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Estimation of the error on the mean velocity and on the Reynolds stress due to a misoriented ADV probe in the horizontal plane: case of experiments in a compound open-channel

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Abstract

This study aims at evaluating the error on the horizontal components of the mean-velocity and of the Reynolds stress measurements due to a misorientation of an Acoustic Doppler Velocimeter (ADV) in the horizontal plane. The misorientation of the ADV is represented by a misalignment angle, which is the angle between the ADV coordinate frame and the reference frame. The error due to the misorientation is first analytically determined. Thereafter, using experiments in a compound channel, the error is evaluated based on an angle of 2.5° representing the maximum possible angle of misalignment by human eyes adjustment. While the maximal error does not exceed 5% for the longitudinal mean velocity and 14% for the normal Reynolds stresses, it can be larger than 100% for the lateral mean velocity and largely greater than 100% for the Reynolds shear stress. Such a degree of error appears to be similar to those worked out for classical flows from the literature with a mean velocity gradient mainly occurring in the horizontal plane (mixing layers, plane jets) or in the vertical plane (boundary layers). This error is finally compared with the uncertainty due to the various sources of noise that pertubate the turbulence measurement. This study reveals that they both are comparable, therefore indicating that the error due to the probe misorientation should not be neglected, as it is too often the case.

Keywords: ADV, error, uncertainty, misorientation, mean velocity, Reynolds stress, compound channel

1. Introduction

The Acoustic Doppler Velocimeter (ADV) is widely used in laboratory experiments and field works for measuring flow velocities. The existing commercial versions (field probes, laboratory probes) make it easy to deploy and to use in any kind of environment such as small estuaries [1, 2], river reaches [3, 4], single [5] and compound [6, 7] open-channels in laboratories.

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Since the development of the ADV in the early 90's [8], numerous studies have been searching for the best ways to set-up the velocimeter parameters in order to get accurate measurements of velocity field in turbulent flows. Lane et al. [9] studied the impact of the sampling frequency, while McLelland and Nicholas [10] discussed the appropriate minimum required signal-to-noise ratio. Roy et al. [11], Chanson et al. [12] worked on the minimal recording length for a time-series depending on what turbulent parameter is considered (mean velocity signal, variance, triple-correlations). Meanwhile, Precht et al. [13], Dombroski and Crimaldi [14] focused their studies on the maximal distance relative to a solid boundary for which the ADV measurements collapse with those performed with a Laser Doppler Velocimeter. As pointed out by Chanson et al. [12], "*Simply, **raw**, ADV velocity data are not **true** turbulence and should never be used without adequate post-processing*". It is well known that the time-series of ADV measurements are polluted by various sources of noises that can be partially corrected [15]. The spikes due to aliasing of the Doppler signal can be corrected using the phase-space thresholding method of Goring and Nikora [16]. In a more general way, all the sources of noise (Doppler ambiguity, electronic circuitry's sampling errors, ...) entering as additional variance terms in the measured fluctuating velocity variances can be corrected using the methods proposed by Nikora and Goring [17], Voulgaris and Trowbridge [18], Hurther and Lemmin [15], Blankaert and Lemmin [19], Doroudian et al. [20].

Among all these studies, a lack of information can be however identified. In most studies dealing with ADV measurements or processing, the precision in the probe orientation is rarely mentioned. The comparison of the resulting error (uncertainty if the orientation is not well known) with the other sources of uncertainty justifying whether the data needs to be corrected is even more rare. Without these information, one cannot be sure that the presented experimental data-set is truly representative of the local physics. In the case of compound channel flows, for instance, this means that without a good confidence on the probe orientation, the measurements of the secondary currents of Prandtl's second kind [21, 22], so as the characterisation of the mixing process between the channels [7] cannot be validated.

As previously pointed out, studies specific to ADV dealing with probe misorientation are rare [23, 24]. Nevertheless, some studies dealing with misoriented electromagnetic current-meters exists [25, 26, 27, 28, 29, 30, 31] and their results can be partly transposed to ADV probes since their working principle are close. Heathershaw [29] estimated the error on the velocity measurements in the bottom boundary layer of a tidal current due to an electromagnetic current-meter misorientation. Roy et al. [30] analysed the effects of such misorientation on the vertical Reynolds shear stress in a gravel bed river and in a laboratory confluence. Trowbridge [31] proposed a method taking into account the surface-waves for measuring the Reynolds stress in the vicinity of shores.

The estimation of the error on the mean velocities due the ADV misorientation is straightforward using the classical matrix of rotation [32]. Similarly, the estimation of the error on the vertical Reynolds shear stress is well known [29, 30]. By contrast, the estimation for the components of the Reynolds stress in the horizontal plane is not established. This paper then aims at evaluating the error on the horizontal components of the mean-velocity and of the Reynolds stress due to a misoriented ADV in the horizontal plane. The error due to the misorientation is first rigorously evaluated through theoretical considerations partly based on previous studies dealing with measurements

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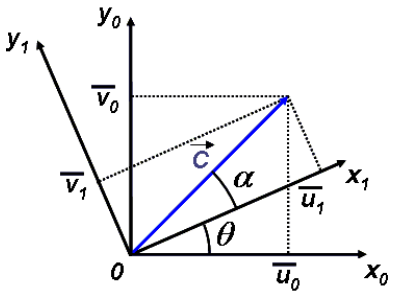


Figure 1: Illustration of the probe misorientation in the horizontal plane with respect to the reference frame aligned with the bank. The subscript "0" refers to the reference frame and the subscript "1" to the ADV coordinate frame.

on the vertical plane [29, 30]. Second, these analytical relationships are used on experimental data measured under various flow conditions in a compound channel [24, 7]. The experimental errors are then compared with those of more classical flows well detailed in the literature. Finally, these results are compared with the typical values of uncertainty due the various sources of noise.

