Laboratory Evaluation of a Shallow-Water Acoustic Doppler Profiling Flowmeter

Tracy B. Vermeyen[1]

[1]Bureau Of Reclamation, Water Resources Research Laboratory, P.O. Box 25007, D-8560 Denver, CO 80225; PH (303) 445-2154; FAX (303) 445-6324; email: tvermeyen@do.usbr.gov

Abstract

A laboratory evaluation was conducted to determine if a newly developed acoustic Doppler flowmeter could be used for a canal seepage reduction project that required flowmeters to continuously measure flowrate through a series of 1.2- to 1.8-m diameter culverts. A set of laboratory tests were designed to determine the uncertainty in the velocity and stage measurements used by the flowmeter to compute discharge. Tests were performed in a section of 1.2-m-wide flume and in a length of 0.45-m diameter plastic culvert. The scope of this evaluation did not include a verification of the vertical velocity profile measurements or the algorithms used by Sontek's Argonaut-SW for the discharge computations for open channels or closed-conduits.

Introduction

The Argonaut-SW (shallow water) is a pulsed Doppler current profiling system designed for measuring water velocity profiles and level that are used to compute volumetric flow rate in natural channels, canals, culverts, or pipes. The goal of this laboratory evaluation was to determine the Argonaut-SW's flow measurement accuracy, without calibration, in a flume and pipe in a controlled setting.

Doppler-based Velocity Measurement Technique

The Argonaut-SW is a pulsed Doppler current meter. It uses a monostatic transceiver configuration, where the acoustic transducers transmit and receive the acoustic signals. The Argonaut-SW has three acoustic beams (figure 1). When correctly placed on the channel bottom, one of these beams is facing straight up, and the other two point upstream and downstream at a 45-degree angle. The upward-looking beam measures water depth. For a bottom mount application, the two diverging beams measure the flow velocities in two dimensions (streamwise and vertical). The manufacturer reports the velocity range, resolution, and accuracy to be ±5 m/sec, 0.1cm/sec, and the larger of ±1% of the measured velocity or ±0.5 cm/sec, respectively (Sontek 2003).

A key technical feature of the Argonaut-SW, which separates it from other Doppler sensors, is that velocity measurements are made to the water surface (in open channels) without any of the contamination normally associated with side-lobe interference. This enables the SW to take full advantage of the vertically-integrated velocity in its internal flow calculations.

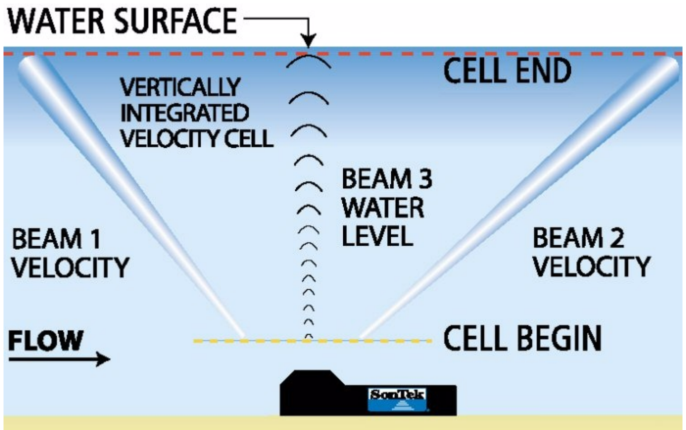

Figure 1. Argonaut–SW beam pattern and profiling extents (Sontek, System Manual, 2003)

Water Level Measurement

A vertical acoustic beam is used to measure water level. The vertical beam sends an acoustic pulse and listens for the reflected pulse from the water surface. To find the surface range from the reflection travel-time the SW uses an internal temperature sensor and user-defined salinity to calculate the speed of sound in water at the site. The SW uses the water level data for dynamic boundary adjustment which changes the velocity profiling range to account for variations in depth. The manufacturer reports the water level range to be 0.2 to 5 m, and the accuracy to be the larger of ± 0.03 cm or ±0.1% of measured depth. The minimum distance to the first velocity measurement (cell begin in figure 1) is about 9 cm above the top of the transducer.

