Development and Application of a New Post-Processing Environment for Vessel Mounted ADCP Measurements

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Abstract

Flow measurements by means of vessel mounted ADCP allow a well-arranged display and close analysis of complex flow fields. Operation in the vicinity of hydraulic structures implies further difficulties as sensors obtaining the instruments position and orientation may malfunction. This paper shows the development and application of a set of new methods which allow accurate determination of position as well as orientation of the ADCP sensor even if single instruments temporarily yield no valid data. The performance of the new post-processing environment for ACDP measurements is shown for an example data set recorded at the river barrage 'Emssperrwerk' in the river Ems in Lower Saxony, Germany.
Keywords: vessel mounted ADCP, post-processing, dead reckoning

1. Introduction

Current measurements in oceans, tidal estuaries and rivers by Acoustic Doppler Current Profiler (ADCP) are state of the art for about 20 years [2]. The operation of vessel mounted devices allows spatial display of instantaneous flow fields. Exact position and orientation of the sensor are essential for the vector wise representation of flow velocities [1].

The position of the vessel and sensor respectively can be determined with high accuracy by means of GPS. Operation of a setup including reference station and a mobile device allows real-time differential GPS (dGPS) measurements. Communication between stationary and mobile device is usually established by VHF link. The position accuracy achieved by this setup is about 0.1 m [6]. The orientation of the ADCP is usually computed from successive GPS fixes or given by internal or external compasses.

The deployment of vessel mounted ADCPs within non-stationary flow situations, e.g. in the vicinity of hydraulic structures, implies additional operational difficulties. The measuring equipment may not be working properly due to influences of the structure itself. Magnetic compasses show severe misalignment close to ferromagnetic elements and GPS navigation may fail due to shadowing effects of the structure. As position and orientation of affected measurements cannot be evaluated, parts of the flow field cannot be captured and displayed even though valid velocities measurements are obtained. The disturbing effects are most likely to occur in direct vicinity of the structure where magnitude and direction of flow are often of highest interest.

2. Sensors and data

2.1. ADCP

The ADCP used onboard the measurement vessel *OTTO F* is a 4-beam 600 kHz broadband Workhorse Rio Grande from Teledyne RD Instruments. In addition to water and bottom velocities water temperature, inclination and absolute heading are measured by internal sensors [3]. The sampling frequency is 2.5 Hz.

Water and bottom velocity are measured by means of the Doppler-effect. After sending an acoustic signal (ping), the echoes reflected by zooplankton or suspended sediment in the water column are recorded at predefined times [4]. Thus, the water column is divided into discrete depth cells with a mean water velocity for each depth cell. For the measurement campaign at the river barrage 'Emssperrwerk' depth cells of 50cm were used.

The four sounder membranes of the ADCP are inclined by 20° against the horizontal. Velocities measured by the change of pitch between the original ping and the echo from the water column are given in beam direction. Using the results from three beams with the best signal to noise ratio (SNR) provides a system of three equations for the solution of three unknown velocities in the spatial directions 'forward', 'starboard' and 'mast' according to ship coordinate system. The fourth beam may be used for quality control of the velocities measured. However, when the inclination of the ADCP becomes large, the beam velocities used for the computation of velocities in geographic directions may result from different depths. In this case, bin mapping is applied to use depth cells not in the same distance from the ADCP but in the same water depth for the calculation of water velocities. Finally, to obtain absolute water velocities the speed of the vessel is subtracted and the true heading of the ship is used to complete the conversion from ship to world coordinate system.

Bottom velocities are obtained by evaluating the strongest echo resulting from the phase boundary at the bottom. Whenever conditions of a solid and immobile bed apply bottom velocities may be used as true speed over ground (SOG).

2.2. GPS

The setup using a reference station and mobile device allows high accuracy positioning by means of real time differential GPS. Comparing the measurements of the mobile and the stationary device, the bias in position information caused by local effects of air temperature, pressure and humidity on the travel time of the positioning signal from the satellites may be evaluated. Using this information in real-time to correct the position information of the mobile device accuracy is increased to decimeter range [6].

The speed over ground made by the measurement vessel needed for the transformation from instrument to geographic coordinates may be obtained from successive GPS fixes. The sampling frequency of the dGPS setup used is 1 Hz yielding an accuracy of speed in the range of 0.1 m/s. The quality of every single fix is evaluated by the mobile receiver. Fixes resulting from real time dGPS measurements are marked with fix quality 4 or real time kinematic (RTK).

