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Cause and Solution for False Upstream Boat Velocities Measured with a StreamPro Acoustic Doppler Current Profiler

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Abstract

In 2003, Teledyne RD Instruments introduced the StreamPro acoustic Doppler current profiler which does not include an internal compass. During stationary moving-bed tests the StreamPro often tends to swim or kite from the end of the tether (the instrument rotates then moves laterally in the direction of the rotation). Because the StreamPro does not have an internal compass, it cannot account for the rotation. This rotation and lateral movement of the StreamPro on the end of the tether generates a false upstream velocity, which cannot be easily distinguished from a moving-bed bias velocity. A field test was completed to demonstrate that this rotation and lateral movement causes a false upstream boat velocity. The vector dot product of the boat velocity and the unit vector of the depth-averaged water velocity is shown to be an effective method to account for the effect of the rotation and lateral movement.

Introduction

Acoustic Doppler current profilers (ADCPs) can measure both water velocity and discharge from a moving boat. The ADCP measures the movement of the boat by bottom tracking, using the Doppler shift of the acoustic pulses off of the stream bottom to determine the velocity of the boat. If there is sufficient sediment transport (suspended or bed load) the acoustic pulses from the bottom track can become biased by the sediment motion. This bias in bottom-track velocity results in a negative bias in both measured water velocity and discharge, which is commonly referred to as a moving-bed bias. An ADCP held stationary in the presence of a moving bed will measure an upstream boat velocity, which integrated over time will show that the instrument has moved in the upstream direction. The U.S. Geological Survey (USGS)

Office of Surface Water (OSW) requires USGS personnel to make a moving-bed test prior to all discharge measurements made by using an ADCP from a moving boat. This test has traditionally been accomplished by holding the ADCP/boat in a fixed position for approximately 10-minutes while recording data. The distance that the bottom-track data show the boat moving upstream divided by the duration of the recorded data is called the moving-bed bias velocity. This test was particularly easy to accomplish when using a tethered boat from a bridge. The tether could be held or tied at a fixed length for the period of the test. Rotation and lateral movement of the ADCP/boat during the moving-bed test was not critical as the ADCP had an internal flux gate compass to measure the heading of the instrument, and both the boat and water velocities were referenced to magnetic north. Only motion in the upstream and downstream direction is important in determining the presence of a moving-bed bias. Teledyne RD Instruments (TRDI) introduced the StreamPro ADCP in 2003. (Note: Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.) This instrument is a small ADCP with a float, and is intended to be deployed in a tethered fashion from a bridge or tagline. The StreamPro does not include an internal compass and measured velocities are referenced only to the instrument because the intended use of the StreamPro is for moving-boat discharge measurements. The cross product of the water velocity and boat velocity vectors, used for the computation of discharge, does not depend on the heading of the instrument (Simpson and Oltman, 1993). However, rotation and lateral movement of the StreamPro on the end of the tether generates a false upstream boat velocity and an incorrect moving-bed bias velocity.

Cause of False Upstream Velocity

The false upstream velocity observed in stationary moving-bed tests conducted with a StreamPro is the result of rotation and lateral movement of the StreamPro on the end of a tether. During a stationary moving-bed test the StreamPro and float often tend to swim or kite from the end of the tether (the instrument rotates then moves laterally in the direction of the rotation). The lack of a compass in a StreamPro does not allow the StreamPro to measure boat or water velocities referenced to a fixed rotational reference, such as, magnetic north. The StreamPro can only measure velocities referenced to the transducers, regardless of their rotation. Figure 1 defines a positive y-velocity towards beam 3 and a positive x-velocity towards beam 1. If the instrument portrayed in Figure 1A is held in a fixed orientation