Discharge Computations

The cross-sectional dimensions for an open channel or closed conduit are user-programmed into the flowmeter before it is deployed. The SW uses the water depth measurement and a depth-area relationship to compute the area of the flow section for each sampling period. The flow rate is computed by multiplying the area by the computed mean channel velocity for each sample. The mean channel velocity is computed from the vertically integrated velocity using an algorithm based on the 1/6th power velocity distribution model (Chen 1991). In addition, the SW has the option to use an index-velocity relationship for discharge computations. Where the index velocity is calculated from an empirical relationship between an independent measurement of the mean channel velocities and the SW-measured velocities and depths.

Laboratory Evaluation

The Facilities – Two Argonaut-SW flowmeters were tested in a large laboratory flume that is located at the Bureau of Reclamation's Water Resources Research Laboratory, in Denver, Colorado. The glass-walled flume is 1.2 m wide, 2.4 m tall and 24.4 m long (figure 2). The flume has a 3.0-m-long headbox which contains a baffle structure to condition the flow entering the flume. The pumped flow capacity to the flume is about 0.56 m^3/sec. The depth in the flume is controlled by a tailgate at the end of flume.

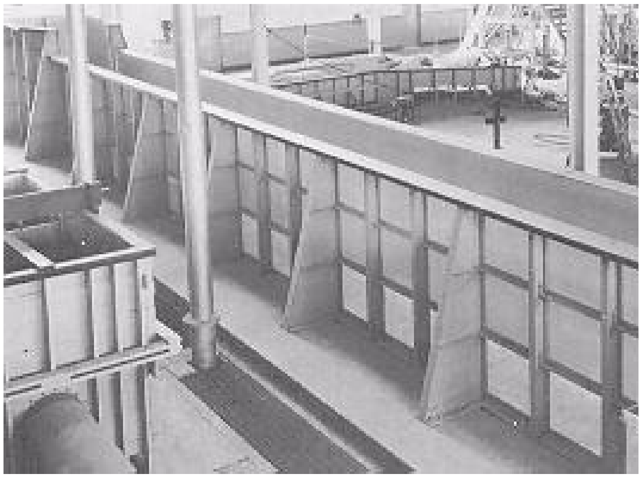

Figure 2. Photograph of the glassed-wall flume. Flow is from left to right.

The first Argonaut-SW instrument was installed 7.6 m downstream from the headbox baffle and was positioned 1.5 m upstream from a 0.51-m-high labyrinth weir. The weir was being studied in the flume and was left in place with the intention of generating non-uniform vertical velocity profiles, especially at higher discharges. The non-uniform profiles would allow evaluation of the SW's theoretical discharge computation algorithm for distorted flow profiles. A staff gage mounted to the flume wall across from the SW transducer was used to measure water depth to the nearest 0.6 cm. Figure 3 is a photograph of the Argonaut-SW flowmeter installed in the flume. A 1.2-m-high by 1.2-m-wide channel geometry was programmed into the SW. The system elevation for this installation (offset from the flume bottom) was 7.4 cm. A second Argonaut-SW was placed in a 2.7-m-long plastic pipe located 6.1 m downstream from the open channel SW. The 0.45 m diameter pipe was placed in the last third of the flume and its entrance was isolated by a 1.2-m-high marine grade plywood bulkhead. The bulkhead was sealed to the pipe and flume walls to direct all flow through the pipe. The tailgate was used to keep the water depth below the top of the pipe inlet bulkhead. The tailgate was about 4.6 m downstream from the plastic pipe outlet. Figure 4 is a photograph of the SW flowmeter installed in the pipe. Notice that the SW within the pipe was situated about 5 pipe diameters (2.3 m) from the pipe entrance. A 0.45 m pipe diameter was programmed into the SW. The system elevation for this installation (offset from the pipe invert) was 9.5 cm.

Test Procedures - Steady flows pumped from the laboratory reservoir were discharged in to the flume headbox. Inside the headbox is an 0.20-m diameter drain pipe which was used to allow a portion of the inflow to bypass the flume. A series of 1 hour tests were conducted for bypass flows ranging from 0 to 10 percent of the flow supplied to the flume. Both Argonaut-SW flowmeters were programmed to store a data set every 2 minutes. During the 2 minute averaging interval, the SW collected 120 velocity profiles and depth measurements that were internally averaged prior to logging the data.

