

Turbulence Measurements from Compliant Moorings - Part II: Motion

Correction

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

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

52 Inertial motion unit (IMU) sensors have been used in the aerospace and aeronautical industries
53 to quantify the motion of a wide range of systems, and to improve atmospheric velocity measure-
54 ments, for several decades (Axford 1968; Edson et al. 1998; Bevly 2004). Over the last 10 years,
55 the smartphone, drone, and 'Internet of Things' markets have driven innovation in microelectrical-
56 mechanical systems, including the IMU. As a result of this growth and innovation, the cost, power

57 requirements, and size of IMUs have come down. These changes have allowed these sensors to be
58 integrated into oceanographic instruments that have small form-factors, and rely on battery power.

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

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

80 turbulence measurements (Lueck and Huang 1999; Doherty et al. 1999; Nash et al. 2004; Moum
81 and Nash 2009; Alford 2010; Paskyabi and Fer 2013).

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

91 **2. Measurements**

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

103 All measurements used in this work were made in Admiralty Inlet, Washington, approximately
104 500 m west southwest of Admiralty Head in 60 m of water near 48° 9.18' N, 122° 41.22' W (Figure
105 1). The site is approximately 6 km east of Port Townsend, and 1 km north of the Port Townsend
106 to Coupeville ferry route. Admiralty inlet is the largest waterway connecting Puget Sound to
107 the Strait of Juan de Fuca, and it possesses a large semidiurnal tidal flow (Thomson et al. 2012;
108 Polagye and Thomson 2013). This work utilizes data from three distinct deployment platforms:
109 the tidal turbulence mooring, a StableMoor buoy, and a simple sounding weight. All data used
110 in this analysis are available from the MHK data repository (<http://mhkdr.openei.org>; submission
111 ids: 49, 50 and 51). Each of these platforms are briefly described below, and additional details,
112 photos, and schematic diagrams can be found in Part 1.

113 *a. Tidal Turbulence Mooring*

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

121 The first TTM deployment was in June 2012 from 17:30 on the 12th until 14:30 on the 14th
122 (local; i.e., Pacific Daylight Time). Two Nortek ADVs were clamped to either side of the fin so that
123 the axis of their cylindrical pressure cases were parallel with the leading edge of the strongback.
124 The ADV heads were spaced 0.5 m apart vertically along the fin. Only one of these ADVs was

equipped with an integrated IMU. This TTM also had an upward-looking acoustic Doppler profiler mounted on the mooring anchor.

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

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

b. The StableMoor platform

The second deployment platform was a cylindrical, StableMoor, syntactic foam buoy (manufacturer: Deep Water Buoyancy) that was anchored to a clump weight that weighed 1,200 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 diameter. The StableMoor buoy weighs 295 kg in air, and has a buoyancy of 185 kg in water.

The StableMoor buoy was deployed with an ADV-IMU mounted at its nose from 11:21 on May 12 to 11:53 on May 13, 2015 (local time). The sample volume of the ADV is 10 cm forward of the nose and 20 cm above the center line of the StableMoor buoy (Figure 4). Based on Wyngaard et al.'s (1985) investigation of a similarly shaped slender body, the velocity measurements should have flow-distortion effects of less than 10%. This configuration was designed to be the most

148 stable platform for measuring turbulence from a moving platform. The StableMoor buoy was
149 equipped with a 1,200-kHz RDI workhorse sentinel acoustic Doppler profiler that was oriented
150 downward-looking to measure water velocity below the platform in twelve 1-m bins and measure
151 buoy motion (“bottom tracking”), all at a 1-Hz sample rate.

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

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

162 *c. Turbulence Torpedo*

163 The turbulence torpedo is a simple sounding weight with an ADV head mounted forward of the
164 nose, and the ADV pressure case strapped below (Figure 5). This platform was deployed on May
165 14, 2015, for 37 minutes starting at 07:41 local time. This measurement was made from a davit
166 that hung the system from the side of the ship to a depth of approximately 25 m. The primary
167 logistical advantages of this platform are its compact size, low cost, and the flexibility to perform
168 spatial transects.

169 *d. Coordinate system and turbulence averaging*

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

178 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
 179 computed using NumPy fast Fourier transform routines (van der Walt et al. 2011). Here, $\mathcal{F}\{x(t)\}$
 180 denotes the fast Fourier transform of a signal $x(t)$. Time series, e.g., $x(t)$, are linearly detrended
 181 and Hanning windowed prior to computing $\mathcal{F}\{x\}$ to reduce spectral reddening.

182 Throughout the remainder of this work, the dependence of S and C on f is implied (e.g., $S\{x\}(f)$
 183 is hereafter $S\{x\}$), and for other variables the dependence on t is implied. Spectra and cross
 184 spectra are normalized to preserve variance: $\int S\{u\}df = \overline{u^2}$, and $\int C\{u, v\}df = \overline{uv}$. The notations
 185 $S\{\vec{u}\} = (S\{u\}, S\{v\}, S\{w\})$, and $C\{\vec{u}\} = (C\{u, v\}, C\{u, w\}, C\{v, w\})$ denote the set of spectra and
 186 cross spectra for each velocity component and pairs of components, respectively.

187 Turbulence dissipation rates are computed as:

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

188 where $\alpha = 0.5$ and $\langle \rangle_{f_{IS}}$ denotes an average over the inertial subrange of the velocity spectra and
 189 where the signal-to-noise ratio is small (Lumley and Terray 1983; Sreenivasan 1995). Throughout

this work, we take this average from 0.3 to 1 Hz for the u and v components, and 0.3 to 3 Hz for the w component.

3. Methodology

The essential approach of motion correction is to measure velocity on a moving platform and make an independent measurement of the platform motion, then subtract the motion from the velocity measurements. This approach has been used to successfully correct sonic anemometer measurements of atmospheric turbulence (e.g., Edson et al. 1998; Miller et al. 2008). In the ocean, previous works have utilized inertial motion sensors to quantify the motion of multiscale profilers for the purpose of measuring the full spectrum of oceanic shear (Winkel et al. 1996).

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

$$\begin{aligned}\vec{u}_h &= \vec{u}_w + \vec{u}_a + \vec{u}_{\text{low}} \\ &= \mathbf{R}^T \cdot \vec{\omega}^*(t) \times \vec{\ell}^* + \int \{\vec{a}(t)\}_{HP(f_a)} dt + \vec{u}_{\text{low}}\end{aligned}\tag{2}$$

Here, $*$ superscripts denote quantities in the ADV’s local coordinate system, and $\vec{\ell}^*$ is the vector from the IMU to the ADV head. \mathbf{R}^T —the inverse of the orientation matrix—rotates vectors from the IMU to the Earth reference frame. The notation $\{\vec{a}\}_{HP(f_a)}$ indicates that the IMU’s accelerometer signal is high-pass filtered (in the Earth’s stationary reference frame) at a chosen filter frequency, f_a . Without such filtering, low-frequency noise in \vec{a} —sometimes referred to as bias

drift—is amplified by integration to the point that it overwhelms the higher frequency information (Barshan and Durrant-Whyte 1995; Bevilacqua 2004; Gulmammadov 2009).

