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Monitoring tidal currents with a towed ADCP at tidal energy site in Alderney Race (Raz Blanchard)

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ABSTRACT: The tidal circulation in Alderney Race (Raz Blanchard) is assessed by using a towed Acoustic Doppler Current Profiler (ADCP) system and modelling. The study site is assumed to have the largest tidal stream potential in France. Optimal Interpolation (OI) was applied to process the underway velocity measurements. The interpolation technique allows reconstructing space-time evolution of the velocity field within the whole study domain for surveys whose duration is comparable or larger than the typical time of tidal variation (~3–6 h). The method employs space-time velocity covariances derived from numerical simulations by a 2D hydrodynamic model MARS (Model for Applications on Regional Scale). Model covariances are utilized by the OI algorithm to obtain the most likely evolution of the velocity field under the constraints provided by the ADCP observations and their error statistics. All tests demonstrated significant (up to 50%) reduction of the model-data misfit as a result of space-time optimal interpolation. An improvement in representation of the temporal and spatial variability of the tidal stream was achieved. The resulting velocity fields were used for assessing the tidal power resource at site at fine scale. It is shown that OI of high resolution velocity measurements in Alderney Race makes the tidal stream potential estimation more accurate.

1 INTRODUCTION

In recent years, converting tidal current kinetic energy into electric power is becoming a reliable alternative solution for rising the proportion of marine renewable energy to the worldwide energy production.

In coastal ocean, the most promising sites have limited size and are located near the shore (straits, passage between islands, or areas close to headlands). In order to optimize energy conversion, it is required to properly characterize the environmental conditions at the sites and thus facilitate the process of selecting tidal power devices appropriate for industrial use.

Over the last decade, standard techniques of field data collection for tidal resource characterization have been proposed (Legrand 2009, Venugopal et al. 2011). In the case of tidal characteristics, direct current measurements are essential and Acoustic Doppler Current Profilers (ADCPs) are often the instrument of choice. An ADCP can work in different setups. A bottom-mounted ADCP is often deployed for measuring temporal variations, while a vessel-mounted ADCP can measure spatial

variations. However, deployment and recovery of ADCPs at tidal energy sites with extreme current and wave climate is difficult. In this environment, underway ADCP surveys may offer a more practical alternative.

The power generating potential of the tidal stream is characterized by significant variations at the scales of a few hundred meters (Li et al. 2006, Goddijn-Murphy et al. 2013) and thus requires very high resolution surveying during multiple tidal cycles. Using broadband ADCP surveys, Goddijn-Murphy et al. (2013), Polagye and Thomson (2013) documented fine scale velocity variations caused by tidal flow interaction with land and islands. However, the rapid change of the tidal flow during surveying period tends to induce errors in the velocity map interpretation. Goddijn-Murphy et al. (2013) showed that the accuracy in reconstruction of the full 4-dimensional tidal flow can be significantly increased by merging observed velocities with the dynamical constraints provided by numerical models.

More recently, Sentchev and Yaremchuk (2016) used the Optimal 4-dimensional Interpolation (OI) technique for reconstructing space-time evolution

