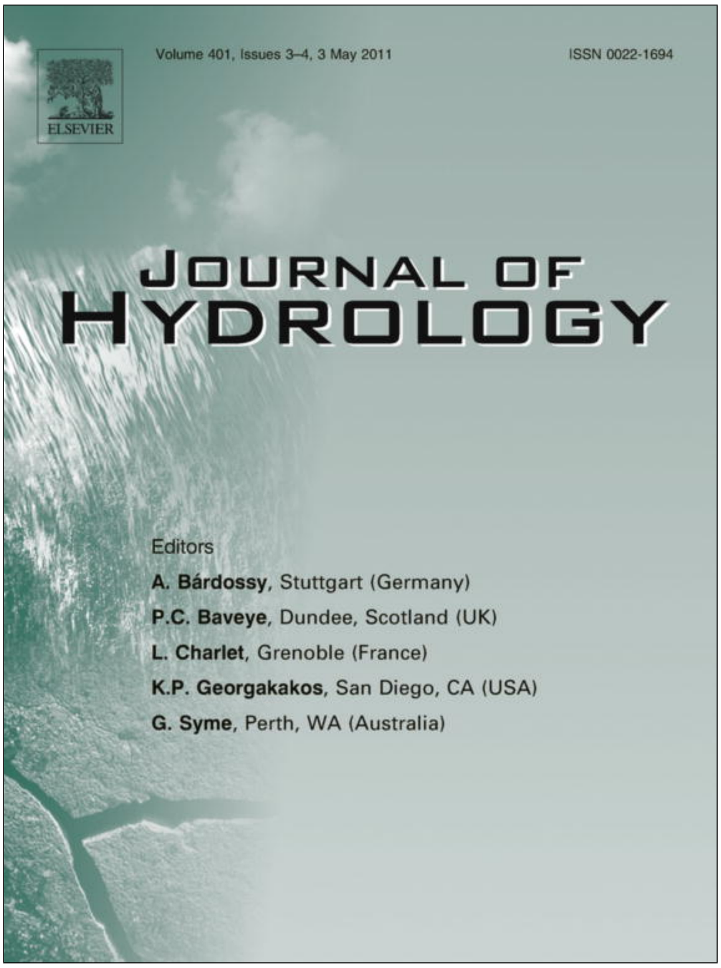
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Comparison of bottom-track to global positioning system referenced discharges measured using an acoustic Doppler current profiler

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S U M M A R Y

A negative bias in discharge measurements made with an acoustic Doppler current profiler (ADCP) can be caused by the movement of sediment on or near the streambed. The integration of a global positioning system (GPS) to track the movement of the ADCP can be used to avoid the systematic negative bias associated with a moving streambed. More than 500 discharge transects from 63 discharge measurements with GPS data were collected at sites throughout the US, Canada, and New Zealand with no moving bed to compare GPS and bottom-track-referenced discharges. Although the data indicated some statistical bias depending on site conditions and type of GPS data used, these biases were typically about 0.5% or less. An assessment of differential correction sources was limited by a lack of data collected in a range of different correction sources and different GPS receivers at the same sites. Despite this limitation, the data indicate that the use of Wide Area Augmentation System (WAAS) corrected positional data is acceptable for discharge measurements using GGA as the boat-velocity reference. The discharge data based on GPS-referenced boat velocities from the VTG data string, which does not require differential correction, were comparable to the discharges based on GPS-referenced boat velocities from the differentially-corrected GGA data string. Spatial variability of measure discharges referenced to GGA, VTG and bottom-tracking is higher near the channel banks. The spatial variability of VTG-referenced discharges is correlated with the spatial distribution of maximum Horizontal Dilution of Precision (HDOP) values and the spatial variability of GGA-referenced discharges is correlated with proximity to channel banks.

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1. Introduction

Discharges measured using vessel-mounted acoustic Doppler current profilers (ADCPs) may be biased by bedload transport; this bias is referred to herein as a moving-bed error. ADCPs mounted on moving vessels measure the velocity of the water relative to the velocity of the instrument. To obtain the true water velocity, the velocity of the ADCP must be measured and removed from the measured relative water velocity. The velocity of the ADCP relative to the streambed can be determined using the Doppler shift in bottom-tracking acoustic pulses reflected off the streambed, assuming that the streambed is motionless. Bottom-tracking, however, can be biased by sediment transport along and near the streambed. If an ADCP is held stationary in a stream and the bottom-tracking is biased by a moving bed, the ADCP will interpret this condition as upstream movement of the ADCP. With this bias, the boat will have an apparent upstream velocity, the calculated downstream water velocity will be reduced, and the corresponding discharge measured in these conditions will be biased low. This underestimation of measured velocity and discharge attributed to the movement of sediment near the streambed has been widely described (Oberg and Mueller, 1994; Callede et al., 2000; Mueller, 2002; Rennie and Rainville, 2006, Rennie et al., 2007).The integration of a global positioning system (GPS) to measure the velocity of the ADCP has been shown to eliminate the biases associated with a moving bed (Mueller, 2002; Mueller and Wagner, 2009; Rennie and Rainville, 2006). Although Rennie and Rainville (2006) provided a thorough analysis of the GPS accuracy at a single location, the accuracy of GPS-based ADCP discharge measurements has not been quantified over a wide range of flow and sediment transport conditions.

1.1. Purpose and scope

The purpose of this paper is to quantify the bias and random noise associated with GPS-based ADCP discharge measurements relative to bottom-track based discharge measurements at sites that did not have a moving-bed condition at the time of measurement. A moving-bed condition is determined to be present when the measured moving-bed velocity is greater than 1% of the mean water velocity at the test location (Mueller and Wagner, 2009). The

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GPS equipment utilized in the analysis was limited to GPS receivers with the capacity of providing sub-meter positional accuracy, and does not include Real-time Kinematic (RTK) GPS units. The analysis discussed here is based on 63 bottom-track and GPS-referenced discharge measurements composed of 579 individual transects collected at 42 different sites across the United States, Canada and New Zealand between 2002 and 2007 by various field personnel from the USGS, Environment Canada and New Zealand's National Institute of Water and Atmospheric Research using various deployment techniques (manned and tethered boats) and ADCPs.

