Mapping tidal energy resources by High Frequency Radar: Application to resource characterization around the Ushant Island (W. Brittany coast)

Alexei Sentchev*, Maxime Thiébaut*
*Laboratoire d’Océanologie et de Géosciences (CNRS UMR 8187), Université du Littoral - Côte d’Opale, 62930 Wimereux, France.
E-mail: alexei.sentchev@univ-littoral.fr; maxime.thiebaut@univ-littoral.fr

Abstract—A methodology of assessing the hydrokinetic resources and tidal flow potential at a near-shore site in the Iroise Sea is presented. More than a year-long surface current velocity time series recorded by high frequency radars (HFR) were used for site screening. We focused on the analysis of tidal current pattern around the Ushant Island which is a promising site of tidal energy generation. Our results revealed current velocities of 4 m/s northwest of the island and in the Fromveur Strait, with 1 m/s value exceeded 60% and 70% of time respectively. The monitoring of surface currents allowed to discover an exceptionally high asymmetry between the flood and ebb flow varying in a wide range, from 0.5 to 2.5, around the Ushant Island. The strongest variation of asymmetry was found in the Fromveur Strait. Spatial distribution of asymmetry coefficient showed persistent pattern and fine scale structures. Asymmetry in current direction was also quantified. Analysis of the bottom mounted ADCP data in the radar coverage zone allowed the quantification of the variation of current velocity with depth, which increased confidence in the HFR results. The power density of tidal flow was estimated in two particular locations where the strongest currents are observed and the highest potential is expected. A method is presented to find the optimal location for energy conversion devices and to optimize the power generation by moving devices in space and to a different altitude. It was demonstrated that in the region of opposing flood- versus ebb-dominated asymmetry occurring over a limited spatial scale (e.g. Fromveur passage), it is possible to provide a balanced power generation.

Index Terms—Tidal flow - Hydrokinetic energy - Resource characterization - HF radar - Iroise Sea

I. INTRODUCTION

Resource characterization is the first step for project development activity. In order to optimize the energy conversion, it is required to properly characterize the environment conditions at the sites and thus facilitate the process of selecting tidal power devices. The European Marine Energy Centre (EMEC) has proposed a number of metrics, which helps to evaluate the potential of tidal flow in the most efficient way. This is usually done by using different approaches.

In early studies, tidal current velocity data from Admiralty Charts have been used to estimate tidal current energy resources [1]. However these estimates suffered from lack of precision. The use of old data survey, not originally intended for resource assessment, also generated big prediction errors [2]. Numerical modeling of coastal circulation appeared as a powerful tool and allowed a considerable gain of the quality of velocity and available power estimation. Nowadays, 3D models are routinely applied for tidal energy site assessment, resource quantification, and studies of the impact of energy devices on the local circulation and environment. For example, numerical simulations by Regional Ocean Modeling System (ROMS) allowed examining the tidal asymmetry in a promising site of Orkney Islands [3], or evaluating the wave influence on tidal stream energy resources [4].

Underway velocity measurements by towed or vessel mounted ADCP is another efficient tool for tidal flow characterization and energy resource quantification. In the recent studies [5], [6], velocity profiles were recorded while the vessel steamed around a circuit with sufficient frequency allowing to resolve the vertical structure of the tidal current and its spatial irregularities. Gooch et al. [7] used spatial interpolation of underway ADCP data to reconstruct a general tidal flow pattern neglecting the tidal phase difference during the surveying period. Goddijn-Murphy et al. [5] 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. [5], [6]

In the absence of spatial coverage with observations, point measurements of velocity by Acoustic Doppler Current Profiler (ADCP) and Acoustic Doppler Velocimeter (ADV) represent a unique opportunity of resource quantification from in situ data [8]. At the same time, the data are used to validate numerical models which provide spatial extension of the study area [7].

In our study, we present a new and very promising technique of site assessment based on the analysis of velocity data recorded by High Frequency Radar (HFR). We applied this technology for site screening and resource evaluation in a region of high potential in the Iroise Sea. As the HF radars measure only the surface current velocity, the knowledge of velocity profile is an important issue for site assessment. In this work, we completed the surface velocity data set with velocity time series recorded by ADCP in radar coverage zone. We used a power law to best fit the ADCP data and, on this basis, we characterized the horizontal velocity variation with depth. A combination of remotely sensed surface velocity and
ADCP velocity profiles allowed performing the analysis of tidal current variability in three dimensions and thus assessing energy resources in the most efficient way.