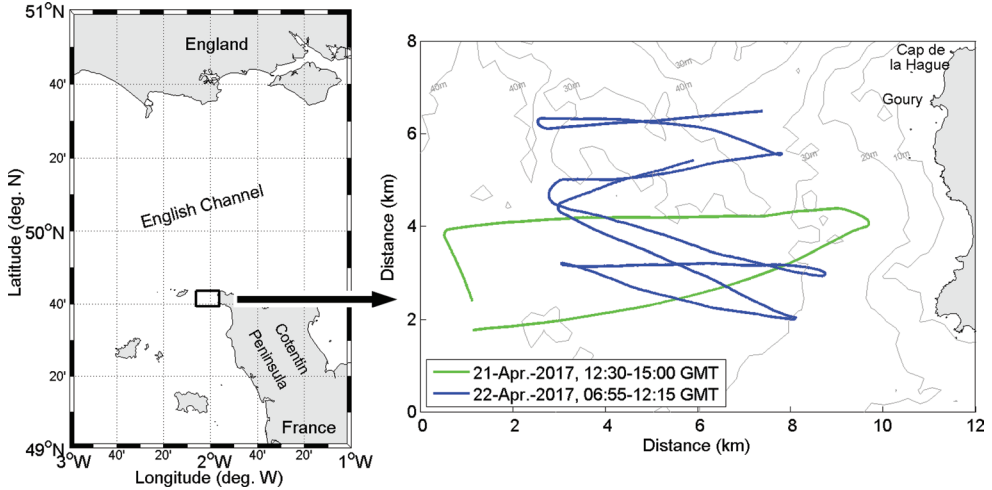


Figure 1. *Left panel:* Map of the English Channel with location of the surveyed area (black rectangle). *Right panel:* Surveyed area, off the West coast of France, with bathymetry (m) given in gray and two successive surveys: 12:30–15:00 GMT on April 21, 2017 (green) and 06:55–12:15 GMT on April 22, 2017 (blue). Geographic names used in the text are also shown.

of the velocity field derived from towed ADCP surveys in the Boulogne harbour (English Channel). This approach, which combines underway velocity measurements and modelling, offers a real opportunity for short-term monitoring of the strong nearshore circulation.

In this work, we applied the OI technique to underway measurements recorded by a towed (not vessel-mounted) ADCP in Alderney Race. Tidal current velocities are synchronized in time using the output statistics from the 2D hydrodynamic model MARS (Model for Applications on Regional Scale) configured for high-resolution simulations in the surveyed area.

2 METHODOLOGY

2.1 Study site

The measurements presented here were performed in the northern sector of the Channel Islands region located to the west of the Cotentin Peninsula in Normandy, France (Figure 1). The surveyed area is approximately 9×5 km square with water depth less than 50 m throughout the domain. The sea surface height (SSH) in the Goury harbor (Figure 1) exhibits strong (up to 8 m) variations depending on the stage of the tide. Tidal variations of SSH and currents are predominantly semi-diurnal and current velocities are higher during ebb tide than during flood tide (Thiébot et al. The maximum tidal current velocities are observed at

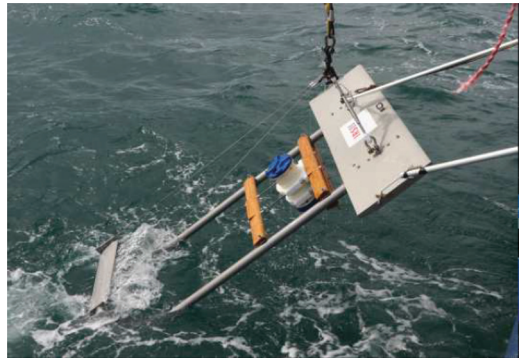


Figure 2. The platform carrying a 600 kHz RDI ADCP towed by the research vessel “Thalia” in Alderney Race.

the eastern side of Alderney Race with values up to 3.5 m/s at mean tide (Bahaj and Myers 2004).

2.2 Underway ADCP measurements

High-resolution current mapping was performed in Alderney Race using an experimental platform carrying a broadband ADCP (600 kHz Teledyne RDI WorkHorse Sentinel) and towed by the R/V “Thalia” (Figure 2). The ADCP was located roughly 8.5 m below the water surface with the third beam aligned along the platform’s centreline. The bin size was set to 1 m. The velocity profiles were obtained from 10 m depth to the sea bottom. The ADCP was set to operate at the ping rate of

1 Hz. Each ping for velocity was composed of three sub-pings averaged within 1-s interval, providing velocity error of 0.04 m/s. Single-ping bottom tracking was enabled to correct for boat's movement, and the recorded velocities formed a current vector in the fixed frame relative to the bottom.

The vessel's speed was typically 5–6 knots for the majority of the tracks. The ADCP data were merged with navigation data provided by an onboard GPS system operating at 1 Hz.

A total of eight surveys were performed to assess the circulation pattern in Alderney Race. Only the results of two surveys are presented in this paper. Their tracks are shown in Figure 1 (right panel). The first survey was performed on April 21, 2017 at 12:30–15:00 UTC, before arriving high water (HW) in Goury (HW–2.5 hours to HW). The second survey took place the next day, on April 22. It was targeted at monitoring the currents during the ebb flow and lasted more than 5 hours from low water (LW)—3 hours to LW+2.25 hours. Both surveys were performed during neap tide.

