

Turbulence Measurements from Compliant Moorings - Part II: Motion

Correction

Levi F. Kilcher*

National Renewable Energy Laboratory, Golden, Colorado, USA

Jim Thomson

Applied Physics Laboratory, University of Washington, Seattle, Washington, USA

Samuel Harding

Pacific Northwest National Laboratory, Richland, Washington, USA

Sven Nylund

Nortek AS, Norway

* *Corresponding author address:* Levi Kilcher, National Renewable Energy Laboratory, 15013 Denver West Pkwy, Golden, Colorado, USA

E-mail: Levi.Kilcher@nrel.gov

ABSTRACT

14 Acoustic Doppler velocimeters (ADV) are a valuable tool for making
15 high-precision measurements of turbulence, and moorings are a convenient
16 and ubiquitous platform for making many kinds of measurements in the
17 ocean. However, because of concerns that mooring motion can contami-
18 nate turbulence measurements and acoustic Doppler profilers are relatively
19 easy to deploy, ADVs are not frequently deployed from moorings. This
20 work demonstrates that inertial motion measurements can be used to reduce
21 motion-contamination from moored ADV velocity measurements. Three dis-
22 tinct mooring platforms were deployed in a tidal channel with inertial-motion-
23 sensor-equipped ADVs. In each case, the motion correction based on the in-
24 ertial measurements dramatically reduced contamination from mooring mo-
25 tion. The spectra from these measurements have a shape that is consistent
26 with other measurements in tidal channels, and have a $f^{-5/3}$ slope at high
27 frequencies—consistent with Kolmogorov’s theory of isotropic turbulence.
28 Motion correction also improves estimates of cross spectra and Reynold’s
29 stresses. Comparison of turbulence dissipation with flow speed and turbu-
30 lence production indicates a bottom boundary layer production-dissipation
31 balance during ebb and flood that is consistent with the strong tidal forcing
32 at the site. These results indicate that inertial-motion-sensor-equipped ADVs
33 are a valuable new tool for measuring turbulence from moorings.

34 1. Introduction

35 Acoustic Doppler velocimeters (ADV) have been used to make high-precision
36 measurements of water velocity for over 20 years (Kraus et al. 1994; Lohrmann
37 et al. 1995). During that time, they have been deployed around the world to
38 measure turbulence from a range of platforms, including the laboratory setting
39 (Voulgaris and Trowbridge 1998), from stationary structures on ocean-, river- and lake-bottoms
40 (Kim et al. 2000; Lorke 2007; Cartwright et al. 2009), in surface waters from a pole lowered from
41 a ship's bow (Geyer et al. 2008), and in the deep ocean from autonomous underwater vehicles
42 ~~(e.g., Voulgaris and Trowbridge 1998; Zhang et al. 2001; Kim et al. 2000; Goodman et al. 2006; Lorke 2007)~~

43 A relatively small fraction of ADV measurements have been made from moorings (e.g., Fer
44 and Paskyabi 2014). Presumably this is because mooring motion can contaminate ADV mea-
45 surements, and acoustic Doppler profilers (ADPs) can be used to measure mid-depth turbulence
46 statistics without a mooring (e.g., Stacey et al. 1999a; Rippeth et al. 2002; Wiles et al. 2006).
47 Still, ADV measurements have distinct characteristics that can be advantageous: they are capa-
48 ble of higher sample rates, have higher signal-to-noise ratios, and have a much smaller sample
49 volume (1 centimeter, as opposed to several meters). That is, compared to an ADP, ADVs are
50 high-precision instruments capable of providing unique information. They could be more widely
51 used as a moored instrument (i.e., at an arbitrary depth) if a method for accounting for mooring
52 motion can be demonstrated to provide more accurate estimates of turbulence statistics.

53 Inertial motion unit (IMU) sensors have been used in the aerospace and aeronautical indus-
54 tries to quantify the motion of a wide range of systems, and to improve atmospheric velocity
55 measurements, for several decades (Axford 1968; Edson et al. 1998; Bevly 2004). Over the last
56 10 years, the smartphone, drone, and ‘Internet of Things’ markets ~~has~~ have driven innovation in

57 microelectrical-mechanical systems, including the IMU. As a result of this growth and innovation,
58 the cost, power requirements, and size of IMUs have come down. These changes have allowed
59 these sensors to be integrated into oceanographic instruments that have small form-factors, and
60 rely on battery power.

61 Nortek now offers a version of their Vector ADV with a Microstrain 3DM-GX3-25 IMU sensor
62 (Nortek 2005; MicroStrain 2012). This IMU's signals are incorporated into the Vector data stream,
63 so that its motion and orientation signals are tightly synchronized with the ADV's velocity mea-
64 surements. This tight synchronization provides a data stream that can be utilized to quantify ADV
65 motion in the Earth's inertial reference frame, and remove that motion from the ADV's velocity
66 measurements at each time step of its sampling (Edson et al. 1998). This work utilizes moored
67 'ADV-IMU' measurements from mid-depths in Puget Sound to demonstrate that motion correc-
68 tion can improve the accuracy of oceanic turbulence spectra, turbulence dissipation, and Reynolds
69 stress estimates from moored platforms.

70 This effort was originally motivated by a need for low-cost, high-precision turbulence measure-
71 ments for the emerging tidal energy industry (McCaffrey et al. 2015; Alexander and Hamlington
72 2015). Experience in the wind energy industry has shown that wind turbine lifetime is reduced by
73 atmospheric turbulence, and the same is expected to be true for tidal energy turbines. In ~~wind~~the
74 atmosphere, meteorological towers are often used to position sonic anemometers at the hub height
75 of wind turbines for measuring detailed turbulence inflow statistics (Hand et al. 2003; Kelley et al.
76 2005; Mücke et al. 2011; Afgan et al. 2013). In the ocean, tower-mounted hub-height turbulence
77 measurements have been made, but they are challenging to install and maintain in energetic tidal
78 sites (Gunawan et al. 2014; Thomson et al. 2012). Therefore, the U.S. Department of Energy
79 funded this work to investigate the accuracy of mooring-deployed ADV-IMUs to reduce the cost
80 of turbulence measurements at tidal energy sites (Kilcher et al. 2016). The approach proved to be

81 successful and potentially useful to the broader oceanographic community interested in moored
82 turbulence measurements (Lueck and Huang 1999; Doherty et al. 1999; Nash et al. 2004; Moum
83 and Nash 2009; Alford 2010; Paskyabi and Fer 2013).

84 The next section describes details of the measurements, including a summary of the hardware
85 configurations (platforms) that were used to support and position the ADV-IMUs in the water
86 column. A detailed description of the motion of these platforms is found in the companion paper to
87 this work, Harding et al. (in review), hereafter Part 1. Section 3 describes the mathematical details
88 of motion correction and Section 4 presents results from applying the method to measurements
89 from the various platforms. Section 5 is a discussion of the energetics of the tidal channel in
90 which the measurements were made and demonstrates that the measurements are consistent with
91 turbulence theory and other measurements in similar regimes. A summary and concluding remarks
92 are provided in Section 6.

93 **2. Measurements**

94 This work focuses on measuring turbulence from ADVs that are equipped with IMUs and de-
95 ployed from moving (moored) platforms. The ADVs utilized for these measurements were Nortek
96 Vector ADVs equipped with Microstrain 3DM-GX3-25 IMU sensors. These IMUs captured all
97 six components of the ADV motion (three components of angular rotation and three components
98 of linear acceleration), as well as the orientation of the ADV pressure case. The sampling of the
99 motion sensor is tightly synchronized with the ADV measurements. The IMU measures its mo-
100 tion at 1 kHz and uses internal signal integration (Kalman filtering) to output the motion signals
101 at the same sample rate as the ADV's velocity measurements. This reduces aliasing of the IMU's
102 motion measurements above the ADV's sample rate (MicroStrain 2010). Cable-head ADVs were

103 used throughout this work to allow for flexibility in the positioning of the ADV head relative to its
104 pressure case.

105 All measurements used in this work were made in Admiralty Inlet, Washington, approximately
106 500 m west southwest of Admiralty Head in ~~60-m~~ 60 m of water near 48° 9.18' N, 122° 41.22'
107 W (Figure 1). The site is approximately 6 km east of Port Townsend, and 1 km north of the Port
108 Townsend to Coupeville ferry route. Admiralty inlet is the largest waterway connecting Puget
109 Sound to the Strait of Juan de Fuca, and it possesses a large semidiurnal tidal flow (Thomson
110 et al. 2012; Polagye and Thomson 2013). This work utilizes data from three distinct deployment
111 platforms: the tidal turbulence mooring, a StableMoor buoy, and a simple sounding weight. All
112 data used in this analysis ~~is~~ are available from the MHK data repository (<http://mhkdr.openet.org>;
113 submission ids: 49, 50 and 51). Each of these platforms are briefly described below, and additional
114 details, photos, and schematic diagrams can be found in Part 1.