Figure 3. Looking downstream at the SW and the 0.51-m-high laybyrinth weir in the open channel section. The bulkhead entrance to the 0.45-m pipe can be seen beyond the labyrinth weir. A staff gage is visible on the steel wall across from the SW transducer.

Figure 4. Looking upstream at the SW in plastic pipe section. The SW was positioned 2.3 m downstream from the pipe entrance.

Flow supplied to the flume was measured independently using a 0.30 m Venturi meter. The Venturi meter was calibrated in the laboratory calibration facility and has an uncertainty of ±0.3% of the volumetric flowrate. A laboratory control system was used to maintain a constant discharge into the flume. A strap-on acoustic flowmeter was installed on the bypass pipe to make an independent measurement of bypass flow. This flowmeter has a manufacturer reported uncertainty of about ±1 to 2 percent. A calibration test for the bypass flowmeter was not performed for this evaluation. For most tests, the bypass flowmeter stored an average flowrate every one minute for the duration of the tests. However, for some tests the data logger memory was filled and some data were lost. For these tests, the bypass flows were observed every 15 minutes to ensure they remained constant. Typically, the mean bypass flows were very stable and the standard error was less than ±0.0003 m^3/sec for a 30-minute test.

A staff gage was used to make an independent measurement of water depth at the flowmeter location in the flume. The staff gage was read to the nearest 0.6 cm with an uncertainty of ±0.3 cm. A tailgate located at the end of the flume was adjusted to keep the pipe completely submerged during each test and to maintain a stable depth at the open channel SW location.

Tests - Two SW units were tested for 1 hour intervals at various flowrates. At each interval, the bypass flow was adjusted to represent leakage. Tests were conducted with flume flows of 28.3, 141.6, and 198.2 L/sec with the bypass flow adjusted once every hour. For the 28.3 L/sec test, data were collected for target bypass flows of 0, 1.4 and 2.8 L/sec. For the 141.6 L/sec test, data were collected at target bypass flows of 0, 5.7, 7.1, 8.5, 11.3 and 14.2 L/sec. For the 198.2 L/sec test, data were collected at target bypass flows of 7.1, 8.5, 9.9, 11.3, 14.2, 17.0, and 19.8 L/sec.

Table 1. Stage Results (in meters) for the Flume Tests

Test Setup	**SW Measured Depth (m)**	**Staff Gage (m)**	**Discrepancy ($y_{flume}-y_{sw}$,m)**	**Within Specs (±0.003 m)**
28.3 L/sec - 0.0 bypass	0.700	0.701	0.001	Meets
28.3 L/sec - 1.4 bypass	0.926	0.933	0.007	Exceeds
28.3 L/sec - 2.8 bypass	0.954	0.945	-0.009	Exceeds
141.6 L/sec - 0.0 bypass	0.653	0.652	0.000	Meets
141.6 L/sec - 5.7 bypass	0.614	0.610	-0.004	Exceeds
141.6 L/sec - 7.1 bypass	0.798	0.786	-0.012	Exceeds
141.6 L/sec - 8.5 bypass	0.787	0.786	-0.001	Meets
141.6 L/sec - 11.3 bypass	0.757	0.756	-0.001	Meets
141.6 L/sec - 14.2 bypass	0.737	0.732	-0.005	Exceeds
198.2 L/sec - 7.1 bypass	0.921	0.908	-0.013	Exceeds
198.2 L/sec - 8.5 bypass	0.889	0.884	-0.005	Exceeds
198.2 L/sec - 9.9 bypass	0.966	0.957	-0.009	Exceeds
198.2 L/sec - 14.2 bypass	0.935	0.939	0.003	Meets
198.2 L/sec - 17.9 bypass	0.906	0.902	-0.003	Meets
198.2 L/sec - 19.8 bypass	0.856	0.847	-0.009	Exceeds

Test Results - Table 1 contains a summary of the depth measurements collected by the SW for the flumetests . The SW depth values are the mean of 30 or more samples. Depths observed using a staff gage were used to evaluate the accuracy of the SW depth measurements. Table 1 also includes the discrepancy (difference) between the two depth values and whether this discrepancy meets or exceeds the water level measurement accuracy specifications, ± 0.003 m. The width to flow depth ratios for these tests ranged from 1.3 to 2.0.

