Application of Acoustic Doppler Velocimeters for Streamflow Measurements

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Abstract: The U.S. Geological Survey (USGS) principally has used Price AA and Price pygmy mechanical current meters for measurement of discharge. New technologies have resulted in the introduction of alternatives to the Price meters. One alternative, the FlowTracker acoustic Doppler velocimeter, was designed by SonTek/YSI to make streamflow measurements in wadeable conditions. The device measures a point velocity and can be used with standard midsection method algorithms to compute streamflow. The USGS collected 55 quality-assurance measurements with the FlowTracker at 43 different USGS streamflow-gaging stations across the United States, with mean depths from 0.05 to 0.67 m, mean velocities from 13 to 60 cm/s, and discharges from 0.02 to 12.4 m^3/s. These measurements were compared with Price mechanical current meter measurements. Analysis of the comparisons shows that the FlowTracker discharges were not statistically different from the Price meter discharges at a 95% confidence level.

DOI: 10.1061/(ASCE)0733-9429(2007)133:12(1433)

CE Database subject headings: Streamflow; Validation; Acoustic techniques; Stream gaging; Discharge measurement; Field tests; Flow measurement.

Introduction

The U.S. Geological Survey (USGS) and other agencies make thousands of streamflow measurements annually. USGS personnel made more than 65,000 streamflow measurements during the 2006 water year, from October 1, 2005 to September 30, 2006 (Oberg and Mueller 2007). Fulford (1992) showed that 77% of the streamflow measurements made by the USGS during the 1990 water year were wading measurements.

Two current meters are used commonly by the USGS and other agencies in North America to make measurements of streamflow: The Price AA and Price pygmy mechanical current meters. The Price meter has been used by the USGS since 1896 (Smoot and Novak 1977). Although these current meters have proven to be robust and accurate, they are subject to limitations regarding their use such as measurements of low velocities (<6 cm/s) and measurements in streams with depths <15 cm. See description by Rantz et al. (1982, pp. 134–135, pp. 143–144) for more details.

Beginning in 2000, the USGS began to explore the application of other technologies for the measurement of streamflow, particularly with a view to providing more accurate streamflow measurements during low flow. USGS personnel collaborated with SonTek/YSI to adapt their acoustic Doppler velocimeter (ADV) for use in wading streamflow measurements as alternative to the Price AA and pygmy meters. (Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.) The ADV was developed in the early 1990s for hydraulic measurements in laboratory settings (Kraus et al. 1994) and has been extensively used for mean flow and turbulence measurements (Voulgaris and Trowbridge 1998; Snyder and Castro 1999).

As a result of this collaboration, SonTek/YSI developed the FlowTracker ADV for use in wadeable streams using a standard top-setting wading rod. Fisher and Morlock's (2002) preliminary comparisons showed that the FlowTracker compared favorably to Price meters for measuring discharge in eight shallow urban streams.

Principles of Operation

The FlowTracker ADV operates at an acoustic frequency of 10 Mhz and measures the phase change caused by the Doppler shift in acoustic frequency that occurs when a transmitted acoustic signal reflects off particles in the flow. The magnitude of the phase change is proportional to the flow velocity. The phase difference can be positive or negative, allowing ADVs to measure positive and negative velocities. The FlowTracker measures the velocity at a rate of approximately 10 Hz, averages the data, and records 1 s velocity-vector data. According to the manufacturer, the FlowTracker can be used in water depths as shallow as 3 cm and in velocities in the range of 0.1 to 450 cm/s with an accuracy of ±1% of measured velocity (SonTek/YSI 2003).

The FlowTracker probe is mounted to a standard top-setting wading rod with a special offset-mounting bracket (Fig. 1). This bracket is designed to locate the FlowTracker probe at the front of the wading rod with the sampling volume 5 cm to the right of the

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Note. Discussion open until May 1, 2008. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this technical note was submitted for review and possible publication on May 2, 2006; approved on August 13, 2007. This technical note is part of the ***Journal of Hydraulic Engineering***, Vol. 133, No. 12, December 1, 2007. ©ASCE, ISSN 0733-9429/2007/12-1433–1438/$25.00.