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

The noise level of $S\{\vec{u}_a\}$ (Figure 6, black), on the other hand, is dominated by a f^{-2} slope that results from integrating the low-frequency noise in \vec{a} . The high-pass filtering reduces this noise so that it does not contaminate motion correction. However, real motion that exists at these frequencies is lost in the low signal-to-noise ratio (Egeland 2014; VanZwieten et al. 2015). This means that there is a residual low-frequency translational motion, \vec{u}_{low} , that is not well resolved by the IMU, and needs to be measured independently—or at the very least considered—when using motion-corrected ADV-IMU data.

The choice of a high-pass filter for reducing low-frequency accelerometer noise depends on the flow conditions of the measurement and the platform being used. In particular, filter selection involves a trade-off between filtering out the 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. We use 4th-order, bidirectional (zero-phase), Hanning filters for all filtering operations.

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 ‘lean’ of this ‘pole’. The position obtained from this model can then be differentiated to estimate \vec{u}_{low} . Because the mooring is not actually a rigid pole this approach is likely to over-estimate \vec{u}_{low} , particularly at high frequencies where wobbling and swaying deviate from the rigid-pole model. At low-frequencies, we believe this approach provides a reasonable estimate of maximum head motion.

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 $n(\vec{u}_a)$ lines (black) for simplicity; beyond this frequency we assume $n(\vec{u}_a)$ provides a better estimate of the translational motion noise-level than the rigid pole model. Together, these two lines provide an ‘aggregated noise level’ of translational velocity estimates from the TTM: the rigid pole estimate of \vec{u}_{low} indicates the amplitude of unresolved motion at low- f (blue), and $n(\vec{u}_a)$ indicates the limits of the IMU at high- f (black). Coincidentally, $n(\vec{u}_a)$ filtered at $f_a = 0.0333\text{Hz}$ is not a terrible approximation for this aggregate noise level. We did attempt to utilize this estimate of \vec{u}_{low} to improve motion correction by applying complimentary filters as described in the previous paragraph, but—because the aggregate noise level is at least $10\times$ lower than the velocity spectra of interest (shaded region)—those results were equivalent to assuming that $\vec{u}_{\text{low}} = 0$ and using $f_a = 0.0333\text{Hz}$ (30-s period). Thus, we simply used $\vec{u}_{\text{low}} = 0$ and $f_a = 0.0333\text{Hz}$ for the TTM and the turbulence torpedo estimates of \vec{u}_h .

For the StableMoor buoy, an estimate of \vec{u}_{low} derived from the ADP bottom-track does appear to improve the velocity spectra (not shown). This is because the StableMoor motion is at a lower frequency where the IMU accelerometers perform poorly (motion contamination is persistent if we assume $\vec{u}_{\text{low}} = 0$), and because the ADP probably provides a more accurate estimate of \vec{u}_{low}

than the rigid pole model does for the TTM. 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.

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:

$$\vec{u}(t) = \vec{u}_m(t) + \vec{u}_h(t). \quad (3)$$

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

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.

279 *b. TTM spectra*

280 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
281 Hz from swaying of the mooring that is most likely driven by eddy shedding from the spherical
282 buoy (Figure 8, red lines). There is also higher-frequency broadband motion that is associated
283 with fluttering of the strongback fin around the mooring line. Both of these motions are especially
284 energetic in the v -component spectra because this is the direction in which the TTM mooring
285 system is most unstable. As is expected from fluid-structure interaction theory, the amplitude of
286 these motions increases with increasing mean velocity (Morison et al. 1950).

287 The mooring motion contaminates the uncorrected ADV measurements of velocity, $S\{\vec{u}_m\}$,
288 whenever the amplitude of the motion is similar to or greater than the amplitude of the turbu-
289 lence. Fortunately, much of this motion can be removed using the IMU's motion signals as de-
290 tailed in Section 3. Lacking an independent measurement of turbulence velocity at this site, we
291 interpret the agreement of these spectra with turbulence theory as evidence that motion correc-
292 tion has improved the velocity measurements. In particular, at high frequencies ($f > 0.3$ Hz) for
293 each mean-flow speed, the spectra decay with a $f^{-5/3}$ slope and have equal amplitude across the
294 velocity components. These results are consistent with Kolmogorov's (1941) theory of isotropic
295 turbulence, and are consistent with spectral shapes of earlier measurements of turbulence in ener-
296 getic tidal channels from stationary platforms (Walter et al. 2011; Thomson et al. 2012; McMillan
297 et al. 2016).

298 For $|\vec{u}| > 1.0$, motion correction modifies the u and v component spectra at frequencies as high
299 as 3 Hz. This outcome indicates that in order for motion correction to be effective, synchronization
300 between the ADV and IMU needs to be within 1/3 s or better. This suggests that asynchronous
301 approaches to motion correction may be challenging, especially considering that the clock drift of

302 some instrumentation can be as high as a few seconds per day. By integrating the IMU data into
303 the ADV data stream, the Nortek ADV-IMU achieves a synchronization to within 1e-2 s.

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

312 As successful as motion correction is, some of the motion contamination persists in $S\{\vec{u}\}$. This
313 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
314 magnitude larger than a spectral fit to the other frequencies would indicate. This persistent motion
315 contamination is evident to a lesser degree in $S\{u\}$ for $|u| > 2$ m/s, and in $S\{v\}$ at lower flow
316 speeds. $S\{w\}$ appears to have no persistent motion contamination because the amplitude of the
317 motion in this direction is much lower than for the other two components. For these measurements,
318 $S\{w_h\}$ is so low that w -component motion correction makes only a minor correction to the spectra.

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

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

331 In the present case, for the u and w spectra, this criteria only excludes a narrow range of frequen-
 332 cies at the 0.15-Hz motion peak for some cases. This criteria is more restrictive of the v -component
 333 spectra at high frequencies for $\bar{U} > 1.0$ m/s, but this may be acceptable because the amplitude of
 334 $S\{v\}$ at these frequencies—i.e., in the isotropic inertial subrange—should be equal to that of $S\{u\}$
 335 and $S\{w\}$ (Kolmogorov 1941).

336 Agreement of the v -component spectral amplitude with that of u and w at frequencies > 0.3 Hz
 337 indicates that motion correction is effective at those frequencies even when $S\{\vec{u}_h\}/S\{\vec{u}\} \gtrsim 3$. This
 338 outcome suggests that our screening threshold is excessively conservative at those frequencies,
 339 and that a more precise screening threshold may be frequency dependent. For example, it might
 340 take into account the f^3 character of the noise in $S\{\vec{u}_a\}$ (Figure 6). For the purpose of this work,
 341 the $S\{\vec{u}_h\}/S\{\vec{u}\} < 3$ threshold for spectral fits is sufficient, and detailed characterization of the
 342 IMU’s motion- and frequency-dependent noise level is left for future work.