2. Theoretical background

In the present paper, we use a Cartesian coordinate system in which x, y and z are respectively the longitudinal, the lateral and the vertical directions. Let $(0, x_0, y_0)$ be the reference frame attached to the experiment and $(0, x_1, y_1)$ be the ADV coordinate frame (Fig. 1), with θ the angle made by the ADV coordinate frame with the reference frame ($\theta > 0$ in the counter-clockwise direction and $\theta = \theta(x, y)$, i.e. without misorientation in the vertical direction).

Let then (U_1, V_1) be the instantaneous velocity components measured in the ADV coordinate frame and C the norm of this velocity. In the reference frame, C is obviously unchanged and the so-called "corrected velocity" components (U_0, V_0) can be worked out as:

$$\begin{aligned} U_0 &= U_1 \cos\theta - V_1 \sin\theta \\ V_0 &= V_1 \cos\theta + U_1 \sin\theta \end{aligned} \tag{1}$$

Using the Reynolds decomposition $U = \overline{U} + u$ and $V = \overline{V} + v$ (over-bars: time-averaging, lowercase: fluctuation) and considering that $\overline{\overline{U} + u} = \overline{U}$, the mean velocities and the fluctuations can be separately rotated, which enables to work out the correlations used for calculating the following components of the horizontal Reynolds stress:

$$\begin{aligned} \overline{u_0^2} &= \overline{u_1^2} cos^2\theta + \overline{v_1^2} sin^2\theta - \overline{u_1 v_1} sin2\theta \\ \overline{v_0^2} &= \overline{v_1^2} cos^2\theta + \overline{u_1^2} sin^2\theta + \overline{u_1 v_1} sin2\theta \\ \overline{u_0 v_0} &= \frac{sin2\theta}{2}\left(\overline{u_1^2} - \overline{v_1^2}\right) + \overline{u_1 v_1} cos2\theta \end{aligned} \tag{2}$$

Notice that for transiting from the plane $(0, x_0, y_0)$ to the plane $(0, x_1, y_1)$ replace θ by $-\theta$ in Eqs. 1 and 2. This transition can be seen as an other type of misorientation [30].

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2.1. Mean velocities

In order to evaluate the error due to the ADV misalignment with the reference frame, a "fractional error" is analytically determined for each mean velocity component. It writes:

$$E_{\overline{U}} = \frac{\overline{U_1} - \overline{U_0}}{\overline{U_0}} = \frac{\cos\alpha}{\cos(\alpha+\theta)} - 1$$
$$E_{\overline{V}} = \frac{\overline{V_1} - \overline{V_0}}{\overline{V_0}} = \frac{\sin\alpha}{\sin(\alpha+\theta)} - 1 \quad (3)$$

with $\alpha = \arctan\left(\overline{V_1}/\overline{U_1}\right)$ the angle between the streamline and the x-wise axis of the ADV coordinate frame (see Fig. 1).

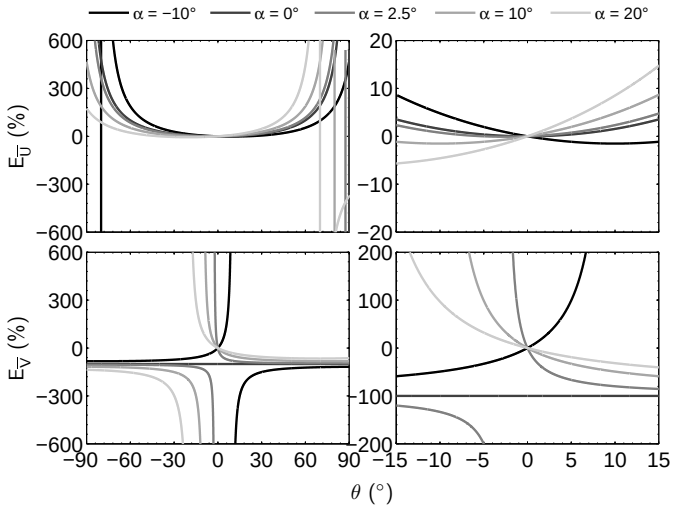


Figure 2: Fractional errors for the mean longitudinal velocity $E_{\overline{U}}$ and mean lateral velocity $E_{\overline{V}}$ with respect to θ for various angle α.

