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Advanced monitoring, simulation and control of tidal devices in unsteady, highly turbulent realistic tide environments

REALTIDE
LOADS FLOWS IMPACT

Grant Agreement number: 727689

Project Acronym: RealTide

Project Title: Advanced monitoring, simulation and control of tidal devices in unsteady, highly turbulent realistic tide environments

WP2 Realistic Tidal Environment

Deliverable 2.1

Deployment and Instrument Specification for Advanced Flow Characterisation

WP Leader: The University of Edinburgh

Authors: Chris Old (UEDIN), Mairi Dorward (UEDIN), Brian Sellar (UEDIN), Erwann Nicolas (Sabella), Julie Marcille (Sabella), Jan Erik Hanssen (1-Tech)

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Abstract: This report forms Deliverable 2.1 and details the work of Task 2.1 within WP2 of RealTide. Following the production of an internal deliverable (D1.5) which captured the consortium's environmental data requirements, a test specification for a targeted high-resolution field deployment has been produced. A generic approach has been developed, which is subsequently applied specifically in relation to the measurement campaign of the Sabella D10 tidal turbine planned within the RealTide project. This includes the required instrument deployment duration, spatio-temporal resolution and instrument configuration along with system installation and recovery methods where appropriate. Marine operations will be coordinated by Sabella using local marine service providers. D2.1 details the use of existing and new sensors on and around the operating Sabella D10 turbine in the Fromveur passage, France. Advanced turbulence measurement sub-systems are proposed and outlined. This report provides a targeted measurement campaign specification, an outline of sensor systems and sub-systems required to achieve this and a data analysis plan to enable subsequent physical and numerical modelling activities in the RealTide programme.

Objective: Deliverable 2.1 captures and disseminates the outputs of work tasks that have produced a measurement campaign plan for the efficient acquisition, parameterisation and exploitation of environmental condition datasets at an energetic tidal test site.

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Abbreviations & Definitions

ADCP	Acoustic Doppler Current Profiler
ADP	Acoustic Doppler Profiler
ADV	Acoustic Doppler Velocimeter
AWAC	Acoustic Wave And Current profiler
BEMT	Blade Element Momentum Theory
BV	Bureau Veritas
BV M&O	Bureau Veritas Marine & Offshore
C-ADP	Convergent-beam acoustic Doppler profiler
CFD	Computational Fluid Dynamics
D	Deliverable
D-ADP	Divergent-beam acoustic Doppler profiler (typically referred to as ADCP)
DAQ	Data Acquisition
Delrin	DuPont™ Delrin® acetal homopolymer resin
EMEC	European Marine Energy Centre
FloWave	FloWave ocean energy research facility, University of Edinburgh.
FloWTurb	Flows, Waves and Turbulence
GA	Grant Agreement
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HO	HydrOcean
IEC	International Electrotechnical Commission
IFREMER	Institut français de recherche pour l'exploitation de la mer
IP	Intellectual Property
Lat	Latitude
LCOE	Levelised Cost Of Electricity
Lon	Longitude
MONITOR	Multi-model investigation of tidal energy converter reliability
MRE	Marine Renewable Energy
MW	Mega-Watt
NTP	Network Time Protocol
PTO	Power Take Off
PTP	Precision Time Protocol
PM	Project Month
QA	Quality Assurance
QC	Quality Control
RAID	Redundant Array of Independent Disks
ReDAPT	Reliable Data Acquisition Platform for Tidal
ROV	Remotely Operated Vehicle
RS232	Recommended Standard 232 communication protocol
RS422	Recommended Standard 422 communication protocol
RS485	Recommended Standard 485 communication protocol
SAB	Sabella
SB-ADP	Single-Beam acoustic Doppler profiler
SCADA	Supervisory Control and Data Acquisition
SEM	Synthetic Eddy Method
SHOM	Le service Hydrographique et Océanographique de la Marine
SR	Sample Rate
SpG	Spectral Generation Method

TCP/IP	Transmission Control Protocol/Internet Protocol
TEC	Tidal Energy Converter
TI	Turbulence Intensity
TiME	Turbulence in the Marine Environment
TKE	Turbulent Kinetic Energy
TSR	Tip Speed Ratio
UEDIN	The University of Edinburgh
UPS	Uninterruptable Power Supply
URL	Uniform Resource Locator (web address)
UTC	Coordinated Universal Time (Temps Universel Coordonné)
WGS84	World Geodetic System 1984
WP	Work Package

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Distribution List

This Document is a RealTide Public Document and is classified as a Public Report.

EXECUTIVE SUMMARY

Deployment and Instrument Specification for Advanced Flow Characterisation

This deliverable and technical report lists key considerations in measuring environmental conditions (waves, currents and turbulence) near operating tidal energy converters (TECs) and proposes an outline methodology to capture realistic conditions for onward use in various physical and numerical simulation activities. These activities comprise blade-resolved computational fluid dynamics (CFD), numerical simulation via Blade Element Momentum Theory, tank-testing in combined wave-current conditions, fatigue studies for composite materials and reliability modelling.

A generic approach has been developed, which is subsequently applied specifically in relation to the measurement campaign planned within the RealTide project at the Sabella D10 tidal turbine.

This report was produced to capture the experiences and requirements of the RealTide consortia and other organisations from work conducted on previous and ongoing projects, including the RealTide programme itself. It is the intention that this report provides useful guidance for those stakeholders operating in the field of tidal energy who are planning field measurement campaigns.

This report includes:

- The motivations behind tidal energy site measurement campaign.
- The flow conditions including waves, currents and turbulence that a campaign seeks to capture and key drivers of these conditions.
- A selected list of off-the-shelf sensors from candidate technologies and recommendations for their configuration and placement.
- Outlines of engineering design and interfacing of a seabed-mounted sensor based on actuated convergent-beam acoustic Doppler profiling, for capturing three-dimensional turbulence measurements at multiple positions upstream from the TEC rotor plane.

1. INTRODUCTION

This report forms Deliverable 2.1 of the RealTide project and details the work of Task 2.1 within Work Package 2. The purpose of Task 2.1 is to capture measurement requirements of the consortium and to design a field campaign around these requirements. This campaign will be targeted and commence in Q2 2019 at the Fromveur Strait, France.

Acquired datasets will provide input to characterisation of environmental conditions required for various physical and numerical simulation activities. This modelling includes tank-testing of generic and proprietary instrumented scale Tidal Energy Converter (TEC) models at the FloWave, UK and IFREMER, France test-tanks, and Computational Fluid Dynamics (CFD) and Blade Element Momentum Theory (BEMT) numerical simulation. The specification builds on community knowledge by incorporating the methods and techniques developed in previous projects including ReDAPT[1], FloWTurb[2] and TiME[3].

1.1 Scope

This report outlines a measurement campaign that meets the overall requirements of the RealTide physical and numerical modelling activities and additionally, the requirements of the turbine developer for a more accurate environmental characterization in order to adapt the design of keys components for improved reliability and operation of their tidal turbines. It is also more widely relevant for tidal turbine developers and the research community focusing on physical resource measurement including waves, currents and turbulence. This report provides:

- Information on sensor selection, configuration, interfacing with and placement on and around an operating tidal turbine.
- Information relevant to external stakeholders in this sector by describing generic issues to be considered when developing and implementing a measurement campaign.
- Background information on the motivation for the measurement of specific parameters with reference to the physical processes driving the flow field and the engineering tools that rely on measurements as their inputs. Where supporting information or a greater level of detail is available in existing literature these are highlighted.

This report does not cover:

- Environmental impact assessment nor tidal turbine wake measurement.
- Detailed engineering design of the C-ADP: design work is ongoing and is subject to design review and change by commercial marine service companies who will carry out deployment and recovery operations. Detailed design work will be reported fully in subsequent publicly available conferences and journal papers, subject to any constraints imposed by intellectual property rights.
- Data analysis, post processing routines and data management: this will be covered in a subsequent report D2.2.
- Data integration with a regional model: this will be covered in D2.2 where a coupled wave-current model will be specified, validated, and used to extend and interpret the *in situ* data.

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[1] ReDAPT - https://redapt.eng.ed.ac.uk
[2] FloWTurb - https://www.flowturb.eng.ed.ac.uk/home
[3] TiME - https://www.partrac.com/turbulence-in-marine-environments-new-guidance-released/

1.2 Background

Task 2.1 of the RealTide project develops the specification and plan required to carry out targeted field measurements (conducted in Task 2.2), incorporating methods developed in previous projects[2],[3],[4],[5]. The measurement plan needs to consider the relationships between site characterisation[2],[4],[6], data collection strategies[3],[4],[6],[7], application to engineering tools[6],[8],[9] (*e.g.*, physical and numerical modelling), and how this process can be integrated to generate reliable outputs which can be utilised by developers.

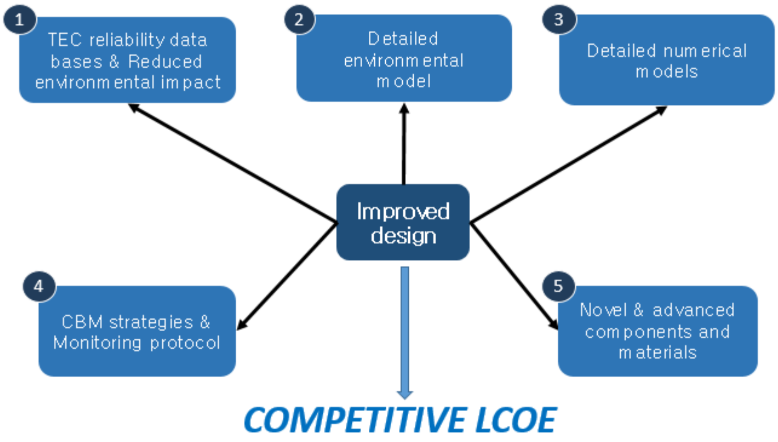

Figure 1: Overview of the RealTide Work Packages

Data acquisition, data characterisation and data management forms the core of RealTide Work Package 2 (WP2). For context, the other WPs, which exploit these datasets, are shown in Figure 1. Table 1 summarises projects and activities related to, and which have input into, RealTide WP2.

Table 1. Related projects, activities and outcomes related to D2.1 and their input to WP2

Title: Reliable Data Acquisition Platform for Tidal energy (ReDAPT) **Objective:** To develop a comprehensive suite of flow field and turbine operation data to advance characterisation of the fluid/machine interaction. **Funder**: Energy Technologies Institute, UK **Completion Date:** Dec 2015 **URL:** www.redapt.eng.ed.ac.uk | www.eti.co.uk/programmes/marine/redapt	
Project Outcome	**Input to RealTide WP2**
• Information on wave measurement techniques at tidal energy sites including pressure gauges and acoustic surface tracking (AST). • Enhanced deployment and retrieval methodologies for seabed equipment specifically ROV assisted deployments for improved sensor location and orientation information. • Sensor-supporting peripherals including communications and power sub-systems. • Information on wave-current interaction related to turbulence characterization. • Development of a prototype convergent-beam acoustic Doppler profiler (C-ADP) • Dataset of environmental conditions closely coupled to the operation of a 1MW TEC. • Information on component resilience	• Equipment and sensors can be reused and/or repurposed. • Cables and connector selection: *e.g.*, larger connectors used and number of connectors minimised. • Produces key specifications on: Time Synchronisation, Turbine Status Information, *etc.* • The C-ADP prototype will be developed with major modifications to configuration required to enable seabed operation. • Waves must be measured and logged. • A hydrodynamic model featuring coupled waves-currents is required to be run in parallel to *in situ* measurements. • Multiple data processing lessons learned to be incorporated in D2.2

Title: Response of Tidal Energy Converters to Combined Tidal Flow, Waves, and Turbulence (FloWTurb)
Objective: Investigate the combined effect of tidal currents, gravity waves, and ambient flow turbulence on the dynamic response of tidal energy converters.
Funder: Engineering and Physical Sciences Research Council, UK **Completion Date:** Oct 2019
URL: www.flowturb.eng.ed.ac.uk

Project Outcome	Input to RealTide WP2
• Information on wave-current interaction and its impact on TEC loading and performance (at scale in physical simulation) • Physical simulation tools to recreate wave-current conditions in a combined wave-current tank. • Production of regional scale wave-current coupled models at tidal energy sites	• Further evidence of requirement for dedicated coupled wave-current hydrodynamic model • Model should be open source and deployed on suitable IT infrastructure. • Model requires significant staff-time in data assimilation, model build, calibration & validation • Test-tank data on flows, waves and TEC response. • Site data (some with usage constraints due to IPR)

Title: Turbulence in the Marine Environment (TiME)
Objective: Evaluation of novel methods and technologies for measuring turbulence in challenging tidal environments (Sound of Islay; Inner Sound, Pentland Firth)
Funder: Marine Renewables Commercialisation Fund, Scottish Government, UK (75%)
Completion Date: Oct 2015
URL: www.partrac.com

Project Outcome	Input to RealTide WP2
• New methods developed and tested to measure and characterise turbulence. • New insight into the impact of underlying turbulence on TEC array layout decisions.	• Multi-site data (pending) • Confirms value in using latest generation of off the shelf ADCPs (D-ADP) • Turbulence characterisation useful inputs to D2.2

Title: IEC Guidance Documents
URL: https://www.iec.ch

Industrial Guidance*	Input to RealTide WP2
IEC/TS 62600-200:2013 Electricity producing tidal energy converters. Power performance assessment. • Systematic methodology for evaluating the power performance of tidal current energy converters that produce electricity for utility scale and localised grids **IEC/TS 62600-201:2015** Marine energy-Wave, tidal and other water current converters. Tidal energy resource assessment and characterization • System for analyzing and reporting, through estimation or direct measurement, the theoretical tidal current energy resource in oceanic area...that may be suitable for the installation of arrays of TECs **IEC/TS 62600-2:2016** Marine energy-Wave, tidal and other water current converters • Provide primary design criteria to ensure engineering integrity throughout the defined design life of marine energy converters such as wave and tidal.	The RealTide measurement campaign recognises this guidance and seeks to implement solutions that are aligned. They reinforce the need to find practical, rationalised, cost-efficient and reliable measurement methods that can be used in future projects. **IEC/TS 62600-200:2013** Defines the placement and configuration of RealTide ADCP placement and operational control points of the TEC. **IEC/TS 62600-201:2015** RealTide adopts a staged approach to calculation of resource assessment with varied levels of complexity. Guidance helps define the requirements of regional models and requisite *in situ* calibration and validation measurements. **IEC/TS 62600-2:2016** Inputs to model requirements and *in situ* sensor configurations specifically around capturing site-specific conditions to predict environmental loads which impact safety factors, present external load cases (extreme, normal) and impact failure probabilities.