1.2. Integration of GPS and ADCP data

Using GPS with ADCPs eliminates the effect of a moving bed on the velocity measurements but introduces various sources of potential error. The computation of water velocity from an ADCP mounted onto a moving boat is a vector-algebra problem. The ADCP measures the water velocity relative to the moving boat (relative water velocity), so the velocity of the boat must be accounted for to obtain the true water velocity. The true water velocity is computed by removing the boat velocity from the water velocity. When bottom-tracking is used, the direction of the boat-velocity vector as measured by bottom-tracking (θ_{BT}) and water-velocity vector (θ_{WT}) are referenced to the ADCP (Fig. 1A). Most ADCPs have an internal fluxgate compass to measure the orientation of the instrument (θ_{Inst}) relative to the local ambient magnetic field (magnetic north). The water-velocity vector can be easily referenced to magnetic north by rotating the vector based on the measured θ_{Inst} and to true north by again rotating the vector by a user-specified magnetic variation (θ_{Mag}). The magnitude of the water velocity is unaffected by any errors in the measurement of θ_{Inst} or entry of θ_{Mag} when bottom-tracking is used as the boat-velocity reference. The basic equation presented in Simpson and Oltmann (1993) for computing measured discharge (exclusive of unmeasured areas) by use of an ADCP mounted onto a moving boat is

$$Q = \int_0^T \int_0^D |\vec{V}_f||\vec{V}_b| \sin\theta dz dt \quad (1)$$

where Q is the total discharge, T is the total time for which data were collected, D is the total depth, $\vec{V}_f$ is the mean water-velocity vector, $\vec{V}_b$ is the mean boat-velocity vector, θ is the angle between the water-velocity vector and the boat-velocity vector (Fig. 1), dz is the vertical differential depth, and dt is differential time.

To compute the discharge, only the angle between the water-velocity and the boat-velocity vectors is needed. When GPS is used to determine the boat-velocity vector, this vector is referenced to true north as determined from the GPS data (Fig. 1B). The orientation of the instrument relative to true north must be determined to put the boat-velocity vector and the relative water-velocity vector in the same coordinate system and allow for the computation of the water-velocity vector and θ. Therefore, in addition to the normal sources of error for bottom-tracking ADCP discharge measurements [i.e. unmeasured areas of a cross section associated with transducer draft and ringing, side-lobe interference and shallow edges, measurement of edge distances, effect of sediment on backscattered acoustic energy, and pitch and roll of boat (Oberg and Mueller, 1994; Mueller and Wagner, 2009)] the use of the GPS for boat-velocity reference is subject to the following sources of error: (1) the quality (accuracy and precision) of the GPS data and (2) the referencing of the ADCP data to true north, which is achieved through an internal compass and relies upon a compass calibration (θ_{Inst}) and an accurate local magnetic variation (θ_{Mag}). This analysis focuses on the quality of the GPS data, and although the effect of compass errors on the accuracy of the GPS-referenced discharges is mentioned, a detailed evaluation is beyond the scope of this paper.

1.2.1. GGA and VTG data strings

GPS provides two options for determining boat velocity: (1) differentiated position using the GGA National Marine Electronics Association (NMEA)-0183 sentence and (2) Doppler-based velocity reported in the VTG NMEA-0183 sentence. The GGA data sentence broadcast by the GPS includes time, positional data (latitude, longitude, and elevation), and information about the satellite constellation used to reach the position solution. When using the GGA sentence from the GPS to measure the movement of the ADCP, the instrument velocity is determined by computing the distance traveled between successive GPS position solutions and dividing that distance by the time between the solutions. Hence, positional accuracy is vitally important to achieve an accurate measure of ADCP velocity using the GGA sentence; therefore, a differential correction signal is required. To use the GGA sentence, differentially

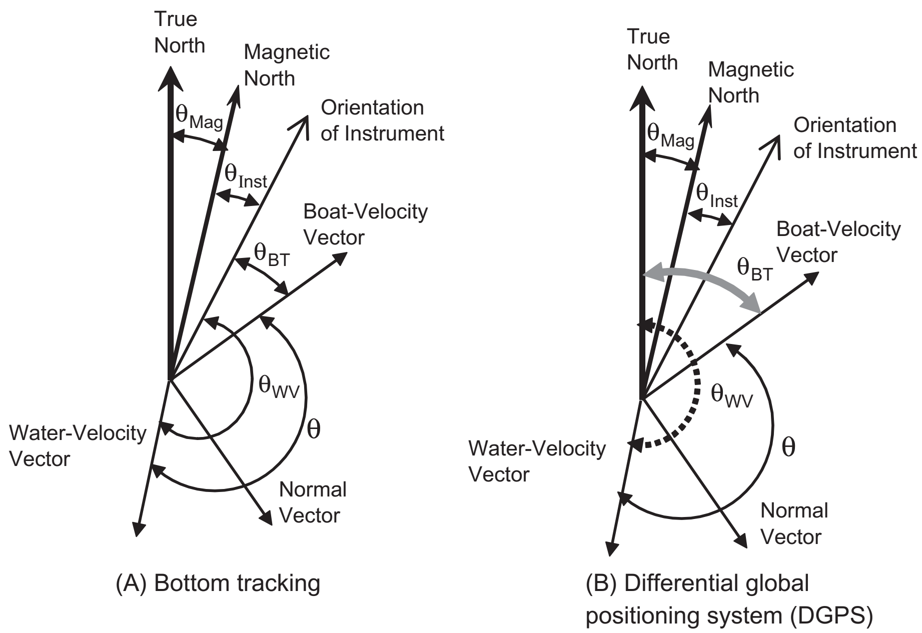

Fig. 1. Vectors illustrating the difference between bottom-tracking and global positioning system (GPS)-referenced boat-velocity vectors (adapted from Mueller, 2002).

corrected GPS (DGPS) receivers are required, and receivers should have a 95% accuracy of about 1 meter (m) or less in the horizontal location.

Whereas GPS is most often used to determine positions, many GPS receivers also can be used to measure velocity relative to ground with an assessment of the Doppler shift in the satellite carrier phase frequencies, which is typically reported in the VTG sentence. The actual signal frequency is used in the method, and not a phase angle, to determine the Doppler shift. As for the position determination, the velocity measurement requires the use of at least four satellites. The quality of the solution also is affected by the number of satellites and the shape of the constellation during the observation (quantified by the Horizontal Dilution of Precision (HDOP) parameter). This method has an advantage over other methods because, in this method there is minimal effect from multipath and satellite changes because of the short sampling time required. In addition, multipath and ionospheric/atmospheric distortions do not affect the precision of the measurement. As a result,

Table 1
Summary of measurement site characteristics for data used in the analysis (Meas No. – measurement number; m – meter; m/s – meters per second; m^3/s – cubic meters per second; GPS – global positioning system).

