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## Turbulence measurements: An assessment of Acoustic Doppler Current Profiler accuracy in rough environment

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### Abstract :

The deployment of tidal turbines requires a precise hydrodynamic characterisation of the production site. Acoustic Doppler Current Profilers (ADCP), usually employed for measuring the time-mean characteristics of environmental flows, could also be used for assessing the main features of turbulence. ADCP measurements are sensitive to many sources of uncertainties associated mainly with the spreading of the beams or the assumptions made on flow homogeneity. The ability of ADCPs to accurately measure the hydrodynamic parameters of a given flow can be tested on a synthetic dataset. However, it is difficult to generate a dataset representative of a real environmental flow. In this work, large-eddy simulation of a high Reynolds flow over a rough seabed is performed and used to assess the accuracy of two, coupled, 4-beam ADCP systems forming an 8-beam arrangement. The study confirms the relevance and efficiency of the tested 8-beam configuration for the characterisation of turbulence. The results near the seabed are of a lower quality, with up to 50 % error on the Reynolds stresses for elevations under twice the roughness height, which questions the interpretation of ADCP measurements in the lower part of the water column. Also, the spatial averaging over ADCP cells leads to an underestimation of the turbulence intensity of 10 % to 20 %.

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## Highlights

► Virtual ADCP measurements are performed on a synthetic LES flow over a rough seabed. ► The use of coupled ADCPs for the measurement of the full Reynolds tensor is validated. ► The Reynolds stresses are underestimated due to the spatial averaging over ADCP cells. ► The quality of ADCP measurements is reduced in the rough boundary layer.

**Keywords** : Turbulence, Lattice Boltzmann Method, Large-Eddy Simulation, ADCP, Environmental flows

15 Tidal power constitutes a potential new source of low carbon power. Although the tidal industry is still  
16 in a development phase, real scale prototypes are being tested in operating conditions (e.g., Simec Atlantis  
17 and Andritz Hydro turbines in the Pentland First, Sabella turbine in Passage du Fromveur, Hydroquest  
18 turbine in Paimpol-Bréhat). As tidal power farms will be composed of arrays of devices distributed  
19 over relatively large areas, the optimal layout will depend, for a large part, on the characteristics of the  
20 hydrodynamics and the variability of the flow in time and space. Regional tidal flow simulations provide  
21 accurate estimates of flow intensity and direction [Thiébot et al. (2020); Lewis et al. (2015); Thiébaud  
22 et al. (2019)]. However, these studies are based on Reynolds averaged numerical simulations, that only  
23 resolve the time-mean flow and model the effect of turbulence. Although they allow for estimating the  
24 turbulence intensity [Togneri et al. (2017b)], they do not simulate turbulent eddies and are limited in terms  
25 of spatial and temporal resolutions. Following the work of [Finnegan et al. (2020)], four main aspects have  
26 been identified that contribute to unsteady loads on tidal turbine blades and their premature fatigue: the  
27 cyclic loading of a blade linked to the vertical gradient of velocity in the swept area, the shadow effects  
28 from the support structure, the force due to the sea surface waves [Lewis et al. (2014)] and the force

29 due to ambient turbulence. As incoming turbulence is an important source of mechanical constraints on  
30 tidal turbines [Thiébaud et al. (2020b); Milne et al. (2016)] and impacts turbine wakes [Grondeau et al.  
31 (2019)], its characterisation is essential [Milne et al. (2016)]. The power production is stable over long  
32 periods of time [Lewis et al. (2019)], however, turbulence might generate electrical surges that need to be  
33 anticipated to preserve the power system. Several Large-Eddy Simulations (LES) have been performed,  
34 such as [Zangiabadi et al. (2015)] in the Ramsey Sound, [Bourgoin et al. (2020)] and [Mercier et al.  
35 (2020a)] in the Raz Blanchard, and [Le et al. (2018)] in the Mississippi River. These simulations enable  
36 the assessment of turbulence metrics, such as the full Reynolds tensor, but are limited in resolution,  
37 temporal and spatial coverage.

38 *In situ* measurements are widely used to estimate the local turbulence metrics [Thomson et al. (2010)].  
39 Bottom mounted Acoustic Doppler Current Profilers (ADCPs) are commonly used for flow characterisa-  
40 tion in situations where simultaneous velocity measurements are desired throughout the water column, to  
41 investigate the vertical distribution of the current velocities. ADCPs use the Doppler shift in the echoes  
42 of a pulsed signal along directed acoustic diverging-beams to estimate flow velocities. Such sensors can  
43 be deployed in various environments such as oceans, rivers or estuaries and for long intervals of time  
44 (several months), allowing for an assessment of the flow variability over a wide range of time scales, with  
45 a typical sampling frequency of a few hertz. They can be employed for an extensive range of applications  
46 and especially for turbulence characterisation [McMillan et al. (2016); Guerra et al. (2017); Thiébaud  
47 et al. (2020a)]. Velocity fluctuations derived from ADCP measurements enable the quantification of sev-  
48 eral characteristics of the turbulent kinetic energy (TKE) budget such as the TKE dissipation and TKE  
49 production rate, as well as the diffusive transport term [Thiébaud et al. (2020c)].

50 The use of 4-beam ADCPs for turbulence characterisation gained popularity since [Lohrmann et al.  
51 (1990)] introduced the so-called variance method. With this technique, profiles with two components  
52 (out of six) of the Reynolds stress tensor are estimated from along-beam velocity measurements, using the  
53 difference between the velocity variances along opposing beams [Lu and Lueck (1999); Stacey et al. (1999);  
54 Rippeth et al. (2003)]. In comparison to 4-beam ADCPs, 5-beam ADCPs allow for a true measurement  
55 of vertical velocities and the estimation of five components of the Reynolds stress tensor [Guerra et al.  
56 (2017)], and reduce wave disturbances [Togneri et al. (2017a)].

57 Recently, 7-beam ADCPs have emerged [Droniou et al. (2019)], enabling the full Reynolds stress tensor  
58 to be solved but they still require development and validation. A valuable alternative to 7-beam ADCPs,  
59 for fully resolving the Reynolds stress tensor, is the combination of two 4-beam ADCPs [Vermeulen et al.  
60 (2011)]. The data from the eight beams allow the six components of the tensor to be resolved. Recently,  
61 this method has been implemented to coupled ADCP measurements performed in the Goulet de Brest,  
62 France [Pieterse et al. (2017)] and in the Raz Blanchard [Thiébaud et al. (2020c,b)].

63 One of the main limitations of ADCPs when it comes to turbulence characterisation is the assumption  
64 of the homogeneity of the flow field over the measurement volume. Indeed, such sensors use beams  
65 that diverge away from the sensor. Hence, the volume in which the flow is assumed homogeneous and  
66 in which the measurements are being integrated, increases, changing the spatial averaging of the flow  
67 characteristics. Although this homogeneity assumption is widely applied, its validity is likely to fail in  
68 particular flow conditions.

