in conjunction with the Salt River Project. The results of these tests demonstrate the ability of the ADFM to accurately measure flow in a variety of conditions without a site-specific calibration. The ADFM obtains accurate flow measurements in areas where traditional discharge measurement devices are impractical. It is suitable for calibrating existing flow measurement structures and for research studies that require velocity profile measurements.

The Instrument

Figure 1 shows a typical ADFM installation for measuring open channel flow in a pipe. The ADFM transducer assembly is mounted on the invert of a pipe or channel. Piezoelectric ceramics emit short pulses along narrow acoustic beams pointing in different directions. Echoes of these pulses are backscattered from material suspended in the flow. As this material

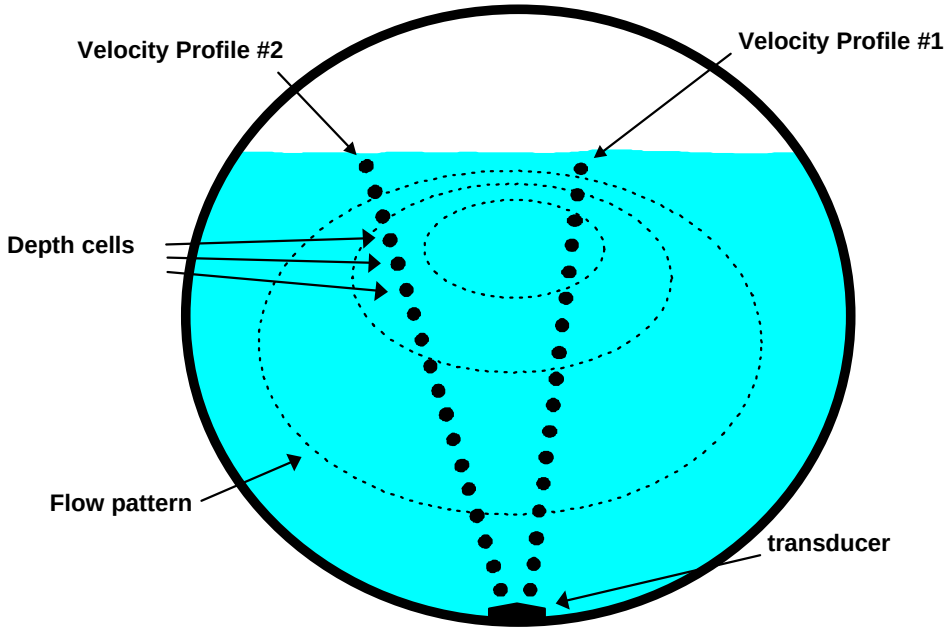

Figure 1. ADFM measurement technique. This figure shows the spatial relationship of the depth cells and the profiles relative to the transducer.

has motion relative to the transducer, the echoes are Doppler shifted in frequency. Measurement of this frequency enables the calculation of the flow speed. A fifth ceramic mounted in the center of the transducer assembly, and aimed vertically, is used to measure the depth.

The ADFM divides the return signal into discrete regular intervals that correspond to different depths in the flow. Velocity is calculated from the frequency shift measured in each interval. The result is a profile, or linear distribution of velocities, along the direction of the beam. Each of the small black circles in Figure 1 represent an individual velocity measurement in a small volume known as a depth cell.

The directions of the velocity profiles in Figure 1 are based on the geometry of the ADFM's transducer assembly. Figure 2 shows a side view of the transducer assembly. The profiles shown in Figure 1 are generated from velocity data measured by an upstream and downstream beam pair. The data from one beam pair are averaged to generate Profile #1, and a beam pair on the opposite side of the transducer assembly generates Profile #2.

Since Doppler measurements are directional, only the component of velocity along the direction of transmit and receive is measured, as shown in Figure 2. Narrow acoustic beams are required to accurately determine the horizontal velocity from the measured component. The narrow acoustic beams of the ADFM insure that this measurement is accurate. Also, the range-gate times are short and the depth cells occupy a small volume - cylinders approximately 5 centimeters long and 5 centimeters in diameter. This insures that the velocity measurements are truly representative of that portion of the flow. Potential bias in the return energy spectrum due to range dependent variables is avoided. The result is a very precise measurement of the vertical and transverse distribution of flow velocities.

