Resource assessment using a combination of seabed-mounted and semi-stationary vessel-mounted ADCP measurements

Larissa Perez, Eloi Droniou, Marion Huchet, Fraser Johnson, Andrew Baldock and Cuan Boake

Abstract— **Accurate resource assessment for tidal sites is crucial to the calculation of the Levelized Cost of Energy of each project or turbine. In its technical specification on tidal stream resource assessment, the main method recommended by the International Electrotechnical Commission involves using numerical models and/or multiple seabed-mounted Acoustic Doppler Current Profilers (ADCPs). MeyGen is a tidal stream energy project, located in the Inner Sound, Pentland Firth, Scotland, where 4 turbines are already installed. Here, we introduce a method that allows the resource assessment with less seabed-mounted ADCPs. The technique used semi-stationary vessel-mounted ADCP measurements to characterize the flow at the planned turbine locations, instead of relying strictly on seabed-mounted ADCP data and a numerical model. A 37-day seabed-mounted ADCP survey was conducted as a baseline. Using harmonic analysis, the current velocities were predicted for an 18.6-year period. The vessel-mounted measurements were undertaken at each turbine location during ~5 minutes every hour, for a 12-hour tidal cycle. During each interval the vessel kept its position within a 15-meter radius around the nominal position. The current velocities obtained from the vessel-mounted measurements at the stations were then correlated with the simultaneous data from the seabed-mounted ADCP. This correlation was finally combined with the 18.6-year predicted time-series at the seabed-mounted ADCP location to obtain long-term times-series and statistics for planned turbine locations. Findings suggest this could be a valuable and cost-effective technique to assess resource spatial variability in tidal energy sites.**

Keywords— **Tidal stream energy resource, spatial variability, resource assessment guidelines, tidal currents, Acoustic Doppler Current Profilers**

I. INTRODUCTION

ASSESSING the spatial variability of tidal stream energy resource across a potential site is crucial to ensure optimal device performance and power generation. Whilst tidal channels are generally characterized by strong currents, flow characteristics may vary substantially across a single site due to aspects such as bathymetry, depth and coastal geomorphology. The International Electrotechnical Commission (IEC) provides well-established guidelines for assessing tidal energy resources [1], [2]. For projects planned to be greater than 10MW, those guidelines consist in combining site measurements taken by seabed-mounted Acoustic Doppler Current Profilers (SMADCPs) with numerical models. For projects planned to be smaller than 10MW, SMADCPs at the turbine locations may be used. Recommendations such as instruments' configurations, minimum deployment length and time-resolution are also provided.

A satisfactory long-term assessment of spatial variability may require the deployment of several SMADCPs across the site of interest, such as done in previous works [3], [4]. Whilst methods involving multiple SMADCPs (up to one at every turbine location) is effective and allows for the investigation of not only long-term currents but also turbulence parameters, it substantially increases costs. Transects conducted with vessel-mounted ADCPs (VMADCPs) may be combined with SMADCP measurements for an extrapolation of transect velocity estimates to a longer period of time. However, the sampling duration of VMADCP transects measurements at each point of interest is necessarily short, which typically leads to inaccuracies.

Here, we introduce a technique that combines semi-stationary VMADCP and SMADCP data through

This work was supported by the Tidal Stream Industry Energiser Project (TIGER), co-funded by the European Regional Development Fund through Interreg France Channel Programme.

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Digital Object Identifier: https://doi.org/10.36688/ewtec-2023-457

correlation studies. The method is based on a measure-correlate-predict (MCP) method, which aims to provide predictions of conditions at sites of interest where only short-term measurements are available, and is commonly applied in the wind energy sector [6]. The main goal is to obtain long-term current velocity predictions at the several stations where VMADCP data were collected, substantially increasing the accuracy of spatial variability investigation. This technique was recently discussed for the tidal stream energy case on a theoretical basis [5]. The work presented here was conducted as part of the plan to expand the existing MeyGen Project, which is located in the Inner Sound, Pentland Firth, Scotland, and already has four 1.5 MW tidal turbines in place. Findings reveal that correlation results between VMADCP and SMADCP velocity estimates were generally satisfactory, with coefficients of determination R^2 close to 0.9. We believe the optimization and future application of this technique have the potential to support the advance of tidal stream energy production in other sites across the globe and could be used to complement and improve the current international guidelines.

II. Methodology

A. *MeyGen Project and study site*

The MeyGen Project is the largest planned tidal stream energy project in the world, aiming to develop up to 398 MW of installed power in the Inner Sound, Pentland Firth, Scotland, and being amongst the pioneers of its kind. Previous characterization studies have revealed that current velocities at the site may reach up to 5 m/s, which represents a great potential for power generation [7]. During Phase 1 of the project, four 1.5 MW turbines were installed. During Phase 2, site characterization campaigns were carried out to plan the deployment of additional turbines, representing 28 MW of tidal power capacity. The datasets discussed here were collected during Phase 2 field campaigns.

