Measuring waves and currents at the European Marine Energy Centre tidal energy test site: campaign specification, measurement methodologies and data exploitation

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***Abstract*—Improved understanding of the dynamics of tidal currents and ocean waves and the loads they impose on tidal turbines is a prerequisite for an economically viable tidal turbine industry. The dynamic environment effects machine design and reliability, has consequences on operations and maintenance and ultimately energy conversion rate. Over the course of a recently completed five year international collaborative project multiple, multi-instrument measurement campaigns were conducted to acquire information on the flow, and recently, the wave-field incident upon an operating commercial-scale tidal energy converter (TEC), the Alstom 1MW DEEPGEN IV. This article summarises the measurement campaign specification and methodology, introduces the project's technical reports and describes access to all of the acquired data. A new research project, FloWTurb: Response of Tidal Energy Converters to Combined Tidal Flow, Waves, and Turbulence has already incorporated "lessons-learned", which are summarised, into upcoming field measurements in the Pentland Firth and has funded a significant re-analysis of these existing data sets beyond the original project's scope. A selection of summarising results are introduced here, where the inclusion of ocean wave measurements and analysis allows the data to be exploited in new ways.**

I. INTRODUCTION

Flow characterisation of a tidal energy site centres on gaining information on water velocity over a range of spatial and temporal scales suitably chosen to capture the key underlying fluid motions. These potentially include information varying across annual and seasonal time scales to fluctuations in velocity at timescales of seconds and below with different scales of motion understood to have a range of effects on energy extraction devices [1]–[3]. Challenges to the tidal sector effecting the cost of energy produced and exhibiting key reliance on access to good ocean data include:

- Understanding the effects of multiple scales of turbulence
- Understanding the drivers of turbulent characteristics
- Optimisation of TEC designs to minimise fatigue loadings and maximise power extraction
- Effect of combined waves and currents
- Effect of array layouts (and device design appropriate for these arrays) to maximise power extraction
- Access to measurement technology to enable site characterisation of the flow for both long term (period of years) variation in resource and very short term (period of less than seconds) turbulence
- Minimising downtime and Operation and Maintenance (O & M) costs

This article summarises an extensive field measurement campaign conducted at the Fall of Warness, Orkney, UK between 2012 and 2015 as part of the Energy Technology Institutes £13M Reliable Platform for Data Acquisition (ReDAPT) project. The project centred around a commercial scale (1MW) tidal turbine developed by Tidal Generation Ltd. deployed at the European Marine Energy Centre (EMEC) Tidal Test Site with the aim of producing a comprehensive suite of data on turbine operation and the flow field. Flow measurement campaign specification was driven by the requirements across the consortium.

The focus here is the methodology of data acquisition, handling and public distribution via (i) a permanent data archive holding end-of-project data and (ii) a new live database being constructed at University of Edinburgh [4] which will also incorporate data acquired during ongoing (e.g., EPSRC FloWTurb) and future offshore renewable energy projects. The authors wish to communicate the availability of this expensive-to-acquire data set and summarise the acquisition process to encourage correspondence, collaboration and accelerated use of the data by both the research community and the tidal energy industry. In addition readers are directed to the detailed information that can be found in multiple project technical reports [5]–[12].

The authors encourage collaboration on the further use and exploitation of the multiple subsea measurement instruments and associated peripherals (see Table II) that have been procured, designed, fabricated and utilised during both previous projects and ongoing work. Introductory information on the Edinburgh met-ocean equipment pool can be found herein and in the project technical reports listed above. For velocimetry techniques related to acoustic Doppler Profiling and their application in tidal energy techniques a brief introduction is provided in section II and for new convergent-beam Doppler Profiling (C-ADP) applications in particular detailed information on a full scale demonstration can be found in [13].