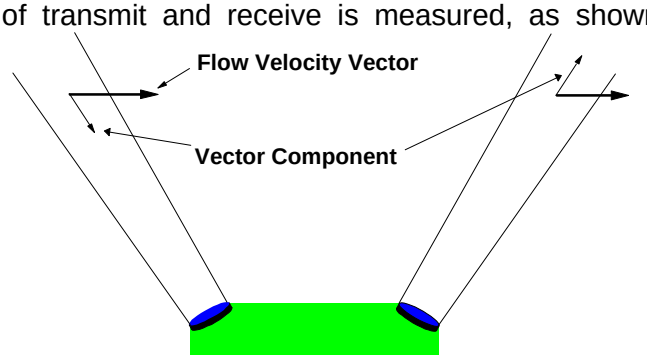

Figure 2. ADFM Beam Geometry

The velocity data from the two profiles are entered into an algorithm to determine a mathematical description of the flow velocities throughout the entire cross-section of the flow. The algorithm fits the basis functions of a parametric model to the actual data. The result predicts flow velocities at all points throughout the flow. These results are integrated over the cross-sectional area to determine the discharge.

The key benefit to this approach is that the system will operate accurately under different hydraulic conditions. As hydraulic conditions change, the change will manifest itself in the distribution of velocity throughout the depth of flow. As the ADFM is measuring the velocity distribution directly, it will adapt to the changes in hydraulics, and generate a flow pattern that is representative of the new hydraulic conditions, insuring an accurate estimate of flow rate.

Test Procedure

The ADFM was first tested in two sites at the Bureau of Reclamation's Water Resources Research laboratory in Denver - 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 flume, centered with the transducer's long axis aligned with the flume's axis (the flow direction). No in-situ calibration or rating was performed.

4 ft flume - The test began with a depth of flow of approximately 4 ft. The depth was increased after about one hour to around 7 ft. ADFM flow measurements were then compared with the supply line venturi meter flows to check for accuracy and repeatability.

The venturi meter 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 ADFM 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.

12 ft rectangular channel - The test began with a depth of flow of approximately 2 ft. The depth was decreased after about one hour to about 1.2 ft. ADFM flow measurements were then compared with the venturi meter flows to check for accuracy and repeatability.

Following the laboratory tests, the ADFM was first placed in a “live” channel - the San Luis Drain near Los Banos, CA. This channel is an irrigation drain for part of the San Joaquin Valley. The channel is trapezoidal in shape, with an 8 ft. bottom width and 2:1 side slopes.

The ADFM was placed on an aluminum strap about 44 ft in length. Hinges were placed on the strap so that the 8 ft. center piece would lay flat on the channel bottom and the rest of the strap would conform to the side slopes of the channel. The channel was in normal operation during the installation with a flow depth of approximately 7.2 ft.

A more extensive test occurred earlier this year. The system was placed in the Arizona Canal downstream from the Grand Reef Dam, and upstream from a measurement weir maintained by the Salt River Project (SRP). The canal is trapezoidal, with a bottom width of 44.2 ft and a top width of 69 ft at a depth of 10.5 ft.

Results

Figure 3 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 ADFM flow data, the squares are the spot readings of the lab’s venturi meter, and the triangles are ADFM depth readings. The ADFM data correlates very well with the venturi meter readings.

At the beginning of the record, there is some scatter to the ADFM 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 ADFM 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. This is a difference of -1.72%.

We also see a change in the ADFM flow measurement after the level is increased to 7 ft at around 10:00 a.m. The ADFM is now over predicting the flow by around 5%. This is because one the beam 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 ADFM’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.