Plotting the fractional errors for θ in the range $[-90° ; 90°]$ (left figures in Fig. 2) reveals the respective evolutions of the two errors, exemplified by asymptotic behaviours. The fractional errors are $2k\pi$ ($k \in \mathbb{Z}$) periodic functions of α and θ and when they are plotted against θ for various positive angles α (Fig. 2), the following statements can be observed:

- For $\theta \in [-45° - \alpha ; 45° + \alpha]$, $E_{\overline{U}}$ is at least one order of magnitude smaller than $E_{\overline{V}}$.
- For $\theta \in [-90° - \alpha ; 90° + \alpha]$, $E_{\overline{U}}$ symmetrically evolves with respect to the axis passing by $\theta = -\alpha$. For this angle, the flow streamline is aligned with the reference frame and the fractional error reaches a local minimum equal to $E_{\overline{U}} = \cos\alpha - 1$. By contrast, the fractional error is nil when $\theta = 0$ or $\theta = -2\alpha$.
- For $\theta \in [-90° - \alpha ; 90° + \alpha]$, $E_{\overline{V}}$ asymptotically tends to infinity when $\theta = -\alpha$, *i.e.* when $E_{\overline{U}}$ reaches its local minimum. $E_{\overline{V}}$ also asymptotically tends to a local minimum (resp. maximum) when $\theta = -\alpha - 90°$ (resp. $\theta = -\alpha + 90°$) if $\alpha < 0$ and $\theta = -\alpha + 90°$ (resp. $\theta = -\alpha - 90°$) if $\alpha > 0$. Both local extrema coincide with the asymptotes to infinity observed in the upper plots in Fig. 2.

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Except if the beams of the ADV are inverted in the flow, realistic values are assumed to be rather in the range $[-2.5° \; ; \; 2.5°]$ and a focus is proposed in Fig. 2 (right).

2.2. Reynolds stress

Using Eqs. 2, the fractional errors are analytically determined for the horizontal components of the Reynolds stress:

$$\begin{aligned} E_{\overline{u^2}} &= \frac{\overline{u_1^2} - \overline{u_0^2}}{\overline{u_0^2}} = (\phi_{uv0}^{-2} - 1)\sin^2\theta - \phi_{uv0}^{-1} r_{uv0} \sin(2\theta) \\ E_{\overline{v^2}} &= \frac{\overline{v_1^2} - \overline{v_0^2}}{\overline{v_0^2}} = (\phi_{uv0}^{2} - 1)\sin^2\theta + \phi_{uv0} r_{uv0} \sin(2\theta) \\ E_{\overline{uv}} &= \frac{\overline{u_1 v_1} - \overline{u_0 v_0}}{\overline{u_0 v_0}} = \cos(2\theta) - 1 - \frac{\phi_{uv0}^{-1} - \phi_{uv0}}{2 r_{uv0}} \sin(2\theta) \end{aligned} \tag{4}$$

with $\phi_{uv0} = \left(\overline{u_0^2}/\overline{v_0^2}\right)^{0.5}$ the ratio of u_0 and v_0 standard deviations and $r_{uv0} = -\overline{u_0 v_0}/\left(\overline{u_0^2}\,\overline{v_0^2}\right)^{0.5}$ the cross-correlation coefficient between u_0 and v_0. Notice that the third line of Eqs. 4 is analogous to the one proposed by Roy et al. [30] for the components of the fluctuating velocities, (u, w), in the vertical plane.

Eqs. 4 are not easy to analyse because of the cosine and sine terms. Nevertheless, as previously observed, a more realistic values for θ is $\pm 2.5°$. As a consequence, considering that $\theta = O(0)$ (*i.e.* $|\tan\theta| \leq 0.1 \Leftrightarrow |\theta| \leq 5.71°$), Eqs. 4 can be linearised so that the fractional errors per degree write

$$\begin{aligned} \frac{E_{\overline{u^2}}}{\theta} &= \frac{\pi}{180}\left[(\phi_{uv0}^{-2} - 1)\theta - 2\phi_{uv0}^{-1} r_{uv0}\right] \\ \frac{E_{\overline{v^2}}}{\theta} &= \frac{\pi}{180}\left[(\phi_{uv0}^{2} - 1)\theta + 2\phi_{uv0} r_{uv0}\right] \\ \frac{E_{\overline{uv}}}{\theta} &= \frac{\pi}{180}\frac{\left(\phi_{uv0} - \phi_{uv0}^{-1}\right)}{r_{uv0}} \end{aligned} \tag{5}$$

$E_{\overline{u^2}}/\theta$ and $E_{\overline{v^2}}/\theta$ (Eq. 5) are plotted with respect to r_{uv0} for various values of ϕ_{uv0} and θ in Fig. 3. Both fractional errors are of the same order of magnitude. They both are almost equal to $5\%/deg$ in absolute value for a coefficient $r_{uv0} = \pm 0.5$ with $\phi_{uv0} = 0.5$ for $E_{\overline{u^2}}/\theta$ and $\phi_{uv0} = 2.4$ for $E_{\overline{v^2}}/\theta$ ($r_{uv0} \in [-0.5 \; ; \; 0.5]$ and $\phi_{uv0} \in [0.5 \; ; \; 2.4]$ are typical values in open channel flows [32]). The fractional error per degree $E_{\overline{u^2}}/\theta$ decreases with increasing ϕ_{uv0}, while the contrary is observed for $E_{\overline{v^2}}/\theta$. Moreover, θ has little influence on the fractional error as shown in the right plots in Fig. 3.

