Turbulence: Best practices for measurement of turbulent flows.

A guide for the tidal power industry.

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The TiME project, funded by the Scottish Government and managed by the Carbon Trust through the Marine Renewables Commercialisation Fund (MRCF) Array Technology Innovation Programme, was developed to improve the understanding of the effect of marine turbulence on tidal arrays in Scottish waters.

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Abstract

Measurement of turbulence for the tidal energy industry is now recognised as a critical necessity in order to support such areas as accurate yield assessment, fatigue modelling and engineering design. This document (MCRF-TIME-KS9a) aims to provide to the sector a framework that documents a safe, t-for-purpose and quality assured survey guidance for the collection of quality, marine turbulence data. The outcome of which is to obtain quality controlled turbulence velocity dataset inclusive of noise (the removal of the noise element during post-processing is discussed within a sister document MCRF-TIME-KS9b).

This document addresses:

- Commercially available (acoustic and non-acoustic) instruments for measurement of marine turbulence;
- Instrument selection and limitations;
- Instrument set up for turbulence investigation;
- Site characterisation;
- Survey planning and operations; and
- Data pre-processing, quality control and management.

An advanced framework draws the manifold considerations into a logical sequence illustrating the various stages involved in the turbulence data acquisition process. This may change in the detail through time as the industry progresses but is intended as a useful framework to guide those involved in this area through the data acquisition process. It is anticipated that adherence to items within this will ensure that future data collection will be conducted in a consistent, reproducible and accurate manner across the tidal power sector.

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Nomenclature

Symbols

f	Frequency (Hz).
f_{bs}	Beam separation frequency (Hz).
f_s	Sampling frequency (Hz).
l	Lengthscale of turbulent fluctuations (m).
z	(Also H) Height from seabed (m).
θ	Angle of ADCP beam from the vertical ($^\circ$).
u, v, w	Velocity component in the streamwise, cross stream, and upward vertical directions (unless subscripts denote a different frame of reference) ($m\ s^{-1}$).
$\bar{u}, \bar{v}, \bar{w}$	Mean velocity component in the streamwise, cross stream, and upward vertical directions (unless subscripts denote a different frame of reference) ($m\ s^{-1}$).
u', v', w'	Fluctuating velocity component in the streamwise, cross stream, and upward vertical directions (unless subscripts denote a different frame of reference) ($m\ s^{-1}$).
Δ_b	Beam spread distance (m).
R_{tip}	Turbine rotor tip radius (m).
I	Turbulence Intensity (%).
F_W, F_B, F_D	Respectively weight, buoyancy and drag forces on an instrument (N).
P	Pressure (Nm^{-2} unless otherwise stated).

Subscripts

b	Denotes NEMO buoy body frame of reference.
i	Relates to a cartesian component x, y, or x ($i = [xyz]$) of position, displacement or velocity ($i = [uvw]$).

j	Relates to a cartesian component x, y or z ($j = [xyz]$) of position, displacement or velocity ($j = [uvw]$).
e	Denotes an earth level frame of reference, where the vertical direction is parallel with the acceleration due to gravity, the x direction is oriented East, and the y direction is oriented North.
min	Denotes a lower limit.
max	Denotes an upper limit.
mid	Refers to lengthscale boundaries defined in the framework of MRCF-TiME-KS10.
$large$	Refers to lengthscale boundaries defined in the framework of MRCF-TiME-KS10.
$small$	Refers to lengthscale boundaries defined in the framework of MRCF-TiME-KS10.

Acronyms

ABPmer	ABPmer Limited (Associated British Ports Marine Environmental Research).
ADV	(Also DCS) Acoustic Doppler Velocimeter (Doppler Current Sensor).
ADCP	(Also DCPS, ADP) Acoustic Doppler Current Profiler (Doppler Current Profile Sensor, Acoustic Doppler Profiler).
AWAC	Acoustic Wave and Current.
BMADCP	Bottom Mounted ADCP.
DQC	Data Quality Control.
DQMS	Data Quality Management System.
EMEC	European Marine Energy Centre.
FORCE	Fundy Ocean Research Centre for Energy.
HWA	Hot Wire Anemometry.
IEC	International Electrotechnical Commission.
IMU	Inertial Motion Unit.

ITP IT Power Limited.

LDA Laser Doppler Anemometry.

MBES Multi Beam Echo Sounder.

MCA Maritime and Coastguard Acency.

MRCF Marine Renewables Commercialisation Fund.

MSL Mean Sea Level.

NTM Notices To Mariners.

OAS Ocean Array Systems Limited.

PIV Particle Image Velocimetry.

PPE Personal Protective Equipment.

PTP Precision Time Protocol.

PUV Pulsed Ultrasound Velocimetry.

RAMS Risk Assessment and Method Statement.

ReDAPT Reliable Data Acquisition Platform for Tidal.

RSI Rockland Scientific International inc..

SBD Single Beam Doppler.

SNR Signal to Noise Ratio.

TEC Tidal Energy Converter.

TGL Tidal Generation Limited.

TiME Turbulence in Marine Environments.

TKE (Also k) Turbulent Kinetic Energy.

UoE University of Edinburgh.

VMADCP Vessel Mounted ADCP.

VMP Vertical Microstructure Profiler.

Preface: The TiME Project

This work is intended to disseminate outcomes of the 'Turbulence in Marine Environments' (TiME) project,[1] undertaken by a consortium comprising Partrac Ltd (Partrac), Ocean Array Systems Ltd (OAS), ITPower Ltd (ITP) and ABP Marine Environmental Research Ltd (ABPmer).

The primary objective of the TiME programme is to develop an improved understanding of turbulence relevant to tidal arrays and help inform the wider industry in applying this knowledge into future projects.To achieve this objective, we aim to provide a validated, integrated framework for site and resource assessment, data acquisition, analysis, and device performance estimation. The framework will holistically address the issue of turbulence and unsteady flow across the contexts of resource characterisation, device analysis, wake effects and array yield.

This report (MCRF-TIME-KS9a) forms part of the framework, encompassing data acquisition in the marine environment. Companion report MCRF-TIME-KS9b covers turbulence theory, characterisation and data analysis. Finally, MCRF-TIME-KS10 documents the engineering effects of turbulence on tidal devices and arrays.

State of the art

At the state of the art, tidal energy device manufacturers do not yet have the means to understand, predict or model unsteady interactions between their devices and turbulence in the marine environment.

Existing international standards for tidal resource assessment and characterisation (IEC 62600-201) recognise this:

> *While there is a potentially significant influence on Tidal Energy Converter (TEC) power performance due to turbulence inherent in the tidal flow, no corrections for the effect of turbulence should be performed in the reported assessment of power performance. Future efforts will be made to quantify this influence; however, this issue is not covered at this stage of the Technical Specification development.*

Array developers have insufficient information on the turbulence at potential sites, as the surveys they commission to characterise the resource almost exclusively use Acoustic Doppler Current Profiler (ADCP) instruments. ADCPs

[1] http://partrac.com/news/turbulence-in-marine-environments-time

produce noisy, band-limited and scale-limited data, i.e. are unable to make measurements across the required range of times, frequencies and turbulent eddy sizes required for characterisation of turbulence.

Insufficient characterisation of marine turbulence leads to devices that are either over-engineered (increasing their capital cost) or under-engineered (leading to device failure or frequent maintenance requirement, adversely affecting the operating cost). It is known that turbulence affects yield, but as yet unclear by how much. This uncertainty in yield is a significant commercial risk for project development. Better quality information will allow reduction of (and better trade-off between) both capital and operational expenditure. Current attempts to deal with the challenge of turbulence are either computationally intensive (e.g. Large Eddy Simulation), or are based on linearised models that do not reflect important aspects of the physics.

Background to the TiME project

The TiME project was proposed in response to the above uncertainties surrounding the effect(s) of turbulence within the tidal power community. In particular, the intention is to address several innovation areas formally identified by the Marine Farm Accelerator[2]:

- **Operations and Maintenance:** By reducing the uncertainties at the design stage, components can be designed to have an appropriate lifespan and breakages can be reduced. This will reduce unplanned maintenance visits and reduce Operations and Maintenance costs.
- **Yield Optimisation:** Characterising turbulence will enable device developers to account for turbulence in a realistic manner. This is likely to lead to improved yield through the adjustment of control systems and the evolution of various components. This will lead to improved performance and availability, both contributing to improved yield.
- **Wakes:** are strongly affected by turbulence and accounting for wakes accurately in array models will allow array layouts to be optimised to maximise array yield.
- **Site Characterisation:** The measurement and modelling techniques developed under this project will allow site characterisation to include turbulence for the first time. This will give a much better definition to the

[2] marinefarmacceleratorURL

tidal flows at a site and will enable project developers to assess potential sites with more confidence.

More specifically, the TiME project objectives are to:

- Develop and implement a safe, fit-for-purpose and quality assured marine survey methodology for the tidal industry, allowing measurement of tidal flows including turbulence.
- Use data collected at multiple sites for future tidal arrays to develop novel turbulence analysis and classification schemes and investigate the underlying structure of marine turbulence.
- Identify the aspects of turbulence that have greatest significance for TEC structural loading and energy yield, using a hydrodynamic turbulence-blade-wake interaction model.
- Develop methods to evaluate the variation in array yield due to turbulence using proprietary array modelling software and the new knowledge developed earlier in the project.
- Contribute guidance documentation on how to incorporate turbulence into the design of tidal turbines and arrays.

Finally, the techniques that will be researched and tested under this project aim to **bridge the communication gap which currently exists between marine surveyors and device developers**. The improved understanding of turbulence, ability to make useful measurements and ability to model its effect on turbine survivability and yield will significantly de-risk upcoming and future tidal projects.

1 Introduction

1.1 Document aim

This document (MCRF-TIME-KS9a) aims to provide a basis that will ensure consistency in the data acquisition process required for characterisation of turbulence (with regard to tidal energy device development and array development). This assumes a decision to collect turbulence data has already been made.

The endpoint in terms of data acquisition is a quality controlled dataset that includes noise, and not generation of a denoised dataset. Denoising and characterisation of turbulence from raw measurements is viewed as an area of post-processing and is dealt with in a sister document MCRF-TIME-KS9b.

Measurement of turbulence for the tidal energy industry is now recognised as a critical necessity in order to support such areas as accurate yield assessment, fatigue modelling and engineering design. A wide raft of areas require detailed consideration ranging across instrument selection, health and safety, site characterisation and data analysis. This document addresses:

- Commercially available instruments for measurement of marine turbulence,
- Instrument selection and limitations,
- Instrument set up for turbulence investigation,
- Survey planning and operations, and
- Data management.

It is anticipated that adherence to items within this, notwithstanding future progress and technological and other developments, will ensure that future data collection will be conducted in a consistent, reproducible and accurate manner across the tidal power sector.

Figure 1.1 attempts to draw the manifold considerations into a logical sequence illustrating the various stages involved in the turbulence data acquisition process. This may change in the detail through time as the industry progresses (e.g. as manufacturers develop more advanced instruments) but we anticipate that it may serve as a useful map to guide those involved in this area through the data acquisition process.

This document (MCRF-TIME-KS9a) along with sister document MCRF-TIME-KS9b provide background to each step of the process in Figure 1.1.

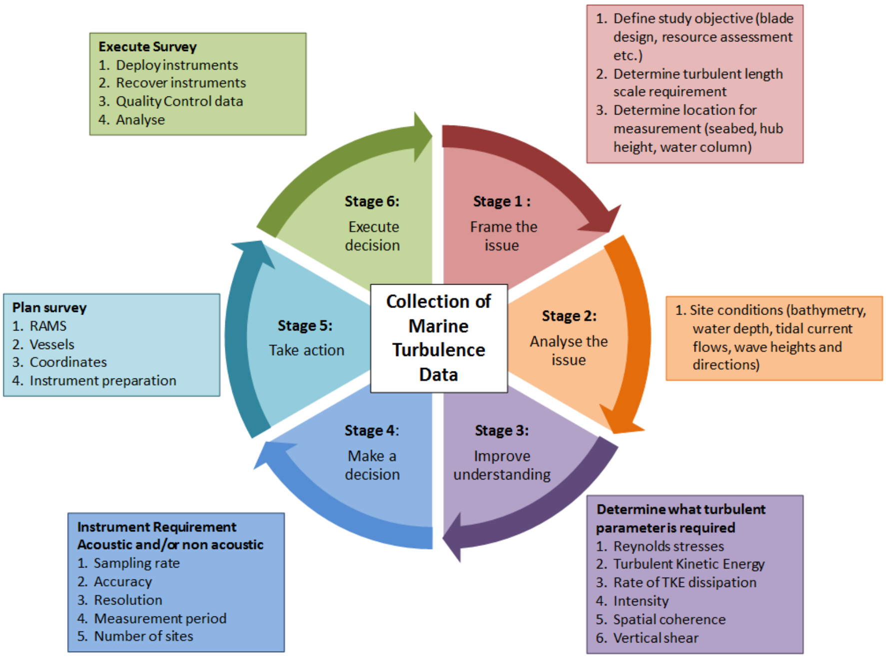

FIGURE 1.1 A suggested framework for collecting marine turbulence data.

1.2 LIMITATIONS

The present guidance document limits its scope to use of acoustic and non-acoustic methods of measuring marine turbulence. There are numerous methods including Laser Doppler Anemometry (LDA), Particle Image Velocimetry (PIV), Pulsed Ultrasound Velocimetry (PUV), and Hot Wire/Film Anemometry (HWA/HFA), all of which can be used to measure turbulence, but which are not field instruments and therefore not covered here.

This document assumes a decision to collect turbulence data has already been made. It is restricted in scope to all the processes involved in generating a quality controlled velocity dataset[1], inclusive of noise. It does not advocate in any way, manner or form any specific commercial turbulence measuring instrument; however, recommendations of relevance are included in this report.

[1]The report includes several non-acoustic instruments which do not directly collect velocity data but alternative fundamental turbulence parameters.

1.3 Format of this report

Since not all data campaigns are the same (having different aims, instrument availabilities and site conditions) it is not the goal of this work to provide a full step-by-step guide for data acquisition.

In order to provide the reader with more generic guidelines for best practices in data acquisition, this report reviews instruments and methods with the following structure:

Chapter 2 Reviews commercially available instrumentation for measurement of marine turbulence together with some upcoming concepts in instrumentation.

Chapter 3 Describes aspects of instrument setup particular to data acquisition in turbulent flows.

Chapter 4 Lists considerations required when planning and undertaking marine surveys in tidal races.

Chapter 5 Contains a case study in which site typology for two sites surveyed during the TiME project is assessed. This forms a critical part of the survey planning discussed in Chapter 4.

Chapter 6 Highlights the need for, and some best practises to achieve, data quality management.

Chapter 7 Collects key points and insights.

To allow the reader a quick overview and enable easy reference, a range of formatting styles are used:

A definition of a key concept, quote or term is set centred in italics.

> A key insight, note, comment, lesson learned or take-away is highlighted in a grey box.

2 Instrumentation for Measurement of Turbulence

This chapter presents and discusses the commercially available instruments that can measure fluid velocity and/or turbulent parameters. The following sections aim to inform the reader on the types of instruments available and their capabilities and limitations. Finally, an instrument selection process is developed, allowing the reader to make an informed decision on the type of instrument to use for measurement of turbulence.

The practical measurement of turbulent parameters in tidal flows presents oceanographers with a unique challenge, since it is generally necessary to obtain high temporal and spatial resolution measurements of velocity. Further, the measurements must be of sufficient signal to noise ratio (SNR) and duration to yield robust quantification of turbulent properties.

