Shipboard Acoustic Doppler Current Profiler Surveys to Assess Tidal Current Resources

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Abstract*- A compelling aspect of power generation from tidal currents is the predictability of the resource, which is generated by the gravitational pull of the sun and moon on the earth's oceans. For technical feasibility studies, it is presupposed that once the currents at a site have been well characterized it is possible to make accurate predictions of the electricity that would be generated by an array of turbines. These data are generally collected by Acoustic Doppler Current Profilers (ADCP), which use active acoustics to measure currents throughout the water column. Stationary ADCP deployments in Admiralty Inlet, WA, indicate operationally important variability over length scales less than 100 m and use of shipboard ADCP surveys aims to identify regions of peak currents without deploying a high resolution grid of stationary ADCPs. Shipboard surveys involve multiple laps during a tidal cycle around a short "racetrack". Data are aggregated within bins such that multiple laps produce time series at 100 m spatial resolution along the track. The time series is then fitted with a half sine wave assuming that each tidal cycle can be represented as such due to the periodic nature of tidal currents. The amplitude and timing of the peak currents along the survey track are estimated from the fit. Multiple ebb current surveys indicate that relative amplitude trends are consistent between cycles of differing strength and time of the year. Therefore, by overlapping surveys, greater spatial coverage can be achieved from multiple cycles without changing the survey characteristics. Results obtained to date suggest a noise floor of approximately ±15 minutes for phase. This method could be applied to other tidal energy sites as a lower cost alternative to siting studies using arrays of stationary ADCPs.

I. Overview

The realization and development of clean and renewable energy is important to the future of power generation throughout the world, due the impacts from fossil fuel use, including global climate change. Hydrokinetic tidal energy devices generate power by harnessing the kinetic energy in periodic tidal current motion. Tidal hydrokinetic power generation faces unique challenges, which and has triggered research on the resource, environmental effects, and device optimization. Unlike wind or wave energy, tidal current energy involves extracting energy from a deterministic resource generated by the gravitational pull of the sun and moon on the earth's oceans. Therefore, while the resource is intermittent, it is mostly predictable [[8].

One useful metric to assess the power generation potential of a site is the kinetic power density P (W/m^2) which depends on the cube of velocity;

$$P = \frac{1}{2}\rho v^3 \qquad (1)$$

where ρ is the seawater density (nominally 1024 kg/m^3) and v is the current velocity (m/s). The sensitivity of the kinetic power density to minor differences in the velocity stresses the importance of resolving spatial variation in current strength. From the standpoint of device performance and design, the peak currents represent maximum power generation and forces on the turbine. For estimates of power generation from an array of tidal energy devices, variations in timing of peak currents or phase as also of importance.

At the northern end of Puget Sound, Admiralty Inlet is the main entrance to the sound and has strong currents due to the tidal exchange through the relative constriction of the channel cross-section. At the constriction between Point Wilson and Admiralty Head, Admiralty Inlet is roughly 5 km across and has a 60 m mean depth. The gravitational (tidal) forcing of water over the Admiralty Inlet sill results in strong currents exceeding 3 m/s during a strong spring tide, making the site favorable for tidal energy device installation. There is currently a proposed hydrokinetic pilot project at this location. Stationary ADCP deployments at this location indicate tidal currents vary significantly over scales less than 500 m [[3].

This material is based upon work supported by the Department of Energy under Award Number DE-FG36-08GO18179, Public Utility District of Snohomish County # 1, and a fellowship from Dr. Roy Martin.

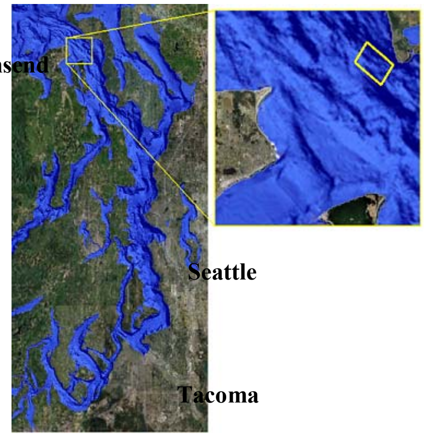

Fig. 1 – Map of Puget Sound (left) and Admiralty Inlet (right). Northern Admiralty Inlet survey area, 1 x 1.5 km (right, yellow). Bathymetric data from [4].

Because of this, stationary ADCP deployments are not an efficient method to identify regions of strongest currents for device siting. Shipboard surveys provide a lower effort option for resolving spatial variability, but a single survey may convolve fundamental differences in current amplitude with sampling at different stages of the tide. This paper presents a survey methodology for resolving these factors.

II. Literature review

A. Introduction

The use of ship-mounted ADCPs has long been in practice throughout the oceanographic community. However, initially the quality of the data collected in this manner was suspect due to inaccuracies associated with separating the ship's velocity from currents. Improvements in the late 1980s resolved this issue with the incorporation of bottom tracking capabilities which could separate ship speed from water velocity with higher confidence. The advantage of ship-mounted ADCP surveys are the measurable spatial variations in current or current structure that singular stationary deployments or interpolations between deployments are unable to resolve.