* Consideration of wave-current interaction and turbulence is recognised within IEC/TS 62600-200:2013 and IEC/TS 62600-201:2015 as an area of active research. IEC/TS 62600-2:2016 requires consideration of turbulence and wave-current interaction in engineering design with sufficient safety factors to ensure a sufficiently conservative design.

2. SITE CHARACTERISATION

Characterisation of a tidal site - informing resource assessment, site selection, turbine design, turbine siting and subsequent operations and maintenance activity – is a key element in the development of any site. Information sources for site characterisation include *in situ* measurements, remotely sensed data, output from numerical models, local knowledge, historical records, *etc.* At the most basic level site characterisation includes the available resource, the local topography, the local wave environment, and site accessibility. Characterisation will come from a mixture of observations and regional model output. These two data sources are complimentary: the data collected provide detailed localised observations of the real environment that can be used to calibrate and validate regional numerical models; the flow structures identified by the regional models can be used to inform the optimal siting for instrument deployments to aid in site characterisation.

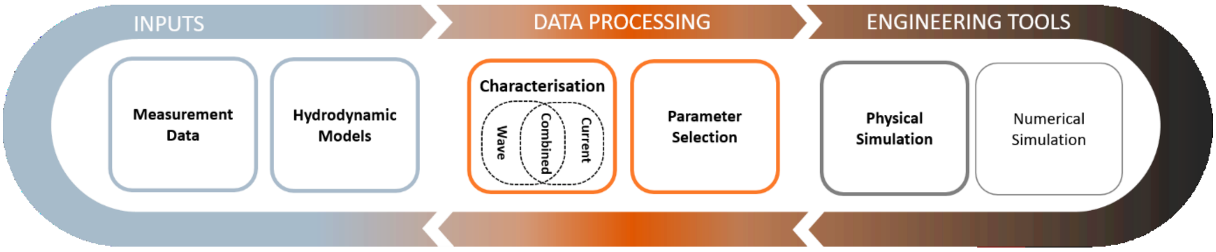

Figure 2. The role of resource data in the development of tidal energy (from [4])

To support site and turbine developers, the *in situ* observations and model constructs need to be integrated with information collected from operating turbines to allow the attribution of turbine response to the observed system state[2],[3]. This is an iterative process based on feedback between the processes and users of the data as shown in Figure 2. The *in situ* measurements and regional modelling need to capture a range of processes on various spatial and temporal time scales[2],[4],[7], with some of the key processes shown in Figure 3. The characterisation data generated are converted to parameters that are used in engineering design tools[2],[5],[8],[9]. Figure 4 illustrates the input of these parameters into fluid-structure and electro-mechanical sub-system modelling. Findings from engineering development will identify new parameters that are required. Complementary to this, new marine measurement techniques will capture new parameters allowing different modelling methods to be used for design.

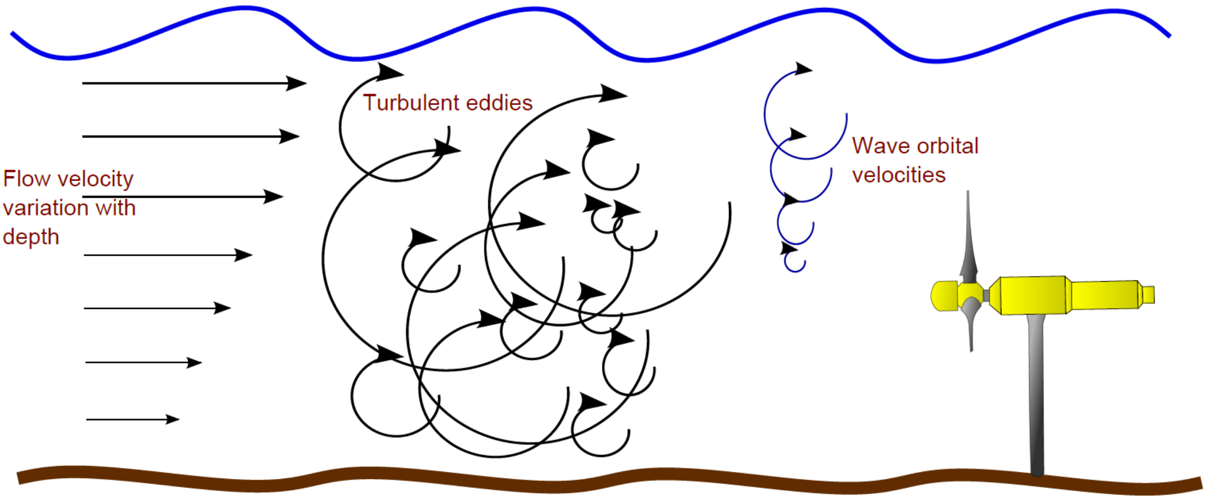

Figure 3: The unsteady characteristics of incident flow on a tidal turbine

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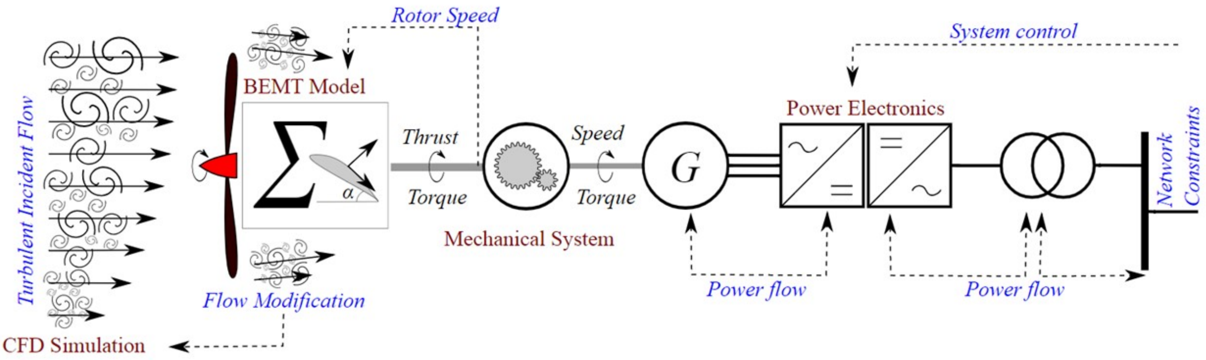

Figure 4. RealTide Tide-to-wire model: overview schematic

In the following section, elements of site characterisation are reviewed, namely hydrodynamics, meteorology and morphology, plus key parameters derived from site characterisation. In each subsection, the effects / consequences of the feature discussed are reviewed and key consequences on the measurement campaign highlighted in an associated box.

2.1 Hydrodynamics

2.1.1 Tidal Resource

The energy being extracted comes from the kinetic energy of the fluid that is generated by the varying gravitational potential associated with the Earth-Moon-Sun system[10],[11],[12]. The locally available kinetic energy is dependent on the distortion of the gravitational tide by the physical topography of the Earth surface. TECs are deployed at locations where the tidal flow is accelerated above the norm by processes such as flow constriction through a channel or strait, and the curvature of the flow as it passes around a headland. Processes and physical constraints that produce an increased head pressure will lead to flow acceleration[13].

There are two components to the tidal process that need to be recorded: 1) the surface elevation as a function of space and time[10], and 2) the resulting 3-dimensional velocity field as a function of space and time[10]. In general there will be a local ebb/flood asymmetry in the magnitude of tidal flows due to the irregular shape of tidal channels and local tidal resonance effects.

The energy available for extraction is defined by the tidal flow generated at a given site. A key feature of tidal flow is that it is non-stationary, *i.e.* it is always changing because of the time varying gravitational forcing. The available energy is cyclic. The tidal flow varies with height above the seabed due to the presence of the solid boundary[10],[11],[13]. The form of the vertical profile depends on the boundary material and roughness, and on any locally generated flow structures in the tidal flow.

CONSEQUENCE TO MEASUREMENT CAMPAIGN

The magnitude of the available tidal resource is fundamental to any MRE development work. The *in situ* measurements need to:

1. Capture intra-tidal to seasonal variability in flow for energy density estimates.
2. Capture spatial variations in flow speed for machine siting.
3. Capture flood/ebb flow asymmetry for optimal machine alignment.

2.1.2 Large-scale Flow Structures

The shape of the tidal channel and the underlying bathymetric structures will generate local large-scale flow structures[5],[10] that will vary spatially over a tidal cycle. Examples of these structures are island wakes and headland eddies. Bathymetric structures (dykes, sills, channels, *etc.*) on the seabed will generate local vertical flow instabilities through the separation of vortex structures[5] from the seabed once the flow speeds are sufficient for the boundary layers to delaminate (typically > 1 m/s). If the TEC is located within the area of effect of the flow separation from these bathymetric features then the velocity profile structures will be more complex leading to different loadings and available energy during a tidal cycle compared to an area of “clean” flow.

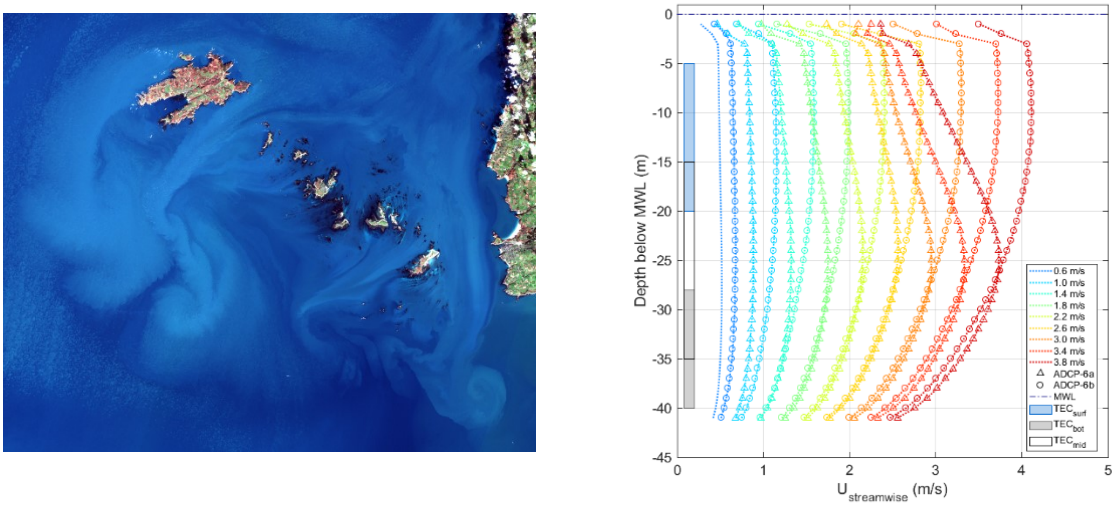

Figure 5. (a) Satellite imagery of large scale flow structures in and around a tidal channel. (b) The impact of flow structures on velocity depth profiles (ReDAPT dataset, Orkney, UK)

The horizontal eddy structures associated with island wakes and headlands can often be identified in satellite imagery (optical and SAR). Figure 5a is a Sentinel 2 image of the Iroise Sea during an ebb tide; the phytoplankton bloom highlights the large-scale eddies formed by flow separation caused by the channels and islands. The horizontal scale of eddies range from tens of metres to kilometres. The impact of these large-scale structures can be seen in the form of the depth profile of flow over a tidal cycle (Figure 5b) where two sensors 90 metres apart exhibit strongly varying forms. To fully resolve the spatial scales and associated flow of these structures from *in situ* measurement requires a large array of fixed instruments, and/or a dedicated vessel-based survey[2],[4]. A well-tuned and validated regional model provides a more cost-effective way of quantifying these features and assessing their impact on the tidal flow.

CONSEQUENCE TO MEASUREMENT CAMPAIGN

Large-scale structures are difficult to capture with in situ measurements; validated regional models are required to better resolve flow separation processes. The in-situ measurements need to provide:

1. Surface elevation data at multiple locations across the site for one or more neap-spring tidal cycles.
2. Velocity profile data at multiple locations to capture significant large-scale structures for one or more tidal cycles.
3. Sufficient data for regional model tuning and validation.

2.1.3 Turbulence

Fast flows are inherently turbulent[14]. Turbulence is generated by shear instabilities both at the physical boundaries and in the interior of the fluid. Turbulence is random in nature and can be related to 3-dimensional vorticity (eddy) structures. The length scales of these structures can be as large as the dimension of the tidal channel. Frictional dissipation processes transfer energy from large scale eddies down to smaller scale eddies until the energy is eventually dissipated as heat at molecular scales. The intensity, spatial scale and spatio-temporal coherence of the turbulence has a significant impact on structure loading and component fatigue.

The turbulence is inherently part of the velocity field, so its measure is embedded within the velocity data[4]. Turbulence is generally described statistically. The turbulence will have a defined set of dominant length scales (associated with the energy containing eddies) that depend on the state of the velocity field[14]. The mean energy associated with the turbulence can be represented as a turbulence intensity (TI), a parameter commonly used in TEC design work[3],[8],[9].

Associated with turbulence are the issues of homogeneity, isotropy, and coherency[14]. The first two affect how the turbulence data are used and interpreted, and the third gives some indication of intermittency or gustiness of the larger scale structures. The coherency is related to up-stream turbulent instabilities which grow and burst[5], and are typically generated from bathymetric structures. An understanding of the generating processes will inform the optimal siting for TECs.

CONSEQUENCE TO MEASUREMENT CAMPAIGN

No single off-the-shelf instrument can provide all the turbulence metrics of interest for TECs. A mixed sensor approach and new designs are needed.