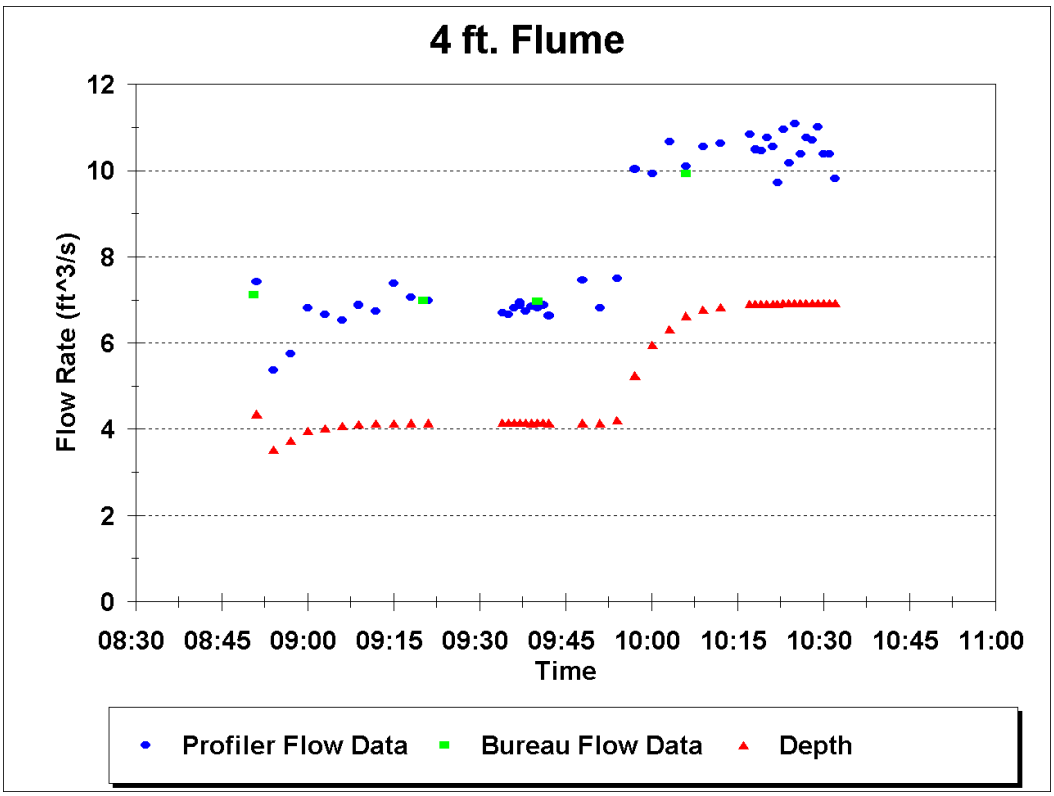

Figure 3. Flow rates measured in the 4 ft. flume plotted as a function of time. When the flume is filled to deeper than 5.5 ft, the ADFM over predicts flow by about 5% because one beam pair is intersecting the wall of the flume.

Figure 4 shows the results from several test runs in the 12 ft channel. The round symbols are the ADFM data, the squares are the spot readings of the lab's venturi meter, and the triangles are ADFM depth readings. Again, the ADFM data were averaged over different sampling intervals.

The first seven ADFM 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 ADFM 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 ADFM'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 ADFM measurements with the two venturi meter readings. The ADFM average was 0.97% different from the venturi meter average.