B. Previous Methodology

A ship-mounted ADCP was used to measure the currents through the Minch between Scotland and Herbides by Simpson et al. [10]. Repetitive transects across the channel were approximately 20 km in length. Vertical resolution of 8 meters and horizontal resolution of approximately 1 kilometer (4 minutes temporally) were successful in mapping the flow through the Minch from two separate ship surveys of 11 and 12.5 hours in February 1988. The least-squares analysis used a sinusoidal representation of the M2 semi-diurnal constituent to fit the depth averaged current $u(t)$ with constituent frequency ω, phase ϕ, and amplitude A;

$$u(t) = A\cos(\omega t + \phi) \rightarrow u(t) = A\cos(\omega t) + B\sin(\omega t). \qquad (2)$$

The S2 semi-diurnal constituent was included based on amplitude and phase corrections to the M2, but the survey period was not long enough to resolve any of the weaker diurnal variation at the channel. The M2 amplitude and phase found across the Minch was in agreement to a 3-D regional model by Proctor and Wolfe [9]. This work served as an early demonstration of the potential for shipboard ADCP surveys.

Geyer and Signell [6] used shipboard ADCP surveys around Gay Head in Massachusetts, peak currents less than 1 m/s, with a similar fitting method as Simpson et al. to map tidal current structure. Survey durations were about 12 hours and the 8 cruises were split between 5 separate tracks between February and June 1988. The 5 survey tracks were trapezoidal with overlapping edges, mapping both sides of the headland. Each lap was 10 km long and required about 1 hour to complete (~ 3m/s vessel speed) and then was divided into 200 m bins, creating a time series of measurements over the survey duration at each bin along the track. A harmonic analysis was implemented for M2, as well as the M4 and M6 over-tides to the observations, allowing the tidal flow field around the headland to be resolved to within 5 cm/s. The different surveys were compared by using a normalization of amplitude and phase depending on the tidal characteristics of the site during the survey. By normalizing the individual cruises, Geyer and Signell demonstrated that observations from different surveys spanning five months showed consistency.

A second method to resolve the spatial resolution of tidal currents from shipboard surveys was developed by Candela et al. [1] and used only one survey spanning five days with no repeat of any transect. This differs from the previously described method which aims to build up a time series of tidal currents in each horizontal bin of a lap. The total survey area in the Yellow Sea was 300 km by 500 km and binned into 20 km segments along the ship's path. For surveys of this spatial scale, repeat transects would have been impractical. A least-squares analysis like that by Simpson et al. was used to fit the data except that Candela et al.

described the amplitudes and phases of the M2 and K1 tidal constituents as functions of spatial position and solved for function coefficients.

Additional work was performed in the early 1990's around Vancouver Island by Foreman and Freeland [5], who applied two different detiding methods for shipboard ADCP measurements from a 3 day cruise. The first method used a barotropic numerical model of the survey region with grid resolution ranging between 2 and 12 kilometers. Corrections to the model for the effects density stratification were made from the previous observations of tidal heights and currents. Use of models to remove tides from observations is limited by the grid resolution and accuracy of the models. The second method used the least squares harmonic method developed by Candela et al., discussed previously. Just like Candela's work in the Yellow Sea, the survey track around Vancouver Island covered an area roughly 50 km by 50 km and only the M2 and K1 constituents were resolved. Through inference, additional tidal constituents (e.g., S2 and O1) could be included in the analysis. Through analysis of the ADCP data around Vancouver Island, Foreman and Freeland found that detiding with the barotropic model performed much better than detiding by harmonic analysis. Reasons for the poor performance of the harmonic analysis include having only three days of observations to separate semi-diurnal and diurnal forcing and that M2 and K1 constituents around Vancouver Island are similar in magnitude, unlike in the Yellow Sea where M2 is dominant.

III. Shipboard Survey Methodology

In northern Admiralty Inlet, the currents during a strong spring tide exceed 3 m/s and both M2 and K1 constituents have considerable amplitude, meaning the methods developed by Candela et al. [1] and Simpson et al. [10] must be applied with caution. The method developed for Admiralty Inlet has data collection similarities with Geyer and Signell's work [5], but uses short shipboard surveys lasting only 4 or 5 hours. The new method focuses on resolving the amplitude and phase of peak currents rather than resolving individual constituents. Surveys on both ebb and flood currents were conducted during research cruises in August 2009, November 2009, February 2010, and May 2010.

A. Survey Specifications

During an ebb or flood survey the ship completes continuous laps around a designed track through the peak of the tidal cycle. Each lap measures the currents along the survey track at a different stage of the tidal cycle. Laps are conducted both before and after the time of peak ebb or peak flood currents. Surveys are conducted from the University of Washington Applied Physics Lab R/V Jack Robertson. The ADCP is a hull-mounted, downward looking, Teledyne RDI Workhorse Monitor. The instrument configuration is summarized in Table 1. The ADCP uses bottom tracking to filter out ship motion from measured water velocities. If the bottom reference is lost, ADCP measurements are badly degraded.