Meas No.	Site name	Stream width (m)	Maximum depth (m)	Mean velocity (m/s)	Mean discharge (m^3/s)	Type of GPS data collected (GGA, VTG)	BT COV	GGA COV	VTG COV
1	Bear River at Pescadero, Idaho	30	1.3	0.58	19	GGA	3.05	2.30	–
2	Wabash River at Covington, Indiana	125	1.9	0.44	111	GGA	3.00	4.20	–
3	Fox River nr Montgomery, Illinois	58	2.2	0.37	44	GGA,VTG	3.04	3.14	3.13
4	Green River near Jensen, Utah	62	0.8	0.75	32	GGA	1.47	1.35	–
5	Green River above Green River, Utah	62	1.3	0.56	35	GGA	3.01	2.25	–
6	Green River above Green River, Utah	61	1.2	0.56	37	GGA	3.02	2.16	–
7	Jacks Fork at Alley Springs, Missouri	23	0.9	0.16	3	GGA,VTG	6.34	7.15	10.6
8	Jacks Fork at Alley Springs, Missouri	24	1.0	0.16	3	GGA,VTG	12.7	13.7	14.1
9	Bear River at Pescadero, Idaho	32	1.2	0.50	19	GGA	4.01	4.59	–
10	St. Francis Creek at Fisk, Missouri	15	1.5	0.63	11	GGA,VTG	11.1	10.5	9.11
11	St. Francis Creek at Fisk, Missouri	15	1.5	0.64	11	GGA,VTG	3.06	2.77	3.81
12	Fox River nr Montgomery, Illinois	59	2.2	0.37	47	GGA,VTG	2.18	2.29	3.88
13	Fox River nr Montgomery, Illinois	73	1.0	0.63	45	GGA,VTG	5.55	4.80	5.71
14	Fox River nr Montgomery, Illinois	73	1.1	0.63	40	GGA,VTG	2.76	4.01	3.74
15	Fox River nr Montgomery, Illinois	74	1.1	0.68	40	GGA,VTG	1.40	1.40	2.36
16	Green River above Green River, Utah	61	1.3	0.58	36	GGA	2.60	2.73	2.60
17	Mississippi River at Chester, Illinois	509	9.1	1.21	5645	GGA	1.05	4.33	1.05
18	Mississippi River at Chester, Illinois	493	6.3	1.01	3266	GGA	1.04	1.72	1.04
19	Ohio River at Louisville, Kentucky	767	8.0	1.18	6777	GGA,VTG	1.09	2.93	2.92
20	Ohio River at Louisville, Kentucky	600	6.3	0.86	3122	GGA,VTG	0.49	1.70	2.90
21	Allegheny River near Pittsburgh, Pennsylvania	278	6.0	0.77	1235	GGA,VTG	1.79	3.35	3.24
26	Monongahela River near Pittsburgh, Pennsylvania	298	5.2	0.08	101	GGA,VTG	4.59	11.4	10.6
27	Ohio River near Pittsburgh, Pennsylvania	352	7.1	0.60	1452	GGA,VTG	0.79	2.17	0.80
28	Ohio River near Pittsburgh, Pennsylvania	314	6.4	0.62	1388	GGA,VTG	0.91	0.27	0.63
29	Roanoke River near Oak City, North Carolina	90	2.0	0.45	80	GGA,VTG	1.86	3.80	4.65
30	Roanoke River at Scotland Neck, North Carolina	78	2.1	0.50	80	GGA,VTG	2.75	1.47	1.77
31	Youghiogheny River at Elizabeth, Pennsylvania	105	3.2	0.11	30	GGA,VTG	15.8	17.2	18.0
32	Bow River at Carsland, Canada	105	1.5	0.66	120	GGA,VTG	1.21	1.71	1.86
33	Hay River near Hay River, Canada	88	2.0	0.64	122	GGA,VTG	1.46	1.71	1.69
34	Niagara River Cableway, Canada	166	10.4	1.54	3083	GGA,VTG	4.72	10.4	10.4
35	Niagara River Cableway, Canada	157	10.8	1.60	3074	GGA,VTG	2.93	7.71	8.21
36	Niagara River Cableway, Canada	145	10.6	1.74	3323	GGA,VTG	3.32	3.78	3.67
37	Niagara River Cableway, Canada	188	14.6	1.92	6619	GGA,VTG	2.92	2.83	3.03
38	Niagara River Cableway, Canada	145	10.8	1.41	2739	GGA,VTG	2.87	3.16	3.10
39	Niagara River Cableway, Canada	191	14.4	1.82	6130	GGA,VTG	2.83	3.00	2.55
40	Niagara River Cableway, Canada	189	14.5	1.88	6354	GGA,VTG	2.31	2.17	2.18
41	Niagara River Cableway, Canada	188	15.0	1.95	6399	GGA,VTG	2.52	0.77	1.66
42	Saskatchewan River at The Pas, Canada	248	5.5	0.58	798	GGA,VTG	1.13	1.21	2.10
43	South Nation River at Plant, Canada	90	6.2	1.32	628	GGA,VTG	2.62	2.20	2.28
44	South Nation River at Plant, Canada	105	3.9	0.42	172	GGA,VTG	1.57	1.76	1.71
45	Waiau River at Tuatapere, New Zealand	74	1.5	0.48	51	VTG	1.06	–	0.80
46	Waiau River at Queens Reach, New Zealand	53	3.0	0.99	134	VTG	3.46	–	2.66
47	Waiau River at Queens Reach, New Zealand	62	3.2	1.22	257	VTG	1.09	–	1.50
48	Clutha River at Balclutha, New Zealand	192	2.7	1.23	639	VTG	0.70	–	1.30
49	Clutha River at Balclutha, New Zealand	176	2.3	1.06	410	VTG	0.45	–	0.67
50	Clutha River at Tuapeka, New Zealand	141	3.8	1.03	437	VTG	2.19	–	1.91
51	Clutha River at Tuapeka, New Zealand	142	3.5	0.85	320	VTG	1.89	–	1.76
52	Clutha River at Roxburgh, New Zealand	67	7.2	0.68	394	VTG	4.53	–	5.08
53	Clutha River at Roxburgh, New Zealand	93	5.5	0.74	405	VTG	1.81	–	1.29
54	Clutha River at Clyde, New Zealand	85	3.8	1.19	390	VTG	2.15	–	1.51
55	Clutha River at Clyde, New Zealand	85	3.8	1.31	412	VTG	0.87	–	0.96
56	Kawarau River at Frankton, New Zealand	88	5.8	0.07	62	VTG	4.37	–	6.30
57	Kawarau River at Frankton, New Zealand	83	6.3	0.14	80	VTG	3.08	–	4.55
58	Clutha River at Wanaka Outlet, New Zealand	71	4.3	0.34	85	VTG	4.90	–	7.81
59	Clutha River at Wanaka Outlet, New Zealand	73	4.6	0.43	113	VTG	2.02	–	2.27
60	Clutha River at Cardrona Confluence, New Zealand	73	2.2	1.64	263	VTG	0.75	–	1.79
61	Clutha River at Cardrona Confluence, New Zealand	73	4.6	0.43	113	VTG	2.02	–	2.27
62	Clutha River at Stirling, New Zealand	85	1.8	0.84	121	VTG	2.11	–	4.64
63	Wairaurahiri River at Lake Hauroko Outlet, New Zealand	34	2.7	1.01	58	VTG	2.13	–	2.45

the Doppler measurement of velocity can be produced without the need for any differential correction (Mueller and Wagner, 2009).

