A Laboratory Evaluation of Unidata's Starflow Doppler Flowmeter and MGD Technologies' Acoustic Doppler Flow Meter

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Abstract

The Starflow Doppler flowmeter and the acoustic Doppler flow meter (ADFM) are unique devices which measure water velocity, depth, and temperature. Both systems have data loggers integrated into their electronics. These flowmeters are part of a new generation of ultrasonic flow measurement systems. Both systems use digital signal processing techniques, and they are able to perform in a wide range of environments. They can be used to compute and record flows in pipes, channels and small streams and operate in a wide range of water qualities from fresh water to wastewater. This paper includes the operating principles of both instruments, and the results of a side-by-side comparison performed in the U.S. Bureau of Reclamation's Water Resources Research Laboratory.

Introduction

Unidata's Starflow ultrasonic Doppler instrument and MGD Technologies' ADFM are unique devices which measure water velocity, depth, and temperature and compute flow rates in open channels and closed conduits. Both instruments have integrated data loggers. They represent a new generation of ultrasonic flow measurement systems. Both systems use digital signal processing techniques, and they are able to perform in a wide range of environments. They can be used to compute and record flows in pipes, channels and streams and they can operate in a range of water qualities from fresh water to wastewater. These instruments use two different methods of Doppler signal processing to measure water velocity, they are (Unidata 1998):

- **Incoherent or continuous Dopplers,** like the Starflow system, emit a continuous acoustic signal with one transmitter and detects signals returning from scatterers passing through the beam with a receiver, see figures 1 and 2. The measured velocities of the particles are resolved to a mean velocity that can be related to an average channel velocity at suitable sites. The Starflow system costs about $1,700 US.

- **Coherent or profiling Dopplers**, like the ADFM, transmit encoded pulses along four beams and are able to target specific locations (depth cells), and only measure these reflected signals, see figures 2 and 3. This allows the velocity distribution in a water column to be profiled. These instruments are generally more complex and expensive when compared to incoherent Doppler systems. The ADFM system costs between $17,000 and $20,000US.

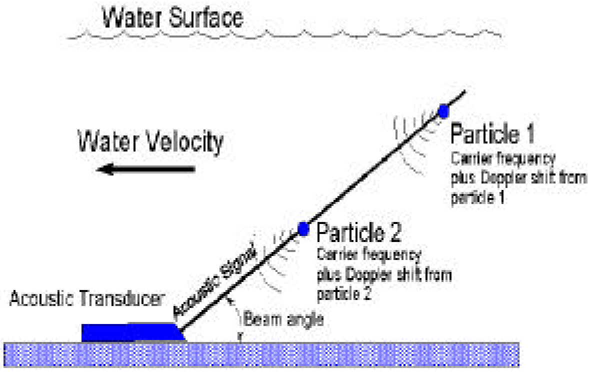

Figure 1. Schematic of Starflow’s incoherent Doppler velocity measurement technique.

Figure 2. Photograph of the ADFM and Starflow transducers.

Doppler-based Velocity Measurement Technique - During a measuring cycle, a ultrasonic pulse is transmitted at a fixed frequency. A receiver detects Doppler frequency shifts in reflected signals from particles moving with the water. A measuring circuit detects the frequency changes. A processing system accumulates and analyses these frequency changes and calculates a representative Doppler shift from the acoustic reflections received. Each Doppler shift is directly related to the water velocity component along the beam. Using the Doppler shift and the speed of sound in water the velocity of the reflector along the beam is computed. Each flowmeter system attempts to measure the average channel velocity. Both system manufacturers claim that the Doppler-based instruments do not need calibration for velocity measurement provided the transducers are not physically damaged.

Discharge Computation Technique - Water depth (or stage) is measured and used with a stage-area relationship to determine the cross sectional area of the flow measurement section. This stage-area relationship or cross section shape (e.g. circular or trapezoidal) is programmed into the flowmeter as part of the site information. The accuracy of this relationship is critical to the accuracy of the discharge computation. The cross sectional area and the average velocity measured by the Starflow instrument are multiplied to obtain a discharge.