Hinze (1975) usefully identified a number of requirements for measuring turbulence. Along with not disturbing the flow, vibrating, or introducing drift into the measurement, the instrument must have adequate temporal response, a sensing volume smaller than the smallest scales of the flow, and the ability to measure fluctuations of only a few percent about the mean flow. This set of pre-conditions is difficult to meet instrumentally.

Correct determination of the mean flow is fundamental to estimation of the turbulent fluctuations around it. MCRF-TIME-KS9b includes a discussion on stationarity and estimation of mean velocity profiles in tidal streams, for which it can be difficult to determine the correct mean velocity profile. The following chapters assume that the mean component of flow is determined robustly from the measured signal(s).

The types of commercially available instruments which can measure marine turbulence, or some aspect thereof, can be broadly classified into:

- acoustic, and
- non-acoustic instruments.

Acoustic instrumentation includes both Acoustic Doppler Current Profiler (ADCP) and Acoustic Doppler Velocimeter (ADV) range of instruments; non-acoustic instrumentation includes shear probes in a range of configurations.

2.1 Acoustic Doppler Current Profilers

Acoustic Doppler Current Profilers (ADCPs) were first developed in the late 1970s and since then have revolutionised the measurement of velocity of water motion. ADCPs measure the speed and direction of ocean currents using the principle of 'Doppler shift'; a change in apparent frequency of a wave measured by an observer with movement relative to its source. The ADCP exploits the Doppler effect by emitting a sequence of high frequency pings of sound which scatter off moving particles in the water. Depending on whether the particles are moving toward or away from the sound source, the frequency, or pitch, of the return signal bounced back to the ADCP is either higher or lower. Particles moving away from the instrument produce a lower frequency return and vice versa.

A key assumption on which the ADCP is based on is that the particles in the water column are moving at the same velocity as the surrounding water. The Doppler shift is therefore directly proportional to the flow speed. Four beams[1], the so-called Janus configuration, are used to measure different directional components of velocity (Figure 2.1) along the beam directions. These four (non-orthogonal) velocity measurements are resolved into a three-component (east, north and vertical) velocity vector along with an 'error velocity' estimate used to determine data quality.

A binning process for different time delays (i.e. between ping and reception) is used to measure simultaneously at different distances from the unit; hence the term 'Profiler'.

ADCP instruments seem to meet a number of the prerequisites outlined by Hinze [16], namely it is a non-intrusive profiling measurement approach, a relatively high sampling rate is feasible and the instruments possess an adequate temporal response. However, the ADCP instruments have some defined limitations in terms of spatial resolution / length scale resolution, instrument stability, noise floor magnitude and acoustic reflections. An understanding of the limitations of the ADCP technology, which may change over time as manufacturers change or improve devices, is critical to the acquisition of good quality, low noise turbulence datasets for the tidal power industry.

The ADCP is increasingly applied to oceanic measurements because its spatial resolution and profiling range are usually adequate to measure the flow speed throughout a large portion of the water column and importantly for the tidal energy industry at the required hub height [20]. ADCPs, as non-mechanical

[1] Modern ADCPs now include a 5th beam, orientated either upwards or downwards.

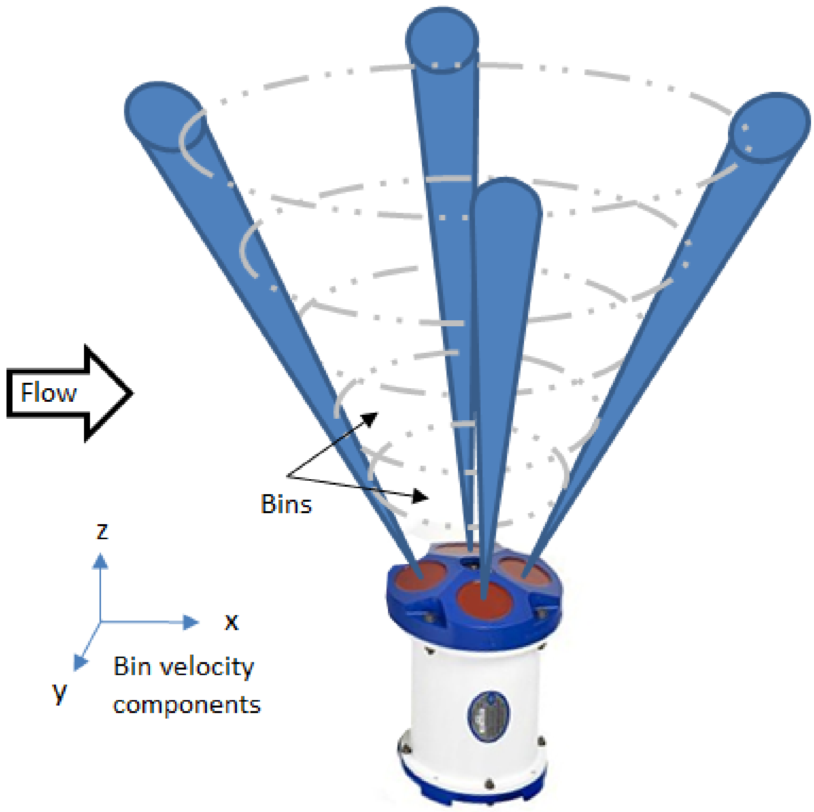

FIGURE 2.1 Vertically oriented ADCP and the Doppler effect. As the acoustic pulse propagates through the water column, a continuous echo comes back to the instrument. The echo is processed for Doppler shift and the current can be calculated for multiple levels or depth cells. After `hydroacoustics.usgs.gov`.

instruments, make non-intrusive measurements and thereby virtually eliminate the possibility of flow disturbance over most of the profile.

The ability of this instrument to sample data rapidly ($O(1\ Hz)$) suggests its use in estimation of turbulent quantities. Bottom mounted ADCPs (section 2.1.1) may be used to observe the mean and turbulent flow components in tidally energetic sites over spring and neap tidal cycles [25]. Known analytical methods such as the Variance Method[2] [20, 21, 25, 26, 31] and the Structure Function

[2]Reynolds Stress estimated from the difference in variance between the along-beam velocities of opposing acoustic beams with a correction for the sampling scheme and bin size. The estimation assumes that the velocity field is horizontally homogenous so that the statistics are the same for each of the four beams [20]. This assumption holds only statistically in a turbulent

method (Wiles et al., 2006) can be applied to the high frequency ADCP beam data to extract estimates of Reynolds Stress and Turbulent Kinetic Energy and the rate of production of TKE. The advantage of using the ADCP for turbulence studies is that it enables the user to obtain relatively long time series (up to a month) of turbulent parameters [33]. However, the application of the Variance Method, is restricted to ADCPs with at least four beams, as well as to highly energetic aquatic systems.

2.1.1 *Bottom Mounted Mode*

In 'Bottom Mounted' mode (a common configuration in the tidal power industry), the ADCP is deployed in a frame on the seabed facing upward. Because the emitted sound extends from the instrument on the seabed to the ocean surface, the ADCP measures the current speed and direction averages at multiple depths simultaneously. Various frequency instruments are available commercially; increasing the acoustic frequency allows the achievement of improved resolution or better accuracy in velocity measurement, but at the same time suffers reduced range.

MCRF-TIME-KS10 highlights the requirement to characterise velocity profile as well as turbulent quantities throughout the majority of the water column (at least spanning the rotor disc and as far above and below as is practicable).

- ✓ Bottom mounted ADCPs can be used to measure throughout the water column.
- ✗ Selecting increased frequency or resolution decreases the effective range of the instrument, which may limit ability at deeper water sites.

2.1.2 *Vessel Mounted Mode*

ADCPs can also be deployed in moving vessel mode since they have the capability of measuring their own motion relative to the Earth using the Doppler shift of echoes received from the seabed. A technique referred to as bottom tracking. In moving vessel mode the ADCP effectively measures the water current by subtracting the velocity of the vessel over the ground from the measured velocity through the water. With this bottom tracking capability,

environment. An assumption of stationarity is also necessary which imposes constraints on the length of record. The averaging period must be of sufficient duration to provide a good sample of the largest turbulent eddies but not so long that the turbulent processes cannot be regarded as quasi-stationary.

ADCPs can be deployed in downward looking mode on a side mount pole over the side of a vessel. The vessel mounted ADCP (VMADCP) is then towed along predetermined transects to measure vertical profiles of current speed and direction and provide information on the spatial variation of the currents over a complete tidal cycle. VMADCP surveys are typically used for measuring mean currents and are not really suitable for estimating the turbulent quantities with the Variance Method since the VMADCP currents are measured along a moving platform, and turbulence measurements require measurements from a rigidly mounted instrument.

However, VMADCP surveys are an excellent way of providing a synoptic view of the tidal current streams at a given tidal energy site [14] over different stages of the tide, and are a recommended survey technique at the tidal energy resource assessment stage [12].

Vessel mounted ADCP surveys:

- ✓ Provide an overview of resource at a tidal energy site at the early assessment stage.
- ✗ Are unsuitable for characterising turbulence due to their inability to achieve a converged average velocity profiles (and the likely added noise levels resulting from rapid instrument motion).

2.1.3 *Spatial resolution*

ADCPs are limited in the vertical profile by the depth cell dimension (bin size) and beam diameter. This is generally 1 m for deployments at tidal energy sites; thus the smallest resolvable eddy is also 1 m. It must be recognised that the current generation of commercially available ADCPs cannot measure quantities that depend on the smallest scales of the flow. Limiting turbulent length scales are $\approx 0.5\ m$ (600 kHz) and $\approx 1.0\ m$ (300 kHz).

Bin size is an ultimate limit on spatial resolution. However, this is not the full story when considering turbulence. The 'beam separation frequency', f_{bs} must also be considered. This is the rate at which an eddy with length scale similar to the beam spread Δ_b will appear when advected by the tidal flow $\overline{u}(z)$, according to Taylor's Frozen Eddy Hypothesis:

$$f_{bs} = \frac{\overline{u}(z_{bin})}{\Delta_b},$$
$$\Delta_b = 2\ z\ atan(\theta) \tag{2.1}$$

where z_{bin} is height of a bin centre from the ADCP instrument face location and θ is the beam spread half angle of the instrument. The velocity signatures of eddies smaller than twice the beam spread $2\Delta_b$ may not be robustly captured in the measurement or suffer aliasing.

Near the free-surface boundary, as the length scale of the turbulent fluctuations decreases, some under sampling of the variance may result. Using a depth cell size of 1 m produces an underestimate of the Reynolds Stress of 5%, but this is reduces to $< 5\%$ when using depth cells of 0.5 m according to Rippeth et al. [25]. It must be noted therefore that an additional effect of decreasing the depth cell size is to increase the instrument noise and decrease the range of the instrument.

2.1.4 *Temporal Resolution*

The temporal resolution of an acoustic profiler depends on the physical response time, processing time in the electronics and measurement frequency. The response time is limited by the acoustic pulse travel time and is typically limited to 1 Hz (ADCPs).

The stationarity period discussed in MCRF-TIME-KS9b gives a number of samples $N = T/\Delta t$, where $T \approx 10$ min. For an example ADCP setting of $\Delta t = 1s$, $N \approx 600$, although as discussed in the companion report these samples aren't necessarily independent for the largest lengthscales. Thus, a 1 to 10 Hz limit on instrument sampling rate is not necessarily a strong limitation in the use of ADCPs to measure turbulence, since techniques will still be required to overcome lack of data convergence (as discussed in MCRF-TIME-KS9b). Nevertheless, using the maximum possible value of N combined with the maximum number of pings in each ensemble will give the best noise reduction and ultimately the most accurate measurement of fluctuating velocity components u_i', especially in the higher wavenumber part of the spectrum.

Similar to the spatial resolution of particular lengthscales in the flow, the temporal resolution is also affected by the beam separation frequency f_{bs}. Whilst sampling may occur at higher rates, only measurements of turbulent fluctuations with timescales less than $1/f_{bs}$ are valid.

Attempts to increase the sampling rates of ADCP instruments will improve accuracy in measurement of smaller scale (faster) fluctuations, although due to the fundamental limitation of the instrument geometry, **any effort to raise the sampling frequency f_s of the instrument above the limiting**

beam separation frequency f_{bs} would be wasted.

2.1.5 *Noise floor magnitude and acoustic reflections*

The quality of ADCP data is partially dependant on the level of Doppler noise, which results from errors in measuring the phase shift of the reflected pulse. Many factors contribute to Doppler noise: the processing scheme, incoherent or coherent, operational mode, bin size, and pulse design coding, length, and strength. Flow conditions such as shear and turbulence also affect the noise level of ADCPs, especially coherent profilers, because they affect the form of the reflected pulse. In pulse-coherent systems, measurement errors or data losses can be due to decorrelation of sequential pings caused by rapid changes in the flow, e.g. turbulence.

Incomplete removal of Doppler noise will cause the resultant fluctuating velocities u_i' to be biased slightly high, and thus be conservative for the purpose of tidal design loading specification, as discussed in MCRF-TIME-KS10. Failing to account for Doppler noise at all would result in unnecessarily high factors of safety for turbine designs [7, 30].

2.1.6 *Ringing, flow disturbance and sidelobe interference*

After transmitting a ping, the ADCP transducers continue to vibrate for a short time, and velocities cannot be measured over the distance that the sound travels while the transducers become quiescent enough to record the backscattered acoustic energy accurately[3]. To exclude regions of the flow affected by ringing, a blanking distance is specified. The fraction of the distance from transducer to the affected boundary is $1 - cos(\theta)$, where θ is the angle between the beam and the vertical. Any bins within or partially within this part of the profile will be affected.

Sidelobe interference biases velocities towards the boundary velocity, or in the case of a stationary boundary, towards zero. Four beam (Janus) ADCP configurations are affected by side lobe interference and data loss is generally the last 6% of the water depth for 20° beam angle and 15% for a 30° beam angle. The five beam Nortek AD2CP and the RDI five beam ADCP Sentinel V, both include a vertical beam which allows for direct measurements of vertical velocity unaffected by side lobe interference. As a result the inclusion of a 5th

[3] Both the ADCP and surrounding equipment (including the vessel) require a finite time frame to allow ringing from the transducers to dissipate. Any signal returning prior to this will be contaminated and thus removed from the data analysis. In reality, this represents the first $\approx 1\mathbf{m}$ of the dataset depending on settings and programming.

beam reduces random noise in the vertical velocity records, a feature which will improve the accuracy of turbulent quantities on a practical level.

Further noise treatments are discussed in MCRF-TIME-KS9b.

2.1.7 *Instrument positioning and stability*

In order to measure turbulence with any confidence, the ADCP instrument must physically be level, pointing upwards at all times[4] and free of tilt adjustments through the deployment period. Bias in the measurement of tilt angles can easily contaminate the velocity dataset, especially the vertical velocity component.

The platform on which the instrument is deployed in will determine how much the instrument will move. ADCPs placed in a specialised gimballed frame on a rocky seabed will ensure that the ADCP is orientated vertically. However, in very high flows, the gimbal might be affected by vibration. The alternative is to deploy the ADCP fixed within a seabed frame; ADCPs placed in a fixed frame will prevent vibration issues but they must be deployed with extreme care to ensure that the frame is level on the seabed. This is not easy at tidal energy sites which are normally areas characterised by rocky seabed and very little sand cover, and this issue remains a challenging area for the collection of good quality turbulence data (this emphasises the utility of using available high fidelity seabed data such as site benthic camera video footage or sidescan / bathymetric in advance of instrument deployment) - see Chapter 5.