343 *c. StableMoor Spectra*

344 The spectra of the StableMoor motion has a broader peak with a maximum amplitude that is ap-
 345 proximately half the frequency of the TTM spectral peak (Figure 9). The motion of this platform
 346 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 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 broadband and the w motion has a narrow peak at 0.3 Hz (Figure 10). Because \vec{u}_h is estimated using $f_a = 0.0333$ Hz and assuming $\vec{u}_{low} = 0$, 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.

370 This increase suggests that unresolved, low-frequency motion of the torpedo is contaminating the
 371 velocity measurements at these frequencies. It may be possible to correct for some of this con-
 372 tamination using a measurement of the ship's motion as a proxy for the torpedo's low-frequency
 373 motion, but this has not been done. Still, above f_a , the torpedo appears to provide a reliable
 374 estimate of spectral amplitude in the inertial subrange and can therefore be used to estimate ϵ .
 375 Considering the simplicity of the platform, it may be a useful option for quantifying this turbu-
 376 lence statistic in a variety of scenarios. Further, if a GPS is positioned above it, it may be capable
 377 of providing even more.

378 *e. Cross Spectra*

379 Inspection of cross spectra from TTM measurements demonstrates that motion correction can
 380 reduce motion contamination to produce reliable estimates of velocity cross spectra (Figure 11).
 381 At low flow speeds (left column), cross spectra between components of \vec{u}_h (i.e., between compo-
 382 nents of head motion, red) are small compared to correlated velocities. As the velocity magnitude
 383 increases (center and right columns), the swaying motion of the TTM at 0.15 Hz appears as a peak
 384 in the amplitude of the cross spectra of \vec{u}_h (red) and \vec{u}_m (black) for all three components of cross
 385 spectra (rows). Fortunately, motion correction reduces the amplitude of this peak dramatically so
 386 that $C\{\vec{u}\}$ (blue) is small at 0.15 Hz compared to lower frequencies. Furthermore, the fact that the
 387 standard deviation of $C\{\vec{u}\}$ is also relatively small at 0.15 Hz suggests that motion correction is
 388 effective for each spectral window, not just in their mean.

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

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

399 5. Discussion

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

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

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

427 Figure 12 presents a time series of the mean velocity (A) and several turbulence statistics that
 428 were measured during the June 2014 TTM deployment. This figure shows the evolution of the flow
 429 through Admiralty Inlet during 1.5 tidal cycles. The tke (B), Reynold’s stresses (C), dissipation,
 430 and one component of turbulence production (D) grow and strengthen with ebb or flood then
 431 subside during slack tide. This component of turbulence production is:

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

432 Where $\partial \bar{u} / \partial z$ is computed from the two ADVs on the TTM. The highest values of ε and P_{uz} occur
 433 at the peak of the ebb or flood, which is in agreement with other measurements in tidal channels.
 434 The agreement of the magnitude of P_{uz} with ε at those times suggests a local production-dissipation
 435 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.

459 In particular, we found that motion-corrected spectra have spectral shapes that are similar to previ-
460 ous measurements of tidal-channel turbulence and have a $f^{-5/3}$ spectral slope at high frequencies.
461 This finding suggests that the motion-corrected spectra resolve the inertial subrange predicted by
462 Kolmogorov’s theory of locally isotropic turbulence.

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

470 This inconsistency indicates that turbulence measurements from moored, motion-corrected
471 ADV-IMUs must be interpreted with care. An inspection of spectra presented here suggests that
472 excluding spectral regions where $S\{\vec{u}_h\}/S\{\vec{u}\} > 3$ removes persistent-motion contamination peaks
473 while still preserving spectral regions where motion correction is effective. Using this criteria, it
474 is then possible to produce spectral fits that exclude persistent-motion contamination, and provide
475 reliable estimates of turbulence quantities of interest (e.g., ε and $k\varepsilon$).

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

480 Finally, we have shown that ε estimates based on motion-corrected spectra scale with the U^3 , and
481 balance P_{uz} estimates during ebb and flood. Together, these results indicate that bottom boundary
482 layer physics are a dominant process at this site, and that the boundary layer reaches the height

483 of the ADV-IMUs (10 m) during ebb and flood. The degree of agreement between P_{uz} and ε also
484 serves as an indicator of the self-consistency of moored 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 (2), and replacing ℓ^* with the vector that points from the IMU to the ADP head. In this case, we use a 5 minute high-pass filter ($f_a = 0.00333$) in (2); 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 (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 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

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

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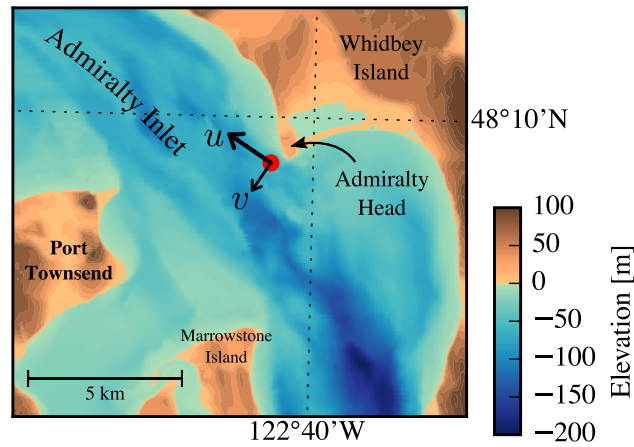
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684	Fig. 5.	The turbulence platform showing details of the ADV head and pressure case configuration. The green arrow indicates the vector from the IMU to the ADV head. The head cable was taped out of the way beneath the sounding weight tail fins shortly after taking this photo.	38
687	Fig. 6.	Spectra of \vec{u}_ω (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) and 5 s (green). Vertical dotted lines indicate the filter frequency. Blue lines are an estimate of \vec{u}_{low} for the TTM. Solid lines are the horizontal components, and dashed lines are the vertical components of \vec{u}_a and \vec{u}_{low} . The horizontal and vertical Doppler noise levels of a Nortek Vector ADV configured to measure $\pm 4\text{m/s}$ are indicated by horizontal dash-dot and dotted lines, respectively. The shaded region indicates the range of u spectral amplitudes presented herein ($0.002 < \text{tke} < 0.03 \text{ m}^2/\text{s}^2$, $1\text{e-}5 < \varepsilon < 5\text{e-}4 \text{ W/kg}$).	39
695	Fig. 7.	Time series of tidal velocity at Admiralty Head from ADV-IMU measurements (black), and an acoustic Doppler profiler on the anchor (red). The profiler measurements—taken at the same depth as the ADV on the TTM—were contaminated by acoustic reflection from the strongback fin when it was inline with one of the profiler’s beams. Note that the vertical scale on the three axes vary by more than an order of magnitude; the small ticks in A and B are equivalent to the ticks in C.	40
701	Fig. 8.	Turbulence spectra from the June 2014 TTM deployment. Each column is for a range of streamwise velocity magnitudes (indicated at top). The rows are for each component of velocity (indicated to the lower right of the right column). The uncorrected spectra are in black and the corrected spectra are blue, and the spectra of ADV head motion, \vec{u}_h , is red (also indicated in the legend). The vertical red dotted line indicates the filter frequency applied to the IMU accelerometers when estimating \vec{u}_h ; below this frequency $S\{\vec{u}_h\}$ is plotted as a dashed line. Diagonal black dotted lines indicate a $f^{-5/3}$ slope. The number of spectral ensembles, N , in each column is indicated in the top row.	41
709	Fig. 9.	Turbulence spectra from the StableMoor buoy. The axes layout and annotations are identical to Figure 8, except that $S\{\vec{u}_h\}$ is plotted as a solid line at all frequencies because it is measured at all frequencies.	42

