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Acoustic Doppler velocimetry (ADV) in small estuary: Field experience and signal post-processing

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ABSTRACT

Estuarine mixing and dispersion are unsteady turbulent processes. The present understanding of estuary turbulence remains limited because of limited suitable measurement techniques and a lack of long-duration high-frequency studies of turbulent properties. Herein turbulence data were recorded in a small estuary at high-frequency using acoustic Doppler velocimetry (ADV). The data sets were analysed, and the results demonstrated that acoustic Doppler velocimetry data cannot be used without suitable post-processing in unsteady estuary flows. Even classical “despiking” techniques are not simply applicable. A new ADV data post-processing technique is developed herein for turbulence analysis of estuarine flows, and it is tested for several field studies.

1. Introduction

In natural systems, mixing is driven by turbulence, and practical applications include sediment motion, release of sewage effluent, and storm-water runoff during flood events. The current knowledge is limited however, especially in estuarine zones despite their considerable practical importance. Mixing coefficient estimates are usually accurate only “within a factor of 10” at best and are rarely applicable to another system [13,10,2]. Although mixing is driven by turbulence, there has been very little systematic research on turbulence characteristics in natural estuarine systems, in particular in small systems. For example, long-duration studies of turbulent properties and structure at high-frequency are extremely limited. Most measurements were conducted for short-periods, or in bursts, often at low frequency: e.g. [1,14]. It is believed that the present situation, in small estuaries, derives partly from the limitations of suitable instrumentation.

Herein the study is focused on high-frequency turbulence data collection using acoustic Doppler velocimetry (ADV) in a small estuary. While the instrumentation is well-suited to study turbulent velocities in shallow-waters, it is assumed, wrongly sometimes, that the velocity signal outputs are “true” turbulent velocity data. This was found grossly incorrect and the paper focuses on a new ADV data post-processing technique for turbulence analysis. Several post-processing methods were tested and a new procedure was developed. Field work data were systematically analysed. The results showed that acoustic Doppler velocimetry data should not be used without suitable post-processing and that all turbulent velocity properties may be affected by the post-processing.

2. A case study: Eprapah creek estuary

A series of field measurements were conducted in the estuarine zone of Eprapah Creek (Australia) in 2003 and 2004. Located in the Redlands shire close to Brisbane city, Eprapah Creek (Long. 153.30°, Lat. −27.567°) is a simple sub-tropical stream, 12.6 km long, flowing directly to Moreton Bay off the Pacific Ocean and with a catchment area of 39 km^2. The estuarine zone is about 3.8 km long (Fig. 1). The tides are semi-diurnal and the range is about 1.5–2 m. The most upstream extent of the estuary corresponds to Sites 3B–4 shown in Fig. 1 depending upon the tidal conditions. In the estuary, the channel is about 1–2 m deep mid-stream and 20–30 m wide. This is a relatively small, shallow estuary system, where the water depth may be less than 0.7 m at low tides in several sections. It is a drowned river valley (coastal plain) type with a small, sporadic freshwater inflow, a cross-section which deepens and widens towards the mouth, and surrounded by extensive mud flats.

Field works took place on four different days (Table 1). Tidal conditions are summarised in Table 1 (3rd line). Acoustic Doppler velocimetry was performed mid-estuary at Sites 2 and 2B shown in Fig. 1, and the corresponding estuary cross-sections are presented in Fig. 2. For each field study, a 3-D Acoustic Doppler Velocimeter (ADV) SonTek ADV 10 MHz was deployed. The ADV probe was