TABLE 1
Shipboard ADCP configuration

Teledyne RDI Workhorse Monitor	
Acoustic Frequency	307.2 kHz
Time per Ping	0.5 sec
Time between Pings	3 - 4 sec
Vertical Bin Size	1.0 m
Pings / Ensemble	1
Transducer Depth	1.18 m
Blanking Distance	2.0 m

On each lap, the ship ideally passes a given spatial location "A". Due to strong currents, wind, and surface waves the vessel track actually varies between each lap and location "A" is never strictly reoccupied. Further, to reduce the noise inherent in single ADCP pings, the track is separated into a series of volumetric bins. The horizontal area of each bin must be large enough to allow for the variations in ship course between laps without merging areas of drastically different current strength or timing.

All ensemble (time and space) averaging is conducted during post processing of the shipboard ADCP, allowing for the user to define ensemble parameters to achieve desirable statistics (e.g., smallest possible bins with low measurement noise).

A few different factors determine whether or not an individual ping will be successfully received and processed by the ADCP, but the most important is the speed of the ship. Ship speeds in excess of 3.0 m/s when combined with excessive pitch and roll, do not allow sufficient time for the ADCP to receive the bottom track, while ship speeds below 1.5 m/s do not provide desirable spatial coverage or allow effective steerage in strong currents. When the surface of the water is calm and the currents are weak, maintaining consistent ship speed is straightforward, but when currents and strong and surface is rough (as is common in Admiralty Inlet), this can be a challenge.

For best results, the duration of the survey must capture both peak currents and more than two hours of the tidal cycle before and after the peak. Specific to this site, some cycles have a secondary peak prior to the true peak. Therefore, it is very important to observe enough of the cycle to distinguish primary and secondary peaks.

Survey tracks are designed so longer segments are perpendicular to the dominant current direction and shorter segments run parallel with the currents. Maintaining constant ship speed (the main factor in a good ADCP return) is easier to achieve moving cross-current (crabbing) because the currents do not act along the heading of the ship. The shorter segments of a track may be compromised if currents substantially increase ship speed. Minor adjustments for variation in the dominant current direction vs. the orientation of the longer track legs are made depending on ebbing or flooding currents.

To plan a survey, tidal current predictions previous analysis provides an estimate of peak current timing on which to base survey start time and duration. If a survey pattern is too long in duration, the timing between each lap may result in large gaps in the time series for each bin and inaccurate identification of peak currents. For the Admiralty Inlet site, lap duration of approximately twenty minutes strikes a balance between adequately resolving the spatial variability in the currents and maximum vessel speed for good ADCP returns. This scheme allows a station to be occasionally missed without compromising the time series generated from the ADCP measurements.

B. Analysis

The individual ADCP pings from each lap are spatially divided into 100m x 100m horizontal bins along a nominal ship track which accommodates variability between different laps. Each ADCP measurement (ping) is sorted into one of the spatial bins, or discarded if outside of all bin boundaries. For example, during ebb and flood surveys in November 2009, several tracks did not pass through any bins due to rough weather. There are four track segments (NW, NE, SE, and SW), as seen in Fig. 1. The alignment and location of the bins is chosen to maximize the number of pings located within at least one track bin.

Approximately one minute is required to transit each bin at 1.5 m/s vessel speed, which was determined by experience to be the practical limit for maintaining good ADCP returns. However, due to the strength of the currents in Admiralty Inlet, as well as wind and waves, there is always a variation in ship speed and course which difficult to plan for prior to the survey. Due to these circumstances, the actual speed at which the laps were transited often exceeded 1.5 m/s. Good ADCP returns are possible from surveys which exceed 1.5 m/s but the sensitivity of the ADCP return to factors such as pitch and roll of the ship increase. Table 2 presents minimum and maximum average velocities for all laps during each of the six surveys.

TABLE 2

SHIPBOARD ADCP SURVEY SUMMARY FROM ADMIRALTY INLET

Shipboard Survey	Currents	# laps	Average Lap Duration	Vessel Speed
August 3, 2009	Flood	10	22.5 min	1.4 - 2.7 m / s
August 5, 2009	Ebb	12	18.1 min	1.6 - 2.8 m / s
November 11, 2009	Flood	7	25.1 min	1.3 - 4.8 m / s
November 11, 2009	Ebb	9	20.2 min	1.4 - 2.6 m / s
February 10, 2010	Ebb	13	10.8 min	1.7 - 4.0 m / s
May 4, 2010	Ebb	14	18.9 min	1.4 - 3.3 m / s

In order to ensure robust statistics, each 100 m x 100 m bin along the tracks is further average 5 m in the vertical, as shown in Fig. 2 and Fig. 3. It is assumed that currents are relatively uniform within these ensemble volumes. Close to the seabed, the velocity profile changes considerably with depth and the presumed homogeneity over 5m depth averaging should be viewed with caution. To calculate an accurate mean velocity for each bin, a minimum of thirty pings is found to be necessary to overcome the inherent Doppler noise in each ping. The typical spread for individual profiles (single ping) versus volumetric ensembles is shown in Fig. 3. The track bin labeled “1” in Fig. 2 is selected as a representative bin with relatively good ADCP returns and subsequent figures refer to this track bin.