In recent years, ocean radar systems, installed on the seashore in many countries, have had stunning success, and their ability to map surface circulation has allowed significant advances in our understanding of circulation and oceanographic conditions in many coastal ocean regions. Today, HF radar networks form the backbone of many ocean observing systems, and the data are assimilated into ocean circulation models (e.g., see [9] for review of HF radar applications). However, this technology is completely underexploited in tidal energy projects. Our study represents the first attempt of using HFR for resource assessing at a very promising tidal energy site in the Iroise Sea. We showed the skill and ability of the system for resource characterization, mapping, and searching the best locations for in-stream tidal devices. Our work aims to popularize its application at sites of high potential, such as Orkney or Bristol Channel, where similar radar systems have been already installed.

II. DATA AND METHODS

A. HFR data

A system of two high-frequency Wellen Radars (WERA) operating at 12.4 MHz is deployed on the western Brittany coast since July 2006. Individual radar sites are located at Cape Garchine (site G), a seashore flat-ground area, and Cape Brezellec (site B), 50 km southward (Fig. 1). The radars measure the current velocity in the surface layer (0.7 m thick). The recorded radial velocities are the projections of the current velocity vector onto radar beam directions. In the present study, the radar network was configured to provide velocity estimates at high spatial resolution: 1.5 km along beam and 2° azimuthal spacing, and time resolution of 20 minutes. The radial velocities measured by the two radars were interpolated on regular grid of 1 km spacing and combined to provide current vector maps. A powerful variational interpolation technique 2dVar [10] was used, providing continuous velocity data on a regular grid within the area shown in Fig. 1 by grey shading. The size and shape of the area was chosen so as to ensure a high degree of coverage by the data (velocities were recorded more than 60% of time) and also high accuracy of the retrieved velocity values. The accuracy of the radar-derived velocities has been estimated by SHOM (Oceanographic Division of the French Navy) through a comparison with surface drifters and ADCP current measurements for a period of 7 months. In the majority of situations, the discrepancy in velocity measured by different instruments did not exceed 0.15 m/s [11]. It was also noticed that a large fraction of this discrepancy might not be due to instrumental errors, but to the definition of the “surface velocity”, as other measurement techniques are sensitive to the shear of the Eulerian current, to Stokes drift, to the sea state, etc.

Nearly 1.5 year long velocity time series (04/2007 - 09/2008) were generated. The contribution of wave induced velocity (Stokes drift) to total surface velocity measured by HFR was estimated using empirical expression derived by Sentchev et al. [12] from numerical studies of wind-current relationship [13], and then subtracted from radar velocity records. The requested wave quantities were provided by the numerical model WAVEWATCH III. Analysis of the wave induced current component during selected periods in 2007 showed that the highest magnitude of Stokes current did not exceed 0.18 m/s and that a peak of occurrence was close 0.05 m/s whereas it was of the order of 0.40 m/s for radar derived velocities. A detailed description of the experimental settings, the methods of data processing of the radar network in the Iroise Sea and the sea state removing can be found in Sentchev et al. [12].

B. ADCP data

The knowledge of velocity profiles is extremely important for resource assessing at marine energy sites. We complemented HFR derived surface velocities by ADCP measurements in two particular locations within the radar coverage zone: in the Fromveur Strait and in the offshore sector – on the southern periphery of the study site (Fig. 1). In both locations, the velocity profiles were recorded by bottom-mounted broadband RDI ADCPs.

The offshore ADCP was deployed at 120 m depth from June 6 to September 13, 2007. Velocities were recorded every 5 m starting from 8 m above the bottom and averaged within 5 min. The data were provided by IFREMER. We removed from the analysis the velocity values in the surface 20 m thick layer because of signal contamination by surface waves. The ADCP velocity profiles for 30-day period (17 July - 17 Aug. 2007) were time averaged within 20 minutes and synchronized with the radar acquisition period for further comparison. This period was characterized by low to moderate wind.
A 600 kHz upward-looking RDI ADCP was deployed by the French Navy - SHOM (Service Hydrographique et Océanographique de la Marine) in the Fromveur Strait during 14 days, from March 19 to April 2, 1993. Velocities were recorded at 0.2 Hz every 4 m, from 6 m to 52 m above the bottom. The deployment depth was 53 m. Given the strength of tidal currents in the Fromveur Strait, in situ data acquisition is very difficult and hazardous. In this sense, the ADCP measurements in 1993 represent the unique data, and we decided to use them for comparison with radar velocity records. We selected a period from September 7, 2007 to September 18, 2007, for comparison and analysis of both ADCP and radar data. It is characterized by similar hydrodynamic conditions: spring season, secondary spring tide flow, and low wind.