Tables 2 and 3 contain a comparison of SW mean channel velocity to the computed mean flow velocity using the continuity equation (**V=Q/A**). Where **Q** is the volumetric flowrate and **A** is the test section cross-sectional area. To compute the mean channel velocities, the actual flow was divided by the cross sectional area of the flume or pipe.

Tables 2 and 3 also include the discrepancy between the two mean velocity values and whether this discrepancy was within the manufacturers water velocity measurement accuracy specifications, ±0.005 m/sec. For pipe tests with flows of 141.6 and 198.2 L/sec, the water velocity measurement accuracy specifications is ±1 percent of the measured velocity. Using the manufacturers velocity specification in this evaluation was especially strict because it included uncertainty contributions from mean channel velocity computations, as well as cross sectional area.

Table 2. Comparison of Mean Channel Velocity to SW Velocity for Flume Tests

Test Setup	**Calculated Flume Velocity (m/sec)**	**SW Mean Velocity (m/sec)**	**Discrepancy (m/sec) (Vflume-Vsw)**	**Within Specs (±0.005 m/sec or ±1% of V)**
28.3 L/sec - 0.0 bypass	0.033	0.031	0.002	meets
28.3 L/sec - 1.4 bypass	0.024	0.026	-0.002	meets
28.3 L/sec - 2.8 bypass	0.022	0.022	0.000	meets
141.6 L/sec – 0.0 bypass	0.178	0.175	0.003	meets
141.6 L/sec - 5.7 bypass	0.182	0.176	0.007	exceeds
141.6 L/sec - 7.1 bypass	0.140	0.139	0.001	meets
141.6 L/sec - 8.5 bypass	0.139	0.140	-0.001	meets
141.6 L/sec - 11.3 bypass	0.145	0.143	0.002	meets
141.6 L/sec - 14.2 bypass	0.145	0.138	0.007	exceeds
198.2 L/sec - 7.1 bypass	0.173	0.173	0.000	meets
198.2 L/sec - 8.5 bypass	0.176	0.178	-0.002	meets
198.2 L/sec - 9.9 bypass	0.161	0.161	0.001	meets
198.2 L/sec - 14.2 bypass	0.161	0.165	-0.004	meets
198.2 L/sec - 17.9 bypass	0.165	0.167	-0.003	meets
198.2 L/sec - 19.8 bypass	0.173	0.167	0.006	exceeds

Table 3. Comparison of Mean Pipe Velocity to SW Velocity for Pipe Tests

Test Setup	**Calculated Pipe Velocity (m/sec)**	**SW Mean Velocity (m/sec)**	**Discrepancy (m/sec) (Vpipe -Vsw)**	**Within Specs (±0.005 m/sec or ±1% of V)**
28.3 L/sec - 0.0 bypass	0.173	0.177	-0.005	meets
28.3 L/sec - 1.4 bypass	0.164	0.164	0.000	meets
28.3 L/sec - 2.8 bypass	0.155	0.159	-0.004	meets
141.6 L/sec - 0.0 bypass	0.862	0.895	-0.032	exceeds
141.6 L/sec - 5.7 bypass	0.824	0.860	-0.035	exceeds
141.6 L/sec - 7.1 bypass	0.818	0.860	-0.042	exceeds
141.6 L/sec - 8.5 bypass	0.813	0.853	-0.041	exceeds
141.6 L/sec - 11.3 bypass	0.816	0.831	-0.016	exceeds
141.6 L/sec - 14.2 bypass	0.788	0.817	-0.029	exceeds
198.2 L/sec - 7.1 bypass	1.164	1.170	-0.005	meets
198.2 L/sec - 8.5 bypass	1.156	1.174	-0.018	exceeds
198.2 L/sec - 9.9 bypass	1.147	1.130	0.017	exceeds
198.2 L/sec - 14.2 bypass	1.123	1.119	0.004	meets
198.2 L/sec - 17.9 bypass	1.104	1.116	-0.012	exceeds
198.2 L/sec - 19.8 bypass	1.090	1.077	0.013	exceeds

Tables 4 and 5 summarize the temporal mean in the flow computations for the 1.2-m-wide flume and 0.45-m diameter pipe tests. The actual flume flow was computed as the difference between the laboratory flow and the mean bypass flow as measured with the strap-on acoustic flowmeter.