2.3. Compasses and gyro system

In order to determine absolute heading of the ADCP with respect to a geodetic coordinate system, magnetic or fluxgate compasses are used. The effects of variation can be compensated using calibration procedures performed at the measurement site. Deviation due to ferromagnetic objects or electric fields onboard the measurement vessel can be compensated by these procedures as well. The ADCP itself is equipped with a fluxgate compass to obtain magnetic heading. However, for redundancy and enhanced accuracy an external fluxgate compass was employed.

Apart from magnetic compasses gyro systems are widely used in modern navigation. Unlike magnetic or fluxgate systems they do not give absolute heading information but rather the rate of turn of the vessel. In combination with an initial value for heading integration of this information can be used to obtain absolute heading. Gyro systems are not affected by ferromagnetic objects and magnetic fields but may malfunction when exposed to severe agitation.

3. Data analysis and processing

3.1 Magnetic heading

The knowledge of the heading of the instrument is most vital for the projection of directions of flow in geographic coordinates. The use of magnetic or fluxgate compasses is only reasonable when failure due to the presence of strong magnetic or electric fields is not likely to occur. Therefore, magnetic headings must be verified before they may be used as instrument heading.

As current measurements by ADCP are mostly done by in straight-line transects, a basic heading can be identified. Deviation from the basic course can serve as quality criterion for the heading information. Furthermore, changes in course are usually expected to be gradual. Fast changes in heading might result from disturbances due to ferromagnetic objects. However, severe and fast course corrections might be necessary to maintain the basic course when flow velocities with a magnitude close to the vessels velocity occur. High values in deviation from main course and change of course alone therefore do not necessarily represent erroneous data from the magnetic compasses. Still, the different compass devices are likely to show different reactions to perturbation effects. High values in the absolute difference of heading from both devices therefore hints at malfunction. Figure 1 provides the quality criteria discussed above. High values in all three criteria namely deviation from main course, change of course over time and absolute difference of internal and external magnetic compass suggest that magnetic heading may be biased in the period from 120s to 200s.

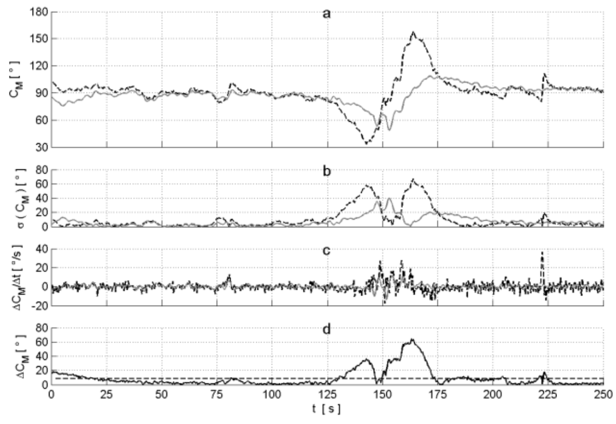

Figure 1. Comparison of internal and external magnetic compasses. a: Heading, b: Deviation from basic course, c: Change of heading, d: Absolute difference. In a-c internal compass is given in dashed black line, external compass is given in solid grey line

The basic course is about 090 as the transect was a west-east passage through the river barrage. Both magnetic compasses show high deviation from the basic course. Magnitudes reach up to 60° for internal and up to 40° for external magnetic heading, respectively. The course first bears away to 030 and 060 respectively to rise to 150 and 100 before it aligns with the basic course again. This general pattern can be found again at a time of around 80s and 220s though with lower magnitude. Furthermore, the rate of change in heading and absolute difference is high in the period from 120s to 200s. The high values of all criteria altogether suggest a malfunction of the magnetic devices. This is easily explained as the period of malfunction coincides with the immediate passage of the main opening of the barrage. The submerged steel gates of the barrage provide an excellent source for failure of magnetic compasses. The deflections of minor amplitude may result from the passage of berthing dolphins alongside the navigational channel in vicinity of the barrage.

For automated detection of periods of bad data from the magnetic compasses, a combination of deviation from basic course and rate of change of heading is used. Whenever both values exceed 10% of their particular maximum value, magnetic headings are regarded erroneous.

3.2 Rate of turn information

Information on the rate of turn (ROT) is provided by the gyro system. To integrate the rate of turn over time an absolute heading is needed as initial condition. Figure 2 shows the comparison of magnetic compass information and integration of rate of turn information from the gyro system. Magnetic headings at the beginning of the measurement were selected as initial condition.