69 An analytical study of the ADCP functioning allows to assess their limits [Guion and Young (2014)].  
70 However, such an analysis does not take into account the specificity of a realistic flow field, and in par-  
71 ticular the potential spatial variability of the flow characteristics. The validity of ADCP data processing  
72 can be assessed through Virtual-ADCP (V-ADCP) methods, which consists in applying ADCP data pro-  
73 cessing to a controlled flow field generated analytically [Crossley et al. (2017)] or by numerical simulation  
74 [Tokyay et al. (2009); Richmond et al. (2015)]. The velocity field should be representative of the studied  
75 environmental flow. In particular, the impact of realistic rough seabed morphology on the turbulent char-  
76 acteristics and on the related accuracy of the data processing method has not, to the authors' knowledge,  
77 been addressed yet.

78 The seabed roughness is known to impact the flow characteristics [Hama (1954); Schlichting (1979);

79 Schindler and Ackerman (2010)]. The structure of flows over a rough seabed is characterised by a rough  
80 sub-layer, in which individual roughness wakes induce three-dimensional variations in the flow character-  
81 istics. The thickness of this layer is typically two to five time the roughness height [Nikuradse (1950);  
82 Perry et al. (1969)], in such a way that in high seabed roughness areas, ADCP measurement validity  
83 could be questioned in a large part of the water column. A specific study of the rough sub-layer and its  
84 impact on ADCP measurement accuracy in typical tidal power flows is thus necessary.

85 The structure of environmental flows can be addressed through canopy flow studies, in which roughness  
86 is represented by macro-roughness distributions. Uniform distributions of wall-mounted cubes have been  
87 investigated experimentally by [Florens et al. (2013); Basley et al. (2019)] and numerically by [Coceal et al.  
88 (2007); Anderson et al. (2015)]. [Hardy et al. (2016); Jiang and Liu (2018)] also performed experimental  
89 and numerical analyses of flows over a pebble bed. [Ikhennicheu et al. (2018, 2019, 2020); Mercier et al.  
90 (2020b)] experimentally and numerically investigated the flow over combinations of real seabed elements  
91 such as big rocks or abrupt changes of seabed elevation. However, these studies are limited to moderate  
92 Reynolds numbers ( $Re \approx 10^6$ ), which is not representative of flows at tidal energy sites ( $Re \approx 10^8$ ). To  
93 conduct numerical simulations at high Reynolds number, the choice of the numerical method is crucial  
94 to handle large and complex simulation domains. The Lattice Boltzmann Method (LBM) is an unsteady  
95 computational fluid dynamic method based on the resolution of the Boltzmann equation [Bhatnagar et al.  
96 (1954); Qian et al. (1992)]. It is well suited to large and complex geometries [Succi et al. (1989)] and can be  
97 combined with LES [Smagorinsky (1963); Eggels and Somers (1995)] in order to resolve a large part of the  
98 turbulence energy spectrum and to investigate the motion of the largest eddies [Sagaut (2006)] (those that  
99 contain most of the turbulent energy and control most of the momentum transfer and turbulent mixing).  
100 For these reasons, LBM-LES has been used for environmental numerical simulations [Parmigiani (2013);  
101 Mercier et al. (2020a)].

102 Here, LBM-LES is chosen to perform a simulation of a channel flow over a uniform distribution of wall-  
103 mounted cubes, designed to be representative of a tidal energy site. The V-ADCP method is performed  
104 on the simulation output to test the accuracy of the ADCP configuration proposed by [Vermeulen et al.  
105 (2011)]. Firstly, the numerical simulation method is presented, as well as the ADCP configuration and  
106 principles of the V-ADCP method. Then, the simulation results are exploited to investigate the sources  
107 of error. Finally, the prospects and limits of the method are discussed.

## 108 2. Methods

### 109 2.1. Numerical flow simulation

110 Simulations are performed with the LBM [Bhatnagar et al. (1954); Qian et al. (1992)], a full description  
111 of which can be found in [Guo and Shu (2013)]. The code is based on Palabos, a C++ library [url]. LES  
112 relies on the static Smagorinsky model [Smagorinsky (1963)], with a Smagorinsky constant of 0.14. The  
113 discretisation scheme is D3Q19, and the collision operator relies on the work of [Latt and Chopard (2006)].  
114 A no-slip boundary condition is used at the seabed, based on the work of [Bouzidi et al. (2001)]. Periodic  
115 boundary conditions are applied at the longitudinal and lateral boundaries. A free-slip boundary condition  
116 is applied at the water surface position. The simulation domain is 320 m long, 80 m wide and 40 m deep.  
117 The seabed is composed of 3 m-large cubic elements disposed regularly over the bottom (see Figure 1).  
118 This macro-roughness aims at generating a vertical variation of the turbulence intensity similar to that  
119 measured with two, coupled, 4-beam ADCPs in the Raz Blanchard [Thiébaud et al. (2020b)], where the  
120 mean vertical profile of longitudinal turbulence intensity ranged from 12% near the surface to 21% near  
121 the ADCPs at the seabed.

122 As the domain is periodic, the load losses tend to decrease the flow velocity. This effect is offset by  
123 a longitudinal volume force that sustains the flow. The time step is 0.010 s. The mesh resolution is  
124 0.21 m near the seabed and 0.42 m near the water surface. The domain contains 28.3 million cells. The  
125 average longitudinal speed is  $3 \text{ m}\cdot\text{s}^{-1}$  for a volume force corresponding to a  $2.5 \times 10^{-3} \text{ m}\cdot\text{s}^{-2}$  acceleration.  
126 The instantaneous longitudinal velocity along a vertical longitudinal plane is shown in Figure 2. The

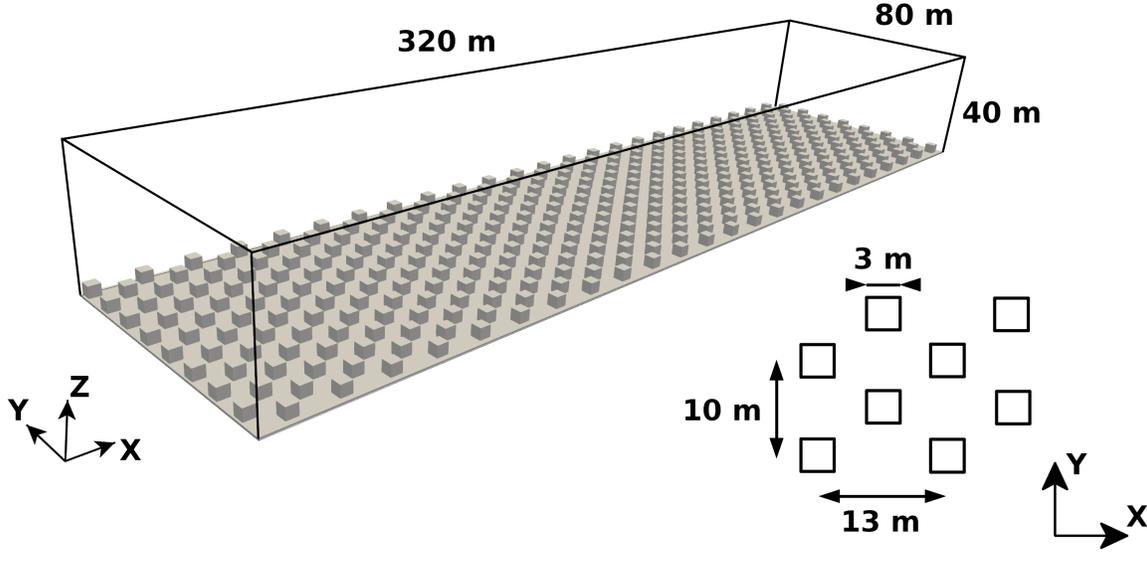


Figure 1: Domain dimensions and cube arrangement.

