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Multi-Scale Tidal Resource Characterisation: A Case Study for Admiralty Inlet, Puget Sound, WA (USA)

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Abstract

Site-specific tidal current resource information is required to optimise power generation from turbines and develop realistic design loads. This is challenging for length scales ranging from several kilometers (preliminary site investigation) to less than one hundred meters (micrositing) and time scales ranging from a month (power generation estimates) to fractions of a second (descriptions of turbulence). Approaches to collect multi-scale data in an accurate, cost-effective manner are, therefore, of interest to the tidal energy industry.

Results are presented from a multi-year resource characterisation study in Admiralty Inlet, Puget Sound, WA (USA). This site has been identified as having the greatest tidal energy resource potential in the continental United States and a pilot-scale tidal energy project is currently under development. Shipboard surveys using Doppler profilers are shown to effectively characterise operationally significant kinetic resource gradients at length scales down to 100 m. Survey effectiveness is benchmarked against ground-truth from simultaneously deployed bottom-mounted current profilers. This type of shipboard survey enables targeted long-term, bottom-mounted Doppler profiler deployments that can quantify, with high accuracy, the time variation of kinetic resources from monthly and turbulent time scales. Observations indicate kinetic resource variations greater than 10% can occur over distances less than 100 m.

Keywords: Doppler profiler, hydrokinetic energy, resource characterisation, tidal energy

1. Introduction

The energy in fast-moving tidal currents can be harnessed to provide predictable, renewable electricity. The approach is analogous wind energy and first-generation tidal turbines have been able to leverage technology developed by the wind energy industry. The time-varying kinetic power density (*K*), a measure of resource intensity closely linked to economic viability, is given by:

$$K(x, y, z, t) = \frac{1}{2}\rho U(x, y, z, t)^3$$

where ρ is the density of the working fluid and U is the magnitude of the horizontal velocity. This cubic dependence amplifies variations in velocity with respect to project economics.

The length scales over which these variations must be characterised depend on the stage of development. Initial site assessments to characterise areas with potentially energetic resources are concerned with length scales ranging from 10^3 to 10^4 m. A preliminary estimate of power generation from a single device or a small, sparse array requires information about variability on the order of inter-turbine spacing in the horizontal dimension (10^1-10^3 m) and over the order of the rotor diameter in the vertical dimension (10^0-10^1 m). Finally, detailed structural designs require information about turbulent length scales ranging from

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the rotor diameter to blade chord (10^{-1}-10^{0} m). In total, these length scales span five decades of resolution.

The temporal scales over which resource variations are of interest are similarly broad. [1] describes tidal currents as a superposition of physical processes as:

$$U(x,y,z,t) = U_{\mathrm{det}} + U_{\mathrm{met}} + U_{\mathrm{turb}}$$

where these are the deterministic, meteorological, and turbulent components. Deterministic currents (U_{det}) are defined as the harmonic forcing from lunar- and solar-induced tides, along with the non-linear response to this forcing resulting from local topography and bathymetry. The harmonic forcing varies meaningfully over time scales from a fraction of an hour (10^3 s) to the 18.6 year tidal epoch (10^9 s). The non-linear response, such as the regular formation and propagation of eddies around headlands contributes to variability on time scales from several minutes (10^2 s) up to an hour. Meteorological currents (U_{met}) include density-driven currents (seasonal variability), storm surges (annual variability), and wave-induced currents (10^1 s for an individual wave to 30 years (10^9 s) for a major storm return period). Turbulence (U_{turb}) contributes to variability on time scales from several minutes (10^2 s) to fractions of a second (10^{-2} s and shorter). In total, temporal variations span eleven decades of resolution.

Given the broad range of length and time scales that are of potential interest and the cost of oceanographic measurements, methods are required to optimise survey effectiveness. It is neither effective, nor recommended, to collect information about all potentially relevant temporal scales over a range of spatial scales. Here, we focus on techniques to resolve scales of spatial variability relevant to siting of individual devices in a small array. Observations from a specific site are provided as a case study. First, the case study site is briefly described. Second, observations of spatial variability derived from a multi-year measurement campaign involving bottom-mounted Doppler profilers are presented. Finally, a technique capable of measuring resource variations over spatial scales of 10^2 – 10^3 m at a fraction of the cost of multiple bottom-mounted deployments is described.

