# Assessing the capabilities of acoustic Doppler sensors for quantifying dynamic phenomena in tidal streams

Jean-Baptiste Richard*, Jochen Bard, Claudia Rudolph and Matisse Milovich

Fraunhofer Institute for Wind Energy and Energy System Technology (IWES),
Kassel & Bremerhaven, Germany

*Corresponding author. E-mail: Jean-Baptiste.Richard@iwes.fraunhofer.de

## Abstract

**At the present state of the technology, accounting for the dynamic effects of waves and turbulence on tidal energy converters is an important challenge for the tidal industry. A particular point is that corresponding measurement instrumentation has not been clearly identified yet. Indeed, the typical devices used for tidal flow measurement are bottom-mounted current profilers and, though some methods have been established to use them for assessing turbulence parameters, they are not designed for capturing dynamic phenomena. On the other hand, sensors dedicated to turbulence measurement only resolve one point of the flow, while larger domains such as swept areas are of interest.**

**The work presented in this paper aims to quantify the limitations of different types of sensors due to Doppler noise and to local homogeneity assumption. In parallel with theoretical considerations, two sensors are modelled. Their response in a 3D turbulent flow field is simulated and benchmarked respect to field experiments, particularly regarding noise levels.**

**Keywords:** ADCP, Aquadopp, Doppler noise, tidal energy converters, turbulence measurement.

## 1. Introduction

Tidal streams represent a great resource for renewable energy, with the fundamental advantage to be highly predictable on the timescales of electricity consumption. Therefore, as Tidal Energy Converters (TECs) industry is now reaching pre-commercial stage, developers are planning the installations of TEC arrays. In contrast, the behaviour of TECs with respect to short-term variations of tidal stream is not fully understood yet. Fluctuations in the current velocities caused by waves as well as turbulence produce fatigue loads and affect output power quality, thus a greater knowledge of the topic would consequently benefit to the maturity of the tidal industry.

Depending on the local site conditions a significant part of those fluctuations will come from waves and one can assume that the remaining part mainly accounts for the generic phenomenon of turbulence, also designated as “background” turbulence in this context. These two disturbances cover overlapping ranges in the frequency domain, which complicates the analysis and separation of these effects.

A part of the challenge is that relevant measurement techniques are not clearly established so far. On the one hand, sensors used with tidal devices do not natively present a compatible resolution. On the other hand, new sensors developed specifically for turbulence measurement are point sensors, whereas information across the water column is required here. Advanced post-processing methods or new hardware designs are therefore needed for characterising the dynamic flow properties of tidal sites, but also for being able to feed TEC control algorithms accounting for those phenomena in an optimum way.

This paper presents some results in the study of measurement techniques with respect to the challenges mentioned above, focusing on two technologies: 4-beam ADCPs, and Aquadopps. It is organized as follows: Section 2 describes the technologies and methods used in tidal energy for flow measurement, and introduces the solutions investigated. Section 3 presents the simulation environment developed. Section 4 gives an insight into the measurement campaigns providing comparison data. Results are presented in section 5, while section 6 draws up conclusions and outlooks.

## 2. State of the art in tidal flow measurement

At the present time, standard hardware used for characterising tidal sites are bottom-mounted acoustic Doppler sensors. They work with acoustic beams orientated upwards at a given slant angle of the vertical, and equally spread in azimuth (Janus configuration) as illustrated in Figure 1 below:

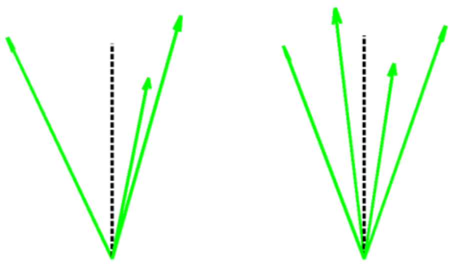

**Figure 1:** Example of beam configurations for bottom-mounted acoustic Doppler sensors with 3 and 4 beams, respectively.

An acoustic transmitter and receiver corresponds to each beam. Thanks to the change in frequency of the signal while being reflected by particles in the water (so-called Doppler effect), this hardware measures along each beam and as a function of the distance to the sensor, the projection of the water speed on the beam direction. These data are called "along-beam speeds" in this paper. The distance between two measurement points from different beams but situated at an equal distance of the sensor is designated as "beam separation".