127 simulation ran on 56 processors for 78 h. The total simulated time is 52 min, with a convergence period  
 128 of 36 min. For *in situ* measurements, the period of data extraction must be long enough to guarantee  
 129 a sufficient number of samples, and short enough not to be affected by changes in the hydrodynamic  
 130 conditions relative to the tidal cycle. This condition is satisfied by using a 10 min period in the case  
 131 studied in the work of [Thiébaud et al. (2020b)]. Here, as there is no variation in the hydrodynamic  
 132 conditions, the period is extended to 16 min. Longitudinal, lateral and vertical velocity components are  
 133 respectively referred to as  $u$ ,  $v$  and  $w$ , acting in the  $x$ ,  $y$  and  $z$  directions. Herein, time averaged ( $\bar{u}$ ) and  
 134 time fluctuating ( $u'$ ) velocities are defined in such way that  $u = \bar{u} + u'$ .

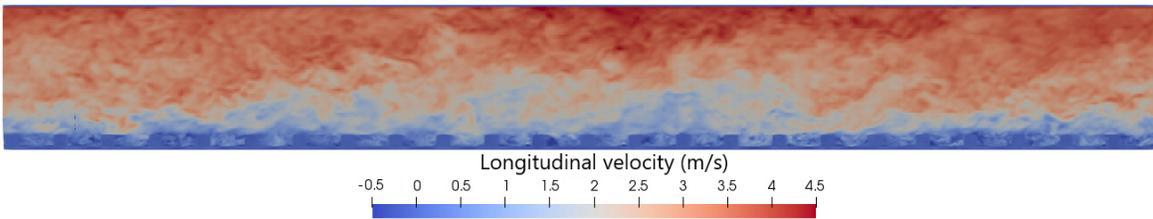


Figure 2: Isosurfaces of instantaneous longitudinal velocity. LBM simulation of a turbulent flow in conditions representative of the hydrodynamics of the Raz Blanchard. Seabed composed of cubic macro-roughness. Image dimensions: 320 m x 40 m.

## 135 2.2. Virtual-ADCPs

136 In the present work, the two, coupled, 4-beam ADCP configuration designed by [Vermeulen et al.  
 137 (2011)] is tested. This configuration is specially conceived for turbulence measurements. Its working  
 138 principle is described hereinafter. The V-ADCPs are modelled to represent the sampling geometry of  
 139 the coupled ADCPs in the representative velocity field derived from the numerical flow simulation. Two  
 140 upward-looking 4-beam V-ADCPs coupled in a master-slave set-up, are positioned on the seabed forming  
 141 an 8-beam arrangement where the beams are numbered from 1 to 8 (Figure 3). The two V-ADCPs are at  
 142 a distance of 0.5 m from each other. The V-ADCPs record alternatively the velocities in beam coordinates  
 143 (radial velocities) at the frequency rate of 2 Hz.

144 The angle  $\theta$  between the transducers and the vertical is  $20^\circ$ , in accordance with the 4-beam ADCPs  
 145 used in [Vermeulen et al. (2011); Thiébaud et al. (2020c,b)]. A Cartesian coordinate system ( $\mathcal{O}$ ,  $x$ ,  $y$ ,  $z$ )

146 is defined relative to the master V-ADCP, with the origin  $\mathcal{O}$  located at the centre of the four transducers  
 147 (Figure 3). The orientation of the master V-ADCP is such that the opposite beams 1 and 2 are oriented  
 148 along the direction of the longitudinal velocity  $u$ , defining the  $x$ -axis, whereas beams 3 and 4 are oriented  
 149 along the direction of the lateral velocity  $v$ , defining the  $y$ -axis. The slave V-ADCP is rotated to an angle  
 150  $\phi_1 = 20^\circ$  around the  $x$ -axis (Figure 3), and  $\phi_3 = 45^\circ$  around the  $z$ -axis resulting in a tilted V-ADCP with  
 151 one beam pointed vertically upward (Figure 4). No rotation is applied around the  $y$ -axis ( $\phi_2 = 0^\circ$ ).

152 The coupled ADCP method, developed by [Vermeulen et al. (2011)], combines (i) the traditional  
 153 transformation method, where two opposite beams of the ADCP are used to transform velocities in beam  
 154 coordinates to velocities in Cartesian coordinates, with (ii) the rotation of the slave relative to the master  
 155 ADCP. The velocities in beam coordinates equates to the velocities  $(u, v, w)$  in Cartesian coordinates as  
 156 in Equation 1:

$$\mathbf{b} = T \cdot \mathbf{u} \quad (1)$$

157 where  $\mathbf{b}$  is an eight-component vector containing all the radial velocity components from the two  
 158 coupled ADCPs,  $\mathbf{u}$  is the velocity vector in the Cartesian coordinate system ( $\mathbf{u} = u\vec{e}_x + v\vec{e}_y + w\vec{e}_z$ ) and  
 159  $T$  is the transformation matrix involving sines and cosines of  $\theta$ ,  $\phi_1$ ,  $\phi_2$  and  $\phi_3$  [Vermeulen et al. (2011);  
 160 Thiébaud et al. (2020c,b)]. The velocities in the Cartesian coordinate system are obtained by inverting  
 161 the transformation matrix,  $T$ .