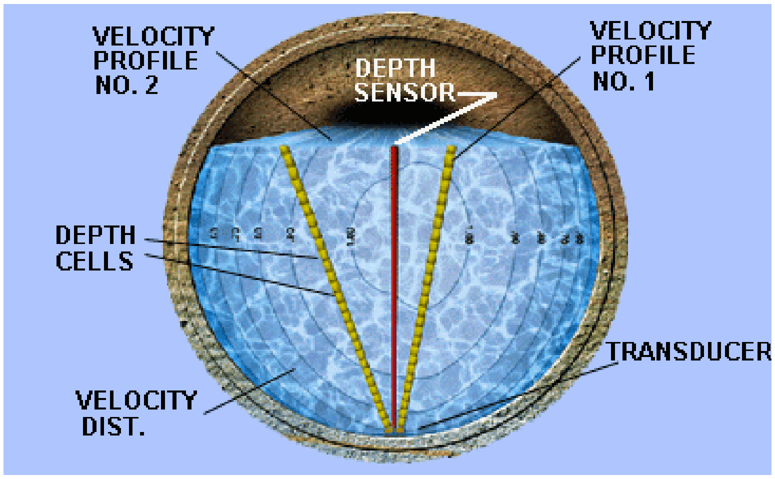

Figure 3. Cross section view of typical ADFM application. This figure shows the spatial relationship of the depth cells and the profiles relative to the transducer housing. The middle beam measures depth.

The ADFM uses two methods to compute discharge. One method (Q_{VA}) uses the depth-averaged velocity computed from the two velocity profiles and the cross sectional area. The second method (Q_{PRO}) uses the velocity data from the two profiles and an algorithm to develop a mathematical description of the flow velocities throughout the entire cross-section. The algorithm fits the velocity data to the functions of a parametric model for a certain type of channel (e.g. circular or trapezoidal). The parametric model is used to predict velocities at points throughout the flow field. The resulting velocity distribution is integrated over the cross-sectional area to compute Q_{PRO}.

Laboratory Evaluation

These tests were conducted in the Bureau of Reclamation's Water Resources Research Laboratory as part of a water measurement technology research program.

The Facilities - A side-by-side evaluation of the Starflow and ADFM was conducted in a rectangular flume that was 2.6-m wide and 1.2-m deep and 18.3-m long. The acoustic transducers were placed in the center of the channel about 6 m downstream from the inlet transition. The pumped flow capacity to the flume was about 0.85 m^3/sec. The flows were measured using Venturi meters and strap-on acoustic flowmeters. The combined discharge uncertainty for the tests was estimated to be ± 1.4% (based on a 2% uncertainty for the strap-on acoustic flowmeter and a 0.5% uncertainty for the Venturi meters).

Test Procedures - Four tests were run over a range of flows and depths in a 2.6-m-wide flume. A staff gage was used for an independent measure of the depth at the discharge measurement section. The average channel velocity was determined for each test by dividing the laboratory-measured discharge by the cross sectional area. The two Doppler flow meters attempt to accurately measure the average channel velocity to calculate an accurate, uncalibrated discharge.

Data collection - For all tests, both flowmeters were programmed to store data every 1 minute. The ADFM collected 160 velocity profiles which were averaged prior to logging the data. The Starflow was set with a scan rate of 15 seconds, with about 500 velocity measurements per scan. The average depth and velocity for the four scans per minute were stored in the Starflow's data logger.

Test Results

Table 1 and figure 4 contain a summary of data collected in the flume including percent error in the Starflow and ADFM measurements relative to the laboratory measured values.

Test Duration - For these tests the duration of data collection varied. This is an important factor because acoustic velocity measurements depend on many individual samples to compute an accurate average velocity. In other words, a single Doppler velocity measurement has a high degree of uncertainty, but the average of hundreds or thousands of measurements results in an accurate measure of the average velocity for the measurement period. Consequently, the results for these tests depend on the duration of the test. The duration of data collection for tests 1 through 4 were 60, 29, 20, and 40 minutes, respectively. This sampling length explains the difference in the ADFM's discharge uncertainty, as presented in table 1. The ADFM's Q_{VA} uncertainty was within ±3 percent of the laboratory discharge for the long duration tests and was within ±8 percent for shorter tests (tests 2 and 3). The average Q_{VA} uncertainty over all four tests was +1.3 percent. The average Q_{PRO} uncertainty covering all four tests was +31.0 percent.