Current velocities recorded by ADCP were vertically averaged for the comparison with the model output. Both velocities and GPS coordinates were subsampled every minute, so that the distance between the thinned along-track data points varied within 120–180 m, depending on the towing speed.

Underway ADCP measurements from repeated tracks have the potential not only to yield the detailed spatial patterns of tidal currents, but also patterns of vorticity and dynamical terms (Geyer and Signell 1990). However, observations contain information on both spatial and temporal variations of tidal currents and the measurements are necessarily affected by tidal changes over the period of a survey, and even over individual tracks. Nowadays, a number of techniques have been used to separate these variations (Candela et al. 1992, Vennell 2006, Vazquez et al. 2010, Goddijn-Murphy et al. 2013).

3 OPTIMAL INTERPOLATION OF VELOCITY MEASUREMENTS

3.1 Principle of optimal interpolation

Optimal Interpolation is a commonly used and powerful method of objective analysis of observations. OI provides estimation of the spatial distribution of a physical quantity at a given time through a linear combination of the available data. The weights used are chosen so that the expected error of the estimate is a minimum in the least squares sense, and the estimate itself is unbiased.

This technique, pioneered by Gandin and Hardin (1965) was widely adopted in geosciences

(Bretherton et al 1976, Thi'ebaux and Pedder 1987, Wunsch 1996, Sentchev and Yaremchuk 2016).

The OI technique can be easily extended to include time dimension by using the space-time correlation functions. In this approach, the optimal correction to the evolution of a background vector field $\mathbf{u}^m(x, t)$ defined on a regular (model) grid is represented by a linear combination of the weighted differences between the background trajectory and the observed velocities. The weights a_i are chosen so as to minimise the mean square difference between observations \mathbf{u}_i^* and the background field values \mathbf{u}^m , interpolated into the space-time locations of the observations by the (linear) operator \mathbf{H}_i , projecting gdded velocity values onto the i -th observation point from the apexes of the enveloping grid cell:

$$J_u = \langle [\mathbf{u}^m + \sum_i a_i (\mathbf{H}^i \mathbf{u}^m - \mathbf{u}_i^*)]^2 \rangle \rightarrow \min(a_i)$$

Here, angular brackets denote the statistical (ensemble) average, and summation is made over all (distributed in space and time) velocity values measured during the survey period. Given the space-time covariance matrices of the model $\mathbf{B} = \langle \mathbf{u}^m(\mathbf{x}, t) \mathbf{u}^m(\mathbf{x}', t') \rangle$ and observations $\mathbf{R}_j = \langle \mathbf{u}_j^* \mathbf{u}_j^* \rangle$, and assuming that observation errors are not correlated with the model (background) errors, the OI interpolation formula takes the form:

$$\mathbf{u}_{\text{opt}} = \mathbf{u}^m + \sum_{ij} \mathbf{B} \mathbf{H}_j^T (\mathbf{H}_i \mathbf{B} \mathbf{H}_j^T + \mathbf{R}_{ij})^{-1} (\mathbf{H}^i \mathbf{u}^m - \mathbf{u}_i^*)$$

In most applications, the observation error covariance is assumed to be diagonal. In the considered case, the diagonal values of \mathbf{R} are equal to the variances of the along track velocity samples taken at 1 minute intervals. The OI takes explicit account of the expected spatial structure of both model and observational errors to produce the velocity field with the least error variance. In order to apply the above equation for interpolating the velocities recorded by the towed ADCP, $\mathbf{u}^m(\mathbf{x}, t)$ and \mathbf{B} were specified using the output statistics from the regional model MARS-2D configured for high resolution simulations in the surveyed area.

3.2 Hydrodynamic model

The estimation of the background dynamics was based on the hydrodynamic model MARS-2D. Numerous modelling studies (Blunden and Bahaj 2006, Coles et al. 2017) have demonstrated that models using two-dimensional horizontal approximation (i.e. shallow-water equations) are useful tool for characterising the spatial and the temporal

variability of the tidal-stream energy resource at a site.