1.3. Description of data

Discharges were measured using both bottom-track and GPS-referenced boat velocities for 63 measurements (which consist of the average of between 4 and 34 transects in reciprocal directions) collected at 42 different sites. Each of the 579 measured transects was processed individually and inspected for data quality issues. The information provided in the discharge summary from WinRiver II software (version 2.03), general comments related to each transect, the GPS positional precision, type of GPS and differential correction source used, update rate for ADCP and GPS data, and the level and location of multipath or boat speed spikes were documented during data processing. Transects with erroneous data resulting from GPS communication and reception problems were identified by simultaneously visually screening the BT, GGA and VTG boat speed time series plots for frequent spikes and areas of missing data occurring only in the GGA and/or VTG-based boat speeds and were subsequently eliminated from the analysis. The final dataset consisted of 59 measurements (39 have GGA data, 49 have VTG data, and 30 measurements have both GGA and VTG data) and 535 transects for analysis (451 transects have GGA data, 421 transects have VTG data, and 337 transects have both VTG and GGA data) from 39 different sites. Stream widths ranged from 15 to 760 m and average depths ranged from 1.5 to 8 m. Average water velocities varied from less than 0.1 meter per second (m/s) to 2 m/s and total discharges varied from 2 cubic meters per second (m^3/s) to 6800 m^3/s. A summary of the measurement site characteristics is presented in Table 1.

Either a 1200 kilohertz (kHz) or 600 kHz Teledyne RD Instruments (TRDI)[1] Rio Grande ADCP was used for all of the discharge measurements. For the measurements made in the United States, Trimble Ag132 GPS receivers were used; Novatel V1 GPS receivers were used for measurements made in Canada and New Zealand. The accuracy specifications for both types of these GPS receivers are approximately equivalent and typically provide sub-meter accuracy (for more detailed specifications please refer to the specifications available from the manufacturer).

2. Data-analysis methods

All measurements were compiled and inspected visually as well as statistically. Box plots and scatter plots were constructed for bottom track, GGA and VTG-based discharges at each site to initially characterize the data and identify potential outliers. GPS inaccuracies were easier to identify in GGA data because of the large spikes in boat velocity, but VTG errors were more subtle. The percent differences (errors) between the GGA and BT-referenced discharges, and the VTG and BT-referenced discharges were calculated for each individual transect, 4-transect averages and the mean discharge of all transects at each of the measurement sites. The Shapiro–Wilk test for normality was applied to determine if the errors followed a normal distribution. The Shapiro–Wilk tests (Shapiro and Wilk, 1965) indicated that the null hypothesis of normality is rejected at a 95% confidence level. Because the data were not normally distributed, a Wilcoxon Signed-Rank hypothesis test (Wilcoxon, 1945) was used to determine if the mean percent differences (errors) between GGA and BT-referenced discharges and VTG- and BT-referenced discharges are statistically different from zero (biased).

[1] The use of brand names in this report is for identification purposes only and does not imply endorsement by the US Geological Survey.

Table 2
Summary of two approaches to evaluate errors between bottom-track and GPS-based measured discharges. [GGA-BT – percent difference between GGA and bottom-track based discharge measurements; VTG-BT – percent difference between VTG and bottom-track based discharge measurements; % – percent].

GPS method	All sites with GGA or VTG data		All sites with both GGA and VTG data	
	Mean (%)	Standard deviation (%)	Mean (%)	Standard deviation (%)
GGA-BT	−0.60	3.44	−0.54	3.70
VTG-BT	0.43	4.08	0.37	4.52

Two approaches to comparing BT-referenced discharges to GGA- and VTG-referenced discharges were used. The first approach evaluated measured discharges for all transects at all the sites with GGA and(or) VTG data regardless of whether both GPS reference sources were available. The second approach contrasted measured discharges for all transects only at sites with both GGA and VTG data. The mean and standard deviation of percent differences between bottom-track and GPS data for the two approaches are presented in Table 2.

Because of the similarity of the means and standard deviations of these two approaches, subsequent comparisons in this paper are based only on the data where both GGA and VTG data were collected. This approach eliminates any difference in site conditions, such as GPS signal obstructions, stream width and velocity, and geography that could affect the results of the analysis.

The spatial variability of GGA, VTG and bottom-track-referenced discharges throughout the cross section at each measurement site was evaluated by computing the coefficient of variation of all the transects measured at a site. The spatial variability within a cross section was evaluated by dividing the cross section of each transect into subsections that extend out from each bank in 5-m increments (for example, the 0–5 subsection consists of the data in the two sections of the channel that lie between 0 and 5 m from each bank and the 65–70 subsection consists of the data in the two sections of the channel that lie between 65 and 70 m from each bank).

For each transect, the measured discharges (referenced to GGA, VTG and bottom track) were summed in each of these regions (see Eq. (2)) and a coefficient of variation for each boat-velocity reference source was computed.

$$Q_{X_{REF}} = \sum_{Y+5}^{Y} Q_{ens} + \sum_{Z+5}^{Z} Q_{ens} \quad (2)$$

where Q_X is the total discharge in the X subsection as defined above for all three boat-velocity reference sources, REF the boat-velocity reference source (GGA, VTG or bottom track), X the subsection of channel as defined above (0–5, 5–10, 10–15, 15–20 , . . . , 65–70), Y the starting distance of subsection measured from left bank (looking downstream), in meters (0, 5, 10, 15, 20 , . . . , 60, 65), Z the starting distance of subsection measured from right bank (looking downstream), in meters (0, 5, 10, 15, 20 , . . . , 60, 65), and Q_{ens} = total discharge in each ensemble of the specified subsection of the channel.

3. Results and discussion

The following section presents the results of a comparison of bottom-tracking and GPS-based discharge measurements using all individual transects and complete measurements (defined as the discharges obtained by averaging all transect discharges together that were used to constitute a single discharge measurement at a site). The errors associated with GGA and VTG-based discharge measurements will be quantified. The effect of stream width, mean boat speed, the spatial location within the measurement cross section, and differential correction source on the errors will also be evaluated.