The discharge uncertainty for the Starflow meter appears to increase with test duration, which is a very peculiar characteristic. The average uncertainty in Starflow discharges over all four tests was +26.2 percent. The Starflow instrument systematically over predicted the depth and velocity for all tests. The ADFM systematically under predicted the depth, but the uncertainty in average velocity varied widely from test to test.

Depth Measurements - Both transducer assemblies were mounted to the flume floor which was level in both directions. The stage measurements were collected to the nearest 1.5 mm at the measurement cross section. For all tests, depth measurements were made in relatively flat water. Waves will add a degree of uncertainty in the depth measurements for both flowmeters.

The Starflow used for these tests had a depth operating range of 0 to 2 m (there is also a model with a 0-5 m range). The reported resolution of the Starflow's pressure sensor, which is used to measure depth, is 1 mm with an uncertainty of ±0.25%, up to a depth of 2 m. The Starflow depth measurements were on average 1.4% greater than the staff gage measurements (table 1). This discrepancy in depth measurement does not perform up to the manufacturer's specified accuracy.

The ADFM's depth measurement operating range is 0.15 to 6.1 m. The specified long-term uncertainty is 0.5% ± 5 mm. While the ADFM's specified uncertainty is greater than the Starflow's, the two performed similarly. The ADFM depth measurements were on average 1.1% less than the staff gage measurements (table 1). The ADFM's acoustic depth sensor performed within the manufacturer's specified depth measurement accuracy.

Velocity Measurements - Velocity measurements were collected in the center of the flume using the Starflow and ADFM. The ADFM collected velocity profiles and the Starflow measured a depth-averaged velocity. The resolution of the Starflow's velocity measurement is specified as 1 mm/sec with an uncertainty of ±2% of the measured velocity. The range of accurate velocity measurement was reported to be from ±0.02 to ±4.5 m/sec (bidirectional). Tow tank tests conducted in Australia (Chalk 1995) and by the USGS (Laenen 1997) confirm the Starflow's accuracy claims, but they both identified a problem measuring velocities less than 0.02 m/sec.

It is important to emphasize that the velocity calibrations for the Starflow instrument were done in tow tanks. For this calibration technique, the transducer is towed at a constant velocity and the water and acoustic scatterers are stationary. As a result, the velocities measured are not part of a velocity profile, but are constant with respect to the towed transducer. This type of calibration is not representative of open channel or pipe flow where the velocity changes with distance from the boundary. To ensure accurate discharge measurements the Starflow user should develop a calibration relationship between measured velocity and the average channel velocity. This means the average velocity has to be determined using another method, such as stream gaging. This point is made in the Starflow manual, but they also say “Starflow instruments do not need calibration for velocity measurement.” Which in a strict sense is true for a tow tank test, but it is not always true when measuring the *average* velocity in a channel or pipe.

Table 1. Summary of average depths, velocities, and flow rates and their standard deviations for the flume tests. The average percent errors in the measurements with respect to laboratory measured values are also included.