B. *Field campaign design*

The field campaign design combined the deployment of an SM ADCP over approximately 37 days, and the collection of several semi-stationary VM ADCP datasets. The SMADCP station is referred to as T00, whilst the stations where VMADCP data were collected are named T2XX, referring to planned turbine locations.

VMADCP data were collected during spring tide, with measurements being undertaken at each location over ~5-minute intervals every hour, for a 12-hour tidal cycle. During each interval the vessel kept its position within a 15-meter radius around the nominal location. For validation purposes, VMADCP measurements were also undertaken above the SM ADCP, at T00, continuously for 12 hours. The site and measurement stations are illustrated in Fig. 1 and specifications of instruments' configurations are provided in Table I.

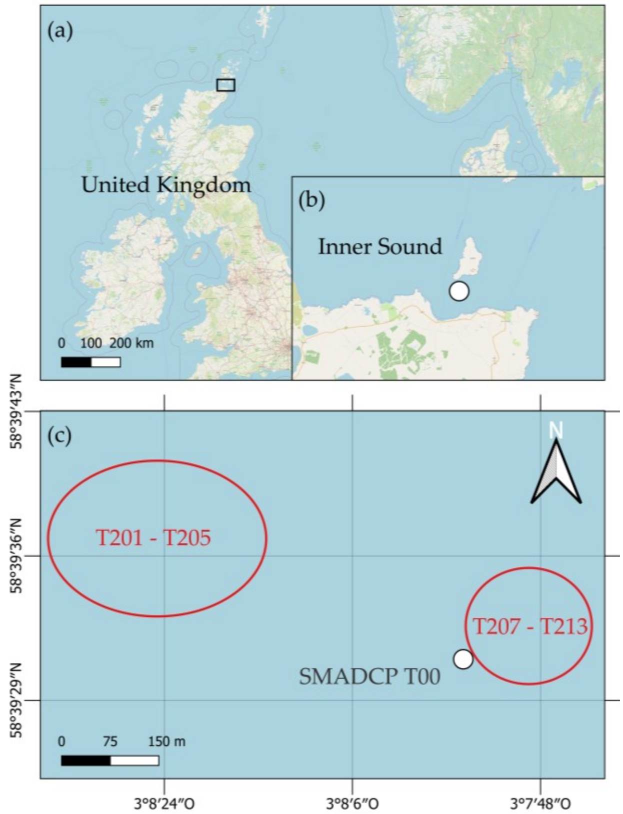

Fig. 1. MeyGen Project location within (a) the United Kingdom, (b) Pentland Firth, and (c) top view of measurement stations. The white circle indicates the location of the SMADCP and the red ellipses show the areas where potential new turbines could be installed, and where VMADCP measurements were conducted.

TABLE I
ADCP CONFIGURATIONS

Instrument	Mounting	Sampling Frequency	Cell size
Teledyne Sentinel V50	Seabed	2 Hz	1 m
Teledyne Workhorse 600 kHz	Vessel	~1 Hz	1 m

C. *Data analysis: SMADCP and VMADCP*

Initially, SMADCP data was screened considering usual quality control parameters such as minimum correlation threshold, assessment of echo intensities and removal of the portion of the water column affected by side-lobe interference. Current velocity magnitudes and direction were computed considering 10-min bursts. It was found that the most energetic direction pointed 92°/272° degrees from North emphasizing that the dominant flow direction in the channel was West-East.

The VMADCP data were processed using the *ADCPTools* MATLAB toolbox made publicly available by Vermeulen et al. [8]. The vessel heading angle was measured using a GNSS compass. The misalignment angle between ADCP axes and GNSS axes was calculated comparing the vessel velocity directions obtained from the ADCP's bottom track and from the GNSS. Datapoints collected when the vessel position was within a 11-meter radius from the target point were selected as valid points and time-averaged, leading to a velocity profile for each stop over a T2XX station. The Lowest Astronomical Tide (LAT) level was calculated from the harmonic analysis of the 37-day SMADCP data. In the following sections the LAT level is referenced as Chart Datum for convenience. Both VMADCP and SMADCP data were interpolated onto cells at fixed depths relatively to Chart Datum using the water level from SMADCP data.

Finally, weighted rotor disk average velocity magnitudes were computed using the "method of bins" proposed by the IEC, relying on cubed velocities [1]:

$$\overline{Vel_{Disk}}(t) = \left[\frac{1}{A} \times \sum_{z=8}^{z\ bottom\ tip} Vel^3(t,z) \times A_z\right]^{\frac{1}{3}} \quad (1)$$

where the overbar represents a spatial average over the rotor swept area, A is the total rotor swept area, z represents the cell depths in mCD (meters above Chart Datum) which are within the rotor swept area, and A_z is the portion of the rotor swept area which is within the cell located at a distance z mCD. A rotor disk diameter of 23 m with z values ranging from -8 mCD to -31 mCD is used for the results in this paper. The operation was first performed to East and North velocities and then transformed into horizontal velocity magnitudes and directions.