2.2 Five-beam Acoustic Doppler Current Profilers

5 beam ADCPs are a recent technological innovation introduced by manufacturers. Six notable improvements when using the two 5 beam commercially available ADCPs (the TRDI Sentinel V ADCP and the Nortek AD2CP) over the 4-beam TRDI Workhorse ADCP have been observed by Scripps University when conducting a study on understanding internal waves and turbulence in the coastal ocean[5]:

- ✓ Five beams provide a significant advantage over four beams because the vertical velocities can be measured directly (rather than derived).
- ✓ Data views of vertical motions show sharper features compared with 4-beam ADCP data. Because the beam measuring the vertical currents

[4] within 5° from the vertical for pitch and roll
[5] www.rdinstruments.com/pdfs/sentinel_v_vertical_hr.pdf

is aligned with the direction of motion, the resulting data quality (low noise, high resolution) is improved.

✓ Surface echoes along the vertical beam have a sharper, more distinct signal as it does not include noise from side lobe interference.

✓ Data adjacent to a boundary can be used for vertical motions because acoustic returns along the vertical beam are not biased by side-lobe interference.

✓ A vertical beam provides reliable measurements up to the surface under highly energetic wave and current conditions.

✓ The fifth beam acts to confirm or otherwise the assumption of homogeneity across the flow volumes seen by the four beams.

2.3 Acoustic Doppler Velocimeters (ADVs)

The Acoustic Doppler Velocimeter (ADV) is a three dimensional acoustic velocity sensor which offers unobstructed three dimensional flow measurements at high sampling rates and with a small sampling volume. The ADV is also suitable for wave measurements using the pressure sensor.[6] It has been demonstrated that the sensors can be deployed either as a motion compensated moored instrument or attached to a fixed structure near the seabed (including the tidal energy device).

ADV operation is based on the Doppler shift effect, similar to the ADCP technology. Commercial ADV instruments consist of three receivers which are positioned in the 'bi-static' configuration; 120° increments around a transmitter (Figure 2.2). The probe is submerged within the flow and the receivers are slanted at 30 degrees from the axis of the transmit transducer, focussing on a common sample volume from the probe to ensure non-intrusive flow measurements [32].

In addition to directional fluctuations, complex spectra from the ADV data can also be used to examine the rotational sense of the directional variations at each frequency.

[6]Wave measurements are processed using the PUV method to extract information on the wave field. The name PUV is a description of the method, and is an abbreviation of the three quantities measured: Pressure and the two horizontal components of the waves orbital velocity, U and V. The pressure measurement provides estimates of the non-directional wave parameters (height, period, etc.) and the combined P, U, and V measurements are used to estimate the directional wave parameters. Co-measurement of waves at tidal energy sites is a useful additional measurement capability.

The ADV can be used to provide a direct method of measuring Reynolds Stresses via the Reynolds Stress method, TKE method and inertial dissipation method[7] (the latter of which uses the spectra of the turbulent fluctuations [17] close to the seabed but is not suited to measurement throughout the water column). All three methods require rapid sampling of the three components of velocity in a small sampling volume, so that terms of the type $\overline{u'w'}$ can be calculated directly from the covariance of u and w at the measurement height or in the case for tidal sites the required hub height.

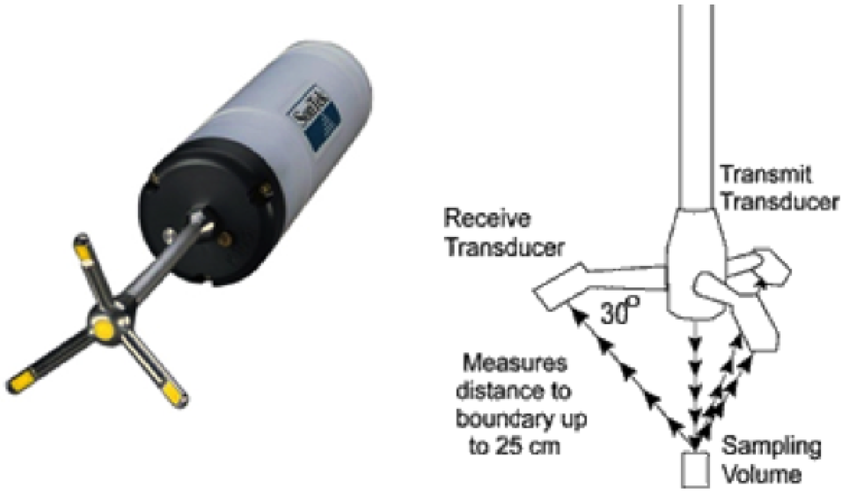

FIGURE 2.2 Operation of an ADV showing the measuring distance of the three components of flow.

2.3.1 *Spatio-temporal resolution*

The fundamental difference between the measurement principle of an ADCP and that of a current meter such as the ADV is that the ADV samples a small volume ($O(1\ cm^3)$) using three (or sometimes four) convergent acoustic beams to infer three components of velocity at a point providing a measure of the instantaneous velocity vector at its position [30]. Acoustic Doppler current profilers (ADCPs) sample larger volumes ($O(1\ m^3)$) and are subject to the beam separation frequency limitation discussed in section 2.1.3. Both instruments have intrinsic standard errors, which result from estimating the Doppler shift of finite-length acoustic pulses and are termed 'Doppler noise'. However, the Doppler noise is typically much larger for ADCPs than for ADVs. ADVs are

[7]The Inertial Dissipation method is based on the relationship between turbulent kinetic energy density and wave numbers in the inertial sub-range, where the cascade of energy from low to high wavenumbers must be equal to the dissipation rate, assuming that there are no local sources or sinks for the energy [17].

capable of examining the majority of the turbulence spectrum, including the smaller scales (down to $\approx 10mm$).

ADVs can sample at much higher rates than ADCPs (up to 64 Hz) and have become the standard for many boundary layer turbulence studies in both the laboratory and field (non-tidal race) experiments. However, it should be noted that higher sampling rates are subject to degraded accuracy due to an increase in noise relative to signal. Furthermore, turbidity at the study site should be considered if high frequency sampling is desired, given that the signal must have a sufficient volume and size of suspended particulate matter from which to scatter from. Where the water is very clear, the data quality may suffer with faster sampling rates and limitation is advised.

The lack of a limiting beam sampling frequency, and a small measurement volume, mean that:

- ✓ ADVs can sample the flow with fine spatial resolution (down to $\approx$ 10 mm), below which turbulence likely to conform to well understood isotropic assumptions and dissipative relations.
- ✓ Reynolds Stresses can be accurately measured, since the complete contribution of large, medium and small lengthscales is well accounted for.
- ✓ ADVs can sample with high frequency, allowing inspection of the majority of the turbulent spectrum.

However:

- ✗ Unless multiple instruments can be mounted through the water column, the ADV is constrained to point based measurements, rather than profiles.
- ✗ Instrument response in the lower frequency range depends on the ability to compensate for motion of the platform or other mounting arrangement.
- ✗ Accuracy of measurements is sensitive to sensor alignment to the flow (i.e. intrusion of the instrument itself upstream of the measurement location).

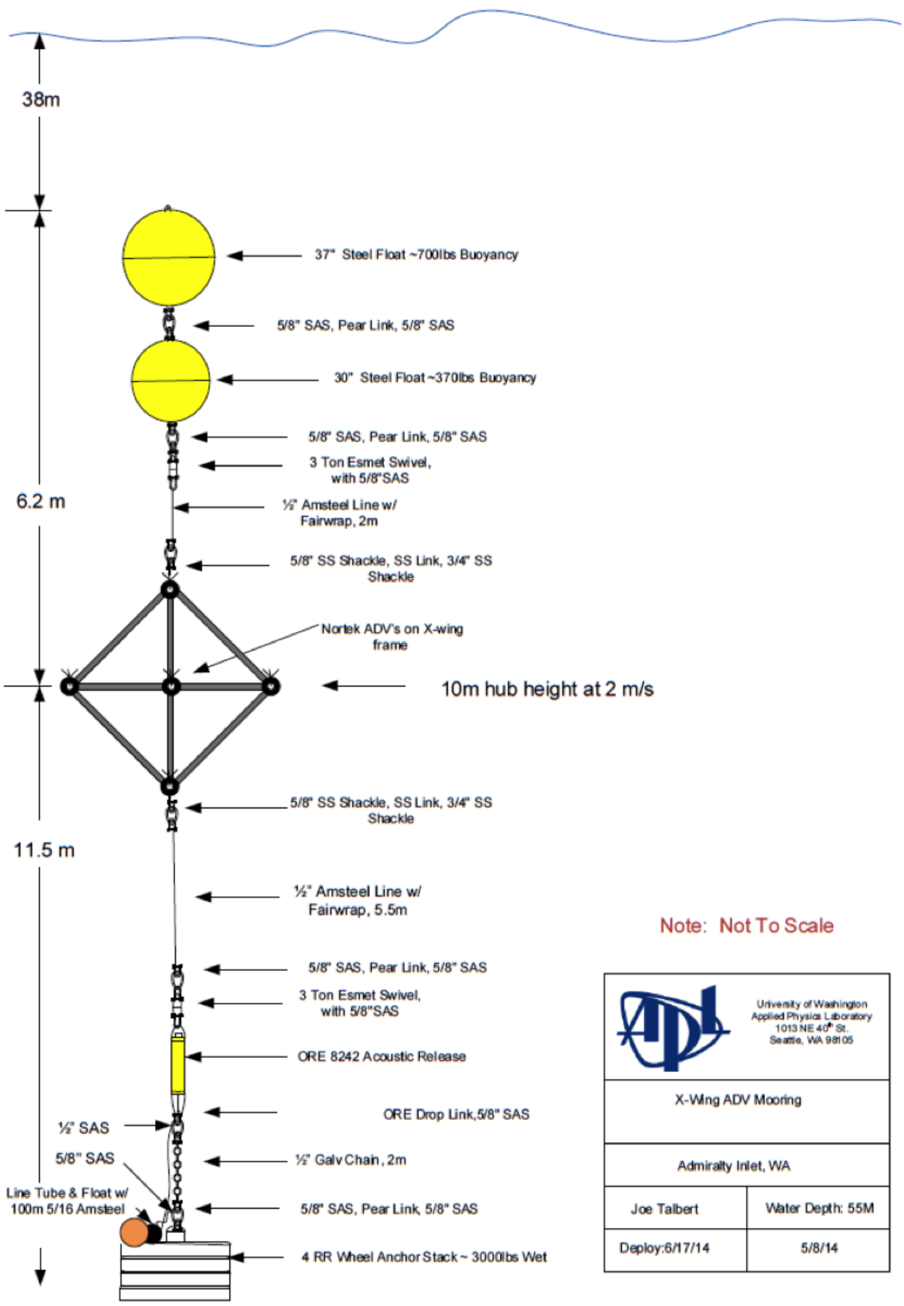

FIGURE 2.3 X-Wing combined IMU-ADV Mooring System from Kilcher et al., (2014).

2.3.2 *Fixed or platform mounted configuration*

ADVs can be attached to subsea frames, to fixed towers/pylons or to subsea buoys/platforms. A more detailed review of the use of an ADV on a subsea platform at hub height is given for the example of a Rockland Scientific 'Nemo' in section 3.4.

2.3.3 *Moored configuration*

Voulgaris and Trowbridge [32] performed a laboratory evaluation of ADVs for turbulence measurements and showed that ADVs measure mean velocities and Reynolds Stress within 1% of the ground truth value. The ADV resolves the vertical velocity variance well, but sensor noise can affect the variance of the horizontal velocity components (see noise treatment options in MCRF-TIME-KS9b).

There is growing confidence that moored ADVs deployed in a vertical array [19] with hi-fidelity Inertial Motion Units (IMU) may be used successfully for determining the spatial coherence of turbulence at marine hydrokinetic turbine deployment sites. ADVs on mooring lines can change orientation and measure a velocity signal that is contaminated by the moorings motion. The as yet unique approach reported by Kilcher et al. [19] showed that moored synchronous IMU-ADV measurements can be used to remove mooring motion in the time-domain and that this provides a framework for estimating coherence from moored ADV measurements. Improvements in mooring design will go a long way to reducing mooring motion and will represent a significant step forward for tidal device site characterisation and ocean measurement capability in general.

2.4 Profiling Shear Probes (non-acoustic)

Micro-structure shear probes were initially developed in the 1970s but have only recently become reliable, commercially available products. The micro-structure shear probe (Figure 2.8, which is commonly deployed on free-fall prolers in the ocean, is a technology used to sense the turbulent fluctuation of the two velocity components orthogonal to the direction of proling. Several manufacturers make shear probes; the working of the shear probe manufactured by the Canadian company RSI is best described in Lueck [22].

The shear probe (Figure 2.4) consists of a piezo-ceramic element 13 *mm* long, 1.6 *mm* wide, and 0.5 *mm* thick, that is embedded halfway into a hollow stainless steel support sling. The free end of the piezo beam is encased in a flexible, bullet-shaped, silicone rubber tip that forms an axially symmetric airfoil. As the probe moves axially through the water at the speed w (which is the fall rate of a profiler), the horizontal component of the turbulence velocity, u', turns the total velocity, u, into the vector sum of w and u', and induces an angle-of-attack (AOA), (Figure 2.4). When the total velocity has an AOA, it induces a lift force over the surface of the probe, and this force microscopically bends the piezo-ceramic beam. The bending of the ceramic liberates or absorbs an electric charge (depending on the direction of bending) and this charge is turned into a voltage, $e = Swu'$, where S is the sensitivity of the probe. This voltage is time differentiated to produce the signal $E = e/t = SWu/t$. With Taylor's 'Frozen Eddy Hypothesis' (Equation 2.2), the time rate-of-change of u' is converted into a spatial gradient, to yield the vertical shear of horizontal velocity. Velocity shear probes resolve velocity fluctuations with length scales ranging from 0.001 m up to approximately 1 m, thereby resolving the turbulent energy spectrum from the inertial sub range to the dissipation scale. Profiles of turbulent TKE dissipation rates (a key parameter for the numerical modelling of turbulence) can be achieved with the shear probes.

$$\frac{\partial u'}{\partial z} = \frac{E}{w^2 S} \tag{2.2}$$

The shear probes are mounted on an instrument package and either free fall or are carried through the water at a known speed, typically 0.5 $m\ s^{-1}$ to 2 $m\ s^{-1}$. Streamlined free fall microstructure instruments have been designed to fall smoothly and freely through the water, falling at a constant speed under gravity before being recovered by a loose tether to the vessel. During deployment the vessel drifts unimpeded with the current flow.

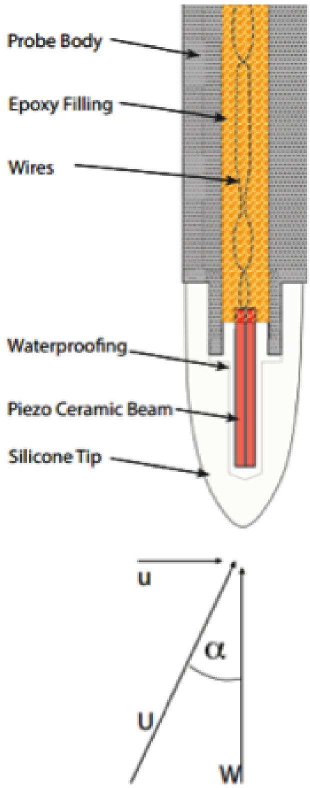

FIGURE 2.4 A schematic representation of the air-foil free-falling shear probe from Lueck [22].