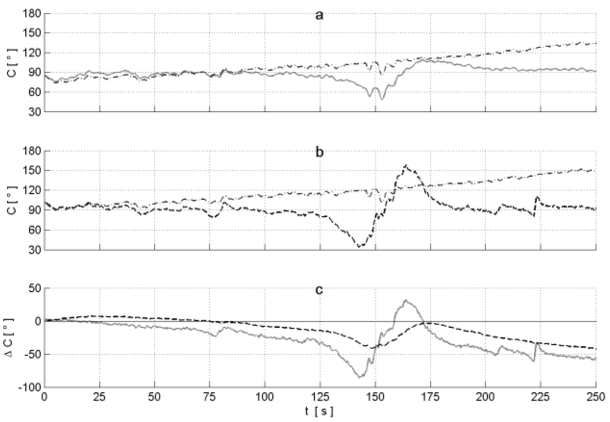

Figure 2. Comparison of magnetic compasses and rate of turn sensor. a: External magnetic compass and integrated rate of turn, b: Internal magnetic compass and integrated rate of turn, c: Absolute difference between magnetic compasses and integrated rate of turn. Internal magnetic compass in solid grey line, external magnetic compass in black dashed line and rate of turn information in dark grey dash-dotted line.

Heading information generated by integration of the rate of turn information confirms the general characteristics of the heading information obtained from the magnetic compasses. Though, on the one hand, the integrated rate of turn does not show the strong deviation from the basic course recorded by the magnetic systems in the period from 120s to 200s. On the other hand, the rate of turn information shows a certain linear trend resulting in a misalignment of about 45° in comparison with the external and about 60° in comparison with the internal magnetic compass over a measuring interval of 250s. Due to this error the use of the rate of turn sensor should be limited in time. However, the information may be used to correct the heading information whenever the magnetic systems fail to work properly. Whilst the criteria for bad data from the magnetic systems apply, the last valid magnetic heading is used as initial condition for the integration of the rate of turn information. When the magnetic compasses obtain valid information again the overall error due to the linear drift of the ROT information is computed. The overall error divided by the time ROT information was used yields the momentary error which is subtracted from the heading information to restore continuity of the time series. The results of the use of ROT information to correct the magnetic heading are shown in Figure 3. The corrected headings remain closer to the basic course in the period the magnetic compasses were assumed to be affected by the steel gate of the river barrage from 120s to 200s measuring time.

Apart from using ROT from the gyro device, the change in the components of velocity in forward and starboard direction obtained by the ADCP may be used to obtain ROT information or even absolute heading in terms of course over ground (COG).

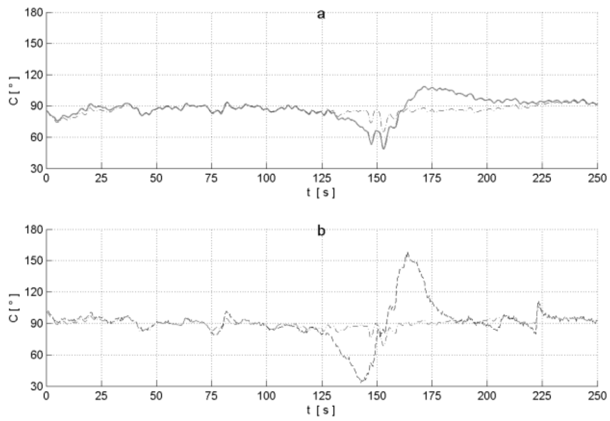

Figure 3. Heading from magnetic compasses corrected using rate of turn information from gyro sensor. a: External magnetic compass, b: Internal magnetic compass. Corrected heading is given in dash-dotted dark grey line.

3.3 Speed over ground

As all raw water velocities measured by the ADCP are given in components relative to the instruments coordinate system the absolute speed of the instrument is needed to compute absolute velocities. Speed over ground (SOG) as absolute velocity of measurement vessel and ADCP respectively is usually obtained using difference in position and time of successive GPS fixes. Furthermore the bottom track velocity measured by the ADCP may be used as SOG, whenever conditions of a solid and immobile bed apply. The latter remains the only means of determining the absolute speed of the instrument when GPS positioning fails. If it is to be used for positioning, the accuracy of the data has to be verified. The comparison of SOG obtained by dGPS fixes and bottom track is given in Figure 4.