1. Coherence – contemporaneous 3D measurement at two or more points.
2. Further terms in the Reynold's Stress Tensor can be derived via D-ADP with 5+ beams.
3. Rotor plane stream-wise inflow – TEC installed sensors or C-ADP.
4. Large scale gusts – need to identify physical drivers and recurrence periods.
5. Length scales are required.
6. Anisotropy levels are required.

2.1.4 Wave Environment

Ocean surface gravity waves are generated by frictional wind stress at the water-air interface[15],[16]. Most TEC sites will be affected by local wind generated waves that have a limited fetch, and some also by open-ocean swell that is generated remotely by storms with a basin scale fetch. The local wave field will be complex, will be affected by the local topography (diffraction, refraction, reflection) and bathymetry (wave-braking), and will interact non-linearly with the local velocity field[16]. Surface gravity waves transport energy horizontally and have an influence on the vertical flow that decreases with depth and is dependent on the amplitude and wavelength of the waves.

The wave environment is represented by either a 1-D spectra of wave height as a function of period (or frequency), or a 2-D spectra of wave height as a function of period (or frequency) and direction[15],[16]. Waves introduce an additional loading on structures as they transport energy. The fluid motion associated with waves is orbital with length scales similar to the turbulent structures. Therefore these processes need to be separated in order to correctly attribute energy to the various physical processes.

The depth of penetration of wave energy is related to the wavelength of the wave. In general it is assumed that significant wave effects on flow characteristics will be observed up to depths equal to half the wavelength[16],[17]. Therefore the location of the site (*i.e.* open to the ocean swell, channel constrictions, *etc.*), the total water depth at the site (*i.e.* is it "deep" relative to the longest wavelengths), and the depth of the turbine (distance of rotor plane from water surface) will determine the level of impact waves have on a turbine.

Extreme events (50yr to 100yr repeats) have an impact on the survivability and operation of TECs. Some method for representing extremes and determining their impact is required. It is not possible to plan a measurement campaign that captures extreme events. To fully investigate the impact of extreme wave events, a well-tuned and fully-validated regional scale wave model is required[9]. This model would need to be driven with wave boundary conditions taken from a larger (*i.e.* basin scale) wave model that is fully coupled with an atmosphere model to obtain a realistic representation of remotely generated storm swell and local wind generated waves[16].

CONSEQUENCE TO MEASUREMENT CAMPAIGN

Wave data need to capture a statistically significant set of events across a range of tide states to characterise the wave environment. The wave data need to:

(1) Capture a representative set of wave events for site characterisation – multiple local storm events, remote storm generated swell *etc*.
(2) Provide data sufficient for validation of a regional wave-only model – wave spectra, multiple locations, wave-only conditions (*i.e.* range of slack water measurements).
(3) Provide wave data to drive open boundaries of a regional wave-only model.
(4) Measure wave effects at the depth of the turbine rotor plane – instrument sensitivity to depth will limit resolution.

2.1.5 Combined Wave-Current Environment

There is significant interaction between waves and currents[16] which has a measurable impact on both the fluid environment and on the loading of TEC systems[2],[9]. An important factor is that the presence of waves can lead to errors in estimates of turbulent parameters, for example leading to over estimation of the TI [2]. There is a 2-way feedback between waves and currents; the presence of tidal flow will alter the steepness, frequency and direction of surface waves, and surface waves will alter the strength and direction of tidal flow with depth.

Methods are being developed to separate the wave and turbulence signals from *in situ* data, but the observations used are limited to point measurements across a given region. To develop a better understanding of the interacting wave-current environment, a well-tuned and fully-validated coupled wave-current regional model is required[2],[9]. The data collected need to represent a range of wave-current states to support model validation. A coupled wave-current model can be used to interpret *in situ* measurements and for predicting the impact of extreme waves on the local tidal flow, TEC structural loads, and TEC power production.

CONSEQUENCE TO MEASUREMENT CAMPAIGN

Wave and current data collected need to allow the identification and quantification of wave-current interactions. The following need to be considered:

1. Choice and location of wave measurement systems – depth-dependent sensitivity of wave recording devices.
2. Relative location of wave and tidal flow measuring devices – ideally co-located.
3. Data cover a range of states – *e.g.* current only, wave-current (with flow, opposing flow, *etc.*), wave-only conditions.
4. Data are sufficient to allow validation of coupled wave-current model – *i.e.* multiple states, multiple locations across the site, TEC rotor plane data, *etc.*

2.2 Seabed Shape and Composition

2.2.1 Bathymetry

The bathymetric structure affects the local tidal flow structure and symmetry[2],[9],[10]. The shape and size of surface features affects the vertical velocity profile and the generation of larger scale turbulent structures. The siting of TECs will depend on how level the seabed is and on the horizontal and vertical scales of variation (*e.g.* dykes, sills, mounds, hollows, *etc.*)[6]. These spatial scales will also affect where and how instruments deployed in bedframes should be located[7]. To inform both developers and modelers, the bathymetry needs to be available at a high resolution in the area of interest. Ideally at a spatial resolution of 10m or better[9],[18].

CONSEQUENCE TO MEASUREMENT CAMPAIGN

Consideration of the following is required:

1. Impact of bathymetry on installation location of seabed frame.
2. Sources of bathymetric data - requirement for ROV study, local knowledge, high-resolution multi-beam survey, open data sources.
3. Location of significant bathymetric features – sills, dykes, outcrops, *etc.* which affect instrument positioning, vibration and sensor performance *e.g.*, highly-sheared flow.
4. Flow up- and down-stream of features – a regional model should resolve these.

2.2.2 Seabed Composition

Seabed composition defines the surface roughness metric and the corresponding boundary friction[10],[11],[13],[14]. Typically in high-flow tidal channels there will be very little sediment, and the bed is a mixture of bed rock, boulders, large gravel, or shells and other marine debris. The seabed composition may vary spatially over a given site; this will lead to the vertical flow structure varying spatially across the site through changes in bed friction[2]. The seabed composition has an impact on both the spatial structure of the tidal flow and the siting of TECs and data collection instruments. Spatial variation in the seabed composition is used to define the bed friction in a regional model[16],[18], a required boundary condition. The bed friction also allows the near-bed tidal flow boundary layer to be parameterised and the expected vertical structure of the velocity profile defined.

CONSEQUENCE TO MEASUREMENT CAMPAIGN

Consideration of the following is required:

(1) Source of composition data – ROV survey, site measurements, open data sources.
(2) How to determine bed friction – velocimeters mounted in bed frames do not measure the boundary layer, this would require ADV or low-profile D-ADP.
(3) Impact on location of instruments in bedframes – levelling, stability, sinking over time, acoustic interference by material entrainment, *etc*.
(4) Definition of boundary-layer structure - required for high end CFD.

2.3 Meteorology

2.3.1 Wind Field

Local wind drives surface currents and generates waves[12],[16]. This will have a varying impact on flow characteristics depending on the fetch length (the length of water over which the wind as blown) and the relative direction of the wind to the tidal flow. Local wind is constrained by the surrounding land forms and depending on the height of surrounding hills and mountains there may be locally generated (*e.g.* katabatic) winds[19]. The wind data are used to resolve the local wave field (*e.g.* spatial gradients, temporal variability, gustiness), as input to regional models (surface stress on free water surface), and to identify wind generated events in a time series of measurements. As with waves, some method for capturing extreme events is required.

When working with wind data it is important to know the height at which the measurement was taken and which convention for wind direction has been used if the data are provided as wind speed and direction. The standard conventions used in meteorology are to provide wind speeds at 10m above the surface[12],[19],[20], and to define the direction as that from which the wind blowing[19],[20]. The height chosen minimises boundary layer effects when calculating surface wind stress. The wind direction convention is historical, and is in contrast to the method used to define oceanographic velocity data, *i.e.* the direction the current is flowing to[7],[11]. There are also two coordinate systems used to define the both wind and flow vectors: (1) navigational coordinates where directions are measured in degrees east of north, or (2) mathematical coordinates where directions are measured anti-clockwise from the x-axis of a right-handed orthogonal coordinate system[7].

CONSEQUENCE TO MEASUREMENT CAMPAIGN

Consideration of the following is required:

(1) Siting of meteorological instruments – multiple locations, measurement height, *etc*.
(2) Data must resolve local wind field – spatial scales across site.
(3) Data should provide realistic estimates of surface wind-stress across the site.
(4) Data should support event attribution in synchronous data sets – *e.g.* attributing gusts in tidal flow to local wind, wave, or turbulent processes.

2.3.2 Atmospheric Surface Pressure

The surface pressure field is a driver for numerical models[18]. Their relevance to TEC development is limited to the impact of deep depressions, which can raise the water height (by effectively opposing local gravity) thereby changing the fluid forces. As a rule of thumb, a decrease in air pressure of 1 hPa raises the water level by 1 cm[12],[19]. Only the extreme events, such as storm surges associated with deep depressions, would have a significant impact on turbine loads. However the local variation in pressure field will indicate the passage of frontal systems across a site, this information can be used in the interpretation and attribution of observed events[19]. There will be a low-frequency atmospheric pressure signal in any pressure sensor data collected within the marine environment[7]. This needs to be accounted for when post-processing these data before extracting required parameters.

CONSEQUENCE TO MEASUREMENT CAMPAIGN

Need to consider the following:

1. Spatial and temporal scales – storm intensity and passage time scales.
2. Pressure gradients - local pressure gradients at site scales.
3. Event attribution methods – association of pressure system dynamics with changes in the tidal flow field.
4. Post-processing corrections to pressure sensor data.

2.4 Measurements and Derived Parameters

The type and volume of data collected, and the sampling regimes used, is defined by what the data are to be used for. Many of the parameters required are derived from measured quantities, *e.g.* turbulence parameters are derived from the observed velocity data. The parameters to be derived will impose requirements on the instrument configuration used in a data collection campaign.

2.4.1 Data Usage

There are multiple uses for the data collected.

- Resource assessment and estimation of annual energy production.
- Site characterization and monitoring – feedback to turbine control in real-time.
- Accurate measurement of structural loading – feedback to turbine design.
- Input data for CFD turbine modelling – feedback to turbine design.
- Input data for tide-to-wire models – feedback to turbine control, economic return, turbine design.
- Input to regional modelling – forcing and validation. Regional model outputs can be used to define long term mean statistics and extreme events and for tasks such as turbine array siting.

2.4.2 Required Parameters

The RealTide internal report (D1.5) captured the data requirements identified across the consortium as well as those from related projects. All relevant parameters are listed in Table 2 with a brief summary of data requirements and usage. Parameters in **bold** are measured, the parameters in *italics* are derived

Table 2: Summary of required parameters and their end-use.

	Parameter	Requirements and key considerations	Parameter Usage by the Tidal Industry
Tidal Flow	**Velocity profile**	Three coordinate components of mean flow. Multiple neap spring cycles. Extreme tides. Vertical profile structure and temporal variation. Capture scale and frequency of horizontal eddy structures. Boundary layer detail for drag coefficients.	Available energy. Flow variability. Hub-height flow. Input to CFD, tide-to-wire models, tank testing, fatigue studies. Validation of regional models.
	Turbulence Power Spectrum	High-frequency velocity data. Low noise base. Identification of quasi-stationary periods.	Input to CFD, tide-to-wire models
	Turbulence Intensity	If assume isotropy can use single sensor. If anisotropic need all velocity components. Capture gusts, bursts, *etc.*	Input to CFD, tide-to-wire models, tank-testing, fatigue studies.
	Turbulence Length Scales	Spectra for each velocity component. Sufficient frequency range to fit von Karman. Low noise base.	Input to CFD, tide-to-wire models.
	Reynold's Stress Tensor	Minimum of 6 independent velocity measurements (7-beam instrument). High-frequency data. Low noise base.	Input to CFD, tide-to-wire models.
	Turbulence Anisotropy	Recovered from spectra. Recovered from Reynolds Stress Tensor.	Input to CFD, tide-to-wire models.
	Coherency	Synchronous velocity measurement at multiple locations.	Input to CFD, tide-to-wire models.
Waves	**Free Surface Elevation**	Mean sea level datum. Astronomical extremes. Weather-driven extremes. High-frequency data to capture waves. Sensor sensitivity to resolve waves.	Validation of regional models Event attribution Input to tank testing
	2D Wave Spectra for TEC and instrument locations. Wave Statistics elsewhere: Significant Wave Height, Peak Wave Period, Peak Wave Direction	Required for a range of storms. Swell + wind wave conditions. Required for system state (wave-current-turbulence) classification.	Input to CFD, tide-to-wire models, & fatigue studies. Validation of regional model.
Meteorology	**Wind Speed**	Horizontal velocity components. Measurement height 10m. Data from multiple locations across site. Measurements site must be unobstructed. Accurate timestamping.	Input to regional models Data post-processing.
	Surface Pressure	Multiple locations across site. Capture weather system passage.	Input to regional models Data post-processing.
Machine (and External Devices)	<u>Type A: Operational System State of Machine</u> Power, Rotor Parked vs Rotor Moving, Turbine Pitch, Roll and Yaw (if relevant to device). Presence of on-station vessels, ROVs.	Required to be synchronous with environmental conditions and available to project partners to allow full use of environmental data.	Essential for separation of ambient vs flow conditions that are due to the presence and/or operation of the TEC machine. Required to ascertain sensor orientation of any TEC installed sensors.
	<u>Type B: Electro-Mechanical System State of Machine</u> Rotor: position, RPM, thrust, torque. Blade Pitch, Strain gauges, Vibrations.	Required to be synchronous with environmental conditions to allow fluid-structure interaction studies.	Validation of BEMT, CFD and tank-testing engineering tools. Structure loading. Input to reliability / fatigue studies.

2.4.3 Time Series Length

The duration of a data collection campaign must meet the competing constraints of data quantity and quality, data storage capacity, power consumption, and hardware resilience in the marine environment[2],[4]. To be of value there are minimum requirements on the data that must be met.