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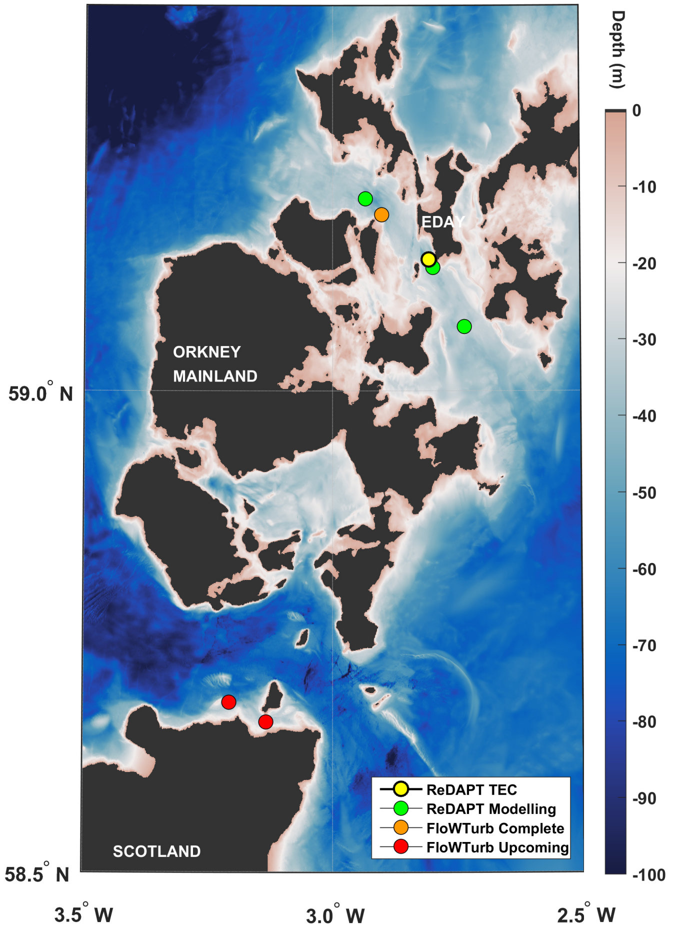

Fig. 1: Map showing the bathymetry of Orkney and the Pentland Firth and the locations of key measurement campaigns. Green markers show data originally acquired during ETI ReDAPT, orange and red markers show, respectively, completed and upcoming EPSRC FloWTurb campaigns.

A. *Reliable Data Acquisition Platform for Tidal (ReDAPT)*

The ReDAPT project was led by Alstom Ocean Energy (having been led initially by Rolls-Royce) and included the University of Edinburgh (UEDIN), DNV-GL Renewable Advisory, EDF Energy, E.ON, Tidal Generation Ltd., Plymouth Marine Laboratory (PML) and the European Marine Energy Centre (EMEC). ReDAPT (2010 to 2015) was created to provide information to the Tidal Industry to help facilitate rapid growth. The original goals were to: accelerate development of tidal energy industry; successfully deploy and operate a 1MW TEC at EMEC, delivering substantial learning to the acceleration of commercial product roll-out; provide data, insights and lessons learned as key reference materials for use by the industry, e.g. device performance; conduct environmental monitoring and resource assessment; assist industry certification standards and protocols; increase confidence in tidal turbine technologies; provide validation and industry acceptance of multiple tidal flow/machine models by combing turbine performance data with comprehensive flow data.

1) Project components: The project comprised multiple work-packages of which two are discussed herein, namely those relating to the TEC *machine*, **(MC)** and the numerical and analytical *modeling*, **(MD)** works underpinned by field measurements. The component parts of the MD programme designed to provide (i) improved environmental understanding and (ii) improved engineering tools are shown in Table I which relates tasks to the project technical reports (see Fig. 3). These reports are available for download at **redapt.eng.ed.ac.uk** (includes updated UEDIN versions) and **www.eti.co.uk** (archived).

Technical Report ID	Research Activtiy
MD2	Site-wide data collection (km scale)
MD5	Site-wide 3D hydrodynamic modelling
MD3	Near-field flow & turbulence characterisation
MD3	Integration of sensors with turbine
MD1	Supercomputer Computational Fluid Dynamics (CFD)
MD6	Desktop Engineering Tools (Tidal Bladed)

TABLE I: Subset of activities reliant on high quality field data.

