A comparison of platform and sea-bed mounted flow measurement instrumentation for SME PLAT-I

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Abstract—**Tidal resource assessment for the characterization of turbine performance or Annual Energy Prediction currently uses the *method of bins* as recommended by international standards. An alternative method is proposed in this paper and applied to the Sustainable Marine Energy PLAT-I deployment in Connel Sound, Scotland. This method may be suitable for tidal turbines which operate from the surface. Three instrumentation types are used in this work, a bed-mounted Acoustic Doppler Profiler (ADP), and platform-mounted Acoustic Doppler Velocimeter (ADV) and Electromagnetic Current Meter (ECM). By comparing the resource characteristics from these three sources, a comparison of their velocity magnitudes and turbulence characteristics is made, demonstrating the difference between methodologies. It was found that the ADP evaluated using the method of bins produced a more conservative velocity distribution, in comparison to the ADV and ECM. Consequently, a representative AEP showed a difference of 3.8 kWh (50% of ADP total) for the month of data collected. When comparing the Turbulence Intensity between devices, the ADP and ECM had similar metrics whilst the ADV had up to 14% higher values. The significance of these differences requires further work comparing them to the SME PLAT-I turbines power output to ascertain which best represents the onset flow experienced by the turbine and if there is a correlation between power performance and turbulence intensity.**

Keywords— **Acoustic Doppler Instrumentation, Tidal Resource Assessment, Turbulence.**

I. INTRODUCTION

TIDAL energy resource is a promising frontier for predictable and reliable renewable energy. Existing tidal energy converter (TEC) technologies employ a range of deployment methodologies and configurations, to reduce the levelized cost of energy (LCoE). In broad categories there are two main avenues of deployment, surface-mounted and seabed-mounted tidal turbines. Surface mounted technology offers a competitive advantage over seabed mounted deployments, as they do not typically require specialist marine vessels to deploy and retrieve (once the moorings have been deployed), permitting a reduction in operational expenditure across the lifetime of the device, and easier access and maintenance. Thus, many surface mounted tidal technologies are in advanced stages of commercialization such as the Sustainable Marine Energy PLAT-I and Orbital Marine Power O2.

To accelerate commercialization and increase sector confidence in attracting investment, there are international standards to which TEC developers and project developers must adhere. Two such standards are the IEC TS62600:200 and :201 which provide a clear path to device performance assessment and resource estimation for a technology at a given site, respectively [1], [2]. Both standards rely on the onset flow conditions the TEC will experience and thus this measurement is critical to investor confidence.

The IEC TS62600:200 largely assumes that the onset flow characteristics is achieved by deploying Acoustic Doppler Profilers (ADP) instrumentation secured to the seabed upstream of the TEC's location. This is viewed as the most dependable way in obtaining onset flow characteristics. Much work has been undertaken in improving these characterizations using bed mounted ADP technology, nevertheless it remains a challenging financial and logistical burden for developers. This is particularly true for surface mounted TEC developers, which aim to minimize seabed operations. Additionally, once tidal energy systems are in place there are operational constraints, such as mooring systems and operating swing radius that may interfere with bed mounted instrument signals. For these reasons, an investigation into an

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alternative method for onset flow characterization of an in-situ surface mounted TEC, that could avoid seabed mounted instrumentation, while preserving a reliable onset flow representation as established by the IEC 62600:200 standard is presented in this paper.

Previous research investigating site characteristics using multiple instruments co-located have previously been performed. Thomson et al study of Puget sound identified sampling parameters using ADP's and ADV's for turbulence measurements, specific emphasis on doppler noise is given [3]. An ADV and ADP were deployed on the seabed at the same location, the ADV sampling at a height of 4.7m from the seabed, within 1m of proposed hub height. Whilst the ADP bins spanned 79% of the water column. Doppler noise removal from ADP data resulted in general agreement between ADV and ADP standard deviations. Accounting for Doppler noise is essential to avoid over-estimates in turbulence intensities. The turbulence intensity was found to be lower in the ADV than ADP and related to incomplete removal of doppler noise. The 'restriction to length scales greater than the beam spread' for ADP's was established as a major limitation requiring along-beam velocities to be used, which limits length scales to the bin size. This is an important limitation for the comparison of surface and bed deployed instruments where the region in the water column could be far from the head of the instrument.