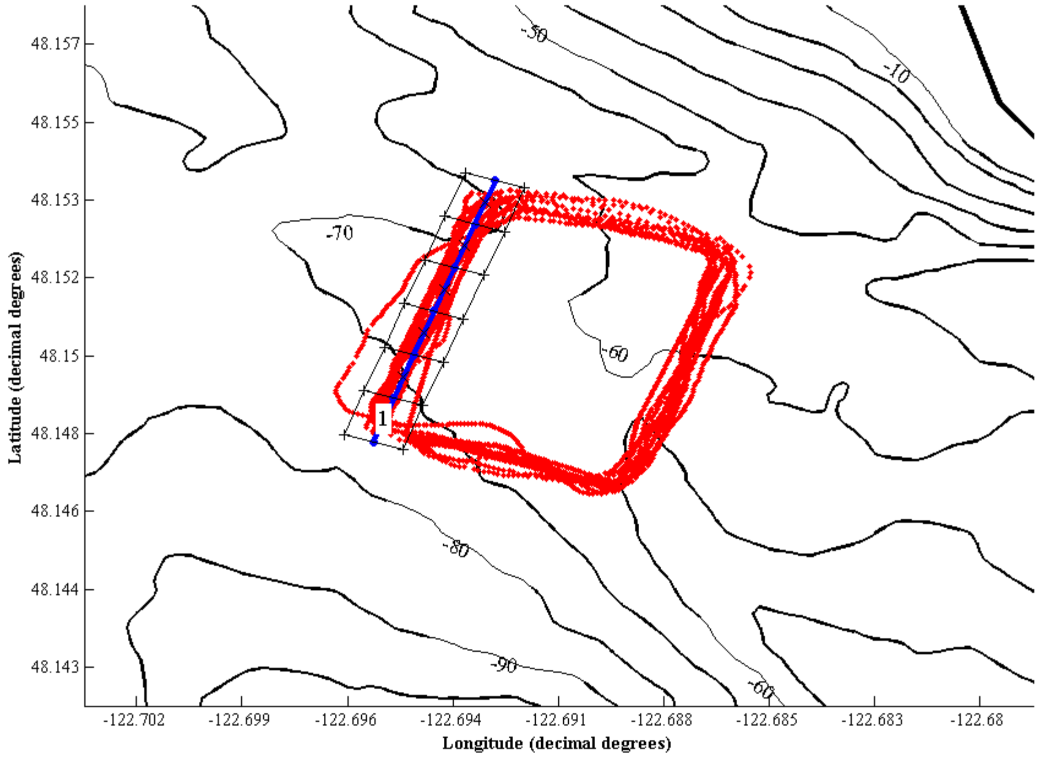

Fig. 2 - Individual pings in red with bin centerlines and outlines from August, 2009. The bin labeled 1 is used as an example for further analysis.

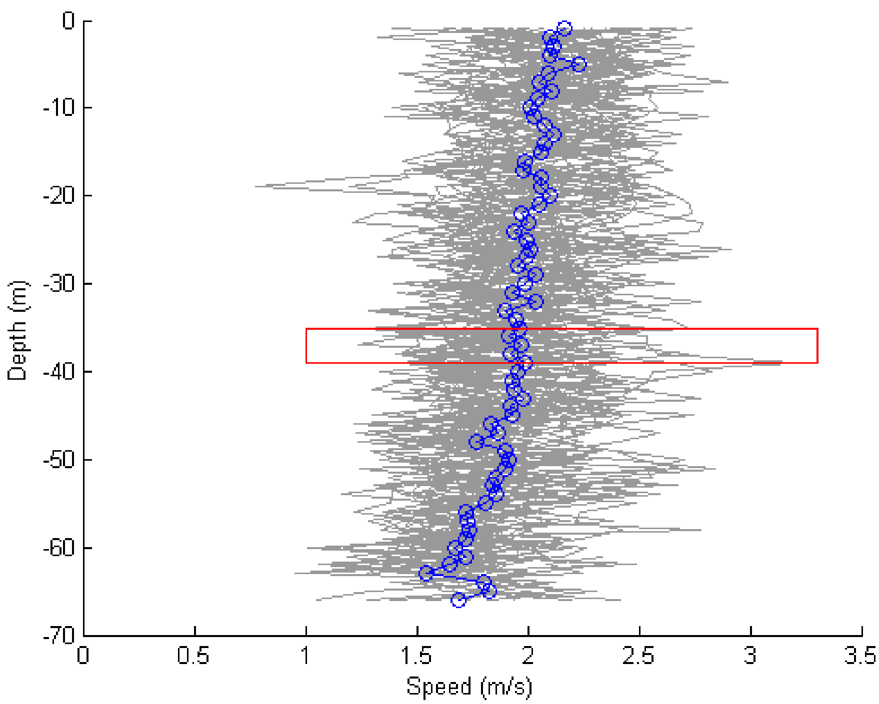

Fig. 3 - Individual ADCP ping velocity profiles (gray) for August 2009 ebb survey, horizontal bin averages for 1m vertical (blue), 5m vertical average region (red box).