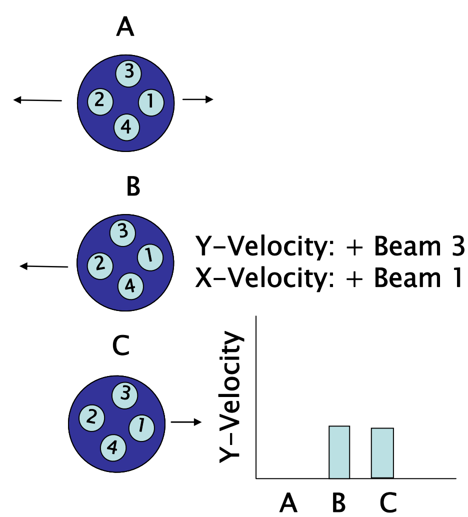

Figure 1. Illustration of the effect of rotation and lateral movement in the direction of rotation on the measured velocity.

and moved laterally the bottom tracking would record a zero y-velocity, because there is no component of the movement in the y-direction. However, if the instrument were rotated to the left and then moved to the left (Figure 1B) this rotation and lateral movement would create a positive y-velocity because some component of the lateral movement is parallel to beam 3 (y-axis). Likewise if the instrument were rotated to the right and then moved laterally to the right, some component of the lateral movement would be parallel to beam 3 and a positive y-velocity would be recorded. Note: this problem does not effect moving-boat discharge measurements where the cross product of the boat and water velocities is used.

A field test was completed to demonstrate that this rotation and lateral movement is caused when a StreamPro swims or kites at the end of a tether. The StreamPro was deployed from a tether, with beam 3 pointed forward, at a site where a false moving-bed was often recorded by the StreamPro. Figure 2 shows the ship track produced by the bottom track data, which clearly shows an upstream progression of the StreamPro. This test was repeated with additional tethers attached to each side of the StreamPro and held along the bank of the stream to limit lateral movement. Figure 3 shows that with lateral movement restricted there is little upstream progression of the StreamPro. Therefore, the rotation and lateral movement of the StreamPro will generate an apparent upstream boat velocity.

Analysis of Moving-Bed Tests using the Vector Dot Product

Careful analysis of ship tracks resulting from the apparent upstream boat velocity, such as Figure 2, indicate that ship movement is typically perpendicular to the water velocity. When the StreamPro rotates both the boat and water velocities are rotated. Thus, the boat velocity and water velocities remain in the correct orientation relative to each other. This characteristic is what permits the discharge to be computed without a compass. This characteristic can also be used to determine the velocity of the boat in the upstream direction. The boat velocity in the upstream direction measured during a stationary moving-bed test can be computed using the vector dot product of the boat velocity and water velocity. The use of the dot product for analysis of a moving-bed test was originally suggested by Randy Marsden (Teledyne RD Instruments, oral communication, 2006). This approach has been subsequently developed for use in stationary moving-bed tests.

The vector dot product of a vector (A) with a unit vector (B) computes the magnitude of vector A in the direction of vector B. The boat velocity in the upstream direction for each ensemble can be computed as the dot product of the boat velocity and the unit vector of the depth-averaged water velocity for each ensemble. Computing the numerical average of upstream boat velocity yields the moving-bed bias velocity, which can be compared with the mean water velocity to assess the potential bias. Because the boat velocity and water velocity are in the correct orientation to each other, this approach is unaffected by the rotation and lateral movement of the StreamPro as it swims or kites at the end of a tether.

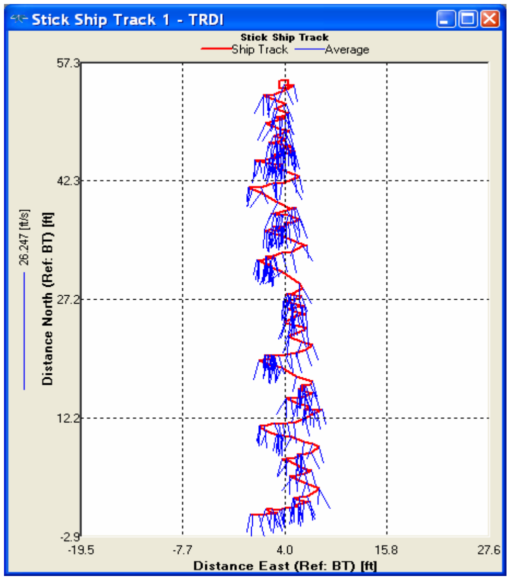

Figure 2. Ship track from WinRiver II (TRDI, 2007) of upstream movement caused by rotational and lateral motion of a StreamPro on a tether held at a fixed location.