162 In order to obtain the components of the Reynolds stress tensor from the velocity variances in beam  
 163 coordinates, a new eight by six matrix,  $Q$ , is computed resulting from the product of the terms in  $T$   
 164 [Vermeulen et al. (2011); Thiébaud et al. (2020c,b)]. The vector  $\mathbf{v}_b$  containing the velocity variances in  
 165 beam coordinates is written as the product of  $Q$  by the vector  $\mathbf{r}$  containing the six terms of the Reynolds  
 166 stress tensor, as in Equation 2:

$$\mathbf{v}_b = Q \cdot \mathbf{r} \quad (2)$$

167 The six-element vector  $\mathbf{r}$  can be rearranged to form the Reynolds stress tensor according to Equation 3:

$$\mathbf{r} = \begin{pmatrix} r_1 & r_4 & r_5 \\ r_4 & r_2 & r_6 \\ r_5 & r_6 & r_3 \end{pmatrix} = \begin{pmatrix} \overline{u'^2} & \overline{u'v'} & \overline{u'w'} \\ \overline{u'v'} & \overline{v'^2} & \overline{v'w'} \\ \overline{u'w'} & \overline{v'w'} & \overline{w'^2} \end{pmatrix} \quad (3)$$

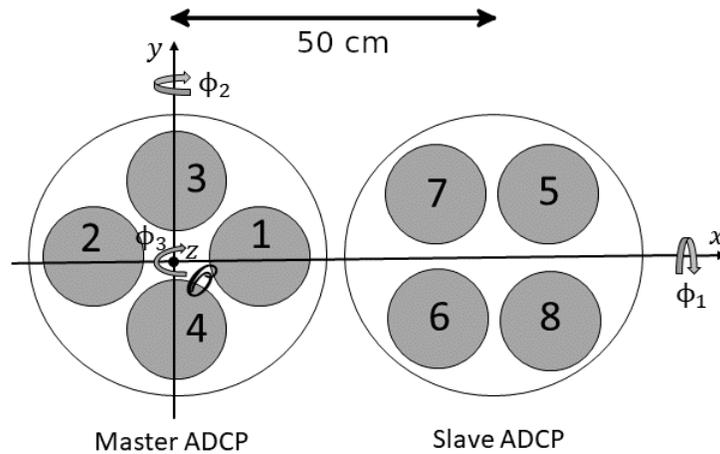


Figure 3: Position and orientation of two coupled 4-beam ADCPs [Vermeulen et al. (2011)].

168 The Reynolds stresses indicate the orientation of the eddies in the flow and are often used to estimate  
 169 fundamental turbulence metrics such as the turbulence intensity, the TKE dissipation rate or the TKE

170 production rate. Here, the  $\overline{u'u'}$ ,  $\overline{v'v'}$  and  $\overline{w'w'}$  components will be referred to as normal stresses and the  
 171  $\overline{u'v'}$ ,  $\overline{u'w'}$  and  $\overline{v'w'}$  components as the shear stresses.

172 V-ADCP cells are defined by all the mesh nodes included in a volume delimited by a frustum of  $4^\circ$   
 173 beam cone. The cells of the master and slave V-ADCP are respectively 1.28 m and 1.37 m thick. This  
 174 corresponds to the configuration used in [Thiébaut et al. (2020c)]. The cells are presented in Figure 4.  
 175 They are composed of a number of mesh nodes ranging from 4 to 135 and their volume ranges from 0.5  
 176  $\text{m}^3$  to 17  $\text{m}^3$ , depending on their elevation. Similarly to real ADCPs, the spatial averaging of the radial  
 177 velocity is performed on each cell volume. This process is replicated on each V-ADCP beam. The issue  
 178 of Doppler noise [Brumley et al. (1991)] and other practical operational considerations are ignored. Also,  
 179 if the acquisition frequency affects the consideration of the smallest scales of the turbulence in standard  
 180 ADCP uses [Guion and Young (2014)], it is not the case for data processing based on the variance method.  
 181 Thus, this matter is not addressed here.

182 The Reynolds stresses are computed directly from the synthetic flow field on a vertical profile centred  
 183 on the master V-ADCP position, with a high frequency data acquisition (100 Hz). This dataset will  
 184 be referred to as the reference dataset. Simultaneously, the Reynolds stresses are calculated from the  
 185 velocities recorded by the V-ADCP. The comparison between Reynolds stresses derived from both methods  
 186 will allow for the assessment of the error inherent to ADCP measurements.

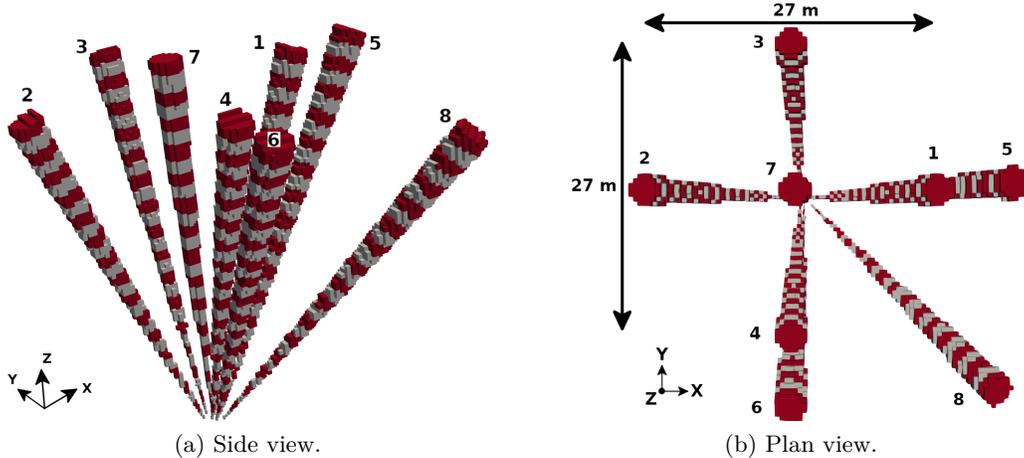


Figure 4: Visualisation of the eight beams of the V-ADCP configuration. Each alternate grey and red stripe corresponds to an individual cell.

### 187 3. Results

#### 188 3.1. Comparison of Reynolds stresses derived from the reference dataset and V-ADCP

189 Figure 5 shows scatterplots of the six components of the Reynolds stress tensor derived from the  
 190 reference dataset and the V-ADCP at each cell elevation. The 1:1 black line indicates perfect agreement  
 191 between Reynolds stresses derived from both methods.

192 In general, a good agreement is found, with the  $\overline{u'u'}$ ,  $\overline{v'v'}$ ,  $\overline{w'w'}$ ,  $\overline{u'v'}$  and  $\overline{u'w'}$  components matching the  
 193 1:1 line. However, a few values are found to be significantly far from the 1:1 line, especially in the normal  
 194 stresses  $\overline{u'u'}$  and  $\overline{v'v'}$ , where these values were calculated near the seabed. Moreover, the component  $\overline{v'v'}$   
 195 exhibits some inconsistencies with two negative values derived from the V-ADCP.

196 The scatterplots of the normal stresses ( $\overline{u'u'}$ ,  $\overline{v'v'}$  and  $\overline{w'w'}$ ) are slightly right-skewed, indicating that  
 197 the V-ADCP underestimates these components. Since the normal stresses allow for the calculation of  
 198 the turbulence intensity, it is expected that the V-ADCP gives underestimated values of this metric.  
 199 Moreover, the shear stress,  $\overline{v'w'}$ , is characterised by very low absolute values. This is imputed to the

200 symmetric characteristic of the domain. The domain symmetry should imply that the  $\overline{u'v'}$  component  
 201 also satisfies this condition, which is not the case.