As $E_{\overline{uv}}/\theta$ is independent from θ (see in Eq. 5), $E_{\overline{uv}}/\theta$ is plotted with respect to r_{uv0} for various values of ϕ_{uv0} in Fig. 4. Unlike $|E_{\overline{u^2}}/\theta|$ and $|E_{\overline{v^2}}/\theta|$, $|E_{\overline{uv}}/\theta|$ decreases for increasing $|r_{uv0}|$. In addition, $|E_{\overline{uv}}/\theta| >> |E_{\overline{u^2}}/\theta|, |E_{\overline{v^2}}/\theta|$ for near-zero values of r_{uv0} and they are equivalent when $r_{uv0} \approx \pm 0.5$.

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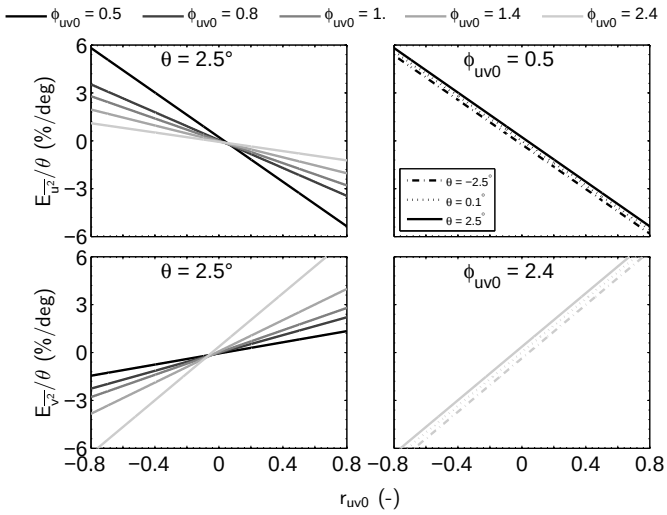


Figure 3: Fractional errors in percentage per degree for the auto-correlations $E_{\overline{u^2}}/\theta$ and $E_{\overline{v^2}}/\theta$ with respect to ϕ_{uv0}, r_{uv0} and θ, considering that $\theta = O(0)$.

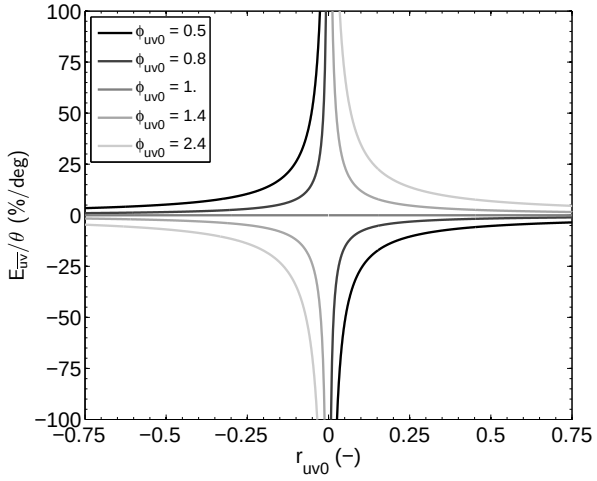


Figure 4: Fractional error in percentage per degree for the cross-correlation $E_{\overline{uv}}/\theta$ with respect to ϕ_{uv0} and r_{uv0}, considering that $\theta = O(0)$.

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3. Experimental fractional error

In the following section, the error due to device misorientation is evaluated through experimental data. The experimental fractional errors are worked out for a misalignment angle θ of 2.5° using ADV measurements performed in a compound open-channel under various flow conditions. These errors are then compared with fractional errors calculated with data of more classical flows (boundary layer, mixing layer, plane jet...) for the same value of θ.

3.1. Case of compound channel flows

Set-up of the experiments

Experiments were conducted at the Laboratoire de Mécanique des Fluides et d'Acoustique (LMFA, Lyon, France) in a 8 m long and 1.2 m wide straight asymmetric compound open-channel, with a longitudinal bed-slope of 0.18%. The flume is PVC-made and its surface state is smooth. The main channel and the floopdlain cross-sections are rectangular (see in Fig. 5) and their widths are respectively equal to 0.4 m and 0.8 m. The bank-full height in the main channel, b, is 5.1 cm. As recommended by Bousmar et al. [33] for accelerating the flow establishment in a compound channel, separated filling tanks, inlets and downstream tailgates are used in the flume.

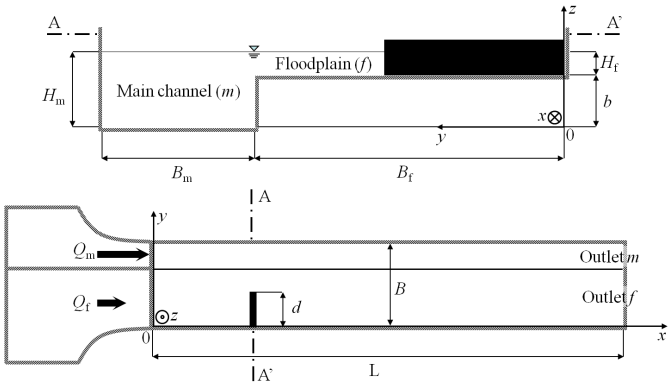


Figure 5: Definition sketch of the flume in the LMFA: cross-sectional and plan views (scheme is not to scale). The system origin is defined as: $x = 0$ immediately downstream from the inlet tanks; $y = 0$ on the lateral side-wall of the floodplain; $z = 0$ on the bottom of the main channel.