MARS-2D solves the shallow water equations (continuity and momentum), derived from the three-dimensional Navier-Stokes equations averaged over the water column. Full details concerning the MARS algorithm are given by Lazure and Dumas (2008).

The present model involves a nesting strategy, starting from a broad region covering the entire North-West European continental shelf (with a 5-km grid resolution) down to a detailed domain covering a few tens of km (with a 110-m resolution).

In the present study, we used the 9-day model run containing seventeen 2.5-h and 5-h periods corresponding to tidal stage of survey 1 and 2 respectively. Each 2.5-h and 5-h model trajectory, sampled at 1 minute resolution, constitutes an ensemble member. The background model trajectories $\mathbf{u}^m(\mathbf{x}, t)$ corresponding to the surveys were obtained by averaging over the respective seventeen 2.5-h and 5-h periods (i.e., ensemble members are separated by one tidal period). In a similar manner, the space-time background covariance matrix \mathbf{B} was computed using the same seventeen ensemble members extracted from the 9-day model runs when the modeled tide was exactly in sync with the one observed during the corresponding survey. The computation of \mathbf{B} was performed two times, one time for one particular survey. The interpolation grid adopted for both surveys contained $n = 56 \times 47$ grid points with 220 m spacing.

The overall interpolation quality was quantified by estimating the mean relative difference with the data:

$$e = \left(\frac{\sum_i (\mathbf{H}^i \mathbf{u}^m - \mathbf{u}_i^*)^2}{\sum_i (\mathbf{u}_i^*)^2} \right)^{1/2}$$

3.3 Tidal circulation in Alderney Race: Observed and modeled velocities

Model simulations showed that the tidal flow direction is towards northeast during flood tide and towards southwest during ebb tide. According to Thiébot et al. (2015) similar hydrodynamic patterns are obtained when considering neap or spring tides. The strongest current for both ebb and flood flow is observed in the north eastern sector of the study domain with maximum velocities reaching 2.5 m/s there.

Vector maps of the observed and modeled velocities are shown in Figure 3. Observations were vertically averaged for the comparison with the model output. For both surveys, underway ADCP measurements started just after the current

reversal, therefore, velocities recorded during the first 30–60 minutes were very low. As a consequence, only vertically velocity vectors recorded from 13:00 to 15:00 on flood tide and from 08:10 to 12:15 on ebb tide, are shown in Figure 3. Velocities derived from the model output were averaged over those two periods.

The time-averaged model fields for each survey provide a general view of the consistency between the data and the model before interpolation. Visual inspection reveals a good agreement for the direction of the velocity vectors but differences in

