

Limits to the Predictability of Tidal Current Energy

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Abstract—The predictability of tidal currents in the context of hydrokinetic power generation are assessed using current data from a series of surveys in Admiralty Inlet, Puget Sound, Washington, USA. Both current speed and kinetic power density are shown to be well-described by harmonic analysis. Three challenges to predictability are identified. First, non-sinusoidal fluctuations over time scales on the order of hours are observed but cannot be replicated by conventional harmonic analysis. Second, turbulent fluctuations over time scales on the order of seconds are relatively large and inherently unpredictable. Third, for this site, predictions may not be extrapolated more than 100 m from the location of measurement. While none of these issues are insurmountable, they contribute to a degree of unpredictability for tidal hydrokinetic power.

I. INTRODUCTION

Hydrokinetic tidal power involves extracting kinetic power from fast moving tidal currents to generate electricity. Because these currents are driven by the gravitational interaction of the moon and sun with the earth's oceans, hydrokinetic tidal power is, in theory, predictable. This would simplify grid interconnection and estimating the economic return for a project.

The predictability of tides (vertical motion of water) is well-established (e.g., [1]). Excepting the influence of extreme weather phenomena (e.g., storm surges), tides may be described as the summation of constituent forcings associated with the periodic variations in the position and orientation of the sun and moon relative to the earth. Each constituent has amplitude (A), period (T), and phase (ϕ), such that the tide (h) is given over time (t) as

$$h(t) = \sum_{i=1}^N A_i \sin\left(\frac{2\pi}{T}t + \phi\right) \quad (1)$$

Harmonic analysis (e.g., [2]) fits the amplitude and phase of a set of constituents to a tidal time series using least-squares. The period of each constituent is known *a priori*. Long-term records are available for many locations, in some cases spanning the full 18.6 year tidal epoch.

While it is possible to describe currents (horizontal motion of water) in an analogous manner, there are a number of fundamental differences which complicate this representation:

- (1) currents are three dimensional and vary with both horizontal position and depth;
- (2) tides smoothly vary over distances $O(100 \text{ km})$, while currents sharply vary over distances $O(100 \text{ m})$; and
- (3) currents contain non-sinusoidal features over a variety of temporal scales which are poorly described by (1), including sub-tidal variations (e.g., density-driven circulation), supra-tidal variations (e.g., influence of eddy fields), and turbulence.

In general, the prediction of currents is less developed than for tides. This may, in part, derive from the relatively greater operational importance placed on tidal predictions (e.g., coastal flooding when storms coincide with high tide) and the relative abundance of long-term observations available to validate predictions. Computational packages have been developed to harmonically analyze and predict currents (in addition to tides) [3,4], but the question of fundamental predictability has received less attention. This lapse has taken place in spite of Godin's 1983 conclusion [5] that "currents cannot be predicted with the same level of precision as the tide" and that "the study of currents is essentially a research problem and should not be considered a matter for routine data processing at the clerical or technical level."

For hydrokinetic applications, these challenges are compounded by a need to reliably predict forces on the turbine (proportional to velocity squared) and power output (proportional to velocity cubed). Because of this, relatively small errors in velocity predictions may result in operationally meaningful residuals. Fortunately, in the context of hydrokinetics, a number of complexities are also relaxed. First, it is generally only necessary to predict speed, rather than speed and direction. If a turbine is designed to passively yaw, it will maintain alignment with the direction of the flow, regardless of directional asymmetries between ebb and flood or directional variability within a particular ebb or flood cycle. If a turbine is fixed yaw and would experience significant performance degradation during periods of misalignment, then it is unlikely to be deployed at the site and an accurate prediction of current direction is irrelevant. Second, in order to characterize inflow conditions for an operating turbine, a prediction is only required at device hub height [6]. Third, tidal turbines only operate above a device-specific cut-in speed (0.7-1.0 m/s). Poor predictive accuracy below cut-in speed is of no consequence.

The predictability of currents for hydrokinetic tidal power are investigated using data collected at a proposed development site in northern Admiralty Inlet, Puget Sound, Washington, USA (Fig. 1). Here, currents over the sill are at a maximum and comparable to other proposed tidal energy sites [7]. These data are used to address three fundamental questions:

- (1) What are the characteristics of the currents at this location as they relate to predictability?

¹ This material is based upon work supported by the Department of Energy under Award Number DE-FG36-08GO18179 and Public Utility District of Snohomish County No. 1.

- (2) Can harmonic analysis describe currents with sufficient completeness to be useful for tidal hydrokinetic applications?
- (3) How accurate are predictions based on harmonic analysis and to what degree can these predictions be spatially extrapolated?