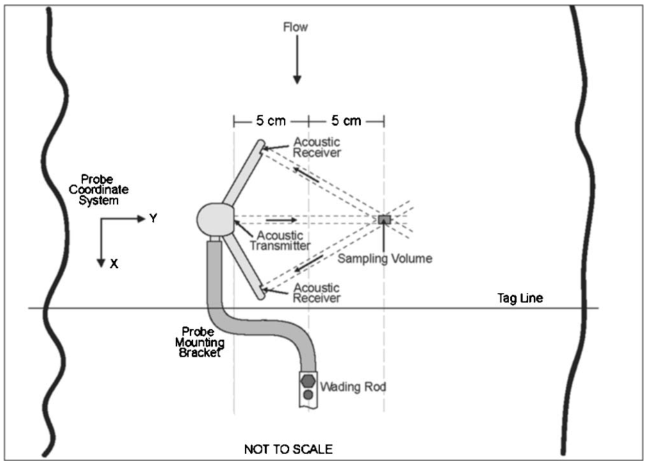

Fig. 1. Diagram of FlowTracker probe mounted on offset bracket and oriented correctly with tag line

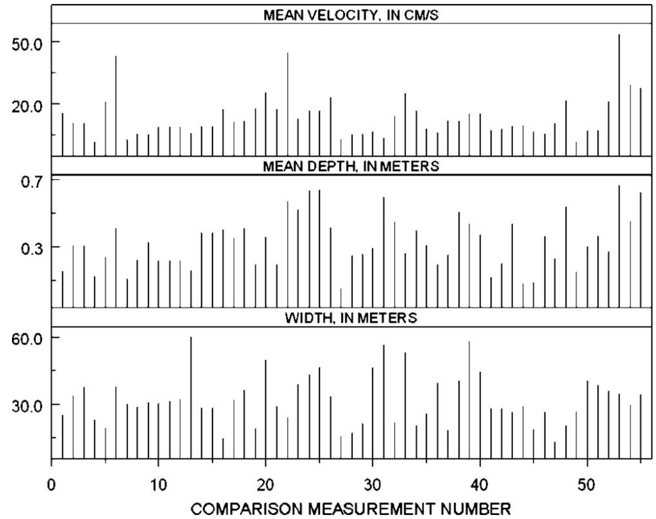

Fig. 2. Measurement characteristics for the 55 comparisons

wading rod. Although the probe is inserted into the flow, the sampling volume is several centimeters away from all physical parts of the probe, so the presence of the probe generally does not disturb the flow in the sampling volume.

FlowTrackers have several unique data-processing requirements because of their method of operation and some of the inherent limitations of the acoustic Doppler measurement technique. Unlike mechanical meters that use the momentum of the water to turn a propeller and directly measure the velocity of the water, the FlowTracker does not measure the velocity of the water. The FlowTracker measures the velocity of particles (sediment, small organisms, and bubbles) suspended in the flow, assuming that these particles travel at the same velocity as the water. Therefore, the quality of the measurement is dependent on the presence of particles within the sampling volume that reflect a transmitted signal. The FlowTracker records the signal-to-noise ratio (SNR), standard error of velocity (based on 1 s data), angle of the measured flow (relative to the *x*-axis of the FlowTracker probe), number of filtered velocity spikes, and a boundary quality-control flag. These velocity and quality-assurance data may be used to evaluate the measurement conditions. Few similar quality assurance data are available for Price current meter measurements.

Although a FlowTracker can measure within 3 cm of a boundary, the velocity measurement might be affected by acoustic interference when the sampling volume is close to boundaries or underwater objects, even when the sampling volume is not directly on or past the boundary. At the start of each velocity measurement, if the probe detects nearby acoustic boundaries that could cause interference with the velocity measurement, a boundary adjustment is automatically made. The boundary adjustment attempts to overcome the possible interference by reducing the lag times of the acoustic signals transmitted by the FlowTracker, causing a reduction of the velocity range that can be measured. Any changes are noted in the boundary quality-control flag. If the sampling volume is on or past a boundary, the velocity data will be erroneous. Care should be taken to avoid boundaries when making measurements in depths less than 9 cm, especially in channels with irregular bottoms.

For each velocity observation, if any 1 s component of velocity is greater than three standard deviations and 3 cm/s from the mean, the 1 s velocity is filtered out and reported as a spike. Because greater variation in 1 s velocities results in a higher standard deviation, a 40 s velocity measurement of highly variable data still typically has fewer than two spikes.