One challenge is that the measurement uncertainties in the acquisition of along-beam speeds (so-called "Doppler noise") is quite high, and it has been shown that the corresponding error has to be accounted for when studying the measurement fluctuations [1].

Similar hardware can also measure along-beam speeds via the change in signal phase rather than in signal frequency. This technique designated as "pulse-to-pulse" provides more precise data, but suffers from much more limited speed and distance measurement ranges (e.g. 0.44 $m.s^{-1}$ and 10m, respectively, in [2]). It is therefore hardly suitable for energetic tidal sites.

The along-beam speeds are then processed assuming horizontal homogeneity of the flow, that is to say that at a given distance from the sensor, the projections measured on the different beams are assumed to correspond to the same velocity vector, despite the beam separation. Under this assumption, estimates of the 3 components of the speed as a function of the vertical elevation above the sensor are computed. With sensors having more than 3 beams, an error indicator can then also be processed (still as a function of the elevation) thanks to the over-determination of the system. More information on the topic can be found in [3-5].

With slant angles being 20° or greater, beam separations are very similar to the corresponding distance to the sensor, which is close to the rotor diameter or such characteristic vertical dimension in the regions of interest. As a consequence, phenomena varying on a distance smaller than twice this length scale are not expected to be quantified adequately with this method. In opposition, eddies with size comparable to blade chords are expected to affect TECs. With an advective mean flow of 2 $m.s^{-1}$, this available resolution corresponds to periods greater than 10s, which becomes in this context a more relevant limiting factor than the maximum sampling frequency of the hardware (generally 1 to 10 Hz). In comparison, natural frequencies of the corresponding structures are typically a few Hz.

Also, regarding waves, in such a configuration the beam separation limitation theoretically means that only motions corresponding to shallow-water waves, i.e. affecting the entire water column, can be measured correctly.

Nevertheless, the relative ease of use and straight forward deployment procedure of such sensors, for instance compared to micro-structure profilers, drives the interest in trying to overcome these limitations through the development of additional post-processing techniques.

An interesting result of this effort is the "variance" method [2-6], which applies to bottom-mounted sensors with four beams. Its principle is to use the variances of along-beam speed time series to calculate two components of the Reynolds stress and an estimate of the Turbulent Kinetic Energy (TKE) density.

Applying power spectral density (PSD) estimates of the along-beam speeds rather than their variances gives additional access to the distribution of the above quantities in the frequency domain [6], e.g. an estimate of the TKE spectral density. This description is particularly interesting with respect to predicting the effects of the dynamic phenomena on TECs. Without this analysis the method cannot cope with waves [8].

Nevertheless, a major drawback of the variance method is that the anisotropy pattern of the turbulence is not an output, but a hypothesis. This assumption has its limitations:

- on the one hand, In-house experience has shown that natural frequencies of the TEC structure are typically a few Hz. The frequency domain of interest is where the transition occurs between the isotropic inertial subrange and the greater anisotropic eddies, in which horizontal and in particular streamwise fluctuations are larger [9-11]. Additional information on turbulence characteristics can for instance be found in [10].
- on the other hand, for the majority of TECs, the streamwise component of the stream fluctuations has more impact than the cross-flow ones.

It is therefore necessary to investigate the impact of this hypothesis on the dynamic performance analysis of TECs.

Another post-processing method is the Structure Function method, which aims to quantify the TKE dissipation rate ε in the inertial subrange. But it assumes turbulence homogeneity and isotropy, and is therefore expected to be less reliable for this purpose than the previous method. It is not suitable to bridge the gap up to the validity domain of the standard post-processing method.

Another type of sensors using acoustic Doppler effect in moving water is state of the art in turbulence measurement. A greater temporal and spatial resolution is achieved at the cost of a smaller sampling volume near the sensor (e.g. 80 to 400 mm$^3$ sampling volume at 10 cm from the sensor, with 25Hz measurement output [7]).

A spatial distribution of a number of such "point" sensors would be necessary to analyse the dynamics of the flow across the water column, and especially over regions corresponding to swept areas of tidal devices. Nevertheless, the individual capacities of those instruments are not necessarily required. Instead, simpler sensors offering a lower temporal and spatial resolution would be preferable.