2. Case Study Site

The case study site is Admiralty Inlet, a narrow constriction at the mouth of Puget Sound, Washington, (USA) (Fig. 1). The channel is 5 km wide at its narrowest point, with water depths ranging from 50-100 m, and peak currents exceeding 3 m/s. Public Utility District No. 1 of Snohomish County has proposed to deploy a pair of turbines manufactured by OpenHydro, Ltd. as a demonstration project at this location [2]. This location could support future large-scale tidal energy development [3].

Tidal currents in northern Admiralty Inlet are mixed, mainly semidiurnal in character with two ebb and flood tides of unequal strength each lunar day. Of the current components described in the introduction, only the deterministic (U_{det}) and turbulent (U_{turb}) currents are significant at this location. The wave climate is mild and orbital velocities decay completely well above the depth of expected turbine deployment, storm surges are not appreciable due to regional wind patterns, and density-driven currents are small in comparison to deterministic currents over most of the water column [1].

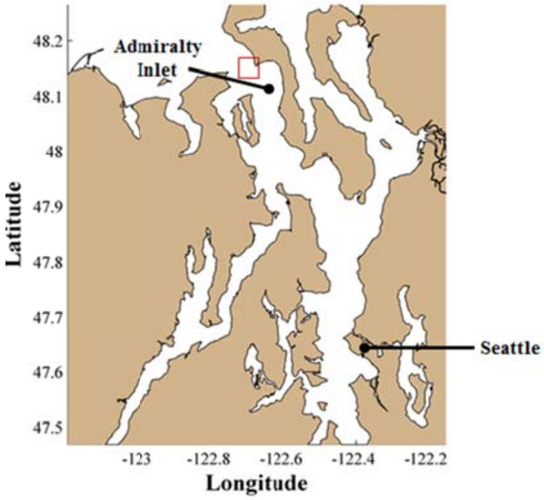

Figure 1: Puget Sound, WA (USA) and Admiralty Inlet

3. Observations with Bottom-mounted Profilers

3.1. Approach

From May 2009 – May 2012, there have been twenty bottom-mounted Doppler profiler deployments at the case study site. This analysis focuses on eight deployments within 500 m of a central, reference location (Fig. 2) to evaluate resource gradients over length scales of 10^2 m. Doppler profilers (a mix of RDI and Nortek instruments with operating frequencies ranging from 300 kHz to 1000 kHz) were deployed on ballasted tripods (OceanScience, Ltd. Sea Spiders) for periods on the order of three months. Instruments recorded vertical profiles at an interval averaging rate of 1 minute or faster and vertical bin sizes of 1-2 m. The purpose of these deployments was to characterise the physical and biological environment over a range of length and time scales, with bottom packages including Doppler profilers, broadband hydrophones, cetacean click detectors, and water quality sensors.

Recorded current profiles were post processed to eliminate contamination by surface reflection and low correlation counts. Following this, data were reduced to five minute averages in order to filter the majority of turbulence from observations [4]. Here, time-averaged kinetic power density is used to quantify spatial resource gradients in the horizontal and vertical dimensions. The uncertainty associated with averaging over a finite observation in comparison to tidal epoch values (18.6 years) is quantified through harmonic analysis of a one year observation in [1]. A 30-day average at this location has an uncertainty of 5% relative to the epoch average. Other metrics, such as asymmetries in power density between ebb and flood and directional variation should also be considered in the course of array planning [1].