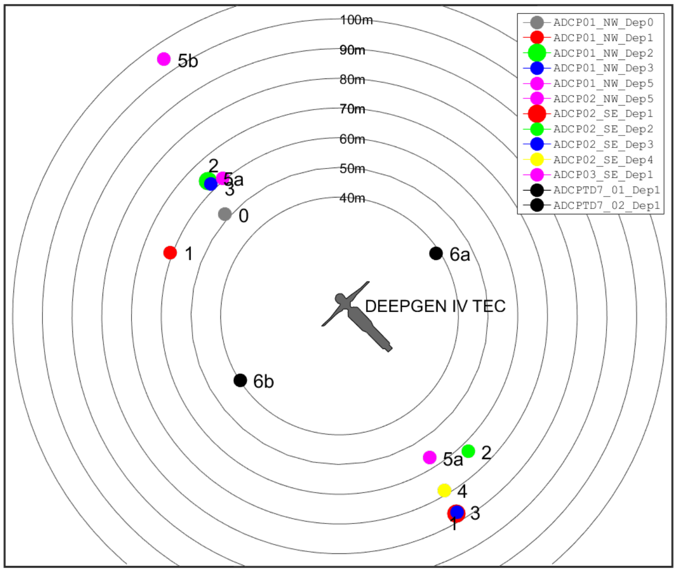

Fig. 2: Locations of completed seabed and TEC measurement campaigns. Range rings show instruments placed at ranges between 40m and 105m from TEC on bearings predominately in the tidal flow directions (with the exception of campaigns 6a and 6b).

2) Modelling activities driving field measurement campaign specification: Within the modelling work package numerical modelling work was undertaken by E.ON, DNV-GL and EDF. MD1 involved cutting-edge numerical simulation (conducted on EDF's IBM Blue Gene supercomputer) of the Alstom 1MW tidal turbine in turbulent flows [6]. The construction and validation of a model of the wider Fall of Warness, Orkney site [7], [14] was carried out under MD5 and incorporated both existing EMEC datasets and new UoE field measurements for model calibration and validation as part of MD2. MD6

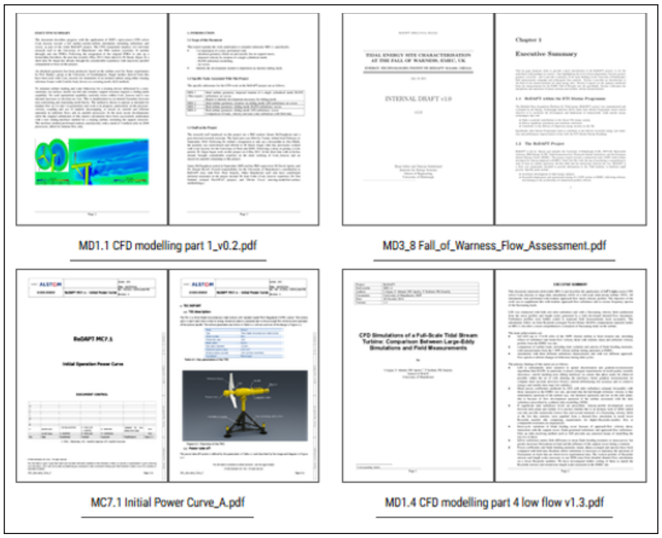

Fig. 3: Screenshot showing a selection of ReDAPT project technical reports accessible at redapt.eng.ed.ac.uk where field Data can also be downloaded (archived versions of the reports are available at www.eti.co.uk)

involves the validation - through comparison to field and machine data - of the DNV-GL RA Tidal Bladed software which seeks to capture environmental and turbine characteristics in a desktop application [8].

B. *Outline of Activities of Turbine Near-Field Flow and Wave Measurement*

The contracted description of work can be found below.