C. Methods of analysis

We applied the principal component analysis (PCA) [14] to quantify the tidal flow dynamics over a long period of observations. As tidal currents in the Iroise Sea are rotational, the current velocity vector evolving over a tidal cycle draws an ellipse. Parameters of synthesized ellipses, retrieved from the PCA, provide two major properties of tidal currents: direction and magnitude, and also indicate the tidal flow anisotropy. The latter is estimated as the ratio of eigenvalues of the velocity correlation tensor. Our approach has a certain advantage over a frequently used harmonic analysis because it allows quantifying the total contribution of all tidal constituents to observed currents and assessing time-space variability of the flow.

A rotary analysis technique [14] has been also applied to velocity time series in order to identify the ellipse polarization or the sign of current vector rotation: positive for counter-clockwise (ccw) rotating and negative for clockwise (cw) rotating currents. The technique involves the decomposition of the velocity vector into cw and ccw rotating circular complex-valued components. First, a rotary spectral analysis was performed to identify the dominant frequencies and to quantify the energy \( S(f) \) of current velocity variability. Both cw \( S_- \) (negative) and ccw \( S_+ \) (positive) power spectra revealed pronounced peaks at the semi-diurnal frequency. After that, using these peak values, the rotary coefficient, \( r = (S_+ - S_-)/(S_+ + S_-) \), was estimated at every grid point. \( r \) ranges from \(-1\) for clockwise motion to \(+1\) for counter-clockwise motion (\(r=0\) is oscillating non-rotational flow). The corresponding sign of \( r \) (positive or negative) was assigned to PCA-derived tidal current ellipses. Other analysis methods, such as harmonic, spectral, and statistical analysis, were applied to both radar derived velocities and ADCP data.

Following a guideline proposed by EMEC [15], we estimated the major parameters of the tidal flow conventionally used for tidal energy site screening. In addition to synthetic properties of tidal current ellipses, we provided a number of statistical estimates of current velocity, including the mean velocity value for different stages of a tidal cycle (spring, neap, and mean tide), probability density and cumulated occurrence of velocity distribution. The maximum sustained velocity was also documented. This establishes design loads on device support structures and foundations.

Tidal flow asymmetry basically concerns the asymmetry of velocity magnitude. It represents the imbalance between the strength of flood and ebb current speeds. We defined the current velocity asymmetry coefficient \( a \) as follows: \( a = < V_{\text{flood}} > / < V_{\text{ebb}} > \), where brackets mean time averaging of velocity values on flood and ebb flow respectively. In addition to \( a \), the direction asymmetry \( \Delta \theta \) was estimated as \( \Delta \theta = |\theta_{\text{flood}} - \theta_{\text{ebb}} - 180| \) [7]. This parameter accounts for a deviation of the flow from a straight line, usually associated with the dominant current direction. HFR velocity measurements in the Iroise Sea provided us with a unique opportunity of mapping all parameters and appeared particularly useful for searching the best location for current tidal turbines.

III. Results

A. Tidal current velocity

Spatial and temporal variability of tidal currents is quantified using the parameters of synthesized current ellipses. Tidal current ellipses, retrieved from PCA analysis of multiple 7-day long spring tide velocity time series (Fig. 2), show a typical tidal circulation pattern for spring tide conditions. The length of ellipse’s semi-axis provides information about the tidal current strength and indicates regions with most powerful flow: west of the Ushant Island and the Fromveur Strait. Ellipse orientation clearly shows that the tidal wave arrives from the Gulf of Biscay and travels northeastward toward the English Channel. The ellipses are almost always parallel to bathymetry contours evidencing that the bathymetry guides the flow. In the vicinity of Molène Islands, the tidal current direction and ellipticity change, the velocity magnitude sensibly drops. White and grey ellipses in Fig. 2 indicate that the current are rotating clockwise (cw) and counter-clockwise (ccw) respectively. In the majority of domain, currents are rotating clockwise. The largest region of the ccw rotating currents is located south of Ushant and Molène Islands. Another specific area of ccw current rotation is located west of Ushant where the tidal current velocity attains its maximum value.