Confidence intervals are required to understand the statistics of the volumetric ensembles. Because the mean and standard deviation of the population are unknown, these must be estimated from the sample mean and standard deviation. The August 2009 ebb survey has enough pings/ensemble for use of normal statistics. However, a *t*-distribution, which converges to a normal distribution for a large sample sizes, is used for conservatism. Equation (3) is used to generate 99 % confidence intervals for the velocity where $\bar{x}$ is the sample mean, s is the sample standard deviation, and n is sample size;

$$\bar{x} \pm 2.58 \times \frac{s}{\sqrt{n}}. \tag{3}$$

The calculation of confidence intervals do not require that the sample mean be normally distributed and different distributions for the sample mean would affect the sample standard deviation, thus changing confidence interval bounds. Considering the distribution of individual ADCP pings in Fig. 3, we see that the individual mid-water column velocities are normally distributed about the sample mean. This provides confidence that the volumetric ensemble is not smoothing spatial variations in current strength with 100m x 100m x 5m bin resolution. If the currents were biased over the bin or sample volume, a non normal distribution would be expected.

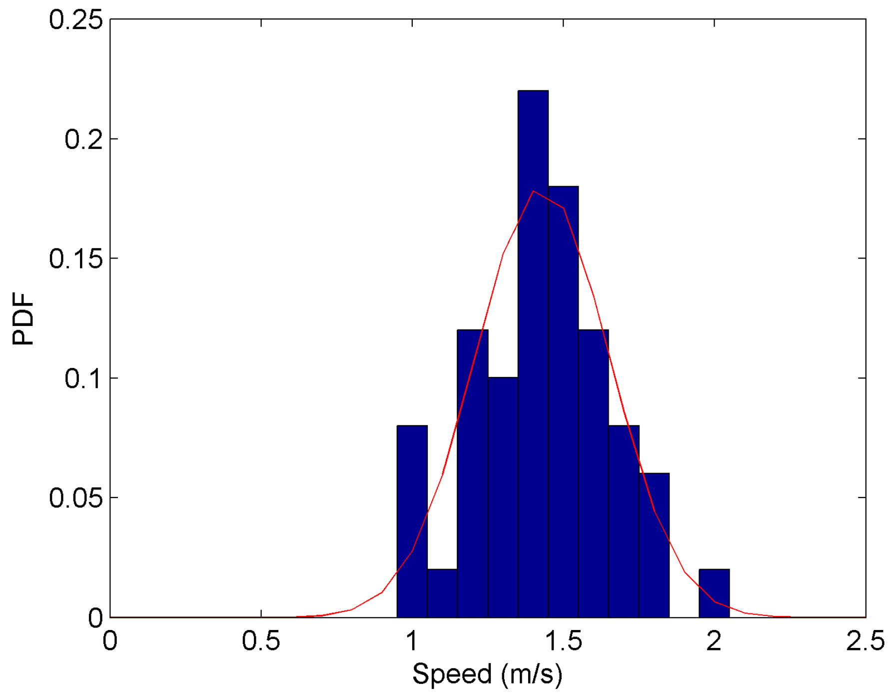

Fig. 4 – Histogram of ADCP Pings (blue) w/ Normal PDF (red) corresponding to sample mean and standard deviation

C. Representation of the Tidal Signal

The ensemble averages for all laps passing through a particular bin form a short time series, encompassing the peak tidal current. Once the short time series has been developed, the data are fit by a sine wave using the unconstrained nonlinear optimization routines built in to MATLAB. The amplitude (*A*), phase (*Φ*), and period (*T*) of the sine fit are all free parameters and the optimization essentially converges to a least squares solution. However, this is based on the assumption that each stage of the tide (slack→peak & peak→slack) can be represented as a single sinusoid of a certain period, phase, and amplitude. To improve convergence efficiency the initial estimates for these parameters are taken from NOAA current predictions for the station 0.5 miles west of Admiralty Head. The fit to the velocity curve (*u*) is assumed to be of the form