1) Procure, test and calibrate a flow velocimetry sensor system, including power, foundations, data logging and retrieval system.
2) Design and construct appropriate instrumentation flexible support structures.
3) Perform multiple measurement campaigns with the instruments, analysing the data and improving the turbulence characterisation.
4) Provide a final report including characterisation of the near field flow, a sensitivity analysis, assumptions and estimate of confidence.
5) Conduct data management activities to enable and provision publicly accessible and indefinite archival.

II. CAMPAIGN SPECIFICATIONS AND METHODOLOGY

A. *Acoustic Doppler Profiling*

Following a review of available technology the primary technique adopted for acquiring flow velocities from multiple locations was acoustic Doppler velocimetry using instruments and instrument-arrays of the classes: divergent, convergent and orientable single-beam, herein labelled respectively D-ADP, C-ADP and SB-ADP. Acoustic Doppler Profilers (ADP) have been successfully used to characterise the mean flow conditions and energy flux in several sites for TEC installations [15]–[19]. Conventional ADPs emit acoustic signals from a number of transducers installed on a single device. While a variety of beam configurations exist, in order to deduce a three-dimensional velocity measurement, these acoustic beams must be transmitted in at least three directions [20] which necessitates, for a single instrument, that beam directions are diverging. During ReDAPT multiple single beam 1MHz ADPs were procured operating on a newly available prototype communications and software platform that enabled instruments to be aligned in any direction (e.g., streamwise, transverse, vertical) whilst offering faster sample rates and accurate control of triggering. This flexible system of instruments offered new opportunities for flow characterisation and latterly wave measurement including the deployment of a prototpye converging Acoustic Doppler profiler.

For deployments outwith immediate proximity to the turbine stand i.e., ranges >approximately 200m (*far-field*), D-ADPs were installed using relatively lightweight frames (approximately 500kg dry weight) and comprising stainless steel square-section welded frames of pyramidal shape featuring stainless steel panelling and lead weights. For deployments in close proximity to the turbine (*near-field*) an existing Alstom concrete foundation was initially used, later augmented with three units to a UEDIN design and shown in Fig. 7.

B. *System integration and commissioning trial on the predecessor 500KW Tidal Energy Converter*

To gain experience on data acquisition and analysis trial deployments were agreed, planned and conducted on the existing Alstom 500kW DEEPGEN III. Five Nortek single-beam ADPs (SB-ADP) were installed to brackets welded in-situ at the top rear of the turbine orientated to capture velocities in the streamwise, transverse and vertical directions. A Nortek AWAC 1MHz D-ADP was installed to the top rear of the turbine orientated vertically (upwards) and a long range low frequency (192kHz) Nortek Continental SB-ADP was installed at the top rear of the turbine orientated backwards along the streamwise direction. Table II summarises the instruments used (across this and subsequent campaigns) and their electrical and communication protocol configurations. Since both the 500KW and 1MW machines can yaw to any angle turbine position and operational status is essential in order to ascertain orientation of sensors relative to flow.

Instrument	**Voltage (VDC)**	**Communications Protocol**	**Number of Units**
Nortek SB-ADP	24	TCP/IP Ethernet	17
Nortek AWAC	12	Serial RS422	1
Nortek Continental	18.5	Serial RS422	1
RDI Workhorse Sentinel	48	Battery/Remote	2

TABLE II: Selection of instruments used across the 500KW and 1MW TEC deployments

C. *System integration on the 1MW Tidal Energy Converter*

In 2012 UoE instrumentation systems were installed and commissioned on the 1MW machine. The instrumentation methodology involved two seabed mounted RDI Teledyne Workhorse Sentinel 600kHz D-ADPs deployed either side of the turbine along the primary flow direction to provide depth profiles and um-impeded inflow (and reference) velocities to the turbine. These deployments are shown in Fig. 2. On DEEPGEN IV three instrumentation mounting points were allocated: one on the top of the rear of the turbine nacelle - where the Edinburgh Subsea Instrumentation Platform 1 (ESIP-1) was installed, one on the rear of the turbine - where ESIP-2 was installed and a single sensor on the centre line of turbine rotating hub. ESIP-1 can be seen in Fig. 4. Fig. 7 shows typical seabed mounted D-ADP campaigns photographs taken from on-board the deployment vessel the KML Severn Sea.