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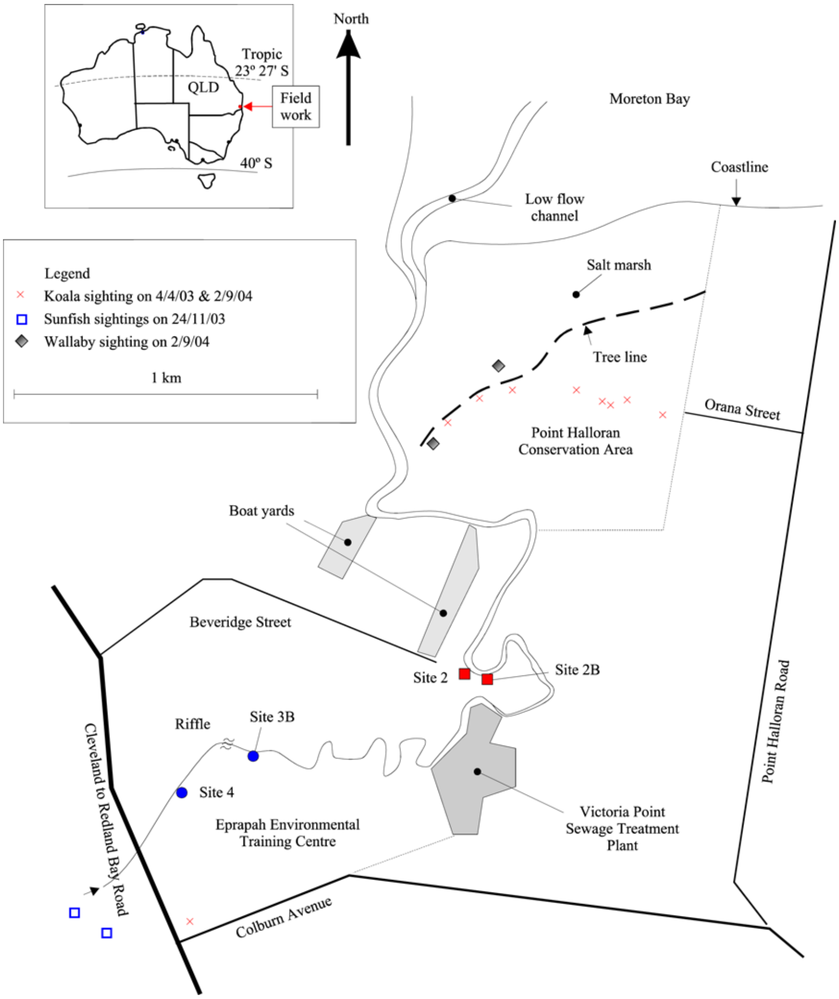


Fig. 1. Map of Eprapah Creek estuary — Red squares: instantaneous velocity measurement sites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

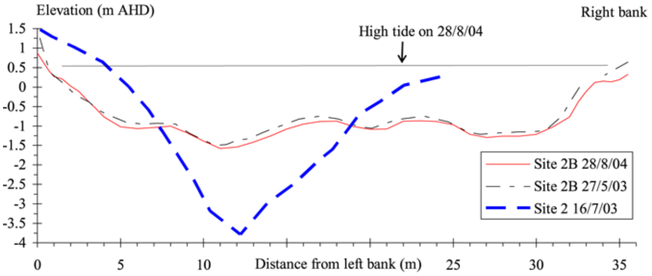


Fig. 2. Surveyed creek cross-sections at Sites 2 (AMTD 2.0 km) and 2B (AMTD 2.1 km) looking downstream.

equipped with a 5 cm down-looking sensor mounted on a rigid stem and data-logged continuously at 25 Hz. The velocity range was 0.3 or 1.0 m/s (Table 1). The probe was installed about the middle of the channel in a moderate bend to the right when looking downstream. The ADV was held by a stiff metallic frame sliding on two poles (Fig. 3). The poles were driven into the river bed, and the frame and pole system did not move during the data logging. The probe was installed outside of the support system to limit the effects of support wake. In the first three studies, the sampling volume was located 0.50 m beneath the free-surface. The probe position was manually adjusted with the tide, by lowering or raising the frame every 20–60 min, to maintain the probe sensor position relative to the free-surface (Fig. 3B). For the last study, the probe sampling volume was located 0.055 m above the bed. Further details on the field work procedures are available in [5,6,9,19].

