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MULTI-SCALE COHERENT TURBULENCE AT TIDAL ENERGY SITES

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ABSTRACT

Turbulence is known to affect the performance and survivability of tidal turbines, yet characterization of turbulence in the field remains limited. Here, we refine and demonstrate a new approach to turbulence measurements, in which an array of multiple Acoustic Doppler Velocimeters (ADV) is suspended above the seabed at the hub height of a tidal turbine. These measurements provide information on the intensity, structure, and coherence of turbulence across the scale of a turbine rotor ($<$ 10 m). Deployment of multiple moorings expands the analysis to array scales ($>$ 10 m). Motion correction of the moored ADV data is essential to this approach and is verified using the turbulent kinetic energy spectra. Additional measurements include a bottom-mounted 5-beam Acoustic Doppler Current Profiler, from which scales can be assessed using the velocities a separation distances along a given beam. These methods are demonstrated with data collected at the site of the Snohomish PUD pilot project in Admiralty Inlet, Puget Sound, WA (USA), where two OpenHydro turbines are planned for deployment. Coherent motion is found to be largely isotropic, such that coherence is high only at scales less than the advective length scale or the water depth, whichever is less.

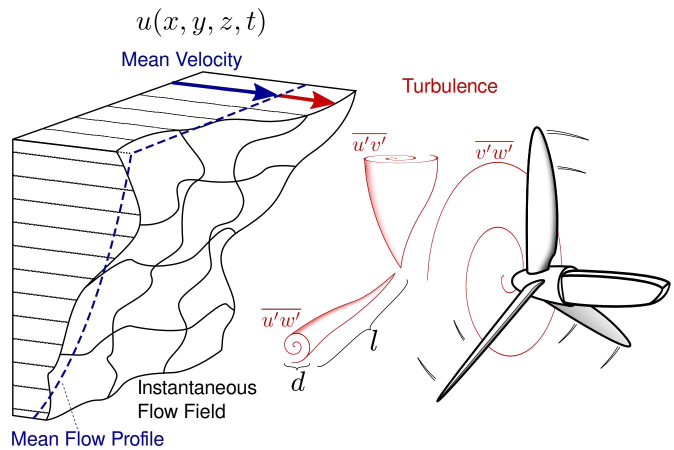

FIGURE 1. A schematic of an MHK turbine in a turbulent flow field. The turbulence (red) is superimposed on the mean velocity profile (blue). Eddies in different orientations contribute to different components of the Reynold's stress ($\overline{u'w'}$, $\overline{u'v'}$, $\overline{v'w'}$). the energy, size (d) and length (l) of these eddies are important to turbine fatigue loading. adapted from [7]

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1 INTRODUCTION

High-fidelity turbulence measurements are needed to generate accurate fatigue-load estimates from numerical simulations of marine and hydrokinetic turbines. In particular, comprehensive turbulence datasets at tidal, river and ocean-current sites are needed. Critical statistics of these datasets include: turbulence intensity, mean shear, the turbulent kinetic energy (TKE) spectrum, Reynold's stresses and spatial coherence (i.e., length) of turbulent eddies (Figure 1). Results from the wind industry indicate that these turbulence statistics determine device fatigue loads and performance [1–3]. Mean shear can induce variable loads across a turbine rotor, for example. The TKE spectrum and Reynold's stresses quantify the size, amplitude and orientation of turbulent eddies that can shake a blade or the entire rotor.

The present study focuses on spatial coherence in the turbulence, which is an indicator of the length l of eddies as a function of their diameter d (see Figure 1). Longer eddies are likely to induce larger fatigue loads on turbines. An eddy that hits the entire blade, for example, will induce a larger load on that blade than an eddy of equal amplitude and shorter length. Measurements of coherence are strongly affected by the Eulerian (fixed) ref-

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erence frame in which the measurements are typically collected (and which is most relevant for a fixed turbine). Following Taylor's hypothesis, eddies are assumed to be 'frozen' as they advect with the mean flow $\bar{u}$, such that time and length scales are related as

$$2\pi l = \frac{\bar{u}}{f}, \tag{1}$$

where f is the cyclic frequency in a TKE spectrum. Of course, at very large length scales and very low frequencies, the frozen assumption is invalid (and the eddies evolve significantly as they advect past a given location).