3.1. Discharge comparisons using individual transects

A comparison of discharges measured using bottom-tracking and GGA or VTG as the boat-velocity reference and the distribution of the percent difference for all 337 transects with both GGA and VTG data are shown in Figs. 2 and 3. Graphically, it appears that there is little difference between the BT and GGA or VTG-based discharges. However, the results of Wilcoxon Signed-Rank test indicate that although the mean difference between GGA and BT-based discharges was not biased at the 95% significance level ($p = 0.056$), the mean differences between VTG and BT-based discharges ($p = 0.015$) and VTG and GGA-based discharges ($p = 0.0001$) are biased. Nevertheless, the mean differences ((GPS-BT)/BT) are small, −0.54% and 0.37% for GGA and VTG, respectively. The mean difference between VTG and GGA-based discharges is 0.93%.

A more detailed examination of the data shows that large deviations in the VTG data result at sites with low mean boat speeds (<0.25 m/s) and/or narrow channel widths (<25 m) (see Fig. 4). The data were filtered to evaluate only the data with mean boat speed less than 0.25 m/s, which resulted in a dataset with a mean boat speed of 0.11 m/s (min = 0.04 m/s and max = 0.25 m/s) and a mean width of 40 m (min = 14.6 m and max = 105 m). For this subset of the data, the mean difference in discharge between BT and GGA is −1.32% with a standard deviation of 3.32%, the mean difference between BT and VTG is 1.94% with a standard deviation of 6.10% and the mean difference between VTG and GGA is 3.33% with a standard deviation of 5.68%. The hypothesis test shows that both the GGA ($p = 0.000$) and the VTG ($p = 0.005$) measured discharges are biased relative to the BT discharges and that VTG is biased relative to GGA-based discharge measurements ($p = 0.000$) at the 95% significance level. When filtering the data to evaluate only data with mean boat speeds greater than 0.25 m/s, the resulting subset of the data had a mean velocity of 0.85 m/s (min = 0.26 m/s and max = 1.67 m/s) and a mean width of 151 m (min = 15.0 m and max = 770 m). For this dataset, the mean difference between BT and GGA discharges is −0.25% with a standard deviation of 3.70%, the mean difference between BT and VTG discharges is 0.00% with a standard deviation of 3.77% and the mean difference between VTG and GGA is 0.26% with a standard deviation of 1.83%. The hypothesis test shows that for measurements with mean boat speeds greater than 0.25 m/s, the mean percent difference from BT discharge for both the GGA ($p = 0.982$), and the VTG ($p = 0.104$) data and the mean percent difference between VTG and GGA-based discharges ($p = 0.134$) are not significantly different from zero at the 95% significance level.

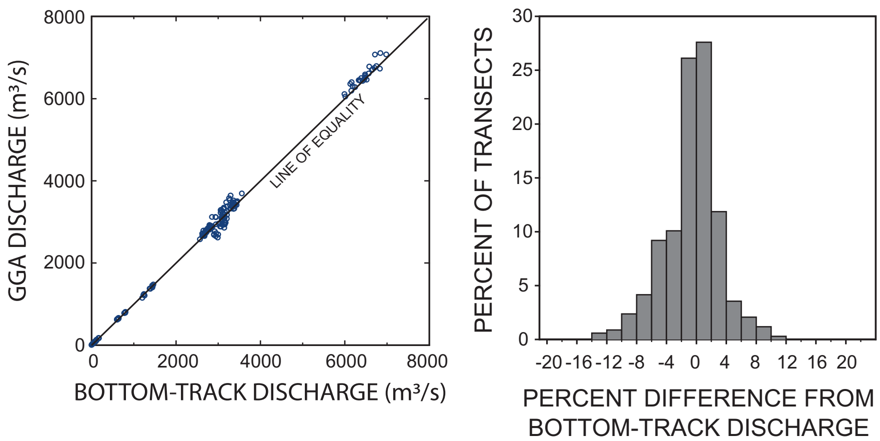

Fig. 2. Comparison of the discharges computed using bottom-track and GGA as the boat-velocity reference illustrated as a scatter plot and a histogram of the percent difference.

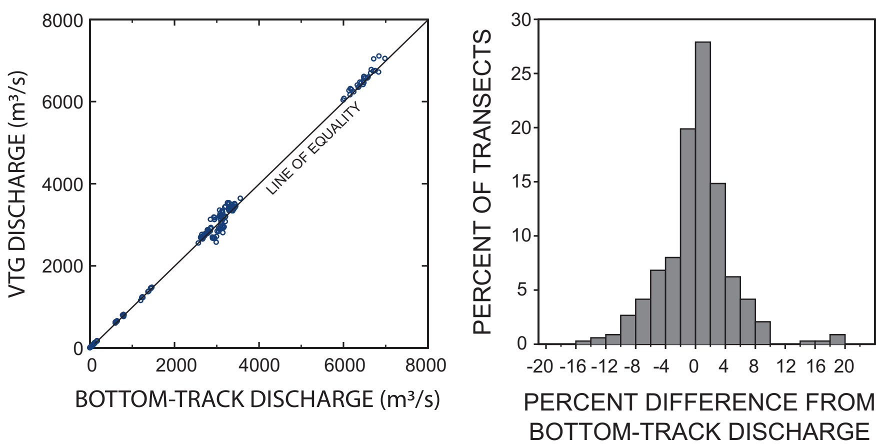

Fig. 3. Comparison of the discharges computed using bottom-track and VTG as the boat-velocity reference illustrated as a scatter plot and a histogram of the percent difference.