Fig. 4: Photograph of ESIP-1 taken from scissor lift platform showing instrumentation mounted atop the 1MW TEC at Hatston Quay, Kirkwall, Orkney prior to turbine deployment.

D. Data acquisition

Turbine installed instrumentation was controlled in real-time remotely by the University of Edinburgh and the data saved to the local servers on the EMEC, Eday substation. This was routinely downloaded over the limited bandwidth from this location and backed up to UoE Engineering dept. servers. Proprietary data was converted to a format that could be read by Matlab from within which all processing was carried out. In most cases this data had to be converted manually, albeit in batches. Seabed installed instrumentation stored data to on board memory cards which was extracted following instrument recovery.

III. RESULTS

The environmental data acquired in parallel to seven turbine deployments exceeded 1TB of raw data in a wide range of formats. This has been processed into a quality controlled and homogenised form over the course of multiple projects. Post-processing included incorporation of long-term signals describing system parameters e.g., local met-mast data and synchronisation and QC of turbine data e.g., turbine average power and turbine heading - without which the measurements taken from ESIP-1 and ESIP-2 cannot be interpreted.

Seabed-Campaign ID	Deployed	Recovered	Days
`ADCP01_NW_Dep0`	2013-02-21	2013-03-17	24
`ADCP01_NW_Dep1`	2013-06-05	2013-07-17	42
`ADCP02_SE_Dep1`	2013-06-05	2013-07-17	42
`ADCP01_NW_Dep2`	2013-07-18	2013-08-02	15
`ADCP02_SE_Dep2`	2013-07-18	2013-08-02	15
`ADCP01_NW_Dep3`	2013-10-15	2013-11-26	42
`ADCP02_SE_Dep3`	2013-10-15	2013-11-24	40
`ADCP02_NW_Dep4`	FAILED	FAILED	N/A
`ADCP02_SE_Dep4`	2014-04-09	2014-06-06	58
`ADCP03_SE_Dep1`	2014-06-20	2014-08-05	46
`ADCP01_NW_Dep5`	2014-06-22	2014-08-02	41
`ADCP02_NW_Dep5`	2014-07-07	2014-08-16	40
`ADCPTD7_01_Dep1`	2014-09-17	2014-12-11	85
`ADCPTD7_02_Dep1`	2014-09-17	2014-11-27	71

TABLE III: Turbine-proximal deployments of D-ADPs showing unique campaign ID, date deployed and duration of deployment. Locations are shown in Fig. 2

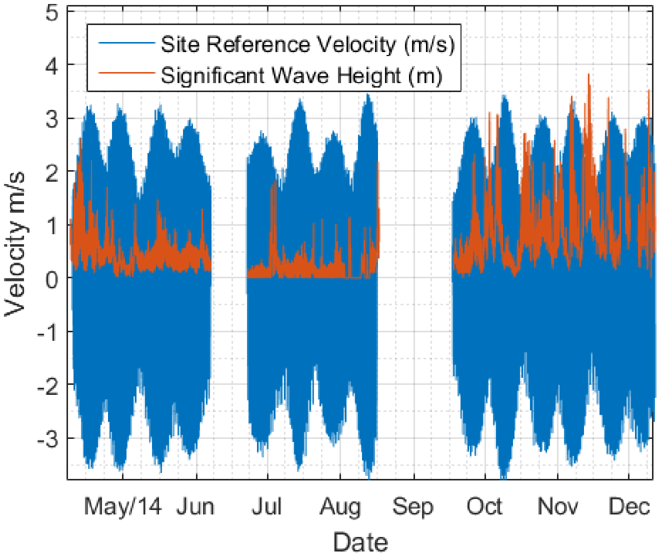

Fig. 5: Two data signals (of hundreds) from the UEDIN database covering 2014. Blue line shows reference velocity values and coverage, red line shows significant wave height.