3. Acoustic doppler velocimetry

3.1. Presentation

Acoustic Doppler velocimetry (ADV) is designed to record instantaneous velocity components at a single-point with a relatively high frequency. Measurements are performed by measuring the velocity of particles in a remote sampling volume based upon the Doppler shift effect (e.g. [20,16]). The probe head includes one transmitter and three receivers (Fig. 4). The remote sampling volume is located typically 5 cm from the tip of the probe, but some studies showed that the distance might change slightly (e.g. [3]). The sampling volume size is determined by the sampling conditions. In a standard configuration, the sampling volume is about a cylinder of water with a diameter of 6 mm and a height of 9 mm.

An ADV system records simultaneously nine values with each sample: three velocity components, three signal strength values and three correlation values. Signal strengths and correlations are used primarily to determine the quality and accuracy of the velocity data, although the signal strength (acoustic backscatter intensity) may related to the instantaneous suspended sediment concentration with proper calibration [11,18,21,7]. Herein the study is focused on the velocity signals.

Table 1
Field investigations at Eprapah Creek in 2003 and 2004

Field study reference	E1	E2	E3	E4
Date	4 April 2003	17 July 2003	24 Nov. 2003	2 Sept. 2004
Tides (Victoria point)	05:16 (0.67 m) 11:03 (2.22 m) 17:24 (0.57 m) 23:31 (2.41 m)	00:00 (2:63 m) 06:44 (0.60 m) 12:19 (1.92 m) 18:01 (0.59 m)	03:27 (0.21 m) 09:50 (2.74 m) 16:29 (0.46 m) 21:53 (2.11 m)	06:02 (0.40 m) 11:52 (2.21 m) 18:02 (0.56 m) 11:59 (2.29 m)
Study period	06:00–18:00	06:00–14:00	08:00–16:00	06:00–18:00
Study focus	Full tidal cycle	Flood tide	Ebb tide	Full tidal cycle
ADV sampling period (s)	10:08–10:42 10:43–10:44 11:45–12:18 11:19–11:57 11:58–12:29 12:29–12:52 12:53–13:11 13:12–13:53 13:53–14:09	6:26–14:10	8:25–15:35	7:51–13:40 14:26–17:57
ADV velocity range (m/s)	0.3 / 1.0 / 0.3 / 0.3 / 0.3 / 1.0 / 1.0 / 1.0 / 1.0	0.3	1.0	0.3
Sampling frequency (Hz)	25	25	25	25
Sampling volume location	Site 2B, 0.50 m below surface, 14.2 m from left bank	Site 2, 0.50 m below surface, 8.0 m from left bank	Site 2B, 0.50 m below surface, 10.8 m from left bank	Site 2B, 0.0525 m above bed, 10.8 m from left bank
Water temperature (°C) (mid-estuary, Site 2)	23.7 [20.4–28.4]	16.7 [15.5–18.5]	25.5 [22.7–28.0]	17.14 [15.9–18.1]
Conductivity (mS/cm) (mid-estuary, Site 2)	34.5 [23.9–48.3]	37.2 [29.8–48.4]	50.0 [42.7–55.1]	48.6 [41.0–53.6]

Notes: water temperature and conductivity measured with YSI6600 probe; mean values [extreme values in square brackets] for the study period.

(A) Field study E2, Site 2, looking upstream — Boat passing next to ADV probe (arrow) around 13:30 (early ebb tide).

(B) Field study E1, Site 2B, view from left bank — Vertical probe adjustment near end of flood tide.

Fig. 3. Acoustic Doppler velocimetry field works in Eprapah Creek estuary.