Timescales of the Physical Processes

The data time series needs to resolve the dominant controlling process frequencies. The driving of tidal flows is dominated by the lunar forcing[10],[11],[12], which is tied to the rotational period of the Earth and the orbital period of the Moon about the Earth. This produces a tidal period of 12.42 hours. The amplitude of the tide over this tidal period is modulated by the variation in the relative position of the Moon and the Sun as seen from the Earth, *i.e.* the lunar phase, for a single orbit of the Moon (27.32 days). This produces the fortnightly neap-spring cycle in the tidal amplitude. This cycle is further modulated by the varying orientation of the Earth’s rotational axis to the orbital plane around the Sun over the Earth’s orbital period of 365.256 days. This produces a variation in the neap-spring range throughout the year, with the largest variation occurring at the equinoxes.

Overlaid on the tidal processes is the meteorological forcing. There is typically a 7 to 10 day shift between stable high-pressure systems and unstable low-pressure systems[12],[19]. The intensity, frequency and duration of low-pressure instabilities varies seasonally. Due to the complex non-linear interactions and feedback between large-scale oceanic and atmospheric processes, annual and decadal variability is observed in the weather patterns[19]. It is the interaction between the meteorological and tidal forcing that produces the extreme conditions that define the operating envelopes for the structural designs of TECs.

The length of a data collection campaign needs to capture a sample of the system state that represents both the tidal and meteorological processes[21],[22],[23]. To capture maximal events the measurement campaign should cover one of the equinoxes (a specific day in March and September). To better understand the annual variability in the tidal resource, a 3- to 6-month deployment is needed[10]. The longer the deployment the greater the chance of observing a range of interacting systems states (*e.g.* wind/current direction combinations, wave/current combinations, extreme events, *etc.*). With more observed states the statistical description of the system is improved. An operational compromise needs to be made between the instruments being deployed during stable weather conditions at a neap tide and a number of large storm events being captured.

Engineering and operational considerations of prolonged measurement campaigns

Ideally deployments would be conducted for as long as possible at high spatial density and high temporal sampling frequency[2],[3]. Sensor and operational constraints require a trade-off in these parameters. Long durations require large memory capacities to store data and large battery packs, or cabled deployments. Long duration stand-alone deployments increase programme risk if it cannot be ascertained that the device is functioning. Long duration cabled deployments suffer increased risk of failure due to cable and connector failure. Biofouling occurs at unpredictable rates and is sensitive to site location and individual sensor geometry and material selection. Lacking *a priori* information of the site could mean biofouling becomes a limiting factor.

From data obtained over a prolonged period (targeting functionality beyond 90 days), an investigation into the sensitivity of resource characterisation to the deployment duration is possible. Already held datasets from other sites can also inform this work which will contribute to future measurement campaign methodology.

CONSEQUENCE TO MEASUREMENT CAMPAIGN

Consideration of the following is required:

(1) Lifetime of hardware in the sea (resilience).
(2) Reduced data quality through bio-fouling.
(3) Time windows of maritime operations.
(4) Probability of recording important events (*e.g.*, storms).
(5) Power consumption rates per instrument configuration.
(6) Interaction between tidal and meteorological time scales – multivariate analysis.

2.4.4 Sensor Sampling Regime

The operation of many of the sensors used to measure oceanographic parameters can be controlled by pre-configuring a number of internal settings[26],[27],[28]. The sampling regime chosen for a sensor depends on the parameter being measured, the parameters to be derived, and any compromise between deployment duration, data volume, and power consumption. The environment in which the instrument is deployed may limit the capabilities of the instrument, thereby defining an operating envelope on the pre-configurable settings[29],[30]. As an example, most commercial ADCP instruments allow the user to set the sampling frequency, sample burst duration and repeat period, the spatial bin size, levels of averaging, blanking distance, maximum range, *etc.* These parameters are used to set the sampling regime. The environmental conditions that define the operating envelope are the maximum flow speeds expected, the level of turbulence, the level of turbidity, *etc.* [26],[31] These will impose sampling rate, averaging, bin size, and measurement range bounds, outside of which there is no point collecting data as it will be below the quality thresholds.

Typically instruments are deployed as stand-alone units that are pre-configured and either turned on before deployment, or set to start collecting from a given time[7],[27],[28]. The limitation is that the configuration of an instrument can only be modified during a deployment period by recovering, reconfiguring and redeploying the instrument. By integrating sensors through a controller that functions either autonomously or has remote operator access, the instrument configuration can be managed without the need for recovery and redeployment[2],[3]. If the controller includes monitoring systems then it is possible to optimise data collection and reduce power consumption by targeting data collection, *e.g.* only measure waves during periods of wave activity (at periods and heights relevant to TEC).

CONSEQUENCE TO MEASUREMENT CAMPAIGN

Consideration of the following is required

(1) Level of automation built into systems – complexity vs failure risk.
(2) Level of intervention built into systems – complexity vs control risk.
(3) Data capture constraints – storage, bandwidth, power consumption.
(4) Environmental limitations on instrument operating envelopes for site.
(5) Tradeoff between optimal instrument configurations for varying derived parameters.
(6) Tradeoff between optimal instrument configuration and auxiliary programme requirements: *e.g.*, long-term mean data in a TEC SCADA system vs short duration, high-resolution turbulence measurements.

3. MEASUREMENT SPECIFICATION

This section will define the instruments used in a measurement campaign and their operational constraints, the issues associated with data integration, data capture considerations, and the data post-processing, archiving and dissemination requirements to be met. The outline process of generating the data required to characterise a MRE site is as follows[2],[4],[6]:

(1) Identify instruments needed to measure the observable properties.
(2) Define instrument configurations based on the required sampling regime.
(3) Calibrate all sensors and set all instrument clocks to a common timestamp.
(4) Deploy, monitor, and recover instruments.
(5) Collect and store raw data from all instruments.
(6) Apply quality controls to data in a traceable way.
(7) Post-process the data to generate the required parameters using validated software tools.
(8) Store data in a secure archive and integrate with a data service to allow external access.
(9) Impose security and controls on data to address issues of wide dissemination vs IP protection.
(10) Apply targeted analysis based on the requirements of developers and operators.

3.1 Measurement Instruments

3.1.1 Tidal Flow Measurement via Acoustic Based Velocimetry

Acoustic-based velocimetry is a proven technique for the measurement of tidal flows[2],[4],[6]. The fundamental operation of all acoustic Doppler profilers (ADP) are essentially the same[26]. An acoustic signal is transmitted by one or more transducers which at a short time later act as receivers. The Doppler shift in the backscattered signal is related to the fluid velocity, and the returned signal is range gated in time to construct a profile of velocities along the transducer beam. Data from beams at different orientations can be used to reconstruct a vertical profile of velocity vectors centered on the vertical location of the range bins. The transmitted signal can be narrow-band or a broadband chirped signal, the pay-off is narrowband gives improved range with more noise, broadband has a shorter range for lower noise. To capture turbulence and fine scale data at MRE sites, broadband signals are used to reduce noise characteristics allowing the retrieval of turbulence parameters.

The constraints on the measurements that can be made are:

- The central frequency of the transmitted pulse – acoustic attenuation is frequency dependent, higher frequencies attenuate faster than lower frequencies, influencing the maximum range at which reliable data can be recorded.
- The sampling frequency, *i.e.* how often a pulse is transmitted, depends on the design of the driving hardware and the size of the transducers. To be able to retrieve turbulence information high sampling frequencies are required.
- The beam angle away from the vertical affects the accuracy of the separation of the horizontal and vertical velocity components. In general the horizontal velocities are an order of magnitude larger than the vertical velocities. The optimal beam angle is between 20°and 30°from the vertical.
- Related to the beam angle is the resulting beam separation. The accuracy of the derived data depends on the assumption that the flow state is homogeneous over the spatial separation of the beams.
- Acquiring data at regions of specific interest to tidal developers (*e.g.*, a TEC rotor plane located at mid-depth in a fast flowing channel) is mechanically difficult to achieve.

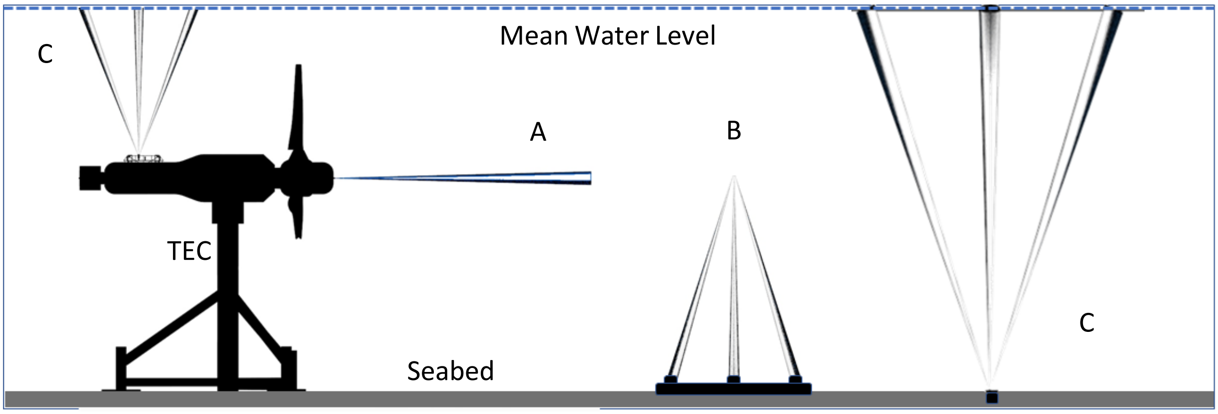

Figure 6: Flow measurement using acoustic Doppler profilers (ADPs), where acoustic beams are represented by narrow cones in along-flow single-beam (A), converging-beam (B) and diverging-beam (C) arrangements.

These constraints define which instruments are suited to the measurement of particular parameters, and how a given instrument should be located (see Figure 6) and configured (sampling frequency, bin size) and deployed (measurement range vs water depth, beam-spread vs length scales). The configuration can be optimised to meet the data accuracy required for parameters that are to be derived from the along-beam velocities. Other operational constraints include the power required to drive the transducers and the amount of data generated[27],[28], *i.e.* the higher the sampling frequency the larger the amount of power required and the larger the amount of data generated. It is possible to operate most ADPs in a burst mode[29],[30] (high frequency acquisition for limited duration before switching to a quiescent state) which reduces the power consumption and data volume, but at the expense of a fragmented time series; this is another compromise that needs to be considered when configuring an ADP.

3.1.2 Tidal Surface Elevation

The spatial and temporal variation of the surface elevation due to the propagation of the tide around the Earth is modified locally by the presence of land boundaries and the topography of the seabed[10],[11]. All main ports and harbors operate tide gauges that are normally located near the coast. These data include the local effects of the coast on the tide, so may not be completely representative of what is occurring at a turbine. For the purposes of tidal resource calculations and regional model validation, elevation data need to be collected across the site[18]. Two standard methods[7],[10],[23],[32] used for *in situ* surface elevation measurement are upward-looking acoustic instruments (*e.g.* an ADP used as an inverted echo sounder) or pressure sensors mounted on a fixed structure (*e.g.* a bedframe, a turbine).

The time scales of the tidal signal in the surface elevation is of the order hours. On top of the tidal signal there will be short period (minutes to seconds) surface gravity waves (these are discussed in §3.1.3). The high-frequency wave signal needs to be removed in order to reconstruct the tidal elevation[7],[10],[32]. There are two approaches: (1) the elevation data can be collected as temporally averaged values, or (2) the high-frequency data can be low-pass filtered to remove the surface gravity wave signals. The configuration of the sensor will depend on whether it is used to only capture the tide, or will be used to extract wave information as well.

For acoustically-derived elevation measurements the depth, orientation and spatial location of the instrument needs to be known, and the instrument should use a surface tracking mode to determine the location of the water-air interface and adjust range-gating[26] to a high-resolution mode. If the instrument does not have a surface tracking mode[29],[30], then the accuracy of surface elevation data is limited by the relatively large bin sizes used for current profiling. This elevation data, however, remains a source of useful data, particularly for energetic wave conditions.

For elevation data collected from a pressure gauge, the sensor needs to be zeroed before deployment[7],[26],[27],[28] and the atmospheric pressure at the time of zeroing recorded. The pressure sensor record will include variations in the atmospheric pressure, which should be removed or at least identified as a further source of error. Depending on the sensitivity and relative depth of the pressure sensor, the pressure record will have some measure of the surface gravity wave signal.

3.1.3 Waves

The method used to collect wave data depends on whether 1-D or 2-D wave spectra are required. For 1-D wave spectra the variation of the surface elevation relative to some fixed datum at a single location is measured over time. To generate 2-D wave spectra the variation of the surface elevation and a proxy for the energy propagation direction (surface slope, wave orbital velocities, *etc.*) are measured over time. The existing methods for collecting wave data are[17]:

1. **Pressure sensors**

   A pressure sensor within the water column will measure the combined hydrostatic and dynamic pressure at the location of the sensor. Linear wave theory can be used to convert this pressure measurement into surface elevation estimates. Wave-current interaction should be considered. A single sensor will provide a time series of surface elevation or 1-D spectra, whilst a suitably time-synchronised array could provide directional information.

   The constraints on using pressures sensors to measure waves are:
   - The sensitivity of the sensor, *i.e.* the minimum pressure change that can be resolved.
   - The frequency response of the sensor – *i.e.* how rapidly the sensor will respond to a change in pressure.
   - The depth of the sensor – depth dependent cut-off frequency, due to wavelength dependent energy penetration, above which no wave information can be derived[17].

2. **Acoustic wave measurement**

   An ADP can be used as an upward looking echo sounder to measure the surface elevation, with the optimal measure being derived from a vertical beam (*i.e.* beam angle = 0°). This can be used to construct a 1-D wave spectra. To construct a 2-D wave spectra multiple pieces of information are required. A mixture of surface tracking and vertical variation in orbital velocities can be used to retrieve 2-D wave spectra. This is the principle that acoustic wave recorders (*e.g.* AWAC) are built on. These recorders can be operated in two modes: (1) PUV (Pressure/U-velocity/V-velocity), or (2) SUV (Surface/U-velocity/V-velocity), where pressure (P) or acoustic surface (S) tracking is used to measure the surface elevation. In both cases wave orbital velocities are determined from the horizontal velocity components (u,v).