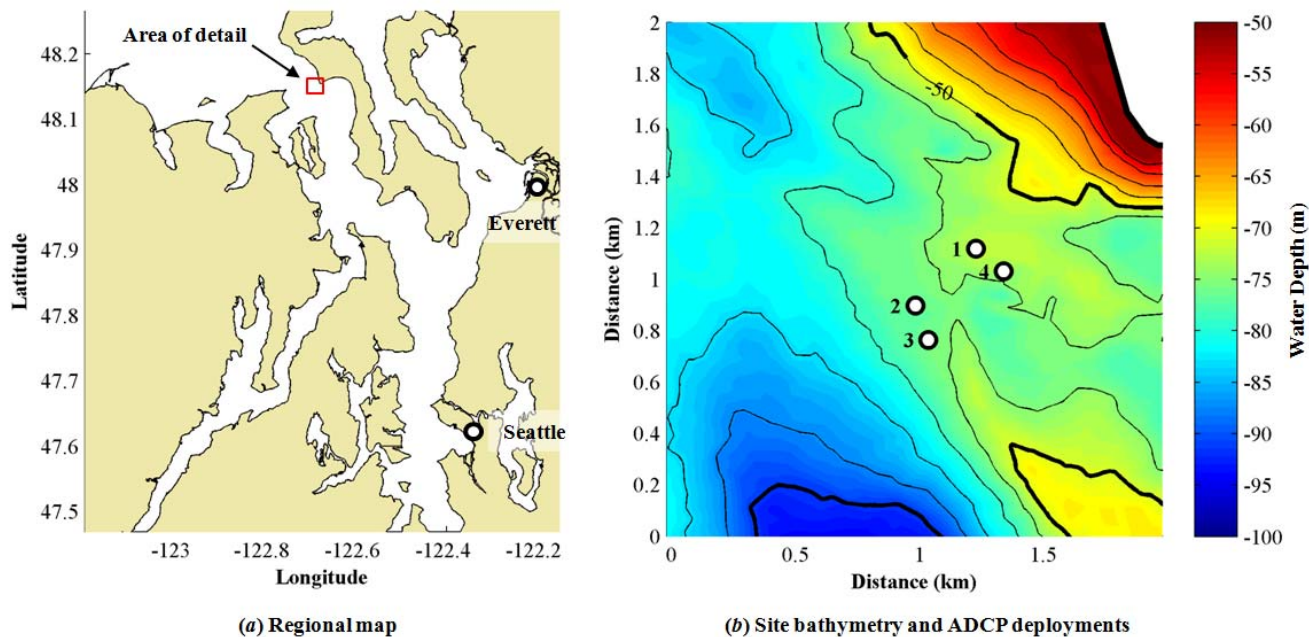


Fig 1. – (a) Puget Sound, Washington, USA and (b) detail of Admiralty Inlet showing locations of ADCP deployments.

II. METHODOLOGY

A. Data Collection

Current data are obtained by a 300 kHz RDI Workhorse Sentinel acoustic Doppler current profiler (ADCP). The instrument is deployed as part of a broader site characterization package on a ballasted tripod and recovered by acoustic releases. Instrument configurations are given in Table 1 for deployments between May 2009 and May 2010. Internal orientation sensors confirm that the instrument package is stable during deployments. Tide data are simultaneously collected by a Star Oddi DST CTD.

TABLE 1
CONFIGURATIONS OF ADCP DEPLOYMENTS IN ADMIRALTY INLET, PUGET SOUND, WASHINGTON, USA

	Station 1	Station 2	Station 3	Station 4
Deployment dates	5/09 – 8/09	8/09 – 11/09	11/09 – 2/10	2/10 – 5/10
Duration (days)	75	97	78	82
Deployment depth (m)	56	67	66	56
Vertical bin size (m)	1	1	1	1
Ensemble interval (s)	30	135	45	60
Expected noise ¹ (m/s)	0.052	0.027	0.044	0.041

¹Based on bin size, pings per ensemble, and ambiguity velocity (4 m/s for all deployments)

B. Current Characteristics

Prior to performing harmonic analysis, it is instructive to characterize the currents. Mean flow properties demonstrate the degree of spatial variability between stations and the potential extrapolation limits for predictions. Properties here are based on those described in Gooch et al. [8], with minor modification.

Mean ebb currents are defined as the average over all velocities less than zero and flood currents as greater than zero. The asymmetry between ebb and flood is defined as the ratio of the mean flood and ebb currents (note, this is not equivalent to the residual currents). The mean current is defined as the time-weighted average of ebb and flood means. In Gooch et al. a slack period, defined by currents less than 0.5 m/s is excluded from analysis, but this complicates interpretation of results. The instantaneous kinetic power density (K) is given by

$$K = 1/2 \rho u^3 \quad (2)$$

where ρ is the density of seawater (nominally 1024 kg/m³) and u is the current speed (m/s). By convention, kinetic power density is expressed in units of kW/m². Mean kinetic power density and ebb/flood asymmetry are calculated similarly to currents.