Further analysis of velocity time series provided by the radars during spring tide periods allowed to identify areas with high flow potential and quantify the major parameters of the tidal flow. The maximum and time averaged current velocity distribution show significant spatial variations with values ranging from 0.5 to more than 4 m/s for the maximum and from 0.5 to 2 m/s for the mean velocity (Fig. 2). High bathymetry gradients in the north-eastern part of the study site and the presence of islands cause flow acceleration, tend to tighten the streamlines and provide the maximum velocities west of the Ushant Island and in the Fromveur Strait. In these two sectors, the mean velocity (during spring tide) and the peak velocity exceed 1.5 m/s and 4 m/s respectively. Tidal ellipses are aligned with bathymetry contours there and ellipse orientation varies from 40° in the Fromveur Strait to 55° north of the island.

Table I shows the details of velocity time series analysis
for two grid points, A and B, where the highest potential is expected: A is located NW of the Ushant Island and B in the centre of the Fromveur Strait (Fig. 2). We expanded the analysis on two other locations, \( B_{n} \) and \( B_{s} \), nearest to the middle point of the strait (black crosses in Fig. 5). The maximum sustained current speed is close to 4 m/s (Table I, 2nd column) there. These values, representing the maximum current observed, are very important for establishing design loads on device support structures and foundations. Globally, similar flow conditions are observed in all three locations in the Fromveur Strait with slightly lower mean neap and mean spring tide velocity in \( B_{n} \) (Table I). NW of the island, the mean neap tide flow speed is also low (0.7 m/s), but the mean spring velocity is the highest (1.8 m/s) providing favorable conditions for energy generation.

### Table I

**Major characteristics of the tidal flow in four particular locations A, B, \( B_{n} \), and \( B_{s} \) around the Ushant Island:** peak velocity in m/s (\( V_{\text{peak}} \)), spring and neap tide averaged velocity (\( V_{\text{spring}}, V_{\text{neap}} \)), velocity averaged over the whole period of observations (\( V_{\text{avg}} \)), direction of the flood flow (\( \theta_{\text{flood}} \)) and ebb flow (\( \theta_{\text{ebb}} \)) in degrees relative to East, direction asymmetry (\( \Delta \theta \)), and current velocity asymmetry (\( a \)).

<table>
<thead>
<tr>
<th></th>
<th>( V_{\text{peak}} )</th>
<th>( V_{\text{spring}} )</th>
<th>( V_{\text{neap}} )</th>
<th>( V_{\text{avg}} )</th>
<th>( \theta_{\text{flood}} )</th>
<th>( \theta_{\text{ebb}} )</th>
<th>( \Delta \theta )</th>
<th>( a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4.6</td>
<td>1.8</td>
<td>0.7</td>
<td>1.3</td>
<td>55°</td>
<td>-137°</td>
<td>12°</td>
<td>1.2</td>
</tr>
<tr>
<td>B</td>
<td>4.2</td>
<td>1.6</td>
<td>1</td>
<td>1.4</td>
<td>40°</td>
<td>-143°</td>
<td>3°</td>
<td>1</td>
</tr>
<tr>
<td>( B_{n} )</td>
<td>3.6</td>
<td>1.3</td>
<td>0.7</td>
<td>1</td>
<td>29°</td>
<td>-130°</td>
<td>21°</td>
<td>1.9</td>
</tr>
<tr>
<td>( B_{s} )</td>
<td>4</td>
<td>1.7</td>
<td>1</td>
<td>1.4</td>
<td>37°</td>
<td>-137°</td>
<td>6°</td>
<td>0.8</td>
</tr>
</tbody>
</table>