   The constraints on acoustic wave measurements are:
   - Vertical bin size – this sets the minimum elevation change that can be resolved.
   - Instrument depth – the deeper the instrument the higher the uncertainty in the near surface velocities.
   - Beam separation at the surface – the greater the beam separation the lower the resolvable wave period (Details in RDI Waves Primer [17]).
   - Instrument used - the wave mode may degrade current measurements depending on the type/model.
   - Wave breaking – air entrainment significantly affects acoustic sensor response.

3. **Multiple sensor / multiple parameter methods**
   An alternate approach to generating 2-D wave spectra is to use a sparse array of sensors (acoustic and/or pressure) to measure wave information, then apply mathematical likelihood techniques to determine the wave direction and amplitude spectra. These techniques include the Fourier Expansion Method, Maximum Likelihood Method, Extended Maximum Entropy Method, and Bayesian Direct Method.

   The constraints on the multiple sensor methods are:
   - Sensitivity of the sensor used to the wave signal.
   - Accurate timing for data synchronization.
   - Accurate spatial location of sensors relative to each other to determine spatial scales and propagation times.

For complete characterisation of the wave environment at tidal sites, data are required on the basin-scale remotely-generated storm swell and the local regional-scale wind-generated waves that propagate into the site[2],[4],[16]. The data collected on site can be supplemented with wave statistics from wave buoys, X-Band radar and satellite (*e.g.* scatterometer) data to define the broader regional wave field.

3.1.4 Turbine Monitoring

The presence of a TEC that is extracting energy from the systems produces a two-way interaction between the machine and the flow[2],[3],[9]. The inherent fluid structures (flow speed, flow shear, turbulence, eddies, *etc.*) affect the behavior of the turbine, while the turbine blocks incoming flow, extracts energy from the flow, and alters the fluid structures at its location and down-stream through blade tip vortices and the wake formed[9]. To understand this interactive process and determine how the site characterisation can be used to inform turbine design and site development, some measure of the behavior of the turbine is required. The machine data will come from sensors integrated with the TEC structures and systems. An example of a comprehensively instrumented TEC system can be found in the ReDAPT MC7.3 report [3].

The acquisition of machine parameters is not within the scope of this report, but these parameters should be collected with their subsequent comparison to contemporaneous datasets in mind. Specific consideration should be given to[2],[6]:

- Interfering sensor technology: *e.g.*, acoustic machine condition monitoring sensors in the proximity of environmental acoustic velocimeters.
- Common syncronised time-stamps for all data sets.
- Turbine operation status is required in many cases to understand ambient flow conditions due to the proximity of the structure in and out of generating mode.
- Data management and rules of engagement on IPR issues and data controls.
- Producing a system of notification between sensor owners when changes of machine state affect operation of third-party systems.
- Transparent treatment of data across machine and environmental datasets.

3.1.5 Meteorology

Meteorological data need to be collected as close as possible to the TEC site to give a realistic representation of local meteorological forcing[20]. The key data required from a weather station are:

- wind speed and direction.
- wind gustiness.

- surface pressure.

Weather stations are typically deployed on land, but measurements can be provided by moored weather buoys. These buoyed weather stations cannot be deployed in high flow regions (*e.g.* TEC sites), so are limited to providing far-field measurements for the site.

Constraints on siting of Weather Stations:

- Open site – there should be no directions from which the weather station is sheltered from the local wind.
- Representativeness of the observations – the data must provide a good representation of what is occurring at the measurement locations, *i.e.* if the station is too far away then is difficult to attribute events in time and the wind speed and direction may be significantly different.

Ideally metorological data should be collected from multiple locations around the TEC site to provide both spatial and temporal structure[20] and to allow interpolation to measurement sites.

3.2 Data Integration

To be able to utilise the information content from multiple data sources, standard reference systems need to be defined and used by all parties[7],[21],[22],[23]. The critical data referencing criteria are:

- Data timestamp.
- Geospatial location of the data.
- Orientation of flow-profilers relative to a fixed coordinate system, typically the TEC.

3.2.1 Common Reference Time

The control of accurate data time-stamping depends on the operational mode of the measurement instrument. The majority of environmental data are collected from stand-alone instruments that are operated autonomously. These instruments will have an onboard clock[27],[28] that is used to timestamp every measurement. For the data to be of use, this clock needs to be accurately set prior to deployment and have either negligible or known drift.

For the synchronization of multiple data sets derived from a collection of stand-alone systems, clock drift must be taken into account[2],[7]. For instruments that allow some form of intervention in their operation it is possible to manage their clock to varying degrees, *e.g.* if the controlling system is connected to an accurate time server, then any instrument clocks managed by the controller could be checked for drift and/or reset as required on a regular basis during the measurement campaign.

In all cases a common clock should be used at the time of initial setting or at times of periodic resetting. Within the scientific community UTC (Coordinated Universal Time) is the recognised standard reference for timestamping data[7],[21],[22],[23]. All measurement instruments should have their clocks set to UTC; if UTC is not used then the reference time (including offsets due to Summer Time changes) must be provided with the data.

When setting an instrument clock, some form of precision time control system should be used. The internet standard is NTP (Network Time Protocol) which is very accurate at the server, but this accuracy is reduced by latency in the transmission of a times stamp across the network. For many instances this level of accuracy is sufficient. However if higher accuracy is required then PTP (Precision Time Protocol) should be used; this is available via a GPS (Global Positioning System) or GNSS (Global Navigation Satellite System) receiver. Ideally all instrument clocks for a given campaign should be set using a single time server point, *e.g.* all set from the same computer or using the same PTP receiver, to minimise latency issues and to ensure all clocks are set to the same reference time.

3.2.2 Coordinate Reference System

The location of the individual measurements in space is essential to the extraction of spatial structures. A common coordinate reference system needs to be used to allow the extraction of spatial structures[2],[5],[7]. At the most fundamental level the data need to be located relative to the Earth, this is typically done using a spherical coordinate system with its origin fixed at the centre of the Earth, and where the mean level of the surface of the Earth is represented by some form of spheroid. The standard generally used across the geophysical sciences is WGS84 (World Geodetic System 1984). Horizontal positions are measured in degrees of latitude and longitude relative to the spheroid equator and meridian, and heights (or depths) in metres relative to the spheroid surface.

If horizontal positions are to be recorded in degrees latitude (lat)/longitude (lon) then it is essential to provide sufficient precision in the location data to achieve the required spatial accuracy. Sub-metre positioning requires the lat/lon values be given to 6 decimal place accuracy when using decimal degrees (0.000001° ≈ 10cm), or to 2 decimal place accuracy in seconds (0.01′′ ≈ 30cm) if recorded as degrees, minutes and seconds of arc. Issues with position precision can be reduced by using a local Transverse Mercator projection from lat/lon into Eastings/Northings in metres. These projections are not length preserving, but if an appropriate map projection is used the distortion is of the order of 1 part in 1000.

3.2.3 Local Reference System

A local coordinate reference system based on a site-specific origin and coordinate orientation should be used for measurement campaigns[2],[4]. This simplifies the merging and interpretation of multiple data sets. Given that the aim is to understand the flow at the turbine, it makes sense to use the turbine location as the local coordinate origin, and to align the horizontal coordinate axes with the dominant along-flow and across flow directions, and the vertical axis pointing positive upwards to retain a right-handed coordinate system. Consideration is required to maintain a relationship between the turbine coordinate system, *e.g.*, located at the center location of the rotor plane, and the global coordinates, since in many cases the rotor plane moves - either by rotating in yaw around a tower (which can also introduce deviations in machine pitch and roll) or by being on a moored floating structure.

Most marine instruments use a pressure sensor to determine their depth relative to the measured mean sea level. The mean sea level generally varies spatially, and this variation can be significant in regions where attached eddies regularly form on the flood and/or ebb tide. The local bathymetry will also vary between instrument locations across the site, so a fixed local vertical measurement datum is required[23],[32] for the data from various locations to be combined. All bathymetric survey data are carried out relative to some fixed datum, so this can be used to set a fixed vertical origin that is to be used for the local coordinate reference system. When using pressure sensors to determine water depth, variations in atmospheric pressure must be accounted for (see §3.1.2 above). In general the local coordinate reference system will be introduced in the post-processing of the various data sets.

3.2.4 Instrument Location and Orientation

Determining the accurate horizontal position of an instrument on the seabed is difficult[2],[3]. Most bed frames are deployed from a vessel that is not on anchor and in some flow. The position of the vessel can be recorded during the deployment and the time when frame hits the seabed determined, but it is not possible to know the relative horizontal motion of the frame to the vessel before it reaches the bed. The positions could be out by 10s of metres depending on the water depth and flow. It is possible to use an ROV to determine the position of the deployed frame relative to the operating vessel. If the position of an existing structure (such as a TEC) is accurately known then it should also be possible to use this as a reference for the ROV positioning. Accurate acoustic-based range-measuring systems can be deployed and if used are typically recovered following deployment.

For instruments that measure vertical profiles the full orientation (pitch, roll, and yaw) needs to be known. Most ADPs have built-in pitch and roll sensors, and a compass for horizontal yaw[27],[28]. In general the seabed is never perfectly level, so bedframes will almost certainly not be level once deployed. To alleviate pitch and roll the instrument can be mounted in a gimbal and protected from flow drag. Otherwise the pitch, roll and heading data need to be used to correct the data orientation and location. Loose gimbals can cause high levels of motion: some users prefer un-gimballed setups and rely on camera feeds during deployment to ensure frames are approximately level (and assume no significant movement of the frame during the data collection period). An alternative approach is to utilise gimbals that feature damped rotation joints.

Sensors need to be correctly calibrated before deployment and checked on recovery to determine if there is any drift from their deployment state[7],[27],[28] (*e.g.* clock offset, changes in pressure sensor zeroing, changes in compass offsets, *etc.*) that needs to be corrected for. The compass will be affected by any local metal structures, so it needs to be calibrated in the bedframe and when portable power packs are installed or swapped out.

3.3 Data Capture

How the data is captured during a measurement campaign depends on the instruments deployed and the level of systems integration used[2]. If the system is of a simple stand-alone design, the data will be stored on an internal recorder and recovered when the instrument is recovered. The next level of complexity is to allow for data off-loading from an instruments internal storage throughout the deployment period. Beyond this is a fully integrated system with a remote shore connection so that the data can be captured in real-time and stored on more reliable shore-based hardware (*e.g.* SSD, RAID) from which the data can be easily ported to an archive. The level of complexity used will be site specific, dependent on local environmental conditions, site accessibility, connectivity options, *etc.*

3.3.1 Internal Data Recorders

Standard oceanographic instruments typically include a built-in data storage system, generally on some form of removable memory card. Sensors integrated into structures will generally have a dedicated data logger that captures the measurements. In both cases the data can only be accessed once the instrument or data logger are recovered.

RISKS:

- No way to determine if instruments are recording data.
- No way to determine if an instrument or storage fault develops.

3.3.2 Periodic or Adhoc Data Off-loading

The next level of control is where there is an external link to the instrument system that can be used to download data. This could be an underwater link that can be accessed by a diver or ROV, or a physical communications link such as an acoustic modem or shore cable. This external link provides the possibility of monitoring the instrument status and recovering internally recorded data before the end of the deployment. This significantly reduces the data collection risks and allows for early intervention if a system fails. The data recovery will be limited by the bandwidth of the communications link, the volume of data being collected, and the frequency of access. A mechanism that allows the internal storage to be reset after data recovery may be required to allow the instrument to continue recording. If the level of intervention allows access to instrument controls/software then it may be possible to reconfigure an instrument if the data indicates a sub-optimal configuration for the local environmental conditions.

RISKS:

- External connector is an extra point of system failure.
- External cabling to the connector is a point of failure.
- Interfacing with a 3rd-party system introduces uncontrollable issues – *e.g.* fusing, access, incorrect connector wiring, *etc.*
- Data transmission loss across communications link – need for error detection/correction.
- Operator error with in-water connections.

3.3.3 Real-Time Data Acquisition

The natural extension is to collect the data on-shore in real-time. This requires a dedicated and robust communications system, with sufficient bandwidth to transmit the data volume, and for the data transmission to be lossless. This approach also allows real-time monitoring of the system as a whole. Real-time access to both the data and system controls means it is possible to assess whether the instrument configurations are suitable for the local conditions, and to alter the configuration to suit on the fly.

RISKS:

- Increased number of failure points – connectors, cables, *etc.*
- Dependence on 3rd party system integration.
- Noise on transmission lines degrading data availability and/or quality and/or bandwidth.
- Level of personnel availability for system monitoring/management.

3.4 Data Management

Methods of data standardization, quality control, storage and analysis are required to ensure the data collected meet user requirements. The data need to be available from a variety of different levels of processing, ranging from the raw data, as captured by the measurement instruments, to tabulated post-processed data that can be used directly as input to the various engineering tools.

3.4.1 Data Standardization

Data standardization allows a variety of different data types and from multiple data sources to integrated and managed easily. This involves the conversion of all data to a common format and the provision of metadata that conforms to some standard. The use of a common data format eliminates the need for multiple data readers. The metadata must provide sufficient information to allow a user to understand what has been recorded without recourse to documentation or direct communication with the data managers.

The chosen data format should be independent of operating systems, easily read by a variety of different programing tools and languages, and allow metadata to be embedded within the data structures. The two most commonly used hierarchical data formats are NetCDF and HDF. Both of these formats allow metadata to be embedded with the data, they support multiple data compression methods, and are platform independent. NetCDF is the standard used for climate data where there is a defined variable naming convention developed for a broad range of variables. To date there is no recognised metadata standard, but this can be informed by the requirements for the data service method to be used.