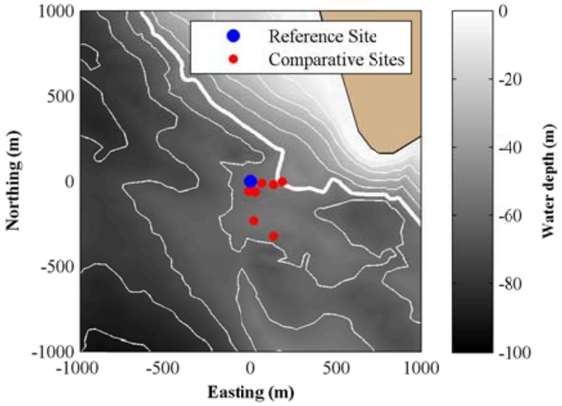

Figure 2: Bottom-mount Doppler profiler deployments

3.2. Observed Spatial Resource Gradients

Fig 3. shows time-averaged kinetic power density at mid-water, as measured by bottom-mounted profilers and normalised to the power density at a reference location (blue circle, Fig. 2). Uncertainties depend on the length of the observation. Power density may be 10% greater than at the reference location at ranges less than 100 m and 10% lower at ranges less than 500 m. As power generation potential is approximately linear with average kinetic power density, these variations are operationally significant for array planning.

Similar variations in power density are observed in the vertical direction, as shown in Fig. 4. All observations have been normalised by time-averaged water depth (H). For example, deployments at distances of 140 m and 230 m from the reference location have nearly identical power densities lower in the water column (e.g., $z/H = 0.2$), but differ by 5% at mid-water. This argues against using depth-averaged metrics for array planning.

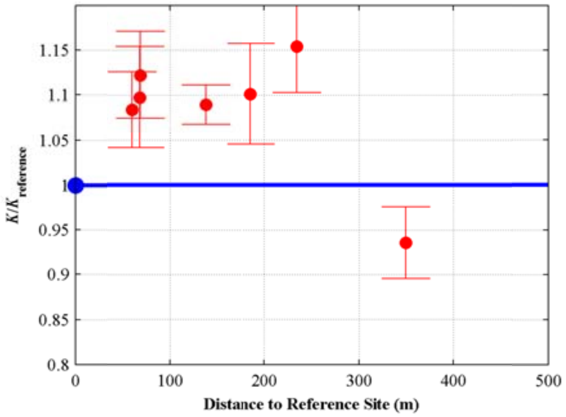

Figure 3: Observed spatial gradients in time-averaged kinetic power density relative to reference location (mid-water depth)

3.3. Survey Effectiveness

Month-long bottom-mounted Doppler profiler deployments are effective at characterising resource variations in time throughout the water column (i.e., in t and z) at a fixed position (x and y). Consequently, bottom-mounted Doppler profiler deployments can provide information about resource characteristics for both power generation estimates and engineering design. However, if, as demonstrated for the case study site, meaningful spatial variations exist over length scales on the order of 10^2 m and these variations are influenced in a non-intuitive manner by topography and bathymetry, how does one determine the optimal locations to collect this type of information?

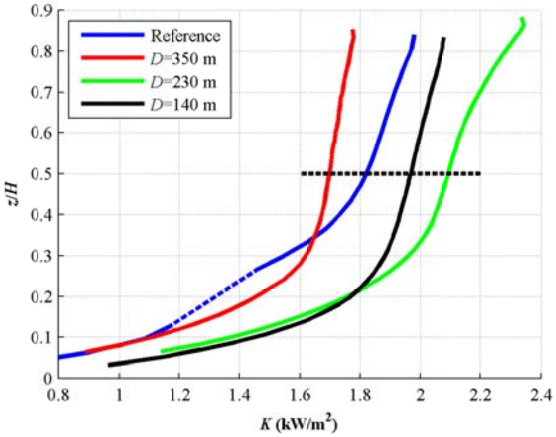

Figure 4: Observed vertical gradients in time-averaged kinetic power density (dashed line denotes depth shown in Fig. 3). Note: dashed portion of reference profile removed due to acoustic interference.

3.4. Turbulence Intensity

Month-long bottom-mounted Doppler profiler deployments also are effective at characterising bulk turbulence levels, if sampled and post-processed appropriately. The available power and memory on modern profilers is sufficient to sample and record 1 Hz data over one month. As discussed [4], the essential step in post-processing this data is to remove the fluctuations caused by instrument noise (which can be large) prior to reporting turbulence statistics. The standard metric in the wind energy industry is the turbulence intensity (I), and the appropriate noise-corrected definition is

$$I = \frac{U_{\text{turb}}}{U_{\text{det}}} = \frac{\sqrt{\sigma^2 - n^2}}{U_{\text{det}}},$$

where σ is the standard deviation of horizontal velocity in a five-minute ensemble of raw 1 Hz observations and n is the predicted Doppler noise given by the vendor software when configuring the profiler. Fig. 5 shows the results of a two separate deployments at 1 Hz, where the average turbulence intensity converges to approximately 10% over all current speeds and stages on the tide. This relative turbulence level is expected to be independent of the the observed spatial variations in deterministic velocity at this location (which demonstrates the practical utility of a normalised turbulence metric).