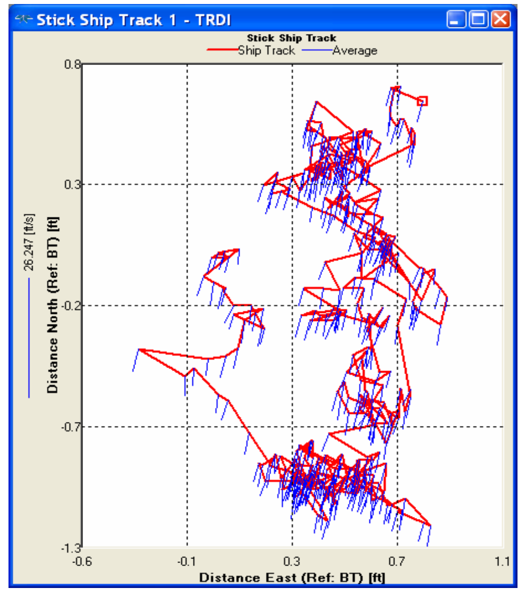

Figure 3. Ship track from WinRiver II (TRDI, 2007) of a StreamPro on a tether held at a fixed location with rotational and lateral motion restricted.

The validity of the proposed approach was evaluated using pairs of stationary measurements at three sites. At each site, data were collected with the StreamPro swimming or kiting on the end of the tether and with StreamPro fixed at approximately the same location by either a 3-point tether or a rod placed through the float but outside of the beams. The moving-bed bias velocity was computed using the manual technique of dividing the distance made good, as computed by the WinRiver software, by the duration for each of the measurements (Table 1). The data in Table 1 clearly show that the measured moving-bed velocities were significantly influenced by the swimming motion of the StreamPro; when the rotational and lateral motion of the StreamPro was restricted the moving-bed velocities were near zero. Software, discussed in the section titled, “Stationary Moving-Bed Test Analysis Software (SMBA)” was written to apply the dot product approach. For all 6 stationary moving bed tests the dot product approach produced a moving-bed bias velocity that was very near zero, consistent with the results obtained for the 3 tests where the rotation and lateral motion was restricted. Therefore, use of the dot product produces a more accurate assessment of stationary moving-bed tests collected with a StreamPro ADCP than the manual computation.

Computing the Corrected Water Velocity

The water velocity measured by a StreamPro held at a fixed station by a tether is dependent on the boat velocity and is thus, affected by the upstream boat velocity induced by the rotation and lateral motion of the instrument. The depth-averaged

Table 1. Summary of moving-bed tests with (Yes) and without (No) rotation and lateral motion.

Site	Motion	Moving-Bed Velocity (m/s)	
		Manual	Dot Product
Crabtree Creek at US 70 at Raleigh, NC	Yes	0.0518	0.0025
	No	0.0006	0.0011
Crabtree Creek at Ebenezer Church Road near Raleigh, NC	Yes	0.0299	-0.0007
	No	0.0006	0.0005
Sudbury River at Ashland, MA	Yes	0.0286	0.0044
	No	0.0012	0.0025

water velocity can be corrected by adding the upstream boat velocity computed from the dot product method.

$$\vec{W}_{c(i)} = \vec{W}_{(i)} + \vec{W}_{u(i)} \left| \vec{V}_{BU(i)} \right|,$$

where $\vec{W}_{c(i)}$ is the corrected depth-averaged water velocity at ensemble i; $\vec{W}_{(i)}$ is the measured depth-averaged water velocity at ensemble i; $\vec{W}_{u(i)}$ is the unit vector of the measured depth-averaged water velocity at ensemble i; and $\left|\vec{V}_{BU(i)}\right|$ is the magnitude of the upstream boat velocity computed from the dot product method. The direction of the water velocity is difficult to assess because without a compass there is no reference for the water direction from one ensemble to the next. Therefore, only the magnitude of the depth-averaged water velocity can be used to compute a mean water velocity for the measurement. Although a stationary moving-bed test or velocity profile measurement should have nearly constant depths, the lateral motion of the StreamPro could result in changes in depth from one ensemble to the next. The mean depth for each ensemble is computed as the depth-weighted average of the valid beams. The mean velocity magnitude is computed as the depth-weighted mean of the magnitudes of the depth-averaged velocities.