Table 4. Flow Measurement Results for Flume Tests

Test Setup	Target Flume Flow (L/sec)	Actual Flume Flow (L/sec)	SW Computed Flow (L/sec)	Percent Difference
28.3 L/sec - 0.0 bypass	28.3	n/a	28.2	0.6
28.3 L/sec - 1.4 bypass	26.9	n/a	26.6	0.9
28.3 L/sec - 2.8 bypass	25.5	n/a	26.1	-2.2
141.6 L/sec - 0.0 bypass	141.6	141.6	139.1	1.8
141.6 L/sec - 5.7 bypass	135.9	135.4	131.4	2.9
141.6 L/sec - 7.1 bypass	134.5	134.2	135.2	-0.7
141.6 L/sec - 8.5 bypass	133.1	133.4	134.6	-0.9
141.6 L/sec - 11.3 bypass	130.3	134.0	132.1	1.4
141.6 L/sec - 14.2 bypass	127.4	129.4	124.0	4.2
198.2 L/sec - 7.1 bypass	191.2	n/a	194.0	-1.5
198.2 L/sec - 8.5 bypass	189.7	n/a	192.8	-1.6
198.2 L/sec - 9.9 bypass	188.3	188.3	189.3	-0.5
198.2 L/sec - 14.2 bypass	184.1	184.4	188.5	-2.2
198.2 L/sec - 17.9 bypass	181.2	n/a	184.6	-1.8
198.2 L/sec - 19.8 bypass	178.4	178.7	174.0	2.6
n/a – time series of bypass flowmeter data not available for this test				

Table 5. Flow Measurement Results for Pipe Tests

Test Setup	Target Flume Flow (L/sec)	Actual Pipe Flow (L/sec)	SW Computed Flow (L/sec)	Percent Difference
28.3 L/sec - 0.0 bypass	28.3	n/a	29.5	-4.1
28.3 L/sec - 1.4 bypass	26.9	n/a	27.3	-1.5
28.3 L/sec - 2.8 bypass	25.5	n/a	26.4	-3.4
141.6 L/sec - 0.0 bypass	141.6	141.6	148.6	-5.0
141.6 L/sec - 5.7 bypass	135.9	135.4	142.9	-5.5
141.6 L/sec - 7.1 bypass	134.5	134.2	142.8	-6.4
141.6 L/sec - 8.5 bypass	133.1	133.4	141.7	-6.2
141.6 L/sec - 11.3 bypass	130.3	134.0	138.1	-3.1
141.6 L/sec - 14.2 bypass	127.4	129.4	135.8	-4.9
198.2 L/sec - 7.1 bypass	191.2	n/a	194.3	-1.6
198.2 L/sec - 8.5 bypass	189.7	n/a	195.0	-2.8
198.2 L/sec - 9.9 bypass	188.3	188.3	187.8	0.3
198.2 L/sec - 14.2 bypass	184.1	184.4	185.9	-0.8
198.2 L/sec - 17.9 bypass	181.2	n/a	185.3	-2.2
198.2 L/sec - 19.8 bypass	178.4	178.7	179.0	0.2

Discussion of Results

Depth Measurements – Measurement of flow depth using the staff gage was often difficult because of small waves in the flume. The staff gage readings shown in table 1 are averages of the observations at the beginning and end of the test. The uncertainty in the staff gage readings was ±0.003 m which was selected to be half of the staff gage resolution, ±0.006 m. Tests were conducted under a near-constant depth, but for some tests it was difficult to achieve this condition, especially for the 28.3 L/sec test. Periodic tailgate adjustments had to be made to keep the pipe submerged during those tests. For the 28.3 L/sec tests, the staff gage readings at the end of the test were compared to measurements logged by the SW at the same time.

The discrepancies between the water depths measured by the SW and the staff gage ranged from -0.012 to 0.006 m for this evaluation (Table 1). The manufacturer specifies the accuracy of the of the instrument's water level measurements as the larger of ±0.1% of the measured value, or ±0.003 m. Since all of the tests were conducted for depths less than 3 m the ±0.003 m criterion applies. Of the 15 tests, 6 depth measurements were within the manufacturers specifications. The mean of all 15 discrepancies in depth were within the manufacturers specification of ±0.003 m. This result was good considering the staff gage was read to the nearest 0.006 m and there were some difficulties maintaining a constant depth for the duration of each test.