Directional variation is defined as the standard deviation in current direction when speeds exceed 0.5 m/s; rapid changes in direction near slack water are not operationally relevant [8]. Directional asymmetry is defined as the departure from 180 degrees for the alignment of ebb and flood principal axes.

As noted by Godin [9], asymmetry in ebb and flood current strength may derive from three sources; (1) density-driven circulation (2) the local influence of bathymetry and topography, and (3) non-linear interactions between tidal constituents. In spectral and harmonic analyses, this asymmetry aliases energy in the primary tidal constituents to higher frequencies (e.g., M2 aliased to shallow water constituents M4, M6, etc.). The contribution of residual currents, which occur over time scales on the order of weeks, is quantified by low pass filtering current observations (PL64, 40 hour half-amplitude period [10]). Turbulence fluctuations over time scales on the order of seconds and supra-tidal fluctuations over time scales on the order of an hour are approached qualitatively. The ADCP configuration used for these measurements is not appropriate to quantify turbulence [11], but a representative current trace over several days highlights its significance.

C. Harmonic Analysis

Harmonic analysis is performed by t_tide [4]. As previously discussed, currents are reduced to a single dimension by neglecting vertical velocities (small) and direction (not operationally relevant) in favor of speed (ebb signed negative, flood signed positive). Consequently, a least squares fit of the form given in (1) is used to characterize the currents, rather than a complex representation required to capture speed and direction. The least squares approach has similarities to Fourier analysis, but is preferable because tidal frequencies are not integer multiples of a fundamental frequency (as is required for Fourier analysis). Measured currents are ensemble averaged over a 15 minute interval prior to harmonic analysis to smooth turbulent fluctuations.

Up to 146 harmonic constituents may be included by t_tide in the least-squares solution by t_tide . The Rayleigh criterion governs constituent inclusion and is a function of the frequency separation between neighboring constituents and record length:

$$(\sigma_i - \sigma_j)T > R, \quad (3)$$

where σ_i and σ_j are neighboring constituents, T is the duration of the record, and R is the Rayleigh constant. Constituents are included in order of strength, as determined by equilibrium tide theory [13]. While a Rayleigh constant of one is common for tidal analysis (and is used here for currents), the additional Doppler noise in ADCP current measurements and turbulence may warrant a more conservative Rayleigh constant. Additionally, Godin [12] recommends $R=0.8\pi$, even for tidal analysis.

The degree of agreement between the ensemble averaged measurement and harmonic fit is evaluated by several parameters:

- (1) variance explained by the fit, defined as the ratio of sum of the variance in the fit to the sum of the variance in the measurements,
- (2) RMS error,
- (3) coefficient of determination (R^2),
- (4) ratio of maximum speed in the fit to the maximum speed in the measurements (effectiveness at fitting peak flood), and
- (5) ratio of minimum speed in the fit to the minimum speed in the measurements (effectiveness at fitting peak ebb).

These comparisons are made only for speeds above a nominal device cut-in (0.7 m/s). Comparisons are repeated for kinetic power density, as the cubic relation between power density and speed amplifies errors. In addition to the above metrics, the average kinetic power density in the fit is compared to measurements (effectiveness at predicting the average hydrokinetic resource).

D. Prediction Accuracy

In the context of tidal energy, reducing a time series to a set of harmonic constituents is an academic exercise; no new operational insight is gained. The benefit of harmonic analysis is the ability to use the derived constituents to predict currents and kinetic power density into the future. As observed by Godin [5], such predictions are of little benefit if no comparison is made against additional measurements (one may simply choose to believe or not to believe the prediction). With the available data, a preliminary assessment is possible along two lines. First, the accuracy of the prediction at the measured location is evaluated by deriving constituents from only a portion of the available record and making a prediction against the remainder. Second, to evaluate the potential for spatial extrapolation of predictions, the harmonic constituents derived for one station are used to predict currents at others. Prediction accuracy is assessed using the same operational metrics as described above for the harmonic fit.

III. RESULTS

A. Current Characteristics

Current characteristics for the four deployments are given in Fig. 2 and show significant variations in spatial position and depth throughout the survey area. These variations exceed the low amplitude modulation of current strength over periods longer than a few months and are reflective of spatial, rather than temporal, variability. As would be expected for a boundary layer flow, current strength increases towards the surface. Currents are stronger closer to the headland (Stations 1 and 4), but also subject to the greatest ebb/flood asymmetry. Variations in currents are amplified for power density and have important implications for siting (e.g., a turbine deployed at Station 1 would produce more than twice as much power as one deployed at Station 2 or 3). For this reason, further analysis and discussion related to predictability are restricted to Station 1. Directional variation within an ebb or flood cycle is moderate and not likely of operational consequence, but the misalignment between ebb and flood is generally greater than 20 degrees and could have implications for some fixed yaw turbines.