The flow conditions of the data-set we use in this paper are described in Peltier [24], Peltier et al. [7] and include:

- Three uniform flow-cases, which relative flow depths, H_r, are close to 0.2, 0.3 and 0.4 in most part of the flume ($H_r = H_f/H_m$, with H_f the mean water depth in the floodplain and H_m the mean water depth in the main channel respectively).

- Six non-uniform flow-cases with a thin obstacle on the floodplain, representing an embankment. The embankment was set at $x = 2.5$ m from the inlet, perpendicularly to the longitudinal direction (see in Fig. 5). Various lengths of embankment, d, were used, but the upstream discharge distributions and the tailgate settings were the same as used for the uniform flows.

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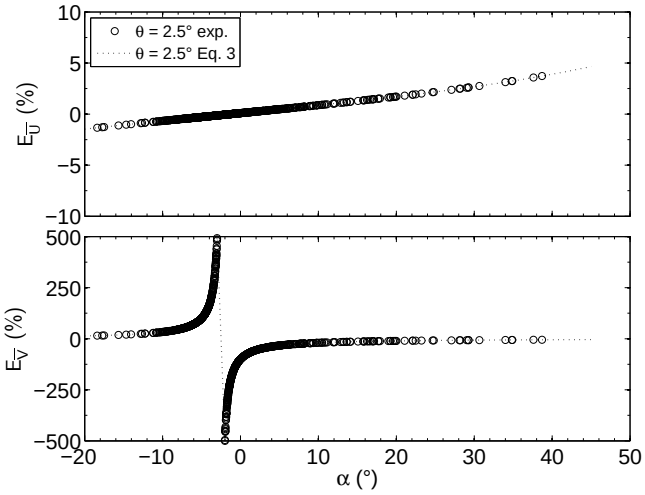


Figure 6: Experimental fractional errors for the mean velocities $E_{\overline{U}}$ and $E_{\overline{V}}$ with respect to θ and α with $\theta = 2.5°$.

The instantaneous velocities were measured using a 2D side-looking micro-ADV (Nortek, Vectrino$^+$). The sampling frequency was set to 100 Hz with a signal-to-noise ratio greater than 20 dB in order to have weak influences of the noise [10]. The recording time was set at least to 3 min to ensure a good convergence of the mean and standard deviation of the signal (according to Chanson et al. [12], 18000 samples lead to an error of $\approx \pm 2\%$ on the standard deviation). The measured velocity signals were finally despiked using the method of Goring and Nikora [16], but no specific method was applied for correcting the other sources of noise.

Due to the varied settings of the experiments, wide ranges of velocities ($C \in [0.1\ ;\ 0.9]$ m/s), of flow deviations ($\alpha \in [-30°\ ;\ 20°]$), of cross-correlation coefficients ($r_{uv0} \in [-0.57\ ;\ 0.72]$) and ratios of standard deviations ($\phi_{uv0} \in [0.8\ ;\ 3.8]$) were obtained.

Fractional errors

In order to estimate the error due to a misorientation of the ADV, we work out the fractional errors of this data-set (1) assuming that the measured data (the raw data) is well oriented in the reference frame $(0, x_0, y_0)$ and (2) imposing an artificial rotation of $\theta = 2.5°$ to this data to obtain the misoriented data in the ADV coordinate frame $(0, x_1, y_1)$. This angle of 2.5° represents the maximal angle of misalignment by human eyes adjustment (above this angle, the misalignment can be easily detected).

The fractional errors are first calculated for the mean velocities using Eqs. 3. Both velocity components are independent from C and $E_{\overline{U}}$ appears to be within ±5%, while $E_{\overline{V}}$ can reach several thousands of percent if $\alpha = -\theta = -2.5°$ (Fig. 6).

The fractional errors for the Reynolds stresses, calculated using Eqs. 4 are then plotted against the cross-correlation coefficient r_{uv0} and $\phi_{uv0} \in [0.8\ ;\ 2.4]$ in Fig. 7. The absolute value of $E_{\overline{u^2}}$ increases with increasing $|r_{uv0}|$ and decreasing ϕ_{uv0}, while the absolute value of $E_{\overline{v^2}}$ increases with both increasing $|r_{uv0}|$ and ϕ_{uv0}. Nevertheless these fractional errors