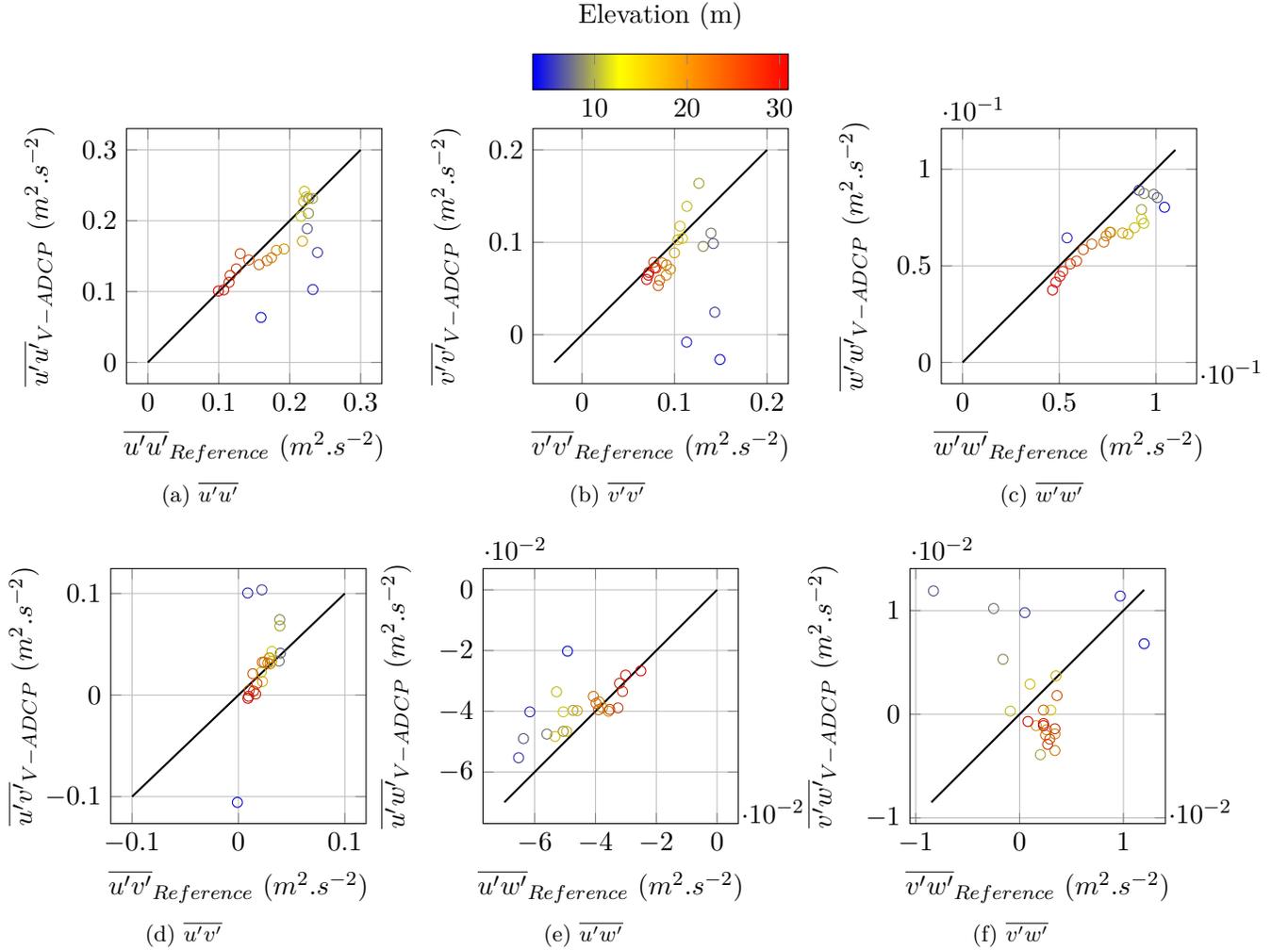


Figure 5: Comparison of the Reynolds stresses derived from V-ADCP and reference data. Each dot stands for a different elevation through the water column, between 3.3 m and 31 m, as shown by the colour bar.

202 Vertical profiles of the Reynolds stresses are shown in Figure 6. This figure exhibits a good agreement  
 203 between profiles derived from the reference dataset and V-ADCP. The absolute error is greater near the  
 204 seabed, which could result from spatial heterogeneity of the flow over a horizontal plane that invalidates  
 205 the homogeneity assumption. This assumption is necessary for the application of the method proposed  
 206 by [Vermeulen et al. (2011)] (Section 2.2). However, as demonstrated by [Nikuradse (1950); Perry et al.  
 207 (1969)], this assumption is true for elevations above 2 to 5 times the roughness height. Therefore, it may  
 208 not be valid in the lower part of the water column, which induces high error. This is consistent with the  
 209 high absolute error observed here up to 8 m above the seabed.

210 The maximum relative error (MaxError - Equation 4) and the root mean square error (RMSE -  
 211 Equation 5) between the Reynolds stresses derived from the reference dataset and the V-ADCP are shown  
 212 in Table 1. Only values calculated at a height above seabed higher than 8 m are taken into account. The  
 213 maximum RMSE is associated with the shear stress  $\overline{v'w'}$  with a value of 137 %. This high value is not  
 214 troublesome as the  $\overline{v'w'}$  component is centred on zero. The RMSE of the five other components of the  
 215 Reynolds stress tensor is relatively low, with values ranging from 8 % to 14 % and up to 33 % for  $\overline{u'v'}$ .