The FlowTracker measures magnitude and direction of velocity. The operator keeps the probe perpendicular to the tag line at all verticals, regardless of flow direction (Fig. 1). To compute discharge, the FlowTracker uses the component of velocity perpendicular to the transmitting transducer for discharge calculations and reports the flow angle from the FlowTracker's *x*-axis as a quality-control value. A flow angle measured by the FlowTracker may be the result of flow that is not perpendicular to the tag line or a wading rod that is not being held perpendicular to the tag line (operator error). Flow angles of less than 20 deg with small variations between verticals are not unusual. Large fluctuations of flow angles between verticals, however, may be indicative of a poor measurement cross section.

Comparison Measurements

Price meters were used as the reference for the FlowTracker measurement comparisons. A detailed plan was developed to provide a consistent approach for field data collection. Sites were chosen such that there was little change in stage throughout both the FlowTracker and Price meter measurements. Typically, the Price meter (either AA or pygmy) and FlowTracker comparison measurement were made using the same stationing and velocity observation depths. In some cases, the Price current meter and FlowTracker measurements were made simultaneously. The data used in these comparisons were collected by personnel from various USGS Water Science Center offices and provided to the author prior to October 2005. Only measurements that followed the test plan were considered for this analysis. FlowTracker firmware version 2.5 was the newest firmware used in any of the discharge measurements.

Fifty-five comparison measurements made at 43 different USGS streamflow-gaging stations were available for analysis. These measurements had mean depths ranging from 0.05 to 0.67 m, mean velocities ranging from 13 to 60 cm/s, and discharges ranging from 0.02 to 12.4 m^3/s. Comparison measurement conditions are summarized in Fig. 2.

Discussion of Results

The discharges measured by Price meters and the FlowTracker can be affected by measurement techniques and site characteristics, including: (1) cross-sectional area measurement; (2) number of verticals used in the measurement; (3) SNR for the FlowTracker; (4) velocity pulsations; and (5) mean cross-sectional depth and velocity. The effect of each characteristic is evaluated before a final comparison of discharge is made. The FlowTracker comparison measurements are summarized in Table 1.

Cross-Sectional Area

Systematic errors for discharge measurements can occur in the depth and width measurements, and can be caused by improperly calibrated equipment or poor technique. These systematic errors are considered to be small, typically less than 0.5% (Sauer and Meyer 1992). Since the methods of positioning the FlowTracker and Price meters and measuring the depth are the same, the systematic errors associated with depth, width, and technique should be similar for both measurements. The effects of these systematic errors on the discharge comparisons were minimized by using the same cross section for the FlowTracker and the Price meter comparison measurement.

To evaluate the effect of depth and width errors on the measured data, the cross-sectional area measured during the Price meter measurements and the FlowTracker measurements were analyzed. Linear regression analysis was used to determine if there was a difference between the area of each FlowTracker measurement compared to the corresponding Price meter measurement. The analysis resulted in a correlation coefficient of 1.006 and coefficient of determination of 0.997, indicating that there was no difference in the measured areas at the 95% confidence level.

Number of Verticals

The number of verticals observed in a cross section help determine the uncertainty of a discharge measurement. The fewer the number of verticals used in data collection, the higher the uncertainty of the measurement (Sauer and Meyer 1992). Six of the measurement comparisons had less than the USGS recommended 25 verticals, and two of those comparisons (Nos. 4 and 49) had less than 20 verticals. The lowest number of verticals in any comparison was 17 (No. 49). According to Sauer and Meyer (1992), a discharge measurement with 17 verticals will have an added standard error of 0.7% when compared to a measurement with 25 verticals. Therefore, the number of verticals should not be a significant source of uncertainty for this set of comparison measurements. Comparison measurement No. 30 was the only comparison with less than 25 verticals, for which the difference between FlowTracker and Price current meter measured discharges was greater than 5%.

Signal-to-Noise Ratio

Adequate SNR is needed to obtain an accurate measurement of the flow velocity. SNR is a measure of the strength of the reflected acoustic signal relative to the ambient noise level of the instrument. SNR is a function of the concentration and size distribution of the particles that reflect the acoustic signal. SNR is recorded for each beam with each 1 s sample. The manufacturer states that optimal SNR is 10 dB or above (SonTek/YSI 2003). USGS policy is that FlowTrackers should not be used for measuring discharge if the SNR for any single beam is less than 4 dB.