$$u(t) = A\sin\left(\frac{2\pi t}{T} + \phi\right). \tag{4}$$

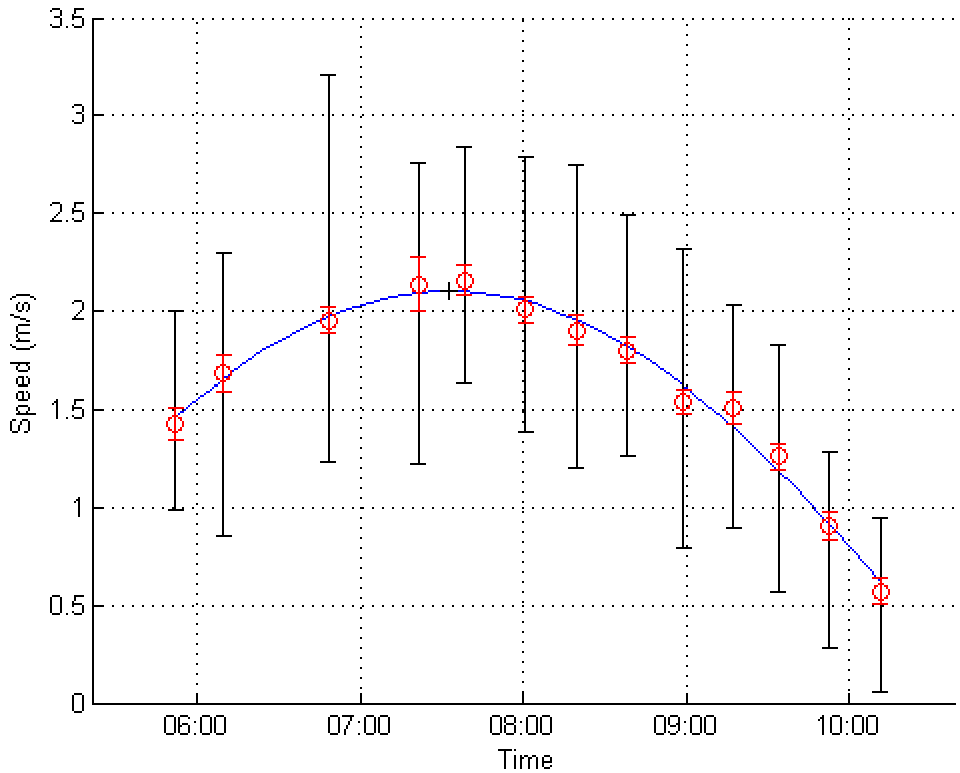

Fig. 5 - Ensemble averaged data (red circles) with half period sine fit (blue) are shown for the ensemble volume noted as 1 on Fig. 2, obtained during the August 2009 survey. The red lines denote the 99% confidence interval for the means. The black bars denote the maximum and minimum values within the ensemble. The coefficient of multiple determination for the since fit is 0.99.

The half period sine fit in
Fig. 5 is representative of a high-quality bin where the fit performs very well. Bin quality is defined by an acceptance criteria consisting of:

1. The ensemble volume contains at least 30 pings
2. There are at least five volumetric ensemble averages (data points) on the tidal curve
3. The half period determined by the optimization is less than 8.5 hrs
4. The time of peak amplitude from the sine fit is contained within the series
5. The coefficient of multiple determination, R-squared is less than 0.80

The R-squared value is given by

$$R^2 = 1 - \frac{\sum_i (\hat{x}_i - x_i)^2}{\sum_i (x_i - \bar{x})^2}, \tag{5}$$

where $\bar{x}$ is the mean of the velocity time series, x_i is each velocity data point in the series, and $\hat{x}_i$ is the sinusoidal fit for each velocity data point in the series. The R-squared value is the proportion of the velocity variation which can be represented by the half sine wave fit [2]. A perfect fit by the sine wave approximation would have an R-squared value of 1.

The acceptance criteria is chosen empirically to easily accept bins were the fit is conclusive as well as bins where the fit was less conclusive but followed the trend of the surrounding good bins. Bin inclusion is therefore an iterative process, with the allowable R-squared value decreased until bins with multiple outliers are rejected, while marginal bins are accepted. If a bin does not meet all the acceptance criteria, then it is excluded from subsequent analysis. Future analysis could focus on better understanding the factors leading to a poor fit.

The implemented sine fit is only an approximation of the actual tidal currents, which are a superposition of several sinusoidal tidal constituents, turbulence, bathymetric influence, and baroclinic currents. These currents have distinct differences in period leading up to and after peak currents, which is ignored by the half period sine wave fit. Surveys with more laps and tighter track pattern generally perform better by reducing the effects of points which may have smaller ensemble sizes and, therefore, larger confidence intervals. Attempts have been made to use a quarter period sine fit to resolve the known differences in period before and after the peak current, but because no surveys encompass both peak currents and slack water, these are by nature, extrapolations, and subject to unacceptably high uncertainty. A longer duration survey could resolve this inaccuracy, but at higher cost.

C. Results

The resulting data ensembles that pass all acceptance criteria are used to compare the peak currents and phase differences over the different ebb and flood survey tracks, as shown in

Fig. 6. The amplitude variations at these bin resolutions demonstrate that current strength fundamental varies over length scales on the order of 100m. When deploying the tidal turbines for the proposed pilot project, the final siting location should be at or near the location of peak velocity. During the NNMREC survey cruises in August 2009, November 2009, and February 2010, and May 2010, four ebb and two flood current surveys were completed. For the approach suggested by Geyer and Signell [5], comparisons are made between like surveys (ebb or flood) for current amplitude and peak timing (phase), normalized to allow comparison between ebbs and floods of different magnitudes. The normalization is relative to the easternmost bin, chosen because two of the racetracks pass through that bin. However, this selection is somewhat arbitrary and the normalization reference could be taken at any point along the survey track. As shown in Fig. 6, the trends in normalized ebb current amplitude are consistent between the three surveys and independent of current strength or time of year. The November 2009 ebb survey is excluded from the analysis because no bins met all acceptance criteria. One explanation for the dissimilar variation between ebbs and floods could be the influence of eddy formation (in the survey area) off of Admiralty Head during ebb, but not flood.