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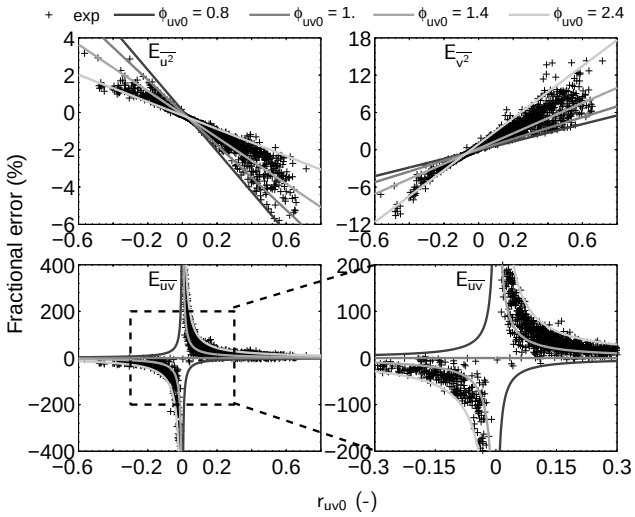


Figure 7: Experimental fractional errors for the Reynolds stresses $E_{\overline{u^2}}$, $E_{\overline{v^2}}$ and $E_{\overline{uv}}$ with respect to r_{uv0} for $\phi_{uv0} \in [0.8\ ;\ 2.4]$ with $\theta = 2.5°$.

remain relatively low. $E_{\overline{u^2}}$ ranges from −5.8% to 3.2%, while $E_{\overline{v^2}}$ ranges from −10.6% to 14.3%. By contrast, the absolute value of $E_{\overline{uv}}$ can reach several hundreds of percent when $|r_{uv0}|$ goes to 0. In the mixing layer of the compound channel, typical values of $|r_{uv0}|$ are greater than 0.2 and $|E_{\overline{uv}}|$ is therefore lower than 90%.

The fractional errors $E_{\overline{u^2}}$, $E_{\overline{v^2}}$ and $E_{\overline{uv}}$ are plotted in Fig. 8 relative to the corresponding values of the Reynolds stresses measured in the reference frame. While no tendency is observed for $-\rho\overline{u^2}$, $E_{\overline{v^2}}$ decreases with decreasing $-\rho\overline{v^2}$, which could indicate that slow flow motions are more prone to orientation imprecisions. Concerning the Reynolds shear stress $-\rho\overline{uv}$, $E_{\overline{uv}}$ is relatively high ($|E_{\overline{uv}}| \geq 10\%$) when $-\rho\overline{uv}$ is smaller than 1 Pa in absolute. Beyond 1 Pa, the fractional error is within ±20%. This result is of importance for the study of shear flows in compound open-channels: in areas of high Reynolds shear stress, we can ensure relatively low error due to a misorientation of the ADV. By contrast, in the areas, where $|-\rho\overline{uv}|$ is smaller than 1 Pa, the error can be prohibitive. The accurate measurement of the Reynolds stresses in the horizontal plane is indeed paramount for validating a turbulent model (notably for 2D depth-averaged models) and an error of several tens (or hundreds) of percent is unacceptable.

3.2. Comparison with more classical flows

In the previous sub-section, we showed that the fractional errors for the mean velocities only depends on θ and α and is therefore independent from the type of the flow. By contrast, the fractional errors for the Reynolds stresses are conditioned by the turbulent characteristics of the flow and can be greater than several hundreds of percent, especially when considering the Reynolds shear stress $-\rho\overline{uv}$. Nevertheless, compound channel flows are quite particular flows and their fractional error values could be specific to this kind of flow. In the literature, the turbulent characteristics of classical flows are well detailed, which allow us to calculate typical fractional errors to be compared with the ones of the present experiments (see Tabs. 1 and 2). The computed fractional errors correspond to hypothetical errors if the measurements would have been performed using an ADV with a 2.5° misalignment angle.

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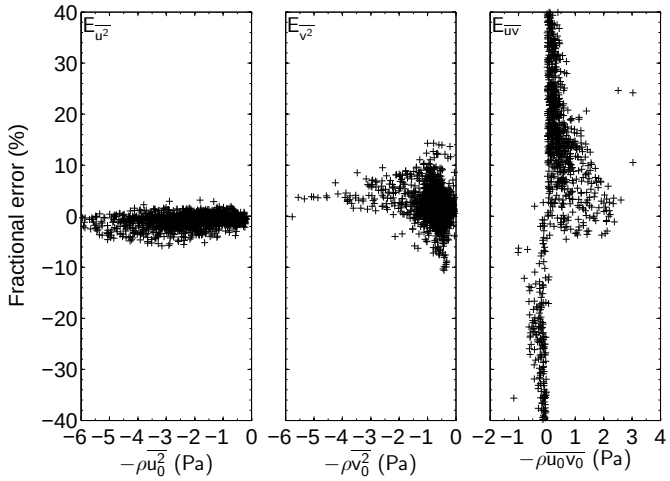


Figure 8: Experimental fractional errors ($E_{\overline{u^2}}$, $E_{\overline{v^2}}$, $E_{\overline{uv}}$) plotted with respect to the corresponding values of Reynolds stresses ($-\rho\overline{u_0^2}$, $-\rho\overline{v_0^2}$, $-\rho\overline{u_0 v_0}$) for $\theta = 2.5°$.

Table 1: Fractional errors for flows with a mean velocity gradient mainly occurring in the horizontal plane. Calculation with $\theta = 2.5°$.