Most flow measurements at tidal, river, and ocean site use acoustic Doppler instruments. Two classes are worth distinguishing: 1) profiling instruments, which can be conveniently bottom-mounted but have high noise levels and poor spatial localization, and 2) point instruments, which are more difficult to deploy at typical turbine hub-heights but have low noise and excellent spatial localization. Thomson et al. apply both at tidal sites [4] and determine that profilers are useful for many bulk statistics, including total Reynold's stress [5], but that point measurements are necessary for high-quality TKE spectra and coherence estimates. Here, we extend ongoing work to use moored acoustic Doppler velocimeters (ADVs) that are equipped with inertial motion sensors as point measurements of the turbulence [6, 7]. We evaluate the coherence at different separations and interpret the results in terms of the length scales in the flow, and we compare with a results from a new 5-beam acoustic Doppler profiler.

2 METHODS

The primary dataset used in this work was collected at the Admiralty Head site (Figure 2, yellow) for three days in June 2014. The water-depth at this site is approximately 55m deep and 500m southwest of Admiralty Head. The data was collected from a compliant 'Tidal Turbulence Mooring' (hereafter TTM) with ADVs mounted at 10 m nominal height above the seafloor. (The actual height varies with mooring angle.) The ADVs were sampled continuously at 32 Hz. Two original TTMs (Figure 3) were deployed with a separation of 50 m, and one new "X-Wing" version was deployed (Figures 4 and 5) nearby.

The ADVs were equipped with MicroStrain 3DM-GX3-25 inertial motion sensors (IMU) that recorded ADV orientation and all 6 degrees of motion (3 rotation, 3 acceleration) synchronous with each velocity measurement [9]. Thomson et al. showed that mooring motion can effectively be removed from the TKE spectrum using quasi-synchronous IMU measurements and 'spectral motion correction' methods [6]. Kilcher et al. show that moored synchronous IMU-ADV measurements can be used to remove mooring motion in the time-domain [7]. The time domain re-

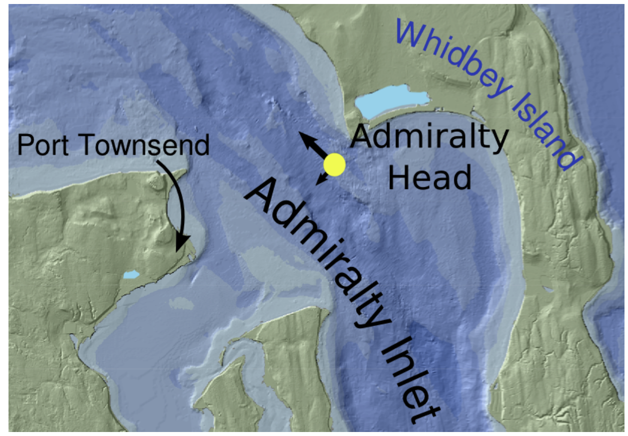

FIGURE 2. Map of admiralty inlet indicating locations of the marrowstone island (blue) and admiralty head (yellow) measurement sites [8]. Stream-wise and cross-stream principal axes directions are indicated by large and small arrows, respectively, at each dot.