D. *Investigation of correlation between SMADCP and VMADCP velocity estimates*

Following the estimation of current velocity magnitudes for each cell located at a given distance below Chart Datum, a linear regression and correlation study was performed, connecting the VMADCP data to simultaneous SMADCP results. Considering that the flow velocity at any station should be proportional to the flow velocity at the reference location T00, when performing the linear regression, the intercept was forced to 0, leading to equations of the format:

$$Vel_{Stopover}(z) = \alpha \times Vel_{Seabed-mounted}(z) \quad (2)$$

where z represents the cell depth in mCD and α gives the slope of the linear regression. The coefficient of determination R^2 was also calculated. This analysis was performed at each depth cell individually, and on weighted rotor disk average velocities.

To evaluate the error associated to VMADCP measurements, and to validate the principle of getting reliable flow characteristics from semi-stationary measurements, the correlation was first assessed at T00: velocities processed from the SMADCP dataset were compared with the results obtained from the 12-hour long semi-stationary VMADCP dataset, also collected at T00.

In a second phase, Equation (2) was used to perform the correlation step of the MCP method, at the various potential turbine locations T2XX (as well as at T00).

E. *Tidal harmonic analysis and prediction*

The East and North velocities and sea level obtained from the SMADCP data were used to perform tidal harmonic analysis and prediction over a period of 18.6 years, ranging from January 2027 to August 2045. The study was performed using the *UTide* MATLAB toolbox, which takes into account corrections for long-term nodal modulations considering the nodal factors f and u [9]. Outputs of these analyses include a list of the most significant tidal constituents ordered by percent energy: the contribution in percentage to the total kinetic energy (in the case of velocities) or potential energy (in the case of sea level) obtained from the time-series, as well as the f and u nodal factors.

UTide 's harmonic analysis results are used to predict new time-series. If the time-vector used in this step is the same time-vector used in the harmonic analysis, then the resulting reconstructed time-series should approximate the observed velocity (or sea level) time series.

Subsequently, a validation of *UTide*'s nodal corrections was performed to the sea level study following the same methodology discussed and presented by Thiébot et al. [10]. For that, 21 years of sea level data collected with tidal gauges at Wick station (58° 26' 27.5" N, 03° 05' 10.7" W) between 2002 and 2022 were used, with a resolution of 15 minutes [11]. More on the theory behind nodal corrections is widely discussed in the scientific literature [12].

III. RESULTS

A. *Tidal harmonic analysis: investigation of residuals and nodal modulation correction*

The quality of the harmonic analysis was initially assessed by investigating the residuals, which are defined as the difference between the observed time-series and the reconstructed time-series and were generally close to 0 (not shown here for conciseness purposes). This shows that the harmonic analysis performed well and that the non-harmonic influences, mostly weather related, were negligible during the observations. In addition, Fig. 2 depicts a comparison between the observed and reconstructed time-averaged cubed horizontal velocity magnitude profiles, revealing good agreement. The cubed horizontal velocity is proportional to power production. Therefore, examining the differences between cubed horizontal velocity obtained from observed and reconstructed velocities allows for the verification of the model accuracy and its effects on power production. The accuracy of the harmonic analysis was also investigated through the confidence intervals of each constituent. For instance, Fig. 3 presents the tidal current velocity ellipse confidence intervals obtained for constituent M2.

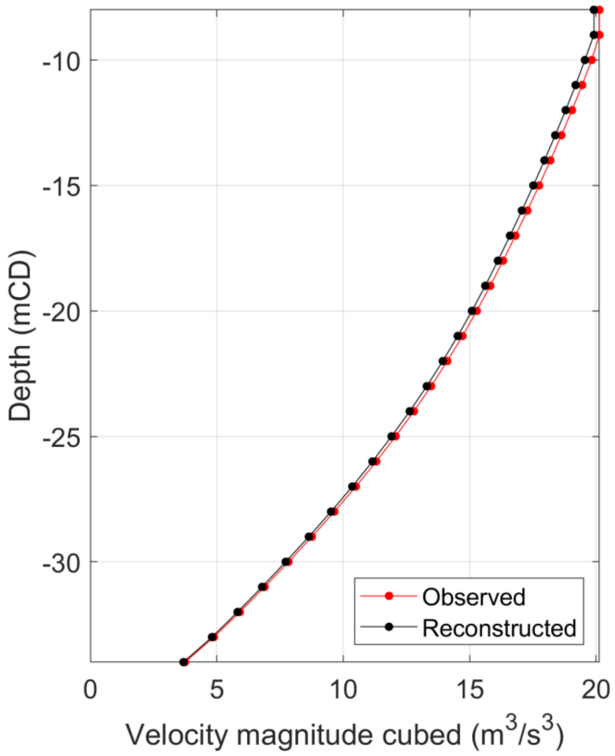

Fig. 2. Profiles of observed and reconstructed cubed horizontal velocity magnitudes. Note that values at -8 mCD are assumed to be equal to -9 mCD as data at -8 mCD was often affected by side-lobe interference and removed during quality control.