In the case of the pipe section, the mean of the SW depth measurements was 0.456 m. Although the resolution of depth measurements was not reported in the specifications it appears to be 0.001 m. All other depth readings were within ±0.33% of that value. As mentioned previously, the 0.45-m diameter pipe was kept submerged for the duration of all tests with the exception of the 28.3 L/sec test with a bypass flow of 1.4 L/sec. During this test the depth was observed to have dropped so that the pipe was no longer completely submerged. The tailgate at the end of the flume was adjusted to correct this. The time was noted and data collected during the period in which the pipe was not fully submerged were excluded from the data analysis.

Velocity Measurements - For the flume tests, computed mean channel velocities were compared to the SW computed mean velocities (Table 2). The discrepancies between these velocities ranged from -0.004 to 0.007 m/sec for this evaluation. For the velocities measured in all 15 flume tests, the ±0.005 m/sec specification applies. In general, the performance of the SW for the flume tests was within the "strict" specifications used for this evaluation. Three flume tests exceeded the accuracy specification by less than +0.002 m/sec. A review of the individual (120 second average) SW velocity readings for each test did not reveal any unusual readings. In fact, for all flume tests the standard errors in SW mean velocity were less than or equal to the 0.005 m/sec specification. This result indicates that for a 60 minute long test in a nearly constant flow field the SW collected enough velocity readings to describe the mean channel velocities within the manufacturer's accuracy specifications. The discrepancies between computed mean channel velocities probably result from errors associated with the mean velocity calculation performed by the SW and/or that the cross sectional velocity distribution in the flume was not fully developed because of the weir downstream. An error in the depth measurement could also affect the mean channel velocity uncertainty.

The SW has the capability to apply an index-velocity equation to compute the mean channel velocity using the SW-computed mean velocity and stage. For the flume tests, SW stage and velocity data were processed using multiple linear regression analysis to determine the coefficients for the index-velocity equation:

$$V_{flume} = V_{const} + V_{SW}\left(V_{coeff} + \left(Stage_{coeff} \times Stage\right)\right) \quad \text{........Index-velocity equation}$$

Where, V_{flume} = computed mean channel velocity, (ft/sec)
V_{const} = regression constant, (ft/sec)
V_{SW} = SW mean velocity for period of V_{flume} measurement, (ft/sec)
V_{coeff} = velocity regression coefficient, (dimensionless)
$Stage_{coeff}$= stage regression coefficient, (1/ft)
$Stage$ = SW measured stage, (ft)

For the flume tests, a multiple linear regression was performed with V_{flume} the dependent variable and the independent variables were V_{SW} and the product of V_{SW} and Stage. Multiple linear regression resulted in this best-fit equation:

$$V_{flume} = -0.00089 + V_{SW}\left(1.124 - 0.0405(Stage)\right) \; with\ an\ R^2 = 0.998$$

R^2 is the coefficient of determination which means that 99.8 percent of the variation in the mean flume velocity was described by the variables V_{SW} and stage, with a 95 percent confidence level. This was a small improvement over a simple linear regression with V_{flume} the dependent variable and V_{SW} the independent variable. Linear regression resulted in the following best-fit equation:

$$V_{flume} = -0.0008 + 1.014(V_{SW}) \; with\ an\ R^2 = 0.996$$

For the pipe tests, mean pipe velocities were compared with the SW computed mean velocities. For the 28.3 L/sec tests, the ±0.005 m/sec specification applies. For the 141.5 and 198.2 L/sec tests, the ±1 percent of the measured velocity specification applies. The discrepancies between velocities ranged from -0.042 to 0.017 m/sec for this evaluation (see Table 3). In general, the velocity discrepancies for 0.45-m pipe tests exceeded the velocity specifications; ten of 15 tests exceeded the velocity accuracy specification. It is interesting that all the 28.3 L/sec tests were within specs, all the 141.6 L/sec tests were outside specs, and the 198.2 L/sec tests were close to the specs. A review of the individual SW velocity readings for each test did not reveal any unusual readings. In fact, for the 28.3 and 198.2 L/sec pipe tests the standard error in SW mean velocities were less than the ±1 percent velocity specification. The discrepancies between computed mean channel velocities probably result from errors associated with the mean velocity calculation performed by the SW and/or that the cross sectional velocity distribution in the pipe is not fully developed. In contrast to the flume tests, stage measurements do not enter in to the uncertainty because the pipe was flowing full.