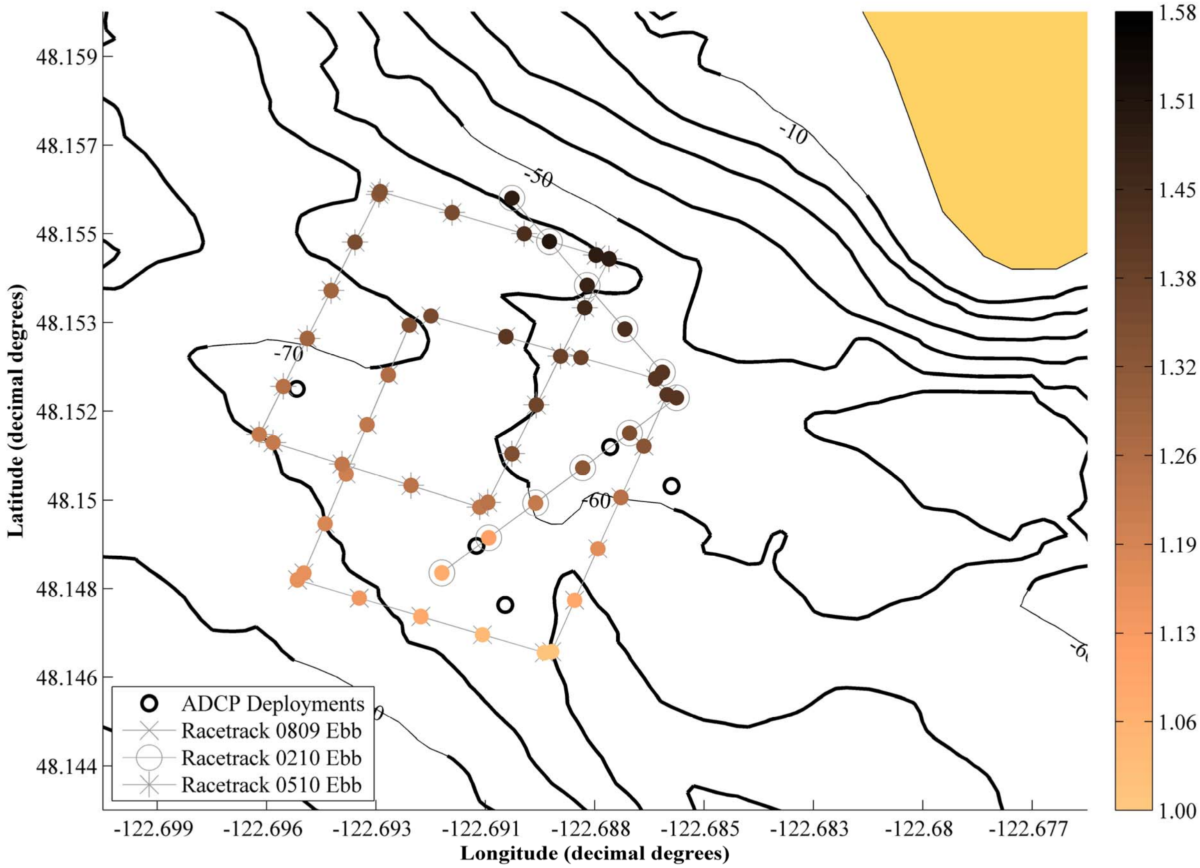

Fig. 6 – Normalized peak ebb current amplitude for the August 2009, February 2010, and May 2010 surveys at mid-water column. Contours are water depth (m).

Resolving amplitude variation between multiple surveys of only 4-5 hours duration represents a novel method to resolve current strength. Additionally, by overlapping surveys successively, greater coverage can be achieved without increasing track length or vessel speeds. The ebb current amplitudes increase towards the headland, which is in agreement with the M2 amplitude map developed from stationary ADCP data [[3]. This suggests that currents are strongest and most energetic in the northeastern corner of the shipboard survey area.

Despite the consistency of current amplitude between ebb surveys, the timing of peak currents through the area has no apparent trend during ebb cycles. The largest differences in peak timing are 15 minutes, which suggests a lower limit for variations which may be resolved by this technique. This is not unexpected as each survey track requires, on average, 18 minutes per lap.

While flood amplitude variations are less pronounced than ebb variations, potentially below the accuracy of this technique, variations in phase are more evident.