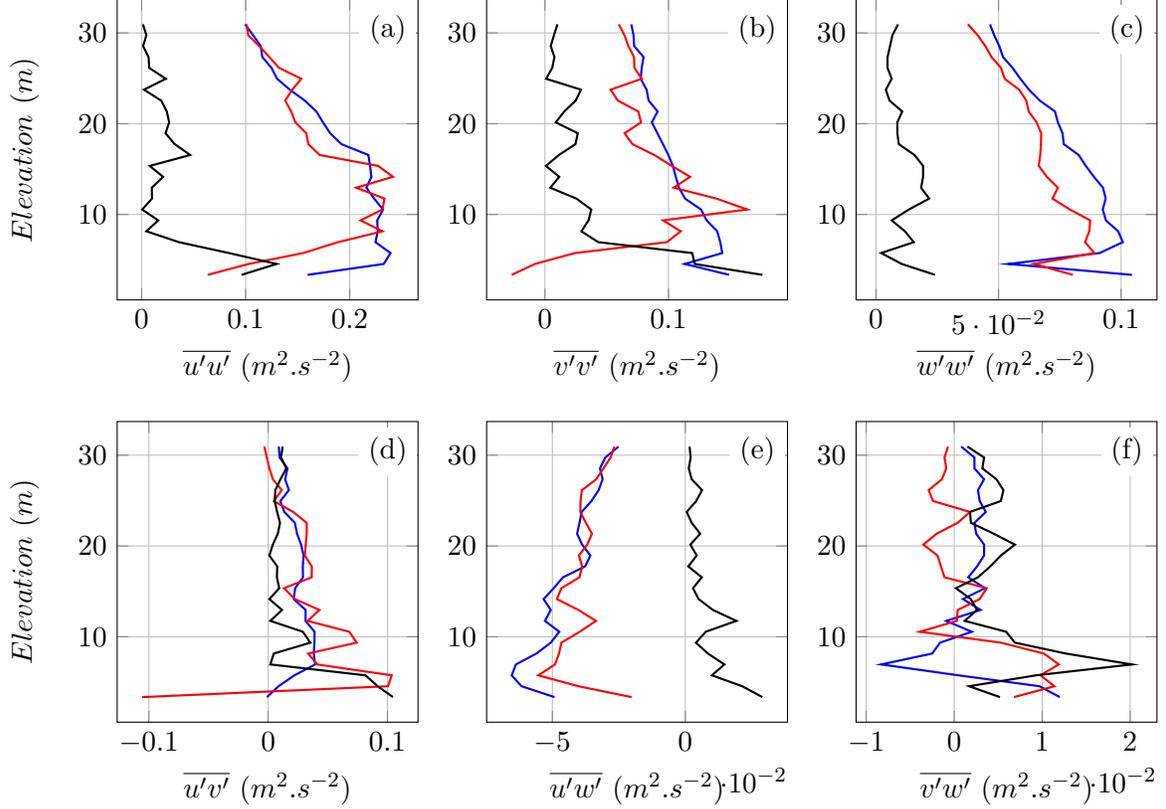


Figure 6: Vertical profiles of the Reynolds stresses derived from the reference dataset (blue —) and the V-ADCP (red —). Black profiles (—) denote the difference between the Reynolds stress estimation from both methods.

	$\overline{u'u'}$	$\overline{v'v'}$	$\overline{w'w'}$	$\overline{u'v'}$	$\overline{u'w'}$	$\overline{v'w'}$
Max relative error (%)	20	27	22	91	34	353
RMSE (%)	8	14	12	33	11	137

Table 1: Max and root mean square relative errors between reference and V-ADCP data for all components of the Reynolds stress tensor above 8 m elevation.

216 The maximum relative error varies over a wide range, with the three components,  $\overline{u'u'}$ ,  $\overline{v'v'}$  and  $\overline{w'w'}$   
 217 associated with maximum relative error lower than 27 % whereas the  $\overline{u'v'}$  and  $\overline{u'w'}$  components exhibit  
 218 maximum values of 91 % and 34 % respectively. The component,  $\overline{v'w'}$  reveals considerable maximum  
 219 error reaching 353 %, which is, once again, explained by the fact that the  $\overline{v'w'}$  component is centred on  
 220 zero.

$$\text{MaxError}(X) = 100 \frac{\max(|X_{ref} - X_{V-ADCP}|)}{\max(|X_{ref}|)} \quad (4)$$

$$\text{RMSE}(X) = 100 \frac{\sqrt{\int_{\Omega} \frac{(X_{ref} - X_{V-ADCP})^2}{L} d\omega}}{\max(|X_{ref}|)} \quad (5)$$

### 221 3.2. Assessment of turbulence homogeneity over the beams

222 The operating principle of the coupled 4-beam ADCP system requires the inherent assumption of  
 223 homogeneity in the flow within the sampled area. The reference dataset computed from the synthetic

224 flow field allows for the direct determination of the vertical evolution of the Reynolds stresses along each  
225 beam of the V-ADCPs (Figure 7). It is thus possible to perform a turbulence homogeneity test over the  
226 beams.

227 Figure 7 shows that, for a given component of the Reynolds stress tensor, the profiles derived from  
228 each V-ADCP beam have the same behaviour. Their magnitude increases abruptly up to an elevation  
229 of 8-10 m and decreases above 10 m up to the maximum elevation. The only component that confirms  
230 the turbulence homogeneity assumption throughout the water column is the normal stress  $\overline{w'w'}$ . For  
231 the components  $\overline{v'v'}$  and  $\overline{u'w'}$  the assumption is not valid for elevations higher than 15 m and 20 m,  
232 respectively. The normal stress,  $\overline{u'u'}$  reveals two ranges in elevation where the homogeneity assumption  
233 may be validated: (i) - from 0 to 8 m and, (ii) - from 20 to 38 m (the maximum elevation). Between  
234 both layers, the Reynolds stress profiles can be split into three groups of beams. The first group is  
235 composed of beams 1, 2, 5 and 7, where these beams are aligned with the flow direction. In this direction,  
236 the turbulence is homogeneous and rapidly advected. The second group is composed of beams 4, 6 and  
237 8, whose associated profiles exhibit similar behaviour. These beams share the same three-dimensional  
238 spanning area (Figure 4). Thus, as expected, these beams capture comparable turbulence processes.  
239 Beam 3 spans a different area and constitutes the last group. This decomposition in three groups is  
240 particularly noticeable for the component  $\overline{u'v'}$ , throughout the water column.

241 Figure 8a shows the vertical profiles of the Reynolds stresses derived from the reference dataset and  
242 averaged over the 8 beams. The profiles used to calculate and normalise the average gap between individual  
243 and spatially averaged beams are represented in Figure 8b. For  $\overline{u'u'}$ ,  $\overline{v'v'}$ ,  $\overline{w'w'}$  and  $\overline{u'w'}$  components, the  
244 discrepancies are high in the lower part of the water column (up to 10 m), low in the medium part of  
245 the water column and increase between 20 m and the maximum elevation. For  $\overline{u'v'}$  and  $\overline{v'w'}$  the same  
246 tendency is observed but with higher magnitudes. The origin of the discrepancies in the lower part of  
247 the water column can be explained by the presence of seabed roughness that is expected to affect the  
248 homogeneity of the flow up to 2 to 5 times its height (6 m to 15 m). Discrepancies observed in the upper  
249 part of the water column could be explained by increasing distance between V-ADCP beams, potentially  
250 reducing the validity of the assumption made on the horizontal homogeneity of the flow.

### 251 3.3. Effect of spatial averaging inside V-ADCP cells

252 Similarly to real ADCPs, the velocities derived from the V-ADCPs were averaged over each bin cell  
253 volume. This spatial averaging is expected to filter small eddies, thus affecting the evaluation of turbulence  
254 metrics. This filtering effect can be assessed through numerical simulation, because the full velocity vector  
255 is accessible at a high spatial resolution. In order to investigate the potential filtering-induced biases when  
256 characterising turbulence, the reference dataset, extracted from individual simulation nodes, are compared  
257 to the data averaged over each cell of the 7th beam of the V-ADCPs (Figure 9). This beam is oriented  
258 vertically upward and matches the position of the vertical reference profile. The vertical evolution of the  
259 Reynolds stresses derived from both the reference dataset and the V-ADCPs are similar. However, the  
260 V-ADCP data significantly and systematically underestimates the magnitude of the Reynolds stresses,  
261 especially for the normal stresses. This result is in agreement with the right-skewed distribution of the  
262 scatterplots associated with the normal stresses presented in Figure 5. For each component, the difference  
263 is more significant in the lower part of the water column and ranges from 10 % to 20 %.