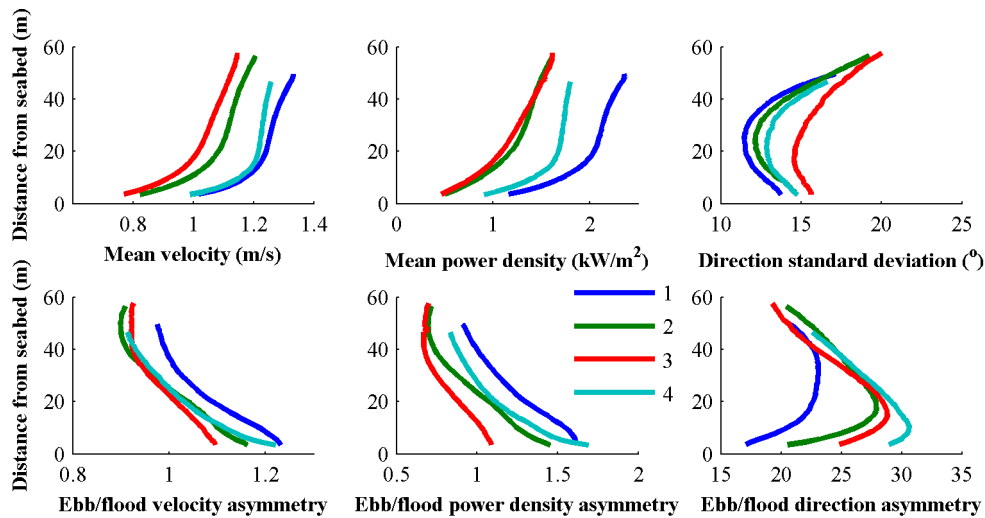


Fig 2. – Current characteristics for four stations in Admiralty Inlet, Puget Sound, Washington, USA.

Current time series for Station 1 at a hypothetical turbine hub height of 10m above the seabed are shown in Fig. 3. Over multiple fortnightly cycles (Fig. 3a) harmonic features are apparent, such as the neap-spring modulation and the diurnal inequality typical of a mixed, mainly semi-diurnal tidal regime. Over shorter time scales (Fig. 3b), non-harmonic features emerge. These include supra-tidal fluctuations on times scales over an hour (e.g., dual peaks on ebb and flood) and rapid, turbulent fluctuations on time scales shorter than a minute. The physical basis for supra-tidal fluctuations is presently being investigated and may be a combination of topographic effects (e.g., eddy fields) and hydraulic control elsewhere in Admiralty Inlet. Residual currents (Fig. 3c) display a classical estuarine circulation pattern with a residual ebb near the surface, residual flood near the seabed, and a modulation in strength with the neap-spring cycle (stratification is strongest during neap tides). Residual currents also show a bias towards ebb during all stages of the neap-spring cycle, suggesting that these asymmetries are not solely due to gravitational circulation. Assuming that gravitational circulation is at a minimum during strong spring tides, this bias is approximately 10 cm/s.

In summary, at Station 1, currents are dominantly periodic, but subject to non-harmonic variability over seasonal time scales (density-driven circulation) and shorter time scales (supra-tidal fluctuations, turbulence). This variability cannot be predicted by conventional harmonic analysis. The spatial variability between stations also suggests that extrapolation limits for tidal current predictions will be less than the smallest inter-station spacing (approximately 100m).

B. Harmonic Analysis

Thirty-five harmonic constituents may be resolved from the measurements at Station 1 with a Rayleigh constant equal to one. Measurements over forty-five days are analyzed, leaving thirty days of measurements to test the accuracy of predictions. Because resolved constituents with a low signal to noise ratio (SNR) may be merely fitting noise, only resolved constituents with $SNR > 3$ (29 in total) are reported in Tables 2-5. A few comments are warranted with respect to constituent resolution and reported values. First, a small set of constituents (M2, N2, S2, K1, and O1) describe the majority of the observed tidal currents. Constituents excluded because of low SNR have amplitudes two orders of magnitude smaller and do not account for the variation between measurements and the harmonic fit. Second, with a record length of this duration, several important constituents are convolved with others. For example, P1, which has an amplitude approximately 1/3 of K1, is included in the K1 constituent, artificially increasing its amplitude. In order to directly resolve P1 (necessary for accurate long-term predictions), at least a six month record is required with a Rayleigh constant of one. Third, the reported amplitudes for shallow water constituents contain energy aliased from the primary constituents due to the ebb/flood asymmetry at this station. As shown in Fig. 4, the power spectrum for currents includes sustained energy at high frequencies, which are not present in the tidal record for the same location. Since this aliasing does not have any effect on predicted currents, this distortion is not of operational significance.