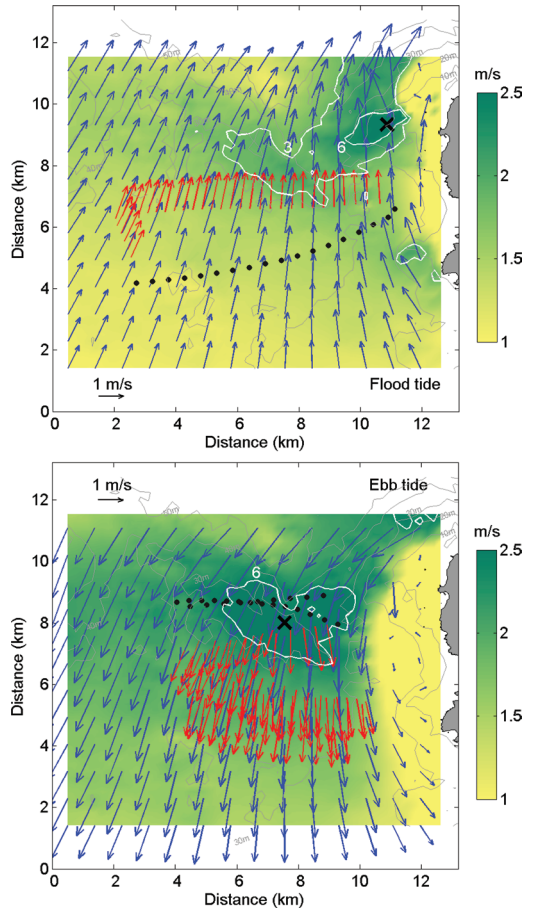


Figure 3. Observed velocity vectors (red) recorded on 21 Apr. from 13:00 to 15:00 (top) and on 22 Apr. from 08:10 to 12:15 (bottom). Modeled velocity vectors (blue) and velocity magnitude (background shading) were obtained by averaging the model output over two respective periods. Black dots represents locations where the surveying velocities were low and velocity vectors are not shown. White contours show the most energetic areas. Black crosses give the location of the maximum kinetic power density P .

current speed are observed depending on the tidal stage.

During flood tide, the model overestimates the velocity magnitude by 11% whereas during ebb tide, this value is almost twice higher and achieves 20%. The discrepancy probably comes from improper model representation of the sea bottom and bottom frictional effects. Such misfits are also quantitatively visible from comparison of mean values of kinetic energy per unit volume (Table 1).

3.4 Space-time interpolation of velocities

Direct current measurements are essential for investigating the velocity field evolution of an area. However, since the surveying time were comparable with the typical time of tidal variations ($\sim 3\text{--}6$ hours), the measurements have to account for time variation of tidal currents. After OI, the resulting fields are a set of velocity snapshots (on a regular grid) covering the whole period of observations.

Figure 4. Interpolated (black) velocity fields obtained at mid-time of the first (top) and second (bottom) survey: HW-1.30h (top) and LW-0.4h respectively. Background shading reflects the difference ε between the survey velocities interpolated in space and time and model velocities at mid-time. Grey circles represent locations of the towed ADCP measurements (1-minute averaged).

Figure 4 shows an example of the interpolated velocity patterns at the mid times: HW-1.30h and LW-0.4h for the first and second survey respectively. The respective observations were projected to the mid time by the OI method, using space-time correlations provided by the model.

The absolute difference $\varepsilon = |\mathbf{u}_{\text{int}} - \mathbf{u}_{\text{mod}}|$ in velocity magnitude were estimated to evaluate the overall agreement between the interpolated (\mathbf{u}_{int}) and modeled (\mathbf{u}_{mod}) velocity fields.

The best agreement is obtained on flood tide where ε is lower than 0.1 m/s in the majority of the

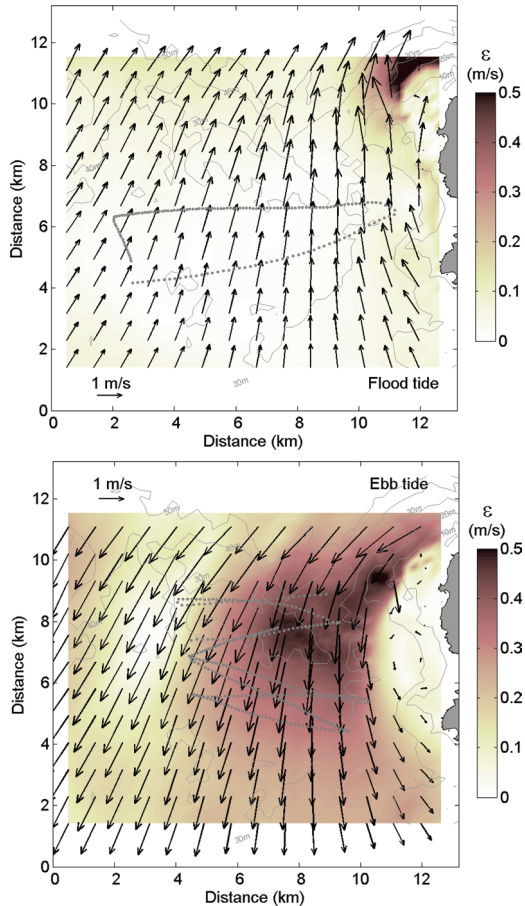


Figure 4. Interpolated (black) velocity fields obtained at midtime of the first (top) and second (bottom) survey: HW-1.30h (top) and LW-0.4h respectively. Background shading reflects the difference ε between the survey velocities interpolated in space and time and model velocities at mid-time. Grey circles represent locations of the towed ADCP measurements (1-minute averaged).