115 *a. Tidal Turbulence Mooring*

116 The tidal turbulence mooring (TTM) is a simple mooring system with a strongback fin sus-
117 pended between a steel clump-weight anchor weighing 1,200 kg when dry and a 0.93-m-diameter
118 spherical steel buoy with a buoyancy of 320 kg. The ADV pressure cases were clamped to one
119 side of the strongback fin and the ADV sensor head was positioned 10 cm in front of the fin's
120 leading edge (Figure 2). The leading edge of the fin is fastened inline with the mooring line. This
121 configuration was designed to work like a weather vane, such that the drag on the fin held the ADV
122 head upstream of the mooring components. This work utilizes data from two TTM deployments.

123 1) ~~JUNE 2012 TTM DEPLOYMENT~~

124 The first TTM deployment was in June 2012 from 17:30 on the 12th until 14:30 on the 14th
125 (local; i.e., Pacific Daylight Time). Two Nortek ADVs were clamped to either side of the fin so that
126 the axis of their cylindrical pressure cases were parallel with the leading edge of the strongback.
127 The ADV heads were spaced 0.5 m apart vertically along the fin. Only one of these ADVs was
128 equipped with an integrated IMU. This TTM also had an upward-looking acoustic Doppler profiler
129 mounted on the mooring anchor.

130 Periods of time during which this mooring interfered with a beam of the Doppler profiler were
131 identified by inspecting the profiler's acoustic amplitude signal. Periods during which one beam
132 of the profiler had $> 5\%$ higher acoustic amplitude than the other beams were flagged as "contam-
133 inated" and excluded from averaging. Five-minute averages in which more than 50% of the data
134 were contaminated in this way were masked as invalid.

135 1) ~~JUNE 2014 TTM DEPLOYMENT~~

136 The second TTM deployment was in 2014 from 06:00 on June 17 to 05:00 on June 19 (local
137 time). Two Nortek ADV-IMUs were mounted on this TTM, with their heads spaced 0.5 m apart
138 along the fin. In this case, the pressure cases and ADV heads were inclined at an angle of 18° to
139 the leading edge of the fin to account for mooring blowdown during strong currents (Figure 3).
140 This change was made to reduce vibrational motion observed during the June 2012 deployment
141 that was believed to be associated with the orientation of the pressure cases.

142 *b. The StableMoor platform*

143 The second deployment platform was a cylindrical, StableMoor, syntactic foam buoy (manufac-
144 turer: Deep Water Buoyancy) that was anchored to a clump weight that weighed ~~2,700 lbs~~ 1,200

145 kg (Figure 4). The buoy is 3.5 m long and 0.45 m in diameter with a tail ring that is 0.76 m in
146 diameter. The StableMoor buoy weighs 295 kg in air, and has a buoyancy of 185 kg in water.

147 The StableMoor buoy was deployed with an ADV-IMU mounted at its nose from 11:21 on May
148 12 to 11:53 on May 13, 2015 (local time). The sample volume of the ADV is 10 cm forward of
149 the nose and 20 cm above the center line of the StableMoor buoy (Figure 4). Based on Wyngaard
150 et al.'s (1985) investigation of a similarly shaped slender body, the velocity measurements should
151 have flow-distortion effects of less than 10%. This configuration was designed to be the most
152 stable platform for measuring turbulence from a moving platform. The StableMoor buoy was
153 equipped with a 1,200-kHz RDI workhorse sentinel acoustic Doppler profiler that was oriented
154 downward-looking to measure water velocity below the platform in twelve 1-m bins and measure
155 buoy motion ("bottom tracking"), all at a 1-Hz sample rate.

156 The buoy was ballasted to pitch upward a few degrees in zero-flow to avoid "flying downward."
157 In the presence of an oncoming current, the tail fins help to orient it into the flow. The anchor
158 for this buoy is similar to that of the TTM, including an acoustic release so the mooring and anchor
159 can be recovered separately.

160 The StableMoor platform has two primary advantages compared to the TTM. First, it is signif-
161 icantly more massive and hydrodynamically stable than the TTM, which reduces the frequency
162 of motions of the platform. Second, the StableMoor platform is capable of supporting a bottom-
163 tracking acoustic Doppler profiler, which provides an independent measure of the platform's trans-
164 lational motion. Disadvantages of the StableMoor include: its size, which adds to the challenge of
165 deployment and recovery, and its cost, which is significantly higher than the TTM system.

166 *c. Turbulence Torpedo*

167 The turbulence torpedo is a simple sounding weight with an ADV head mounted forward of the
 168 nose, and the ADV pressure case strapped below (Figure 5). This platform was deployed on May
 169 14, 2015, for 37 minutes starting at 07:41 local time. This measurement was made from a davit
 170 that hung the system from the side of the ship to a depth of approximately 25 m. The primary
 171 logistical advantages of this platform are its compact size, low cost, and the flexibility to perform
 172 spatial transects.

173 *d. Coordinate system and turbulence averaging*

174 Unless stated otherwise, vector quantities in this work are in a fixed “principal-axes” coordinate
 175 system that is aligned with the bidirectional tidal flow: positive u is in the direction of ebb (310°
 176 True), positive w is vertically upward, and v is the cross-stream component in a right-handed
 177 coordinate system. The full velocity vector, $\vec{u} = (\tilde{u}, \tilde{v}, \tilde{w})$, is separated into a mean and turbulent
 178 component as $\vec{u} = \bar{\vec{u}} + \vec{u}$, where the over-bar denotes a 5-minute average. Turbulence kinetic
 179 energy, $\text{tke} = \overline{u^2} + \overline{v^2} + \overline{w^2}$, and Reynold’s stresses, \overline{uv} , \overline{uw} , \overline{vw} , are computed by averaging over the
 180 5-minute window. Throughout this work, we use $\bar{U} = (\bar{u}^2 + \bar{v}^2)^{1/2}$ to denote the mean horizontal
 181 velocity magnitude.

182 All spectra, $S\{x\}(f) = |\mathcal{F}\{x(t)\}|^2$, and cross spectra, $C\{x, y\}(f) = \text{real}(\mathcal{F}\{x(t)\}\mathcal{F}\{y(t)\})$, are
 183 computed using NumPy fast Fourier transform routines (van der Walt et al. 2011). Here, $\mathcal{F}\{x(t)\}$
 184 denotes the fast Fourier transform of a signal $x(t)$. Time series, e.g., $x(t)$, are linearly detrended
 185 and Hanning windowed prior to computing $\mathcal{F}\{x\}$ to reduce spectral reddening.

186 Throughout the remainder of this work, the dependence of S and C on f is implied (e.g., $S\{x\}(f)$
 187 is hereafter $S\{x\}$), and for other variables the dependence on t is implied. Spectra and cross
 188 spectra are normalized to preserve variance: $\int S\{u\}df = \overline{u^2}$, and $\int C\{u, v\}df = \overline{uv}$. The notations

189 $S\{\vec{u}\} = (S\{u\}, S\{v\}, S\{w\})$, and $C\{\vec{u}\} = (C\{u, v\}, C\{u, w\}, C\{v, w\})$ denote the set of spectra and
 190 cross spectra for each velocity component and pairs of components, respectively.

191 Turbulence dissipation rates are computed as:

$$\varepsilon = \frac{1}{\bar{U}} \left(\alpha \left\langle (S\{u\} + S\{v\} + S\{w\}) f^{5/3} \right\rangle_{f_{IS}} \right)^{3/2} \quad (1)$$

192 ~~Where~~ where $\alpha = 0.5$ ~~;~~ and $\langle \rangle_{f_{IS}}$ denotes an average over the inertial subrange of the velocity
 193 spectra and where the signal-to-noise ratio is small (Lumley and Terray 1983; Sreenivasan 1995).
 194 Throughout this work, we take this average from 0.3 to 1 Hz for the u and v components, and 0.3
 195 to 3 Hz for the w component.

196 3. Methodology

197 The ~~essential approach of motion correction is to measure velocity on a moving platform and~~
 198 ~~make an independent measurement of the platform motion, then subtract~~ fundamental approach
 199 of this methodology is to take velocity measurements from a moving velocity sensor, \vec{u}_m , and use
 200 independent measurements of that sensor's motion, \vec{u}_h , to remove the motion from the velocity
 201 measurements and thus estimate the 'motion corrected velocity':

$$\vec{u}(t) = \vec{u}_m(t) + \vec{u}_h(t) \quad (2)$$

202 Note here that the '+'-sign is correct because head motion, \vec{u}_h , induces a measured velocity in
 203 the opposite direction of the head motion itself ($\vec{u}_m = \vec{u} - \vec{u}_h$). This approach has been used to
 204 successfully correct sonic anemometer measurements of atmospheric turbulence (e.g., Edson et al.
 205 1998; Miller et al. 2008). In the ocean, previous works have utilized inertial motion sensors
 206 to quantify the motion of multiscale profilers for the purpose of measuring the full spectrum of
 207 oceanic shear (Winkel et al. 1996).