3.4.2 Data Quality Control

Data quality is assessed in two inter-related ways. The first is Quality Assurance (QA) which aims to prevent defects in the data product by ensuring the best available techniques and methods have been used to generate a given data set. This must be done in a traceable manner. The second is Quality Control (QC) which is the process of identifying defects that occur in the data despite following the data QA protocols. QC activities need to both monitor the data processing and verify that the data meet the quality standard required by the end users. QA/QC Standards are currently being developed for marine data. Table 3 gives a limited set of QA/QC considerations for ADP velocity data to help explain the distinction.

Table 3: Example of the difference between data QA and QC

	QUALITY ASSURANCE	QUALITY CONTROL
ADP Velocity Data	Method for siting instrument.	What is location uncertainty?
	Method for setting optimal configuration.	Does data resolve required signals (spatial/temporal)?
	Method for calibrating instrument.	Clock and compass drift.
	Method for calibrating data collected.	Uncertainties in data calibration.
	Method for identifying bad/missing data.	Data flagging of bad/missing data.
	Method for deriving parameters.	Can parameters be derived from data?
	Method for propagation of errors.	Error in derived parameters.

3.4.3 Data Storage and Access

All raw data and key post-processed data (*i.e.* calibrated and quality controlled) must be stored securely with read-only access so that it cannot be modified. For re-processing and higher levels of post-processing there needs to be a system of version control with clear documentation of modifications. There is a need to archive the various versions so that users can evaluate the impact of changes.

Data access must be considered on two levels. The first is the physical method used to provide access to the data, *e.g.*, manual requests to the data providers, ftp access to a data archive, a web portal interface that provides a data query service, *etc.* The type service provided is constrained by the resources available to support the data service. The second level of data access is related to data protection. There are a range of data licenses that can be applied that defined how open the data and what the data can be used for. The openness of the data is limited by the need to meet IP protection constraints. The level of openness needs to be agreed by all parties providing data.

3.4.4 Data Analysis

There are a range of levels of data analysis that can be applied. The first level is the extraction of derived parameters from the measurements. This process needs to be carried out using quality controlled and validated software tools. The next level of analysis seeks to integrate the multiple streams of data to define improved or new metrics used by both developers and operators. These can include data clustering, multi-variate analysis, identification of useful transfer functions, *etc.*

4. CAMPAIGN SPECIFICATION

The complexity of the data collection campaign will depend on available resources, whether the task is an initial survey or an advanced characterization with one or more TECs in-place, the level of site accessibility, and the level of connectivity available to instrument platforms. Measurements should be targeted to meet clearly defined goals – since it is resource intensive to post-process and manage large quantities of heterogeneous data sets.

4.1 Sensor System Configurations

Three categories of sensor packages have been identified, based on increasing levels of interfacing required with the tidal turbine:

(1) Self-contained and battery powered instruments. These can be mechanically affixed to a TEC or to a mooring and are available with or without external communication functionality.
(2) TEC-installed or seabed-installed sensors using a one-cable-per-instrument direct connection to TEC internal (dry) sub-systems.
(3) Independently controllable and multi-sensor platforms connected to a TEC via a consolidated cable-set.

The systems configuration and corresponding data flows can be represented schematically. A generic examples is presented in Figure 7; this includes a range of integrated sensors, data streams, and end-users.

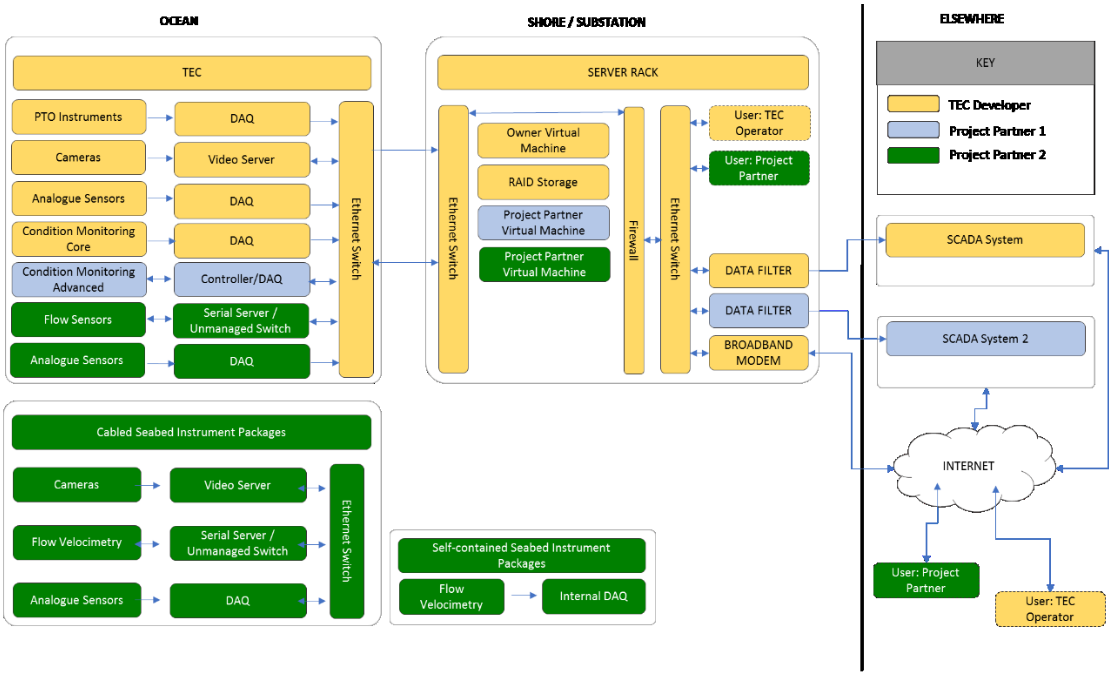

Figure 7: Schematic showing "typical" TEC and Sensor system relationships and data flows

Designing a measurement campaign around the availability of a TEC presents opportunities including:

- Remote operation - internet-connected TECs can provide internet-connected instrumentation enabling real time communication, state knowledge and instrument control and configuration.
- TEC provided power enables long duration deployments.
- Mounting instruments on a TEC (see Figure 8) enables measurements that cannot be made from classic emplacements (seabed, boat) - hub height horizontal measurements, mid-water

D-ADP to improve resolution over rotor plane, measurement of the wave field (using pressures and velocities) from a region featuring less wave attenuation (*e.g*. atop the TEC).

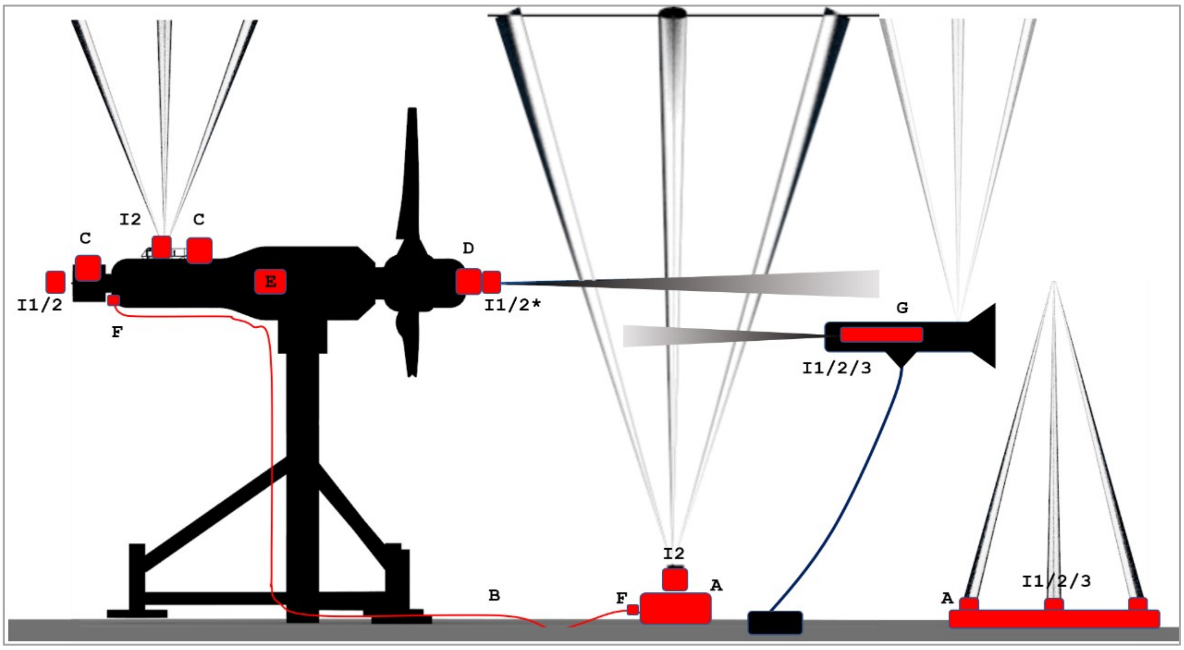

Figure 8: Sensor installation options showing instrumentation mounting configurations (not to scale). Sub-system labels provided in Table 4.

Table 4: Sub-systems description and function

Sub system	Short Description	Function
A	Gravity Foundation & Pressure Vessel for Communications & Power	Provide power and comms to I2. To be deployable and recoverable by as small a vessel as possible. To be deployable in close proximity to TEC & TEC assets. To remain stable in fast tidal flows .
B	TEC-Seabed Cable	To transfer power and comms to A/I2.
C	Pressure Vessel for Communications and Power	To allow the remote operation of instruments in a flexible scale-able way using a fixed electrical and comms interface to the TEC.
D	Pressure Vessel for Communications and Power	To enable power and comms to the rotor hub that traverses the rotating systems.
E	Internal TEC Communication and Power	Dry (inside TEC) comms and power peripherals (*e.g.*, cabinet mounted PSUs, fuses) to supply power and comms to instruments either directly or via A/C/D.
F	Connectors	Electrical and communication connections between sub-systems.
G	Floating tethered platform	To carry high resolution sensors in to TEC relevant regions of the water column.
I1	SB-ADP	Measure wake, near turbine flows, ambient flows (where TEC not generating thus affecting local flow), Streamwise Lengthscale, Streamwise TI.
I2	D-ADP	Measure depth profiles, waves, ambient flows.
I3	C-ADP	Measure wake, ambient flows, waves and advanced turbulence.

4.2 Design Considerations

4.2.1 Pressure Vessels for Communications and Power

When integrating systems, some method for providing subsea power, communications and control systems is required. If these systems cannot (for reasons related to logistical, financial, risk, project or technical constraints) be housed inside the existing infrastructure (typically control cabinets) of a TEC, then a pressure vessel is required to house the integrated controller systems.

The pressure vessel design depends on intended lifespan, internal volume requirements, attachment mechanism, connector sizing and depth of installation. Consideration should be given to material selection (typically Stainless Steel 316, Anodised and Painted Aluminium, Acetal/Delrin®), anodic protection, the avoidance of galvanic corrosion via bracketry to frames and TEC elements.

Desired functionality / housing Provides:
- Robust and marine-proof enclosure.
- Individual fusing of multi-sensor systems.
- On-board diagnostics – temperature, humidity *etc.*
- Spare connectors for expansion.
- Intermediate power supplies (voltage transformers and redundant power).
- Voltage regulation.
- Communication bus providing serial and Ethernet connectivity *e.g.*, RS232, RS422 and TCP/IP over Ethernet.

4.2.2 Communication channels

Various options exist for communication protocols. Variants identified as suitable candidates:
- RS232 serial communications for short distance (metres) connections and typically direct communication with single instruments (although sensor manufactures can include functionality to allow addressable multi-instrument connections). Cabling in a single-ended arrangement with low levels of noise immunity.
- RS422 serial communications for long distance connection (1-1500m) of single instruments with twisted pairs of signal wire in a differential arrangement, high levels of noise immunity.
- TCP/IP over Ethernet communications for high bandwidth data transfer over distances up to 100m. Multiple instruments are connectable using off the shelf Ethernet switches.

Ethernet is preferred for systems using cables up to 100m length and where power consumption is not a limiting factor. Serial communications are preferred on systems where local power availability is constrained or where programmatic instrument control and/or over-watch is implemented.

4.2.3 TEC mounted instruments

Whilst retrofitting of instrumentation mechanical bracketry is possible, it should ideally be conducted at the time of TEC design using future-proofing configurations *e.g.*, simple low profile flanges, rails or lugs, *etc*. Scheduling should include contingency for studies, such as Finite Element Analysis, which may be required by the TEC operator if penetration of the TEC shell is required to mount the instruments. One or multiple electrical penetrations are required along with suitable cable-routing features. Use of a connector size that provides spare channels is ideal along with conductor sizes suitable for providing high current when low voltage DC (*e.g.*, 24V DC) is being used.

4.2.4 Cables and connectors

Challenges associated with procurement, maintenance and refurbishment of cables and connectors should not be underestimated. Lead times for connectors are routinely 12 weeks. For prolonged deployments, supplier discussions are required; experience from tidal sites indicates accelerated failure rates for small diameter (*e.g.*, MCIL8M/F) connectors across multiple suppliers. Strain relief on cable cables is required.

4.2.5 TEC Interface considerations

Considerations for planning measurement campaigns around TEC-interfaced equipment are listed below:

- Can the instruments be fully tested post-installation *e.g.*, is there a turbine power and communications connection quayside, when will this cease to be available?
- Is it possible to fully test the communications systems and network; typically firewall settings will not allow direct replication/simulation of the installed-state?
- Is TEC supplied power only available when the TEC is in a generating state or is an auxiliary power supply from shore available for the instruments when the TEC is not generating (UPS battery power is usually reserved for emergency systems)?
- How do instruments respond to power failures; what intervention to restore instruments following power failure is possible?
- What is the electrical specification of the TEC interface, *e.g.*, fuse specifications, voltage regulation, electrical behaviour of the installed instruments, in-rush current, *etc.*?
- Can galvanic corrosion occur, *i.e.* are there mixed-metal contacts at the instrument-TEC interface?
- Can fault information be relayed to instrument users *e.g.*, via email/text alerts?
- What additional constraints arise from the substation location, *e.g.*, accessibility of sub-station server equipment and data, remote communication bandwidth limitations?

4.3 Installation and Recovery Methods

In order to ensure the structure/frame used to house the sensor system can be installed and retrieved, the following questions should be considered in planning for design and operations.