Seven of the FlowTracker measurements had SNRs below the manufacturer's reported optimum of 10 dB. Of these seven measurements, three (comparison Nos. 5, 29, and 50) had SNRs below the USGS minimum of 4 dB. These three measurements had larger numbers of velocity spikes filtered than measurements with SNR above 4 dB. Nevertheless, the three comparisons generally agreed well (discharge differences $<6.8\%$). However, while it may be possible to use the FlowTracker in low SNR environments, the velocity measurements are more likely to contain erroneous velocities. If a large number of the 1 s velocities are erroneous, the spike filter may not recognize the erroneous values as a spike and the resulting velocity may not be correct.

Velocity Pulsations

Velocity pulsations can vary by depth and location in the cross section. Typically, as the velocity of a stream decreases from the water surface to the streambed, the uncertainty from pulsation increases (Pelletier 1988). To minimize the impact of the pulsations of the stream, velocity data are collected over a period of time (typically 40 s). As the time duration of velocity measurements increases, the uncertainty of the velocity data decreases (Carter and Anderson 1963). To further minimize the impacts of pulsations, multiple observations can be measured at the same vertical location. The observed velocities are then averaged to determine the velocity for the vertical. Standard error of velocity, computed by the FlowTracker as the standard deviation of the 1 s velocity samples divided by the square root of the number of samples, is reported with each velocity measurement. The standard error of velocity can be interpreted as the uncertainty of the mean velocity. Standard error of velocity usually is dominated by velocity pulsations and varies based upon the environment.

When comparing mean measurement standard error of velocity with percent departure from the reference discharge (Fig. 3), as the standard error of velocity increases, the variability of percent departure also increases. This is expected because a high standard error of velocity indicates more turbulent or pulsating measurement conditions and pulsating flow conditions result in measurements with higher uncertainty. In addition, turbulent or pulsating flow can cause velocity measurement errors in meters. For mechanical meters, the inertia of a meter's moving parts and the efficiency with which the meter translates linear velocity into angular velocity affects the ability of a meter to measure accurately in pulsating velocities (Fulford 1995). The FlowTracker does not have the issues associated with moving parts and should be less sensitive to flow pulsation measurement errors. The limiting factor in measuring velocity pulsations with the FlowTracker is the sampling frequency. The six comparisons that departed in discharge more than 8% had mean standard errors greater than 1 cm/s. Two (Nos. 22 and 28) of the six comparisons that departed in discharge greater than 8% also had angles larger than 20 deg for more than 25% of the velocity observations. Large varying angles are another indication of poor measurement conditions. More testing is needed to compare the accuracy of the Price meters and the FlowTracker in these turbulent conditions.

Mean Measurement Depth and Velocity

To examine possible relations between water velocity or cross section depth and comparison differences, the distribution of the