2.4.1 *Example: Vertical Microstructure Profiler*

An example of a free-fall vertical microstructure profiler for measurement of micro-scale turbulence is the Rockland Scientific Vertical Microstructure Profiler VMP-200. The VMP profilers carry microstructure velocity probes (shear probes) and high-resolution temperature sensors (thermistors) to measure turbulence parameters. These turbulence sensors are mounted on the nose of the VMP, pointing downward (Figure 2.9). This instrument consists of a cylindrical profiler (0.1 m diameter, 1.5 m length) with turbulence and thermistor sensors mounted on the 'nose'. The aft-end of the VMP has a radial array of filaments that control the fall-rate of the profiler and stabilise its orientation.

The two FP07 thermistors mounted next to the shear probes sense the turbulent fluctuations of temperature. Their frequency response is approximately 30 Hz at the speed of the VMP, and thus insufficient to resolve the complete spectrum of the gradient of temperature. However, they can resolve fluctuations with spatial scales as small as $w/(2\pi 30) \approx 0.01\ m$, where $w = 1.4\ m\ s^{-1}$

FIGURE 2.5 RSI Vertical Microstructure Profiler VMP200 with mounted sensors.

is the speed of profiling, and provides a measure of the size of the overturning vortices found in a tidal channel.

Vertical profiles of turbulent dissipation ϵ can be made with a loosely tethered free falling VMP. The spectrum is integrated over a range of wavenumbers $[k_{min} : k_{max}]$ making it possible to exclude high wavenumbers where the spectrum might be contaminated by profiler vibrations. The lower limit of integration (k_{min}) is set to a value slightly smaller than the inverse of the length of the profiler, because eddies with spatial scales larger than the length of the profiler will advect the profiler laterally and, thereby, attenuate the fluid velocity relative to the velocity of the shear probe.

- ✓ The shear probe is used to sense the turbulent fluctuation of the horizontal (orthogonal) components of velocity.
- ✓ Vertical profiles may be taken approximately 3 m below surface to within 10 m of the seabed, with high spatial resolution (sampling at0.15 cm intervals).
- ✓ Provides up to two estimates of the dissipation rate ϵ (assuming

isotropic turbulence) and spectra of velocity shear up to the Kolmogorov wavenumber.

✓ Dissipation rate, ϵ can be estimated every 1.4 m using a shear spectrum spanning 2.8 m, with one estimate from each shear probe.

✓ Provides a high resolution thermal profile of water column temperature useful semi-quantitative supplementary insight into the vertical length scales of overturning eddies.

✗ The VMP can only resolve turbulent length scales between 0.01 m and 1 m. The VMP must free fall exceeding speeds of 0.3 $m\ s^{-1}$ for the shear probes to measure turbulence.

✗ The terminal velocity is normally reached 2 m below the surface. This is not a major limitation since the flow near the surface is dominated by free surface effects and not turbulence.

✗ The VMP can only provide a snap shot in time of the vertical turbulence structure (although repeat deployments can generate time series data).

✗ There are weather constraints for deployment and recovery of VMP.

✗ Shear raw data measured by the VMP can be polluted by anomalous spikes resulting from plankton particles and low- and intermediate-frequency disturbances from profiler vibrations and the brushes at the aft end of the profiler [34]. However, these effects are usually eliminated with routine data processing.

✗ The angle of attack of the turbulent velocity fluctuations must be less than 20 degrees for a linear response from the shear probes. The speed of proling, therefore, must be greater than three times the peak horizontal velocity of eddies with scales smaller than 1 m.

2.5 Fixed or platform mounted shear probes (non acoustic)

The shear probe can be mounted on any platform so long as it points, on average, into the flow and the angle of attack of the orthogonal turbulent velocity fluctuations is smaller than 20 degrees. For example, the shear probes could be mounted on to a turbine housing and aligned into the expected flow. The signal measure is then the horizontal gradient of vertical and across-stream velocity fluctuations. One realization of using shear probes at a site-xed platform is the Nemo mooring (Figure 2.4). The probes are carried by a self-contained recording system (the MicroRider) which is mounted into the leading edge of a streamline float. Fins direct the float into the oncoming current, to maintain a small angle of attack, for both directions of the tide. This permits a long time-series of measurements near hub height. The Nemo is large enough to accommodate other instrumentation, such an ADV and a downward looking ADCP. The shear probes do not need to be converted into earth-based velocity components in order to derive the rate of dissipation of kinetic energy. However, an attitude heading reference system (AHRS) is needed to transform the instantaneous ADV and ADCP measurements into earth-based coordinates. ADV data averaged over one minute can be transformed into earth coordinates using only the Euler angles derived from the two-axis inclinometer. The Nemo points itself into the flow but up- and down-drafts, from horizontal eddies with scales larger then the length of Nemo, will make it pitch during the passage of such eddies. The height of the Nemo above the bottom is determined by the force balance of its net buoyancy and drag. The drag is quadratically dependent on the current speed. Consequently, the height above bottom various over the tidal cycle.

- ✓ Long time-series of the rate of dissipation of kinetic energy near hub-height, limited only by data logger capacity and battery power.
- ✓ Three-component velocity measurements (with an ADV) in platform coordinates and in earth coordinates with an AHRS.
- ✗ The height above bottom of the measurements varies with tidal speed for a mooring. Height above bottom can be constant when deployed on a xed platform but this has not been demonstrated.
- ✗ The angle of attack must be smaller than 20 degrees.

2.6 Commercial availability of instruments

2.6.1 *Acoustic Instruments*

Previous studies to capture turbulent fluctuation have been carried out using instruments manufactured by T-RDI (four and five beam ADCPs), Nortek (five beam ADCP and ADV) and Sontek (ADCPs and ADV), although the latter have been tested more thoroughly in a fluvial environment. However, as the importance of collecting turbulence data for its own sake has only recently been highlighted for the renewable energy sector, Doppler instruments produced by manufacturers including LinkQuest, Aandeera and ROWE Technology should be considered during survey planning as the niche construction may be more suitable for the site in question.

Full technical specifications for ADCPs and ADVs suitable for turbulence measurements may be found on the manufacturer website and are provided below for the following instruments:

Nortek (`www.nortek-as.com`)
Five beam AD2CP Signature 500, ADV Vector.

Teledyne RDI (`www.rdinstruments.com`)
Four beam ADCP (300 kHz, 600 kHz and 1 MHz) and five beam Sentinel V ADCP (500 kHz). Doppler Volume Sampler (DVS).

Sontek YSI (`www.sontek.com`)
Four beam ADP. Sontek 10-MHz ADV. Sontek 16 MHz MicroADV.

Rowe Technology (`rowetechinc.com`)
Seawatch 4 beam ADCP.

Linkquest (`www.link-quest.com`)
Flow quest 4 beam ADCP (300 kHz, 600 kHz, 1000 kHz)

Aanderra (`www.aanderra.com`)
Seaguard II Doppler Current Profiler Sensor DCPS 5400, 5400R (600 kHz), Doppler Current Sensor DCS 5800, 5810

Table 2.1 provides a summary of the technical data for the acoustic profilers and single point current meters currently available on the commercial market.

Instrument	Four Beam ADCP					Five Beam ADCP					ADV	
	Sontek		RDI			Nortek (AD2CP)		RDI (Sentinel V)			Nortek (Vector)	Sontek (ADV / Micro ADV)
Acoustic Frequency	500 kHz	1 MHz	1.2 MHz	600 kHz	300 kHz	1 MHz	500 kHz	1 MHz	500 kHz	300 kHz	n/a	10 MHz
Profiling Range (m)	70-120	25-35	11-15	38-51	83-116	30	70	20	44-67	94-114	Single Point (0.15 m^2)	Single Point
Velocity Range (m^{-1})	±10		±5 (default) ±20 (max)			< 5		±5 (default) ±20 (max)			±7	±2.5
Velocity Accuracy ($cm\ s^{-1}$)	±0.5		±0.3		±0.5	0.5		±0.3	$\pm$ 0.5		±0.1	±0.25
Ping Rate	2.5 Hz	6 Hz	$<=$ 10 Hz			8 Hz (5 beam) 16 Hz (4 beam)	4 Hz (5 beam) 8 Hz (4 beam)	$>$ 4 Hz			1-64 Hz	0.1 Hz
Battery Capacity	1800 Wh		450 Wh			540 Wh (alkaline) 1800 Wh (lithium)		100 Wh			100 Wh	
Memory Capacity	-		4 GB			16 GB - 64 GB		16 GB			4 GB	4 MB

TABLE 2.1 Instrumental data for four beam and five beam ADCPs and ADV currently used for turbulence measurements: Sontek (orange), RDI (black), Nortek (blue).

2.6.2 *Non-acoustic Instruments*

Whilst a less well established technology than the range of acoustic devices, there are a range of commercial options for shear probes:

Rockland Scientific (www.rocklandscientific.com)
Vertical Microstructure Profiler (VMP 200), Micro Rider.

Sea and Sun Marinetech (www.sea-sun-tech.com)
Microstructure Profiler (MSS90D).

Precision Measurement Engineering (www.pme.com)
Portable microstructure profiler (SCAMP).

2.7 Platforms for Measuring Turbulence

2.7.1 *Fixed towers*

Fixed-tower ADV measurements (see Figure 2.6) provide reliable estimates of inflow conditions (including spatial coherence) but are expensive to maintain and deploy in comparison to seabed moorings, especially at hub heights greater than 5 *m* above the seabed. Furthermore, in order to fully characterise the inflow environment at tidal and river hydro-kinetic sites, coherence will need to be estimated at multiple spatial separations (e.g. r = 0:5; 3; 15 *m*). This will necessitate multiple measurement platforms (towers or moorings) at additional cost.

Figure 2.6 Measuring flow and turbulence at near-hub height; a 5-Tonne, 5 *m* tall frame was deployed to place a point current meter at 5 *m* above the bed (left photo; ADV at 5 *m* above bed). The large silver frame is shown during deployment on the right hand photo.

2.7.2 *Sub-sea moored platform (Rockland Scientific 'Nemo')*

The Rockland Scientific Inc. Nemo (formerly called the 'Stablemoor') buoy system (Figure 2.4) is an autonomous moored multi-instrument measurement system capable of directly measuring the turbulent parameters in the mid-water column (hub height) in swift tidal streams (up to 5 $m\ s^{-1}$). The system consists of a 3 *m* long streamlined torpedo shaped flotation body with cut outs to house the various instruments, which include:

- **A Rockland Scientific Inc. (RSI) Micro Rider** which which carries four shear probes and two fast response thermistors mounted at the nose of the buoy.
- **A downward facing ADCP** - A downward-facing ADCP with bottom tracking capability, for profiling the flow beneath the device and tracking height from the seabed.
- **A Nortek Vector ADV** probe measuring three components of velocity, located above the Nemo.
- **Inertial motion reference unit** with 9-degree of freedom motion package (acceleration, rotation rate, and magnetic eld) plus a precision 2-axis inclinometer.

The buoy is deployed on a single line mooring, with a gravity anchor. A pivot and bridle allows the buoy to passively orient and level itself. The buoy is deployed from a crane on a multi-cat style device and has the operational benefit of being able to be deployed in a running tide, as opposed to waiting for slack water as required for seabed deployments. The rear section of the Nemo buoy has stabilising fins that align the bodys principle axis with the flow. A bridal arrangement attached near the bodys mid-point allows it to stay aligned with the current even when the mooring line leans during high flow speeds. Nemo has two horizontal and two vertical stabilising fins at its tail, as well as a circular fin. Trim weights are attached to the front, or to the rear, to bring the float to a nearly static horizontal equilibrium, where the net torque about the bridle axel is zero. The ns provide dynamic stability. The floatation balls (Figure 2.7 were necessary because of an initial miss-design by the manufacturer. The lower end of the mooring lines has an acoustic release, safety buoyancy, chain, and a 1000 kg anchor weight.

The Nemo buoy has been successfully deployed at several sites in the Grand Passage (Nova Scotia) and at two commercial tidal energy sites in Scotland; the data returned from the shear probes, and ADV (ADCP data yet to be analysed) was, following advanced pre-processing, of sufficient quality data to measure turbulence parameters at approximately hub height [24] during $\approx 80\%$ of the time.

However, the two separate deployments noted the following practical points:

- The Nemo buoy turns randomly over slack water period, giving rise to unreliable data during this period - this is not critical for our purposes since tidal generators are expected to be turned off.

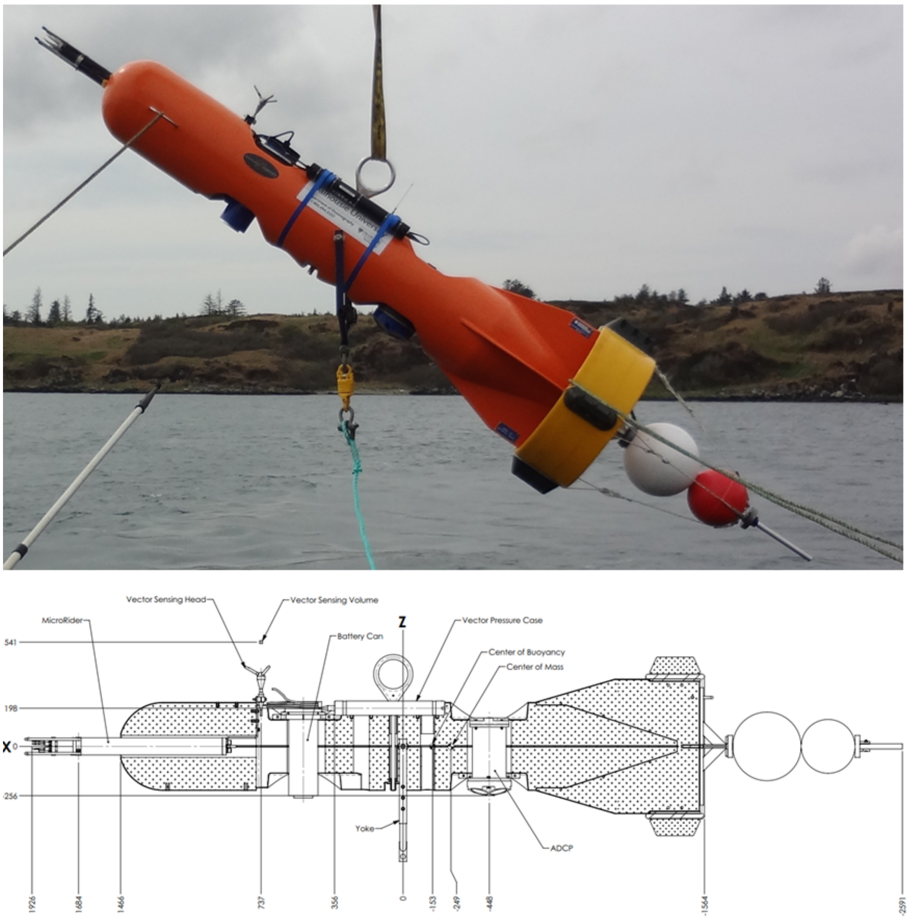

FIGURE 2.7 The NEMO mooring buoy system being hoisted for deployment (top) and schematic (bottom).

- The absolute height of the Nemo buoy above the seabed varies with tidal speed (although remains within $\approx 3m$).
- The system produced a high rate of data return when current speed ¿ 0.5 $m\ s-1$, although required the redundancy of four shear probes to form a complete dataset. Design improvements for robustness are ongoing.
- Although the buoy was generally stable, rapid pitch and roll motions (ranging between $13°$ to $-25°$ and $+/-17°$ respectively), resulted in an inability to reliably convert velocity data from the ADCP into an earth fixed frame of reference (except with extensive averaging). The onboard ADCP is therefore not suitable for use estimating turbulent quantities

(other than the velocity profile shape).