Past and present experiences demonstrated recurrent problems with "raw" ADV velocity data that are evidenced by high levels of noise and spikes in all velocity components [17,16]. In turbulent flows, the ADV velocity fluctuations characterise the combined effects of the Doppler noise, signal aliasing, velocity fluctuations, installation vibrations and other disturbances. The signal may be further affected adversely by velocity shear across the sampling volume and boundary proximity [8]. Lemmin and Lhermitte [15] and Chanson et al. [3,4] discussed the inherent noise of an ADV system. Spikes may be caused by aliasing of the Doppler signal. McLelland and Nicholas [16] explained the physical processes while Nikora and Goring [17], Goring and Nikora [12] and Wahl

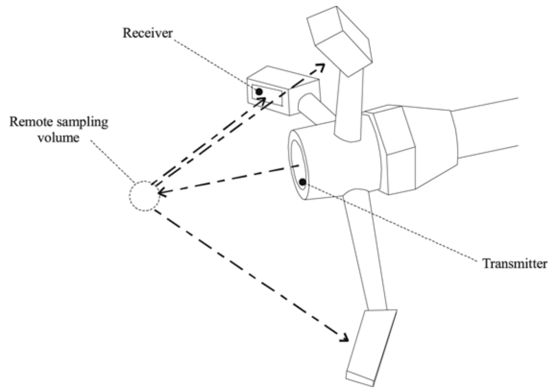
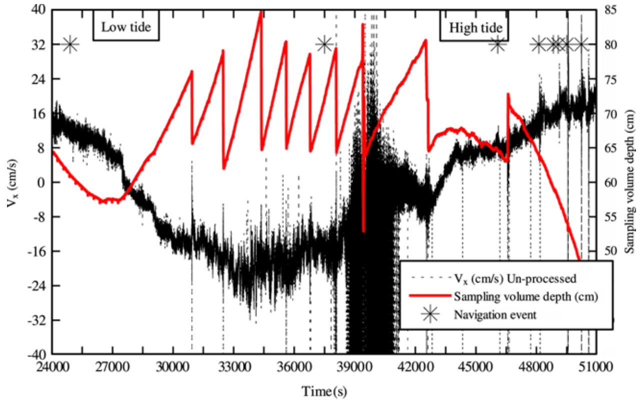
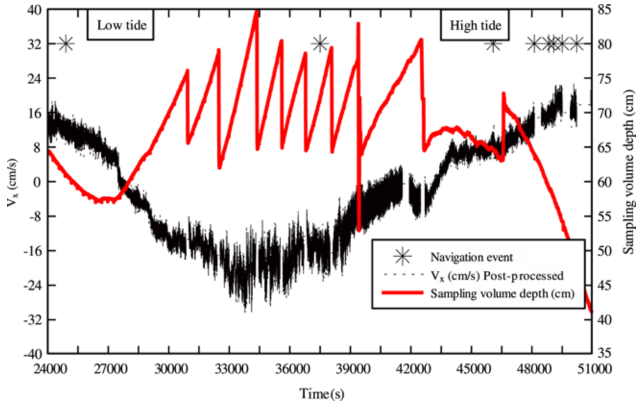


Fig. 4. Sketch of a 3D acoustic Doppler velocimeter head.



(A) Instantaneous velocity data before post-processing.



(B) Instantaneous velocity data after complete post-processing.

Fig. 5. Instantaneous velocity data (V_x component), probe sampling volume depth data and navigation events during the field study E2 on 7 July 2003 at Site 2 — Time is expressed in seconds since midnight (GPS time).

[22] developed techniques to eliminate these "spikes". These methods were developed for steady flow situations ad tested in man-made channels.