Table 1. Summary of FlowTracker Comparison Measurements

Comparison number	Number of verticals	SNR	Mean velocity (cm/s)	Mean standard error of velocity (cm/s)	Total area (m^2)	Discharge (m^3/s)	Comparison meter type	Departure from reference (%)
1	26	13.6	24.84	0.30	2.392	0.594	Pygmy	0.4
2	31	6.9	33.41	1.22	3.209	1.072	Pygmy	−9.7
3	31	30.5	37.31	1.83	3.174	1.184	Pygmy	4.6
4	19	21.6	22.93	0.61	0.183	0.042	Pygmy	−1.9
5	27	3.6	18.98	0.91	4.955	0.941	Price AA	6.8
6	27	29.6	37.41	0.61	17.559	6.570	Price AA	−1.3
7	27	29.4	29.72	1.52	0.297	0.088	Pygmy	9.5
8	24	24.9	28.52	0.61	1.211	0.345	Pygmy	4.0
9	32	31.9	30.54	0.91	1.656	0.506	Pygmy	0.0
10	26	20.1	30.06	0.61	1.831	0.550	Pygmy	−3.9
11	26	18.2	31.25	0.61	1.831	0.572	Pygmy	−0.1
12	26	16.4	31.85	0.61	1.831	0.583	Pygmy	1.8
13	26	20.6	59.93	1.83	0.917	0.550	Pygmy	11.4
14	29	17.3	28.14	0.91	3.488	0.982	Price AA	0.0
15	29	17.1	28.07	0.61	3.501	0.983	Price AA	0.1
16	29	23.6	14.59	0.61	6.847	0.999	Price AA	−3.1
17	26	29.1	31.34	0.91	3.932	1.232	Pygmy	1.9
18	34	11.4	36.01	1.22	4.724	1.701	Price AA	−3.7
19	28	19.1	19.00	0.30	3.428	0.651	Pygmy	−7.3
20	25	19.4	49.77	0.91	9.036	4.497	Price AA	−3.8
21	29	13.6	28.69	1.22	3.323	0.953	Pygmy	2.3
22	29	13.5	23.89	1.83	25.237	6.029	Price AA	−8.9
23	30	21.9	38.62	0.61	6.487	2.505	Price AA	5.7
24	29	18.6	42.90	0.91	10.558	4.530	Price AA	−1.6
25	29	19.2	46.22	0.91	10.599	4.899	Price AA	6.4
26	25	32.0	33.50	0.52	9.424	3.157	Price AA	3.0
27	28	26.8	15.35	1.22	0.127	0.020	Pygmy	−5.5
28	25	10.0	16.93	8.84	1.286	0.218	Pygmy	−12.4
29	26	0.4	21.19	3.66	1.405	0.298	Pygmy	−0.6
30	23	23.9	46.39	1.22	1.867	0.866	Pygmy	10.0
31	23	30.4	56.21	3.35	1.989	1.118	Price AA	−3.5
32	28	7.5	21.48	0.61	6.257	1.344	Price AA	−2.2
33	27	22.7	53.05	1.83	6.539	3.469	Price AA	−0.4
34	26	13.3	20.22	0.55	6.510	1.316	Price AA	−1.7
35	33	19.3	25.64	0.61	2.469	0.633	Pygmy	4.5
36	25	23.2	39.26	1.22	1.215	0.477	Pygmy	−0.3
37	30	9.3	18.28	0.61	2.948	0.539	Pygmy	2.9
38	30	14.8	40.38	1.22	5.871	2.371	Price AA	−1.8
39	22	20.4	57.84	0.61	6.479	3.747	Price AA	4.5
40	25	23.8	44.39	0.76	5.639	2.503	Price AA	0.7
41	34	33.2	27.90	0.55	0.872	0.243	Pygmy	−2.7
42	27	6.6	27.93	0.91	1.599	0.447	Pygmy	−0.5
43	30	38.6	26.21	0.82	3.932	1.031	Price AA	−0.3
44	30	37.8	28.67	0.58	0.753	0.216	Pygmy	1.4
45	25	39.3	18.43	0.40	0.569	0.105	Pygmy	2.1
46	32	26.1	26.13	0.91	1.973	0.516	Pygmy	2.3
47	27	20.4	12.91	0.30	2.350	0.303	Pygmy	−3.1
48	31	23.4	20.21	0.30	11.671	2.359	Price AA	−6.9
49	17	33.1	26.06	1.83	0.240	0.062	Pygmy	−3.7
50	25	1.7	40.39	1.83	2.040	0.824	Pygmy	1.4
51	26	31.0	38.29	1.83	2.706	1.036	Pygmy	−4.4
52	30	26.8	35.57	0.61	5.739	2.041	Pygmy	0.4
53	26	28.7	34.51	0.46	35.796	12.353	Price AA	0.4
54	29	20.1	29.32	0.61	12.983	3.806	Price AA	2.2
55	28	31.2	33.98	0.76	17.011	5.780	Price AA	−3.3
Mean	27	21.2	31.65	1.03	5.318	1.759		−0.1

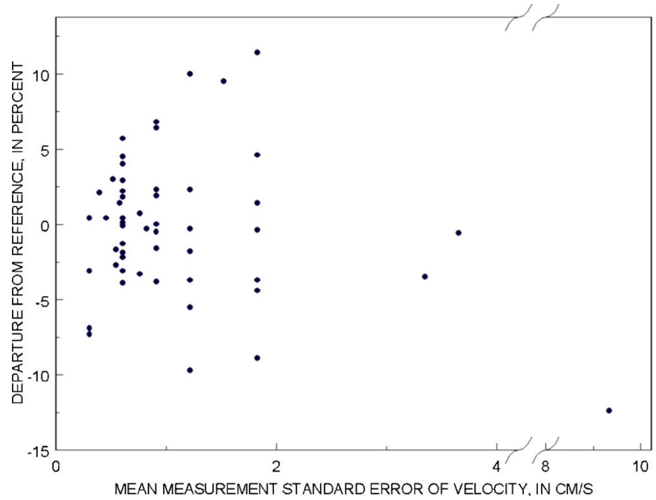

Fig. 3. Comparison of percent departure in discharge and mean measurement standard error of velocity with Price pygmy and Price AA meters identified separately