Test	**Depth (m)**	**Measured Velocity (m/sec)**	**Q_{VA}-flow (m^3/sec)**	**Q_{PRO} -flow (m^3/sec)**	**% Error in Q_{VA}- flow**
Laboratory Measurements					
Test 1	0.460	0.286	0.341	n/a	0.0
Test 2	0.572	0.327	0.484	n/a	0.0
Test 3	0.654	0.354	0.600	n/a	0.0
Test 4	0.800	0.399	0.826	n/a	0.0
Starflow Measurements					
Test 1	0.469±0.007	0.377±0.013	0.460±0.04	n/a	34.3
Test 2	0.579±0.000	0.387±0.012	0.572±0.03	n/a	18.9
Test 3	0.664±0.000	0.427±0.011	0.748±0.04	n/a	23.2
Test 4	0.805±0.000	0.504±0.016	1.06±0.07	n/a	28.4
Avg. % Error	1.4	24.2	26.2	--	26.2
ADFM measurements					
Test 1	0.457±0.000	0.296±0.038	0.35±0.04	0.60±0..39	2.9
Test 2	0.564±0.001	0.303±0.027	0.44±0.04	0.51±0.17	-8.3
Test 3	0.647±0.001	0.400±0.033	0.67±0.06	0.74±0.14	11.8
Test 4	0.789±0.001	0.400±0.047	0.82±0.10	0.98±0.45	-1.1
Avg. % Error	-1.1	2.5	1.3	31.0	1.3

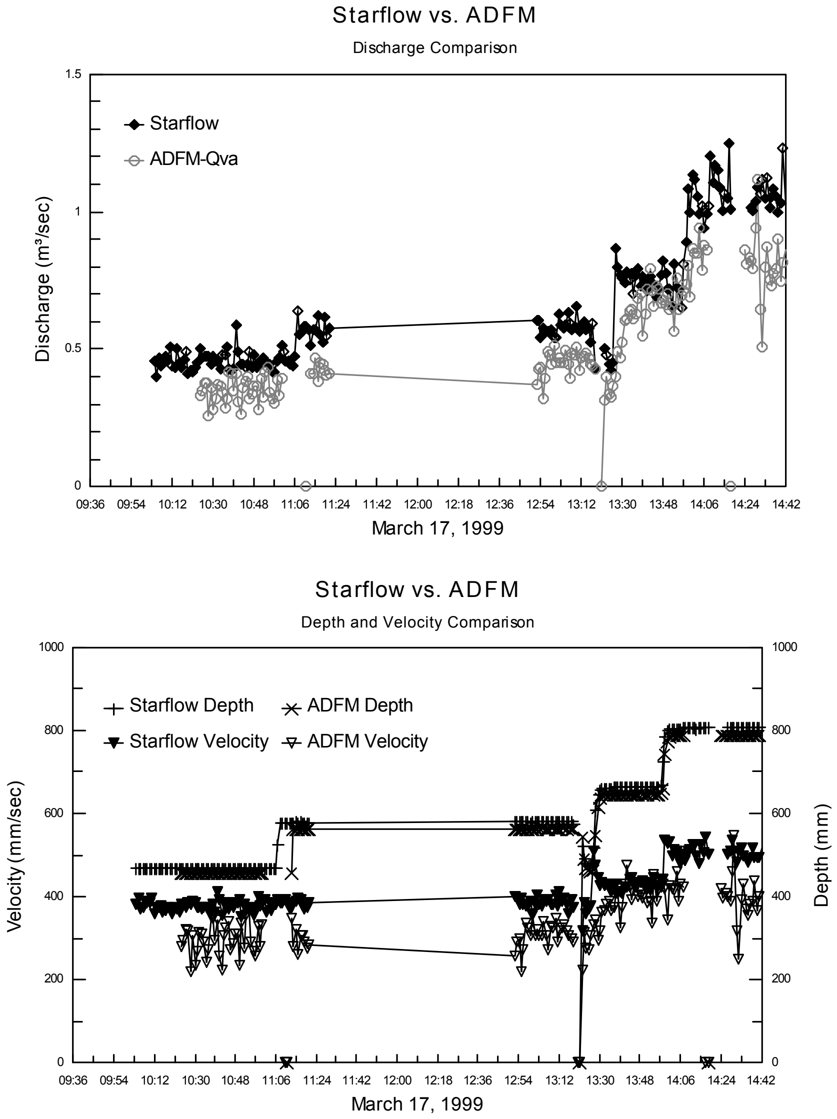

Figure 4. Discharge (upper plot), velocity and depth comparisons from the Starflow and ADFM discharge measurement systems. Note: data from the period from 11:45 to 12:45 were lost because of a power outage.