3.2. Velocity measurement experience in a small estuary

In Eprapah Creek, the acoustic Doppler velocimetry system provided instantaneous values of the three velocity components. It was oriented with the *xy*-plane being horizontal, the *x*-direction aligned with the flow direction and positive downstream, and the *z*-direction positive upwards. Typical results are shown in Fig. 5. Fig. 5 presents the V_x velocity component recorded during the field study E2 for 7 h 44 min, starting at low tide ($t = 24{,}240$ s) and ending during the early ebb tide. The low and high tides (slack tides) corresponded to about the periods of zero streamwise velocity. Fig. 5A shows the un-processed (raw) velocity data. The right vertical axis corresponds to the sampling volume depth below the free-surface, and the vertical see-saw steps highlighted the manual vertical displacements of the velocimeter to maintain the sampling volume about 0.5 m below the free-surface. Fig. 3B shows a vertical probe position adjustment. Navigation events are also marked with an asterisk (*) in Fig. 5, while Fig. 3A illustrates such a boat passage. For all field works, the present field experience demonstrated recurrent problems with the raw velocity data, including a large numbers of spikes. For example, a lot of "noise" is seen in Fig. 5A between $t = 39{,}000$ and 41,000 s, but smaller numbers of "spikes" are also seen between $t = 31{,}000$ and 51,000 s. The noise was probably caused by a combination of Doppler noise and aliasing errors around high tide slack, and it did not characterise true turbulent velocities. Some problem was also experienced with the vertical velocity component, possibly because of some wake effect of ADV stem. Since the probe was mounted vertically down-looking, vertical velocities were small and these effects were deemed negligible.

Practical problems were further experienced. During the last field study (E4), the computer lost power and it could not be reconnected to the ADV for nearly 50 min. For the first field work (E1), two notebook computers were used alternately to data log the ADV outputs and to backup the data. The interchange of computers lasted less than 2 min and was carefully recorded. For the other two field works (E2 and E3), the velocity data were recorded continuously into a single data file. Details of data records are given in Table 1. For the first three field trips, the ADV sampling volume was maintained about 0.5 m below the free-surface and the vertical probe position was adjusted up to 3 times per hour at mid-tide (Fig. 3B). Lastly, navigation and aquatic life were observed during all field works (Fig. 3A). They were found to have some impact on the turbulence data. In several instances, birds were seen diving and fishing next to the ADV location, while in other occasions fish were jumping out of the water next to the probe.

In summary, the present experience suggested that turbulence properties could not be extrapolated from the unprocessed data sets during field works. Classical ADV "despiking" techniques were tested in-depth, especially the acceleration thresholding and phase-space thresholding methods [12,22]. The results demonstrated systematically that "conventional" ADV despiking techniques were not suitable for velocimetry data collected in a natural estuarine system. Indeed velocity fluctuations might be induced by large disturbances such as aquatic life, navigation and experimental procedure as observed first-hand. Even in optimum conditions, natural estuarine systems are characterised by unsteady flows, and the hydrodynamics cannot be assumed to be quasi-steady over a statistically-meaningful data sample. However the selection of more appropriate techniques is difficult since no independent data sets are available. Existing comparisons between "despiking" techniques are often limited to a comparison of the number of removed spikes, and of the differences in turbulent velocity fluctuations and in Reynolds stresses.

4. ADV data post-processing technique

4.1. Presentation

Turbulent velocity analyses were conducted systematically for all field data. The present experience yielded a new three-stage post-processing method for estuarine studies. The post-processing technique includes (1) an initial velocity signal check, (2) the detection, removal and replacement of large disturbances and (3) the treatment of small disturbances. Each stage comprises two steps: velocity error detection and data replacement.

(1) **Velocity signal check**. The ADV velocity data are "cleaned" by removing all communication errors, low signal-to-noise ratio data (<5 dB) and low correlation samples ($<60\%$–70%). This stage may be performed by industrial software (e.g. WinADV^{TM}).

(2) **Event detection and removal ("Pre-filtering")**. The effects of major disturbances are removed. Such disturbances may include navigation, probe movement, aquatic life activities. For each velocity component, the signal is filtered with a low-pass/high-pass filter threshold F ($F_{ref} = 0.1$ Hz). The occurrence of navigation, probe motion and other events is tested on the high-pass filtered component by comparing the ratio of local standard deviation to the event search region standard deviation with a threshold value CE ($CE_{ref} = 1.5$). Exceedance implies disturbance. Note that local standard deviations are calculated for WS data points ($WS_{ref} = 1000$).