Deterministic time-domain turbulence information is not readily obtained from Doppler profiler measurements, but the noise-corrected statistical metric *I* has been validated against higher-fidelity point measurements [4].

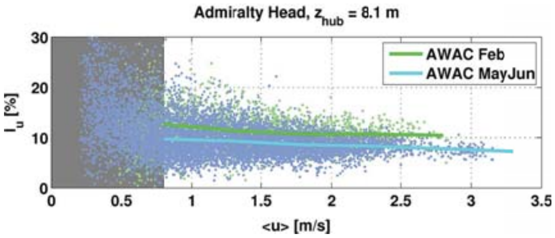

Figure 5: Turbulence intensity versus deterministic velocity (<u>) for two bottom-mounted Doppler profiler (Nortek AWAC) deployments at the comparative sites in Fig. 2. Thick lines are average intensity values for a given velocity. Gray shading below 0.8 m/s indicates a hypothetical turbine cut-in speed.

4. Observations with a Vessel-mounted Profiler

Resolving spatial gradients with vessel-mounted profilers is a potential alternative to more costly, longer-term bottom-mounted deployments. The challenge for such surveys is to avoid convolving observations of spatial resource variations with observations of temporal resource variations. Several approaches to resolving continuous velocity gradients are described in the oceanographic literature [5 – 12]. However, given the magnitude and temporal scales of turbulence and non-linear deterministic currents at energetic locations, these techniques may not produce information suitable for tidal energy array planning. For example, comparisons between locations may be biased by turbulence and not be reflective of variations in deterministic currents. Further, information about velocity variations is not as useful as information about kinetic power density variations, since the former is not directly correlated with power generation potential from a tidal turbine.

4.1. Approach

"Station-keeping" surveys are structured to obtain information about gradients in kinetic power density, over short spatial scales (i.e., 10^2 m), that is directly comparable to the information that could be obtained from bottom-mounted profilers. During a survey, a vessel with a Doppler profiler holds position against the current at a set of predetermined "stations". Each station should be observed at least five times for at least five minutes. Observations should bracket the time of peak currents, with each observation separated by 30-40 minutes. The number of stations that can be included in a survey depends on the vessels' ability to manoeuvre against strong currents and the separation between stations. In locations with diurnal inequalities, surveys should be conducted during greater tides. Survey optimisation is discussed in [13]. Much like bottom-mounted profiler observations, station keeping surveys yield discrete observations of spatial resource gradients.

Data collected during each observation of each station (i.e., each five minute period) are ensemble averaged, resulting in one point for each depth bin per observation. As with bottom-mounted profiler data, this filters the majority of turbulence from the measured velocity and limits Doppler uncertainty. Kinetic power density is then calculated from measured velocity and a second order polynomial is fit to the resulting time series at each station:

$$K(t) \approx \tilde{K}(t) = x_o + x_t t + x_2 t^2$$

where $\tilde{K}$ is the approximate polynomial representation of the observed power density at a given depth and x_i is an empirical coefficient. This function is integrated to obtain the kinetic energy density (*KE*) over a two hour window, with the starting point chosen iteratively to maximise the kinetic energy within the window. The use of approximate energy density, rather than observed power density is preferred in order to compare sites on equal footing when significant variations in the phase and structure of the tidal currents may exist between stations.

4.2. Observed Spatial Resource Gradients

A demonstration of this technique was conducted in Admiralty Inlet in June, 2011. Station keeping locations are shown in Fig. 6. The survey was conducted during a greater ebb tide with peak currents around 2 m/s.

A comparison between kinetic power density measured by the vessel-mounted profiler, the 2nd order polynomial fit to vessel data, and observations from co-spatial bottom-mounted profilers is presented in Fig. 7. The comparison is excellent at all three stations for which bottom-mounted profiler data are available, with relative errors in calculated kinetic energy density within 10% throughout the water column. In other words, a vessel-based survey technique can observe kinetic *energy* density with a comparable effectiveness to bottom-mounted profilers.