712	Fig. 10.	Turbulence spectra from the turbulence torpedo during a 35-minute period when the mean velocity was 1.3 m/s. Annotations and line colors are identical to Figure 8.	43
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714	Fig. 11.	The real part of the cross-spectral density between velocity components measured by the TTM. The upper row is the u - v cross-spectral density, the middle row is the u - w cross-spectral density, and the bottom row is the v - w cross-spectral density. The columns are for different ranges of the stream-wise mean velocity magnitude (indicated above the top row). The blue line is the cross spectrum between components of motion-corrected velocity, the red line is the cross spectrum between components of head motion, and the black line is the cross spectrum between components of uncorrected velocity. The light blue shading indicates one standard deviation of the C for the motion-corrected cross-spectral density. N is the number of spectral ensembles in each column. The number in the lower-right corner of each panel is the motion-corrected Reynold's stress (integral of the blue line) in units of $1\text{e-4 m}^2\text{s}^{-2}$	44
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725	Fig. 12.	Time series of mean velocities (A), turbulence energy and its components (B), Reynold's stresses (C), and turbulence dissipation rate (D) measured by the TTM during the June 2014 deployment. Shading indicates periods of ebb ($\bar{u} > 1.0$, grey) and flood ($\bar{u} < -1.0$, lighter grey).	45
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729	Fig. 13.	$P_{u\bar{z}}$ vs. ε during the June 2014 TTM deployment for values of $ u > 1$ m/s. Values of negative production are indicated as open circles.	46
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731	Fig. 14.	A log-log plot of ε vs. \bar{U} for the June 2014 TTM (diamonds) and May 2015 StableMoor (dots) deployments, during ebb (left) and flood (right). Black points are 5-minute averages. Green dots are mean values within speed bins of 0.2 m s^{-1} width that have at least 10 points (50 minutes of data); their vertical bars are 95% bootstrap confidence intervals. The blue line shows a U^3 slope, wherein the proportionality constant (blue box) is calculated by taking the log-space mean of ε/U^3	47
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737	Fig. 15.	Coherence between IMU-measured motion of StableMoor buoy and ADP bottom-track velocity for $1.0 < \bar{U} < 1.5$. The horizontal dashed line indicates the 95% confidence level for the 102 spectral windows in this estimate. The vertical dotted line indicates the frequency of the high-pass filter applied to the IMU accelerometers in estimating \vec{u}_h	48
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741 FIG. 1. Bathymetry of Admiralty Inlet near Port Townsend, Washington, U.S.A. (Finlayson 2005). The red
 742 dot indicates the location of all measurements. The positive u direction is the direction of ebb flow (thick arrow
 743 originating from red dot), and positive v is away from Admiralty Head (smaller arrow).

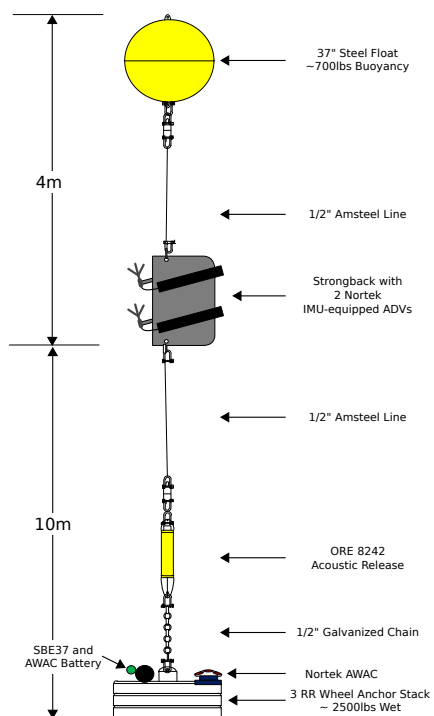


FIG. 2. Schematic diagram of the TTM; not to scale.



744 FIG. 3. TTM components on the deck of the R/V Jack Robertson. The TTM includes two ADVs, with
 745 pressure cases mounted on opposite sides of the fin. The anchor stack includes a pop-up buoy for retrieval. The
 746 green arrow indicates the vector from the IMU to the ADV head (face of the transmit transducer).



