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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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SUMMARY

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

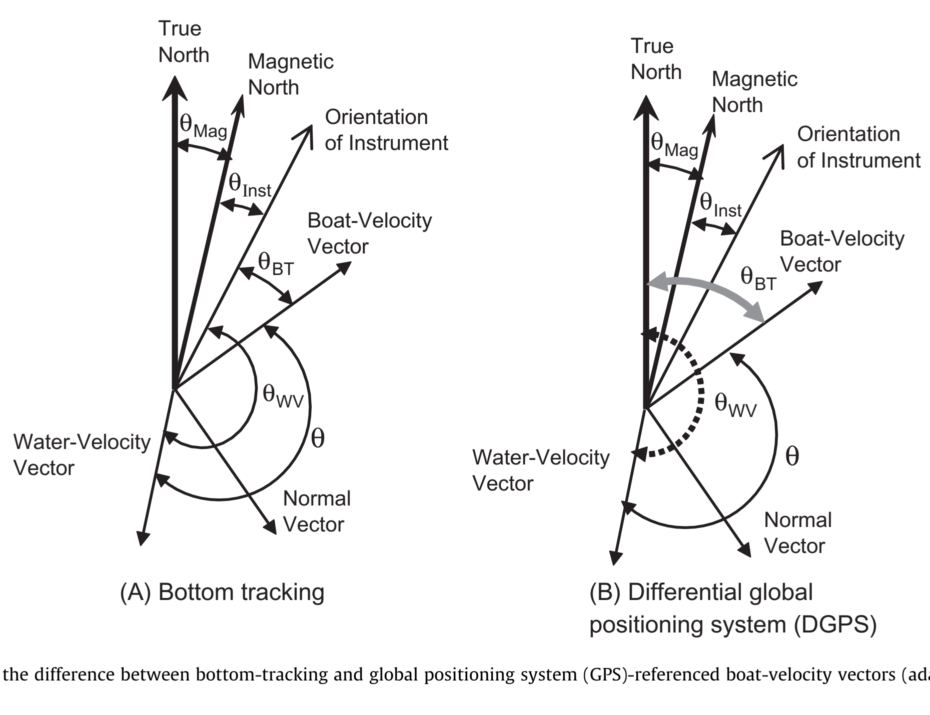

Fig. 1. Vectors illustrating the difference between bottom-tracking and global positioning system (GPS)-referenced boat-velocity vectors (adapted from Mueller, 2002).