- Presently the system is limited to 15 days of memory, requiring multiple accesses to span a typical 35 day measurement period.

The ADV mounted on the Nemo buoy was used to characterise turbulence at hub height during the TiME project. Further to the capabilities and limitations discussed in section 2.3, a number of practical issues associated with use of the ADV were highlighted by this campaign:

- The velocity range measurable by the instrument is adjustable. However, it is advised to ensure that the ADV is set to measure the full range of velocities known at the study site to avoid data wrapping (note that increasing the range above default will cause some loss in resolution).
- Aligning the ADV velocities to earth coordinates may be achieved through a frame of reference change (as in work of Kilcher et al. [19], discussed in section 2.3.3). However, due to sampling rates, discretisation and inaccuracy in the inclinometers, geo-referencing is not possible without added positional information.
- Memory capacity of the ADV is dependent on sampling rate. Present instruments possess $\approx$ 16 days memory (sampling at 4 Hz), although newer versions of the Nortek ADV have a memory capacity which is 26 times larger.

The signals reported by the shear probes can be compromised or contaminated in several ways, which can influence (increase) dissipation rate estimates.

- The most common interference is vibration of the platform holding the shear probes. Almost all of this signal degradation is eliminated by a vibration-coherent noise removal algorithm, which is effective up to frequencies of $\approx$ 200 Hz (the wavenumber corresponding to 180 Hz). The level of vibration of the Microrider varies with flow speed. Pronounced vibrations of the Microrider at 30 Hz and 200 Hz occur when the current reaches 4 $m\ s^{-1}$.
- Collision of plankton with the shear probes is another source of anomaly that has to be removed. A collision results in a large-amplitude spike followed by a few tenths of milli-seconds of damped oscillation. This irritant can be detected by a 'despiking' routine, which removes 15 $m\ s$

of data before the collision and 30 $m\ s$ after the collision and replaces these data with a local average.

- Another source of contamination is the snagging of seaweed. This can make the signal from the shear probes anomalously large. The snagging of seaweed causes the spectrum to rise strongly above the Nasmyth spectrum at higher wavenumbers which results in both an anomalous spectral shape and anomalously high estimate of the rate of dissipation.
- Snagging anomalies can be eliminated by sorting the four probe estimates in ascending order. If the ratio of the largest to the smallest exceeds a critical value, then the largest one is eliminated. This process continues until the ratio of the largest to the smallest is below critical. This process of elimination is denoted as 'sifting' [23]. There is no accepted standard for eliminating estimates based on the ratio of values. Snagging, like all other forms of signal contamination, always increases the estimate of the rate of dissipation.
- Successful use of the shear probes requires that the flow over the probes have an angle of attack smaller than 20°.

2.7.3 *Turbine-fixed: ReDAPT*

ReDAPT (Reliable Data Acquisition Platform for Tidal) is a UK-based consortium commissioned and funded by the Energy Technology Institute, led by Rolls-Royce and including Plymouth Marine Laboratory, Tidal Generation Limited (TGL), Garrad Hassan, the University of Edinburgh (UoE), EDF Energy, E.ON, and the European Marine Energy Centre (EMEC). A central aim of the University of Edinburghs work in ReDAPT was to characterise the tidal flow surrounding the TGL 1MW turbine at EMECs Tidal Test site in the Fall of Warness in the Orkney Isles.

Seven acoustic Doppler instruments were installed on the turbine for a two month long campaign of flow data acquisition (Figure 2.8). The aim of this deployment was to commission the instrument package, highlight areas for instrumentation development and to capture the turbulence parameters deemed most likely to affect blade loadings. A range of Doppler sensors were selected in order to allow the capture of different scales of motion at different sample rates and ranges. A broadband Single Beam Doppler (SBD) was chosen for its flexibility and limited spatial averaging compared with a traditional multi-beam device, although it is limited to capture only along beam velocities. A long range single beam device, a Nortek Continental, was used to capture velocity inflow at a range of up to 100 m and larger scales of motion.

An 'Acoustic Wave and Current' profiler (AWAC), which has a four beam arrangement, was used to resolve flow velocities above the turbine into three Cartesian vectors i.e., streamwise (u), transverse (v) and vertical (w). An RDI Workhorse ADCP which was deployed as a standalone device on the seabed to provide a separate reference velocity for future analysis work.

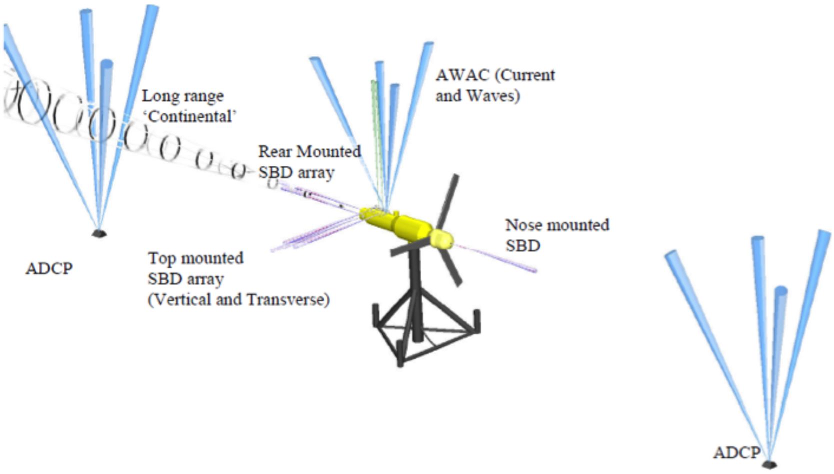

FIGURE 2.8 Outline of the instrumentation on and around the TGL 1MW Turbine, from Sutherland et al. [27].

The reader is referred to the ReDAPT partners for more information.

2.7.4 FORCE

Fundy Ocean Research Centre for Energy (FORCE) in partnership with Nortek Scientific and Dalhousie and Memorial Universities is developing the Worlds first instrument to accurately measure turbulence throughout the water column, called the Vectron. The Vectron will solve two conventional challenges with measuring turbulence using existing instruments:

- Acoustic Doppler current profilers (ADCPs) use diverging beams to approximate water velocity, but averaging across the beams filters out turbulent signals below the beam separation frequency.
- Acoustic Doppler velocimeters (ADVs) use converging beams to measure turbulence accurately, but have very limited range.

The Vectron will combine the range of the ADCP with the accuracy of the ADV and will be able measure turbulence through turbine hub height and to resolve turbulence down to blade chord length scales.

The Vectron is a new pulse-coherent Doppler sonar system that has been developed by Nortek Scientific to allow remote measurement of turbulent velocities at mid-water depth ($O(10\ m)$ distance from the instrument transducers) to meet the measurement and monitoring needs of the in-stream tidal generating industry. Multiple sonar units (based on the Nortek AD2CP hardware platform) are networked together and the instrument is configured with a modular philosophy that allows a great deal of flexibility in acoustic sampling schemes. Time synchronisation between the essentially independent instruments is achieved through a low latency Ethernet switch using a master Precision Time Protocol (PTP) clock. Pulse-to-pulse coherent sampling is achieved by taking advantage of bistatic beam geometries that isolate a small sample interval (at 7 m from the central transducer). Velocity ambiguity is overcome using a completely new technique based on multiple computations of the pulse-to pulse correlations.

The Vectron is currently being tested on an instrument platform (Figure 2.9) which is capable of providing high resolution real time measurements of turbulent water flows at turbine hub height for long periods of time [13]. The test site is in the Bay of Fundy, Nova Scotia.

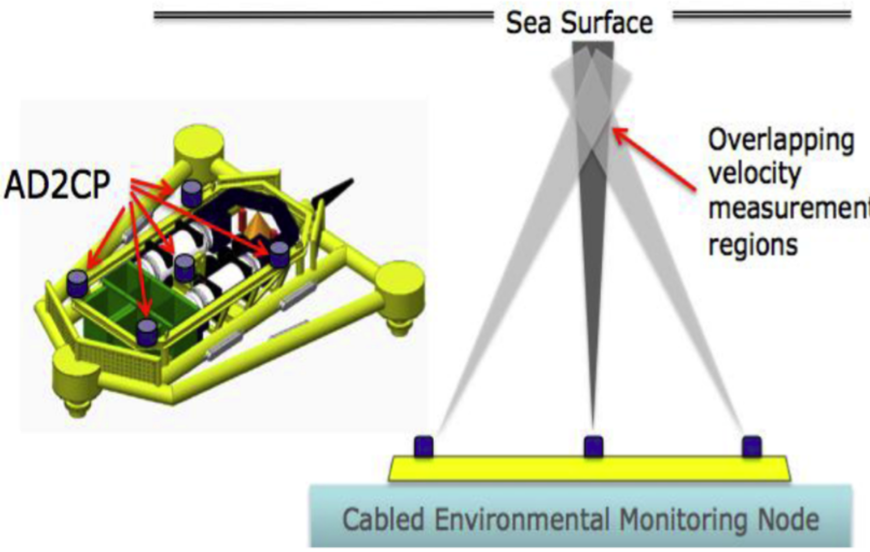

FIGURE 2.9 Vectron uses converging beams to measure turbulence [13].

The reader is referred to the FORCE and Nortek for more information.

2.8 Instrument selection

2.8.1 *Selection by turbulence characterisation metric*

Turbulence measurements are required at many stages of the tidal array development process [MCRF-TIME-KS9b]. Choice of instrumentation is driven by a range of factors dictated by the overall project objective, including the scale of turbulent motions of interest, the spatial aspects of the project (e.g. single or multiple sites), the specific nature of the turbulent effects from an engineering standpoint, which in turn governs the turbulence metric(s) required to be measured.

Table 2.2 provides a non-prescriptive, metric-centric matrix designed to inform the reader what turbulent parameters can be measured by the acoustic and non-acoustic instruments. This information should offer a useful starting point in terms of which instrument to select for site specific turbulence data acquisition.

	4 beam ADCP	5 beam ADCP	ADV	VMP	Nemo
Measured Parameter					
Velocity u,v,w (profiles)	✓	✓			✓✗
Pressure	✓	✓	✓	✓	✓
Direct measure of vertical velocity w		✓	✓		
Velocity u, v, w (near bed or at hub height)			✓		✓
Thermal microstructure profile				✓	
Derived Parameter					
Vertical shear of horizontal velocity (profile)	✓	✓			✓
Vertical shear of horizontal velocity (hub height)	✓	✓			✓
Reynolds Stress	✓	✓	✓		✓
Turbulent Kinetic Energy (profile)	✓	✓			✓
Turbulent Kinetic Energy (hub height)	✓	✓	✓		✓
Dissipation rate	✓	✓	✓	✓	✓
Integral length scales based on energy spectrum	✓	✓	✓	✓	✓

TABLE 2.2 Applicability of instrument to turbulence measurements / metrics. Note that the Nemo system includes both 4 beam ADCP and an ADV.

2.8.2 *Process for instrument selection*

The choice of instrument for measuring the flow field and turbulent quantities at tidal energy sites is dependent on the nature of deployment, the site conditions, the metrics required for engineering aspects and the study goal. Figure 2.10 is designed to assist the reader in the choice of instrument most suited for their study objectives.

When considering the engineering implications of turbulence, the framework in sister document MCRF-TIME-KS10 uses the scale of turbulent motions as a classifier, since different scales of motion are generally associated with different effects. We can draw on the same classification for the purpose of instrument selection. From MCRF-TIME-KS10, the length scales are divided as follows:

- **Small-scale eddies** are here defined as turbulent fluctuations having characteristic length scale less than a typical blade chord length, $l_{small} < O(chord)$. Turbulence in this range generally affects the detailed aero/hydrodynamic performance of a device without exerting direct loadings, since its scale is much smaller than the equipment itself and direct loading averages out over the surface of a unit, for example a turbine blade.
- **Mid-scale eddies** have a characteristic length scale larger than l_{small} but not so large that they could be mistaken simply for a change in the mean flow. The turbine disc diameter is taken as a convenient upper limit for this range: $O(chord <= l_{mid} <= O(2R_{tip})$.
- **Large-scale eddies** having characteristic length scale $O(2R_{tip}) < l_{large}$ generally exert fairly uniform gusts when evaluated over, say, a turbine disc area but describe intermittency and fluctuations on a larger scale (e.g. over the propagation length of a turbine wake or on the scale of turbine separations within an array).

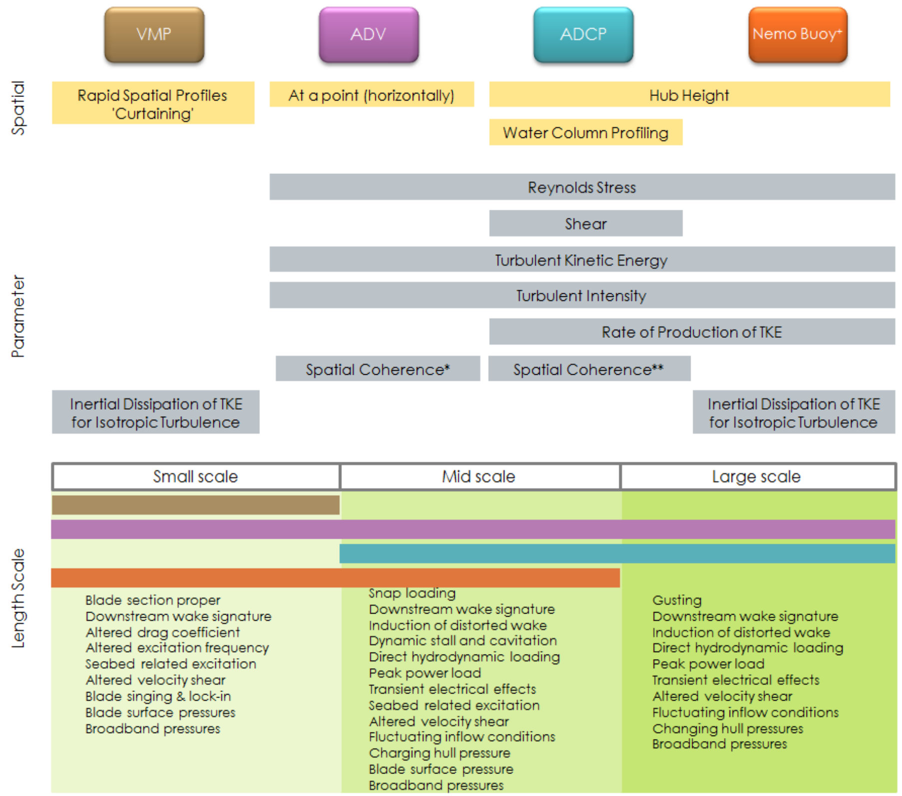

FIGURE 2.10 Relationship between instrument type, turbulence parameter of interest, turbulent length scale and study objectives.

3 Instrument Configuration and Deployment

The following section provides information to help guide the user in the instrument configuration and set process in order to optimise instrument performance with regards to measuring turbulence. In addition to not disturbing the flow, vibrating or introducing drift into the measurement, considerations must be given to the following aspects:

3.1 Acoustic Doppler Current Profiler setup

Obtaining the most accurate turbulence measurements with the currently available commercial profilers will require that the sources of error discussed in Section 4.2.1 to be minimised. The following approaches will help minimise the effects of these sources of error and thereby provide the most reliable data from commercially available profilers.