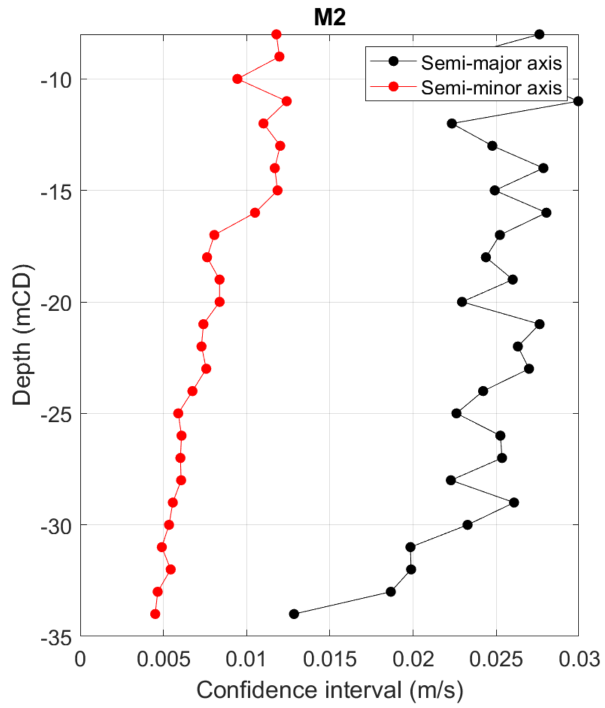

Fig. 3. Profiles of M2 constituents' confidence intervals around semi-major and semi-minor tidal current ellipse axes.

The effectiveness of *UTide*'s nodal corrections in the region of the Pentland Firth was also assessed using the 21-year sea level measurements from Wick station. The most energetic constituents at the site were M2, S2 and N2, with 82.52 %, 9.66 % and 3.31 % of the total potential energy respectively. The harmonic analyses were conducted for the full period and then for every consecutive year. The resulting amplitudes are presented in Fig. 4, which shows that uncorrected amplitudes accompany the shape of the nodal factor time-series f and that corrected amplitudes remain relatively constant across the years, as desired. M2, as the dominant lunar constituent, was the most affected, whilst S2, which is a solar constituent, barely varied with the correction.

B. Validation of VMADCP measurements against co-located SMADCP

As described in Section II-D, correlation analyses were performed for each depth cell and for weighted rotor disk averages. To evaluate the performance of velocity measurements using VMADCPs, Fig. 5 shows the linear regression fit for rotor disk averaged velocity estimates obtained at station T00 through co-located VMADCP and SMADCP measurements. In this validation step, the VMADCP dataset consists of a 12-hour time series. The slope coefficients α as well as the coefficients of determination R^2 computed during both flood and ebb tides were very close to 1. The slope and R^2 values show that the two measurement methods provided time-series of rotor disk averaged velocities that closely agree.

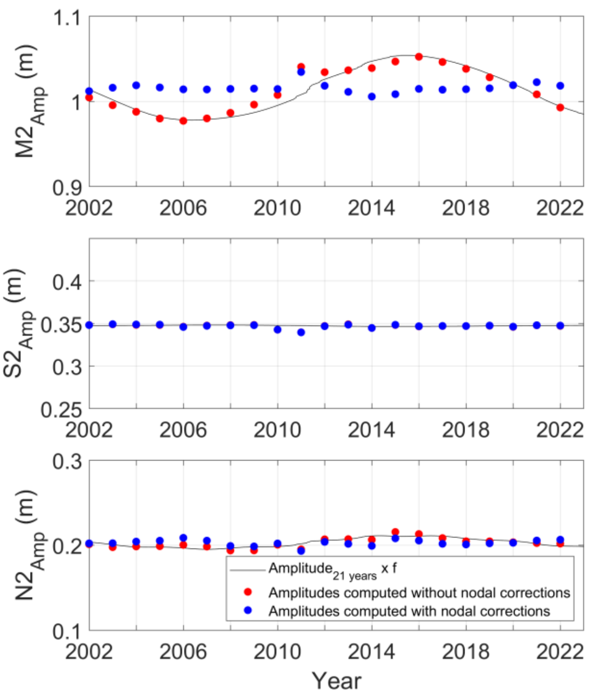

Fig. 4. M2, S2 and N2 amplitudes obtained from sea level harmonic analysis. Circles represent amplitudes computed from the analysis of consecutive years. The continuous line is the amplitude obtained from the analysis of the 21-year period multiplied by the nodal factor f.