For instance, "Aquadopp Current Meter" point sensors with a spatial resolution under 2m and 4Hz output. Hence the study which is the background of this paper. It aims at benchmarking the relevance of advanced post-processing methods applied to "ADCP" bottom-mounted sensor, in respect to the data provided by an array of Aquadopps. This is illustrated in Figure 2:

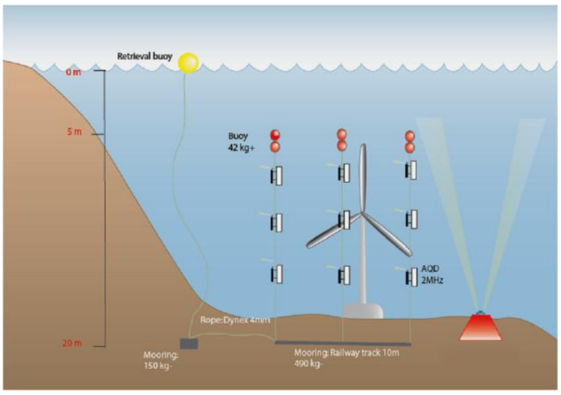


**Figure 2:** schematic representation of the two measurement solutions focused on (source: Nortek).

## 3. Simulation tools and hypothesis

Modelling the sensor configurations as discussed above poses two challenges: on the one hand, simulating a turbulent tidal flow and on the other hand, modelling the response of the different sensors themselves.

For the turbulent flow generation, a stochastic model based on Mann's work [12-13] has been chosen. The underlying theory was initially developed for wind turbulence, and the current approach towards simulating turbulent tidal flows is to use model implementations in the same way as they are in wind energy. This is justified by the observed similarities in the turbulence patterns of those two kinds of flow [11]. Previous versions of this model had already been used at Fraunhofer IWES in the past, for wind and for tidal turbine simulations [14]. For both of those two technologies, the streamwise flow variations are known to have considerably more impact than the other ones, and those versions were consequently restricted to the computation of this component of the fluctuations.

In the context of sensor characterisation, however, the acoustic beams are all pointing at different directions. Consequently, each of the flow components has an impact on the measured speed, even if only one component of this output is needed. For this purpose, the model is then upgraded to generate the full 3D description of the turbulence.

The turbulence model uses the common Frozen Turbulence Hypothesis (FTH) for the spacio-temporal description of the flow. In a similar way, at each time-step of the simulated flow, the points of the grid that correspond to each measurement volume of the sensors are identified under this assumption. The local, instantaneous 3d speed is then computed as a weighting of the speed value at those points. Its projection on the corresponding beam direction gives the along-beam speed, in an ideal case where no Doppler noise would occur. This phenomenon is then accounted for by altering those simulated along-beam speeds by an additional Gaussian error. This means assuming a white noise distortion, which is the standard hypothesis in this case [6]. Simulated estimates of the 3d speeds are then computed from numerical along-beam speeds for both of the two cases (with and without noise).

## 4. Field data

The field data used in this study come from two separate measurement campaigns.

Aquadopp data were collected in January 2012 in the North Sea, at a sampling frequency of 4Hz with a 2Mhz current meter, standard head. Speeds were recorded in raw beam coordinates (along-beam speeds). This campaign also covered investigations on mooring solutions, which are not treated in this paper.

**Figure 3:** Aquadopp deployment in the North Sea.

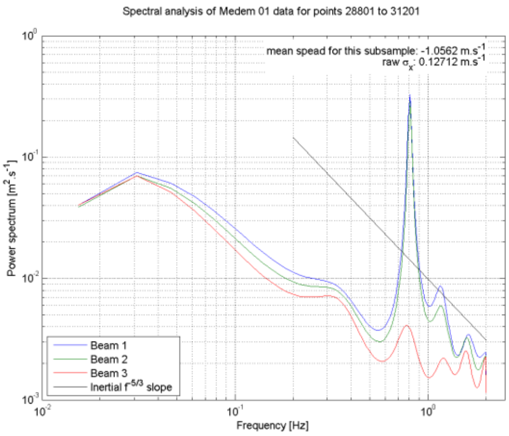


**Figure 4:** example of PSD analysis for 10 minutes of raw Aquadopp along-beam speeds.

Bottom-mounted data were collected with a 600kHz ADCP from August to November 2004 in the Bristol Channel, for studying turbine behaviour in the framework of the SeaFlow project. They were recorded at 2Hz in post-processed instrument coordinates, with a bin size of 1m. Previous coupled analysis of those data with performance data showed that the waves played an important role in the power quality of this prototype. A power fluctuation of 5% was determined which was caused by waves of only 0.5 m significant wave height.