The field experiment conducted by Sentchev et al, utilized a mechanical current meter, ADP and ADV to characterize the influence of turbulence on a Darrieus type turbine [4]. All instruments were surface mounted upstream of the turbine. The ADV was submerged to 1m depth, equating to the second bin away from the ADP. The findings established the necessity for high resolution turbulence data to be recorded at a tidal turbine site, recommending ADV as the most appropriate instrument for this analysis.

Torrens-Spence et al conducted similar co-current deployments of ADP and ADV instruments at two locations, in Strangford Lough [5]. The vertical beam of the ADP provided some insight into the TKE spectra with agreement at low frequencies to the ADV, however further development of ADP technology is required to provide the relevant insight into turbulent behavior of onset flow.

In this paper the experimental work was conducted at commercial scale in partnership with Sustainable Marine Energy, Queen's University Belfast and Swansea University. The project was funded by the SURFTEC project and utilised the PLAT-I platform deployed in Connel Sound, Scotland.

II. EXPERIMENTAL DESIGN

A. Scenario

The aim of the experiment is to evaluate the onset flow using local onboard instrumentation and a bed mounted ADP as prescribed in the IEC standards. Three flow measurement instruments were used in this assessment. A bed-mounted five beam ADP (RDI Sentinel V workhorse) was deployed on the seabed with 0.5m vertical bin size at coordinates of 56.455008N and -5.398992W in accordance with IEC standards (2-5 effective diameters upstream of the rotor plane).

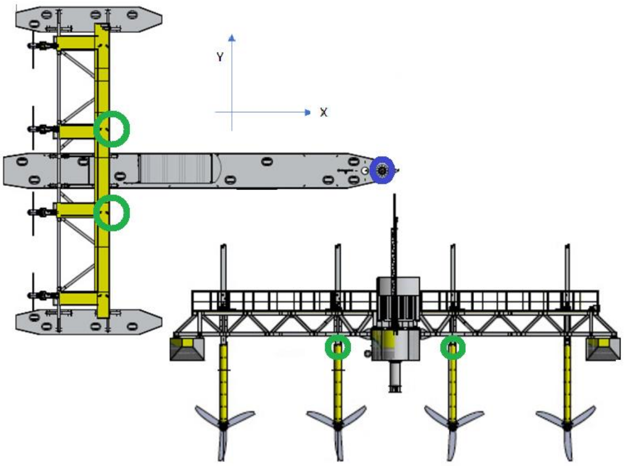

Fig. 1. SME PLAT-I Layout. Green circles indicate ADV and ECM locations, Blue circle is the mooring turret and datum for instrument locations at the waterline.

TABLE I
INSTRUMENT LOCATIONS RELATIVE TO PLATFORM MOORING TURRET AND WATERLINE

Instrument Locations	X (mm)	Y (mm)	Z (mm)
ADV	-22299	-3484	360
ECM	-22374	3468	227
Outer Turbines	-28499	12850	4678
Inner Turbines	-28499	6550	4678

Note: Positive Z direction is downward from water's surface.

On the PLAT-I device, a Nortek Vector ADV and Valeport MIDAS Electromagnetic Current Meter (ECM) were deployed. These are point velocimeters. A representative schematic of the instrumentation layout can be found in Figure 1.

The on-board instruments (ADV and ECM) have synchronised datasets with data acquisition systems, with the SURFTEC monitoring system and the PLAT-I SCADA respectively; the remote seabed ADP was independently deployed. Further information regarding the SME PLAT-I device and SURFTEC instrumentation is available [6]–[9].

The deployment window for the instruments overlapped for the month of December 2017. This overlapping period covers a spring and neap tidal cycle and provides a sufficient dataset for onset flow comparison. The nature of ADP is that measurements close to the waters surface are contaminated by sidelobe interference due to echoes from the water's surface. A five beam ADP is capable of tracking the waters surface as an elevation, but not resolving the flow field close to the surface. As such there is a disparity between the nearest usable ADP depth cell and ADV/ECM sample points. On average the ADV sample volume is 2.62 m above the nearest usable sample cell of the ADP, across the dataset.