Table 1. Number of the observation points N , the mean kinetic energy per unit volume diagnosed from the surveys, KE_{obs} , and the respective model runs, KE_{mod} , misfits e between the observed and modeled, e_{mod} , and observed and interpolated, e_{int} , velocities.

Survey	N	KE_{obs} (J/m^3)	KE_{mod} (J/m^3)	e_{mod}	e_{int}
Apr. 21, 12:30–15:00 UTC	240	780	800	0.11	0.09
HW-2.5h – HW					
Apr. 22, 07:00–12:15 UTC	320	1050	1400	0.2	0.09
LW-3h – LW+2.25h					

domain. An exception is found in the northern part where ε is higher than 0.5 m/s. Nevertheless, this high difference need to be put into perspective— notably because of large uncertainties in bathymetry (essential input for hydrodynamics models) in this sector. The more significant effect of the OI is revealed during the second survey, on ebb tide. In the surveyed area, ε varies from 0.3 to 0.5 m/s revealing a large overestimation of current velocities by the model, especially in the eastern part of the domain (Figure 4).

The interpolating skill of the OI method was then assess by performing a space-time interpolation of the model velocity into measurement

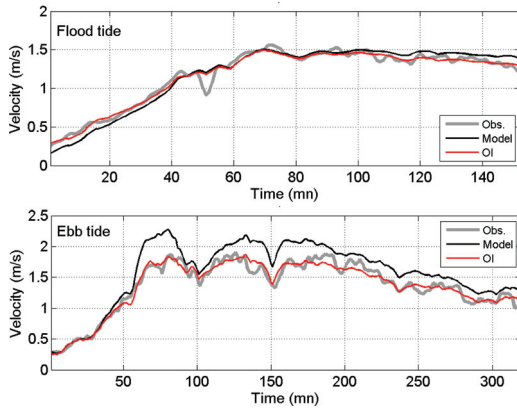


Figure 5. Tidal velocities of the interpolated and modeled fields projected at measurement points (red and black line respectively). Observed velocities obtained on flood (top) and ebb (bottom) tide are shown in gray.

points. The interpolated and modeled velocities were then compared (Figure 5). During flood tide, observed, modeled and interpolated velocity curves fit well. The only exception occurs around $t = 50$ minutes after the beginning of the survey, when the observed velocity suddenly decreased. This observation is an artifact, consequence of the changing of the vessel' heading. During ebb tide, large discrepancies between observed and modeled velocities are found. Globally, the model always overestimates the velocity by up to 0.5 m/s. After OI, this difference does not exceed 0.1 m/s.

Quantitatively, the general agreement between both observed/modeled velocities and observed/interpolated velocities is given by the calculation of the mean relative difference e .

On flood flow, the calculation of e_{mod} was found to be 0.11 (Table 1). Thus, the model appears to be very effective for predicting the tidal circulation during that tidal phase. After performing OI, the mean relative difference drops to 0.09. On ebb flow, e_{mod} is of order of 0.2. The OI provides a significant improvement in term of velocity magnitude estimation with a 50% gain in accuracy due to taking into account time evolution of the current field.

4 DISCUSSION

Due to the growing interest in tidal energy conversion technique worldwide, a detailed assessment of the natural resource is required to determine commercial viability of any project prior to device deployment.

Understanding the spatial distribution of tidal stream resource can be gained via underway ADCP measurements. This is particularly useful in harsh current environment, such as in Alderney Race, where deploying and retrieving long-term bottom-mounted ADCP can be problematic.

In the early stages of resource assessment, ADCP transects are vital to provide understanding of the spatial variability in resource (Fairley et al. 2013). The end goal of the surveying of any area under tidal influence is to assess the velocity field evolution. In that purpose, a hydrodynamic model can be applied to evaluate tidal circulation and interpolate the transect data to a fixed (central) time of the survey (Goddijn-Murphy et al. 2013).