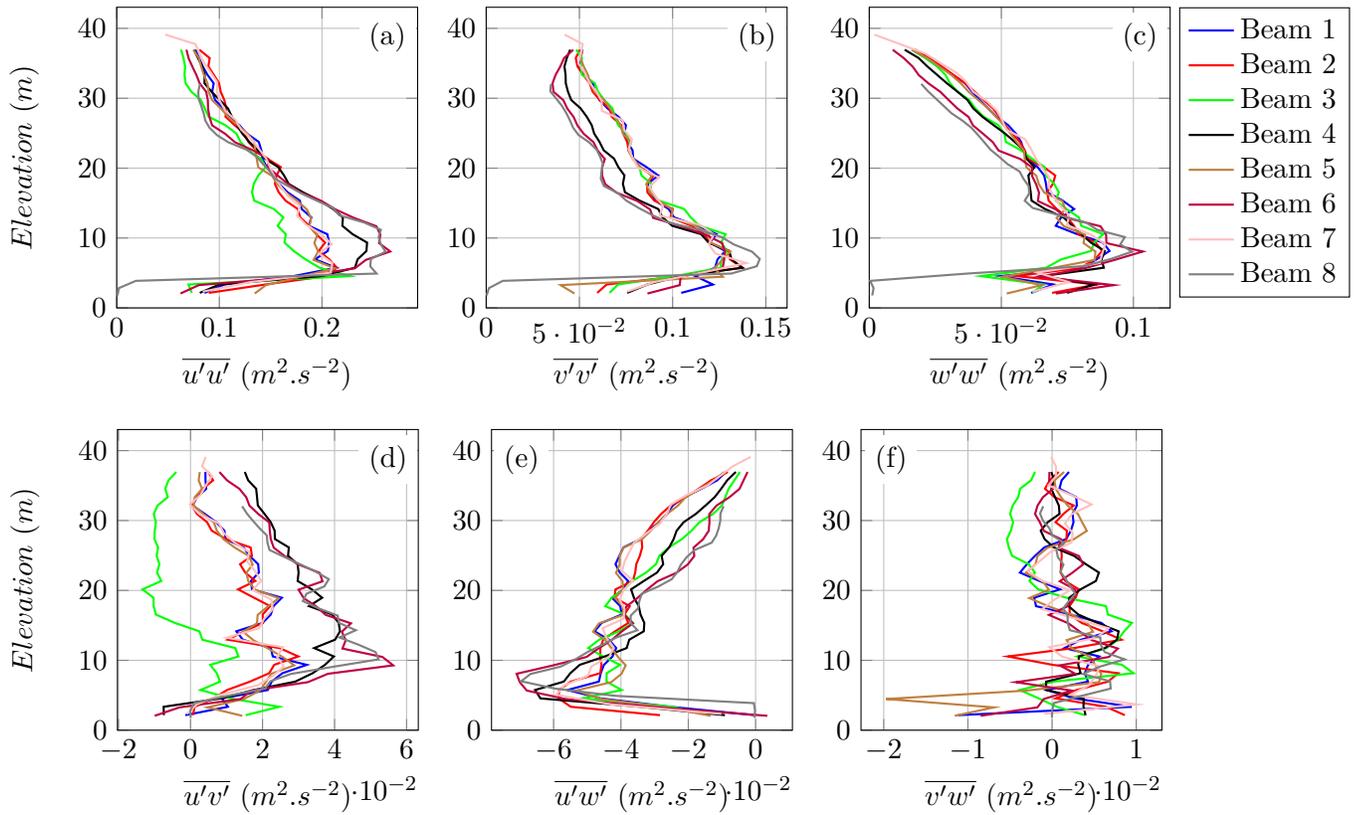


Figure 7: Vertical profiles of the Reynolds stresses derived from the reference dataset along each beam of the V-ADCP.

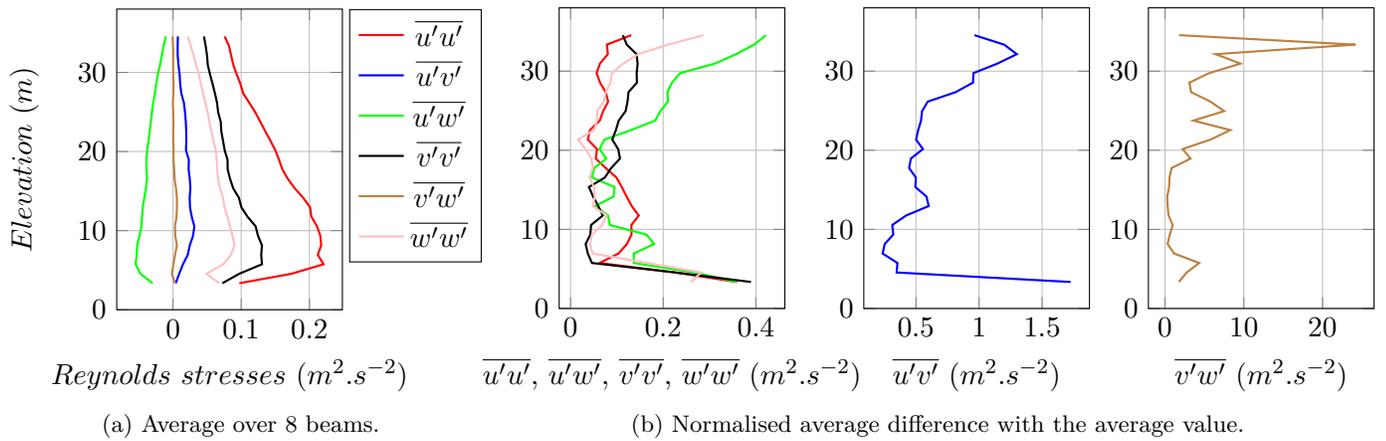


Figure 8: Evaluation of the dispersion of Reynolds stresses over the 8 V-ADCP beams.