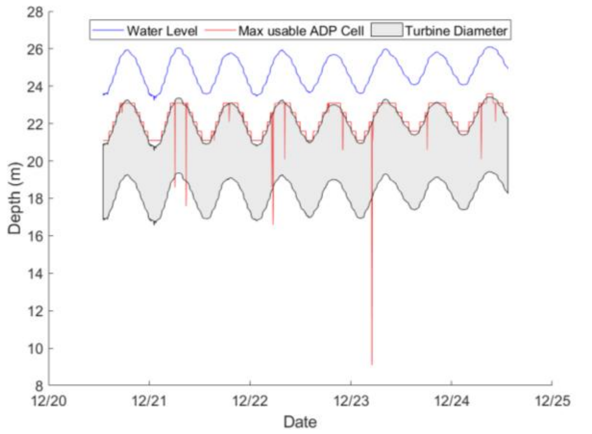

Fig. 2. Sample period showing water depth (blue line), area of water column occupied by turbine (grey area) and the maximum usable ADP cell (red line).

Fortunately, this issue does not occur for the velocity profile over the projected area of the turbine, as the maximum usable ADP cell was on average 0.14 m below the top of the projected area of the turbine. The 4 m projected diameter of the turbine can be seen in figure 2 as the shaded grey colour, with the surface tracking from the ADP as the Blue line, showing the depth from waters surface and the maximum usable cell of the ADP as the red line.

Given this close correlation between the maximum usable cell and the top of the turbines projected area, the maximum usable cell will be taken as the top cell for the IEC standards *method of* bins.

Another issue with comparison between ADP measurements and the vessel mounted instruments is obtaining an appropriate reference frame. The ADP is geostationary and represented in the earth reference frame (ENU); the ADV and ECM are fixed to the platform and so free to move and are easily represented in the vessel reference frame (XYZ) as shown in Fig. 1. To avoid a costly process of transforming either of these reference frames into the other (doable using differential GPS and Inertial Motion Unit, IMU) all datasets use the velocity magnitude, for the ECM this is only the two horizontal velocity components, UV.

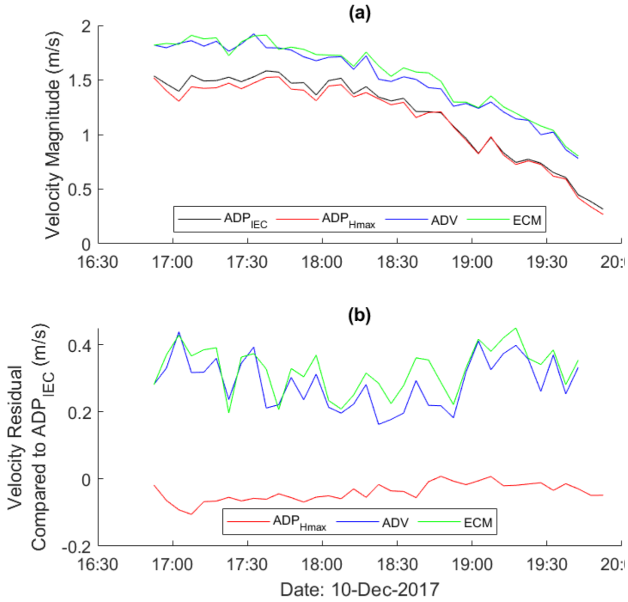

Fig. 3. Sample period showing (a) velocity magnitude (m/s) from ADP, ADV and ECM, (b) residual velocity when subtracted from ADP$_{IEC}$ data set.

Due to the nature of the site in Connel Sound, where tidal currents during flood work against the outflow from Loch Etive and result in very low mean flow speeds, the operational window of the turbine was limited to the ebb phase of the tide. A common ebb window was determined using the ADP data with the following steps:

1. Obtain High Water Time from *tidetimes.co.uk* [10]
2. Perform a peak analysis of the ADP flow magnitude for seven-hour window following HW
3. The ebb window considered is +/- 1.5hrs either side of this peak flow. Giving a total of 3 hrs per ebb cycle in which the flow is analysed.
4. The same time stamps are used for ADV and ECM instruments.

Whilst an effort was made to maintain time synchronisation, any synchronisation error is statistically negligible over the periods and scales being considered in this analysis.