A linear regression analysis was performed to describe the systematic error in pipe velocities. The linear regression for all tests comparing the SW computed mean pipe velocity (V_{mean}) and the computed mean pipe velocity (V_{pipe}) resulted in the following relationship: $V_{pipe} = 0.9907 * V_{mean}$ *with an* $R^2 = 0.997$

For this application, the R^2 of 0.997 indicates that SW mean velocities can be adjusted to reduce the discrepancies and improve the discharge computation accuracy. This small systematic error is most likely attributed to the algorithm used to convert V_x to V_{mean}. Another important factor that likely affects the velocity accuracy is the small diameter pipe used in this evaluation. In an 0.45-m diameter pipe the velocity measurement was determined from velocities profiled from about one half the pipe diameter because of the blanking distance above the SW transducer and the exclusion of velocity data collected near the top of the pipe because of side-lobe interference. Sontek reports that the last 20 percent of the velocity profile in a pipe may include side-lobe interference and that their algorithm automatically excludes this data (Sontek 2003).

Flow Measurement - Tables 4 and 5 present the target, actual, and SW computed flows for the flume and pipe tests. Actual flows were computed by subtracting the average flow measured in the bypass pipe from the flow supplied to the headbox. The percent differences in Tables 4 and 5 were calculated using the SW computed flow and the actual flow when possible; otherwise the target flow was used in place of the actual flow. The equation used to compute the percent difference is: $(Q_{flume}-Q_{SW}) / Q_{flume} \times 100\%$.

For flume tests, all the average SW computed flowrates were within ±5 percent of the laboratory flowrate. The mean percent difference for the 15 flume tests was -0.2 percent. The SW computes flowrate using velocity and area (computed from a programmed depth-area relationship) measurements. As a result, discrepancies in velocity and depth will factor into the uncertainty in the computed flowrate. However, since the flow depth was held nearly constant throughout each test, the majority of the variation in flowrate can be attributed to velocity. For pipe tests, 12 of 15 tests were within ±5 percent of the laboratory flowrate. The mean percent difference for the 15 pipe tests was 3.1 percent greater than the known pipe flow. In 13 of the 15 pipe tests, the Argonaut-SW measured a flowrate greater than the flume flowrate. This systematic error in discharge seems to be related to the computation of mean pipe velocity, as described earlier.

An analysis was performed to determine the minimum averaging interval required to reduce instrument uncertainty in discharge computation to below ±5 percent. Figure 4 shows the relationship between the standard error in discharge computations for a 141.6 L/sec test over a range of averaging intervals. For the flume test, a 12 minute averaging interval was required to reduce the standard error in the SW discharge to below ±5 percent. It is important to note that this result was for steady flow conditions which may not be duplicated in a field application. Selecting an appropriate averaging interval should balance the need to capture varying flow conditions within the data storage or power limitations for the deployment. For full pipe flow, a 4 minute averaging interval was adequate to reduce the standard error in the SW discharge computation to below ±5 percent. This improved performance is likely attributed to removing the uncertainty in depth measurement (full pipe) from the discharge computations and pipe velocities that were 5 times larger than the flume velocities.