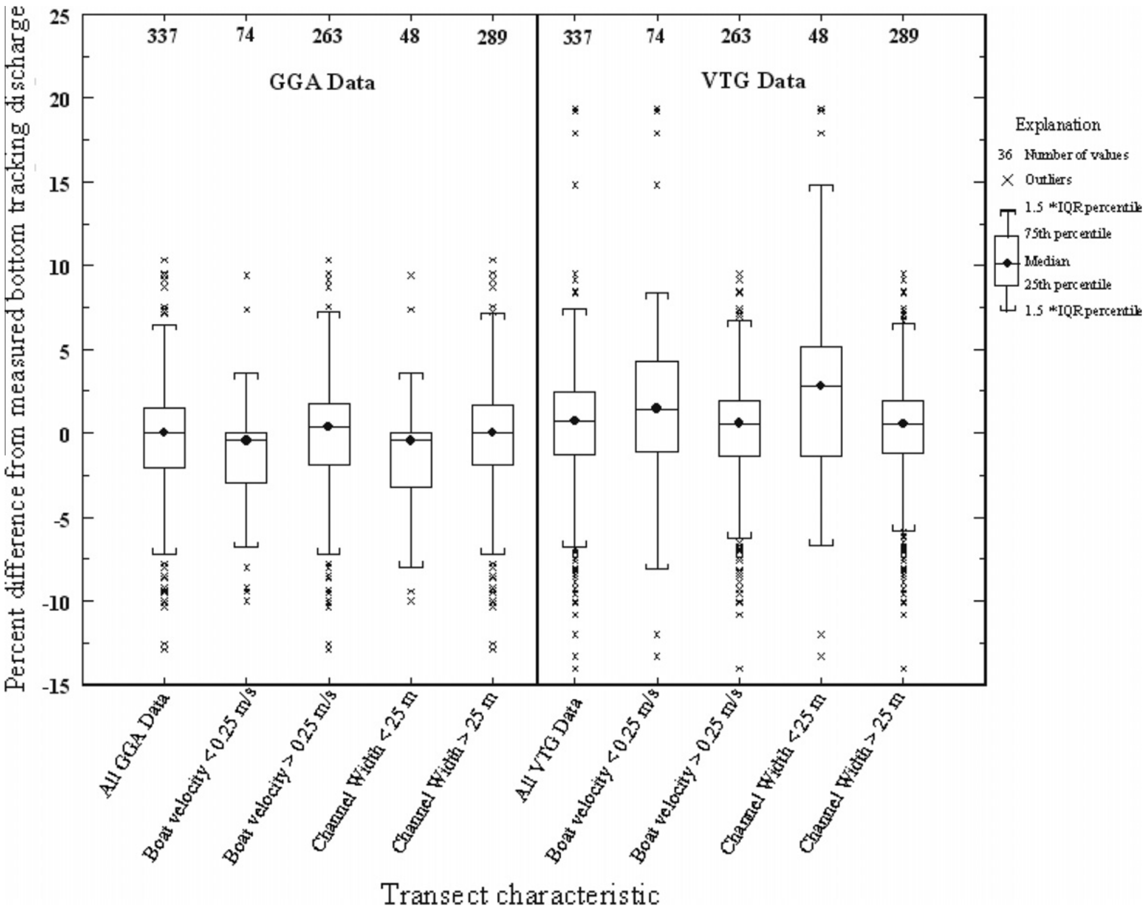

Fig. 4. Box plot showing the variation in percent difference from bottom-track referenced discharge for transects based on mean boat velocities and stream width.

The data were also filtered based on stream width. When the data with channel widths <25 m were analyzed, the resulting subset of the data had a mean velocity of 0.08 m/s (min = 0.04 m/s and max = 0.13 m/s) and a mean width of 19.5 m (min = 14.5 m and max = 24.9 m). For this dataset, the mean difference between bottom-track and GGA is −1.15% with a standard deviation of 3.73%, the mean difference between bottom-track and VTG is 2.65% with a standard deviation of 7.02% and the mean difference between VTG and GGA is 3.88% with a standard deviation of 6.67%. The hypothesis test on these data shows that the mean percent difference from BT for both the GGA ($p = 0.011$) and the VTG ($p = 0.009$) data and between the VTG and GGA data ($p = 0.000$) are significantly different from zero at the 95% significance level. When the data were filtered to include only sites with channel widths >25 m , the resulting subset of the data has a mean boat speed of 0.80 m/s (min = 0.10 m/s and max = 1.67 m/s) and a mean width of 151 m (min = 56.9 m and max = 770 m). There are no data available for channel widths between 25 and 56.9 m. For channel widths >25 m, the mean difference between bottom-track and GGA is −0.35% with a standard deviation of 3.63%, the mean difference between bottom-track and VTG is 0.05% with a standard deviation of 3.74%, and the mean difference between VTG and GGA is 0.44% with a standard deviation of 2.04%. The hypothesis test on these data shows that the mean percent difference from BT for both the GGA ($p = 0.337$) and the VTG ($p = 0.129$) data are not significantly different from zero at the 95% significance level but the mean percent differences between VTG and GGA data ($p = 0.006$) are significantly different from zero.

Based on the data and the hypothesis tests described above, the discharges measured using GGA as the boat-velocity reference can be considered to have no bias relative to BT for sites with widths greater than 56 m or mean boat speeds greater than 0.25 m/s, but a mean bias of between −1.15% and −1.32% on streams less than 25 m wide and/or when mean boat speeds are less than 0.25 m/s. The hypothesis test on the VTG data indicate that there is no bias in discharge relative to BT for streams greater than 56 m wide or mean boat speeds greater than 0.25 m/s, but a bias of between 1.94% and 2.65% for streams with widths less than 25 m and/or when mean boat speeds are less than 0.25 m/s. The hypothesis test also indicate that there is not a bias between VTG and GGA discharge data with mean boat speeds greater than 0.25 m/s, but a bias of between 0.44% and 3.88% when mean boat speeds are less than 0.25 m/s and/or for both conditions where data where filtered by stream width. A limitation of the dataset used in the analysis is the inability to adequately separate the relative effect of widths and mean boat velocity on the biases in GPS-measured discharges. The sites with slower mean boat speeds (<0.25 m/s) also tended to have narrower widths.

3.2. Discharge comparisons using complete measurements

The discharge comparisons based on individual transects more heavily weights the effects of hydraulic conditions at sites where a larger number of transects were collected. To eliminate this potential problem the mean discharge at each measurement site was computed using each reference, which resulted in 30 measurements for each boat-velocity reference for the purpose of comparison. The variability of GGA-, VTG-, and BT-referenced discharges at each measurement site was evaluated by computing the coefficient of variation of all the transects used in a measurement (Table 1). A

Table 3
Summary of the coefficient of variations of measured discharges for all transects collected at each measurement site (BT – bottom track; COV – coefficient of variation).

Statistic	Mean BT discharge COV	Mean GGA discharge COV	Mean VTG discharge COV
Average	3.57	4.40	4.72
Standard Deviation	3.54	4.13	4.18

summary of the mean coefficient of variations for all three discharge references is presented in Table 3. The data indicate that the variability of the GGA- and VTG-referenced discharges are essentially the same and confirm that BT-referenced discharges are less variable than GPS-referenced data. As discussed in Section 1.2, errors in the magnetic variation or heading errors from the compass result in errors in discharge referenced to GPS. These errors typically cause a directional bias between transects (i.e. transects collected while traveling in one direction across the stream have a consistently higher or lower discharge than transects collected in the reciprocal direction). Preliminary analysis of the directional bias present in these data suggest that errors in compass heading or magnetic variation may contribute as much as 8% to the coefficient of variation for a single measurement, but average contribution appears to be about 1%, which is consistent with the additional variability observed in the GPS-referenced data (Table 3). Due to small sample sizes within each measurement the statistical significance of these results requires a more detailed analysis to properly account for errors not associated with the magnetic variation or heading and is beyond the scope of this paper. Additional research is needed to address the contribution of magnetic variation and heading errors on GPS reference discharges.