B. *Theory*

To derive the mean current velocity, the *method of bins*, employed by the IEC 62600:200, is recommended. This method discretises the projected area of the rotor into a minimum of 10 bins, and assigns each bin an area weighting. The power weighted velocity is then calculated using sample velocities, over a 10-minute averaging period, as shown in equation 1.

Whilst results should be based in a 10-minute averaging period, supplementary data sets may be processed at averaging periods less than 10 minutes. Data maybe discarded if the current profiler is not able to resolve the flow over 90% of the bins in the projected area of the rotor.

The IEC 62600-200 [1] does not currently consider the contribution of turbulence to the power extraction. However, for the purposes of this study, the turbulence intensity (TI) has been calculated from the turbulent kinetic energy k and the mean flow speed $\bar{u}$ as shown in Equations 4-6.

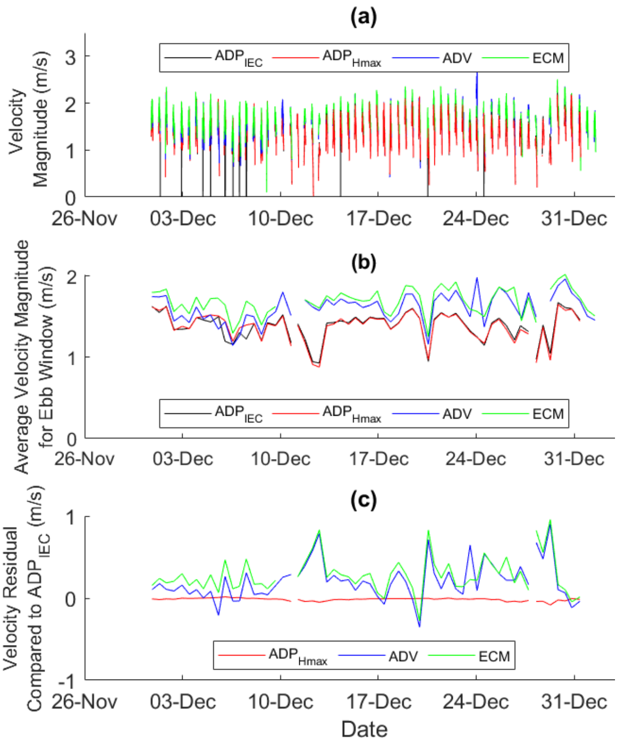

Fig. 4. (a) Velocity magnitude for each ebb window (b) Average velocity for each ebb window (c) Residual velocity when subtracted from ADPIEC data set.

III. EXPERIMENTAL RESULTS

A. *Flow Conditions*

The ADP data is processed in accordance with the IEC *method of bins*. The ADV and ECM data, having only one bin, are simply presented as flow magnitudes. Figure 3 (a) shows a sample of this from a single ebb tide; the black lines represent the IEC *method of bins* (ADPIEC) data set whilst the red line is the velocity magnitude of the top ADP cell, the blue line is the ADV and the green line the ECM. It is clear the ADP data sets closely align, as shown in Figure 3 (b), it is also clear the ADV and ECM data sets closely align suggesting there is some homogeneity in the horizontal plane, and a shear profile in the vertical plane. Figure 4 shows the velocity magnitude as a full time series, and as an average point for each ebb window considered for the entire dataset. This further demonstrates the close connection between the ADP data sets, showing very little difference, and the separation to the ADV and ECM datasets, which remain closely aligned with one another. The full time period mean and standard deviation of the velocity residuals is shown in Table II. The ADPHmax has the lowest magnitude residual, closely matching the IEC standard, with a very small standard deviation. The ADV and ECM have a 0.20 and 0.28 m/s mean residual, respectively with an equivalently magnitude standard deviation. Whilst this may seem a small deviation, the velocity is related to turbine power in a cubic relation making the error in performance predictions such as CP or in AEP significant. This is followed through in the next section.