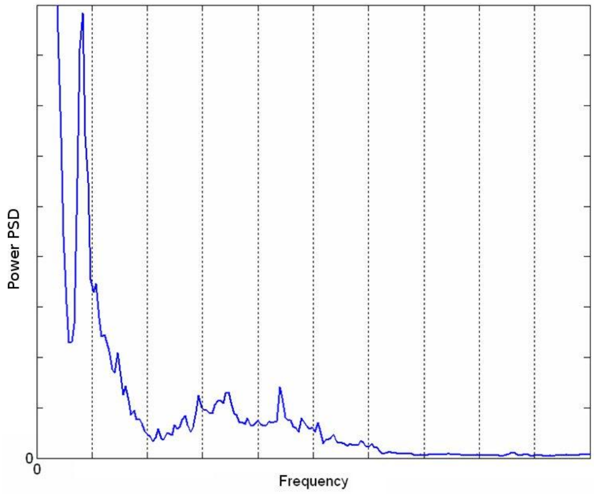


**Figure 5:** example of PSD analysis of the electrical power delivered by the SeaFlow prototype. The peak on the left corresponds to the peak wave frequency.

## 5. Results and discussion

The first point of interest in both of the two sensors is the level of Doppler noise pollution in the measured signals.

In terms of statistics (e.g. so-called "Turbulence Intensity"), it affects linearly the variance of the measured signal:

$$\sigma^2_{measured} = \sigma^2_{ideal} + \sigma^2_{noise} \quad (1)$$

Where $\sigma_{measured}$ is the measured standard deviation, $\sigma_{ideal}$ depends on the flow and on the geometry of the sensor, and $\sigma_{noise}$ is the instrument error due to Doppler noise.

In terms of spectral analysis, it results in a summation of PSDs: the ideal spectrum is contaminated by a layer corresponding to the noise. At frequencies for which the PSD of the speed fluctuations is high, the relative importance of the noise contamination is small. On the opposite, in situations where the speed fluctuation PSD is negligible respect to the noise spectral density, the latter dominates the measurement and prevents from assessing the former. This is called "saturation" in the present paper.

In our case of turbulent flow as illustrated in Figure 6, low speed PSDs occur in the high-frequency domain. Namely, their values decrease dramatically in the inertial subrange, where they exhibit a typical $f^{-5/3}$ pattern (with f being the frequency). In a log-log diagram, this gives a straight line with a slope of -5/3 m$^2$, here designated as "Kolmogorov slope". The noise PSD alone, still assuming it is white, draws itself as a horizontal line. The saturation is consequently a horizontal asymptote of the measured signal in the high frequencies. If the noise is low enough, the level of the Kolmogorov slope can be identified. This means accessing ε estimates, and being able to quantify the velocity PSD even in the saturated area (up to the Kolmogorov scale at higher frequencies).

If the noise is too high, it is not possible to identify the level of this slope directly without any noise correction.

Hence the concern in quantifying the noise, and in benchmaking it with the expected performances of the sensor. Those are generally expressed as a precision of the horizontal speed, and vary with the square root of the output sampling frequency because of ensemble averaging.

For the ADCP data, we find a good agreement with the accuracy provided by the manufacturer ($6.1*10^{-3}$ m.s$^{-1}$ standard deviation on the horizontal velocity at 10Hz sampling [15]). This corresponds to a noise PSD between $10^{-3}$ m$^2$.s$^{-1}$ and $3*10^{-3}$ m$^2$.s$^{-1}$, as it can be seen in Figure 6.