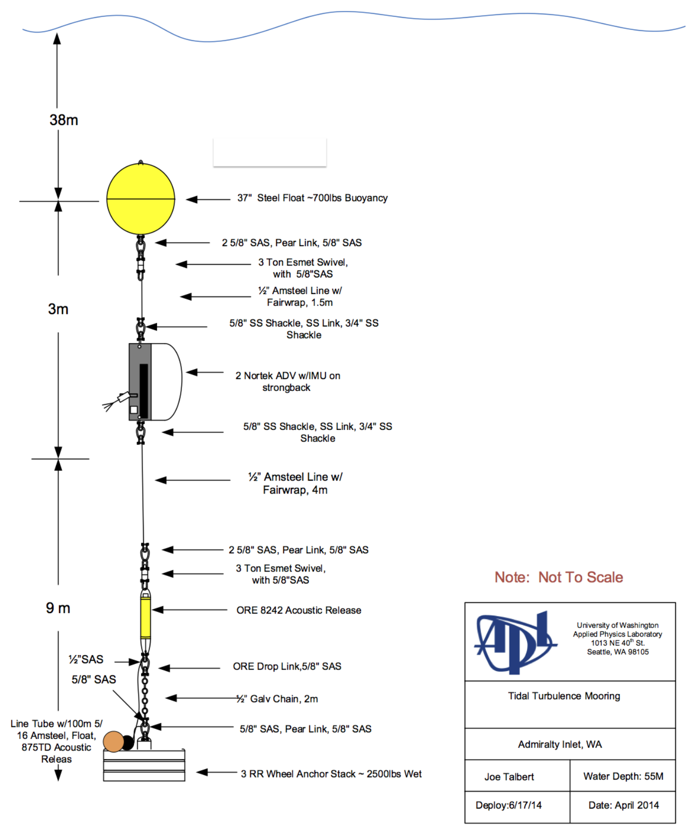

FIGURE 3. Original TTM mooring.

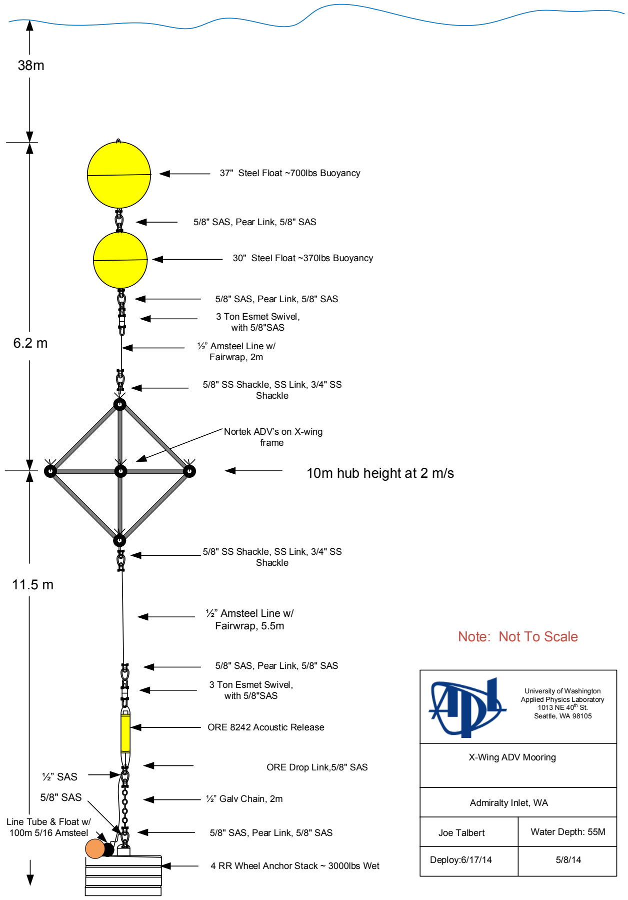

FIGURE 4. Xwing version of TTM mooring (face view).