208 ~~Nortek's ADV-IMU~~ The Microstrain IMU available in the Nortek Vector ADV measures the
 209 linear acceleration, \vec{a} , rotational motion, $\vec{\omega}$, and orientation matrix, \mathbf{R} , of the ADV pressure case
 210 (body) in the Earth reference frame. ~~The Microstrain IMU integrated into the Nortek Vector ADV~~
 211 ~~has been configured to provide estimates of the ADV's orientation and motion~~ at every time step of
 212 the ADV's sampling ~~(the time synchronization is $\mathcal{O}(10^{-2})$ s)~~. So long as the ADV head is rigidly
 213 connected to the IMU (i.e. the ADV pressure case), the motion of the ADV head is calculated
 214 from these signals as the sum of rotational and translational motion:

$$\begin{aligned}\vec{u}_h &= \vec{u}_\omega + \vec{u}_a + \vec{u}_{\text{low}} \\ &= \mathbf{R}^T \cdot \vec{\omega}^*(t) \times \vec{\ell}^* + \int \{\vec{a}(t)\}_{HP(f_a)} dt + \vec{u}_{\text{low}}\end{aligned}\quad (3)$$

215 Here, * superscripts denote quantities in the ADV's local coordinate system, and $\vec{\ell}^*$ is the vec-
 216 tor from the IMU to the ADV head. \mathbf{R}^T —the inverse of the orientation matrix—rotates vectors
 217 from the IMU to the Earth reference frame. The notation $\{\vec{a}\}_{HP(f_a)}$ indicates that the IMU's
 218 accelerometer signal is high-pass filtered (in the Earth's stationary reference frame) at a chosen
 219 ~~filter frequency~~ filter frequency, f_a . ~~This is necessary because accelerometers have~~ Without such
 220 filtering, low-frequency noise ~~, sometimes in \vec{a} —sometimes~~ referred to as ~~bias-drift~~ bias drift—is
 221 amplified by integration to the point that it overwhelms the higher frequency information (Bar-
 222 shan and Durrant-Whyte 1995; Bevly 2004; Gulmammadov 2009). \vec{u}_{low} is the low-frequency
 223 translational motion that is unresolved by \vec{u}_a , and it is discussed in more detail below. Note that,
 224 to avoid double counting, \vec{u}_{low} should be estimated by applying the complementary low-pass filter
 225 to the independent measurement of low-frequency motion. We use fourth order, bidirectional
 226 (zero-phase), Hanning filters for all filtering operations.

227 ~~Integrating \vec{a} to estimate~~

228 The spectra of \vec{u}_a ~~amplifies the bias-drift noise at low frequencies, which dramatically reduces~~
 229 ~~the signal-to-noise ratio at those time scales (Figure ??)~~ and \vec{u}_ω from an ADV-IMU resting

230 motionless on a table are instructive in understanding the importance of filtering (Figure 6).
 231 Because the IMU is stationary, these spectra indicate the noise levels of each signal. The noise
 232 level of $S\{\vec{u}_\omega\}$ (yellow) is several orders of magnitude lower than the velocity spectra we measured
 233 (grey region), and also more than an order of magnitude smaller than the Doppler noise levels of
 234 the ADV. Here we have used $\vec{\ell}^* = 1$ m; which is the order-of-magnitude of the typical distance
 235 between the ADV head and the IMU. This indicates that the precision of \vec{u}_ω (i.e. the angular rate
 236 sensor) is adequate for making corrections to ADV velocity measurements without filtering.

237 The noise level of $S\{\vec{u}_a\}$ (Figure 6, black), on the other hand, is dominated by a f^{-2} slope that
 238 results from integrating the low-frequency noise in \vec{a} . The high-pass filtering reduces this noise so
 239 that it does not contaminate motion correction, but any real motion that ~~exists~~ does exist at these
 240 frequencies is ~~still lost in the low signal-to-noise ratio~~ lost (Egeland 2014; VanZwieten et al. 2015).
 241 This means ~~that low-frequency motion is not well resolved by the IMU, and so~~ there is a residual
 242 low-frequency translational motion, \vec{u}_{low} , that needs to be measured independently—or at the very
 243 least considered—when using ~~motion-corrected~~ ADV-IMU data. ~~The $\vec{\omega}$ and \vec{u}_ω estimates do not~~
 244 ~~have the same issue because there is no integration involved, from moving platforms.~~

245 For the StableMoor buoy, the ADP bottom-track agrees with \vec{u}_a over a narrow frequency band
 246 (see appendix A1), indicating that the ADP and IMU are resolving the same motion. Furthermore,
 247 \vec{u}_{low} derived from the ADP bottom-track gives a noteworthy improvement in the shape of $S\{u\}$ and
 248 $S\{v\}$ when compared to similar spectra that assume $\vec{u}_{\text{low}} = 0$. In the latter case, spectral peaks and
 249 dips are present between 0.01 and ~~because low-frequency bias-drift in the $\vec{\omega}$ sensors is stabilized by~~
 250 ~~the IMU's on-board Kalman filtering (i. e., the accelerometer and magnetometer signals provide~~
 251 ~~estimates of down and north, respectively, which stabilize orientation estimates and eliminates~~
 252 ~~bias from rotation estimates).~~ 0.1 Hz that are inconsistent with other measurements of oceanic
 253 turbulence (not shown). This indicates that ADP bottom-track measurements are important for

resolving turbulence spectra from the StableMoor buoy platform. For the StableMoor buoy we utilize $f_a = 0.2\text{Hz}$ (5-s period); further details of this choice can be found in appendix A1.

For the TTM the ADV position, relative to its base, can be estimated by assuming the mooring acts like a rigid pole and using the IMU orientation matrix to estimate the pole's 'lean'. The position obtained from this model can then be differentiated to estimate \vec{u}_{low} (this model does not apply at high frequencies). Spectra of \vec{u}_{low} estimated using this approach for the June 2014 TTM deployment (Figure 6, blue) are plotted up to the point where they cross their respective $S\{\vec{u}_a\}$ noise level (black). Together, these two lines provide an 'aggregate noise level' of translational velocity estimates for the TTM: the rigid pole estimate of \vec{u}_{low} indicates the amplitude of unresolved motion at low- f (blue), and $S\{\vec{u}_a\}$ indicates the limits of the IMU at high- f (black). Coincidentally, $S\{\vec{u}_a\}$ filtered at $f_a = 0.0333\text{Hz}$ is not a terrible approximation for this aggregate noise level. Furthermore, because this aggregate noise level is more than an order of magnitude lower than the velocity spectra of interest (shaded region), the results of motion correction are essentially identical whether we use the rigid pole model to estimate \vec{u}_{low} , or if we simply assume that $\vec{u}_{\text{low}} = 0$. Either way, we use $f_a = 0.0333\text{Hz}$ (30-s period) for the TTM.

The choice of ~~a high-pass filter~~ f_a for reducing low-frequency accelerometer noise depends on the ~~flow conditions~~ ~~application~~ of the measurement and the platform being used. In particular, filter selection involves a trade-off between filtering out the ~~bias-drift~~ ~~bias drift~~ noise while not filtering out measured motion that is unresolved by an independent measurement of \vec{u}_{low} . **Note that, to avoid double-counting, \vec{u}_{low} should be estimated by applying the complementary low-pass filter to the independent measurement of low-frequency motion.**

With this estimate of ADV head motion, it is straightforward to correct the measured velocity,

\vec{u}_m , to estimate the velocity in the Earth's inertial reference frame:

$$\vec{u}(t) = \vec{u}_m(t) + \vec{u}_h(t).$$

Note here that the '+' sign is correct because head motion, \vec{u}_h , induces a measured velocity in the opposite direction of the head motion itself ($\vec{u}_m = \vec{u} - \vec{u}_h$).

For the TTM and turbulence torpedo, we utilize $f_a = 0.0333\text{Hz}$ (30-s period) and assume that $\vec{u}_{low} = 0$. For the StableMoor buoy, $f_a = 0.2\text{Hz}$ (5-s period). The bottom-track velocity was low-pass filtered at this frequency to provide an estimate of \vec{u}_{low} , and \vec{a} was high-pass filtered at this frequency. We use 4-pole, bidirectional (zero-phase), Hanning filters for all filtering operations.

Spectra of \vec{u}_w (yellow) and \vec{u}_a signals from the Microstrain IMU sitting on a motionless table. The \vec{u}_a signals are unfiltered (black), and high-pass filtered at 30 s (magenta), 10 s (blue), 5 s (green). Vertical dotted lines indicate the filter frequency. The black horizontal dotted line indicates the noise level of a Nortek Vector ADV configured to measure $\pm 4\text{m/s}$. The shaded region indicates the range of spectra presented herein ($0.002 < \text{tke} < 0.03 \text{ m}^2/\text{s}^2$, $1\text{e-}5 < \epsilon < 5\text{e-}4 \text{ W/kg}$).

Additional details on motion correction—including a detailed accounting of the distinct coordinate systems of the IMU, ADV pressure case, and ADV head—can be found in Kilcher et al. (2016). Open-source Python tools for performing motion correction of ADV-IMU data—including scripts that write processed data in Matlab and tabulated formats—are available at <http://lkilcher.github.io/dolfyn/>.