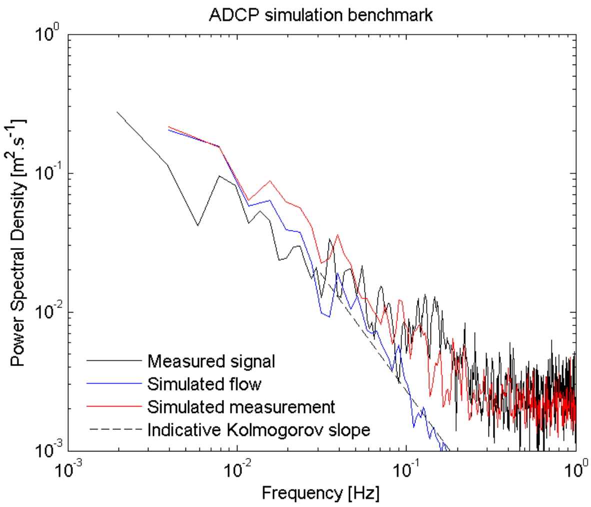


**Figure 6:** Simulated (red) and physical (black) ADCP measurement PSDs, with the corresponding simulated flow (blue) and an the $f^{-5/3}$ Kolmogorov slope (dashed).

In the case of the Aquadopps, the "horizontal velocity precision" announced by the deployment software for this configuration is $4.6*10^{-3}$ m.s$^{-1}$. For matching the noise observed in the measurement, we need to increase this value by 40% in the simulation. This still has to be investigated further, but it is foreseen that the presence of other sensors plays a role here, as two sensors were measuring 2 meters apart one from another. This precision also depends on the presence of particles in the flow, and is therefore indicative.

Regarding the bottom-mounted sensors, the variance method simulations look encouraging, as is illustrated in Figure 7. With standard post-processing, the speed homogeneity hypothesis creates a mutual contamination of the speed components. This is one source of overestimation of the fluctuations, above all for the horizontal components. In addition, the vertical fluctuations is taken as a mean of 4 values, and therefore underestimated (without noise). In comparison, the "noiseless" TKE spectral estimate is more accurate.

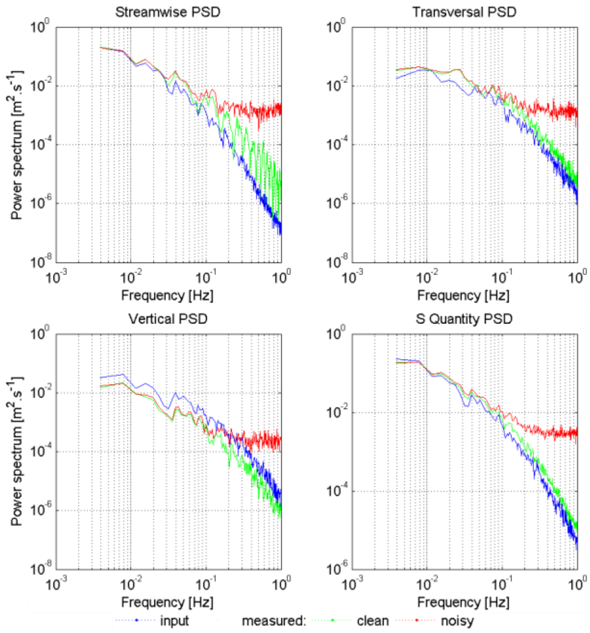


**Figure 7:** Simulated ADCP measurement PSDs: 3 speed components computed with the standard method, and TKE density estimate.

In the case of the Aquadopps, one interesting thing is that different beam configurations are possible. With the standard head, two perpendicular beams measure the horizontal velocities, and one slanted beam is used to deduct the vertical component. It is also possible to use a horizontal Janus configuration, for concentrating on the streamwise component. However, the degradation of the perpendicular components is greater than in the case of the vertical Janus configuration of a bottom-mounted sensor, because the direction the sensor is pointing at prevails in the mutual contamination.

**Figure 8:** Standard head for Aquadopp Current Meters, and other aquadopp heads (source: Nortek).

In addition, the sensor orientation has an impact on the measurement quality. It appeared disadvantages to having more than 20° of tilt.

## 6. Conclusions and future work

The current results are encouraging, by giving confidence in the simulation tools developed for modelling the response of acoustic Doppler sensors in dynamic tidal flows, and by providing first useful information on the configurations investigated. All this is ongoing research, and aspects to be examined further are numerous.