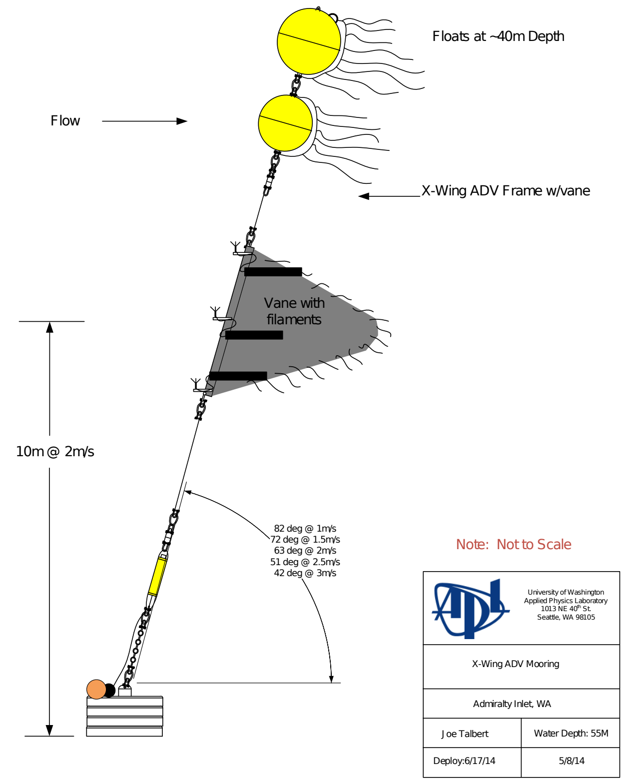

FIGURE 5. Xwing version of TTM mooring (side view).

sults are essential for estimating coherence between different instruments.

This dataset also includes velocity profile measurements from an upward-looking Nortek Signature 5-beam Doppler profiler mounted on a "sea spider" tripod place on the seafloor. This sampled raw along-beam velocities at 8 Hz in 0.5 m bins.

2.1 Motion Correction

ADVs on mooring lines change orientation and measure a velocity signal that is contaminated by the mooring's motion. Motion correction is crucial to the goal of coherence estimates between velocity measurements, because the shared motion of two instruments on the same mooring can cause spurious appearance of significant coherence in the two velocity measurements. Or, the independent motion of two separate moorings can cause the spurious appearance of no coherence between two velocity measurements, when in fact the flow may be coherent at those scales.

The orientation and motion resolved by tightly synchronized (with the ADV measurements) low-noise, low-bias IMUs can be used to correct for these effects in post-processing via

$$\vec{u}(t) = \vec{u}_{\mathrm{ADV}}(t) + \vec{u}_{\mathrm{m}}(t) \quad . \tag{2}$$

Here $\vec{u}_{\mathrm{ADV}}$ is the uncorrected (raw) ADV velocity signal and $\vec{u}_{\mathrm{m}}$ is the ADV sensor's motion. Note that the sign of $\vec{u}_{\mathrm{m}}$ in (2) is correct because the motion-induced velocity measured by the ADV is opposite its motion. $\vec{u}_{\mathrm{m}}$ is computed from the IMU rotation rate vector ($\vec{\omega}$) and linear-acceleration ($\vec{a}$) as,

$$\vec{u}_{\mathrm{m}}(t) = \vec{\omega}(t) \times \vec{\ell} + \int \vec{a}'(t)\mathrm{d}t \quad , \tag{3}$$

where ℓ is the vector from the IMU to the ADV sensor-head and $\vec{a}'$ is the high-pass filtered IMU acceleration and all quantities