The ADFM's reported resolution of velocity measurement is ±1.0% ± 3 mm/sec of the measured velocity. The range of velocity measurement is reported to be ±9.1 m/sec (bidirectional). The ADFM's velocity profiling range is 0.15 to 6.1 m, and a depth cell size which can be varied from 5 to 30 cm.. MGD Technologies reported that calibration tests were conducted in a flume to determine the uncertainty in velocity measurements (Metcalf 1996). The ADFM calibration test setup was similar to the WRRL facilities used for these tests.

When Starflow and ADFM velocities were compared to the average channel velocity computed using the known discharge and the cross sectional area, the average errors were 24.2 and 2.5 percent, respectively.

Discharge Measurements - As previously mentioned, discharges were computed using the velocity measurements and a stage-area relationship specified by the user. All of the tests were done in rectangular channels. As a result, the area calculation was straight forward and subject only to uncertainty in the depth and width measurements. The flume had a measured width of 2.6 m. The width measurement was accurate to the nearest 1.6 mm. This represents an uncertainty in width of the flume of ± 0.06 percent. This error was quite small compared to the errors in the depth measurements, as described earlier.

The Starflow computed discharge was on average 26.2 percent larger than the laboratory discharge. The ADFM's Q_{VA} discharge had an average error of +1.3 percent of the laboratory measured discharge (table 1). The ADFM's average error for Q_{PRO} discharge measurements was +31.0 percent higher than the laboratory measured discharge (table 1). The Q_{PRO} discharge measurements also had a large standard deviation. For all the tests, the average standard deviation of the Q_{PRO} discharge was 5 times greater than the Q_{VA} standard deviation.

Temperature Measurement - Both transducer assemblies are equipped with temperature sensors to measure water temperature. Water temperature is a necessary measurement in order to compute the speed of sound in water. Neither manufacturer specified an uncertainty in their temperature sensors, but both sensors have a resolution of 0.1˚C. The specified operating range for the Starflow and ADFM temperature sensors are -17 to 60˚C and -5 to 35˚C, respectively.

For the first set of tests, both temperature sensors followed the temperature trend closely, but the ADFM's temperature sensor consistently measured a temperature 2˚C lower than the Starflow's temperature sensor. The average temperatures for the Starflow and ADFM sensors were 21.2 and 19.1˚C, respectively. An independent temperature measurement was not collected for this evaluation.

Limitations - Limitations in this comparison which may impact the results of the side-by-side evaluation tests is that the two transducers acoustic signals and subsequent reflected signals might interfere with each other. The Starflow and ADFM transducers transmit acoustic pulses at 1.56 and 1.23 MHZ, respectively. However, a comparison of side-by-side tests and stand-alone tests showed that there was a small difference between the two sets of velocity data measured by the Starflow. For example, for the same flowrate, the errors for the stand-alone and side-by-side velocity measurements were 24.8 and 22.3 percent, respectively. A similar analysis for the ADFM was not performed because its velocity measurements were close to the computed average channel velocity.

The width to depth aspect ratio for the flume tests varied from 3.3:1 to 5.7:1, which is typical for small to medium sized canals, but the aspect ratio for large canals can be much greater than what was tested in the laboratory. MGD technologies claims that the ADFM accurately measures discharge for aspect ratios up to 10:1. The Starflow manual does not specify a maximum width to depth ratio.

Water quality in a laboratory setting is much different than a field application. In Reclamation's laboratory, the particles are primarily small air bubbles and miscellaneous debris. In the field, the particles will likely be sediment and aquatic debris which will likely have an impact on the performance of both the Starflow and ADFM systems. Acoustic flowmeter applications must take into consideration the water quality at the site for all seasons. For example, during spring runoff the sediment load may be substantially higher than later in the year. Sediment may bury the transducer during this time period. In the late summer, algae growing on the transducer or on the channel bottom may interrupt the acoustic signal. In both cases, maintenance will be required to keep the system operating properly. A system to place the transducer back on the bottom of the channel in the proper position is needed to make regular maintenance practical.