4. Results

a. Mean velocity

Figure 7 shows a comparison of \vec{u} measured by an ADV-IMU mounted on a TTM, to an upward-looking acoustic Doppler profiler mounted on the TTM anchor. This comparison shows excellent agreement between the ADV and Doppler profiler measurements of mean velocity. The \bar{u} , \bar{v} , and \bar{w} components have a root-mean-square error of 0.05, 0.13, and 0.03 m/s, respectively. Although it is important to note that there is some discrepancy between ADP- and ADV-measured velocities (especially in \bar{v} , which is most likely due to incomplete motion correction), the agreement between the magnitude and direction of these independent velocity measurements indicates that moored ADV-IMUs provide a reliable estimate of mean velocity in the Earth’s reference frame.

b. TTM spectra

As discussed in detail in Part 1, the mooring motion of the TTM, $S\{\vec{u}_h\}$, has a peak at 0.1 to 0.2 Hz from swaying of the mooring that is most likely driven by eddy shedding from the spherical buoy (Figure 8, red lines). There is also higher-frequency broadband motion that is associated with fluttering of the strongback fin around the mooring line. Both of these motions are especially energetic in the v -component spectra because this is the direction in which the TTM mooring system is most unstable. As is expected from fluid-structure interaction theory, the amplitude of these motions increases with increasing mean velocity (Morison et al. 1950).

The mooring motion contaminates the uncorrected ADV measurements of velocity, $S\{\vec{u}_m\}$, whenever the amplitude of the motion is similar to or greater than the amplitude of the turbulence. Fortunately, much of this motion can be removed using the IMU’s motion signals as detailed in Section 3. Lacking an independent measurement of turbulence velocity at this site, we

interpret the agreement of these spectra with turbulence theory as evidence that motion correction has improved the velocity measurements. In particular, at high frequencies ($f > 0.3$ Hz) for each mean-flow speed, the spectra decay with a $f^{-5/3}$ slope and have equal amplitude across the velocity components. These results are consistent with Kolmogorov’s (1941) theory of isotropic turbulence, and are consistent with spectral shapes of earlier measurements of turbulence in energetic tidal channels from stationary platforms (Walter et al. 2011; Thomson et al. 2012; McMillan et al. 2016).

For $|\vec{u}| > 1.0$, motion correction modifies the u and v component spectra at frequencies as high as 3 Hz. This outcome indicates that in order for motion correction to be effective, synchronization between the ADV and IMU needs to be within 1/3 s or better. This suggests that asynchronous approaches to motion correction may be challenging, especially considering that the clock drift of some instrumentation can be as high as a few seconds per day. By integrating the IMU data into the ADV data stream, the Nortek ADV-IMU achieves a synchronization to within 1e-2 s.

At low frequencies the spectra tend to become roughly constant (especially at higher flow speeds), which is also consistent with previous works. Note that the very low magnitude of $S\{\vec{u}_h\}$ at low frequencies is partially a result of filtering the IMU’s accelerometer signal when calculating \vec{u}_a . The true low-frequency spectrum of ADV head motion is unknown (indicated using a dashed line below f_a). A comparison of $S\{\vec{u}\}$ measured by the TTM to that measured by the ADP—during the June 2012 deployment—reveals agreement at low frequencies (not shown). This finding suggests that the assumption that $\vec{u}_{low} = 0$ at these frequencies and at this site for this platform is justified—even if $S\{\vec{u}_h\}$ is not as low as indicated in Figure 8.

As successful as motion correction is, some of the motion contamination persists in $S\{\vec{u}\}$. This is most notable in $S\{v\}$ at the highest flow speeds (> 2.0 m/s): a peak at 0.15 Hz is an order of magnitude larger than a spectral fit to the other frequencies would indicate. This persistent motion

contamination is evident to a lesser degree in $S\{u\}$ for $|u| > 2$ m/s, and in $S\{v\}$ at lower flow speeds. $S\{w\}$ appears to have no persistent motion contamination because the amplitude of the motion in this direction is much lower than for the other two components. For these measurements, $S\{w_h\}$ is so low that w -component motion correction makes only a minor correction to the spectra.

The amplitude of the persistent motion contamination peaks in $S\{v\}$ at 0.15 Hz is a factor of 5 to 10 times smaller than the amplitude of the ADV head motion itself. This observation suggests that the Microstrain IMU can be used to effectively correct mooring motion at 0.15 Hz when the amplitude of that motion is less than 5 times the amplitude of the real turbulence spectrum. As a result, we have chosen a value of 3 as a conservative estimate of the motion correction's effectiveness.

In addition to the primary benefit of correcting for mooring motion, the IMU measurements can also be used to identify and screen out persistent motion contamination. For example, one of the most common uses of turbulence spectra is for the calculation of ε and tke . For these purposes, and based on the relative amplitudes of the 0.15-Hz peaks, we assume that persistent motion contamination is likely, where $S\{\vec{u}_h\}/S\{\vec{u}\} > 3$, and thereby exclude these regions from spectral fits.

In the present case, for the u and w spectra, this criteria only excludes a narrow range of frequencies at the 0.15-Hz motion peak for some cases. This criteria is more restrictive of the v -component spectra at high frequencies for $\bar{U} > 1.0$ m/s, but this may be acceptable because the amplitude of $S\{v\}$ at these frequencies—i.e., in the isotropic inertial subrange—should be equal to that of $S\{u\}$ and $S\{w\}$ (Kolmogorov 1941).

Agreement of the v -component spectral amplitude with that of u and w at frequencies > 0.3 Hz indicates that motion correction is effective at those frequencies even when $S\{\vec{u}_h\}/S\{\vec{u}\} \gtrsim 3$. This outcome suggests that our screening threshold is excessively conservative at those frequencies,

and that a more precise screening threshold may be frequency dependent. For example, it might take into account the f^3 character of the noise in $S\{\vec{u}_a\}$ (Figure ??6). For the purpose of this work, the $S\{\vec{u}_h\}/S\{\vec{u}\} < 3$ threshold for spectral fits is sufficient, and detailed characterization of the IMU’s motion- and frequency-dependent noise level is left for future work.

c. *StableMoor Spectra*

The spectra of the StableMoor motion has a broader peak with a maximum amplitude that is approximately half the frequency of the TTM spectral peak (Figure 9). The motion of this platform also does not have high-frequency “subpeaks” or other high-frequency broadbanded excitation (Part 1). These characteristics of the motion are most likely due to the more massive and hydrodynamically streamlined properties of the platform.

Like the TTM, the motion-corrected spectra from the StableMoor buoy are consistent with turbulence theory and previous observations. Most importantly, there is an improvement in the quality of the motion-corrected spectra compared to the TTM. In particular, the persistent motion contamination peaks are completely removed. That is, this measurement system provides an accurate estimate of the turbulence spectra at this location from low frequencies to more than ~~1 Hz—well~~ 1 Hz—well into the inertial subrange—for all three components of velocity.

Note that this level of accuracy cannot be obtained without the independent estimate of \vec{u}_{low} . If we assume that $\vec{u}_{low} = 0$, a similar plot to Figure 9 (not shown) reveals persistent motion-contamination peaks and troughs in the u and v spectra regardless of the choice of f_a . This assumption indicates that the low-frequency motion of the StableMoor buoy is below a threshold in which the IMU’s signal-to-noise ratio is high enough to resolve its motion. In other words, compared to the TTM, the StableMoor platform provides a more accurate measurement of turbulence

when it includes an independent measure of \vec{u}_{low} (here a bottom-tracking ADCP), but it does no better—and perhaps worse—when it does not.

d. Torpedo spectra

The u and v motion of the turbulence torpedo is ~~broadbanded~~ broadband and the w motion has a narrow peak at 0.3 Hz (Figure 10). Because \vec{u}_h is estimated using ~~$f_a = 0.0333 \text{ Hz}$~~ $f_a = 0.0333 \text{ Hz}$ and assuming $\vec{u}_{\text{low}} = 0$, its spectra rolls off quickly below f_a . Motion correction of the torpedo data appears to effectively remove a motion peak from $S\{w\}$ at 0.3 Hz, and straightens out $S\{v\}$ between 0.04 and 0.6 Hz. $S\{u\}$ is mostly unaffected by motion at these frequencies, because the torpedo motion is smaller than the turbulence in this direction. At frequencies below f_a , $S\{u\}$ and $S\{v\}$ increase dramatically. This increase suggests that unresolved, low-frequency motion of the torpedo is contaminating the velocity measurements at these frequencies. It may be possible to correct for some of this contamination using a measurement of the ship's motion as a proxy for the torpedo's low-frequency motion, but this has not been done. Still, above f_a , the torpedo appears to provide a reliable estimate of spectral amplitude in the inertial subrange and can therefore be used to estimate ε . Considering the simplicity of the platform, it may be a useful option for quantifying this ~~essential turbulence quantity~~ turbulence statistic in a variety of scenarios. Further, if a GPS is positioned above it, it may be capable of providing even more.

e. Cross Spectra

Inspection of cross spectra from TTM measurements demonstrates that motion correction can reduce motion contamination to produce reliable estimates of velocity cross spectra (Figure 11). At low flow speeds (left column), cross spectra between components of \vec{u}_h (i.e., between components of head motion, red) are small compared to correlated velocities. As the velocity magnitude

increases (center and right columns), the swaying motion of the TTM at 0.15 Hz appears as a peak in the amplitude of the cross spectra of \vec{u}_h (red) and \vec{u}_m (black) for all three components of cross spectra (rows). Fortunately, motion correction reduces the amplitude of this peak dramatically so that $C\{\vec{u}\}$ (blue) is small at 0.15 Hz compared to lower frequencies. Furthermore, the fact that the standard deviation of $C\{\vec{u}\}$ is also relatively small at 0.15 Hz suggests that motion correction is effective for each spectral window, not just in their mean.