747 FIG. 4. Top: Alex DeKlerk checks to ensure that the StableMoor buoy is properly fastened to its anchor; the
 748 RDI workhorse ADCP can be seen in the rear instrument bay. A bridle is draped across the top of the buoy
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 750 close-up of the StableMoor buoy with the ADV head and the top of its pressure case. The green arrow indicates
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752 FIG. 5. The turbulence platform showing details of the ADV head and pressure case configuration. The green
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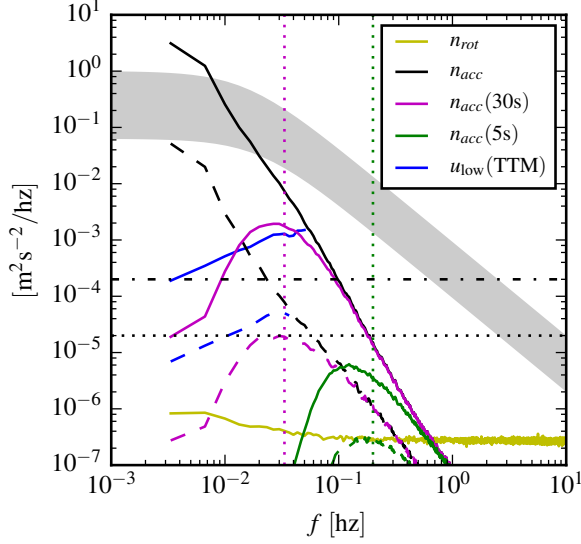
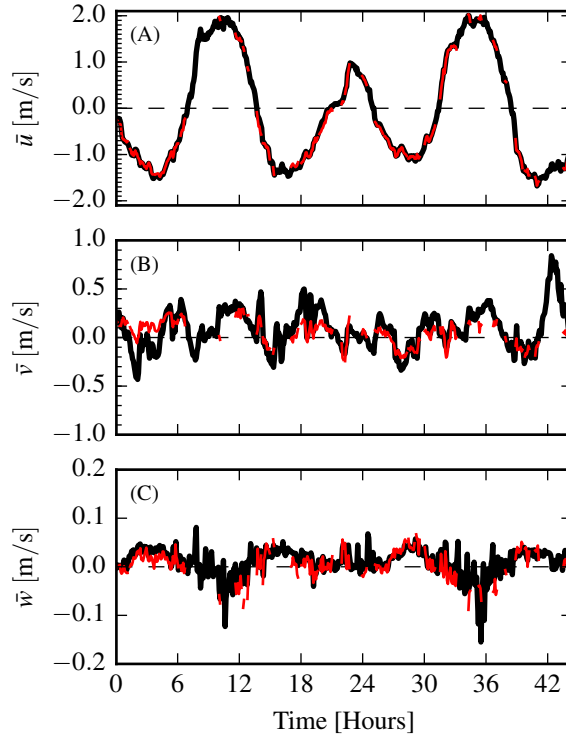


FIG. 6. Spectra of \vec{u}_ω (yellow) and \vec{u}_a signals from the Microstrain IMU sitting on a motionless table. The \vec{u}_a signals are unfiltered (black), and high-pass filtered at 30 s (magenta) and 5 s (green). Vertical dotted lines indicate the filter frequency. Blue lines are an estimate of \vec{u}_{low} for the TTM. Solid lines are the horizontal components, and dashed lines are the vertical components of \vec{u}_a and \vec{u}_{low} . The horizontal and vertical Doppler noise levels of a Nortek Vector ADV configured to measure $\pm 4\text{m/s}$ are indicated by horizontal dash-dot and dotted lines, respectively. The shaded region indicates the range of u spectral amplitudes presented herein ($0.002 < \text{tke} < 0.03 \text{ m}^2/\text{s}^2$, $1\text{e-}5 < \varepsilon < 5\text{e-}4 \text{ W/kg}$).



762 FIG. 7. Time series of tidal velocity at Admiralty Head from ADV-IMU measurements (black), and an acoustic
 763 Doppler profiler on the anchor (red). The profiler measurements—taken at the same depth as the ADV on the
 764 TTM—were contaminated by acoustic reflection from the strongback fin when it was inline with one of the
 765 profiler's beams. Note that the vertical scale on the three axes vary by more than an order of magnitude; the
 766 small ticks in A and B are equivalent to the ticks in C.

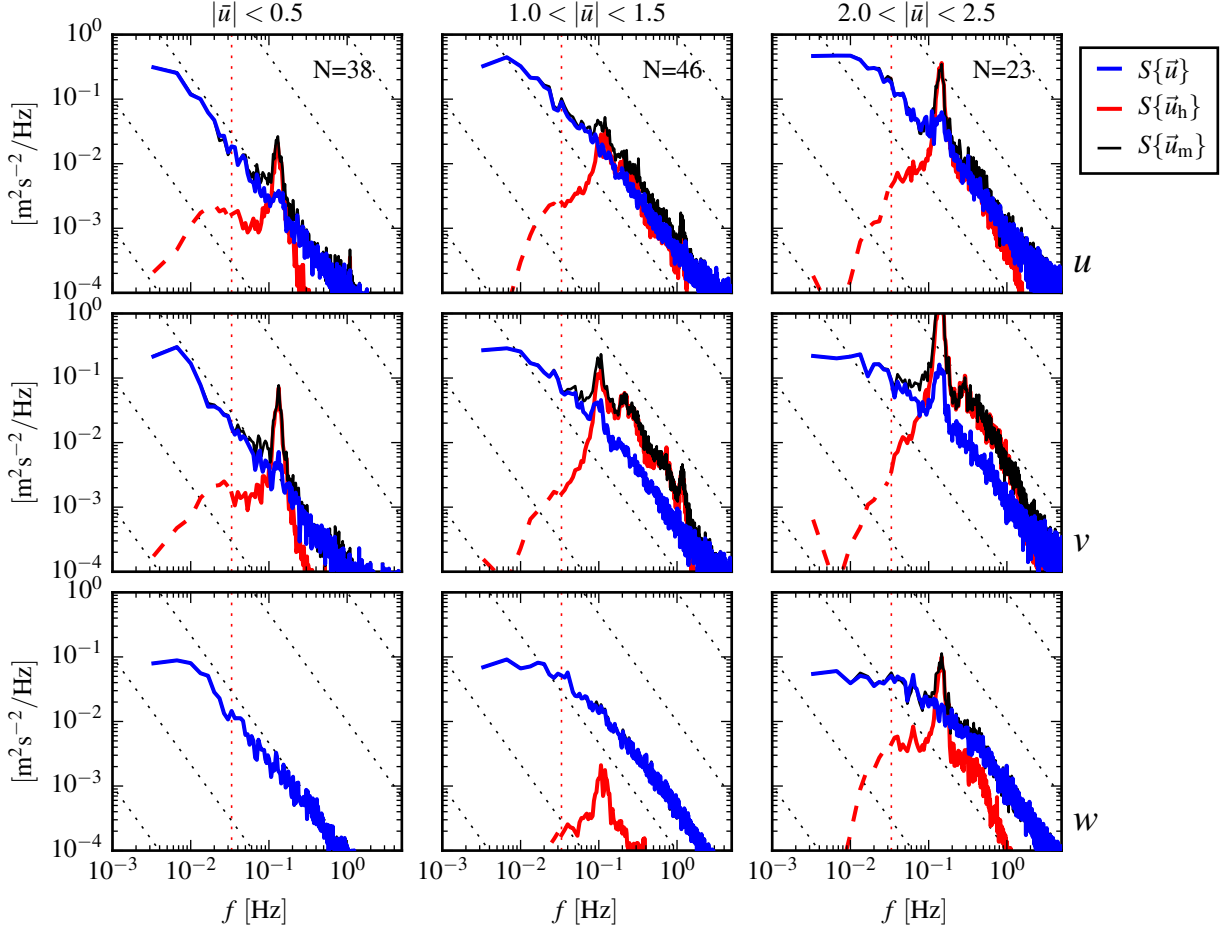


FIG. 8. Turbulence spectra from the June 2014 TTM deployment. Each column is for a range of streamwise velocity magnitudes (indicated at top). The rows are for each component of velocity (indicated to the lower right of the right column). The uncorrected spectra are in black and the corrected spectra are blue, and the spectra of ADV head motion, \vec{u}_h , is red (also indicated in the legend). The vertical red dotted line indicates the filter frequency applied to the IMU accelerometers when estimating \vec{u}_h ; below this frequency $S\{\vec{u}_h\}$ is plotted as a dashed line. Diagonal black dotted lines indicate a $f^{-5/3}$ slope. The number of spectral ensembles, N , in each column is indicated in the top row.