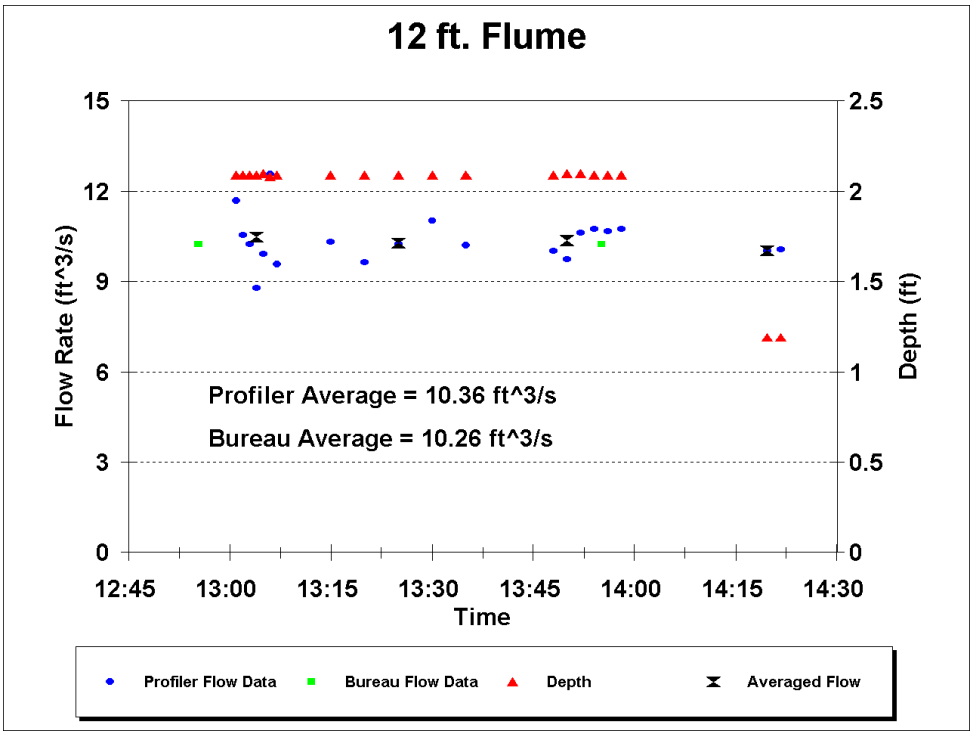

Figure 4. Flow rates measured in the 12 ft. channel plotted as a function of time. The addition of "Averaged Flow" is explained in the text.

The final ADFM reading on this plot was acquired at a depth of flow of 1.2 ft. This measurement was made with a width to depth aspect ratio of 10:1. This demonstrates the ADFM's unique capability to measure flows in wide, shallow channels.

Figure 5 is a plot of the flow rate, depth, and average velocity measured in the San Luis Drain near Los Banos, CA. All three measured parameters were steady. Variations in the flow rate correlate with variations in the average velocity, as the depth remains fairly constant. The average flow rate over the duration of the test is 91.1 ft^3/s. Flow rates of approximately 80 and 86 ft^3/s were measured using the traditional method of stream gaging.

The first stream gaging value was obtained by manually measuring velocities at 0.2 and 0.8 of the depth measured from the water surface, at regular intervals across the channel. These velocities were used to compute an average velocity for a particular section of the channel. Multiplying this average velocity by the cross-sectional area of the individual section gives a flow rate for that section. The section flow rates are summed to determine the total flow rate for the channel.

The second value was obtained by making a single velocity measurement at a height above the bottom of 0.6 of full depth, at regular intervals across the channel. This value was used as the average value for the section in order to compute a flow rate for the section. Again, section flow rates are summed to determine the total flow rate in the channel. Note: This velocity measurement should have been made at 0.6 of the depth as measured from the ***surface***, not the bottom.

It should be mentioned that there was some concern over the accuracy of the manual velocity measurements. The relationship between the velocities measured at the various depths was

not as expected. In particular, the velocity value measured at a height above the bottom of 0.8 of full depth, in some cases, was lower than anticipated.