These results indicate that motion-corrected TTM velocity measurements can be used to obtain reliable estimates of turbulence Reynold’s stresses, which are the integral of the cross spectra. Without motion correction, Reynold’s stress estimates would be contaminated by the large peaks in the cross spectra that are caused by the swaying and fluttering motion of the TTM vane.

A similar investigation of StableMoor cross spectra (not shown) indicates that cross-spectral motion contamination is at a much lower amplitude than for the TTM. The low-frequency (< 0.3 Hz) “swimming” motion of that platform produces a minimal cross-spectral signal, and the relative large mass of the platform minimizes the kinds of higher-frequency swaying and fluttering that creates large values of cross-spectral head motion. Thus, the StableMoor platform also produces reliable estimates of Reynold’s stresses, which are presumed to be improved by motion correction.

5. Discussion

The previous section presented a comparison of \vec{u} measured by a TTM-mounted ADV to measurements from a co-located ADP. This comparison demonstrated that the IMU provides a reliable estimate of the ADV’s orientation and that this can be utilized to estimate mean velocity in the Earth’s reference frame. Turbulence velocity estimates from the same ADP are also in agreement with low-frequency TTM turbulence estimates (not shown), but the ADP does not resolve turbulence at the scales where motion contamination is strongest (0.1 to 1.0 Hz).

431 Ideally, moored motion-corrected turbulence velocity measurements would be validated against
432 simultaneous independent validated measurements of turbulence velocity at the same scales and
433 exact time and location. Accomplishing this, however, involves significant technical challenges
434 that are not easily overcome—most notably the difficulty of measuring turbulence at the same point
435 as the moving ADV. A slightly less ideal but much more realistic confirmation of the methodology
436 might involve comparing the statistics of moored turbulence measurements to those from a nearby
437 fixed platform, or a fixed platform placed at the same location at a different time (e.g., the “TTT”
438 platform described in Thomson et al. 2012). Unfortunately, to our knowledge, these measurements
439 have not yet been made.

440 Lacking a relevant, fixed, independent turbulence measurement to compare to it is instructive
441 to demonstrate the degree to which the moored measurements are consistent with turbulence
442 theory and other turbulence measurements in similar flow environments. The previous section
443 showed that the shape of the turbulence velocity spectra from moored ADVs is consistent with
444 Kolmogorov’s theory of locally isotropic turbulence, which has been observed consistently in tur-
445 bulence measurements for decades (Kolmogorov 1941; Grant et al. 1962; McMillan et al. 2016).
446 In particular, we observed an isotropic subrange—an $f^{-5/3}$ spectral slope and equal amplitude
447 spectra between components—that is driven by anisotropic turbulence at longer timescales (Fig-
448 ures 8, 9, 10). This finding is interpreted as the first indication that the measurement systems
449 presented are capable of accurately resolving turbulence. The degree to which uncorrected spec-
450 tra were corrected toward this theoretical and observationally confirmed shape is interpreted as a
451 measure of the improvement of the spectral estimates by motion correction.

452 Figure 12 presents a time series of the mean velocity (A) and several turbulence statistics that
453 were measured during the June 2014 TTM deployment. This figure shows the evolution of the flow
454 through Admiralty Inlet during 1.5 tidal cycles. The tke (B), Reynold’s stresses (C), dissipation,

and one component of turbulence production (D) grow and strengthen with ebb or flood then
subside during slack tide. This component of turbulence production is:

$$P_{uz} = \frac{\partial \bar{u}}{\partial z} \overline{uw} \quad . \quad (4)$$

Where $\partial \bar{u} / \partial z$ is computed from the two ADVs on the TTM. The highest values of ε and P_{uz} occur
at the peak of the ebb or flood, which is in agreement with other measurements in tidal channels.
The agreement of the magnitude of P_{uz} with ε at those times suggests a local production-dissipation
balance that is often observed in tidally forced channels (Trowbridge et al. 1999; Stacey et al.
1999b; McMillan et al. 2016). At other times, the value of P_{uz} is insufficient to balance ε or is
negative.

Inspection of the negative P_{uz} values reveals that most of them are caused by a reversed sign of \overline{uw}
rather than a reversed sign of $\partial u / \partial z$ (i.e., when compared to the sign of u). This finding suggests
that uncertainty in \overline{uw} may be contributing to discrepancies between P_{uz} and ε . Furthermore,
considering the complex nature of the shoreline near this site (i.e., the headland), it is not surprising
that P_{uz} does not balance ε perfectly. Other terms of the tke equation are likely to be important,
such as other components of production, advection terms, or turbulent transport terms. The fact
that these two terms are in near balance as often as they are is a strong indication that bottom
boundary layer physics are important to the dynamics at this site.

Figure 13 compares individual values of P_{uz} with ε directly. Given the assumptions implicit in
this comparison and the discussion above, the agreement between P_{uz} and ε is an encouraging
result that suggests the turbulent boundary layer reaches the depth of these measurements (10
m) during the highest flow speeds. This result is further supported by a comparison of \bar{U} with
 ε (Figure 14). Here we see a $\varepsilon \propto \bar{U}^3$ dependence that is again suggestive of bottom boundary
layer physics (Trowbridge 1992; Nash et al. 2009). At lower flow speeds, ε deviates from this

relationship, which suggests that the boundary layer is no longer the dominant physical process at the depth of these measurements.

6. Conclusion

This work presents a methodology for measuring turbulence from moored ADV-IMUs and demonstrates that motion correction reduces mooring motion-contamination. Comparison of spectra of ADV head motion, $S\{\vec{u}_h\}$, to that of motion-corrected, $S\{\vec{u}\}$, and uncorrected spectra, $S\{\vec{u}_m\}$, reveals that motion correction improves spectral estimates of moored ADV measurements. In particular, we found that motion-corrected spectra have spectral shapes that are similar to previous measurements of tidal-channel turbulence and have a $f^{-5/3}$ spectral slope at high frequencies. This finding suggests that the motion-corrected spectra resolve the inertial subrange predicted by Kolmogorov’s theory of locally isotropic turbulence.

Motion correction reduces motion contamination for all platforms we presented but it does not necessarily remove it completely. This outcome seems to depend on the relative amplitude of platform motion compared to the underlying turbulence being measured. The most notable example of this is from the TTM, which has a large “swaying” peak at 0.1 Hz. Where this peak is very large—especially in the v component—it is not reduced to a level that is consistent with earlier measurements of tidal-channel turbulence—i.e., there is no smooth roll-off between the low-frequency energy-containing scales and the $f^{-5/3}$ inertial subrange.

This inconsistency indicates that turbulence measurements from moored, motion-corrected ~~IMU~~ ~~ADV~~s ADV-IMUs must be interpreted with care. An inspection of spectra presented here suggests that excluding spectral regions where $S\{\vec{u}_h\}/S\{\vec{u}\} > 3$ removes persistent-motion contamination peaks while still preserving spectral regions where motion correction is effective. Using this cri-

teria, it is then possible to produce spectral fits that exclude persistent-motion contamination, and provide reliable estimates of turbulence quantities of interest (e.g., ε and k_ε).

We ~~ve~~have also shown that motion correction reduces motion contamination in cross spectra. This finding is important because it suggests that moored ~~IMU-ADV~~ADV-IMU measurements may be used to produce reliable estimates of Reynolds stresses. We utilized these stress estimates and vertical shear estimates, both from the TTM, to estimate P_{uz} .

Finally, we have shown that ε estimates based on motion-corrected spectra scale with the U^3 , and balance P_{uz} estimates during ebb and flood. Together, these results indicate that bottom boundary layer physics are a dominant process at this site, and that the boundary layer reaches the height of the ~~IMU-ADV~~s ADV-IMUs (10 m) during ebb and flood. The degree of agreement between P_{uz} and ε also serves as an indicator of the self-consistency of moored ~~IMU-ADV~~ADV-IMU turbulence measurements.

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A1. Comparing StableMoor \vec{u}_{low} to IMU \vec{u}_{h}

To better understand the IMU’s signal-to-noise ratio, we compare the motion of the StableMoor buoy from the ADP bottom track measurements, \vec{u}_{BT} , to the IMU’s estimates of ADP motion. To do this, we compute the IMU’s estimate of ADP motion using equation (3), and replacing ℓ^* with the vector that points from the IMU to the ADP head. ~~We then~~ In this case, we use a 5 minute high-pass filter ($f_a = 0.00333$) in (3); this reduces spectral reddening that otherwise contaminates coherence estimates and preserves the \vec{u}_a estimates at the frequencies where we wish to compare to \vec{u}_{BT} (Figure 15). We also linearly interpolate the ADP measurements of \vec{u}_{BT} onto the times of the ADV-IMU measurements.