With the bottom-mounted principle, extension of the variance method looks promising, and the next step is to benchmark model data with measured along-beam speeds. Nevertheless, mid-frequency anisotropic pattern deserves further description. New bottom-mounted sensors with a vertical additional beam [16] should theoretically provide the lacking information, but only if noise is negligible or efficiently corrected.

In the case of Aquadopps, noise characterisation has progressed, as well as knowledge on the different heads. The ability to measure the TKE dissipation rate still requires investigation, and tests in more energetic flows are planned.

A configuration with a vertical matrix of sensors should provide a more precise transversal description of the flow, as well as more real-time information. For this, the mooring solution plays an important role in terms of deployment & retrieval, survivability, and above all sensor motion. Research on the topic is out of the scope of this paper, and its effects still have to be incorporated into the simulation environment presented here.

In both cases, highest output sampling rates should be preferred, to enable the best identification of the noise PSD. Automated correction should be considered.

Regarding the flow generation model, the next step is to couple it with Wave-Current-Interaction models in a 3d+t approach. Wake considerations are of course interesting too, but depend on the characteristics of the TEC itself.

## Acknowledgements

The Aquadopp measurement campaign was carried out with vessel and staff support from the Federal Water and Ship Navigation Office Bremerhaven. The use of the SeaFlow project ADCP data in this research study was enabled via national funding from the German Federal Ministry of Environment. Further investigations will be conducted within the MARINET project funded by the European Union Seventh Framework Programme (FP7) under grant agreement No. 262552.

## References

[1] J. Thomson, M. C. Richmond, B. Polagye, V. Durgesh, 2010: Quantifying turbulence for tidal power applications, OCEANS 2010, Seattle, Washington, USA.

[2] A. Lohrmann, B. Hackett, L.P. Roed, 1990: High resolution measurements of turbulence, velocity, and stress using a pulse-to-pulse coherent sonar, J. Atmos. Ocean. Technol. 7, p19–37.

[3] Nortek AS, 2005: Acoustic Wave And Current Meter, user guide, Revision E.

[4] R. L. Gordon, RD Instruments, 1996: Acoustic Doppler Current Profiler, principles of operation, a practical primer, 2nd Edition.

[5] Y. Lu, R.G. Lueck, 1999: Using a broadband ADCP in a tidal channel. Part I: Mean flow and shear, J. Atmos. Ocean. Technol. 16, p1556–1567.

[6] Y. Lu, R.G. Lueck, 1999: Using a broadband ADCP in a tidal channel. Part II: Turbulence, J. Atmos. Ocean. Technol. 16, p1568–1579.

[7] Nortek AS, Vectrino Field Probe datasheet.

[8] E. Osalusi, J. Side, R. Harris, 2009: Structure of turbulent flow in EMEC's tidal energy test site. International Communications in Heat and Mass Transfer 36 p422-431l.

[9] J. Thomson, B. Polagye, V. Durgesh, M. C. Richmond, 2012: Measurements of Turbulence at Two Tidal Energy Sites in Puget Sound, WA, Journal of Oceanic Engineering, Vol 37, issue 3, p363-374.

[10] E. Lévêque, 2006: An introduction to turbulence in fluids, and modelling aspects. EAS Publications Series, vol 21, pp 7-42.

[11] I. Milne, R. Sharma, R. Flay, S. Bickerton, 2011: Characteristics of the Onset Flow Turbulence at a Tidal-Stream Power Site, 9th European Wave and Tidal Energy Conference, Southampton, UK.

[12] J, Mann, 1994: The spatial structure of neutral atmospheric surface-layer turbulence, Journal of Fluid Mechanics, vol. 273, p141-168.

[13] J. Mann, 1998: Wind field simulation, Probabilistic engineering mechanics, vol 13, No. 4, p269-282.

[14] P. Caselitz, M. Shan, J. Giebhardt, B. Panahandeh, 2006: Hardware-in-the-loop development and testing of new pitch control algorithms. EWEA 2006.

[15] RD Instruments, Workhorse Monitor Hardware features.

[16] RD Instruments, Sentinel V Hardware features.