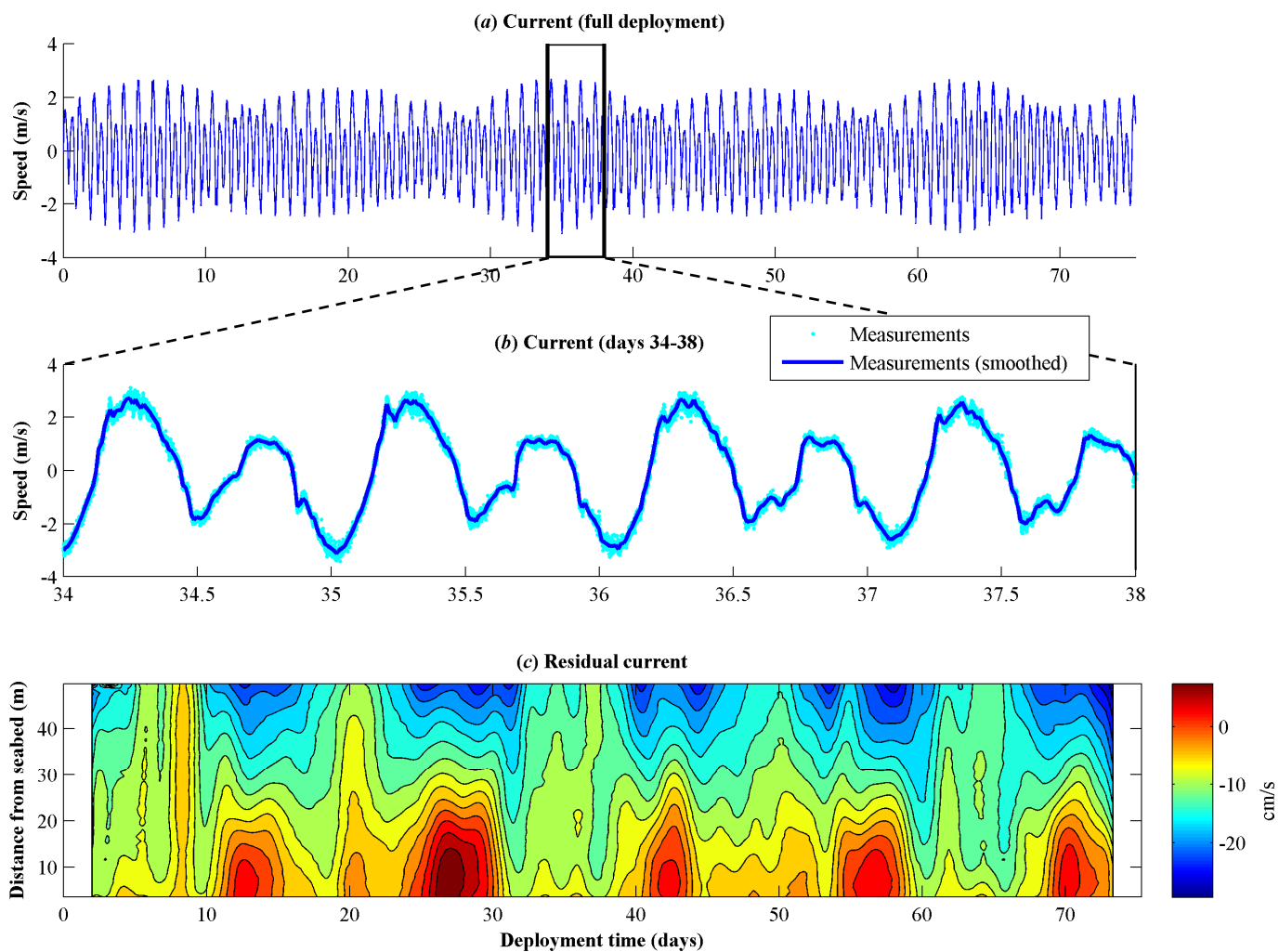


Fig 3. – Current traces at Station 1, 10m above seabed.

TABLE 2
RESOLVED DIURNAL CONSTITUENTS (STATION 1, 10m ABOVE SEABED)

Constituent	Period (h)	Amplitude(m/s)	SNR
K_1	23.9	0.77	19000
O_1	25.8	0.31	3700
OO_1	22.3	0.07	150
Q_1	26.9	0.066	130
NO_1	24.8	0.017	9.3
v_1	21.6	0.015	6.8

TABLE 3
RESOLVED SEMIDIURNAL CONSTITUENTS (STATION 1, 10m ABOVE SEABED)

Constituent	Period (h)	Amplitude(m/s)	SNR
M_2	12.4	1.6	53000
N_2	12.7	0.32	1400
S_2	12.0	0.26	1100
μ_2	12.9	0.11	170
L_2	12.2	0.096	160
η_2	11.8	0.033	18
ε_2	13.1	0.02	6.7