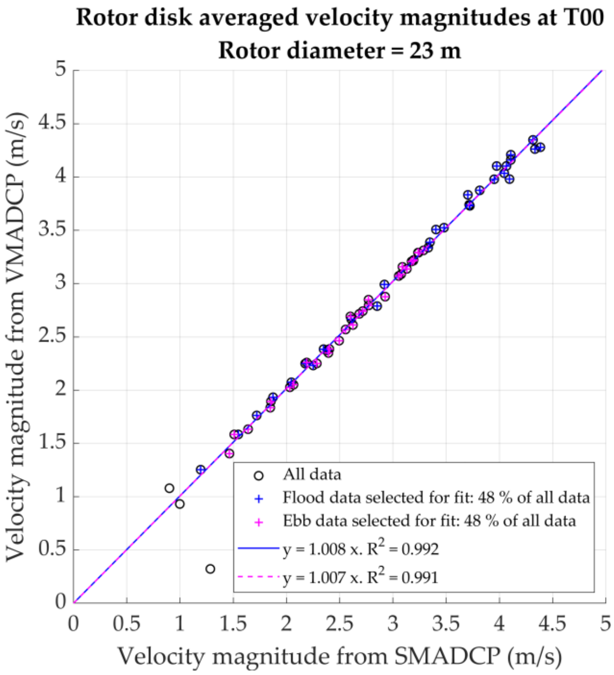

Fig. 5. Linear regression fit between VMADCP and SMADCP rotor disk averages of horizontal current velocity magnitude estimates at station T00. The results were obtained for two correlation analyses performed separately on flood and ebb events. Only velocity magnitudes > 1 m/s were used for the linear regression fit.

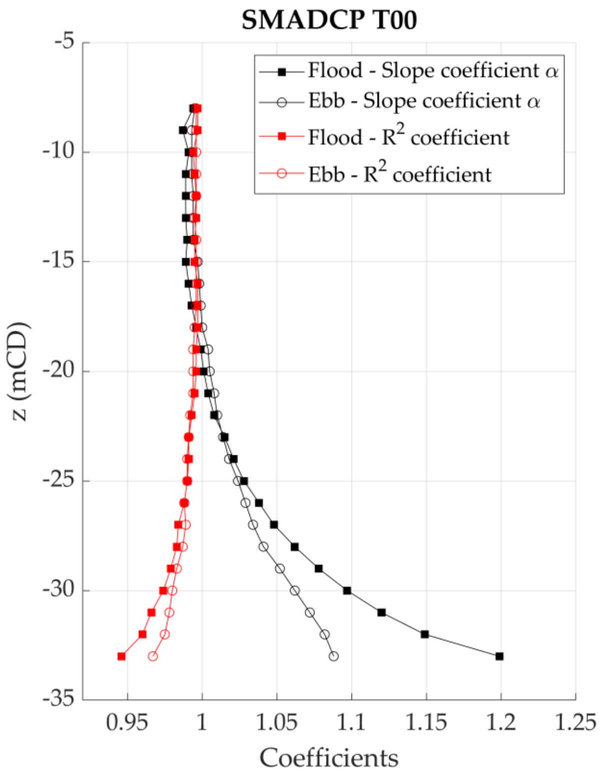

Fig. 6. Profiles of α (slope) and R^2 coefficients obtained from the linear regression fit between VMADCP and SMADCP velocity estimates at T00.

However, Fig. 6 highlights that the correlation obtained at cells located closer to the seabed was poorer when compared to the upper part of the water column. The slope coefficients deviate from 1, suggesting an overestimation of the velocity by the VMADCP, and the associated R^2 coefficients show lower values. The data quality control procedure was investigated, but since no cause was found for this discrepancy, no correction was applied to the VMADCP dataset. Further investigation is required to better understand this overestimation. It may be due to vessel motions too dynamic to be captured by the coordinate transformation. Using a better pitch and roll sensor coping with dynamic motions instead of the simple sensor within this ADCP may help reduce this overestimation. This large overestimation close to the seabed does not reflect in the results for rotor disk averaged velocities displayed in Fig. 5, because of the location of the rotor disk in the water column, and because the velocities involved at these depths are lower and the IEC's method of bins uses cubed velocities.

C. *Correlation between VMADCP at turbine locations and SMADCP at T00.*

Subsequently, an investigation of correlations between velocity estimates from SMADCP at T00 and VMADCP at T2XX stations was conducted. Table II presents the slope and R^2 coefficients obtained for weighted rotor disk averages for 10 of the locations (for conciseness). Results show that slope coefficients differ between flood and ebb events. This may mostly be due to the inhomogeneity, across the site, of the tidal asymmetry between flood and ebb. Fig. 7 shows the example of T204, the furthest from T00 location, with ebb and flood slope coefficients significantly different while they are associated with high R^2 coefficients. Specifically, the tidal asymmetry at T204 is much smaller than at the reference point T00.

Although the coefficient of determination R^2 tends to decrease with the distance from T00 location, it is also influenced by the flood and ebb events as shown in Fig. 8.

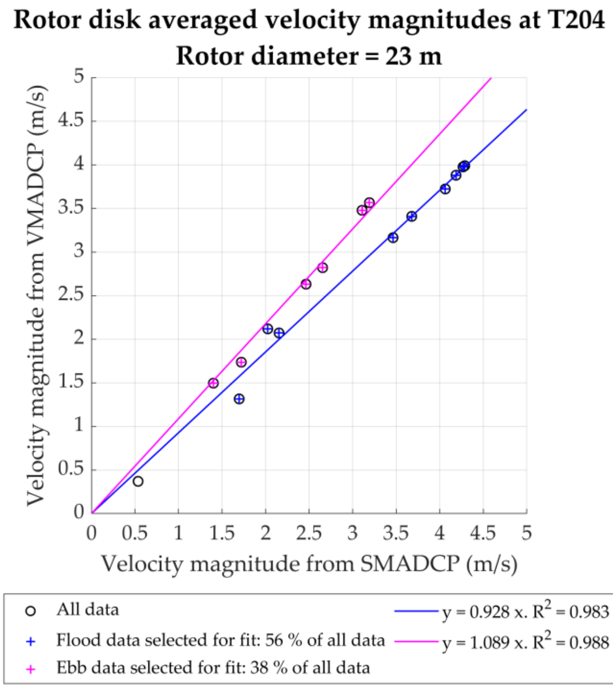

Fig. 7. Correlation results for rotor disk averaged velocity magnitudes at T204 station.