3.1.1 Depth range of measurements

For all profilers, the range of acoustic penetration of the ADCP is subdivided into a large number of depth cells (bins). More cells provide increased resolution about how velocity and turbulence fluctuations vary through depth. When working at tidal energy sites, maximising the amount of detail or resolution of the data set is considered as being a primary instrument setup objective. By definition, cell size sets the depth resolution for parameter measurement. This reduces the volume of water over which the ADCP provides an average, providing more data points over the water depth and reducing the error velocity (increasing precision of the data).

The water depth at the site of interest will determine what acoustic profiler to use (table 2.1). The velocity profile ends at a range where acoustic energy density drops below a signal-to-noise threshold. Factors internally (e.g. system frequency) and externally (e.g. temperature) to the ADCP affect the profiling range by changing the signal-to-noise ratio of the acoustic energy. Instrument frequency is the dominant control of profiling range. Energy at lower frequencies is absorbed less and subsequently penetrates farther. The lower frequency ADCPs are therefore more suited for deeper depths but there is a loss of resolution due to the cell size being inherently larger.

Typically for tidal energy sites with depths ranging between 30 m and 100 m, the 600 kHz 4 beam (operating range 50 m) and 300 kHz 4 beam (operating range 110 m) are the most suitable. ADCPs at the 300 kHz and 600 kHz range can be configured to record in 1 m bins (depth cells). The 600 kHz and 1 MHz ADCPs can also be configured to record in 0.5 m bins. In very shallow water depths < 15 m the 1 MHz ADCP is the most suitable choice of instrument.

Environmental factors can have a significant influence on profiling range. These factors include temperature, salinity and the concentration of backscattering materials. With some exceptions, profiling range is enhanced by colder and fresher water and by more suspended material. It should be noted that having too much suspended material (in highly turbid environments such as estuaries) can also be inhibitory to data return. In this instance lower frequency units are more suitable.

3.1.2 *Trade-off between resolution, range and accuracy*

There is a trade-off between higher resolution, range and accuracy. High resolution data provides more accuracy but also increases the amount of random noise and reduces the profiling range as well as increasing power consumption. The traditional means for controlling random noise are either increasing the averaging period or using larger depth cells. Both include more scatterers in the average velocity so the random noise contributions tend to cancel each other. Averaging is a means of reducing noise and increasing signal to noise ratio but it inherently reduces the accuracy of the turbulent quantity of interest.

The recommended depth cell configuration for tidal energy sites in water depths > 30 m should be set to 1m cell size and in depths < 30 m should be set to 0.5 m cell size. If a 5 beam system is available then this should be used to collect direct measurements of vertical velocity.

3.1.3 *Sampling rate*

The maximum sampling frequency for a commercial 4 Beam (Janus) ADCP is 2 Hz. The maximum sampling frequency for the newer commercial 5 beam systems is 8 Hz. The higher the sampling frequency the more data is collected, which may be preferable from a turbulence perspective but which increases the memory and power requirements, both of which are finite. Hence, there is a trade-off between sampling frequency and memory capacity and also power requirements. The recommended sampling frequency of an acoustic profiler (both 4 beam and 5 beam systems) for turbulence measurements is either 1 Hz

or 2 Hz (4 beam ADCP) or 8 Hz (5 beam). Issues such as power capacity can be addressed through use of additional subsea battery packs, and some (not all) manufacturers have systems which can accommodate additional memory cards.

3.1.4 *Ping rate and sampling frequency*

The ping rate i.e. pings per ensemble, sets the number of pings to average in each data ensemble (set by the sampling frequency) before recording the data. A data ensemble consists of the data collected and averaged during the ensemble interval. For turbulence measurements, the ping rate must be set in the configuration software to single ping for each time ensemble (sampling rate) to prevent the ADCP performing averaging of the data (and dampening the record of turbulent fluctuation). Time averaging can then be used in post-processing to reduce Doppler noise, at the expense of temporal resolution.

An appropriate sampling frequency f_s can be determined by considering the 'beam separation frequency' f_{bs}, discussed in section 2.1.3.

In practice, f_s should be twice the estimate of f_{bs} to avoid aliasing, but may be limited by the instrument. For isotropic turbulence, the vertical bin size Δ_z could be substituted for the beam spread Δ_b in Equation 2.1, and along-beam velocity fluctuations could be analysed. However, horizontal fluctuations are most relevant to tidal turbines, and these fluctuations require information from multiple ADCP beams. Thus, the beam spread is the limiting length scale. Either way, the goal is to restrict analysis to length scales (and corresponding frequencies) that are accurately measured by the instrument. The beam spread Δ_b increases with distance from the instrument, so this requirement will be more restrictive for hub heights farther above the seabed (assuming a bottom-mounted ADCP).

3.1.5 *Survey duration*

Recommended minimum deployment time that the instrument should measure currents and turbulence at tidal energy sites is 30 days. In this way, variation in current magnitude and turbulent fluctuations around the mean flow over a spring and neap tidal (lunar) cycle will be captured. It is paramount that the user calculates the required power consumption and memory requirements for the set up parameters they have chosen and to ensure that the external batteries and memory cards are capable of recording > 30 days of data.

3.1.6 Memory

Memory requirement for a 30 day deployment (single ping, 1 *Hz* data) approximates to 4 *GB* memory.

3.1.7 Power

Power for 30 day deployment (single ping, 1 *Hz* data) requires 1125.25 *Wh*. Typically an ADCP with an additional battery canister can be deployed for up to 50 days at 1 *Hz*, but this depends on many factors as discussed above and is best determined with the instrument deployment planning software.

Note: Most (not all) manufacturers of acoustic profilers have developed deployment planning software which allows the user to enter known or best guess values for the acoustic profiler profiling parameters and provides the ability to determine range, battery and memory requirements over x survey days and evaluate the trade-off that may have to be made with regards to standard deviation, profiling range and timing. It is strongly recommended to develop command files using the planning software available.

3.1.8 Recommended coordinate system

In order to characterise turbulence from velocity measurements using a 4 beam or 5 beam acoustic profiler, the instrument must record velocities in beam coordinates. The beams can then be transformed to Earth coordinates using the internal compass in post processing. To ensure the compass is not being affected by external magnetic interference, a compass calibration of the acoustic profiler should be conducted prior to deployment with the profiler secured in its deployment frame. Once the instrument has been calibrated in its particular frame (inclusive of fully charged batteries) it cannot be removed and placed in an alternative frame without repeating the compass calibration procedure. Note that strong magnetic interference at site may also affect the internal compass which will have an erroneous effect on the resolved directions from the acoustic profiler which rely on the internal compass in the transformation process from beam to earth coordinates.

3.2 Acoustic Doppler Velocimeter setup

Single-point measuring ADVs typically ping at about 250 *Hz* but their maximum recording rate is 25 *Hz*. For tidal energy sites, ADVs should be configured to sample at a rate of 4 or 8 *Hz*, and recording in 1 minute averages. A trade-off between sampling rate and instrument memory is required since a sampling rate of 8 *Hz* will exhaust the memory of an ADV in eight days.

Additionally, it is important that the velocity scale setting on the ADV is not set too low. Knowledge of the expected velocities at the study site (e.g. from a tidal model) should help determine this setting. Otherwise, if the velocity scale exceeds the true velocity, the velocity may wrap around producing an erroneous result.

For fixed point ADV deployments, it is necessary to record the orientation of the X, Y and Z frame of reference.

3.2.1 *Acoustic Doppler Velocimeter on Nemo buoy*

Use of the ADV technology on the Nemo Buoy requires additional specific considerations. In addition to the above recommendations, the ADV measurements should be transformed into Earth coordinates using Euler angles. Since the Nemo buoy moves in time and space, pre / post processing called 'levelling' in a horizontal plane is necessary and is accomplished by rotation about the two Euler angles that are measured by the inclinometers. Rotation about the vertical axis is then necessary to bring the horizontal axes into a geographical orientation.

Experience from the TiME project suggests that the quality and synchornisation of measurements from the Inertial Motion Unit is key to robust determination of earth-fixed velocities from a moving ADV unit; the method adopted by Kilcher et al. [19] is recommended; suitability of the IMU should be ensured beforehand.

3.3 Vertical Microstructure Profiler setup

3.3.1 *Rockland Scientific VMP*

The RSI VMP-200 is optimised for work in tidal channels by increasing its fall-rate to 1.4 $m\ s^{-1}$, increasing its sampling rate to 1024 Hz, and decreasing the gain of its electronics to accommodate the strong velocity fluctuations occurring in a tidal channel. The VMP-200 records its data internally and can operate for approximately 30 hours on its internal battery.

3.3.2 *VMP deployment*

A profile is taken by deploying over the side of a vessel. During a profile, the boat drifts with a static propeller. A light tether is attached to the VMP and this line is deployed so that there is always several metres of slack at the surface. This decouples the profiler from the boat and allows it to fall freely at its nominal rate of 1.4 $m\ s^{-1}$. The depth of the profiler is judged approximately from its time-of-descent and by the amount of line deployed. The profile is terminated by raising the VMP back to the surface, and then the boat transits to the next station. This broadly is the deployment method statement for the instrument.

3.4 Rockland Scientific Nemo buoy

3.4.1 Mooring configuration

The mooring line and its components should be set to keep Nemo within the aperture of the rotor proposed defined by the hub height and rotor diameter. Nemo should be anchored by a mooring line and a swivel attached to its bridle near mid-body. The swivel allows the Nemo Buoy to point into the current for all directions of its flow. The bridle axle permits Nemo to maintain a horizontal attitude for all current speeds. The Nemo is 4.5 m long and is composed mostly of syntactic foam. It has a buoyancy of $F_B = 4396\ N$ when it carries the instrumentation. It weighs $F_W = 2767\ N$. Net buoyancy is 1629 N, and its drag is approximately $F_D = 142\ u^2\ N$ where u is the current speed in $m\ s^{-1}$. The mooring line can be up to 50° from the vertical. Nemo has two horizontal and two vertical stabilising fins at its tail, as well as a circular fin. The Nemo should be trimmed with fore or aft weights to bring it, as close as possible (less than 5 degrees), into a horizontal position in static water (Figure 2.7). That is, this assembly moves the centres of mass and buoyancy so that their net torque about the bridle axle is zero. The fins provide dynamic stability. The lower end of the mooring line should consist of an acoustic release, safety buoyancy, chain and a 1000 kg cast steel anchor.

3.4.2 Sensors and their locations

Nemo carries three instrument systems and other devices. The Rockland Scientific (RSI) MicroRider package protrudes from the front nose of Nemo. The transducerreceiver assembly of a Nortek Vector current meter (ADV) is attached about midway between the bridle axle and the front of Nemo. New model Nortek ADVs have a pressure case that is short enough to t into a vertical cavity aft of the transducer head, so that the case and the cable connecting it to the transducer head are completely out of the flow. A downward looking 600 kHz ADCP is mounted aft of the bridle axle. A battery package of two primary lithium cells is mounted in a cavity just aft of the ADV transducer and supplies power to the MicroRider and to the ADV: one cell pack for each instrument. The ADCP carries its battery internally. The electronics for the ADV are fastened to the side of Nemo with cargo-ratchet straps. A satellite

Instrument	Symbol	x	y	z	Description
MicroRider					
	sh1-4	1926	25	15	Shear probe 1-4
	APz,APy	1619	-10	5	Piezo vibration sensor for z-direction & y-direction
	T1	1926	0	30	Thermistor temperature sensor 1
	P	1684	0	0	Pressure sensor port
	Incl X, Y	1179	-20	0	Inclinometer, rotation around the x & y-axis
	Rx,Ry,Rz	1604	0	-25	GyroCube, rotation rate around x, y & z
	Ax,Ay,Az	1604	0	-25	GyroCube, acceleration along x, y & z
	Mx,My,Mz	1224	0	28	MiniMag, magnetic field along the x, y & z
ADV					
	U	737	0	541	Velocity along the x-direction
	V	737	0	541	Velocity along the y-direction
	W	737	0	541	Velocity along the z-direction
ADCP					
		-448	0	-256	

TABLE 3.1 The sensors carried by Nemo and their locations with respect to the bridle axle, in units of mm. For the ADV, the coordinates give the location of the sampling volume, and for the ADCP they give the transducer face.

beacon is mounted aft of the lifting ring.

The MicroRider carries the majority of the sensors (Table 3.1) and records its data internally. It also records the analog velocity, u_b, v_b, and w_b, produced by the ADV, where subscript $_b$ denotes velocity in the buoy-fixed frame of reference. The ADV also records its data internally and outputs three analog voltage signals for the three components of velocity. The ADCP records its data internally. The location of the sensors with respect to the axle of the bridle are listed in Table 3.1.

3.4.3 Deployment

The NEMO buoy is a substantial mooring to be introduced into a tidal race, and consequently great care (with attendant risk assessments ad method statements) is required to safely deploy. The buoy is deployed from a crane on a multi-cat style device and has the operational benefit of being able to be deployed in a running tide, as opposed to waiting for slack water as required for seabed deployments. Nemo can descend at a rate of $\approx 3\ m\ s^{-1}$ from the surface and reach its anchoring depth. During slack water, the tether on Nemo is vertical and the distance of the bridle axle above the bottom is at its maximum. It must be noted that during slack water, Nemo has considerable pitch but this is rectified during speeds greater than $\approx 0.75\ m\ s^{-1}$.

3.4.4 *Height of Nemo above seabed*

The pressure record, P , represents the depth of the transducer in the MicroRider. The depth of the bridle axle, $P_b a$ is;

$$P_b a = P L_P sin() \tag{3.1}$$

where LP , the separation of the transducer from the axle, and is the rotation around the body y-axis (the negative pitch). During slack water, the mooring line is vertical, the depth is at a minimum and its height above the water is at a maximum. The maximum height above the bottom is determined by the mooring components. During current flow, Equation 3.1 for pressure still holds but the mooring line will be off vertical and Nemo will be at less than maximum height above the bottom. There is an additional pressure signal because the surface itself is moving vertically at tidal frequency. If the tidal elevation is known, perhaps from a nearby bottom mounted ADCP, then it is possible to estimate precisely the height of Nemo above the bottom. A good approximation to its height above the bottom is obtained from using the average pressure of adjacent times of slack because the amplitude of the surface deviation is usually less than about 2 m. The speed dependence of the height above the bottom can then be computed, to determine the blow-down and blow-back of the Nemo. An acoustic altimeter is planned for future deployments.

3.4.5 *Instrument sampling rates*

Microrider shear probes. All turbulence sensors sampled at 2048 Hz.

Vibration sensors.[1] Also sampled at 2048 Hz.

Pressure sensor. Sampled at 256 Hz, and is used to measure the mean depth of the Nemo system, as well as the heave motion of Nemo.

[1]The axes of sensitivity of vibration sensors are aligned with those of the shear probes and measure the inertial accelerations of the shear probes. This information is used to remove erroneous signals in the shear probe data caused by vibrations in the 1100 Hz range.

IMU. The system's attitude is measured with a high-accuracy two-axis inclinometer (pitch and roll), a magnetometer (yaw), a three-axis rotation-rate sensor, and a three axis accelerometer, all sampled at 256 *Hz*.

ADV. The ADV operates independently from the MicroRider and records all data (velocity, echo intensity, correlations, etc.) internally. The sampling rate of the ADV should be set to a value that is congruent with its memory capacity and the duration of deployment. For a unit with a capacity of 154 MB, the memory is exhausted after 15 days when the sampling rate is 4 *Hz*, for example. New versions of the ADV have a memory capacity of up to 4 GB. The ADV should also be configured to output analog voltages of its three components of velocity so that they can be recorded simultaneously by the MicroRider. In addition, the clocks on the MicroRider and in the ADV should be synchronised to a GPS clock shortly before deployment. Shortly after recovery, both clocks should be compared against a GPS clock to determine the drift rate of each instrument.