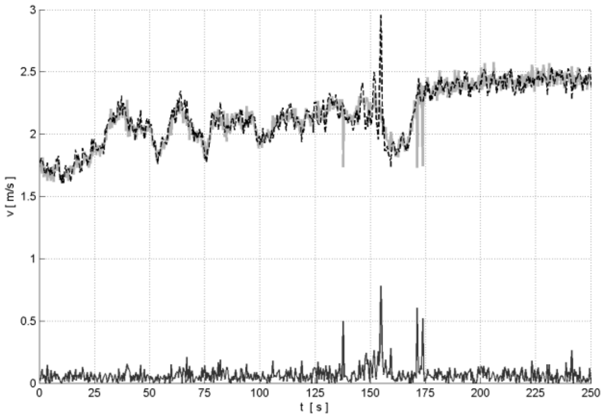

Figure 4. Comparison of instrument velocity obtained by GPS and bottom track. GPS velocity is given in solid grey line, bottom track velocity is given in dashed black line. Magnitude of difference is given in solid black line.

In general, the time series show good agreement. However, around 150s measuring time the bottom track velocity shows considerably higher values than the GPS velocity. Furthermore, the bottom track velocity exhibits sudden changes in magnitude. The point in time corresponds with the passing of the opening of the barrage. Rapid and heavy changes of the course in the high velocity flow region in the opening cause fast rotation of the ADCP. The instrument may therefore either fail to obtain valid velocity information or the accuracy of the latter may be decreased. Nevertheless, the accuracy of the velocity obtained by evaluation of the bottom track is in the range of accuracy of the GPS velocity i.e. 0.1 m/s.

3.2 Positioning by dead reckoning

When both heading and velocity of a vessel as variables of time are known, its position can be determined by means of dead reckoning. Based on an initial position, the current position of the vessel is established by successively advancing the position in the direction of the current heading. The reach is determined by integrating velocity over time. In discrete terms this means multiplying the current speed by the sampling rate. Accelerated translations and rotations not resolved by the sampling frequency result in an error cumulating over time as rate of turn and velocity are presumed to be constant for the intervals used for dead reckoning. The applicability of this method is therefore limited in time.

The error made by dead reckoning increases almost linearly over time. It may therefore be corrected and the track fitted in between the last and next good GPS position. This means both rotating the path to correct the cumulative error in heading and scaling the path length to correct the cumulative error in velocity. These operations require an isogonic coordinate system. Therefore the GPS positions are transferred from WGS 84 to Gauß-Krüger coordinates.

The resulting path will most likely violate the continuity in the actual heading time series at the transition point from dead reckoning to GPS positioning. Bending the path as a means of gradually changing the headings by the fracture of overall error in heading at the transition point and duration of dead reckoning may serve to overcome this problem. Yet, in the measurement campaign described later, these effects were of minor magnitude and bending of the path was not applied.

The result of the corrected dead reckoning path and the high accuracy dGPS path can be found in Figure 5. The time of dead reckoning is 85s and the distance covered in this time is about 100m. The absolute error in Northing and Easting over the dead reckoning time ranges up to ±1.5m. The error in Northing is larger than the error in Easting. As the basic course of the transect is 090 or West, the error in Northing corresponds with the error perpendicular to the travel direction.

Whenever positioning by GPS fails, the position of the measurement vessel can be reconstructed using further onboard sensors. In this manner gaps in the display of the flow field can be closed. Valuable information can be regained especially in the direct vicinity of hydraulic structures.

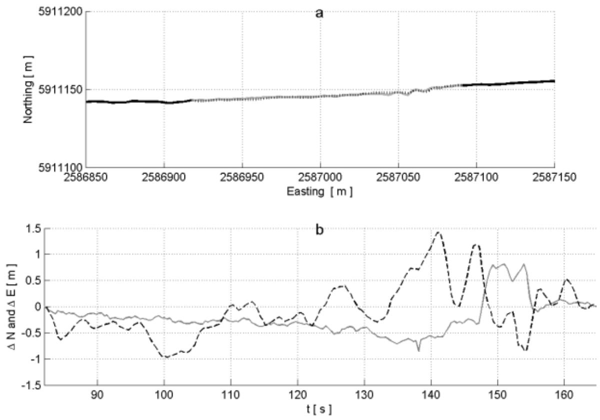

Figure 5. a: Dead reckoning reach after scaling and rotation. Original GPS track is given in solid black and dotted black line. Dead reckoning reach is given in solid gray line. b: Absolute error in Northing given in black dashed line and absolute error in Easting given in solid grey line.