TABLE 4
RESOLVED SHALLOW WATER CONSTITUENTS (STATION 1, 10m ABOVE SEABED)

Constituent	Period (h)	Amplitude(m/s)	SNR
M ₄	6.21	0.11	900
MK ₃	8.18	0.098	140
2MK ₅	4.93	0.097	50
3MK ₇	3.53	0.076	65
2MS ₆	4.09	0.052	25
MS ₄	6.10	0.051	200
MO ₃	8.39	0.046	32
SN ₄	6.16	0.045	180
MN ₄	6.27	0.042	140
M ₈	3.11	0.035	7.4
M ₆	4.14	0.029	6
SK ₃	7.99	0.028	9.9
S ₄	6.00	0.026	48

TABLE 5
RESOLVED LONG TERM CONSTITUENTS (STATION 1, 10m ABOVE SEABED)

Constituent	Period (days)	Amplitude(m/s)	SNR
M _{sf}	14.8	0.053	470
M _m	27.6	0.033	130

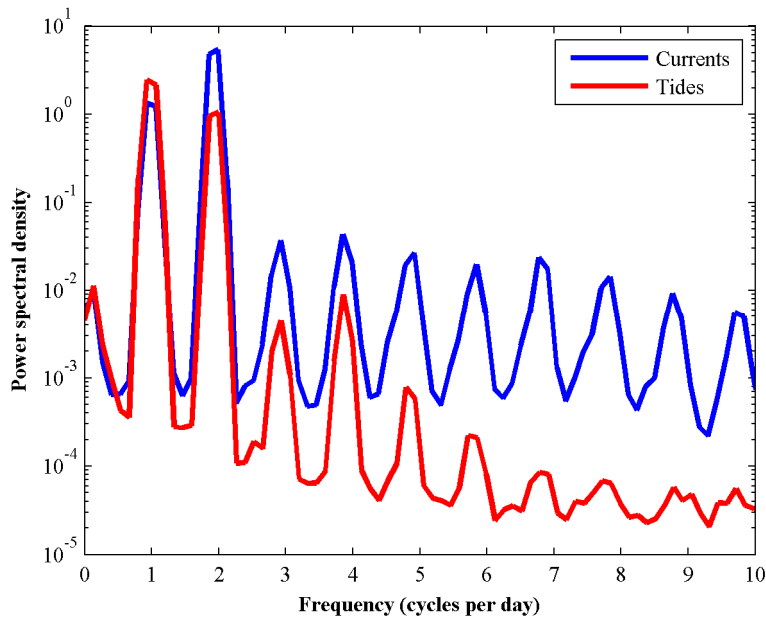


Fig 4. – Power spectral density for tides and currents (Station 1, 10m above seabed).

Fig. 5 shows measurements (smoothed to remove the effect of turbulence), the harmonic fit, and residual between fit and measurements for both currents and kinetic power density. The harmonic fit describes the major features of the currents, but there are residuals of up to 1 m/s for currents and up to 5 kW/m² for power density throughout the tidal cycle. However, these residuals have little effect on operational metrics, as shown in the first column of Table 6. For the base case discussed above (column 1), the explained variance and coefficient of determination are high for both speed and power density. Peak flood and ebb currents and average kinetic power density are also well-described. Interestingly, metrics for speed and power density are comparable, even with the cubic dependence of power density on speed. Removing density-driven circulation (column 2) or including all speeds (column 3) does not significantly alter any operational statistics. This is expected, since the contribution from density-driven circulation at 10m hub height is no greater than ~15 cm/s (assuming a 10 cm/s ebb bias from topographic effects) and strongest during neap tides, when limited power is generated. From these results, we conclude that harmonic analysis provides a robust fit to measured currents in the context of tidal energy.