The coherence between these two signals is high and statistically significant over 1.5 decades—from 0.03 to 0.8 Hz ~~(Priestley 1981)~~ (Figure 15, Priestley 1981). The v component has the highest coherence, 98%, because this is the direction that has the most motion (i.e., these estimates have a higher signal-to-noise ratio). The u and w components have a slightly lower coherence, 80% and 65%, respectively.

On the low-frequency side, our interpretation is that the signal-to-noise ratio of the IMU ~~increases~~ decreases dramatically below 0.03 Hz, resulting in low coherence. On the high-frequency side, Doppler noise in the ADP measurements contaminates its estimates of motion, causing the decrease in coherence at 0.8 Hz. A comparison of the phase between these signals shows that there is no lag between the measurements (not shown).

These results help to inform the selection of zero-lag filters used to estimate \vec{u}_{low} from \vec{u}_{BT} . In particular, by selecting 0.2 Hz, we target the middle of the coherence peak between the two measurements. Furthermore, the rapid decrease in coherence below 0.03 Hz provides an objective

548 measurement of the frequency at which IMU measured velocity becomes unreliable in the flow
549 conditions we observed.

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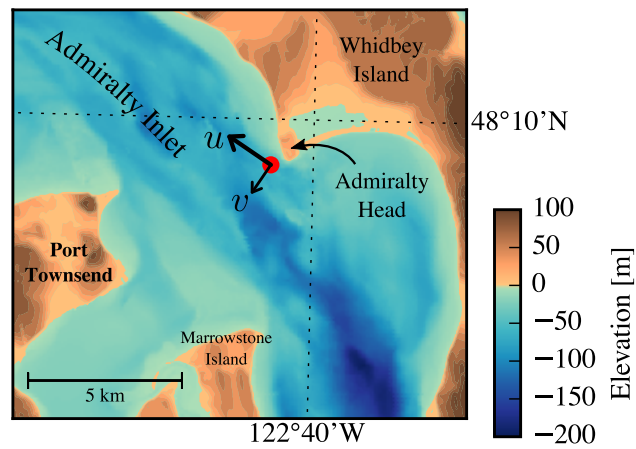
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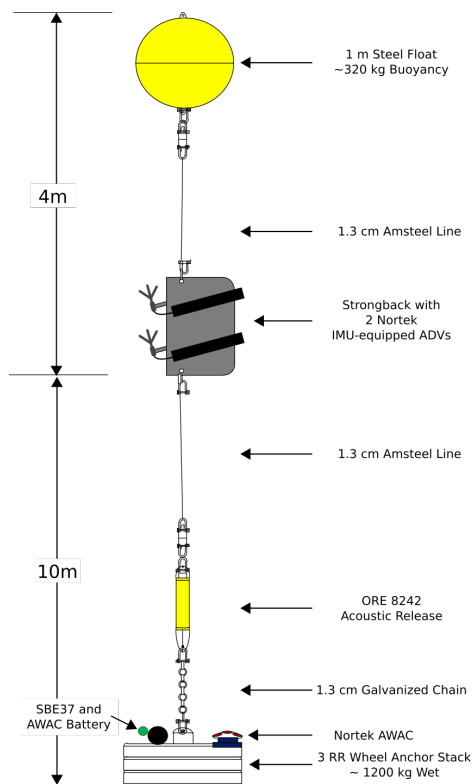


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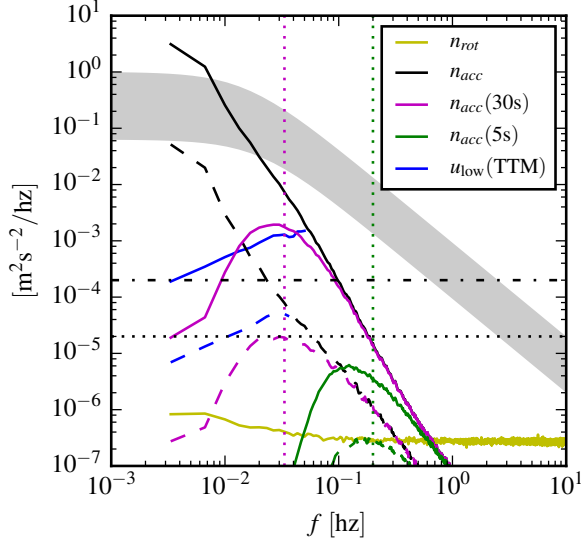
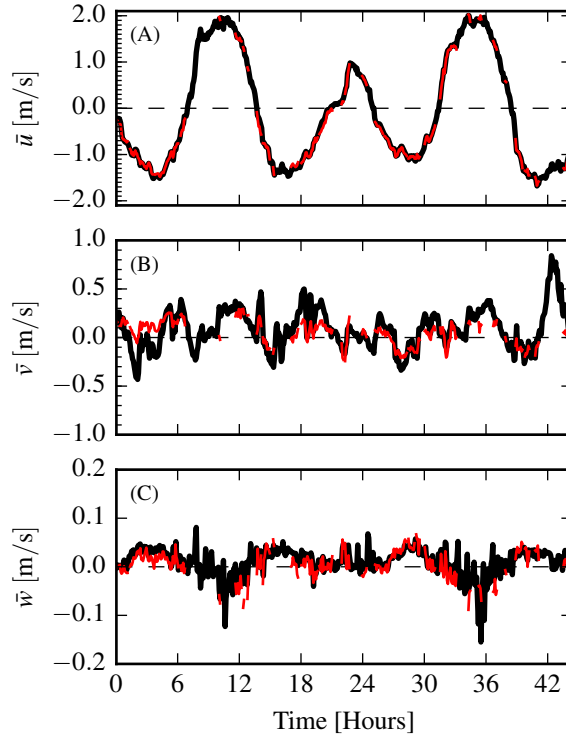


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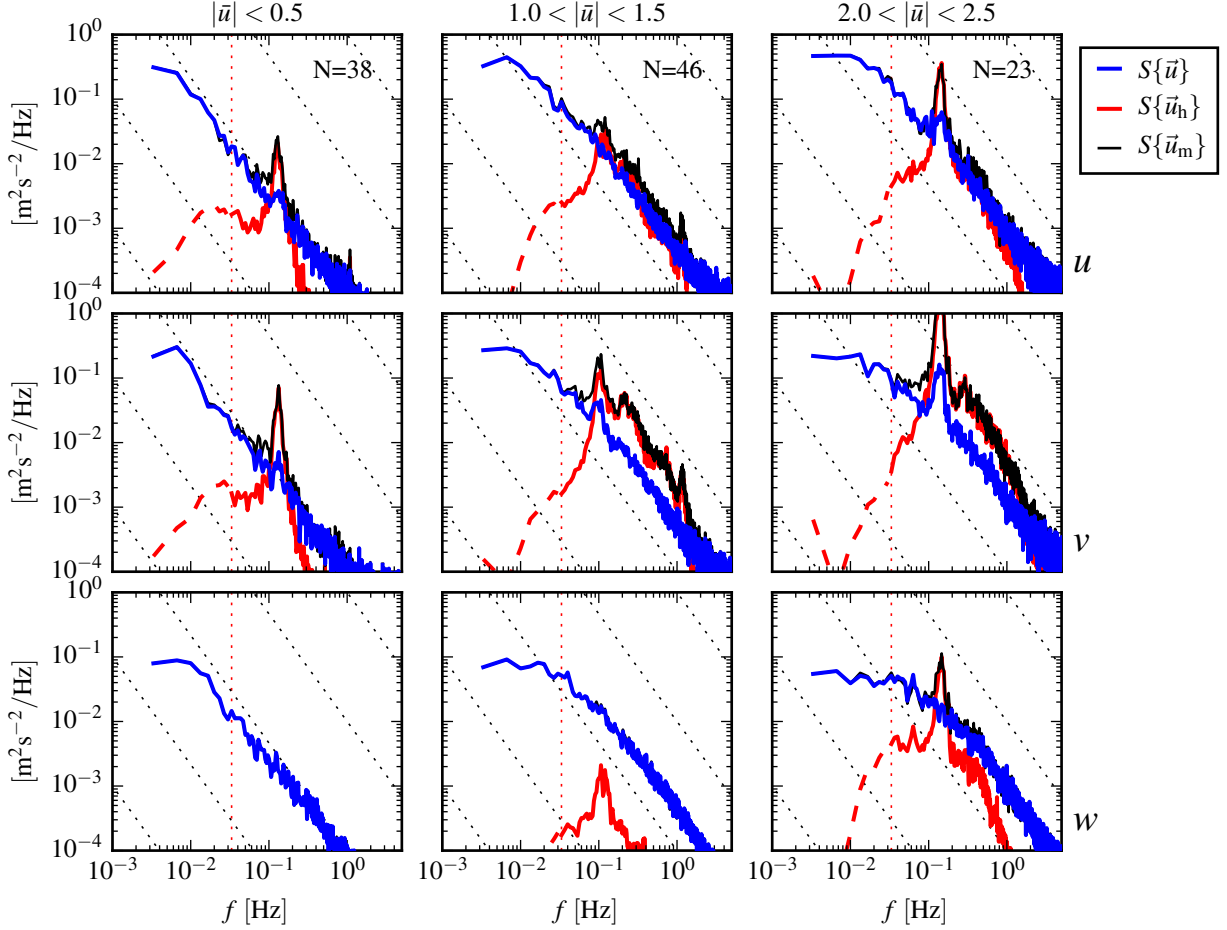