(3) **Small disturbance detection and removal ("Despiking")**. The phase-space thresholding technique is used. For each velocity component, the signal is filtered with a low-pass/high-pass filter threshold F ($F_{ref} = 0.1$ Hz). The same frequency threshold F is used for "pre-filtering" and "despiking". The high-pass filtered signal is tested with an "universal" criterion [12].

4.2. Comments

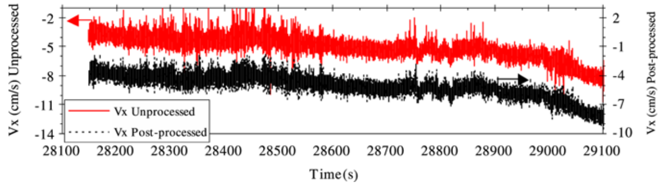
In Stages 1, 2 and 3, all erroneous data are replaced by an overall mean of the signal between end points. This technique was selected for its simplicity, reliability and suitability to very-large data sets similar to present data records. Replacement is performed on the velocity signal in Stage 2 and on the high-pass filtered signal in Stage 3. Stage 3 is iterated until the number of new errors in an iteration converges to zero. At the end of Stage 3, the low-passed filtered signals are added back in before further turbulence analysis. Further, all velocity components are considered erroneous if anyone velocity component is replaced in Stages 1, 2 or 3. The justification is based upon the ADV transformation of radial velocities into Cartesian coordinates implying that a corrupted Cartesian velocity component must derive from corrupted radial components (e.g. [16]).

In Stage 3, the present experience and data analyses showed that the initial pre-filtering stage has a significant effect on the quality of the data sets. Further the acceleration thresholding technique was thoroughly tested with acceleration threshold criterion λ_a between 0.012 and 1.5. The technique was totally unsuited to the estuarine flow conditions, while the phase-space thresholding method appeared more robust.

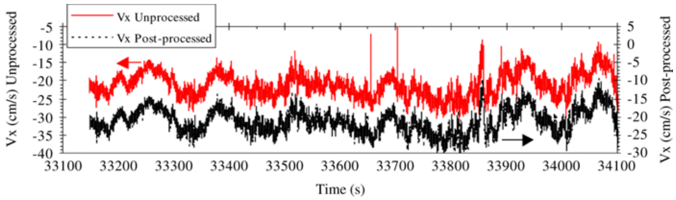
5. Applications

The new ADV post-processing method was developed based upon the experience gained during the study E1. It was successfully validated with the data sets E2, E3 and E, while the post-processed time-averaged longitudinal velocity data were successfully compared with surface velocity observations and one-dimensional numerical modelling of the estuary flow.

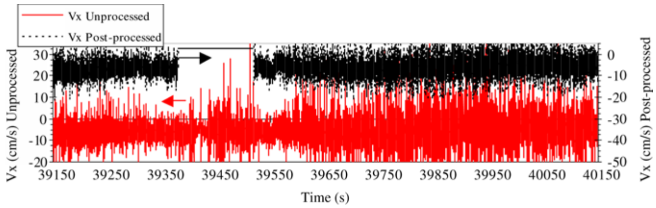
A systematic sensitivity analysis was conducted for all listed parameters within the ranges: $0.001 \leq F \leq 1$ Hz, $1.2 \leq CE \leq 1.8$, $100 \leq WS \leq 5000$. For the tested data sets, the optimum coefficients were a low-pass/high-pass filter threshold $F_{ref} = 0.1$ Hz, a threshold value $CE_{ref} = 1.5$ for the occurrence of navigation, probe motion and other events, while local standard deviations were calculated over $WS_{ref} = 1000$ data points. Importantly it was found that the selection of the low-pass/high-pass filter frequency threshold F has a significant effect on the pre-filtering, but little impact on the "despiking". Frequency thresholds within 0.1–0.01 Hz were found most suitable for this small estuarine system. It is likely that the optimum parameter F_{ref} is a function of topographic and hydrodynamic characteristics of each estuary Herein, the optimum range of frequency thresholds was within C/W and C/d where W is the mean free-surface width of the channel, d is the mean water depth, and C is the celerity of a small disturbance ($C = \sqrt{g \times d}$) with g the gravity acceleration.