$$\hat{U}_{i,j,n} = \left[\frac{1}{A}\sum_{k=1}^{S} U_{i,j,k,n}^{3}.A_k\right]^{\frac{1}{3}} \qquad (1)$$

$$P_i = \frac{1}{2}\rho A_T U_{i,n}^{3} \qquad (2)$$

$$AEP = N_h \sum_{i=1}^{V_B} P_i(U_i).f(U_i) \qquad (3)$$

$$\bar{u} = \sqrt{\bar{u}_x^2 + \bar{u}_y^2 + \bar{u}_z^2} \qquad (4)$$

$$k = \frac{1}{2}\sum\nolimits_{d=x,y,z} (u_d - \bar{u}_d)^2 \qquad (5)$$

$$TI = \sqrt{\left(\frac{2}{3}k\right)}/\bar{u} \qquad (6)$$

B. *Annual Energy Prediction*

The AEP using the IEC62600:200 standards must take the complete tidal cycle into account and relies upon knowledge of the TEC power conversion at each velocity bin. As this study is not concerned directly with the SCHOTTEL Instream Turbine (SIT) performance, the theoretical power performance values have been used as shown in Equation (2). The velocity bins used are in 0.1 m/s increments from 0 to max experienced velocity of 2.8 m/s. The velocity probability distribution for all ebb tidal phases has been accumulated into Figure 5. From the figure it is evident that all data sets show a gaussian distribution, however the ADP data can be seen to have peak velocity probability of 12% at circa 1.5 m/s whilst the ADV and ECM data have peak velocity probabilities of circa 13% at 1.7 m/s and 15% at 1.8 m/s respectively.

Using equation (3) the AEP can then be estimated, typically this would be estimated for the period of 1 year. Therefore, Table III could be multiplied by 12 to give an AEP estimate, however this is not recommended as 1 month is too short a sample period and a simple multiplication does not account for monthly variation.

When considering Table III there is a significant difference in AEP for the given period for the ADV and ECM data sets relative to the ADP. This clearly shows the disparity and significance between the IEC *method of bins* from the seabed and a platform-based flow monitoring. A comparison to the power performance of the surface

TABLE III: AEP FOR EACH METHOD OVER SAMPLE PERIOD

Method	**AEP (kWh)**
ADPIEC	7.72
ADPHmax	7.53
ADV	11.56
ECM	12.73

mounted turbines is required to determine which is the more accurate energy resource estimate.

C. *Turbulence*

Another important flow metric to consider is the effect of turbulence. Currently there is no international standard for the approach to characterising turbulence at a tidal energy test site. Therefore, this section simply seeks to take well established approaches and apply them to the ADP, ADV and ECM data sets. It is anticipated that the ADP data will differ from the ADV and ECM, due to the distance from the ADP instrument to sample volume and subsequent beam spread effecting the results. Note, that the ADP$_{\mathrm{IEC}}$ data set (which covers the projected area of the turbine) is not used in this turbulence consideration due to the impact of the *method of bins.*

The turbulence intensity is calculated using equation 6 and shown in Figure 6 for the same sample period as above, using the three instruments. The instruments give overlapping readings, ranging from 9% to 29% TI. The ADV and ECM follow the same trend, whilst the ADP has an anomaly at circa 19:00 and towards the end of the sample period diverges from the other two instruments. The vertical component of velocity is much lower in magnitude than the longitudinal and lateral components, so in some circumstances it is more helpful to neglect this when calculating TI; turbulence intensity calculated from ADV measurements without the contributions from the vertical fluctuations are plotted in figure 6 as ADV$_{\mathrm{2D}}$. Furthermore, as the ECM only measures the velocity magnitude and not any individual components, it is not possible to exactly reconstruct any of the traditional measures of turbulence intensity; what we present here as the "1D" TI from the ECM is the variance of the velocity magnitude anomaly, expressed as a fraction of the mean velocity magnitude.

TABLE II: RESIDUAL VELOCITIES MEAN AND STANDARD DEVIATION

Instrument	Average Residual	St.Dev Residual
ADP$_{\mathrm{Hmax}}$	-0.0151	0.0178
ADV	0.2056	0.2700
ECM	0.2824	0.2673

The difference between turbulence intensity values from the three instruments has been plotted as a time series by plotting the average over the ebb window, giving a representative for the entire data set, this can be seen in Figure 7 (b). The results show ebb window average TIs ranging up to circa 50%. It is of interest to note the trend in the data, the highest TI occurs at the peak of the spring tides and lowest at the peak of the neap tides. This correlation between TI and neap/spring cycle was not anticipated and indicates that the site and hight in the water column is dominated by turbulence production turbulent kinetic energy is increasing faster than would be anticipated from the velocity scale of the mean flow. This suggests that turbulence at the measurement location is not in equilibrium; instead, production appears to be significantly exceeding dissipation.