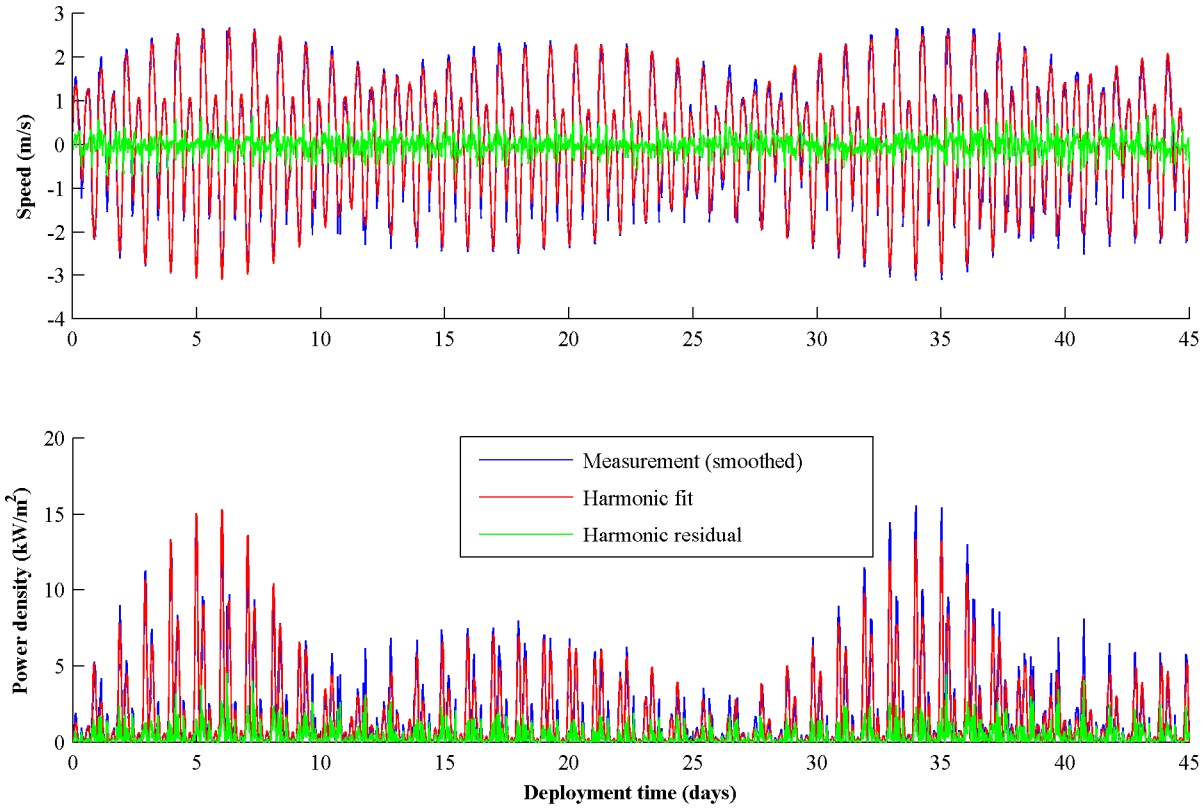


Fig 5. – Comparison between measured and fit currents (top) and kinetic power density (bottom) (Station 1, 10m above seabed).

TABLE 6
OPERATIONAL METRICS FOR HARMONIC FIT (STATION 1, 10m ABOVE SEABED)

	Base	Residual currents removed	All speeds included
<i>Speed</i>			
Variance explained	0.98	0.98	0.98
RMS error (m/s)	0.15	0.17	0.15
Coefficient of determination	0.99	0.99	0.99
$u_{\max, \text{fit}}/u_{\max, \text{measurement}}$	0.97	1.01	0.97
$u_{\min, \text{fit}}/u_{\min, \text{measurement}}$	0.99	0.96	0.99
<i>Power density</i>			
Variance explained	0.99	0.93	0.98
RMS error (kW/m ²)	0.52	0.60	0.38
Coefficient of determination	0.96	0.94	0.96
$K_{\max, \text{fit}}/K_{\max, \text{measurement}}$	0.98	0.89	0.98
$\langle K_{\text{fit}} \rangle / \langle K_{\text{measurement}} \rangle$	0.98	0.89	0.98

The preceding discussion pertains only to measurements which have been smoothed to remove the effects of turbulence. Fig. 7 shows a detailed comparison between measurements (smoothed and raw) and the harmonic fit over the same window as Fig. 3b. Mismatches between the fit and smoothed measurements are primarily due to supra-tidal departures from sinusoidal behavior and contribute to the RMS error of 15 cm/s. The Doppler noise associated with the ADCP measurement is lower (4 cm/s). For this station, low frequency variations from gravitational circulation are on the order of 15 cm/s. In contrast, turbulent fluctuations over short time scales (e.g., 30 s) can exceed 50 cm/s during periods of peak currents. For more than 70% of measurements greater than the cut-in speed, the harmonic fit is within the range of these fluctuations. Therefore, the mismatch between harmonic fit and smoothed measurements is, in a majority of cases, subordinate to turbulence.