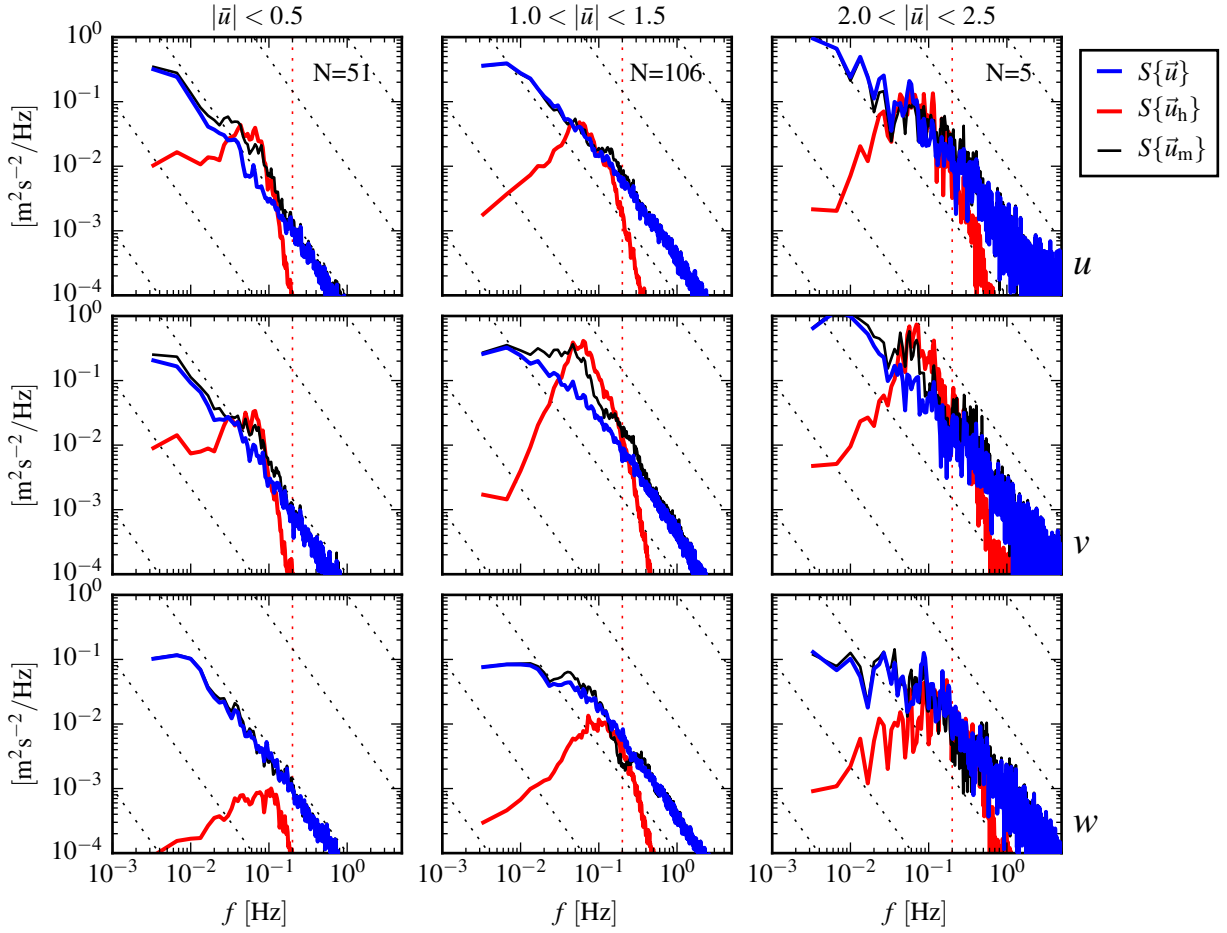
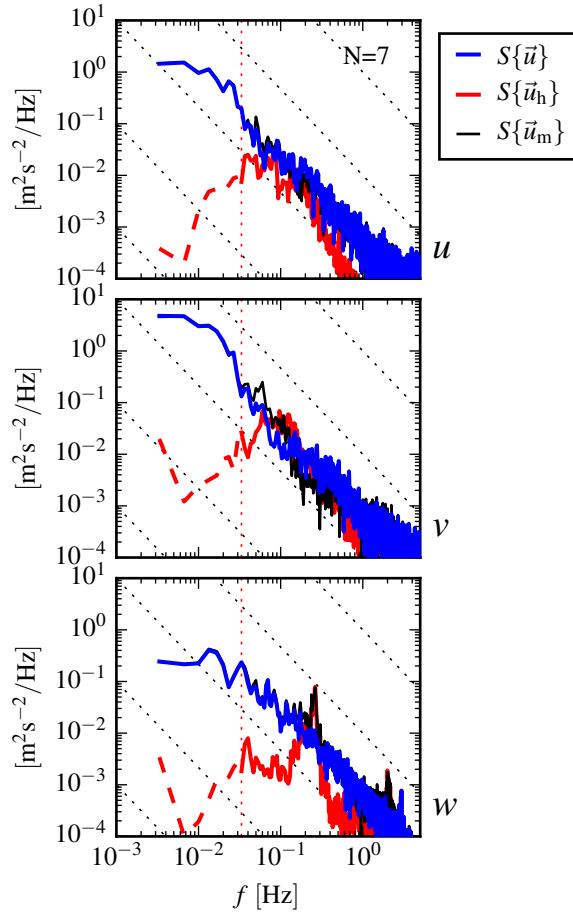


FIG. 9. Turbulence spectra from the StableMoor buoy. The axes layout and annotations are identical to Figure 8, except that $S\{\vec{u}_h\}$ is plotted as a solid line at all frequencies because it is measured at all frequencies.



776 FIG. 10. Turbulence spectra from the turbulence torpedo during a 35-minute period when the mean velocity
 777 was 1.3 m/s. Annotations and line colors are identical to Figure 8.