(A) Early flood tide.



(B) Mid flood tide.



(C) End of flood tide.

Fig. 6. Comparison of original and post-processed velocity signals — Field study E2, V_x velocity component — Time is expressed in seconds since midnight (GPS time).

Fig. 5 illustrates the outcomes of ADV data post-processing for an entire field study. Fig. 5B shows the post-processed data set which may be compared with the un-processed data set (Fig. 5A). Both graphs are plotted with the same horizontal and vertical scales. The comparison shows the successful detection and removal of all major disturbances (vertical probe displacement, navigation) and of a lot of spikes and noise (e.g. $38{,}000 < t < 41{,}000$ s). Fig. 6 illustrates more detailed comparisons of velocity signal for 1000 s segments before and after post-processing. In each graph, the curves are offset vertically for clarity and the range of both vertical scales is the same with the left axis for un-processed data and the right axis for post-processed data. Note that the vertical scale range differs between Fig. 6A–C. Fig. 6A corresponds to the early flood tide; Fig. 6B to the mid flood tide; Fig. 6C to the end of flood tide (Fig. 5). For these three 1000 s samples, Table 2 lists the statistical properties of each velocity component before and after post-processing. The results illustrate the impact of post-processing on all turbulent flow properties, including on the time-average velocity components. For these three 1000 s segments, about 1%, 2% and 18% of all data points were removed and replaced respectively. Note that Fig. 6C (also Fig. 5A) illustrates a appalling situation with some problem with the instrumentation for which we should have no confidence in all velocity data set, unless the post-processed data could be validated with an independent instrument.

The new post-processing technique was applied thoroughly to the field studies E2, E3 and E4 using the reference post-processing coefficients. The results are summarised in Table 3.

Table 2
Turbulent velocity statistics for three time intervals (Field study E2): (A) $t = 28{,}148$ to $29{,}148$ s; (B) $t = 33{,}148$ to $34{,}148$ s; (C) t = 39,148 to 40,148 s (expressed since midnight, GPS time)

	Un-processed			Post-processed			Remarks
	V_x	V_y	V_z	V_x	V_y	V_z	
Segment (A)							$t = 28{,}148$ to $29{,}148$ s
Average (cm/s)	−5.20	0.322	−0.254	−5.210	0.321	−0.25	1.1% of data errors
Std deviation (cm/s)	1.39	0.61	0.142	1.37	0.607	0.14	
Skewness	−0.91	0.021	−0.31	−0.97	0.020	−0.34	
Kurtosis	0.86	−0.48	0.71	0.81	−0.50	0.62	Excess kurtosis
Segment (B)							$t = 33{,}148$ to $34{,}148$ s
Average (cm/s)	−21.2	3.56	−1.499	−21.2	3.57	−1.500	2.0% of data errors
Std deviation (cm/s)	3.29	2.23	1.608	3.27	2.22	1.586	
Skewness	0.24	0.085	−0.19	0.23	0.080	−0.21	
Kurtosis	−0.20	−0.043	1.39	−0.27	−0.109	1.15	Excess kurtosis
Segment (C)							$t = 39{,}148$ to $40{,}148$ s
Average (cm/s)	−6.07	0.67	−0.982	−4.86	1.19	−0.995	18.4% of data errors, but
Std deviation (cm/s)	5.00	3.20	1.36	4.73	2.41	0.683	99.9% data error on V_x
Skewness	0.42	−4.34	0.42	0.33	−0.341	0.031	
Kurtosis	10.4	162.7	80.2	−0.27	0.10	1.37	Excess kurtosis

Notes: (A), (B) and (C) correspond to the data samples shown in Fig. 6A–C respectively taken during the early, middle and end of flood tide of the field study E2.