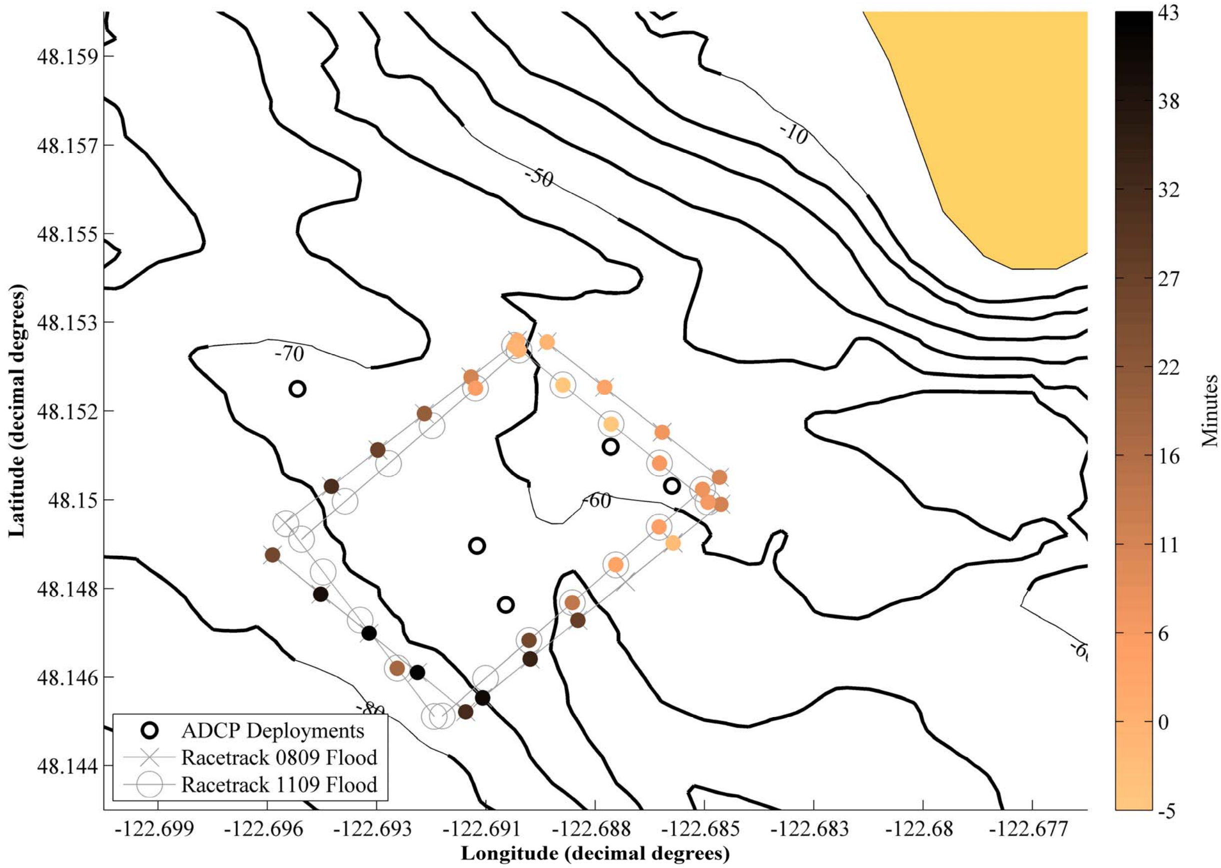

Fig. 7 - Peak flood current phase (minutes relative to northernmost bin) for the August 2009, November 2009 surveys. Contours are water depth (m).

Phase differences through the site peak at almost 50 minutes. These results suggest that ebb tides are characterized by large variations in current magnitude and small variations in phase, while flood tides are characterized by small variations in current magnitude and large variations in phase.

Fitting the observed tidal currents with a half period sine wave is not without its limits. Primarily, the half period sine fit does not allow for known asymmetry in the timing from slack to peak and peak back to slack. A quarter period sine fit to the data before and after peak could provide this flexibility. All the surveys conducted to date do not survey through slack water and, therefore, the timing of slack water must be extrapolated. Initial attempts to fit quarter period sine waves show promise in some cases.

The use of short duration shipboard ADCP surveys to characterize a site informs decisions on where to deploy additional stationary ADCPs or hydrokinetic devices. New surveys conducted from slack water through the time of peak currents might be better suited to being reliably fit by a quarter period sine wave.

IV. CONCLUSION

The shipboard ADCP current observations from Admiralty Inlet provide a unique tool to for characterizing spatial variability in the hydrokinetic tidal resources. Admiralty Inlet has very strong currents, providing a robust test case for the shipboard methods and the promising performance thus far warrants application to other potential tidal energy sites.

Further work should consider the assimilation of the shipboard ADCP surveys with stationary ADCP records. The long time series captured by stationary ADCPs are better suited for harmonic analysis and, therefore, predictions of tidal currents. The short time series and spatial variability of current amplitude captured by shipboard ADCP surveys shows this to be an efficient tool and potentially a means by which stationary predictions could be modified. A first concept for assimilation would deploy a stationary ADCP in an area for a three month period to characterize the currents at one location. To resolve nearby spatial variability, a shipboard survey could map how amplitudes vary relative the stationary location. Assuming the survey passes over the stationary deployment, the amplitude ratios can normalized to the stationary location and provide a means to scale current predictions and power generation estimates at the stationary deployment throughout the surrounding area.

ACKNOWLEDGMENTS

The authors thank Joe Talbert for keeping the all equipment in working order for more than a year in the marine environment, Sam Gooch, Chris Bassett, and Alex DeKlerk for helping to turn around instrumentation, and Captains Andy Reay-Ellers, Eric Boget, and Mark Anderson for their piloting skills during instrumentation recovery and redeployment.

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