### B. Exceedence probability of velocity

A valuable characteristic, customary calculated in tidal energy projects, is the exceedance probability of velocity distribution, showing the percentage time that a specified current velocity is exceeded. Percentage time velocities exceeded 1 m/s and 2 m/s are presented in Fig. 3. Comparison between two areas of high potential (NW of the Ushant Island and Fromveur) shows that for the same percentage time the spatial extent of the northwestern sector is bigger. Here, the velocity value 1 m/s is exceeded more than 60% of time, and 2 m/s – more than 20% of time. In the Fromveur Strait, the area of high velocity is more limited in size. However the exceedence probability for the same velocity values is higher: 70% and 30% of time (Fig. 3). For the statistical description of surface current velocities we used a Weibull distribution. This helps to evaluate the importance of velocity ranges for energy production, and also limitations and stresses acting on the energy conversion devices. The cumulative distribution function of current velocity can be approximated by a Weibull law: \( F(v) = 1 - exp[-(v/\lambda)^k] \), where \( \lambda > 0 \) is the scale parameter and \( k > 0 \) is the dimensionless shape parameter [16]. We used a linear regression method to determine these parameters. Fig. 4 shows the probability density and cumulated occurrence...
of tidal current velocity in $A$ and $B$. In the northwestern sector (location $A$), the probability density roughly follows the Weibull distribution with maximum probability (50\%) achieved for velocity 0.6 m/s, and then gradually decreasing in the range from 1 to 4 m/s (Fig. 4a). Cumulated occurrence distribution (Fig. 4b) is perfectly reproduced by the Weibull law with scale and shape parameters $\lambda = 1.5$ and $k = 1.6$. In the Fromveur Strait (location $B$), the probability density looks different (Fig. 4c). The maximum probability is lower (45\%). We can not recognize a clear bi-modal distribution, but rather the distribution flattening within the large velocity range, from 0.6 to 2.5 m/s. This affects the cumulative occurrence curve (Fig. 4d) by stretching it toward slightly higher occurrence values in the range 1 – 2.5 m/s ($k = 1.7$).

C. Flow asymmetry

If the properties of tidal currents, such as ellipses orientation, current strength and polarization, exceedance probability, are similar in the NW sector of the study area and in the Fromveur Strait, we highlighted a noticeable difference between these two areas. It concerns the current velocity asymmetry $a$ (Fig. 5). An imbalance between the strength of flood and ebb current speeds (quantified by $a$) can exist, generating a considerably more power production during one stage of the tide.

Globally, the asymmetry varies in a wide range, from 0.5 to 2.5, and shows spatial pattern with $a > 1$ in the West and $a < 1$ in the South of the domain. The strongest variation of asymmetry is observed in the Fromveur Strait. Here, the asymmetry values reach 2.5 in the onshore (northeastern) sector, indicating that flood flow velocities are far higher than ebb flow velocities. The asymmetry decreases toward the centre of the Strait, where the tidal flow reaches a balance ($a = 1$, Table I). However, another distortion of velocity curve appears seaward, at the exit of the Strait. Here, and within an extended zone, south of the Ushant Island, the asymmetry values decrease until 0.5 (Fig. 5) evidencing that the flow regime is ebb dominated. The asymmetry variability along the Fromveur Strait constitutes a remarkable phenomenon.

To highlight the difference in flow regime occurring at very short distance, we present in Fig. 6 velocity time series in two locations ($B_n$ and $B_s$) nearest to the middle point of the Strait – point $B$. The asymmetry coefficient values reveal very strong variation from 1.9 to 0.8 (Table I). Fig. 6 shows the difference in flood flow velocity up to 2 m/s in these locations, whereas ebb flow velocities have similar order of magnitude. At two extremities of the Fromveur Strait separated by 8 km, the difference in current velocity between ebb and flood

![Fig. 4](image4.png)

![Fig. 5](image5.png)
flow is even bigger, providing respective asymmetry values 0.5 and 2.5. We pay much attention to spatial distribution of $a$ because we assumed that, in the Fromveur Strait, such extreme variation of asymmetry values might be very important for the choice of appropriate in-stream tidal devices and also for array configuration.

D. Direction asymmetry

Current direction is a relevant metric for tidal stream energy conversion as the predominant design concept for energy converter is that of a fixed horizontal axis turbine. Tidal current ellipse orientation provides a general view of the flow direction. We analyzed ebb and flood flow direction and performed an estimation of the direction asymmetry $\Delta \theta$ which is a measure of deviation of the flow from a straight line. A deviation of the ebb and flood flows from a mean direction creates difficulties for turbine models designed for bi-directional tides. Fig. 7 shows the orientation of ebb and flood flow in two locations $A$ and $B$. It also shows individual flood and ebb flow velocity values and the average velocities used for estimation of the flow asymmetry $a$. The results for four grid points ($A, B, B_n, B_s$) are summarized in Table I. For two locations in the Fromveur Strait the direction asymmetry is reasonably low (< 6°). It strongly increases up to 21° in $B_n$ located in the northern sector of the strait. According to Sentchev et al. [12], the increase of $\Delta \theta$ is related to transient eddy dynamics producing tidal ellipse distortion there. Regarding the northwestern sector (location $A$), we estimated the direction asymmetry as 12°.