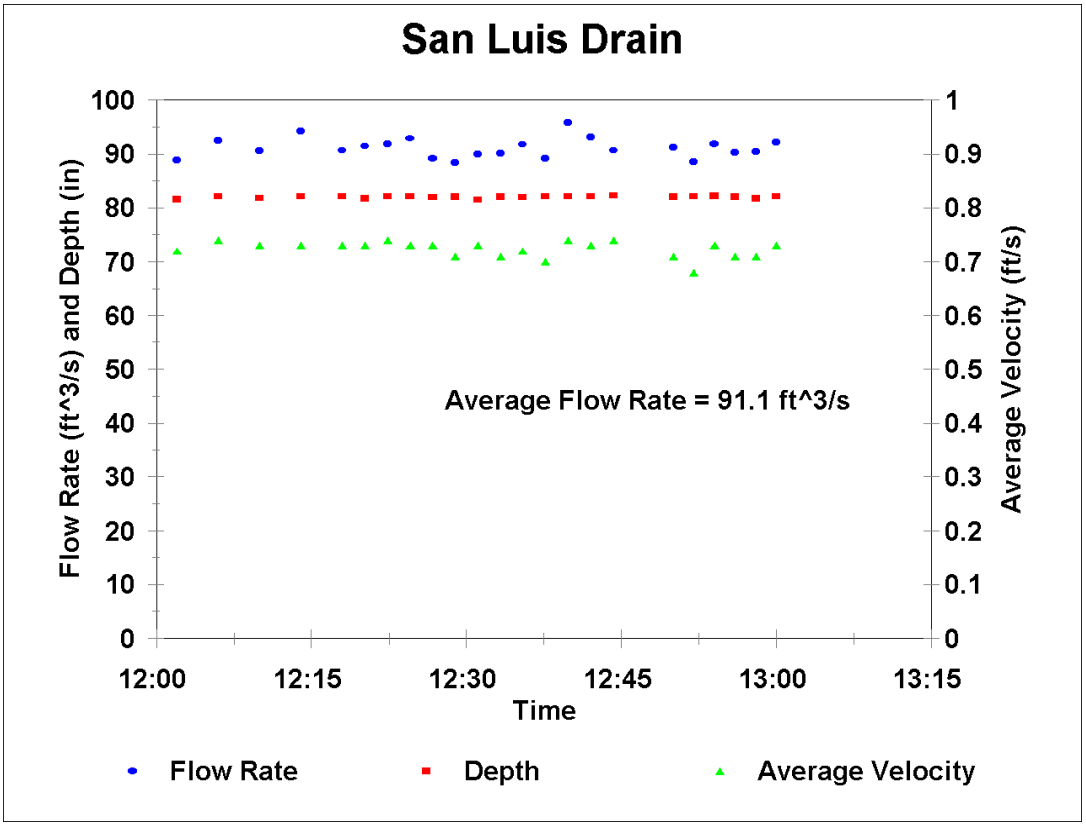

Figure 5. Flow rate, depth, and average velocity plotted as a function of time. The average flow rate was 91.1 ft^3/s.

Figure 6 is a comparison plot of flow rate data from both the Arizona Canal weir and the ADFM. Also shown are the daily flow averages for each device. Clearly both measurement systems track very closely. Over the four (4) weeks of the comparison, the difference between the two devices in total flow measured was less than 0.5%. This is accomplished with an installation as described above – no calibration.

Figure 7 is a one day plot of the above data. A key point to note is the ADFM appears to resolve high frequency variations in the flow better than the weir. This is because the ADFM relies on velocity measurements throughout the depth of flow, as well as the depth of flow, to determine the flow rate. The weir flow depends only on an instantaneous stage measurement. This ability to resolve short duration (transient) changes in flow is particularly useful in determining how a canal or channel responds to changes in upstream flow.

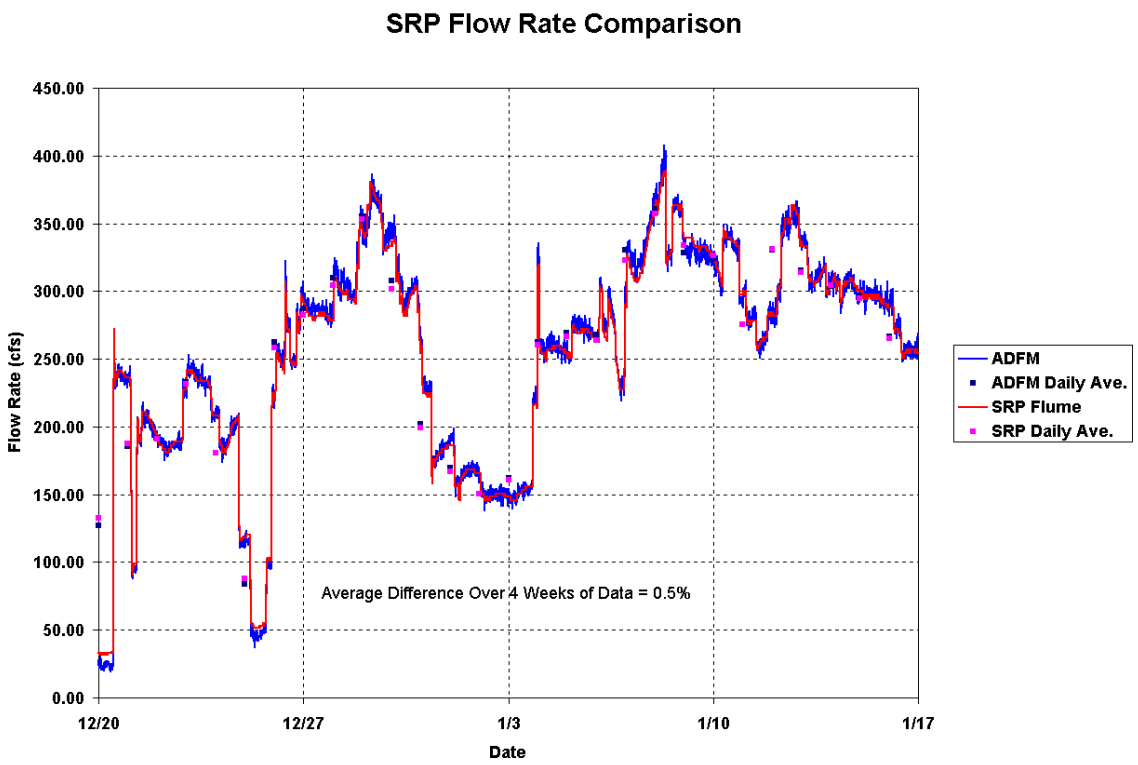

Figure 6. Comparison of ADFM and canal stage flow measurements. The total difference between the two flow measurements over 4 weeks was 0.5%.