Stationary Moving-Bed Test Analysis Software (SMBA)

Software (SMBA) was written in Matlab® to allow application of the computations, described herein, to raw data files collected using the StreamPro software, WinRiver, or WinRiver II. SMBA has a user interface (Figure 4) that allows the user to open and process a raw data file by clicking on the Start button. Once the file has been processed the results can be stored to a text file by clicking on the Save button and providing a filename. Multiple stationary measurements processed sequentially will be saved to the same output file. To assist the user in evaluating the quality and consistency of the stationary moving-bed test, two graphs are provided. The graph on the right side of the user interface is a ship track plot, which has been referenced so that water velocity is always oriented in the down (negative y) direction. The graph at the bottom is a time history of the cumulative mean moving-bed velocity. These two graphs can be used to evaluate if bottom track was maintained, there were no large jumps in the ship track, and the moving-bed test was long enough to achieve a reliable mean. SMBA computes the moving-bed

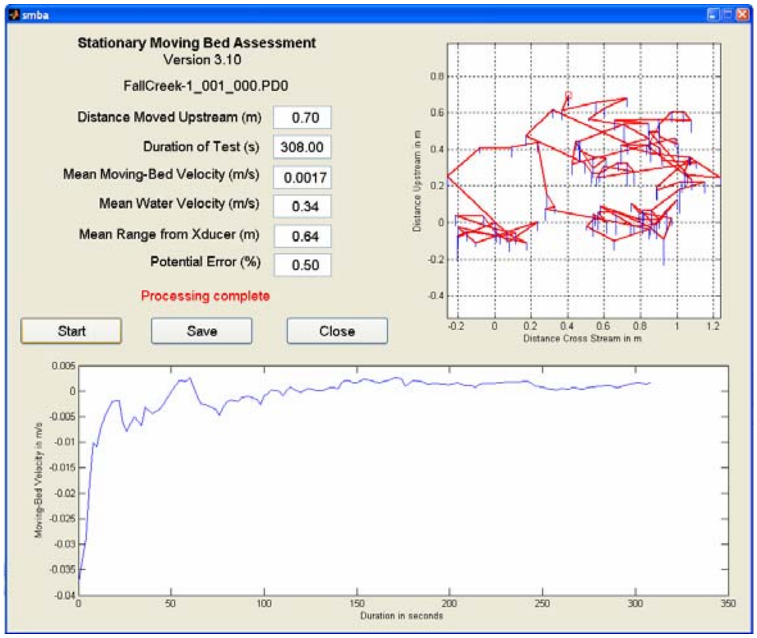

Figure 4. Graphical user interface for the stationary moving-bed analysis (SMBA) software.

velocity and if it is positive (in the upstream direction) computes the percentage of the moving-bed velocity relative to the mean water velocity. The user can then assess the best way to proceed with a streamflow measurement.

Summary and Conclusion

The StreamPro ADCP, when held at a fixed station by a tether, can measure a false upstream boat velocity due to the absence of a compass and the tendency for the float to swim or kite back and forth at the end of the tether. Field data clearly show that the false moving bed is caused by the rotation and lateral motion of the StreamPro as it swims or kites in the flow. Using the typical moving-bed determination method, which examines the distance made good over the duration of a stationary moving-bed test, the false upstream boat velocity cannot be distinguished from a moving-bed bias velocity. However, the vector dot product of the boat velocity and the unit vector of the depth-averaged water velocity is an effective method to account for the effect of the rotation and lateral movement. Software (SMBA) written in Matlab applies the dot product approach and provides a simple and efficient user interface to allow users to apply the dot product approach to all StreamPro stationary measurements.

References

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Teledyne RD Instruments (TRDI). (2007). *WinRiver II User's Guide*, San Diego, Calif.