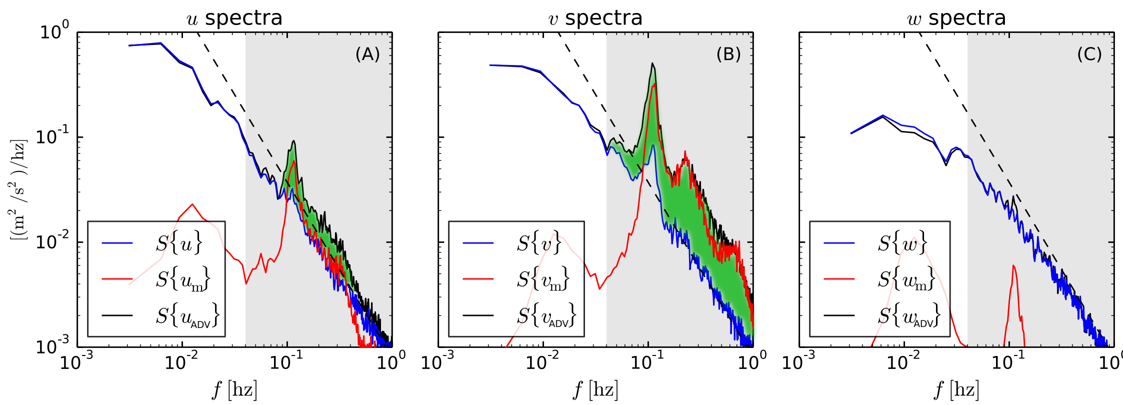

FIGURE 6. Velocity spectra from a single ADV on a TTM, A: u-component, B: v-component, C: w-component). Spectra are of uncorrected velocity measurements ($\vec{u}_{\mathrm{ADV}}$, black), ADV-head motion ($\vec{u}_{\mathrm{m}}$, red), and motion-corrected velocity ($\vec{u}$, blue). Green shading indicates the influence of motion correction. The gray-shaded region indicates the isotropic 'inertial sub-range'.

are in the earth-frame (rotated using the time-dependent IMU-supplied orientation matrix). Finally, all velocity signals are rotated into a right-handed 'principal axes' coordinate system such that u,x are aligned with the ebb-flood direction ($+u,+x$: ebb), v,y the cross-stream direction and $+w,+z$ the vertical-up direction. For the Admiralty Head sites this corresponds to the $+u$ direction at 312°T (Figure 2).

While spectra of $\vec{u}_{\mathrm{ADV}}$ have peaks that indicate motion contamination (Figure 6), motion correction removes the vast majority of this contamination such that the u, v and w motion-corrected spectra have similar amplitude and have a $f^{-5/3}$ slope in the inertial sub-range [10,]. The v-component spectra has a persistent motion-contamination peak due to the large amplitude of the sensor-motion in that direction, but it seams reasonable to interpolate over this peak when estimating the v-component spectra. This suggests that motion corrected moored ADV measurements can provide reasonable estimates of the TKE spectrum.

2.2 Data processing

The mean ($\bar{u}$) and turbulent (u') components of the stream-wise velocity are defined as,

$$u = \bar{u} + u' \qquad . \tag{4}$$

Here the over-bar denotes a 5-minute average. Analogous expressions apply for the v and w components. The separation of mean-flow from turbulence at 5-minutes was chosen so that tidal variability can be considered negligible - and turbulence stationary - within a segment [11].

TKE spectra are computed using a fast Fourier transform (FFT or $\mathscr{F}$) of 5-minute detrended, hanning-windowed segments with 50% overlap, $S(u) = |\mathscr{F}(u')|^2$. Spectra are then grouped by mean velocity to obtain spectra with approximately 20 degrees of freedom. Spatial coherence (Γ) is estimated from two independent measurements of the same component of velocity (e.g. u_1 and u_2) that are separated in space by a distance $r = (\Delta x^2 + \Delta y^2 + \Delta z^2)^{1/2}$,

$$\Gamma(u) = \frac{|\overline{\mathscr{F}(u_1')\mathscr{F}(u_2')}|^2}{\overline{S(u_1)}\,\overline{S(u_2)}} \qquad . \tag{5}$$

Here the over-bar denotes a 5-minute ensemble average of 128-second FFTs. The 95% confidence level of Γ measurements - above which Γ estimates can be considered valid with 95% confidence - is equal to $\sqrt{6/n_{\mathrm{DOF}}}$, where n_{DOF} is the number of degrees of freedom in the coherence estimate [12].

3 RESULTS

Results from both the ADVs on the moorings and the profiler on the seabed suggest that spectral coherence is a strong function of separation distance. This is expected, because in the theoretical turbulent cascade from large eddies to small eddies, the small scale fluctuations (high f) evolve rapidly and are less correlated than large scale fluctuations (low f). Thus, in equation (1), there is an expected change around the frequency $f_r = \frac{\bar{u}}{2\pi r}$ for a given separation r. At frequencies higher than f_r, the eddy length scales l are less than the separation r of the measurements and thus motions are not expected to be correlated. At frequencies lower than f_r, the eddy length scales l are longer than the separation r of the measurements and thus the motions can be expect to be correlated.