Conclusions

- The Starflow consistently computed discharges that were 26 percent greater than the known discharge for tests conducted in a 2.6-m-wide rectangular flume. The Starflow's velocity measurements were consistently 24 percent greater than the average channel velocity. While this over prediction in discharge is undesirable, the consistency in the percent error suggests that the Starflow could have a stable calibration over a range of flows and depths.

- The ADFM's Q_{VA} discharges were on average within ±1.3 percent of the known discharge for a range of flows and depths in a 2.6-m-wide flume. The ADFM's velocity measurements were, on average, within ±2.5 of the average channel velocity.

- The ADFM's Q_{PRO} discharges were on average within ±31.0 percent of the known discharge for a range of flows and depths in a 2.6-m-wide flume. Over this range of flows, the average standard deviation of the Q_{PRO} discharge measurement was 5 times greater than the Q_{VA} standard deviation.

- This evaluation demonstrated that a Starflow flowmeter will probably require a site-specific calibration in order to verify the computed discharge in an open channel application. However, the ADFM performed well enough to be installed without an in situ calibration, if the accuracy requirements are within ±2 to 3 percent of the known discharge and if the width to depth ratio is less than 10:1. Accurate ADFM discharge measurements were made without any special consideration to the installation, aside from placing the transducer in the middle of the channel and aligning it with the direction of flow.

- Depth and temperature sensors in both instruments performed as specified. The ADFM's acoustic depth sensor requires no maintenance; while the Starflow's pressure sensor uses a vent tube opened to the atmosphere. Maintenance of a desiccant-filled drying cannister is required to keep the vent tube dry and free from condensation. Depth measurements were made for smooth water surfaces. Waves will add a degree of uncertainty in the depth measurements for both flowmeters.

- Both systems require a communications cable between the electronics and the transducer. The cable will likely collect debris and will have to be cleaned. Debris build-up may cause the transducer to move. A solid anchorage for both systems is required to prevent movement. Likewise, vandalism may be another source of transducer movement.

- Both systems are equipped with data loggers that were easy to program and download data. Both systems can be set up to work with SCADA systems, but this function was not evaluated.

Recommendations

Acoustic flowmeters are a new technology which are well suited for difficult flowmetering sites where traditional discharge measurement structures (e.g. weirs and flumes) are not practical. For example, sites with backwater conditions caused by downstream gates and tides. These instruments combine, in a small package, the capability to measure depth, velocity, and temperature, and using this information calculate and log a discharge. Like all electronic systems, acoustic flowmeters require periodic maintenance which will vary from site to site.

The Starflow system has a niche in the discharge measurement market. It is capable of logging a continuous record of depths and velocities at a very reasonable price. The hidden cost of the Starflow system is the calibration cost. Depending on the accuracy required, the user should check the Starflow's discharge computation with an independent measurement as frequently as the user would normally stream gage the site until they are comfortable with the flowmeter's accuracy and stability. After an acceptable calibration is established, stream gaging should be done monthly, or as frequently as needed, in order to have a record for quality assurance and quality control (QA/QC) purposes. Used in this way, the Starflow logs a continuous discharge record and eventually the number of manual discharge measurements can be reduced.

As previously mentioned, there are many factors which can affect the performance of the Starflow's velocity measurement and depth measurement. Consequently, each installation will have unique performance characteristics that may require more or less attention.

At sites which may require unacceptable levels of calibration, I would recommend spending the extra money for the ADFM system. The ADFM is more robust in its ability to accurately measure velocities in variable water quality and hydraulic conditions. For the same site, this system will usually require fewer calibration checks than the Starflow system.

Because this technology is relatively new, I do not know how durable these systems are in field applications. Consequently, I would not suggest that a new user purchase several of these systems until the reliability and accuracy are established for a season in order to evaluate the system's ability to meet their specific water measurement needs.

Acknowledgments

This evaluation was funded by Reclamation's Water Measurement Research Program (project WR99.24). The Starflow equipment was loaned to Reclamation by Mr. Geoff Carrigg from Unidata America. Mr. Carrigg was very helpful in assisting with this evaluation and his willingness to loan Reclamation a Starflow system for these tests was greatly appreciated.

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