E. Velocity profiles

HFR data allows assessing only the surface current velocity. Generally the maximum velocities are observed near the surface and minimum values near the seabed. To determine a beneficial hub-height and optimize the turbine design, the knowledge of velocity profile is required. Using the ADCP data collected in the radar coverage zone, we reconstructed a time-average velocity profile for ebb and flood flow in each ADCP location and compared it with the time average radar derived surface velocity in the nearest grid point. The results are shown in Fig. 8.

For the offshore ADCP deployment, we considered the flood end ebb flow profiles only if the depth average velocity exceeded 0.5 m/s (Fig. 8a,b). For the deployment in the Fromveur Strait, this value was set to 1 m/s (Fig. 8c,d). Velocity distribution in the water column was approximated by the power law: $V(z) = V_0(z/d)^{1/\alpha}$ [17] which is customary used in oceanographic studies [7]. Here, $V_0$ is the surface velocity, $d$ is the bottom depth, $z$ is the distance above the seabed, and $\alpha$ is an empirical coefficient estimated from linear regression fit of a LogLog representation of velocity. From the individual profiles, the time average profile was estimated for each stage of the tidal flow, and then approximated by a power law function. In the offshore location, the best fit of velocity profiles was achieved for $\alpha = 6.5$ and $\alpha = 6.9$ for flood and ebb flow respectively. In the Fromveur Strait, the best fit was obtained for $\alpha = 5.8$ for both stages of the tidal cycle.

Fig. 7. $u$ and $v$ velocity components derived from HFR measurements of surface currents. Red and blue points represent velocity of flood and ebb flow respectively. Only velocities exceeding 0.5 m/s are shown. Full and empty circles indicate the time average flood and ebb flow velocity values. Black lines give the mean direction of ebb and flood flow.

Extrapolation of the mean velocity profile in the surface layer revealed a very good agreement between time average ADCP and radar derived velocity values (Fig. 8). The relative error does not exceed 4% for the offshore ADCP and 3% for the deployment in the Fromveur Strait. However the overall
variability of radar velocity (std) was found bigger for both locations. This is not surprising as wind and waves also contribute to total currents measured by the radars.

We compared the radar derived surface velocity and the depth averaged ADCP velocity time series in two ADCP locations (Fig. 9). The comparison revealed a very good overall agreement with zero phase lag, high degree of correlation (0.84 for offshore location, 0.82 for the Fromveur Strait) and indicated that the radars overestimate the depth average velocity by approximately 20%. We estimated the ratio of depth averaged to surface velocity as 0.83 and 0.78 for the offshore location and for the Fromveur Strait respectively. These values are in close agreement with the value 0.8 documented by Prandle [18] in the Dover Strait.

F. Power density

A simple way to characterize the available resource at a site is to estimate the power density $P$ for different stages of tidal cycle and to represent its spatial distribution. As the HFR measurements are particularly efficient for monitoring of ocean currents, it is possible to evaluate the available power density at different time and space scales using the conventional formula $P = 0.5 \rho C_p V^3$ [19], where $\rho$ is the water density, $V$ - current velocity and $C_p$ - dimensionless power coefficient set to 0.59. To take into account the velocity decrease with depth we used a power law relationship derived from the best fit of the ADCP data in the Fromveur Strait.

We estimated the power density in two locations, $A$ and $B$, assuming different altitudes of device’s deployment. Many types of devices are designed for deployment on the sea floor (e.g. Open Hydro, Sabella). Some others are installed in the surface layer (e.g. Hydro-Gen, Evopod by Oceanflow). In the former case, we assume that rotating blades occupy the near bottom layer 15 m thick, where strong velocity shear occurs (Fig. 8). We also assumed that the velocity profile derived from the ADCP data in the Fromveur Strait (location $B$) is representative for three other locations: $A$, $B_n$ and $B_s$. Using the radar velocity times series, the power law expression for velocity profile ($\alpha=5.8$), and the layer extension, we averaged the velocity values within the surface and bottom layers and generated the power density time series. Only flood end ebb flow velocities bigger than 1.2 m/s were used for power estimation (the corresponding threshold for power is 0.5 $kW/m^2$). We remind that the velocity profile was reconstructed for high (>1 m/s) current speed values (Fig. 8).