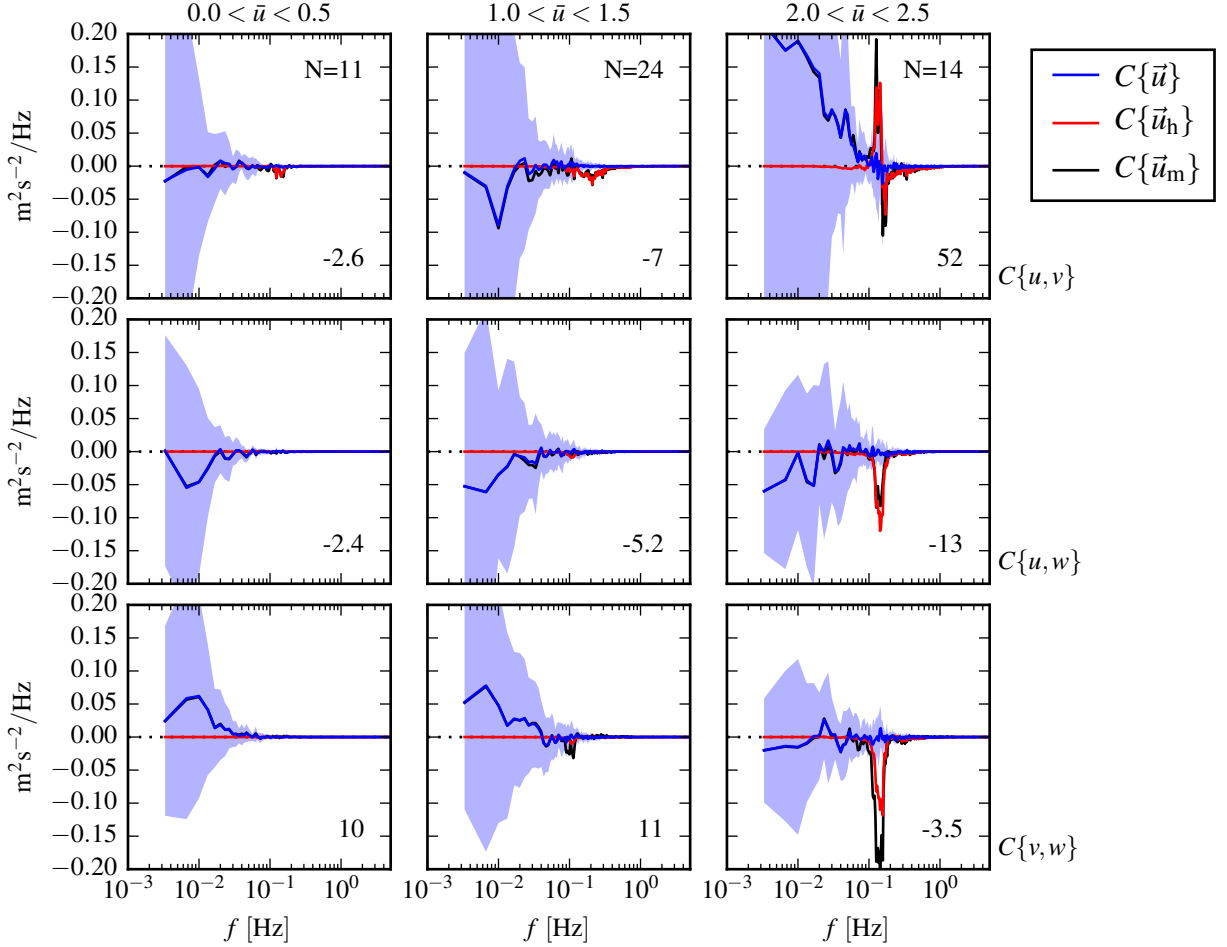


FIG. 11. The real part of the cross-spectral density between velocity components measured by the TTM. The upper row is the u - v cross-spectral density, the middle row is the u - w cross-spectral density, and the bottom row is the v - w cross-spectral density. The columns are for different ranges of the stream-wise mean velocity magnitude (indicated above the top row). The blue line is the cross spectrum between components of motion-corrected velocity, the red line is the cross spectrum between components of head motion, and the black line is the cross spectrum between components of uncorrected velocity. The light blue shading indicates one standard deviation of the C for the motion-corrected cross-spectral density. N is the number of spectral ensembles in each column. The number in the lower-right corner of each panel is the motion-corrected Reynold's stress (integral of the blue line) in units of $1\text{e-}4 \text{ m}^2\text{s}^{-2}$.

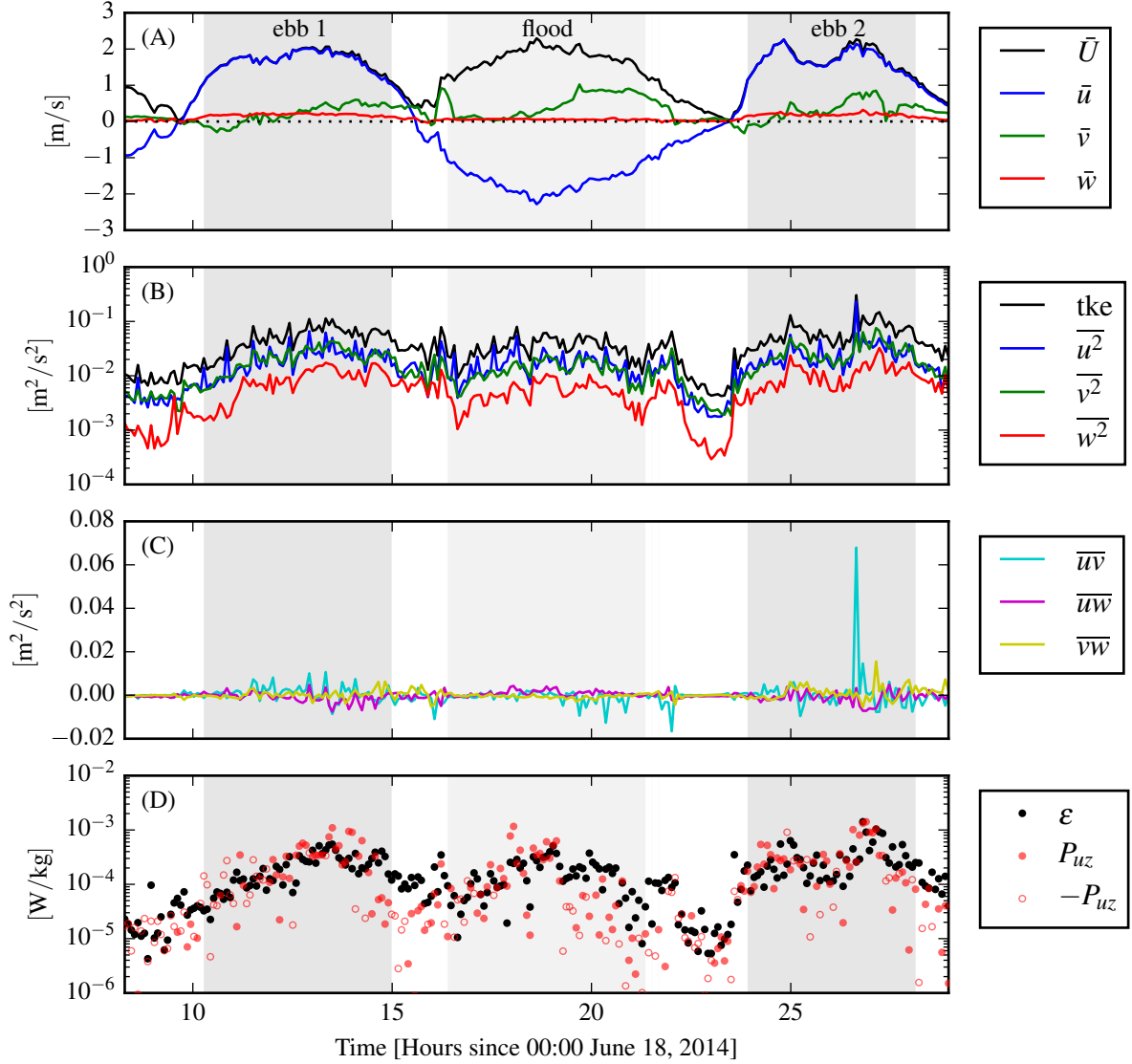
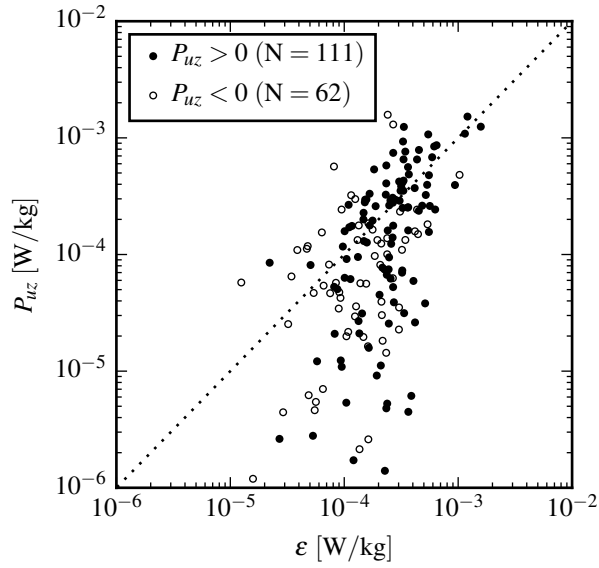