Evaluation of the discharges for complete measurements shows the mean difference from the BT discharges was −0.54% for GGA and 0.37% for VTG. Distributions of the percent differences in discharge are shown in Fig. 5. The mean difference between VTG and GGA-based discharges was 0.89%.

Although the variability of GPS-based data are higher than the BT data (Table 3), the Wilcoxon Signed-Rank hypothesis test on complete measurements indicates that the mean percent difference from bottom-tracking for both the GGA ($p = 0.136$) and the VTG ($p = 0.457$) data are not significantly different from zero but the difference between VTG and GGA is significantly differently from zero ($p = 0.012$) at the 95% significance level. This result is noteworthy as it indicates the errors between BT and GPS-based measured discharges are reduced to a statistically insignificant level by averaging at least four transects consisting of pairs collected in opposite directions (reciprocal pairs), which is consistent with USGS field methods for making ADCP discharge measurements (Mueller and Wagner, 2009).

3.3. Comparison of differential correction sources and GPS Receiver types

Three wide-area satellite-based differential correction sources commonly used in North America were evaluated using GGA as the navigation reference for measured discharge. The Wide Area Augmentation System (WAAS) is a free correction service provided by the Federal Aviation Association and can provide sub-meter accuracy depending on the GPS receiver being used (http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/). OmniSTAR VBS (www.omnistar.com) is a fee for service correction source that also provides sub-meter level differential corrections. CDGPS (www.cdgps.com) is a wide-area differential correction source initially developed for the Canadian global positioning market. The CDGPS signal can be acquired throughout Canada and northern areas of the United States. WAAS and OmniSTAR correction services were evaluated using Trimble AgGPS 132 receivers and CDGPS was evaluated using data collected in Canada with Novatel receivers. This evaluation is complicated because discharges based on multiple correction sources were not collected at any sites, which would have resulted in direct comparisons of the accuracy of the correction sources. The dataset used in the evaluation is a compilation of data from different sites under varying hydraulic and site conditions. The results of this comparison are summarized in Table 4.

The source of the differential correction is likely only one of the reasons for the differences between GPS- and BT-referenced discharges shown in Table 4. Large variability in average stream width and maximum depth between the differential correction sources is also observed in Table 4. Both the maximum depth and mean velocity of the streams represented in the CDGPS data are overall larger than those represented in the other data (although the mean stream width for the OminSTAR data is larger than that of the CDGPS data, the standard deviation of stream width for the OmniSTAR data is nearly 6 times higher than the CDGPS data). Typically the variability in discharges measured with an ADCP on large streams is less than that measured on small streams. The lower variability on larger streams is attributed to (1) the additional data collected, which averages turbulence, and GPS and acoustic noise and (2) the unmeasured portions of the cross section that must be estimated using the measured data are a smaller percentage of the overall discharge than for smaller streams.

The advantage of VTG data over GGA data for determining boat velocity is that VTG data do not depend on differential corrections. VTG data collected in Canada with Novatel receivers, in New

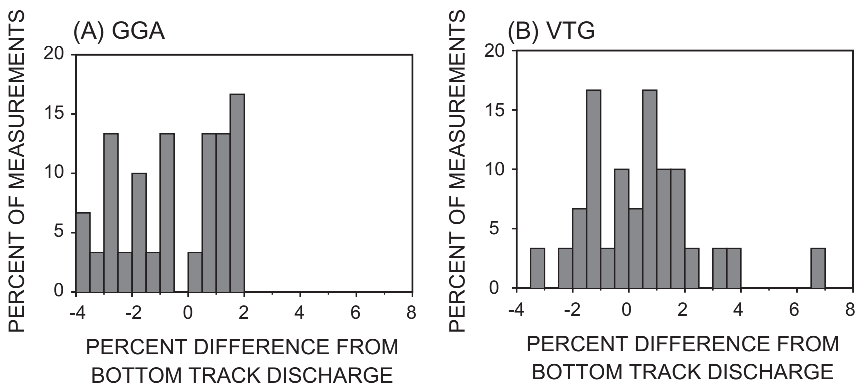

Fig. 5. Histograms showing the distribution of the percent difference between discharges computed using either (A) GGA or (B) VTG and bottom-track as the boat-velocity reference.

Table 4
Summary of data analysis for different differential correction sources. (none – only VTG data were collected; s – seconds; m – meters; m/s – meters per second; – no data).

Differential correction source	Receiver	Number of transects	Duration (s)	Width (m)	Max depth (m)	Mean velocity (m/s)	Q-Diff% (GGA-BT)	Q-Diff% (VTG-BT)
			Average					
CDGPS	Novatel	168	164.02	149.38	9.68	1.43	0.64	0.46
None	Novatel V1	84	212.58	92.56	3.92	0.82	–	0.45
OMNI	Trimble AgGPS 132	157	276.37	220.98	3.78	0.65	−1.46	−1.25
WAAS	Trimble AgGPS 132	126	207.54	47.21	1.33	0.49	−1.28	1.31
			Standard deviation					
CDGPS	Novatel	168	90.54	37.41	3.52	0.44	3.62	3.82
None	Novatel V1	84	47.99	42.04	1.63	0.42	–	1.96
OMNI	Trimble Ag GPS 132	157	190.68	215.02	2.80	0.32	3.31	3.78
WAAS	Trimble Ag GPS 132	126	116.31	25.05	0.40	0.19	3.04	5.69

Zealand with Novatel V1 Smart Antennas, and in the United States using Trimble AgGPS 132 receivers are also summarized in Table 4. The average percent differences from BT observed in the VTG data are comparable to the differentially-corrected GGA data. The differences between VTG- and GGA-referenced discharges relative to BT-referenced discharges are smaller for the Novatel receivers than for the Trimble receivers.

Considering the data limitations it appears that the free WAAS correction source performs as well as the fee for service OmniSTAR source for the purpose of making discharge measurements with ADCPs. The WAAS and OmniSTAR both produce discharge measurements with errors less than 1.5%. The data also indicate that VTG provides similar discharges to those based on GGA data and could be a valuable alternative where differential corrections may be difficult or impossible to obtain. Additional controlled testing to allow better comparisons is needed to quantitatively compare the receivers and differential correction sources.