percent departure of the FlowTracker discharge from Price meter measurements was evaluated against mean FlowTracker measurement velocity (Fig. 4) and mean measurement depth (Fig. 5) using a simple linear regression analysis. The relation between mean measurement velocity and percent departure from reference discharge was found to be statistically significant (p-value of 0.008), with a correlation coefficient of 0.147. Only 12% of the variability in comparison discharges could be explained by mean measurement velocity. Furthermore, if the comparison measurement with the highest mean velocity (No. 13) is removed from the analysis, the linear regression is no longer statistically significant (p-value of 0.053). Therefore, although the statistical analysis showed a statistically significant trend, this trend is highly dependent on the leverage of one measurement. Additional data at higher velocities are needed to determine the significance of the trend. No significant relation between mean measurement depth and departure from reference was found (p-value of 0.43).

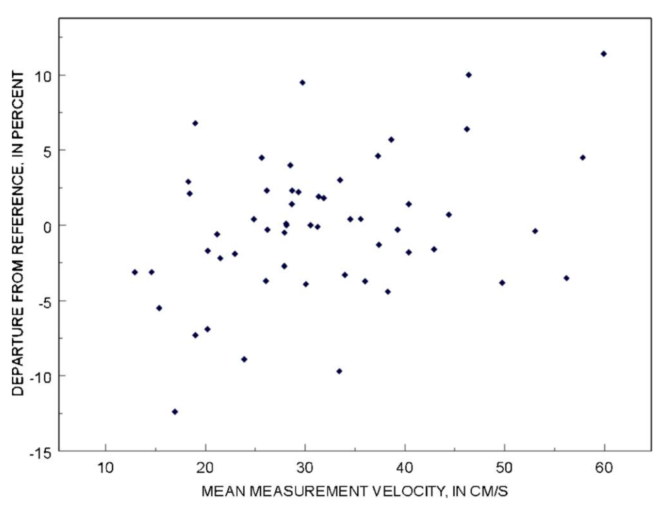

Fig. 4. Comparison of percent departure in discharge and mean measurement velocity

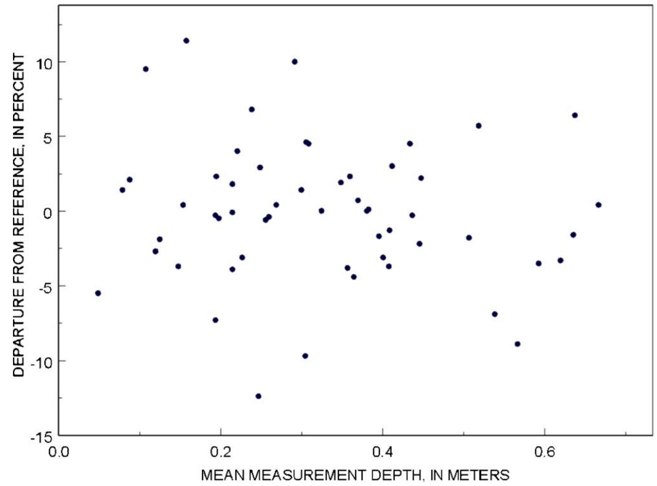

Fig. 5. Comparison of percent departure in discharge and mean measurement depth

Discharge

The discharges of 31 measurements made with Price AA meters and 24 with Price pygmy meters were compared with the discharges measured by the FlowTracker. The percent departure from the Price meter measurement was computed for each FlowTracker measurement. Of the discharges measured with the FlowTracker, 76% were within 5% of the comparison discharges and 89% were within 8% of the comparison discharges.

The percent departure of the discharge measured using the FlowTracker from that measured using Price current meters was evaluated separately for Price AA and Price pygmy meters (Fig. 6). When comparing the departures for FlowTracker discharge measurements to Price AA measurements, 58% of the FlowTracker discharges were lower than the Price AA discharges with a mean departure of −0.53%. When comparing the departures for FlowTracker discharge measurements to Price pygmy measurements, 52% of the FlowTracker discharges were greater than the Price pygmy discharge with a mean departure of 0.15%.