4. Application ‘Emssperrwerk’

The four-day measuring campaign ‘Emssperrwerk’ was accomplished in September 2009 at the river barrage of the same name located at the river Ems in Lower Saxony, Germany [5]. Trial operations of the barrage were carried out during this time. This included temporarily closing all secondary openings of the barrage. Only the main navigation opening and inland navigation opening remained fully open. The objective of the measurements

was to determine if navigation would be severely influenced due to transverse flow resulting from closure of the secondary openings. Transects were navigated parallel and perpendicular to the barrages axis.
Figure 6 gives an overview of the transects done in between 15:54 and 17:16 MESZ during flood tide stream. About 500m upstream from the barrage, the flow velocities are still unaffected. Closer to the barrage the concentration of the flow to the navigation openings can easily be observed. The close view of the openings in Figure 7 offers a good representation of the transverse flows and the acceleration of the flow in the openings. Velocities up to 3m/s were measured.

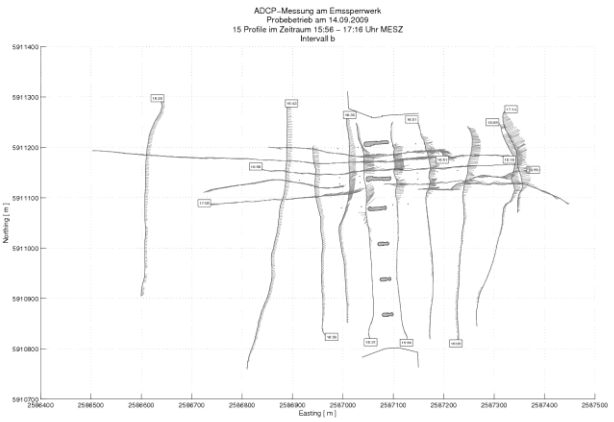

Figure 6. Overview of transects in the period of 15:54-17:16 MESZ at the river barrage ‘Emssperrwerk’ during trial operations on 14 September 2009. The northernmost secondary opening (NÖ1) and four southern secondary openings (NÖ2-5) are closed. Only main navigation opening (HSÖ) and inland navigation opening (BSÖ) remain fully open.

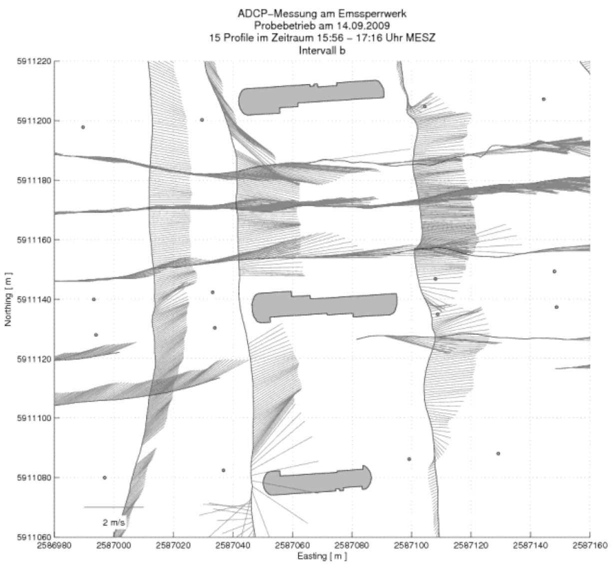

Figure 7. Close view of the flow field in main navigation opening (HSÖ) and inland navigation opening (BSÖ) during flood tide stream. Adjacent secondary openings are fully closed.

5. Conclusions

Vector wise representation of flow fields allows well-arranged spatial display and close examination of flow phenomena in areas with complex geometry. Measurement of flow velocities and directions by the use of ADCPs is state of the art. As velocity components are recorded according to the instruments inherent coordinate system, absolute position and heading of the instrument are needed for the transformation to world coordinates. The data are usually obtained from GPS positioning and magnetic compasses, respectively. Whenever these systems fail, it is still possible to obtain position and heading of the ADCP with sufficient accuracy by evaluating the data of other onboard sensors and the ADCP itself. The rate of turn obtained by a gyro device can serve to correct erroneous magnetic heading information. By the use of dead reckoning techniques, position information can be restored using aforesaid corrected heading information and speed over ground obtained by the ADCP as bottom track. However, the use of these methods should be limited in time as their iterative character cumulates small errors made in every single measurement. If, after a limited period of failure, valid GPS positions are available again, the error made by dead reckoning can be corrected. The results show good agreement with high accuracy dGPS positioning. The methods developed in this paper can therefore help to re-gain valuable information of a flow field, especially in the vicinity of hydraulic structures.

6. References

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