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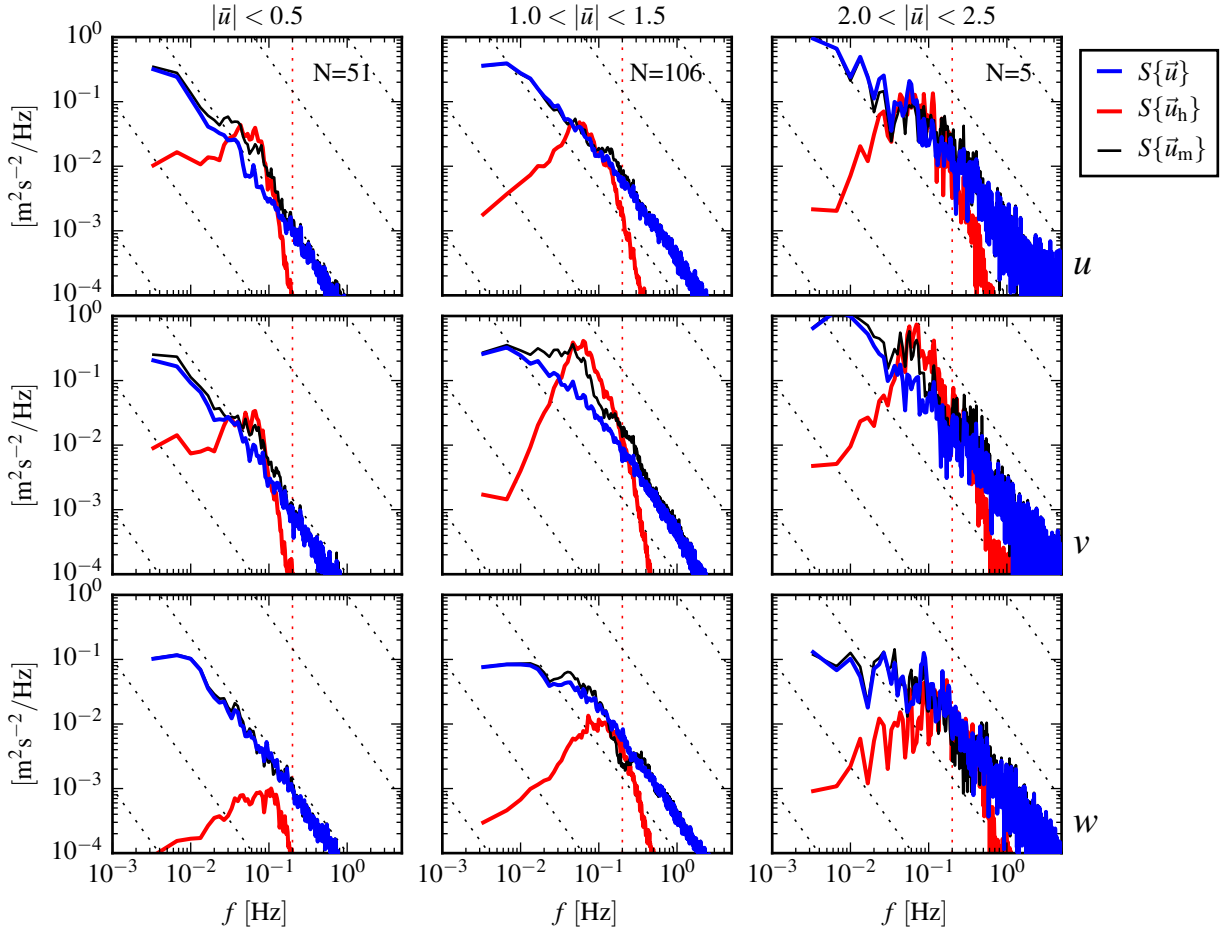


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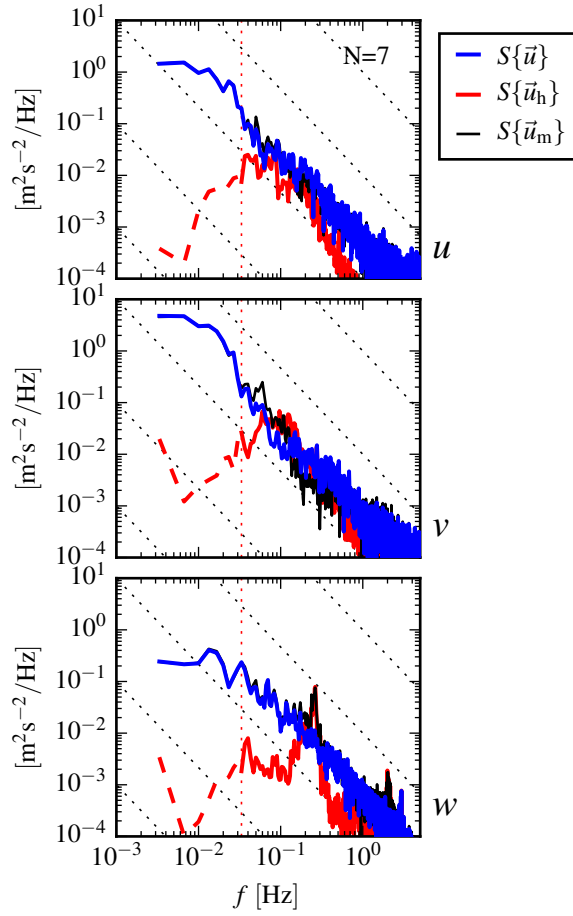


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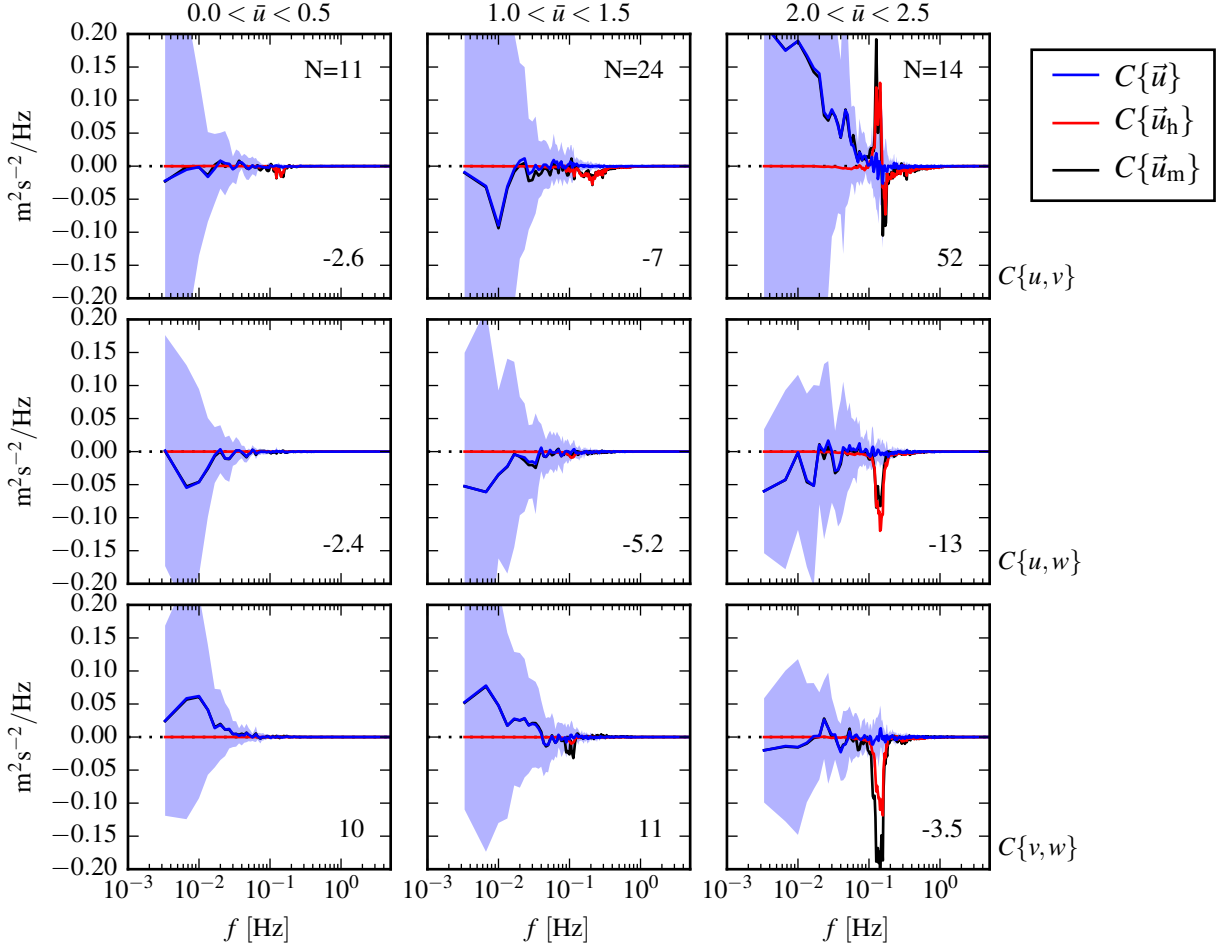