The mean percent departure for all comparisons was −0.1%, with a mean absolute departure of 3.4%. These departures are within the expected accuracy of 5% for Price AA and Price pygmy meter measurements. A linear regression analysis was per-

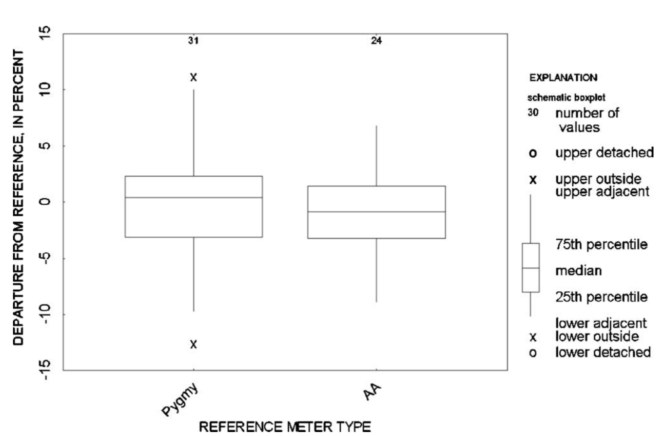

Fig. 6. Boxplot of the FlowTracker discharge percent departure with Price AA or Price pygmy meter measurement as the reference discharge

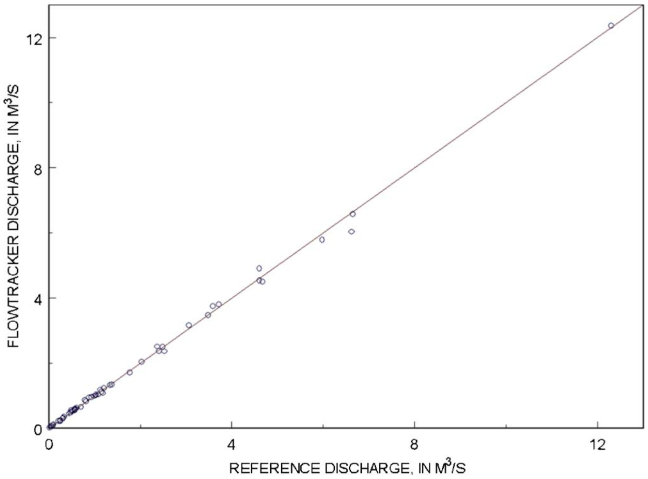

Fig. 7. Comparison of FlowTracker discharge to Price meter discharge with a line of perfect agreement

formed on the 55 comparison measurements to determine if there was a significant difference in the FlowTracker and Price meter discharges. The linear regression line from the analysis was not statistically different from a line of perfect agreement at a 95% confidence level, indicating the FlowTracker discharge measurements are not biased relative to the Price meter discharge measurements (Fig. 7). Based upon the data available, discharges measured using a FlowTracker across a range of measurement characteristics compared well with discharge measured by Price meters, with no evident statistical bias.

Summary and Conclusions

FlowTracker acoustic Doppler velocimeters (ADVs) are hydroacoustic instruments designed for wading streamflow measurements. Fifty-five streamflow measurements made with Flow Trackers at 43 USGS streamflow-gaging stations were examined to evaluate the performance of ADVs in field conditions. The FlowTracker discharge measurements were compared with discharge measurements made under the same flow conditions using Price mechanical current meters. The field evaluations were conducted at sites ranging in mean depth from 0.05 to 0.67 m, mean velocity from 13 to 60 cm/s, and discharge from 0.02 m^3/s to 12.4 m^3/s.

The evaluation of the FlowTracker streamflow measurements indicates that FlowTrackers can be used successfully for data collection under a variety of field conditions. On average, the FlowTracker has proven capable of measuring discharge within 5% of standard USGS wading measurements that use mechanical current meters. Comparisons with differences larger than 8% were made at sites with more turbulent measurement conditions, as measured by the FlowTracker standard error of velocity, resulting in a larger measurement uncertainty. The additional velocity and quality-assurance data collected as part of FlowTracker's discharge measurements can be used to evaluate the measurement conditions better than data available with Price meter measurements. The evaluation measurements indicate the FlowTracker is unbiased when compared to Price meter measurements and is a feasible alternative for wading discharge measurements at a wide variety of sites similar to those in this analysis.

Acknowledgments

The USGS and Environment Canada provided financial support for this work. The writer gratefully acknowledges the assistance of many USGS field personnel for their efforts to collect and summarize the comparison measurements used in this paper.

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