A. Wave Measurement

Recent re-analysis during the FloWTurb project has allowed wave data to be incorporated into the main dataset (see Fig 5). This was achieved via an instrument calibration process involving deriving reliable wave elevation data from surface tracking from a vertically orientated turbine-installed SB-ADP as shown in Fig. 6. Acoustic backscatter shows a marked increase at the air-water interface. Using this reliable echo-location method to derive wave statistics allows less direct methods using velocity and pressure readings from surrounding sensors e.g., seabed mounted D-ADPs to be calibrated taking into account the target wave spectra and knowledge of prevailing currents (required for example in transforming pressure gauge measurements to surface wave spectra).

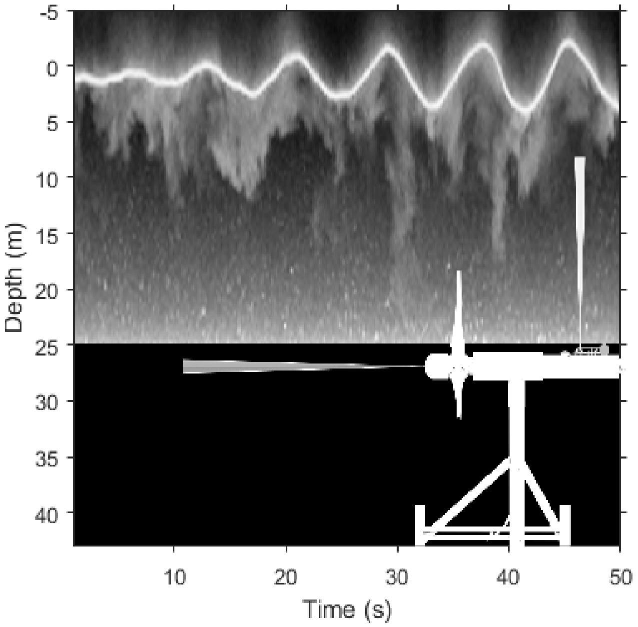

Fig. 6: Schematic showing the 1MW TEC and a turbine-installed vertically orientated SB-ADP to the same vertical scale as the resulting post-processed wave elevation time series recorded by the vertical sensor and shown as a white outline.

B. Flows in large waves

Reliable wave parametrisation enables searching and extraction of data by wave-current conditions. An example result of searching for data on a flood tide with significant wave heights exceeding 2.5m is shown in Fig. 8. Clear evidence of the wave velocities can be seen in this time series plot. The relationship across the entire data set is currently being investigated.

C. Flow features and spatial variation

Figure 9 shows depth profiles of streamwise velocity after binning by reference velocity for the two D-ADP deployments shown as ID 6a and 6b in Fig 2. This positioning corresponds to IEC/TS 62600-200:2013 *Type B* i.e., placed along the rotor plane of the turbine at a distance of 45m from the TEC. Large variation in flow regime (highlighted by the shaded regions) across this short distance (90m) is evident and is the subject of ongoing study. Additionally, the depth profiles exhibit a parabolic shape with slower flows at the surface. This feature has consequences on both resource characterisation and affects selection of numerical modelling tools.

Fig. 7: D-ADP featuring custom damped gimbals set, concrete gravity mooring and custom anodised aluminium battery canister being lowered by the crew of KML's Severn Sea vessel.

IV. DISCUSSION

Due to the volume of results and the scope of this article a selection of highlights from analysis are included. Multiple publications on individual research areas are in preparation and the authors welcome collaboration to expedite their release.