4. Spatial variability

The spatial variability of GPS-referenced discharge measurements relative to bottom track-referenced discharges throughout the cross section at each measurement site was evaluated by computing the coefficient of variation for bottom track-, GGA- and VTG-referenced discharges measured within 14 different 10-m subsections (combination of two 5-m subsections) of the channel (see Eq. (2)) at each measurement site. The mean spatial variability of the GPS-referenced discharges relative to simultaneous bottom track-referenced discharges is illustrated in Fig. 6. This result indicates that the variability in measured discharge decreased for all reference sources as the boat moved away from the banks. GPS-referenced discharges measured in sections of the channel near the banks are typically more effected by satellite signal reception issues and multi-path errors than sections near mid-channel because of overhanging trees and(or) steep banks. The variations of

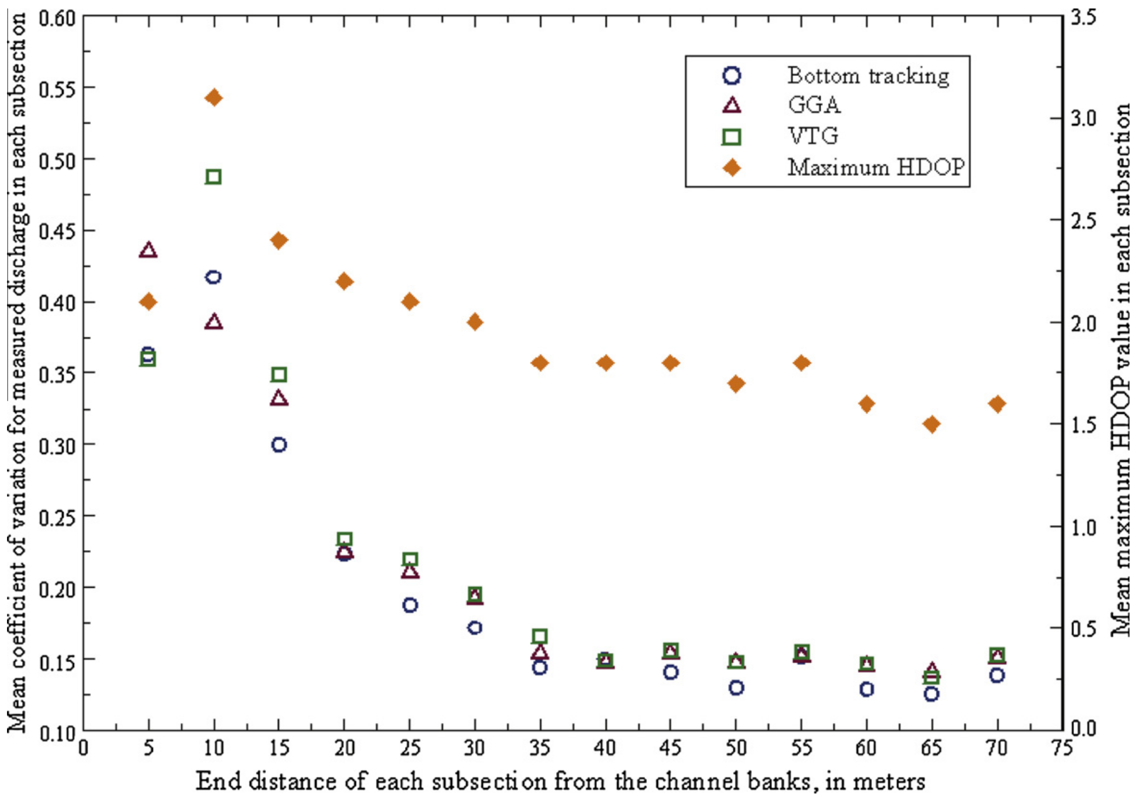

Fig. 6. Spatial variability of GPS and bottom-tracking referenced measured discharges and maximum horizontal dilution of precision (HDOP) value in each transect subsection for all measurements.

discharge referenced to bottom-track were also higher along the bank, which may be related to boat speed variations caused by maneuvering the boat near the banks, bottom-track inaccuracies caused by the sloping streambed, and lower water velocities and shallower depths. The variability of VTG-referenced measured discharges is shown in Fig. 6 to be correlated with the maximum Horizontal Dilution of Precision (HDOP) value measured in each subsection. The HDOP is a measure of the GPS accuracy related to the configuration of the satellite constellation at the time of the measurement (higher HDOP = lower GPS accuracy). Although the variability of the GGA-referenced discharges is related to maximum HDOP values, the variability is more closely correlated with proximity to the channel banks where multipath issues from trees and steep banks are more prevalent (Fig. 6).

5. Summary and conclusions

A systematic bias in discharge measurements made with an acoustic Doppler current profiler (ADCP) attributed to the movement of sediment near the streambed leads to underestimation of measured velocity and discharge. The integration of a global positioning system (GPS) to track the movement of the ADCP can be used to avoid the systematic bias associated with a moving bed. Differences between bottom-track and GPS (GGA or VTG) referenced discharges can be attributed to either the quality of the GPS data or the accuracy of the ADCP heading measurement as referenced to true north (compass calibration and magnetic variation). The impact of compass errors on the GPS accuracy was not specifically evaluated in this analysis. This analysis is based on 63 bottom-track and GPS-referenced discharge measurements composed of 579 individual discharge measurement transects collected at 42 different sites across the United States, Canada and New Zealand between 2002 and 2007 by various field personnel from the USGS, Environment Canada, and New Zealand's National Institute of Water and Atmospheric Research using various deployment techniques and ADCPs. The data and analysis presented herein indicate that discharge measured using either the GGA or VTG data from GPS receivers as the navigation reference are generally within ±0.5% on average of that measured using bottom-tracking. Measured discharges referenced to VTG are generally within 1% on average of GGA referenced discharge data. Statistical hypothesis testing showed that the bias for VTG-referenced discharges was statistically significant at the 95% significance level for analysis of all individual transects, but was not significant when evaluating the mean of all transects collected as part of the measurement. Hypothesis testing showed that the bias for GGA-referenced discharges was not statistically significant at the 95% level for the individual transects or the complete measurements. The hypothesis testing showed that the bias between VTG and GGA-referenced discharges was statistically significant at the 95% significance level for the individual transects and the complete measurements. There were considerably more random errors and outliers in the percent differences between GPS and bottom-track-referenced discharges and VTG and GGA-referenced discharges for sites with mean boat speed velocities less than 0.25 m/s and/or channel widths less than 25 m.

Dataset limitations prevented the relative impact of widths and mean boat velocity on the biases in discharges to be separated because the sites with slower mean boat speeds (<0.25 m/s) also tended to have narrower widths. Spatial variability of measured discharges referenced to GGA, VTG and bottom-tracking is higher near the channel banks. The spatial variability of VTG-referenced discharges is well correlated with the spatial distribution of maximum HDOP values and spatial variability of GGA-referenced discharges is well correlated with proximity to channel banks.

Although this study has shown that VTG can be a valid alternative for measuring discharge with an ADCP in moving bed environments, appreciable inaccuracies in VTG-based discharges were observed and are more difficult to detect in the variation in boat speed than for GGA data. Additional research is required to identify and quantify the readily available metrics in the data collection software that indicate when VTG data are not adequate for accurately measuring discharge with an ADCP.

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