TABLE II
RESULTS OF CORRELATION STUDY BETWEEN SMADCP AT T00 AND VMADCP DATA AT 10 OF THE POTENTIAL STATIONS. ROTOR DISK WEIGHTED AVERAGE

Station	Distance to SMADCP T00 (m)	Flood		Ebb	
		α	R^2	α	R^2
T201	614	0.97	0.97	1.22	0.94
T202	577	0.97	0.98	1.22	0.94
T203	509	0.96	0.96	0.94	0.94
T204	614	0.93	0.98	1.09	0.99
T205	386	1.01	0.99	1.18	0.99
T207	137	1.01	0.98	0.96	0.98
T209	109	1.08	0.98	0.99	0.98
T210	59	1.04	0.98	0.97	0.98
T213	173	1.11	0.99	0.98	0.98
T214	126	1.04	0.98	0.99	0.98

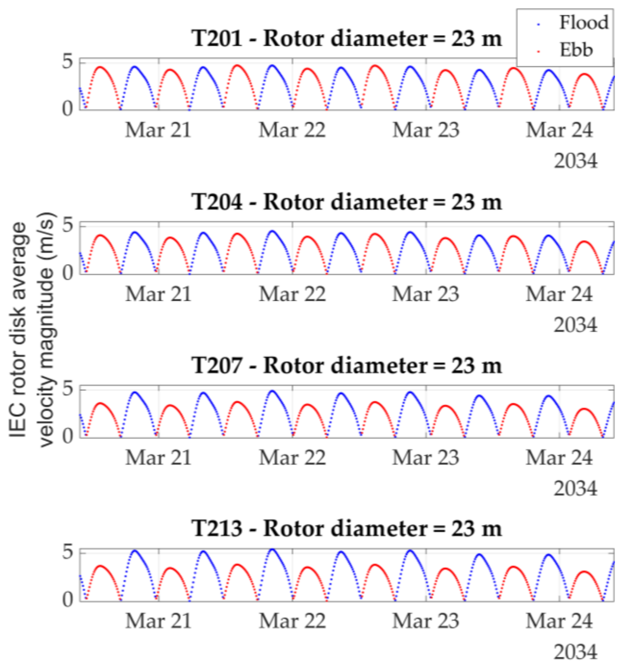

Fig. 9. Sample of weighted rotor disk averages of velocity magnitudes at four stations. Predictions considered flood and ebb slope coefficients separately.

D. *Velocity predictions at several stations*

Once the slopes of the linear regression fit were calculated for all locations of interest, Equation (3) was used to combine the velocity predictions obtained at T00 from the tidal harmonic analysis of the SMADCP data with the correlation study, leading to current velocity predictions for the 18.6-year period at all stations:

$$Vel_{T2XX}(z) = \alpha \times Vel_{SMADCP\ Harmonic\ analysis}(z) \qquad (3)$$

where T2XX are the stations where VMADCP measurements were collected, and *α* is the slope coefficient obtained from the previous correlation study.

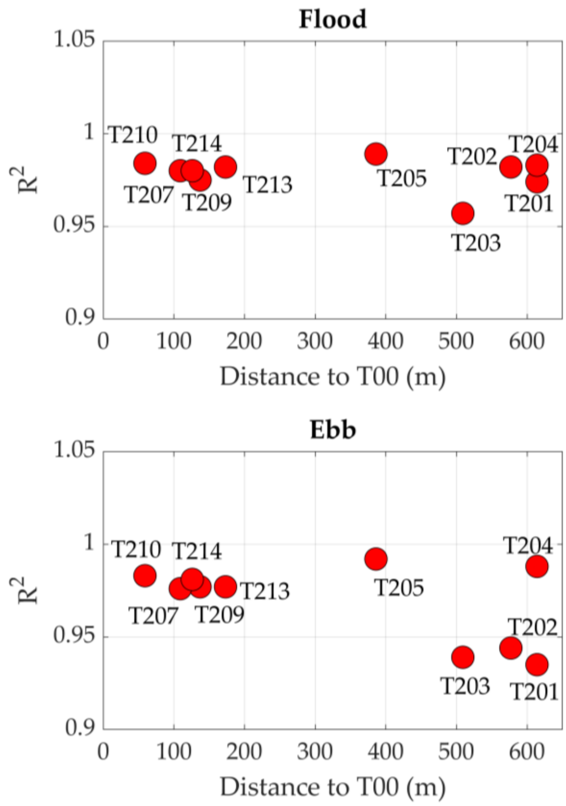

Fig. 8. R^2 coefficients plotted against distance to T00 location for 10 of the potential stations as shown in Table II.