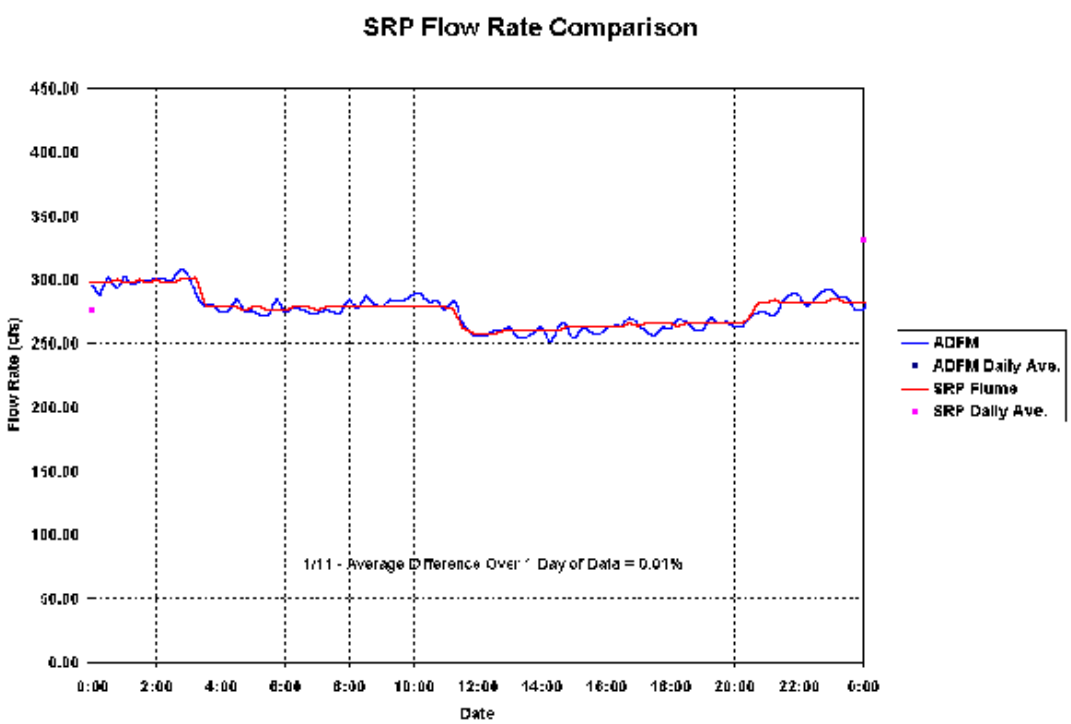

Figure 7. Comparison of one day of data.

Conclusions

The ADFM measured flow rate with an accuracy of approximately 1.7% in the 4 ft. flume and 1.0% in the 12 ft. channel. The ADFM was able to accurately measure flow rate even with a width to depth aspect ration of 10:1.

This test demonstrated a significant benefit of the ADFM; in situ calibration, or rating of the ADFM, was not required. Accurate flow measurements were attained without any special consideration to the installation, aside from placing the ADFM in the middle of the flow and aligning it with the direction of flow.

The ADFM was successfully installed in two different “live” channels, without interrupting the flow. In the first, flow rates measured were repeatable and within roughly 10% of a traditional stream gaging measurement. However, there was some concern that the stream gaging measurement might not be accurate, as some velocities appeared lower than anticipated. This would lower the flow rate estimate generated by this method.

In the second installation, the total ADFM generated flow measurements were within 0.5% of the total measurements of an installed weir. This weir has been calibrated repeatedly and is considered to be accurate. The ADFM was able to show higher frequency variation in the flows than the stage measurements were for the weir.

These demonstrations are useful in showing the ability of the ADFM Velocity ADFM™ to measure flow in a variety of conditions and with a minimal amount of time required to install and setup the instrument. This new technology has the potential to provide flow measurement in areas where traditional discharge measurement devices are impractical. It could also be a valuable tool for calibration of existing flow measurement structures and for research studies that require velocity profile measurements.