In Figure 7, two ADVs on the same mooring demonstrate this effect. Coherence is close to unity at low frequencies, for

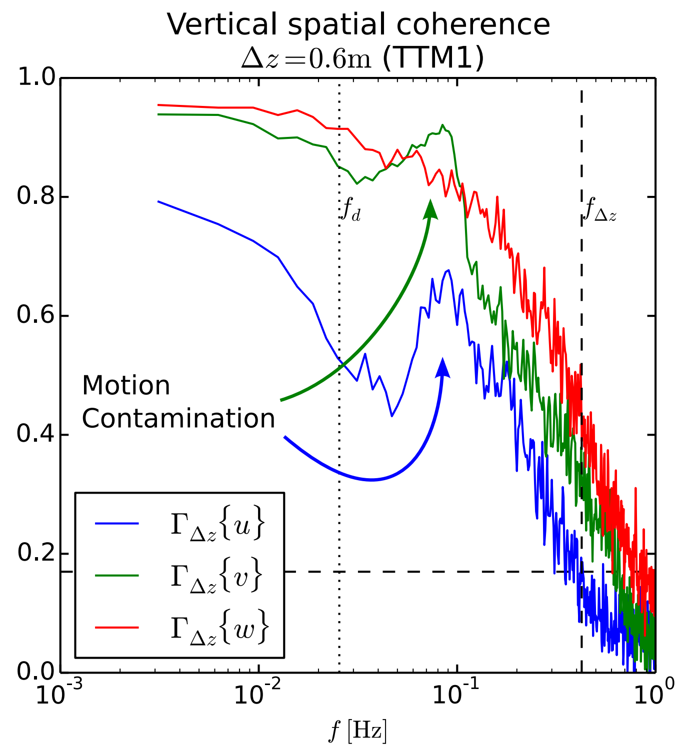

FIGURE 7. Coherence of ADVs separated 1 m on a single TTM. The u and v component coherence estimates are contaminated by mooring motion at 0.1Hz.

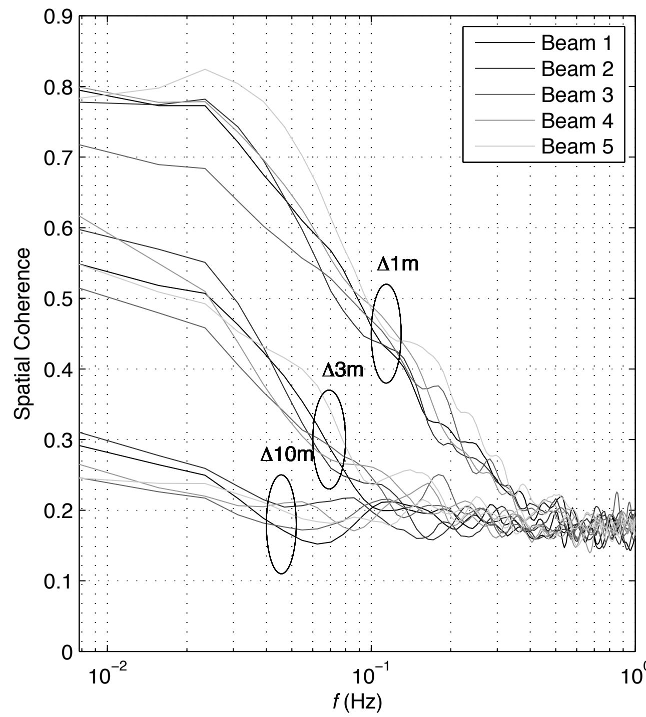

FIGURE 8. Coherence of along-beam velocities as a function of frequency for three vertical different separation distances

which large eddies completely engulf both instruments. Coherence decreases with frequency, and at approximately $f \approx 0.5$ Hz, coherence becomes statistically insignificant. For the $\bar{u} \approx 2.5$ m/s flows that are common to this site, the loss of coherence is very close to the predicted separation frequency $f_r = f_{\Delta z} = 0.42$ Hz.