Predictions were computed for individual depth cells (not shown here) as well as for rotor disk averages, using the flood and ebb slope coefficients separately. As an example, Fig. 9 reveals a sample of the predicted rotor disk average velocities during spring tide in March 2034. The plot confirms the tidal asymmetry that marks some of the locations more than others, with flood tides (in blue) being more energetic than ebb tides (in red). This asymmetry is particularly clear at T207 and T213 stations, located in the Eastern part of the area and close to T00 location, compared to T201 and T204 stations which are in the Western part of the area (see Fig. 1) and show more balanced flow speeds.

The velocity predictions allowed for an assessment of velocity magnitudes probability distributions, which are directly related to how much energy may be produced at each station. The investigation was performed at all stations so that the tidal energy resource as well as its spatial variability could be further understood. For instance, Fig. 10 and Fig. 11 depict the probability distributions obtained for stations T201 and T207, located at the Western and Eastern points respectively. Comparing the two stations confirms that the tidal asymmetry is intensified towards the Eastern side of the channel.

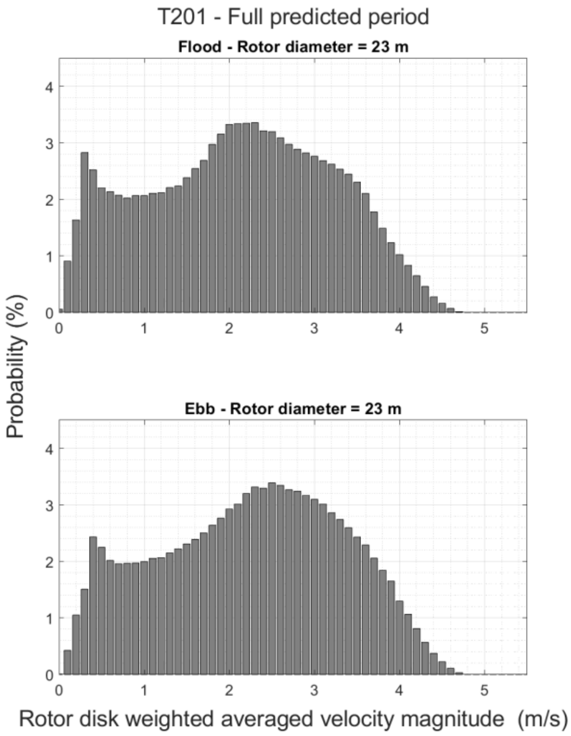

Fig. 10. Probability distribution of rotor disk average current velocity magnitude predictions over the 18.6-year period ranging from January 2027 to August 2045 at T201. Results are split between flood and ebb.

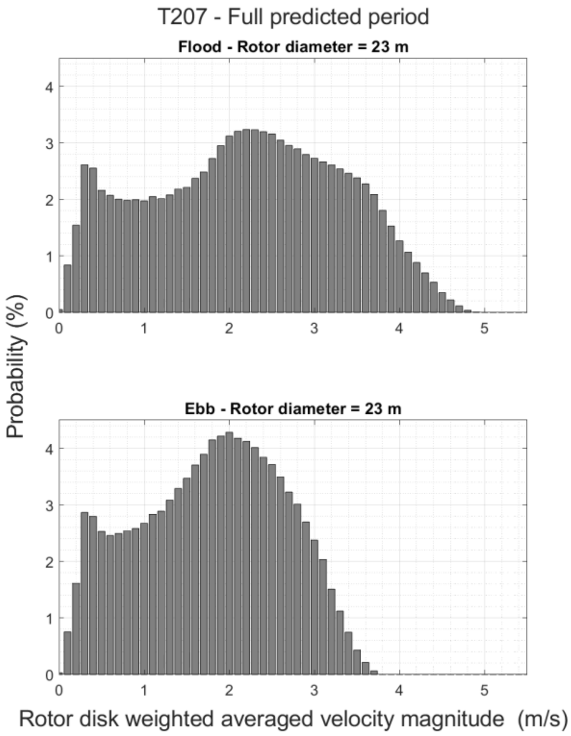

Fig. 11. Probability distribution of rotor disk average current velocity magnitude predictions over the 18.6-year period ranging from January 2027 to August 2045 at T207. Results are split between flood and ebb.

IV. Discussion

A. *Effectiveness of the technique proposed: correlating VMADCP and SMADCP measurements*

We proposed and validated an MCP methodology using fixed SMADCP and semi-stationary VMADCP measurements to provide an optimized assessment of the tidal energy resource at any potential turbine location across the Inner Sound in Pentland Firth. The method aimed to optimise the balance between the costs associated with field campaigns and the accuracy of the resource assessment for larger projects, and it is similar to that assessed by Xu et al. [5] on synthetic data.