Fig. 10 shows the cumulated distribution of power density in the surface layer in the Fromveur Strait and NW of the Ushant. It looks quite similar for both locations. The 1 $kW/m^2$ value is reached more than 40% of time, the mean power density is equal to 1.6 (Table II) and the maximum power $P > 6 kW/m^2$ is observed 6% of time. In the bottom layer, the estimated power density distribution is very different. The 1 $kW/m^2$ value is reached 15% and 22% of time respectively in locations $A$ and $B$, and the overall mean power does not exceed 0.5 and 0.6 $kW/m^2$. There is also a big difference in power generation during spring and neap tide and, to lower extent, during ebb and flood tide flow (Table II). In the Fromveur Strait, the power generation seems to be more balanced during the fortnight tidal cycle only in the central part - location $B$ (variation from 0.7 to 2.2 $kW/m^2$). For other locations, further shoreward or seaward from $B$, more unbalanced power production is expected. Strong imbalance of power density is also documented in $A$. Our analysis indicated that in $B_s$, distant from $B$ by 1.4 km, the mean power density is the highest: 1.8 $kW/m^2$ in the surface layer and 0.7 $kW/m^2$ in the bottom layer (Table II). This difference in $P$ is related to the ratio of surface to bottom layer velocity equal to 0.7 in the Fromveur Strait, and to 0.65 NW of the Ushant Island.
II reveals that, for locations $B$ and $B_s$, the power density is in opposite phase with respect to neap and flood tide flow. This is the consequence of velocity asymmetry which varies from 1 to 1.9 (Table I).

In order to assess the effect of velocity asymmetry on power production we reconstructed power density time series from radar velocity records in three neighbouring grid points in the Fromveur Strait ($B_n$, $B_s$ and $B$) during spring tide (Fig. 11). The distance between two points is 1.4 km. The recovered power density, related to velocity cubed, is strongly unbalanced during a day for two former locations (Fig. 11b), and much more balanced for $B$ (Fig. 11a). But if we aggregate tidal turbines deployed in $B_n$ and $B_s$, the total power production during the period of interest could be much more balanced (Fig. 11b, grey shading), with the mean cumulative value of the order of $4 \text{ kW/m}^2$. Higher degree of equilibrium of energy generation is achieved by exploiting the asymmetry variation in space.

| TABLE II | POWER DENSITY ESTIMATION IN FOUR PARTICULAR LOCATIONS ($A$, $B$, $B_n$ AND $B_s$) AROUND THE USHANT ISLAND, FOR DIFFERENT STAGES OF THE TIDAL CYCLE AND IN TWO WATER LAYERS (BOTTOM AND SURFACE): AVERAGE SPRING ($P_{\text{spring}}$) AND NEAP FLOW POWER ($P_{\text{neap}}$), AVERAGE EBB FLOW ($P_{\text{ebb}}$) AND FLOOD FLOW POWER ($P_{\text{flood}}$), SURFACE LAYER ($P_{\text{surface}}$) AND BOTTOM LAYER ($P_{\text{bottom}}$) POWER DENSITY. |
|----------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| $P_{\text{spring}}$ | $P_{\text{neap}}$ | $P_{\text{flood}}$ | $P_{\text{ebb}}$ | $P_{\text{surface}}$ | $P_{\text{bottom}}$ |
| $A$ | 2.8 | 0.3 | 1.9 | 1.5 | 1.6 | 0.5 |
| $B$ | 2.2 | 0.7 | 1.8 | 1.3 | 1.6 | 0.6 |
| $B_n$ | 1.4 | 0.3 | 1.5 | 0.2 | 0.9 | 0.3 |
| $B_s$ | 2.6 | 0.7 | 1.1 | 2.2 | 1.8 | 0.7 |

IV. CONCLUSIONS

An array of two HF radars is deployed on the W. Brittany coast since 2006 providing monitoring of the surface circulation in the Iroise Sea in a large area extending up to 140 km offshore with high spatial and time resolution. We
analyzed more than a year-long velocity time series and estimated the major metrics required for quantifying hydrokinetic resources of the tidal flow and their variations around the Ushant Island. We also compared radar derived velocities in the surface layer with velocity profiles recorded by ADCP in the radar coverage zone. The data analysis revealed a very good agreement between in situ and remotely sensed velocity measurements (correlation higher than 0.8, relative error less than 4%) for both the central sector and periphery of the study area. This increased confidence in the HFR results and allowed quantifying the variability of hydrokinetic resources in three dimensions. The results are summarized below.