ADCP 600 *kHz* ADCP unit set to single ping at 1 *Hz*.

3.4.6 Data collection

The MicroRider should be configured to collect data into files of one hour length to keep their size manageable (approximately 140 MB). These files are transformed into Matlab mat-files of about 1 GB after their conversion into physical units and other processing. About 2 to 6 seconds of data are not recorded due to the closing of a data file and the opening of a new data file. The loss increases with increasing number of data files.

4 Survey Planning and Operations

A systematic and comprehensive approach to planning a survey to collect turbulence data is necessary to minimise risks to both the collection of good quality turbulence data and to people, vessels, equipment etc. It is recommended, as a matter of Good Practise, that marine surveys for turbulence considerations should be planned well in advance (at least one month) of survey activities. The following sections provide guidelines and considerations for pre-survey planning and deployment planning.

4.1 Site selection

When selecting a site for turbulence measurements it is essential that an appraisal of the site conditions are conducted prior to survey. The information obtained may determine the choice of instrument to use, the health and safety risks associated with the site and the specific method[s] of deployment. Site selection considerations should include:

4.1.1 Metocean and related considerations

- Tidal amplitude and phase.
- Tidal range (through lunar cycle).
- Tidal currents - magnitude and direction (through lunar cycle), plus the general circulation patterns.
- Timings and durations of high and low water (commonly these do not coincide with published data).
- Range of wave directions.
- Water depth.
- Bathymetry/topography.
- Any (marine) conservation designations.
- Local magnetic declination / variation.
- Nature of seabed (habitat/benthic/sediment type).
- Necessity for weather forecasting service.

The use of local vessels for deployment of instrumentation, and thereby local knowledge of the sea and site, is highly recommended.

4.1.2 *Logistical considerations*

- Suitable port access to site.
- Tidal constraints of port.
- Vessel availability.
- Vessel capability (an audit is recommended, do not assume any vessel can accommodate the deployment requirements).

4.1.3 *Mooring considerations*

- Proposed mooring coordinates.
- Flow alignment with respect to laying mooring.
- Water depth/bathymetry. It is very important prior to survey that the bathymetry of the seabed is known. This will determine the type of frame and housing to use to deploy the acoustic profiles for example, as well as highlight any likely topographic sources of site turbulence. For accurate estimates of horizontal and vertical velocities, the seabed deployed ADCP in upward looking mode must be secured in its frame with minimum tilt. Ideally a Multi-Beam Echo-Sounder survey (MBES) of the site will be available, else a side scan survey. Any benthic survey video / still footage is also valuable.
- Marine Licence application (where applicable) for mooring/survey programme.

4.2 Vessel suitability

Deployment of acoustic profilers in frames (or on moorings) and Nemo mooring systems should be conducted on a suitable vessel which at a minimum should have the following:

- Large deck space, preferably with an A frame.
- Deck crane capable of lifting one Tonne. Preferably located in the stern of the vessel.
- Vessel which has suitable free deck space for loading, moving frames, laying out moorings etc. is recommended. The vessel must have an accurate echo sounder for depth soundings and accurate navigation systems.

- The wheel house should be large enough to accommodate third party navigation equipment and survey personnel.
- The skipper must have previous experience working in highly energetic sites and preferable have experience of working at the site of interest.
- At a minimum the personnel should consist of skipper, deck hands and an appropriate number of oceanographers to deploy the equipment safely.

4.3 Mooring equipment requirements

- Delivery of instruments to be on time for survey and in time for pre testing.
- Frames should be used that are sufficiently weighted (500 kg) to prevent movement under the tidal current.
- Ensure the instruments are secured to prevent movement.
- Ensure frames are deployed so that instrumentation is orientated within the tolerances set by the instrument manufacturers.
- For turbulence measurements, ADCP units should be deployed within $5°$ of the vertical and no more than $10°$. If some system to qualify the tilt immediately post-deployment can be devised then this will form a useful quality assurance process.
- Ground lines should be used that can survive the harsh seabed conditions for lengthy periods.
- Rope canisters should be used for recovery systems where surface markers are not allowed.
- A secondary recovery system should be considered in the event of the primary system failing.
- All lifting equipment including wires and slings should be checked for certification.
- Ensure that instruments are correctly calibrated including compasses which should be calibrated as close to the deployment site as possible (but not on the vessel).
- Ensure all equipment is working before deployment (audible verification sometimes is possible). Save this data.

4.4 Applicable regulations (Health and Safety)

All offshore survey works must be carried out as a minimum in accordance with Government legislation (or statutory law). The main purpose of legislation is to regulate, authorise, prescribe, grant, declare or restrict actions. For all offshore survey works in the UK the following legislations must be adhered to (overseas people should consult their own specific domestic legislative requirements):

4.4.1 Health and Safety legislation (UK)

- The Health and Safety at Work Act 1974.
- The Control of Pollution Act 1974.
- The Environmental Protection Act 1990.
- The Water Resources Act 1991.
- The Environment Act 1995.
- The Pollution Prevention and Control Act 1999.
- The Water Act 2003.
- Lifting Operations and Lifting Equipment Regulations (LOLER) 1998.
- SI 1655 The Docks Regulations 1998.
- SI 635 The Electricity at Work Regulations 1989 + Guidance.
- SI 2793 The Manual Handling Operations Regulations 1992 + Guidance.
- SI 2966 The Personal Protective Equipment Regulations 1992 + Guidance.
- SI 3163 The Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1995.
- SI 1713 The Confined Spaces Regulations 1997 + ACOP.
- SI 2776 The Diving at Work Regulations 1997.
- SI 2306 The Provision and Use of Work Equipment Regulations 1998 + ACOP.
- SI2307 The Lifting Operations and Lifting Equipment Regulations 1998 + ACOP.

- SI3242 The Management of Health and Safety at Work Regulations 1999 + ACOP.
- SI 2677 The Control of Substances Hazardous to Health Regulations 2002 + ACOP.
- SI 978 The Control of Substances Hazardous to Health (Amendment) Regulations 2003.
- SI 3386 The Control of Substances Hazardous to Health (Amendment) Regulations 2004.
- SI 1643 The Control of Noise at Work Regulations 2005 + Guidance.
- SI 320 The Construction (Design and Management) Regulations 2007.

4.4.2 Fire Safety

- SI 1541 Regulatory Reform (Fire Safety) Order 2005

4.4.3 Merchant Shipping (covers discharge from vessels)

- SI 2962 The Merchant Shipping and Fishing Vessels (Health and Safety at Work) Regulations 1997.
- SI 1838 The Merchant Shipping (Code of Safe Working Practices for Merchant Seamen) Regulations 1998.
- SI 881 The Merchant Shipping (Accident Reporting and Investigation) Regulations 2005.

4.4.4 Offshore survey operations licences for UK and Ireland

Any structure (whether related to commercial or scientific activities and that which will be placed on the seabed, requires permission from the Crown Estate in the UK. The following regulatory bodies in the UK must also be informed of the intention to conduct works in the marine environment and the nature of the works (overseas people should consult their own specific domestic arrangements):

- England Marine Management Organisation.
- Wales Natural Resource Wales.
- Scotland Marine Scotland.
- Northern Ireland Marine Management Organisation.

4.4.5 Vessel certification

It is necessary to ensure that all vessels used are fit for purpose, adequate for the job and that the crew and skipper are suitably experienced to undertake the works. As a minimum, in the UK the following is required:

- MCA coding of vessels.
- Hull insurance
- Lifting certificates for all Hiab, lifting cranes etc.
- Personnel competencies and certification.

It is considered good practice to use skippers and crew that have operated at the site previously in order that their knowledge of the tides and interaction with the weather can be used to effectively manage the operations on site. Very often, the tide does not follow the predictions at these sites and so local knowledge becomes useful, even critical.

4.5 Safe working practice

Working safely forms an especially important aspect to working at tidal race sites and deploying and recovery marine instrumentation safely. A 'building block' approach to Health and Safety (Figure 4.1) is advocated, and should aim to eliminate/reduce risk via control measures to prevent any unsafe work practices that could lead to harm to either employees, sub-contractors or members of the public during the survey operations.

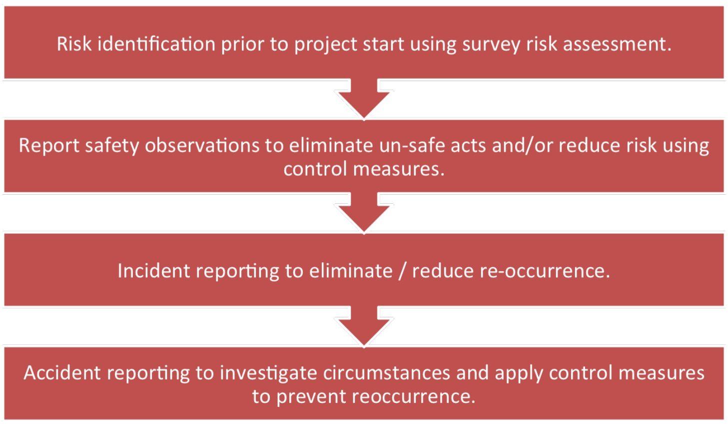

Figure 4.1 Building block approach to Health and Safety

4.5.1 Risk Assessment and Method Statement (RAMS)

A comprehensive Risk Assessment and Method Statement (RAMS) document must be produced prior to any survey operations. The objective of the RAMS is to ensure the Health and Safety of all persons affected by the various activities throughout the project during marine operations. All potential risks are identified and control measures put in place to eliminate and/or reduce these risks. Critically, all persons involved in the field phase of data acquisition should physically sign the document.

The RAMS document should include the following:

- Survey plan: detailing instruments, seabed mooring and frames, instrument configuration, vessel details, method statements for the mobilisation and survey works, tide times and programme of works.
- Risk assessment of all activities relating to survey works and document the findings in the RAMS.
- Emergency contact details including local hospitals.

The RAMS document should then be read and signed off by all concerned parties, including the vessel personnel and the Client (if relevant). The RAMS document should be a working document and must be updated regularly in response to any issues arising during survey, or to changes in the work scope.

Further to the RAMS document it is recommended that attention is given to the following:

- Ensure adequate marine verification (licensing).
- Ensure vessel certificates are adequate and in date for proposed offshore survey works.
- Plan the operations according to recognised industrial standards.
- Co-ordinate personnel and equipment and ensure personnel are sufficiently qualified to conduct the works.
- Produce and send out Notice to Mariners (NTM; UK).
- Ensure all vessels are MCA (Maritime and Coastguard Agency; UK only) coded, and have vessel audit/vessel insurance/lifting certificates.

4.6 Survey operations

The deployment of instrument moorings and bed frames in tidal race environments is not a trivial task. The following sections detail the areas that must be considered for a successful and safe deployment in tidal race environments.

4.6.1 *Tidal window and weather conditions*

- All acoustic instrumentation in frames should ideally to be deployed on the seabed two days either side of neap tide or at neap tide and at slack water.
- Deployment should only occur in favourable weather conditions.
- Very often the slack water following the flood tide gives the greatest operational window (in the UK).
- Personnel should be aware of tidal interaction with any waves, especially tide against waves since waves may increase significantly in height as the tide starts to run.
- The Nemo buoy has the operational benefit of being able to be deployed in a running tide, as opposed to waiting for slack water.

4.6.2 *Vessel operations*

- Only experienced and qualified personnel should be managing the deployment operations including managing the vessel and crew.
- One appointed person should be chosen to manage all deck operations.
- Number of personnel should be minimal on the deck of the vessel during survey operations.
- Clear lines of communication should be in operation between skipper and crew.
- All personnel should wear the appropriate Personal Protection Equipment (PPE).
- Operations should not start unless tide has reduced to $< 0.25\ m\ s^{-1}$ (for ADCP deployments).
- Positioning should be monitored independently of the vessel systems. Set deployment targets.

- The skipper should complete test runs to check on positioning with respect to the wind and tide.
- All lines should be checked that they are correctly spooled or coiled on deck and are free running.
- Should be aware of personnel standing in the bites of ropes or in line of the lifting wires between the winch drum and the weight.
- Should be aware of ropes and lines over the side that may become entangled with the vessel propellers.
- Should always inform the skipper when equipment is going over into the water and await approval.
- Should be aware of other marine traffic before commencing deployments.
- Port should be advised of all operations, on the point of departure and on return.
- Tide and weather forecast should be carried out prior to survey to provide an informed decision on whether the deployment/service visits/recovery operations are undertaken.

4.6.3 Safe survey practice

All survey offshore crew and marine crew should participate in a vessel induction prior to survey. The induction program should be held on the vessel and includes:

- General vessel tour including, but not limited to, vessel alarms, muster stations, location of lifesaving and fire-fighting appliances and escape routes, lifeboat allocation, restricted areas (where applicable) and location of first aid equipment.
- Fire, lifeboat and man overboard drills.
- Security awareness.
- 'Stopping the job'.
- Permit to work system, utilising permit to work system training materials.
- Waste disposal on board the vessel protecting the marine environment.

- Reporting of safety incidents.
- Safe operation of watertight doors and automatic fire doors (where applicable).
- Increased hazard awareness necessary in rough seas or high wind.
- Safety checks should be performed on lifesaving equipment, fire-fighting equipment, watertight doors and escape routes.
- Toolbox Talks should be conducted and documented and Lift Plans should be conducted prior to mobilisation and every operation on board.

5 Assessing Site Conditions and Typology

The Sound of Islay and the Inner Sound Pentland Firth have both been identified as potential sites for renewable tidal energy, due to the strong tidal currents at these locations. The potential energy yield from tidal currents is subject to site conditions and the Tidal Energy Converter (TEC) device size and efficiency. The typology of a site can indicate the type of flow and the potential for turbulence in the flow, which is also an important factor in the viability of a tidal energy scheme. Crucially, the site conditions can have dramatic impact on the effectiveness of marine operations and equipment deployment discussed in Chapter 4.

Resource typology is here discussed in terms of the Inner Sound Pentland Firth and the Sound of Islay sites.

5.1 Site typology

EMEC (the European Marine Energy Centre) developed and published standards in marine renewables energy, such as assessing performance of TECs [11] and for assessing the tidal energy resource [12]. These were the basis of the International standards for marine renewable energy which have been developed by the IEC (International Electrotechnical Commission). For example, a system for measuring and analysing tidal currents and reporting on their suitability for the installation of TECs has been prepared in a Technical Specification [18]. A purpose of this present report is to lend further consideration to include the resource typology when considering whether a site is suitable for TEC installation.

The resource typology of a site has a number of influencing factors, including:

- Tidal current/hydrodynamic regime.
- Bathymetry/depth.
- Channel dimensions. Is the location:
  - Open water, unbounded flow, or
  - Geologically constrained for example narrower channels, or where headlands are present.
- Seabed composition.
- Seabed roughness/rugosity.

The resource typology plays a large role in the viability of implementing a TEC scheme, both in terms of placing, installing and maintaining the turbines (through knowledge of the flow, the landscape topography, and the seabed material suitability), and the potential amount of tidal energy that could be harnessed (through knowledge of the current speed, direction and potential for turbulence). There are a number of factors that should be considered when assessing the practicality and potential difficulties of exploiting tidal energy at a given site, including the tidal flow conditions, depths and tidal range, seabed suitability, extreme weather/weather window [29].