However, although model predictions generally agree with measurements, the spatial resolution of bathymetry and the model grid are not high enough to assess the smaller-scale phenomena such as eddies, cross currents or jets. In the present study we extended the approach of underway velocity profiling by employing the optimal interpolation technique in both space and time to retrieve the entire evolution of tidal currents from the survey data.

Two surveys were performed over neap tide conditions in Alderney Race. The resulting velocity fields were obtained by blending observations with the output of a numerical model in the framework of optimal interpolation of the data in both space and time. The utilized MARS-2D model provided the first guess (background) evolution of velocities in the study area which was then corrected by the data.

The quality of the currents' reconstruction was validated against the model simulations of the neap tide dynamics. Significant (up to 50%) reduction of the model-data misfit for the velocity field obtained as a result of space-time interpolation have been demonstrated.

The use of model output allows the calculation of other metrics commonly used for tidal stream energy quantification. Among them, the kinetic power density, defined as: $P = 0.5\rho u^3$, where ρ is the seawater density. The spatial distribution of the mean kinetic power density $\langle P \rangle$, averaged over the selected period of flood (Apr. 21, 13:00–15:00) and ebb flow (Apr. 22, 08:10–12:15), was established. White contours in Figure 3 show that the "most energetic" area is located in the northern part of the study domain with a wider extension of the zone during ebb tide. According to model simulations, the maximum value of $\langle P \rangle$ (black crosses in Figure 3) was found to be 11.5 kW/m² and 10.4 kW/m² during the flood and ebb tidal phase respectively.

In addition, analysis of the spatial distribution of P was performed by considering the interpolated

velocities (results not shown). The mean power density distribution, for both flood and ebb tide, revealed very similar spatial patterns compared to that shown by white contours in Figure 3. However the mean level of energy significant decreased (by 26% and 34%) as the result of velocity interpolation. The maximum values of $\langle P \rangle$ were found to be 8.5 and 6.9 kW/m² on flood and ebb tide respectively.

Comparison between the observed and modeled velocity magnitude revealed that the model overestimates the velocity magnitude by 11% during flood tide and 20% during ebb tide. Since the kinetic power density is related to velocity cubed, even small overestimation in velocity can lead to substantial overestimation of P . The kinetic power density derived from observations and model output, projected onto observation points, were compared. The results show that the velocity overestimation by the model leads to an overestimation of P by 16% and 65% on flood and ebb tide respectively.

A spectacular reduction of these gaps is obtained by using optimally interpolated velocities. Calculation of P from interpolated velocities showed a drop of the misfits of kinetic power density estimation down to 10% and 16% for the flood and ebb tidal phase respectively.

On flood tide, MARS-2D model results have demonstrated a very good agreement with observations. We believe that during that tidal stage, the model might provide relevant estimations of the major parameters of the tidal flow conventionally used for tidal energy site screening (Legrand 2009, Thiébaud and Sentchev 2017). However, large uncertainties appear when estimating those parameters during the ebb tide.

Although, numerical modelling tools are most of the time retained for the site selection process, very often they have difficulties to provide accurate assessments of available tidal stream power. Therefore, precise estimates and description of available tidal energy resources at high spatial and temporal resolution are needed for proper planning and the optimization of the design of tidal energy converters.

5 CONCLUSIONS

The method of space-time interpolation of underway velocity measurements, presented in this paper, demonstrated its efficiency in evaluating more accurately the kinetic power density of the tidal stream in Alderney Race—a highly energetic area where reliable, good quality measurements of tidal flow are scanty. The presented synthesis of the vertically averaged velocity observations and the 2D

model output provided a significant improvement in spatial distribution of velocities in terms of both the decreased discrepancy and better correlations with independent observations. Constraining the model simulations by velocity measurements for evaluation of the kinetic power density demonstrated a noticeable reduction (up to 30%) of the energy resource, especially during ebbing tide, compared to pure model estimates. We believe that, in spite of its relative simplicity, the use of OI method for tidal energy site screening will strongly reduce uncertainties concerning the available resources and will also increase the confidence of investors as it allows a better determination of the value of investments and minimizing risks.

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