A. Deployment and Recovery Method

Positioning of the D-ADPs is important as clearly evidenced by the degree of spatial variation shown in Fig. 9. Positioning also plays a role in TEC power curve production. A power curve was produced using available advice from IEC/TS 62600-200:2013 and reported in [21]. An important lesson learned is that even with an experienced crew, capable vessel, ROV access and a large budget installing sensors to a stable bed position in the desired position to a tolerance of +/- 5m is challenging. Furthermore data acquisition must be synchronous with the turbines operation adding complexity and requiring extended periods of operation. Recent D-ADP technology improvements mitigate this however by offering larger as-standard data storage capacity.

To facilitate improved and more efficient deployment of seabed instrumentation an improved type of gravity mooring system is being developed by the author and trials of a full scale-model are scheduled to take place in Spring 2017 at the Flowave combined wave and current test tank.

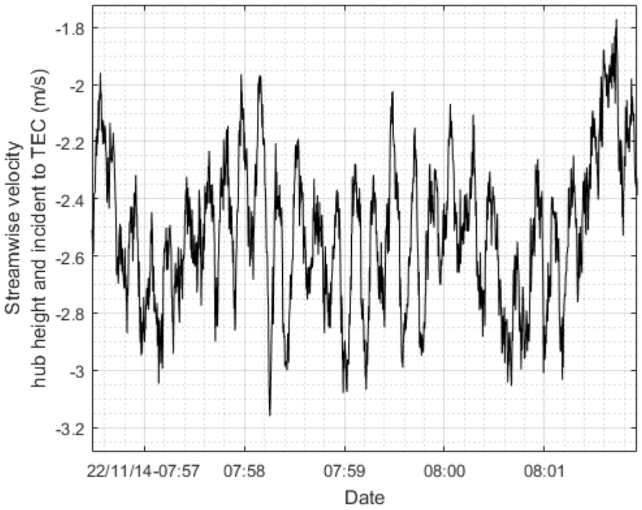

Fig. 8: Streamwise velocity during a flood tide with reference velocity of 2.7 m/s and significant wave height of 2.8m, turbine orientated to flow. Data recorded from SB-ADP sensor (at range approximately 10m) positioned on turbine rotating hub.

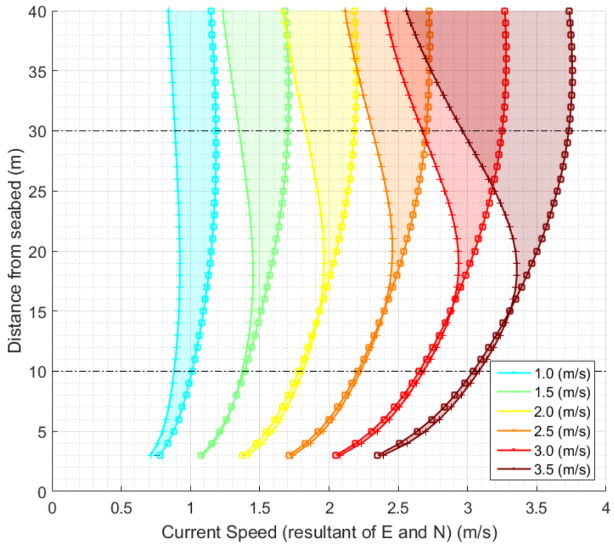

Fig. 9: Depth profiles of flow speed across two months of Ebb tides (binned by velocity against the site reference velocity). Square markers used to indicate D-ADP to south west (6b in Fig 2). D-ADP to north east (6a in Fig 2) marked by +.

B. Wave Measurement

An article specifically on wave measurement in the presence of strong currents for ORE applications is in preparation. The re-analysis of existing data focusing on waves and the development in parallel of a coupled wave-current model (which can be calibrated and validated using this analysis) provides new opportunities to extract information from the dataset. Wave-current interaction is a key area of ongoing study. Multiple methods to extract wave information have been developed with promising results from TEC installed pressure gauges, reliable 2D spectra from D-ADPs operating at sub-optimal sample rates (to allow extended current-measuring deployments) and acoustic surface tracking using vertically orientated beams. Gaining 3D directional spectra is the current focus of work (since wave direction relative to current determines the level of wave-current interaction) and is being developed in tandem with new numerical modelling tools.