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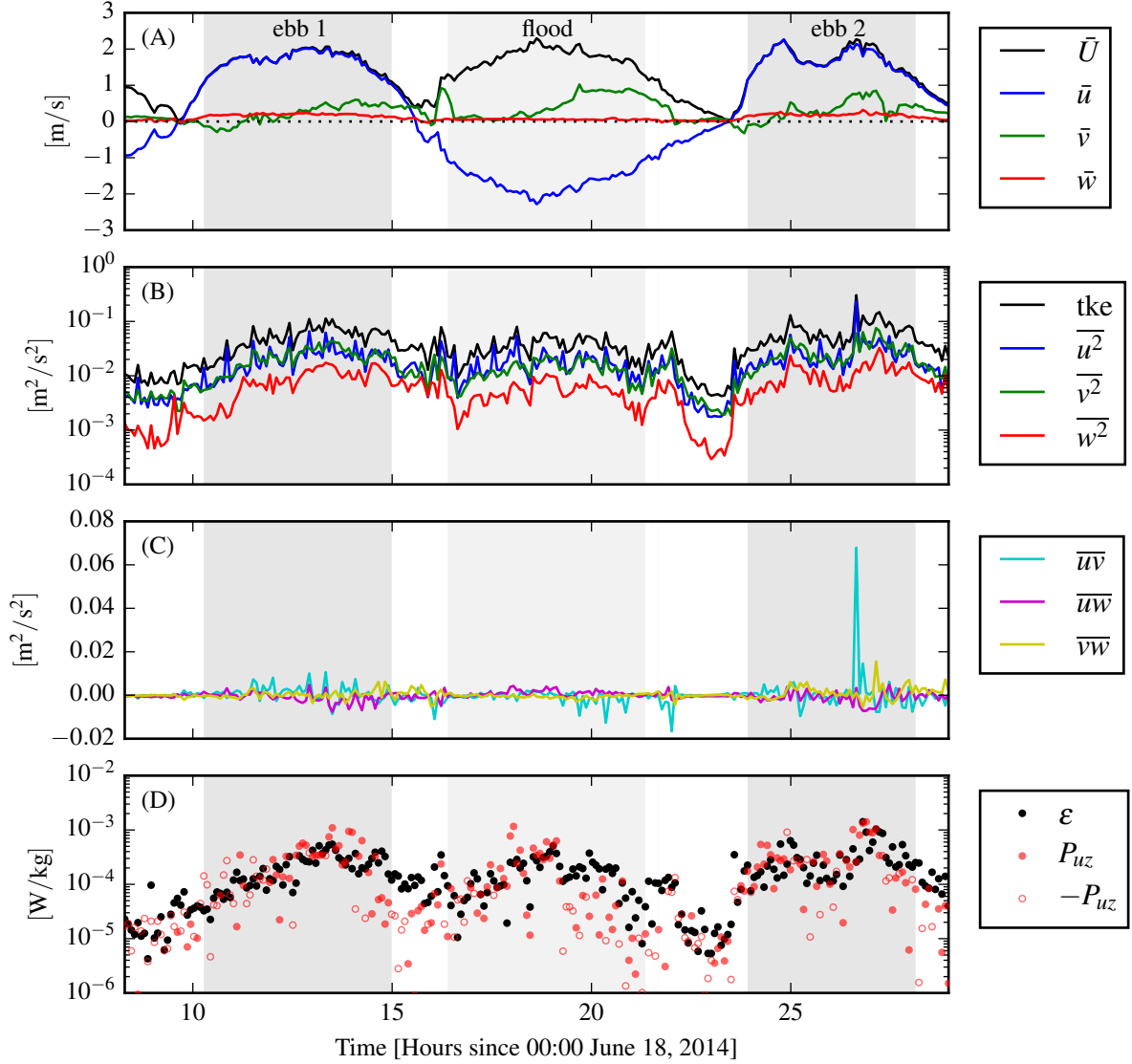
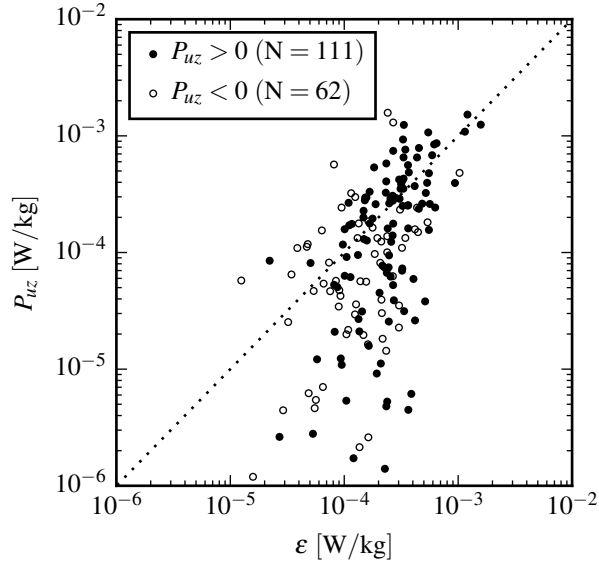


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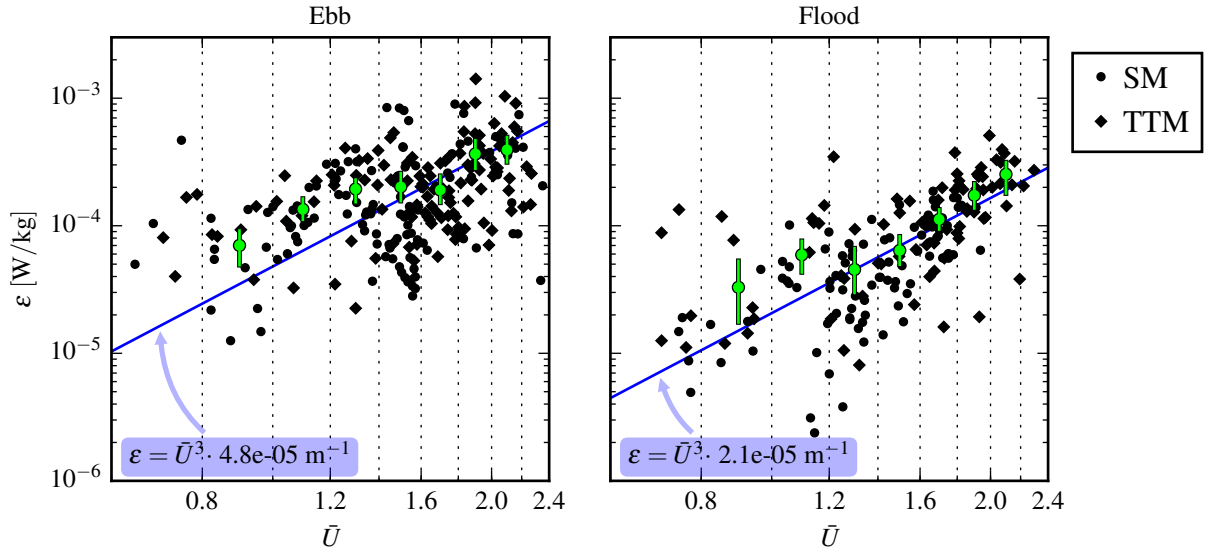


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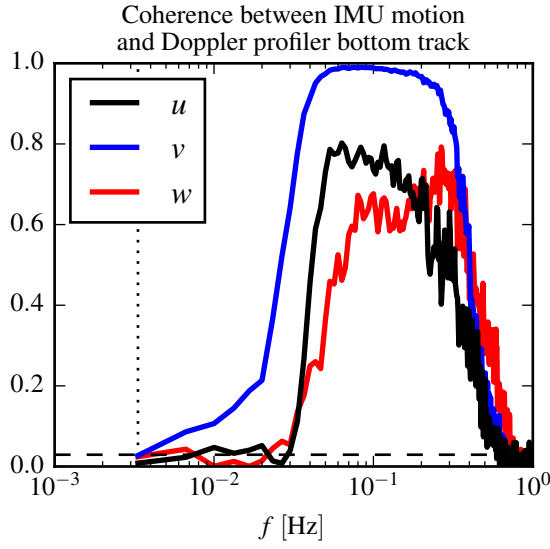


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