4.3.1 Vessel

- What vessels are available, suitable for and experienced in this type of work?
- What is the vessels' crane capacity across the lifting radii?
- What is the bollard pull of the vessel's winches?
- Accuracy of station-keeping, will the vessel be moored during installation/retrieval activity?
- What is the vessel's Dynamic Positioning (DP) capacity, how effective is this at the tidal site?
- Is vessel availability likely to be limited? Will vessel availability affect deployment schedules?
- From where will the vessel mobilise? From where will the frame be lifted onto the vessel?
- What is the transit time to site once the frame is on the vessel?
- What notifications/approvals are required for the scope of work (*e.g.* regulatory approval for deployment/notice to other sea users/vessel traffic services)?
- Whose responsibility are these notifications/approvals?

4.3.2 Logistics

- What logistic constraints are there on the frame specifications (weight, dimensions) *e.g.* weight/size limit for lifting by vessel crane, size limit to facilitate transport from fabrication site, size limit to enable palletisation of parts for final assembly quayside?

- Are batteries to be transported? Note that the transport of batteries can be problematic due to dangerous goods regulations. Can batteries be procured locally to minimise transportation?

4.3.3 Frame lifting

- How will the frame be lifted *e.g.* number of lifting points?
- Where is the centre of gravity?
- What approval/review of the fabricated frame will be issued? By which entity?
- How will the lifting bridle be disconnected from the frame post installation?
- How will the lifting bridle be re-connected for retrieval?

4.3.4 Divers

- What tasks will the divers undertake *e.g.* external compass measurement of frame position; connection of frame to power/communications; levelling of frame?
- What has been done to minimise diver intervention? What work can be done by ROVs?
- Is a safety/standby vessel required when diving is occurring from the primary vessel?
- What is the size of the dive team?
- How many dives can be conducted in a day?
- Per dive, how long can divers work at the sea floor?
- How is dive scope optimised to separate turbine and seabed work related dives?

4.3.5 Weather windows

- Given the strong tidal currents at the site, when can the installation and retrieval work be planned *e.g.* slack water during neap tides?
- What are the weather windows (wind and swell) for installation/retrieval given the lifting activity on/off deck and through the splash zone (noting that the ultimate decision to proceed with the operation lies with the vessel skipper)?

4.3.6 Initial commissioning following installation

- Following installation and in advance of vessel departure, what tests are conducted to ensure sensors are active, *e.g.* pinging each instrument to confirm operational, power cycling instruments, acquire data to confirm that data is being written to memory and required software configurations are in place, check all beams on ADPs are operating, check all connectors, check all bolts/lock nuts, *etc.*?
- Is there a detailed commissioning test plan to define all tests and record the results?

4.3.7 Work planning

- What documentation will be developed in advance of executing the installation/retrieval? *e.g.* detailed method statements, lift plans, dive plans and risk assessments.
- Who will review these documents *e.g.* turbine operator, vessel crew, divers.
- When will these reviews take place *e.g.* in advance of scope, toolbox talk on the day.

4.3.8 Safety

The safety of all those involved in a site or marine operation is paramount.

While planning and preparation aims to ensure the tasks are conducted without harm to people, property or the environment, anyone who has concerns during execution of the tasks has the right to stop the job.

5. THE REALTIDE FROMVEUR SPECIFICATION

This section presents specifications for the data collection campaign for D2.2 based on the considerations identified in §2, §3 and §4 of this document. This includes the level of systems integration, the new measurements to be collected using the instrument being developed at The University of Edinburgh (UEDIN), and opportunities which have been exploited due to scheduling changes since the RealTide project was initially submitted.

To capture the required measurement parameters (see §5.3 and Table 6) collection of site characterisation data proximal to the TEC is prioritised over multiple wide-area ADCP deployments. A coupled wave-current regional model will be developed in Work Package 2 to provide broader site coverage.

5.1 Deployment Strategy: Multi-Sensor Campaign Proximal to the D10 TEC

The recovery of the D10 turbine in August 2016 for maintenance work and its re-installation in October 2018 allowed UEDIN to mount instruments on the turbine. Sabella provided direct access to power and communications from spare connection points on the rear bulkhead of the turbine. This allowed UEDIN to integrate instrument systems providing the option to monitor and manage the instruments remotely.

Power and communications functionality has been extended to the seabed via installation of power and communications enclosures and a diver-accessible external connector. This connector will mate with an 80-metre external cable via diver operations, enabling interactive management of the UEDIN seabed instrumentation package and improved resilience of the deployment.

The instrumentation deployment scenario based around a multi-instrument campaign proximal to the D10 TEC is summarised in Figure 9 with target headings and ranges relative to the D10 TEC shown in Figure 10. Electrical, communications and computing interfaces of the deployment is captured in Figure 11.

The C-ADP will be deployed using a launch and recovery system to be designed in collaboration with Sabella and a local vessel contractor. Divers will be used over multiple dives to connect instrumentation to the TEC connector manifold, their use in periodically retrieving data should cable connections fail is subject to ongoing discussions.

The deployment duration target is 90 days with a minimum of 14 days of data acquired for high-frequency turbulence and instrument-instrument benchmarking and a minimum of 30 days for standard measurements to capture mean flows and basic turbulence parameters. Additional data will be provided by the regional modelling activities of D2.2.

5.2 Instrument Pool

The instruments available for deployment will be used to extend the data set being collected from the two Sabella-owned ROWE 600kHz 4-Beam ADCPs whose frames have already been deployed on site by Sabella. Divers will install the ADCPs and cabling in Q2 2019. The instruments available for on-site deployment are described in Table 5.

Table 5: Instrument pool available for Fromveur Strait data collection

Instrument	Name	Quantity	Nominal Range	Sampling Frequency
RDI Workhorse (600kHz, 4-Beam)	RDI600	1	1m - 60m	2Hz
Nortek Signature (500kHz,5-Beam)	SIG500	1	1m - 60m	4Hz (8Hz Max)
UEDIN C-ADP Single-beam at 1MHz (existing) / 600kHz (in procurement)	C-ADP	7	0.4m - 20m (1MHz) 0.4m - 60m (600kHz)	2/4 Hz (1MHz) 8/16 Hz (600Khz)
Nortek Signature (1000kHz,5-Beam)	SIG1000	1	0.2 - 30m	Max 16Hz
ROWE ADCP (600kHz, 4-Beam)	ADCP	2	0.16 - 45m	Max 10Hz

5.3 Targeted Parameters

Parameters derived from all instruments will provide input to CFD, BEMT, and tide-to-wire modelling (WP3). Parameters derived from RDI600, ADCP (FWD) and ADCP (AFT) will provide spatial information on the flow and wave characteristics that will be used to validate the regional model (WP2) and provide spatially and temporally separate measurement of intermittent process that can be used for event attribution (WP2). All instruments except SIG500 will collect coupled wave-current data and capture turbulent processes (to varying extents) providing blade element and structural load parameters (WP4), and site characterisations of flow and waves for tank testing (WP5).

Table 6: Parameter Acquisition by Available Instrumentation

Instrument	Parameters	Baseline Configuration*,‡	
RDI600 D10 (Top)	Velocity profiles Wave statistics TKE, TI, Length scales	Sampling Rate: Bin Size: Max. Range:	2 Hz 0.5 m To capture max. tide + max. wave.
SIG500 D10 (Rear)	Axial velocity profile Axial turbulence parameters Coherency	*Mean Flow Conditions* Beams: Sampling Rate: Bin Size:	All 5 beams. 4 Hz 0.5 m
		Streamwise Only Beams: Sampling Rate: Bin Size:	Central beam only. 8 Hz 0.5 m
C-ADP Bedframe (FWD, $2D_R$)	Velocity profiles to mid-water TKE, TI, Length scales Hub-height full Reynolds Stress Tensor Anisotropy, Coherency	*Hub-height Conditions* All settings:	To be assessed when sensor on-line.
		Spatial Coherence All settings:	To be assessed when sensor on-line.
		Surface elevation / waves All settings:	To be assessed when sensor on-line.
SIG1000 Bedframe (with C-ADP)	Velocity profiles to mid-water TKE, TI, Length scales Reynolds stresses	*Flow Conditions* Beams: Sampling Rate: Bin Size:	All 5 beams. 8 Hz 0.5 m
		C-ADP Cross Validation All settings:	To be assessed when sensor on-line.
ADCP FWD Bedframe (FWD, $3D_R$)	Full water column velocity profiles Surface elevation (pressure) Waves via beam velocities	Sampling Rate: Bin Size: Max. Range::	2Hz 1 m To capture max. tide + max. wave.
ADCP AFT Bedframe (AFT, $3D_R$)	Full water column velocity profiles Surface elevation (pressure) Waves via beam velocities	Sampling Rate: Bin Size: Max. Range:	2 Hz 1 m To capture max. tide + max. wave.

*Based on prior experience and subject to change based on data analysis once online. Other settings, beyond those specifically mentioned, to be assessed once sensor online.

‡For all instruments, data are always collected in beam coordinates for full control of data quality.

5.4 Target Installation Locations

The placement of the instruments have been selected to capture as many of the parameters required through WP dependencies and to meet the needs of WP2 for the development of improved site/resource characterisation methods, measurement tools, and data processing. Sabella have two bed-mounted ADCPs that can be used for power curve assessment (see IEC TS 62600-200:2013[24]) and to provide reference velocities and depth profiles of ambient conditions for multiple data analyses in WP2. The instruments being added will complement the data from these two instruments through location (see Figure 9, Figure 10) and configuration (see Table 6). The following list describes the instrument location and why it was selected.

RDI600:	Top-mount on the rear bulb of the D10 to collect at-turbine measurements of flow conditions, turbulence parameters and wave conditions.
SIG500:	Rear-mounted at axis height on the rear bulb of D10 to axial flow conditions and horizontal length scales and coherency data.
C-ADP:	On the rotor side of the fixed D10 on a heading from the TEC corresponding to the mean direction of incoming streamwise flow at a distance between 2D and 5D if this is possible given the deployment location of the Sabella ADCP FWD.
SIG1000:	Integrated with C-ADP structure. This instrument has a dual purpose, cross-validation of the C-ADP data, and high-resolution rotor plane parameters.
ADCP(FWD):	To be installed on the rotor side forward of the fixed D10 on a heading from the TEC corresponding to the mean direction of incoming streamwise flow at 3D upstream which represents the central location of the bounded area outlined in IEC TS 62600-200[24] power curve assessment.
ADCP(AFT):	To be installed on the rearward side of the fixed D10 on a heading from the TEC corresponding to the mean direction of incoming streamwise flow (ebb tide) at 3D upstream which represents the central location of the bounded area outlined in IEC TS 62600-200[24] power curve assessment.

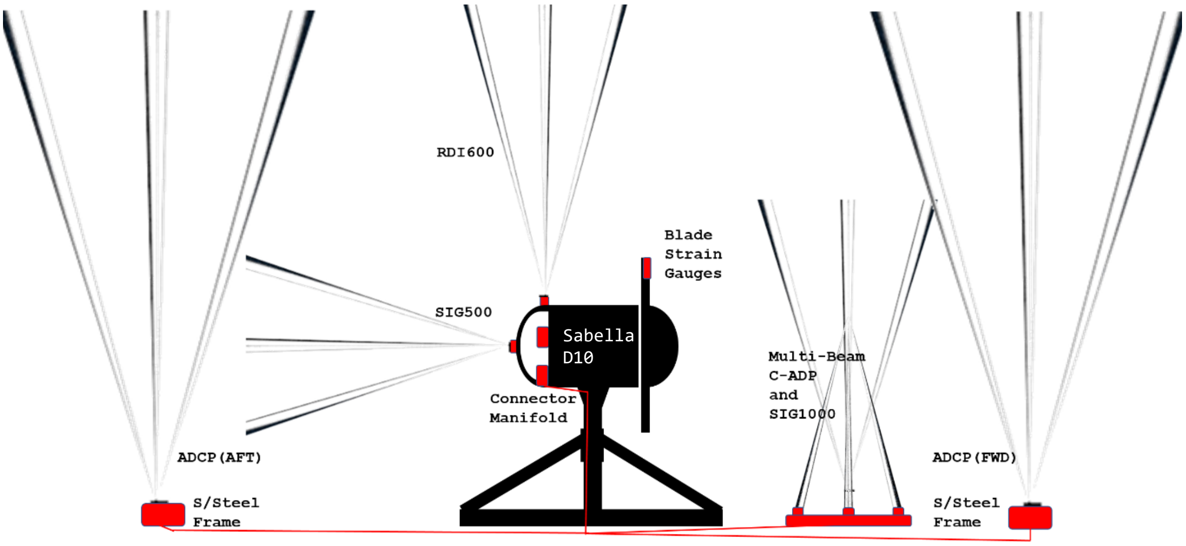

Figure 9: Outline instrument deployment strategy for Fromveur Strait.

The spatial variability in the bathymetry in and around the location of the D10 turbine will determine where the instruments are located and, in the case of UEDIN C-ADP will inform instrument configuration options (*e.g.*, platform physical dimensions). Target installation locations are shown on the chart in Figure 10.