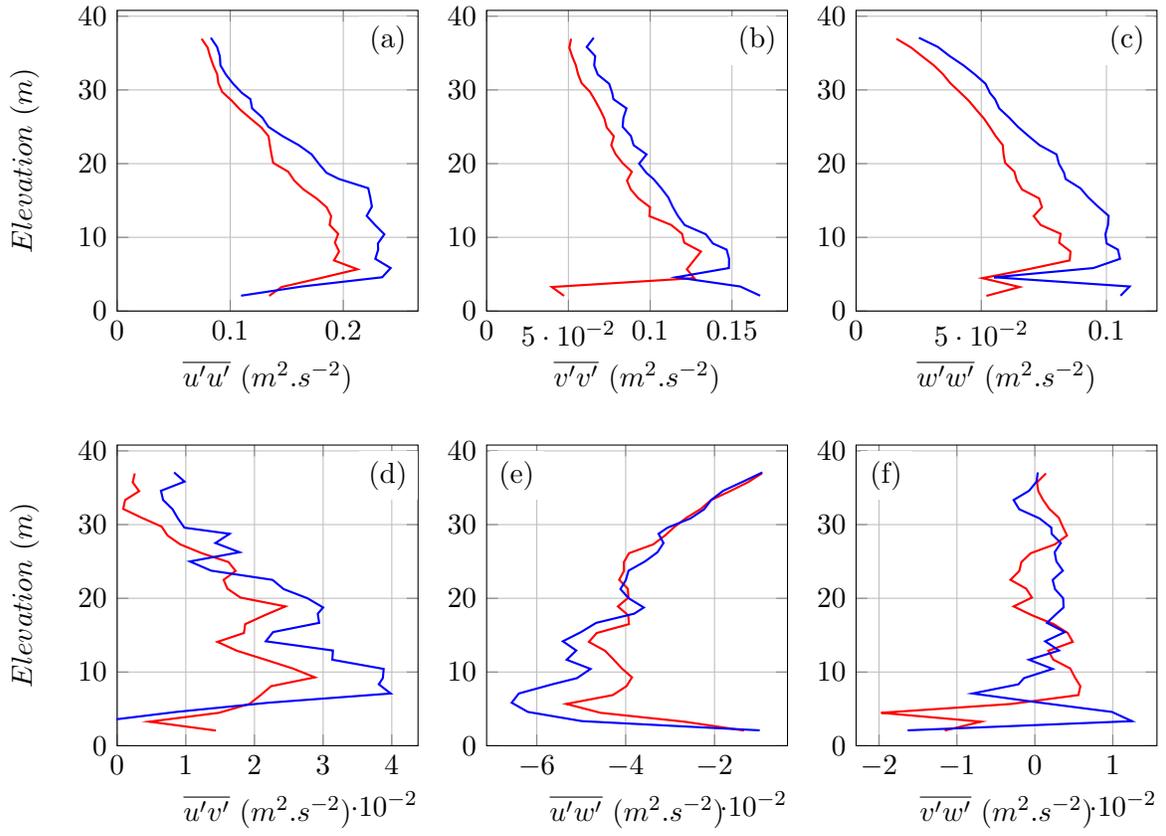


Figure 9: Comparison of the Reynolds stress calculated from beam number 7 (in red) and the reference dataset (in blue).

## 264 4. Conclusion

265 In this study, the ability of a coupled 4-beam ADCP system to characterise the six components of the  
266 Reynolds stress tensor is assessed. LES of high Reynolds flow over a rough bed is performed in order to  
267 build a reference synthetic dataset used to directly estimate the Reynolds stresses. The coupled ADCP  
268 system (V-ADCP) is assumed to be located on the seabed measuring the along-beam velocities of the  
269 synthetic flow [Vermeulen et al. (2011)]. The Reynolds stresses derived from the V-ADCPs are estimated  
270 following the methodology proposed by [Thiébaud et al. (2020c,b)].

271 Comparison between Reynolds stresses derived from both the reference dataset and the V-ADCPs are  
272 generally in good agreement. The flow heterogeneity over the ADCP beams and the spatial averaging over  
273 ADCP cells are found to be the two main sources of error in the interpretation of ADCP measurements.

274 Flow heterogeneity is observed in the lower part of the water column, where the seabed roughness  
275 wakes have a local influence on the turbulence metrics. It is significant up to twice the roughness height  
276 (6 m). This leads to high discrepancies between V-ADCP and reference results. As a consequence, ADCP  
277 measurements should be interpreted with caution near the seabed in the case of a high seabed roughness.

278 Flow heterogeneity is also observed in the upper part of the water column, where the distance be-  
279 tween beams increases. The heterogeneity is observed in the lateral direction and not in the longitudinal  
280 direction. Indeed, the transport of turbulence characteristics in the longitudinal direction is expected to  
281 be faster than its diffusion in the lateral direction, resulting in a higher homogeneity in the longitudinal  
282 direction than in the lateral direction. However, this heterogeneity is expected to have a minor effect  
283 on the accuracy of the measurements, since Reynolds stresses derived from the reference dataset and the  
284 V-ADCPs are found to be consistent.

285 The spatial averaging over the cells in the numerical model is found to underestimate the Reynolds  
286 stresses by 10 % to 20 %, in particular the normal components which are used to estimate the turbulence  
287 intensity. The spatial averaging is performed to simulate the working principle of a real ADCP. However,  
288 for this type of sensor, the averaging is not uniform over the cells. Instead, the cells are most sensitive  
289 to velocities at their centre and least sensitive at the edges. The velocity in each depth cell is a weighted  
290 average using a triangular weighting function. This is not considered in the present study.

291 These insights could help reducing uncertainties and systematic bias of *in situ* measurements and thus  
292 improve the knowledge about environmental flows. This improvement would benefit turbine manufactur-  
293 ers in the optimisation of turbine design.

294 This work is based on a unique simulation configuration characterised by its flow velocity, size and  
295 spacing of roughness and water column height. These conditions are representative of flows at typical  
296 tidal energy sites, where the general conclusions of this work would apply. Nevertheless, it is expected  
297 that different types of flow would potentially lead to different conclusions.

298 Real seabed morphology is diversified, as well as environmental flow characteristics. The flow obtained  
299 in this study from an idealised seabed roughness cannot be assumed to be representative of all environ-  
300 mental flows. Thus, the conclusions of the present work must be put into perspective with the actual  
301 seabed and hydrodynamic conditions of any other specific studied site.

302 V-ADCPs do not take all biases into account. Numerical simulations are an idealised environment that  
303 do not include physical processes leading to the acquisition of data outliers. The conclusions proposed  
304 here, give insight for quantifying some sources of error but do not exonerate from usual corrections and  
305 uncertainties applied in ADCP measurements such as the bias in turbulence measurements induced by  
306 the Doppler noise.

307 For future work, new simulations could be conducted, using different seabed geometries, water depth  
308 and averaged velocity magnitudes. This would help in understanding the effect of these parameters on  
309 the accuracy of the tested ADCP configuration and provide more insight into the interpretation of real  
310 ADCP measurements. V-ADCPs could be implemented with more detailed numerical models to take

311 into account physical phenomena that are neglected in this study (such as spatial averaging over an  
312 ADCP cell). This would improve the fidelity of V-ADCP data acquisition with respect to real ADCPs  
313 and reinforce the relevance of the conclusions and prescriptions obtained from V-ADCP analysis. Also,  
314 the V-ADCP method could be used, not only for turbulence measurements, but also for average velocity  
315 measurements. In particular, it could be used to assess the potential improvement brought by ADCPs  
316 based on higher acquisition frequencies. Finally, the simulation of realistic environmental flows combined  
317 with the V-ADCP method could help testing new ADCP beam configurations. The sensitivity of the  
318 measurements to the number of beams, beam orientations, cell thickness or acquisition frequency could  
319 be assessed to optimise these parameters for measurements performed in specific environments.

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