4.3. Method Effectiveness

[13] benchmarks the effectiveness and accuracy of the "station-keeping" method against bottom-mounted profiler data. This was done by decimating bottom-mounted data to simulate the sparser data collected during a vessel-based survey. Different decimation scenarios are undertaken to investigate the effect of various survey parameters (e.g., interval between observations, number of times each station is occupied) and errors in kinetic energy density calculated relative to the undecimated bottom-mount data. Analysis of these scenarios is the basis for the recommended survey structure presented in Sec. 4.1, as well as the approach to calculating kinetic energy density. The primary

limits to spatial resolution are the beam spread of the downward looking profiler (on the same order as water depth) and the ability of the survey vessel to hold station. Even without a dynamic positioning system, a skilled pilot should be able to hold station within a 50 m radius for a five minute observation. Consequently, this technique is suitable for resolving resource gradients over spatial scales on the order of 10^2 m and greater.

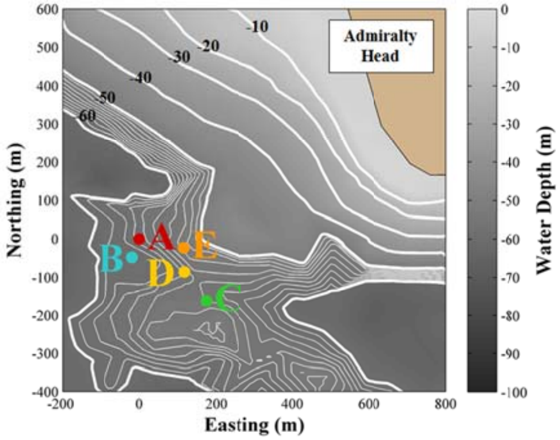

Figure 6: Locations occupied during station-keeping survey. Thick white lines denote 10 m depth contours. (Source: [13])

[13] also compares the relative kinetic energy density between stations to that which would be obtained by long-term bottom-mounted profiler observations at the same locations. Results from individual station-keeping surveys have high uncertainty, but the average of at least four surveys on consecutive greater ebbs or floods is equivalent to the accuracy that would be obtained from long-term, bottom-mounted deployments. This is shown in Table 1, where stations A and C are separated by 230 m. For the station-keeping survey, the comparative metric is kinetic energy density, averaged over the given number of surveys. For the bottom-mounted survey, the comparative metric is kinetic power density, time-averaged over the duration of the survey. Station-keeping is, therefore, effective at resolving *relative* spatial resource gradients, but cannot quantify *absolute* spatial resource gradients without a long-term, bottom-mount reference station.

Station	**Station-Keeping Survey**		**Bottom-Mount Survey**	
	$KE^{A/C}$	**Surveys (number)**	$K^{A/C}$	**Duration (days)**
A	1.00±0.04	4	1.00±0.04	356
C	1.13±0.04	4	1.13±0.08	30

Table 1: Comparison between relative spatial resource gradients (mid-water) obtained from station-keeping (simulated from decimated bottom-mount data using recommended survey parameters) and bottom-mount surveys.

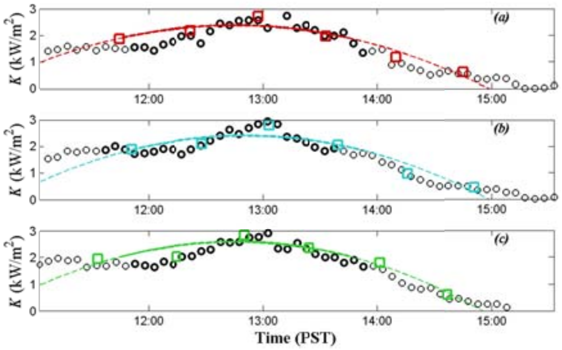

Figure 7: Comparisons between kinetic power density measured by co-spatial vessel-mounted and bottom-mounted Doppler profilers for three station-keeping survey locations (mid-water). The colour scheme for each station is as in Fig. 6. Open circles denote 5-minute ensemble averages from continuous bottom-mounted profiler measurements. Open squares denote 5-minute ensemble averages from station-keeping surveys. The dash line is the polynomial fit. Bolded points denote the 2 hour window used for kinetic energy density calculations. (Source: [13])