1. Our analyses revealed two areas with high energy potential and particularly suitable for tidal stream device deployment: the Fromveur Strait and the area NW of the island. The current velocity is higher than 4 m/s there, and time average velocity of 1 m/s is exceeded 60% of time NW of the Ushant Island and more than 70% of time in the Fromveur Strait. The mean spring tide current velocity attains 1.6 m/s and 1.7 m/s respectively. The map of maximum and mean velocity (Fig. 2) indicated that the spatial extension of the former area is much bigger, and that the dimension of a zone in the Fromveur Strait with extremely high velocity values does not exceed 6 x 2 km.

2. Regarding the velocity variation with depth, a joint analysis of the radar derived and ADCP velocities in the Fromveur Strait and farther offshore showed that time average velocity profile follow the power law. The best fit of time average velocity profiles provided the following values of the empirical constant $\alpha$: 6.5 and 6.9 for flood and ebb tide respectively in offshore sector, and 5.8 in the Fromveur Strait. The values of $\alpha$ appear to be dependent upon geographic location and tidal flow regime. Extrapolating ADCP velocity profile to the surface layer showed that the surface velocity estimate is very close to that derived from radar measurements (relative error 3%). Moreover, our results provided the ratio of depth average to surface velocity values equal to 0.78 in the Fromveur Strait and to 0.83 farther offshore, which is in close agreement with the ratio 0.8 documented by Prandle [18] in the Dover Strait, and also by Gooch et al. [7] at US sites.

3. We analyzed the velocity asymmetry values, $\alpha$, for typical spring, neap and mean tide conditions, discovered coherent spatial patterns, and documented variations of $\alpha$ in a wide range: from 0.5 to 2.5. Globally, the values $\alpha > 1$ are found in the western sector of the study area, $\alpha < 1$ in the southern sector and the strongest variation is observed in the Fromveur Strait. Neill et al. [3] investigated the spatial variation of asymmetry at EMEC site and documented the values ranging from 0.7 to 1.3. Somewhat higher flow asymmetry was identified by Fairley et al. [20] and Evans et al. [21] at different sites of high potential off the Pembrokeshire coast in Wales, UK. However such a strong variability of asymmetry coefficient like in the Fromveur Strait, to our knowledge, was newer documented before.

4. We documented a strong but spatially varying fortnightly modulation of the current magnitude around the Ushant Island. HFR measurements showed that, NW of the island, the ratio of neap to spring velocity amplitude is close to 2.6 whereas it is close to 1.6 in the central part of the Fromveur Strait. The distribution of velocity occurrence there is flattened and does not follow Weibull function, conventionally used for evaluation
of the energy production. We evidenced that in the Fromveur Strait, the neap tide flow is slightly stronger, spring tide flow is weaker, and the fortnightly velocity variation is more balanced.

5. We analysed the power density time series reconstructed by using the surface velocities measured by the radar in combination with the velocity profile derived from the ADCP data in the Fromveur Strait. We compared the power density variations in key locations and documented significant difference between two areas of high potential. The overall average power density appears higher in the Fromveur Strait: 1.6 kW/m² (1.8 kW/m² in the southern sector). It considerably drops at a short distance going away from the centre of the strait. The corresponding power in the bottom layer, 15 m thick, is approximately 3 times lower. The power density in the northwestern sector is also high (1.6 kW/m²) but a strong imbalance of power occurs during the spring-neap cycle.

6. Finally, we demonstrated that in the region of opposing flood- versus ebb-dominated asymmetry, occurring over limited distance in the Fromveur Strait, it is possible to provide balanced power generation by aggregating devices and moving devices in space and to a different altitude. This can help in searching solution for array configuration and optimizing the power production by tidal power converters.

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