Type of flow	Authors	ϕ_{uv_0} (-)	r_{uv_0} (-)	$E_{\overline{u^2}}$ (%)	$E_{\overline{v^2}}$ (%)	$E_{\overline{uv}}$ (%)
Compound channel flows	Present data	[0.8 ; 3.8]	[−0.57 ; 0.72]	[−5.8 ; 3.2]	[−10.6 ; 14.3]	> 100
Mixing layer:						
- Centre	[34]	[1.2 ; 1.6]	[0.42 ; 0.62]	[−4 ; −2]	[6 ; 7]	[3 ; 10]
- Side		[0.8 ; 1.8]	[0.14 ; 0.5]	[−3 ; 0.8]	[2 ; 5]	[3 ; 30]
Plane Jet:						
- Near the centreline	[35]	1.6	-0.42	2.1	-5.6	-10.4
- Near the edges		1.1	-0.22	1.6	-2.1	-4.7
Homogeneous shear flows ($x/B = 7.5$)	[36]	1.67	0.45	-2.4	6.9	10

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Table 2: Fractional errors for flows with a mean velocity gradient mainly occurring in the vertical plane. Calculation with $\theta = 2.5°$. $E_{\overline{uw}}$ is calculated using the formula proposed by Roy et al. [30].

Type of flow	Authors	ϕ_{uw_0} (-)	r_{uw_0} (-)	$E_{\overline{uw}}$ (%)
Smooth boundary layer:				
Viscous sub-layer	[14]	[3.4 ; 6]	[0.19 ; 0.34]	[63 ; 110]
Log-layer and outer layer		[0.8 ; 4]	[0.03 ; 0.4]	[−0.3 ; 50]
Transition boundary layer:				
Near the bottom	[37]	[2.3 ; 3.9]	[0.47 ; 0.52]	[15 ; 33]
In the bulk		[1.7 ; 2]	[0.38 ; 0.53]	[10 ; 12]
Fully rough boundary layer:				
Near the bottom	[38, 39]	[3.1 ; 4.1]	[0.13 ; 0.46]	[25 ; 122]
In the bulk		[2.2 ; 2.9]	[0.41 ; 0.5]	[16 ; 22]
Boundary layer in a tidal current	[29]	[1.5 ; 2.5]	[0.07 ; 0.25]	[18 ; 151]

The parameters ϕ_{uv0} and r_{uv0} were first determined for three types of flow for which the mean velocity gradient mainly occurs in the horizontal plane (Tab. 1): mixing layer created by a splitter plate at the flume entrance [34], plane jet [35] and homogeneous shear flow [36]. It results that ϕ_{uv0} and r_{uv0} for the three cases are within the ranges of the compound channel flow, which leads to fractional errors of the same order of magnitude. Similarly to the compound channel flows, the fractional errors $E_{\overline{u^2}}$ and $E_{\overline{v^2}}$ increase with the Reynolds shear stress magnitude, while $E_{\overline{uv}}$ is minimal in the zone of intense shear, where it can still reach 10%.

Although, the main aims of this paper was to assess the error due to a misorientation of an ADV with respect to the horizontal plane, we also compare these errors with the ones on the vertical plane from data in the literature. As pointed out in section 2, by replacing v by w (the vertical fluctuating velocity) in the third line of Eqs. 4, Roy et al. [30] found an expression for $E_{\overline{uw}}$ similar to the one of $E_{\overline{uv}}$, but none for $E_{\overline{u^2}}$ and $E_{\overline{w^2}}$. In Tab. 2, only $E_{\overline{uw}}$ is therefore presented.

The parameters ϕ_{uw0} and r_{uw0} in Tab. 2 were determined with data of four different boundary layers with a mean velocity gradient mainly occurring in the vertical plane. The ranges of ϕ_{uw0} and r_{uw0} are similar to those of ϕ_{uv0} and r_{uv0} in Tab. 1. The magnitude of $E_{\overline{uw}}$ is also similar to $E_{\overline{uv}}$, the greater errors due to a misorientation being located in the viscous sub-layer of the smooth boundary layer [14] or in the roughness layer of the transitional [37] and of the fully rough boundary layers [38, 39].

4. Discussion

In the previous section, we showed that the error due to the ADV misorientation can be very high, especially when estimating the Reynolds shear stress components. This section now aims at comparing this error with the classical

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sources of uncertainty generally considered in ADV measurements.

According to Hurther and Lemmin [15], any deployment errors aside, six sources of noise affect the turbulence measurements using an ADV:

1. the Doppler ambiguity at high frequency
2. the effects of the mean flow shear stress present within the sampling volume
3. the phase distortion of the emitted front wave
4. the electronic circuitries
5. the effects of the turbulent structures smaller or of the same size as the sampling volume
6. the spatial averaging of the instantaneous velocity field in the sampling volume.

Among these six sources, the five first ones can be corrected by applying the methods described in Hurther and Lemmin [15], Blankaert and Lemmin [19] for an Acoustic Doppler Velocimeter Profiler. The remaining source (the sixth) is a problem inherent to the geometry of the device and cannot be corrected. These sources of noise mainly affect the normal Reynolds stress [15]. By contrast, the Reynolds shear stresses are theoretically independent from the five first sources, but the spatial averaging within the sampling volume (the sixth source) can be responsible for large uncertainties, especially if the measurements are performed close to irregular boundaries (gravel-bed) or obstacles (embankment).