Table 3
Effect of post-processing of acoustic Doppler velocity data during the entire field studies E2, E3 and E4 — Summary of each post-processing stage

Field study	Study E2 (17/07/2003)	Study E3 (24/11/2003)	Study E4 (2/9/2004)	
Total Number of data points	696,129	593,297	841,807	Single data file.
(1) Number data points with communication errors, low signal to noise ratio and low correlation	5,580	12,762	441	Using WindADV.
(1) + (2) Number of removed/replaced data points after "pre-filtering"	83,847	66,820	25,572	
(1) + (2) + (3) Number of removed/replaced data points after "pre-filtering" & despiking	137,181	75,938	86,779	Complete post-processing.
(1) + (3) Number of removed/replaced data points after despiking BUT NO "pre-filtering"	56,069	24,248	58,769	Post-processing without "pre-filtering", similar to the methods of [12] and WinADV^{TM} v. 2.018.

In Table 3, the 2nd line gives the total number of data points per velocity component for each field study. The 3rd and 4th lines are respectively the number of data errors after velocity signal check, and after velocity signal check and large disturbance removal ("pre-filtering"). The 5th line represents the total number of data errors after the entire three-stages post-processing method. For comparison, the last line (6th line) gives the number of data errors for a velocity signal check and "despiking" with the phase-space thresholding technique that would typically be achieved with WinADV^{TM} version 2.018 (and later) and with the phase-space thresholding method of [12]. For the field trip E2, a post-processing without large disturbance removal ("pre-filtering") would accept 81,112 erroneous data points that would be otherwise rejected by the new post-processing method (Table 3, line 6). This would represent nearly 12% of erroneous data in the entire data set ! These methods are simply improper for unsteady estuarine flows.

Overall, between 11 to 20% of all data sets were removed and replaced in these three field studies. Such quantities are fairly significant and must impact onto the turbulent flow properties. Comparative turbulence analyses of unprocessed and post-processed signals were conducted systematically in terms of the first four statistical moments (mean, standard deviation, skewness and kurtosis) of each velocity component and of the tangential Reynolds stresses. The statistical quantities were integrated over 5,000 data points corresponding to 3 min. 20 s and the calculations were repeated along each data set. The systematic comparisons demonstrated that all turbulence characteristics were affected by the post-processing (e.g. Table 2). In plain words, the turbulent properties, including the time-average velocities, were improperly estimated from un-processed data sets. More generally, the results highlighted that hydrodynamic properties in unsteady estuarine flows could not be simply deduced from unprocessed acoustic Doppler velocimetry data.

6. Conclusion

Past studies [17,16,12] and the present investigation have shown that acoustic Doppler velocimetry (ADV) is a well-suited metrology for small shallow-water system. The present study was focused on the analysis of turbulent velocity measurements in small estuarine system based upon long-duration high-frequency velocity records. The data analysis showed conclusively that turbulence properties cannot be derived from unprocessed ADV signals and that even "classical" despiking methods were not directly applicable to unsteady estuary flows. Instead a detailed post-processing technique was developed and applied. A new three-stages post-processing method is presented. The technique includes (1) an initial velocity signal check, (2) some detection and removal of large disturbances ("pre-filtering") and (3) some detection and removal of small disturbances ("despiking"), while each stage includes velocity error detection and data replacement. The method was applied successfully to three long-duration field studies during which ADV signals were recorded at high-frequency (25 Hz). Reference coefficients were derived for a small sub-tropical estuary. Comparative analyses of un-processed, "despiked-only" and post-processed velocity data highlighted the necessity of an advanced post-processing method. While the acoustic Doppler velocimetry is a relatively simple technique, the present results illustrated that unprocessed ADV data should not be used to study the turbulence field, including time-averaged velocity components.

Importantly, further field data are necessary to validate the post-processing technique, by comparing post-processed data with independent data acquired simultaneously at the same location in the natural system. At present, the selection of more appropriate techniques is intricate since no independent data set (i.e. “true data set”) is available. Comparisons between post-processing techniques are basically limited to an assessment of the number of removed spikes, and some subjective evaluation of differences in turbulent velocity properties.

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