This pattern is continued in the beam-wise velocity measurements from the seabed-mounted profiler. Using the bins at 10 m above the seabed (i.e., the nominal turbine hub height) as a reference, the coherence in the beam-wise velocities at positive vertical separations of 1, 3, and 10 m along each of the five beams was calculated. The results are presented in Figure 8. Coherence is highest at low frequencies and decreases to no significance at $f_r \approx 0.42$, 0.13 and 0.08 Hz, respectively, each at nearly the expected separation frequency. Note that each beam is at a different angle and thus each along-beam velocity is a different projected component of the flow. The similar results for each beam suggest that isotropy is a valid assumption at these scales.

Finally, two TTMs deployed at different locations demonstrate the limitations of predicting coherence with the separation frequency. For two TTMs separated by 50 m, Figure 9 shows that there is no coherence at any frequency. This is likely because the separation distance is close to the water depth, which Thomson et al. suggest is the limiting length scale for isotropic turbulence [6]. Furthermore, the predicted $f_r \approx 0.008$ Hz for 50 m separation is close the lowest frequency band of the TKE spectrum, which is expected to be contaminated by non-stationarity in the tidal flow. Even though the turbulence is not coherent at these separations, the mean flow has spatial variations on these scales that are repeatable and can be quantified to high precision [13].

4 Conclusions and Future Work

In order to accurately estimate MHK device lifetimes, hub-height measurements of the spectra and coherence of turbulence at tidal energy sites are needed. This paper demonstrates that mooring-deployed, IMU-equipped ADVs provide reasonable estimates of these quantities. The u- and w-component spectra have an ‘inertial sub-range’ in which the spectra decay as $f^{-5/3}$ and have the same amplitude throughout this region. The v-component spectra has ‘persistent’ motion contamination at the ‘mooring sway’ frequency of 0.1Hz, but this can be easily accounted for by interpolation and/or comparison with the u- and w-spectra.

Spatial coherence estimates indicate that the separation dis-

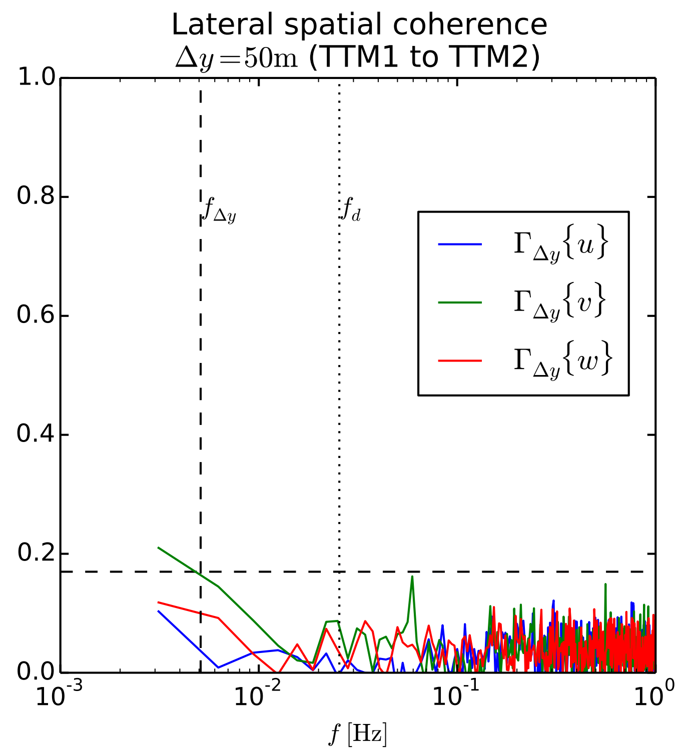

FIGURE 9. Coherence of ADVs on separate TTMs 50 m apart

tance is the dominant variable that defines this statistic. This is consistent with coherence measurements in the atmospheric boundary layer [14]. ADVs on a single mooring produces reliable estimates of the *w*-component spatial coherence, but *v*- and *u*- component coherence estimates are contaminated by 'persistent' motion contamination. These early results indicate that the water-depth, provides an outer limit on the length-scale of the coherence.

Reducing mooring motion will increase the accuracy of the measurements and reduce persistent motion contamination in the *v*-component spectra, and *u*- and *v*-component coherence estimates. The team is currently investigating new, larger ADV-mounts that are expected to significantly reduce mooring motion.

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