The measurement method was validated by comparing VMADCP and SMADCP data collected at T00 simultaneously. Findings suggest the technique has proven to be effective, with high coefficients of determination R^2. These results emphasize the reliability of the method.

In most stations, with the exception of T203 and T207, the absolute difference in slope coefficients between flood and ebb was ≥ 0.05. In this study the SMADCP was deployed in an area where the currents were more tidally asymmetric (East), which reflected as larger differences between flood and ebb slope coefficients obtained on the opposite side of the channel.

This confirms that the MCP method should at least differentiate ebb and flood events. For reversing currents, as in this study and typically found in commercially viable tidal stream sites, this is probably sufficient to obtain high R^2 coefficients. For rotary currents or currents in-between reversing and rotary, the MCP method should probably be applied to all velocity direction bins which contain relevant velocity magnitudes.

The tidal harmonic analysis and reconstruction led to negligible residuals, which indicates that predictions were satisfactory. Generally, velocity magnitude predictions led to weighted rotor disk averages reaching 5.0 m/s, with probability peaks ranging mostly between 2.0 m/s and 3.5 m/s. Ebb tides at the Eastern points revealed to be less energetic, with narrower probability peaks centred around 2.0 m/s.

B. *Sources of uncertainties and limitations*

Even though the technique has shown to be promising, sources of uncertainties related not only to the data collection but also to the analysis must be highlighted.

A broader limitation, which would be extended to any dataset, is related to uncertainties associated with the tidal harmonic analysis and prediction. The results depicted in Fig. 4 show that *UTide* is able to accurately correct for long-term nodal modulations in sea level analysis. Nonetheless, Thiébot et al. [13] highlight the limitations of simply extrapolating the findings obtained from sea level studies to current velocity analysis. This is mostly attributed to the fact that current velocities are more prone to present nonlinear behaviour, due to aspects such as bottom friction, hydrodynamic variations introduced by bathymetry and local geomorphology. Therefore, the application of nodal corrections to these strong tidal currents must be further assessed comparing the results from the nodal factor type analysis with results from numerical simulations over an 18.6-year cycle. This assessment was not completed in this study

To get a more precise estimation of the confidence intervals and uncertainties around predicted velocities obtained through the proposed MCP method, the combination of several parameters should be accounted for. Aspects that influence the overall uncertainty include: ADCP measurement uncertainties and Doppler noise, uncertainties around the estimation of misalignment angles from VMADCP data, varying confidence intervals around tidal current velocity ellipse parameters and phase differences between tidal constituents as well as standard errors of the linear regression fits.

C. *Guidelines for tidal energy resource assessment and future work*

Currently, the IEC and the European Marine Energy Centre (EMEC) propose guidelines for the assessment of tidal energy resources, which are internationally acknowledged [2], [14]. The assessment is recommended to be performed by a combination of numerical models and SMADCP deployments (for more accurate fine-scale assessments) and VMADCP transects (for broader-scale earlier-stage assessments). Whilst VMADCP transects may provide some characterization of the spatial variability across large areas, long-term predictions which rely on tidal harmonic analysis require longer stationary datasets. The technique proposed here could enhance the traditional methods for tidal energy resource assessments, and potentially complement the existing guidelines.

Increasing the reliability and applicability of the method, including so that it can be used to improve current guidelines, requires testing and application at other tidal stream energy locations. Ideally, it would be useful to test the effectiveness of the technique in sites which present different characteristics from those found in the Pentland Firth. To further evaluate the performance of this technique, comparing the predicted velocities obtained at a potential turbine station from semi-stationary VMADCP with those from a (second) co-located SMADCP would also be valuable.

V. Conclusion

The work presented here introduced a novel method for obtaining long-term assessments of tidal stream energy resources. The proposed method requires a single month-long SMADCP dataset and a semi-stationary VMADCP instrument, which can collect measurements at several stations over a relatively short time. The alternative of undertaking multiple SMADCP measurements at many stations would be more costly and would take more time if the number of SMADCPs are limited or if acoustic interferences forbid simultaneous measurements at all stations of interest. The other alternative of combining a single or reduced number of SMADCP measurement locations and numerical modelling may not be as accurate. In this study the MCP method used a single SMADCP dataset. To reduce uncertainties or for more complex or larger sites, a few more SMADCP datasets spread across the site would be relevant.

Residuals of the tidal harmonic analysis and prediction as well as confidence intervals were examined and revealed to be small, indicating the analysis performed well. *UTide*'s nodal corrections were also investigated using a 21-year sea level dataset, leading to positive outcomes. However, certain limitations of extrapolating this conclusion to current velocities due to their nonlinear nature were noted.

The MCP method has proven to be effective, with high coefficients of determination R^2.

Our findings are expected to be useful in complementing and improving the existing guidelines for tidal energy resource assessments. To the authors' knowledge, this is the first time a method of this kind has been field tested and, therefore, this work may have a substantial impact on driving forward tidal stream power harvesting.

Acknowledgement

The authors would like to thank Dr Jérôme Thiébot for enriching discussions on the improvement of tidal harmonic analysis.

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