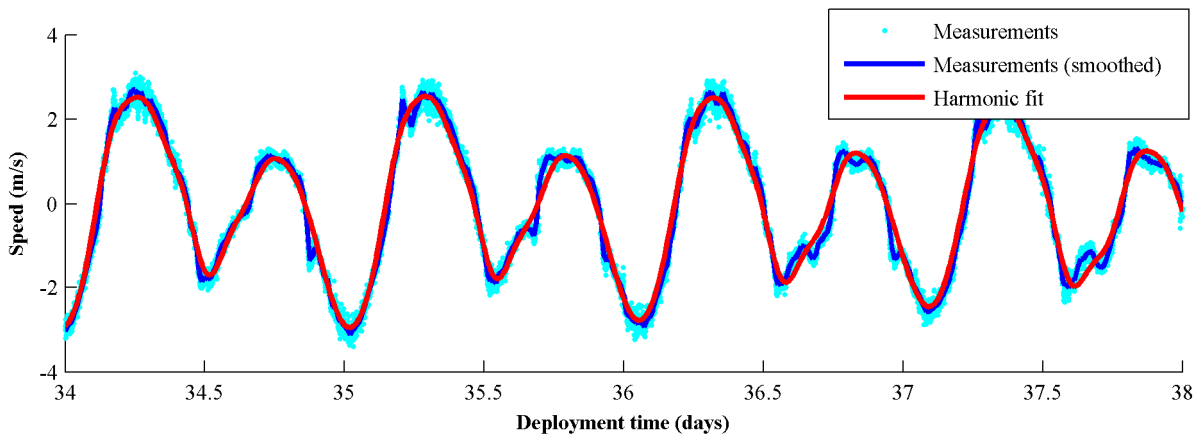


Fig 7. – Detailed comparison between current measurements and harmonic fit (Station 1, 10m above seabed).

C. Prediction Accuracy

As shown in Table 7, the harmonic constituents derived for Station 1 predict speed and power density for the remainder of the record with the same accuracy as the harmonic fit. However, the prediction is not operationally valid at other stations, even at Station 4, less than 200m away. This is expected from the variation in mean flow characteristics and the inability to resolve a number of important constituents (e.g., P_1) in the available record length. The second consideration would likely lead to poor predictions at Station 1 over longer time scales (e.g., several years).

TABLE 7
OPERATIONAL METRICS FOR PREDICTIONS (10m ABOVE SEABED)

	Station 1 (fit)	Station 1 (prediction)	Station 2	Station 3	Station 4
<i>Speed</i>					
Variance explained	0.98	0.96	1.45	1.66	1.00
RMS error (m/s)	0.15	0.25	0.38	0.35	0.36
Coefficient of determination	0.99	0.98	0.94	0.97	0.93
$u_{\max, \text{prediction}}/u_{\max, \text{measurement}}$	0.97	0.91	1.16	0.97	1.05
$u_{\min, \text{prediction}}/u_{\min, \text{measurement}}$	0.99	0.90	1.33	1.34	1.05
<i>Power density</i>					
Variance explained	0.99	0.79	5.07	5.17	1.70
RMS error (kW/m ²)	0.52	0.84	0.96	1.02	0.77
Coefficient of determination	0.96	0.85	0.77	0.88	0.77
$K_{\max, \text{prediction}}/K_{\max, \text{measurement}}$	0.98	0.72	2.28	1.35	1.17
$\langle K_{\text{prediction}} \rangle / \langle K_{\text{measurement}} \rangle$	0.98	0.95	1.89	2.20	1.09

IV. DISCUSSION

The results for this site confirm Godin’s 1983 conclusion: currents are less predictable than tides. However, from an operational standpoint for tidal hydrokinetic power generation, harmonic analysis provides a useful description of observed currents and can be used to make an accurate prediction. However, there are several challenging characteristics of tidal currents, which could be addressed by future work.

First, observed currents contain non-sinusoidal fluctuations over time scales $O(1 \text{ hour})$ which cannot be described by conventional harmonic analysis. Since these supra-tidal fluctuations exhibit a degree of periodicity, it may be possible to describe them by empirical functions of predicted currents. These relations would be site specific and would need to describe ebb and flood variations, as well as modulation on the greater and lesser tides of the diurnal inequality.

The second, and more considerable, barrier is turbulence. As previously discussed, turbulent fluctuations occur over time scales less than a minute, are large (e.g., 50 cm/s during peak currents), and are inherently unpredictable. Because the response of tidal energy devices to turbulence has not been characterized, the implications for these fluctuations are largely unknown. As a secondary effect, the noise introduced by turbulence may increase the Rayleigh constant, requiring longer records to resolve neighboring constituents. This would be best investigated by long-term (i.e., greater than a year) observations at a single location.

Third, spatial variability limits the extrapolation of current predictions. At this particular location, the limit to accurate extrapolation is likely not more than 100m, though the rapidly varying bathymetry and close proximity to the headland may pose an extreme case. Conducting long-term current measurements at high resolution over the area occupied by a commercial array would be costly.

An open question is whether numerical modeling could prove to be a more feasible approach. While models can achieve the required spatial resolution, a model for an area as large as Admiralty Inlet at $O(10\text{m})$ spatial resolution would be computationally demanding and perhaps no less expensive than a large-scale survey effort. In any event, measurement data will be required for model calibration and validation.

While tidal currents are not completely predictable, the degree of uncertainty should not prove a barrier to commercialization. Wind farms harness a stochastic resource, yet are financed, connected to the grid, and deliver power at a comparable cost to thermal power plants. By comparison, tidal hydrokinetic power generation is far more predictable.

ACKNOWLEDGMENT

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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