C. Data Processing, Archival and Distribution

As part of these projects over 300GB of environmental data has recently been made publicly available by the authors. Data has been made available under two parallel activities: field data acquired to October 2014 is archived permanently at the UKERC Energy Data Centre (http://data.ukedc.rl.ac.uk) whilst the latest data and re-analyses are hosted locally (http://redapt.eng.ed.ac.uk) and via the University of Edinburgh's permanent digital archive (http://dx.doi.org/10.7488/ds/1687). Data from new field measurements around Orkney and the Pentland Firth will be added to the Edinburgh platform as they become available.

D. Single Beam Acoustic Doppler Profiling (SB-ADP)

The Nortek AD2CP platform upon which their supplied Mark I prototype 1MHz SBDs operate is a useful tool when integrating ADP instrumentation with a commercial scale tidal turbine. Robust remote access to the instruments over TCP/IP communications (internet) is easily achieved and is accurate timing control through the use of an external broadcast Precision Time Protocol (PTP) clock. Acoustically, useful instrument range was found at this site to be limited to approximately 17m. This was increased to approximately 20m through upgraded power supplies and grounding methods.

E. Diverging Beam Acoustic Doppler Profiling (D-ADP)

Two Teledyne RDI Workhorse Sentinel 600kHz were used during fifteen deployment campaigns. Data capture success was 93% (failure due to a suspected data storage card error). The author is developing a controller including increased data storage to enable improved remote operation at faster sampling rates. By deploying at either side of the turbine in a pair a long-term reliable reference velocity was provided, enabling all subsequent analysis of turbine-mounted measurements and the generation of turbine power curves. Multiple deployment campaigns featuring multiple instruments also reveals significant temporal and spatial variation at the site. The latest generation RDI D-ADP features five beams (allowing surface tracking), faster sampling rates and improved storage capacity but was not available at the time of project procurement. A newly released Nortek D-ADP instrument, the 500kHz Signature 500 also features five beams and is based on their AD2CP platform. The Signature 500 will be deployed alongside RDI five-beam and RDI four-beam Workhorse Sentinels as part of the FloWTurb campaigns.

F. Converging Beam Acoustic Doppler Profiling (C-ADP)

Large scale converging ADPs with significantly smaller measurement volume than diverging beam instruments offer new ways to measure flow and turbulence and a prototype system was successfully trialled in 2014. Comparison of C-ADP to standard divergent D-ADP velocity measurements is reported in [13].

G. Instrumentation Platforms

Two major instrumentation platforms were designed, deployed and successfully operated over three years which involved considerable design and fabrication work, TEC integration and O&M. Multiple lessons have been learned around this process from mechanical fixings to electrical grounding. The platforms survived prolonged deployments in the marine environment, performed well, were amenable to adaptation and were relatively simple to detach and re-attach from the turbine.

V. CONCLUSION

This article summarises the motivation for and the results of multiple measurement campaigns conducted as part of the five-year ReDAPT Tidal project. The requirement to meet the specifications of multiple numerical modelling activities was outlined along with the requirement to meet the demands of the tidal energy converter operators e.g., to provide data to the guidance outlined in IEC/TS 62600-200:2013 for performance assessment. Meeting these varied and sometimes conflicting needs, for example supplying long term deployments but with maximum sampling rates to capture turbulence, required many deployments utilising a suite of instrumentation. This instrumentation repository has been outlined and the authors invite suggestions for collaborative works.

The availability of archived field data for use by the research community and tidal industry has been highlighted as has a new database where upgraded existing data and data from live projects will be made available. In terms of results, wave-current interaction has been highlighted as an area of ongoing research with the levels of velocity variation shown to be significant throughout the water column, even in a relatively sheltered location. Spatial variation has been shown to be an important consideration for resource characterisation.

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