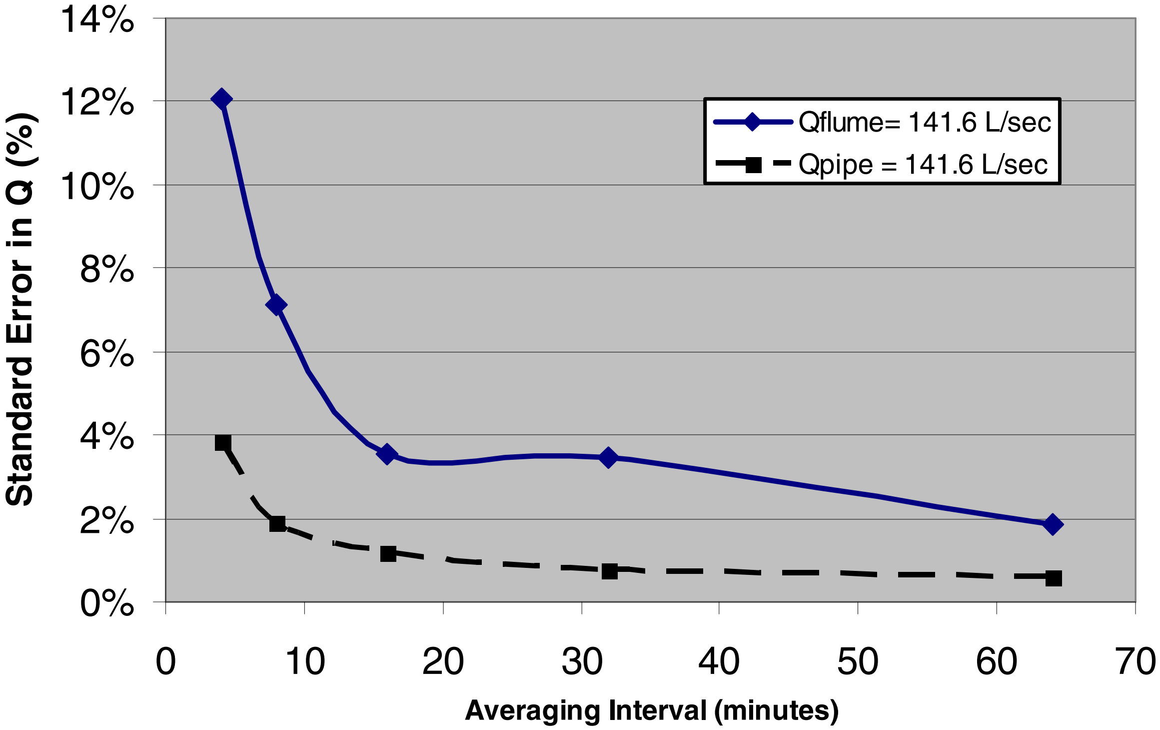

Figure 4. Standard error in SW discharges versus averaging interval for the 141.6 L/sec set of flume and pipe discharge measurements.

Conclusions

- Two Argonaut-SW flowmeters performed well in this laboratory evaluation for a wide range of flows. The SW-computed discharges were, on average, within +0.2 percent of the known flume discharges. For pipe tests, the SW-computed discharges were, on average, within +3.1 percent of the known pipe discharges.

- For the majority of flume tests, the SW performed within the accuracy specifications for mean channel velocity and depth measurements. These results were notable considering the potential for a non-standard velocity profile generated from the weir located downstream.

- For the majority of pipe tests, computed mean velocities did not meet the accuracy specifications. This can most likely be attributed to the small pipe size and the algorithm (mean velocity calculation method) used by the SW to convert V_x to V_{mean}. The SW depth measurements in the pipe were within the accuracy specifications for all tests.

- For flume tests, an averaging interval of 12 minutes was sufficient to reduce the instruments standard error in discharge to below ±5 percent.

- For full pipe flow an averaging interval of 4 minutes was sufficient to reduce the instruments standard error in discharge to below ±5 percent.

References

Chen, C.L. "Unified theory on power laws for flow resistance," Journal of Hydraulic Engineering, ASCE, Vol. 117, No. 3, March 1991, pp. 371-389.

Sontek/YSI, Inc., 2003, Argonaut-SW System Manual, firmware version 9.3.

Taylor, J. R., *An Introduction to Error Analysis –the study of uncertainties in physical measurements,* 2nd edition (University Science Books, 1997).

Acknowledgments: This evaluation was funded by Reclamation's Science and Technology program. Jennifer Rupp assisted with the data collection and analysis. Joe Kubitschek, hydraulic engineer, peer reviewed this report. Craig Huhta from Sontek/YSI provided technical assistance.

***Disclaimer*:** This evaluation was intended for internal use only and does not constitute acceptance or rejection of the product tested. The information contained in this report regarding commercial products or companies may not be used for advertising or promotional purposes and is not to be construed as endorsement of any product or company by the Bureau of Reclamation.