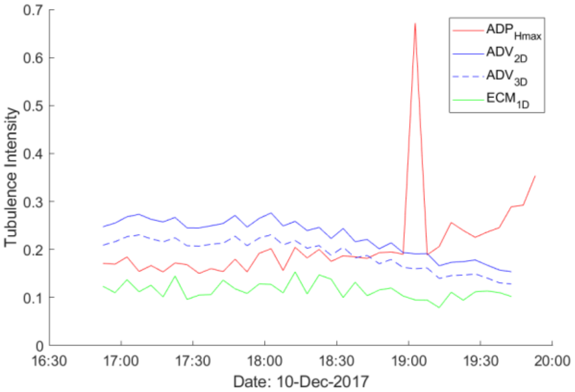

Fig. 6. Sample period showing Turbulence intensity from ADP, ADV and ECM.

TABLE IV: EBB AVERAGE TURBULENCE INTENSITY VALUES

Instrument	Average TI
ADP$_{\mathrm{Hmax}}$	0.2346
ADV$_{\mathrm{3D}}$	0.3094
ADV$_{\mathrm{2D}}$	0.3691
ECM	0.2207

The average of all ebb windows is plotted in Table IV, which shows the ECM and ADP to have close overall average TI values, whilst the ADV 2D and 3D are up to 14% higher.

IV. DISCUSSION

It was anticipated that there would be some discrepancy between the platform mounted instrumentation (ADV and ECM) and the seabed mounted ADP. The top usable ADP cell, power weighted velocity from the method of bins have a close correlation to one another. Whilst the ADV and ECM velocities, despite being only 3m closer to the water's surface, there is consistently higher velocities, which can be attributed to the shear profile of the flow and turbulence, as has been shown. The significance of this has been shown (by way of an example) using the AEP. Further consideration of AEP is required, as the results presented have not considered what energy the turbine captured, and only the theoretical maximum energy was used for the AEP calculation. Only by direct comparison with energy captured, can it be established which instrumentation best reflects the onset flow experienced by the turbine.

When considering standard deviations of the residual velocities (In Table II) they were of a similar magnitude to the mean velocity residual, this reflects the highly turbulent regime the device is situated in. To explore this further, turbulence intensity was calculated for each device and compared. It was found that the ADV and ECM had 8-14% greater and 1.4% lesser TI on average than the ADP, respectively. The ADP and ECM trends closely aligned with one another which is unexpected. However, in further work the continued use of turbulence intensity is not recommended [4] as shown by Sentchev et al, who found clear correlation between the length scale of the turbulence and the power fluctuations of the turbine. This avenue of analysis should be considered for this site also. Unlike the work of Sentchev et al [4], it is anticipated the site is dominated by turbulent production rather than dissipation and as such is of high interest for further work into the impact of turbulence on device performance.

V. CONCLUSIONS

The aim of the research was to evaluate the onset flow into the SME PLAT-I device from three data sources (ADP, ADV and ECM) whilst being tested in Connel Sound, Scotland. The ADP data was processed in accordance with the IEC *method of bins* and when compared to the ADV and ECM data sets showed some disparity in mean velocity. On average the ADV and ECM were 0.21 and 0.28 m/s faster than the ADP, respectively. The impact on these variations in onset flow is significant, when considering AEP for the site, the variation in mean velocities equates to a difference of 3.8 - 5.0 kWh of energy over the calendar month (December 2017). As discussed, this significant difference demonstrates the importance of a correct methodology for evaluating onset flow.

Assessment of TI values from the three instruments showed that the ADP and ECM have similar average values throughout the data set, whilst the ADV was up to 14% higher as an average for the entire dataset. The disparity between ADP and ADV was expected, given the locations in the water column. Further work will be undertaken to correlate the onset flow measurements with the turbines output performance, establishing the best metrics for relating turbulence and turbine power production, thus validating which instrumentation is most suited to represent the available resource as seen by the turbines.

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