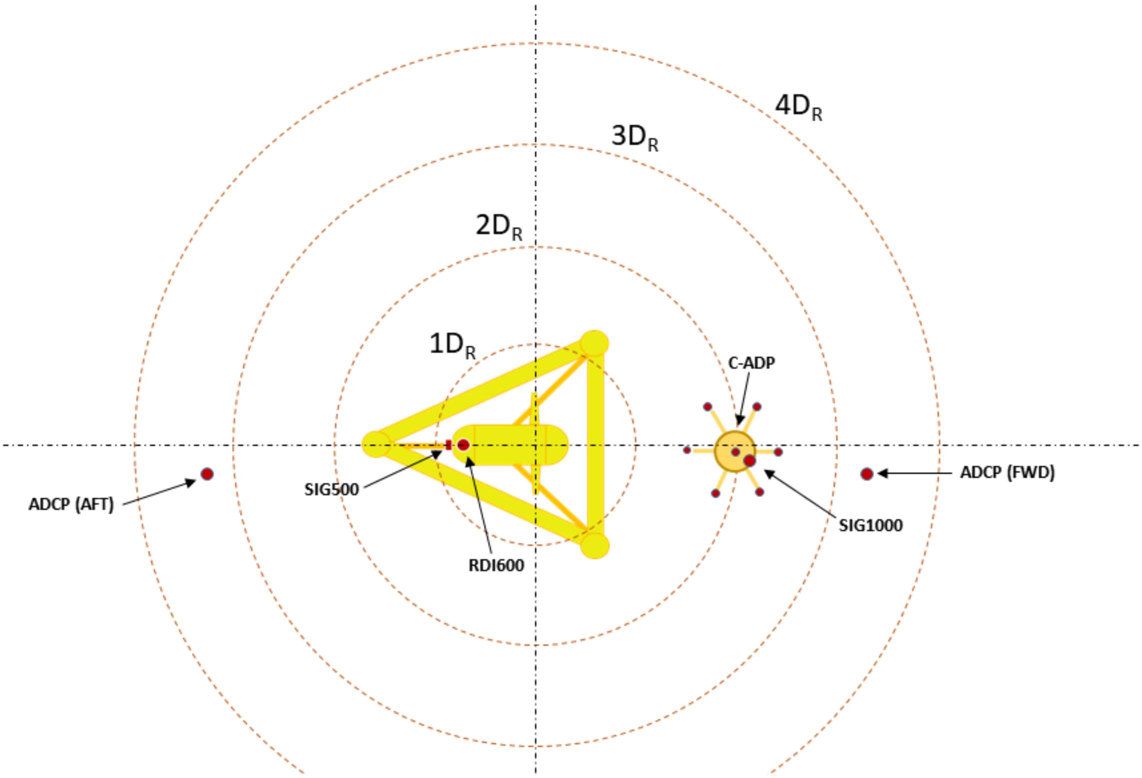

Figure 10: Target instrument location relative to Sabella D10 turbine

5.5 Instrument Integration and Systems

There are three levels of integration being used in the instrument deployment strategy:

(1) Direct integration with the D10 system [RDI600, SIG500 with D10].
(2) Seabed power and communications via D10 [C-ADP system from D10].
(3) Instrument integration on the seabed frame [SIG1000 with C-ADP].

A schematic diagram of the communication and data systems implemented in the RealTide Fromveur Strait data collection campaign is shown in Figure 11.

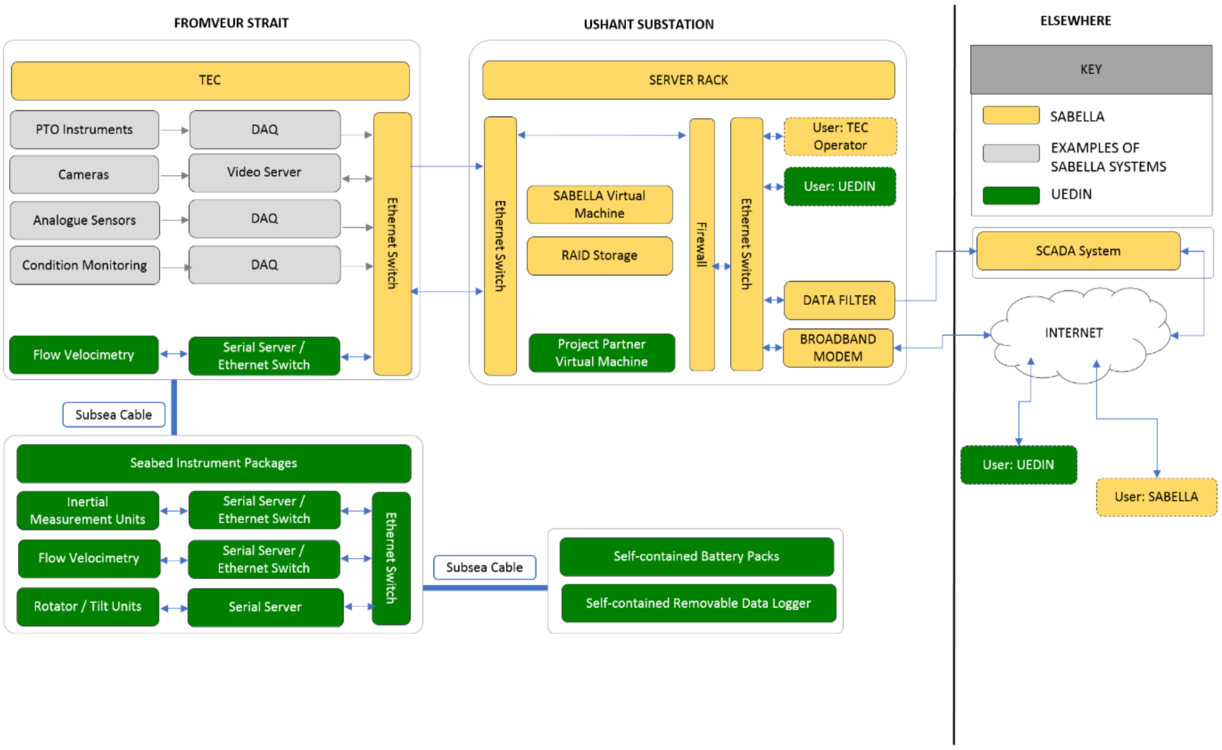

Figure 11: Instrument integration systems and sub-systems schematic for the RealTide programme.

5.5.1 Direct D10 Integration

The RDI600 and SIG500 have been mounted into the body of the D10, attached to the rear bulb. A 240V (nominal voltage and wide ranges are expected due to TEC operation) power supply point and two Ethernet communications ports have been provided by Sabella. The communications can be accessed remotely via the internet through the Sabella shore station on Ushant. The power/ communications connection points are accessed within the rear bulb of the turbine through the bulkhead of the dry turbine control module. A dedicated instrument control box (ICB) developed at UEDIN and mounted within the rear hub of the D10 is used to link the two instruments to the 240V supply and one of the communications ports. The ICB provides power management (instruments require clean DC power), switchable fusing, Ethernet switching and a controller that can be operated remotely to allow managed control of the instruments. This set-up allows a range of instrument configurations to be tested, different parameters targeted, and data capture throughout the deployment period. Real-time monitoring of this system can be instituted through the remote access.

5.5.2 Seabed Power/ Communications via D10

A second pressure vessel, the bypass-ICB, was installed to redirect power and the second communications port directly to a seabed patch cable which terminates at the outer shell of the D10. The purpose of the bypass-ICB is to provide a communication link to the seabed mounted C-ADP system to enhance the operational options of this instrument and to provide alternate power supply options to extend the operational life. Bespoke seabed cables have been procured allowing deployment of the C-ADP system up to 100m from the D10. The bypass-ICB is isolated from the ICB, so that in the event of the ICB failing there is still access to the seabed system. As with the ICB, this level of connectivity allows a range of instrument configurations to be tested, different parameters targeted, data capture throughout the deployment period, and the potential for system monitoring.

The seabed instruments will also be powered from battery packs (which may be diver swappable) in the event of loss of power and communications from the TEC over the cabled system.

5.5.3 C-ADP/SIG1000 Integration

The C-ADP will have a built-in control system that is required to manage the triggering, timing, signal strength, *etc.* of the acoustic transducers and to manage the local data capture. There will also be a set of system status sensors that will be used to determine optimal configuration settings. This control system will manage and monitor the power supply and provide the link to the seabed cable. The control system will have extra connection points to allow other instruments to be connected to the seabed cable and to be monitored locally as well as remotely. The SIG1000 D-ADP / ADCP will be integrated with the C-ADP through this controller.

5.5.4 Monitoring strategy

The intention is to take advantage of the shore-based network connection to implement a remote monitoring system. The shore computer will regularly check systems status (using scheduling) to capture critical states and send an e-mail message to prompt intervention. Integrated sensors including accelerometers will be included. Sensors and software will be used to manage the power, alter configuration to mitigate transducer failure, and indicate if physical intervention of the system is required.

5.6 C-ADP Advanced Sensor Outline Specification

Initial development of a convergent beam ADP (C-ADP) system tailored for tidal energy applications occurred in Orkney, UK on the ReDAPT project[5] and in Nova Scotia, Canada (the Vectron[6]) with this work aiming to extend the applicability of acoustic instruments to measure turbulence at rotor plane locations. The C-ADP concept in this context uses convergent beam geometry to achieve high resolution, three-dimensional measurements of mean and turbulent flow at a focal point distant (metres to tens of metres) from the sensor platform. Actuation of the transducers was trialled on ReDAPT in 2014 and will be further developed during RealTide in order to selectively and remotely control the location of the focal point which measurements are made. A variety of beam configurations will be implemented to obtain advanced turbulence measurements at and around hub height. The installation of the instrument relative to the D10 TEC rotor is shown in Figure 10. An outline of the structural, mechanical and systems specifications for the UEDIN C-ADP are given in Table 7.

Table 7: C-ADP (7-beam) outline specification, with integration of D-ADP (SIG1000) system

Outline Design	Quantity	Description
Seabed Frame Structure	1	Mild Steel (painted) Open Frame. Legs to accommodate uneven terrain. Mass concentrated centrally with lightweight radial "arms." Outline dimensions: 8m x 8m x 0.5m. Total weight not exceeding 1000kg (dry). Modular bolted assembly. Can be shipped on pallets and assembled on site.
Generic Battery Enclosures	3	Aluminium pressure vessels. Anodised and Painted and Anodic Protection. Non-rechargeable Alkaline battery packs. Approximately 30kg (dry).

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[5] Sellar et al. High-resolution velocimetry in energetic tidal currents using a convergent-beam acoustic Doppler profiler. 2015. Measurement Science and Technology.

[6] Hay et al. The Vectron. 2015. IEEE/OES Current, Waves and Turbulence Measurement (CWTM) Workshop

D-ADP Nortek 5-Beam 1Mhz (Off the Shelf Profiler)	1	Nortek Signature 1MHz. Profiling from 1m above Seabed to Rotor Top. Baseline configuration: - Sample Rate 8Hz; Bin Size 0.5m; Powered by dedicated external battery pack and TEC control and power connection via CCE.
Communications and Computing Enclosure (CCE)	1	New pressure vessel. Material TBC – likely to be 100% Acetal/Delrin®. Connects to TEC via 80m control and power cable. Controls UEDIN custom ADPs and connects to 5-Beam D-ADP.
TEC control and power connection	1	80m cable to be installed by divers to existing D10 connector on rear-bulb and CCE.
C-ADP Custom Multi-beam SB-ADP (Supplier TBC)	7	7 SB-ADPs arranged in a convergent beam configuration and featuring motorised actuation to allow remotely operable focal point positioning.
Miscellaneous bracketry	N/A	Acetal/Delrin and stainless steel bracketry (isolated from mild steel components).
Inertial Measurement Unit	7	IMU installed to each SB-ADP and connected to CCE for: -remote actuation controller. -vibration assessment. Measure acceleration in 3 axis and pitch, tilt and roll.
Launch and Recovery System (LaRS)	1	Custom installation and retrieval mechanical frame to add with frame lowering and to mitigate frame-arm / rope entanglement. Features leased equipment *e.g.*, dive cameras and positioning aids, which return to surface post deployment.

5.7 Data Management

The aim is to collect all available data sets from both the UEDIN instruments and Sabella ADCPs and integrate them with an internal-to-project database system being developed under D2.3. Any data from RealTide or held by UEDIN previously that can be made openly available subject to IPR restrictions will be served via this database. Data will continue to be sought from external sources (*e.g.*, other tidal sites) if their availability improves the data analysis activities of D2.2 (subject to any data controls).

The data capture will depend on the level of system integration. For fully autonomous deployments, the instruments are operating in stand-alone mode so the data will be captured on the instruments in internal memory cards. An operable communications link via the D10 will allow data to be recorded on the instruments internal memory and periodically downloaded, or captured directly across the communication link subject to available bandwidth. To minimise the risk of data loss, data should always be recorded on the instrument memory by default and ideally elsewhere in a redundant setup.

Outline Data Recovery Protocol:

1. Build pre-defined data archive directory structure on UEDIN Datastore.
2. Recover data from instrument memory cards onto the UEDIN Datastore with read-only permissions.
3. Store all supporting metadata digitally with the raw measurements (proprietary format).
4. Convert raw data to common data format (NetCDF) with standardised naming conventions, integrating all metadata, applying any relevant calibrations and conversions, then store on archive as read-only files. This provides Level 0 data from which all post-processing will build.
5. Apply data quality controls to the Level 0 data, introducing all relevant quality flags, uncertainty estimates, and additional metadata. This provides the Level 1 data, which is version controlled as the quality controls may be improved over time.

6. The Level 1 data are then post-processed to generate all required derived parameters with associated uncertainties, and additional metadata using the standardised naming convention. This provides Level 2 data.

Higher levels of post-processed data can be generated which meet end user needs. The level of post-processing provided depends on the level of control over the data processing the end users need. All raw instrument data will be recovered from the memory cards and stored, along with all supporting metadata, on the UEDIN Datastore as read-only files so that they cannot be modified. The Datastore is a secure, backed-up, and managed service that is a self-funded service provided by UEDIN. All post-processed data up to Level 2 will be stored on the Datastore with read-only access. The Level 1 and 2 data will be integrated with the database system being developed in D2.3.

An archival service, UEDIN's centrally provided DataShare, will be used to permanently archive derivative datasets, reports, meta-data and analyses and will generate digital object identifiers (DOIs).

5.8 Equipment Installation and Recovery

Instruments will be deployed in phases from April 2019, dependent on factors such as component procurement, weather windows, vessel, and diver availability. A flexible deployment programme has been identified as essential in order to realise a campaign that is both ambitious and technically and financially achievable. This allows the optimisation of deployments and recoveries around the best weather windows the utilisation of already mobilised vessels and staff.

A potential local vessel has been identified, the TSM Penzer.

Full details of the multi-instrument campaign deployment and recovery methods are being planned in conjunction with Sabella and marine service suppliers.