According to Hurther and Lemmin [15], in a flow over a gravel bed, the uncertainty due to the sum of the six sources of noise can reach $\approx 5\%$ for the normal Reynolds stresses and the Reynolds shear stress in absence of irregular boundaries and obstacles. In the "pertubated" zones this uncertainty is much higher. Hurther and Lemmin [15] indeed showed that in the rough sub-layer, the uncertainty on the Reynolds shear stress can reach 120%. These orders of magnitude for this uncertainty are similar to the error due to a misorientation of the probe in the flow (Tabs 1 and 2). As a consequence, both error and uncertainty should then be taken into account.

In the paper, we have considered that errors due to the probe misorientation and uncertainties listed above were independent from each other. This is actually not the case. Indeed, the error due to the probe misorientation depends on the quality of the velocity measurement. As shown in Figs. 3 and 4, if r_{uv0} and ϕ_{uv0} values are badly estimated due to uncertainties, the errors induced by the probe misorientation can be strongly affected. For instance, a change in 60% of ϕ_{uv0} for high r_{uv0} induces a change of 38% in $E_{\overline{u^2}}/\theta$ and a change of 70% for $E_{\overline{uv}}/\theta$.

5. Conclusion

The error due to a misorientation of an Acoustic Doppler Velocimeter in the horizontal plane was estimated on the horizontal components of the mean velocity and of the Reynolds stresses, first analytically and then using an experimental data-set of compound channel flows with a misalignment angle of 2.5°. The following conclusions are drawn:

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1. The fractional error for the mean longitudinal velocity is never greater than |5|%.
2. The fractional error for the lateral mean velocity can be several order greater, especially when the misalignment angle is equal to the opposite angle between the velocity direction and the x-axis of the ADV coordinate frame.
3. The absolute fractional errors for the normal Reynolds stresses $-\rho\overline{u^2}$ and $-\rho\overline{v^2}$ do not exceed 5.8% and 14.3% respectively.
4. The absolute fractional error for the Reynolds shear stress $-\rho\overline{uv}$ increases when the absolute value of the coefficient correlation r_{uv0} decreases. The fractional error can reach several thousand percent at low r_{uv0}. Nevertheless, in the zones of high velocity gradient, where $-\rho\overline{uv} \geq 1$ Pa or $-\rho\overline{uv} \leq -1$ Pa, the fractional error does not exceed ±20%.

The fractional errors worked out with the compound channel flows were then compared with the ones of classical flows from the literature. The error appears to be of the same order of magnitude as the compound channel flows.

We finally discussed the necessity of taking into account the ADV misorientation for assessing the uncertainty on the ADV measurements. Using the numerous studies dealing with noise cancellation and uncertainty estimation due to the various sources of noise, we highlighted that the error due to the misorientation is of the same order of magnitude as the uncertainty due to the noises. As a result, they should both be used by ADV users in order to interpret their measurements, especially when working with the components of the Reynolds shear stress.

ADV users must keep in mind that even if the error on the ADV orientation can be high, such a device is a powerful tool to measure good turbulent characteristics of flows in which more “accurate” measurement methods could not be used. Moreover, these errors can be reduced by attentively deploying the device in the flume or in the field or by applying an adequate correction on the data during post-processing. In the literature, one can find studies dealing with correction methods for ADV measurements [3, 5, 18]. However, as pointed out by several authors, unless misalignment angles of each sampling station with respect to the reference frame are known, most of these methods can only correct for a constant misalignment angle across the entire section. To the authors knowledge, a simple way to correct one sampling location at the time must still be found.

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289 **Notations**

290 *The following symbols are used in this paper:*

b = bank-full height (m)

B = total width of the flume (m)

B_i = width of the sub-section i (m)

C = norm of the velocity (m)

E_i = fractional error calculated on the parameter i (-)

h = local water depth (m)

H_i = water depth in the sub-section i (m)

H_r = relative flow depth (-)

L = length of the flume (m)

r_{uv} = correlation coefficient of u and v (-)

r_{uw} = correlation coefficient of u and w (-)

Q_i = discharge in the sub-section i (m^3/s)

U = instantaneous longitudinal velocity (m/s)

$\overline{U}$ = mean longitudinal velocity (m/s)

u = longitudinal fluctuating velocity (m/s)

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V = instantaneous lateral velocity (m/s)

$\overline{V}$ = mean lateral velocity (m/s)

v = lateral fluctuating velocity (m/s)

w = vertical fluctuating velocity (m/s)

x = streamwise direction (m)

y = spanwise direction (m)

z = vertical direction (m)

α = angle of the streamline velocity with respect to the x-axis of the ADV coordinate frame (°)

ϕ_{uv} = ratio of the standard deviation of u by the one of v

ϕ_{uw} = ratio of the standard deviation of u by the one of w

θ = angle between the reference frame and the ADV coordinate frame (°)

ρ = water density (Kg/m^3)

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The following subscripts are used in this paper:

0 = refers to the reference frame

1 = refers to the ADV coordinate frame

f = floodplain

m = main channel