5. Conclusions

Bottom-mounted Doppler profiler deployments provide essential information for estimating power generation from tidal turbines and establishing design loads. These surveys are, however, an inefficient and expensive approach to identifying large regions of high resource intensity. Surveys utilising vessel-mounted Doppler profilers can develop this spatial information at much lower cost, thereby targeting bottom-mounted deployments at locations with the highest relative power generation potential.

Results are presented for a case study of Admiralty Inlet, Puget Sound, WA (USA) from bottom- and vessel-mounted Doppler profiler surveys. Operationally meaningful resource variations are shown to exist over distances on the order of 10^2 m and can be resolved by vessel-based “station-keeping” surveys. These resource gradients are likely to occur at other potential tidal energy sites in close proximity to headlands (e.g., Pentland Firth, Bay of Fundy, Cook Inlet).

Whether employing bottom-mounted or vessel-based surveys, the resulting information will always be sparse. High-resolution numerical models (e.g., [14]) can provide information about continuous resource gradients over regions on the order of tens of square kilometers. These models must, however, be appropriately calibrated and the techniques described here are two approaches to obtaining such data relevant to the development of tidal energy projects.

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References

[1] B. Polagye, J. Thomson (*submitted*): Tidal energy resource characterization: methodology and field study in Admiralty Inlet, Puget Sound, US.

[2] Public Utility District No. 1 of Snohomish County (2012): Final Pilot License Application for the Admiralty Inlet Pilot Tidal Project, FERC Project No. 12690-000.

[3] B. Polagye, M. Kawase, P. Malte (2009): In-stream tidal energy potential of Puget Sound, Washington, *Proc. Inst. MechE, Part A: J. Power and Energy*, 223(5).

[4] J. Thomson, B. Polagye, V. Durgesh, M. Richmond (2012): Measurements of turbulence at two tidal energy sites in Puget Sound, WA (USA), *IEEE J. Ocean. Eng.,* 37(3).

[5] W. Geyer, R. Signell (1990): Measurements of tidal flow around a headland with shipboard acoustic Doppler current profilers, *J. Geophys. Res.*, 95(C3).

[6] R. Vennell (1994): Acoustic Doppler current profiler measurements of tidal phase and amplitude in Cook Strait, New Zealand, *Cont. Shelf Res.*, 14(4).

[7] R. Vennell, N. Collins (1991): Acoustic Doppler current profiler measurements of tides in Cook Strait, New Zealand, *Proc. of the 10th Australian Conference on Coastal and Ocean Engineering*.

[8] J. Candela, R. Beardsley, R. Limeburner (1990): Removing tides from ship-mounted ADCP data, with application to the Yellow Sea, *Proc. of the IEEE 4th Working Conference on Current Measurements.*

[9] M. Foreman, H. Freeland (1991): A comparison of techniques for tide removal from ship-mounted acoustic Doppler measurements along the southwest coast of Vancouver Island, *J. Geophys. Res.*, 96(C9).

[10] A. Münchow, R. Garvine, T. Pfeiffer (1992): Subtidal currents from a shipboard acoustic Doppler current profiler in tidally dominated waters, *Cont. Shelf Res.*, 12(4).

[11] M. Cáceres, A. Valle-Levinson, L. Atkinson (2003): Observations of cross-channel structure of flow in an energetic tidal channel, *J. Geophys. Res.*, 108(C4).

[12] C. Stevens, M. Smith, B. Grant, C. Stewart, T. Divett (2012): Tidal energy resource complexity in a large strait: The Karori rip, Cook Strait, *Cont. Shelf Res.*, 33.

[13] M. Palodichuk, B. Polagye, J. Thomson (*submitted*): Resolving spatial resource gradients at tidal energy sites.

[14] K. Thyng (2012): Numerical simulation of Admiralty Inlet, WA, with tidal hydrokinetic turbine siting application, PhD dissertation, University of Washington, Seattle, WA (USA).