FIG. 12. Time series of mean velocities (A), turbulence energy and its components (B), Reynold's stresses (C), and turbulence dissipation rate (D) measured by the TTM during the June 2014 deployment. Shading indicates periods of ebb ($\bar{u} > 1.0$, grey) and flood ($\bar{u} < -1.0$, lighter grey).



790 FIG. 13. P_{uz} vs. ε during the June 2014 TTM deployment for values of $|u| > 1$ m/s. Values of negative
791 production are indicated as open circles.

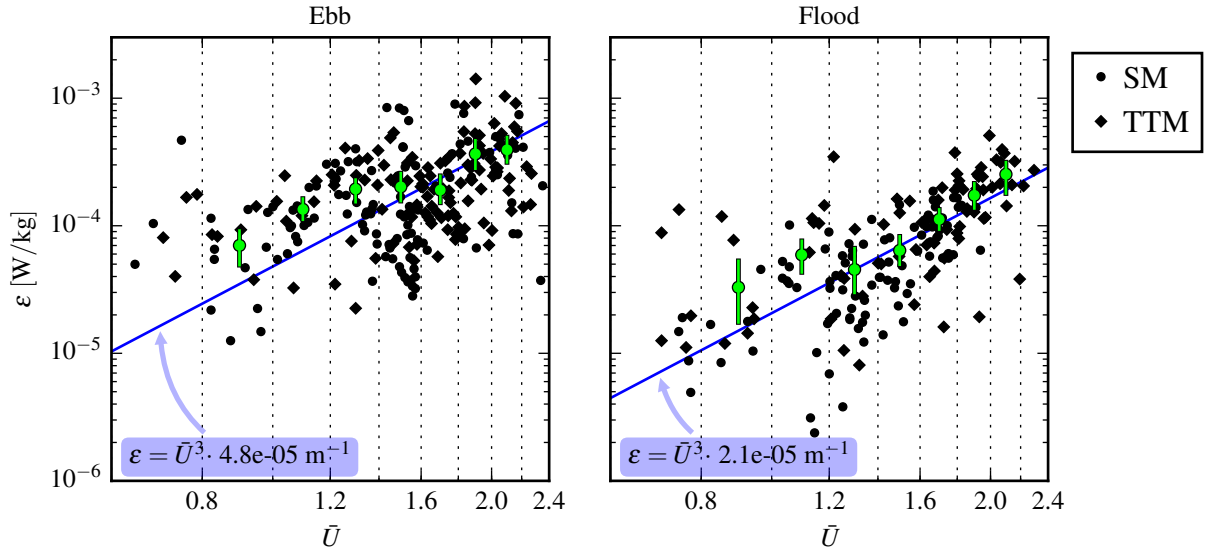


FIG. 14. A log-log plot of ϵ vs. \bar{U} for the June 2014 TTM (diamonds) and May 2015 StableMoor (dots) deployments, during ebb (left) and flood (right). Black points are 5-minute averages. Green dots are mean values within speed bins of 0.2 m s^{-1} width that have at least 10 points (50 minutes of data); their vertical bars are 95% bootstrap confidence intervals. The blue line shows a U^3 slope, wherein the proportionality constant (blue box) is calculated by taking the log-space mean of ϵ/U^3 .

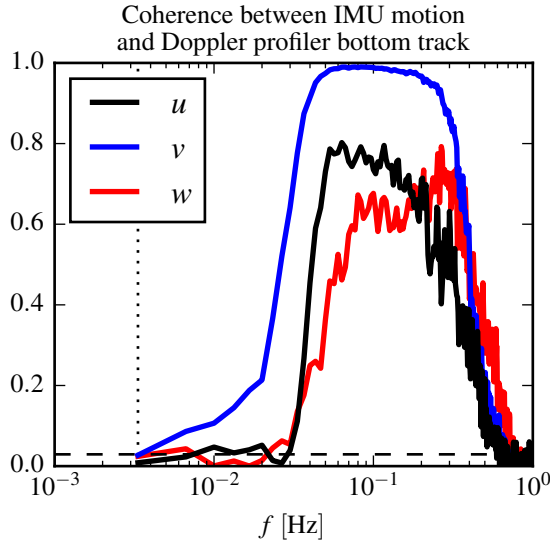


FIG. 15. Coherence between IMU-measured motion of StableMoor buoy and ADP bottom-track velocity for $1.0 < \bar{U} < 1.5$. The horizontal dashed line indicates the 95% confidence level for the 102 spectral windows in this estimate. The vertical dotted line indicates the frequency of the high-pass filter applied to the IMU accelerometers in estimating \vec{u}_h .