5.1.1 Tidal currents

Tidal currents which are suitable for TEC deployment (Tidal Energy Converter) can be parameterised into different hydraulic types which can all induce a fast flow: tidal streaming, a hydraulic current, or a resonant basin [28, 29]. A hydraulic current is when a water level difference exists between two bodies of water, often due to a shift in tidal phase, which results in a pressure gradient and accelerated currents. A resonant basin is where the incoming tidal wave and reflected tidal wave constructively interfere and a standing wave is established causing the tidal range and tidal currents to become amplified (the Bristol Channel is an example of a resonant basin). Tidal streaming/tidal races occur when flow is constricted and accelerated locally, such as through a narrow channel or around a headland.

Developing knowledge on the nature of the tidal flow to expect at a site can give an indication of the degree to which the site is likely to be prone to turbulence in the flow. For example, if the tidal flow acceleration is pronounced and the flow becomes sufficiently fast then overfalls can be created (such as the tidal races off Portland Bill, UK). If formed, overfalls would contribute to the turbulence in the hydrodynamic flow. Tidal races and overfalls are often documented on marine navigational and Admiralty Charts, and such information can be a good first indicator as to whether a site is subject to strong current speeds and likely to be subject to turbulent flow conditions.

5.1.2 Bathymetry

The bathymetry, geography and the nature and composition of the seabed of tidal streams/tidal races can have significant impacts on the resource. Bathymetry can include aspects such as depth variations, channel dimensions, and the presence of rugged rocky outcrops, islands or headlands. For example if a channel becomes narrow and restricted the flow can become 'squeezed' and accelerated, forming strong tidal streams. Or if rocky headlands are present this can also accelerate the flow around the promontory, and possibly generate eddies and other localised flow variations.

5.1.3 Seabed composition

The seabed composition and its spatial variation can affect the gradient and roughness which can affect the roughness and turbulence of the hydrodynamic flow. The seabed substrate is generally categorised by material and grain size, ranging from bedrock, to boulders, cobbles, gravels, sands and muds. Rugosity is a measurement of the variation in height of a surface and can influence whether the flow is laminar or rough and turbulent. Marine Scotland has published bathymetric and rugosity maps showing the 3D shape of the seabed for some areas in Scottish waters. The presence of flora and fauna on the seabed can also be an important factor when characterising the seabed (for example the presence of seagrass, kelp or mussels can significantly affect the seabed roughness).

5.2 The Inner Sound Pentland Firth

5.2.1 Bathymetry

The Inner Sound Pentland Firth separates the Island of Stroma from the Scottish mainland Caithness region (location shown in Figure 5.1). The Sound is around 6 *km* in length and around 2.5 *km* in width. The depth within the channel is generally shallower than 40 *m* below Mean Sea Level, (MSL). Figures 5.2 and 5.3 show the bathymetry map and rugosity map of the Pentland Firth as published by Marine Scotland. Bathymetry of the Inner Sound Pentland Firth from numerical modelling of the region undertaken by ABPmer is shown in Figure 5.4.

5.2.2 Tidal currents

The tidal currents here are among the fastest in the UK, with peak speeds in excess of 4 $m\ s^{-1}$. The tidal currents here can be described as a hydraulic current due to the pressure gradient which results from a shift in tidal phase, but tidal streaming also contributes to the tidal currents here [10]. Tidal streaming occurs as the flow accelerates as it enters the constraints of the channel between the island of Stroma and the Scottish mainland. There is also localised acceleration of the flow as it rounds the rocky headland at the south-west corner of Stroma and the Stroma Skerries.

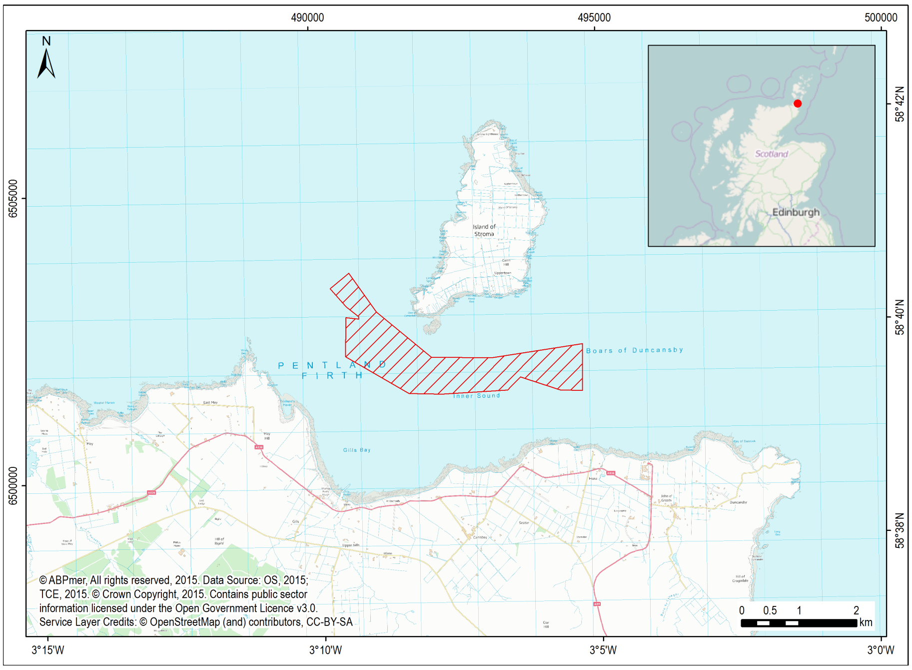

FIGURE 5.1 Location of the Inner Sound Pentland Firth

5.2.3 *Seabed composition*

The strong tidal currents have led to extensive areas of exposed rocky outcrops, although there are some areas where there is gravelly sand on the sea bed [4].

In the regions of the channel where the flow speeds are greatest, there can be boulders, and the exposed bedrock can be irregular and of a steep gradient, while in areas to the east and west of Stroma there are deposits of medium and coarse sand [9].

Partrac conducted a survey in 2014, deploying instruments in the Inner Sound for measuring the flow. Images and videos of the seabed were recorded during the deployment of the instruments. Figures 5.5 and 5.6 show some of these images of the sea bed at the deployment locations in the Inner Sound Pentland Firth. These images show the predominance of exposed rock and the variable topography and gradient of the rocky outcrops on the seabed.

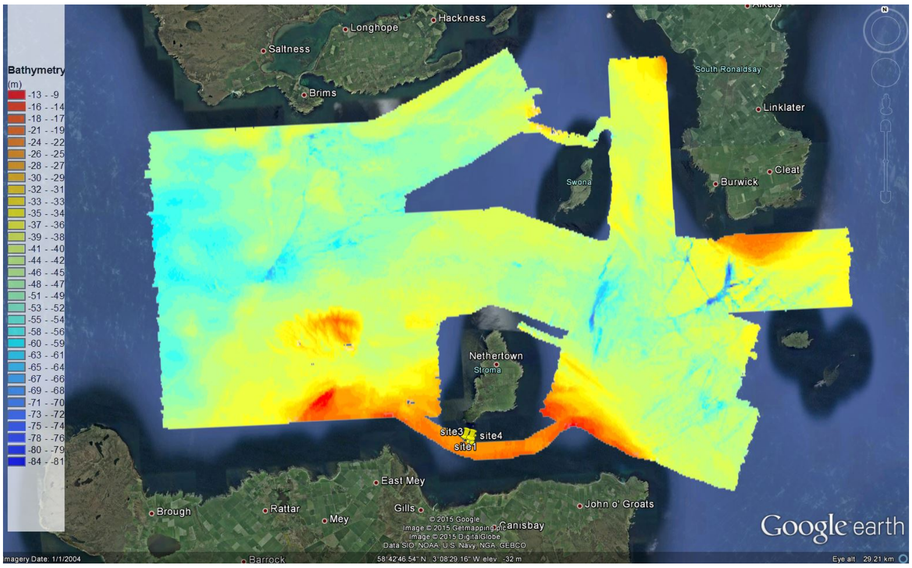

FIGURE 5.2 Bathymetry of the Pentland Firth in 2009 published by Marine Scotland. Image is courtesy of Google Earth.

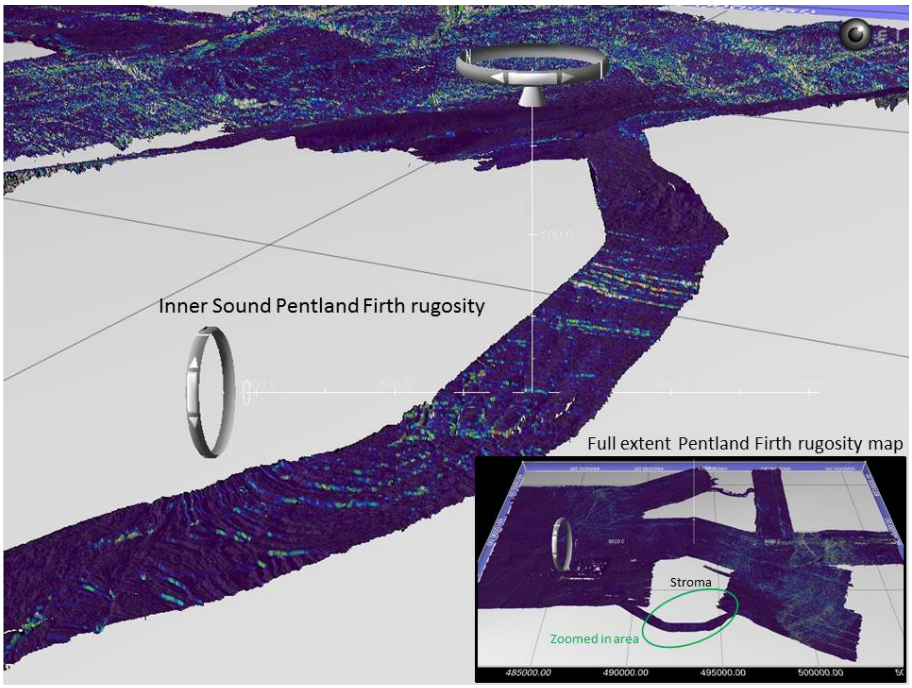

FIGURE 5.3 Rugosity of the Pentland Firth in 2009 published by Marine Scotland.

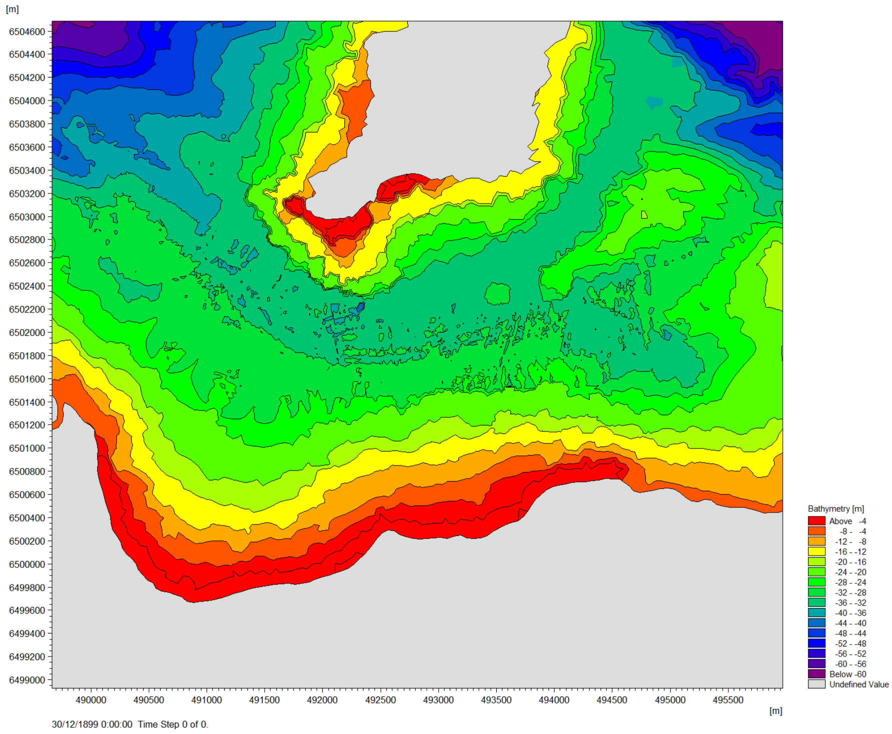

FIGURE 5.4 Model bathymetry of the Inner Sound Pentland Firth

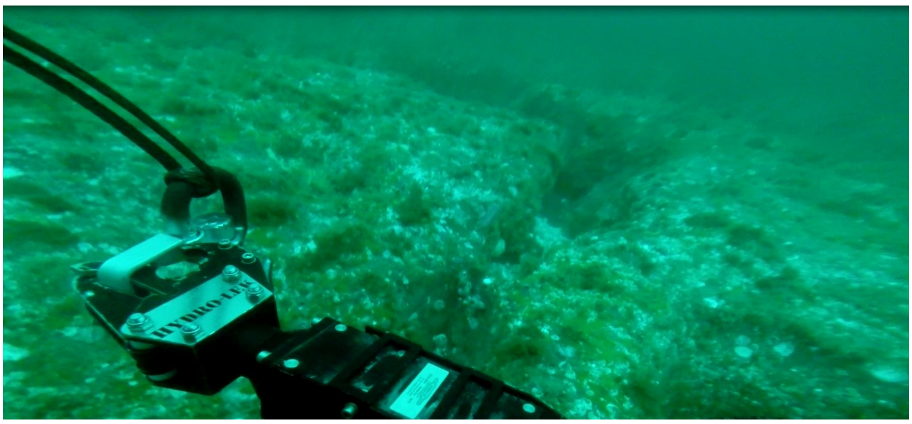

FIGURE 5.5 Pentland Firth Inner Sound seabed at deployment location image courtesy of Partrac

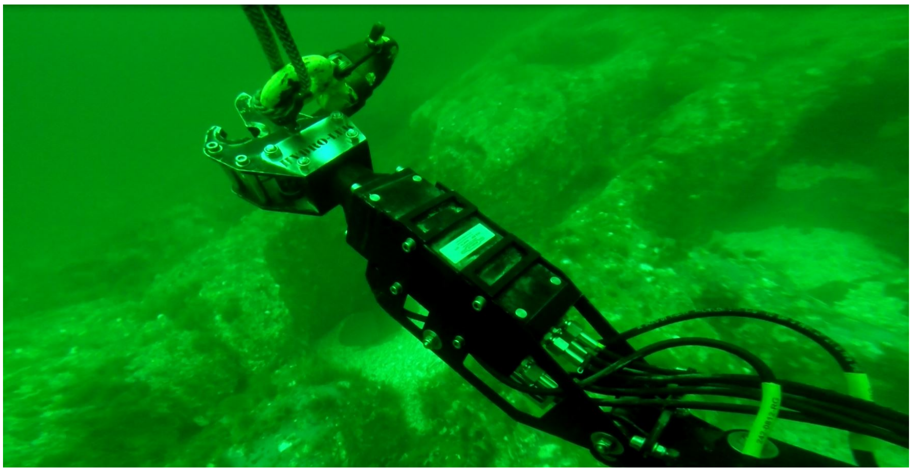

FIGURE 5.6 Pentland Firth Inner Sound seabed at deployment location image courtesy of Partrac

5.3 The Sound of Islay

5.3.1 *Bathymetry*

The Sound of Islay off the coast of Scotland, is a narrow channel separating the islands of Islay to the west and Jura to the east (location shown in Figure 5.7). The sound is relatively long and narrow, being around 20 *km* in length and around 700 *m* in width at the narrowest section.

The sides of the channel have fairly steep slopes, and the middle areas of the channel are in general, relatively flat. Depths in the Sound of Islay are typically less than 30 *m* below MSL but there is a deeper channel in the middle of the sound in the region between Port Askaig and the Feolin slipway where the depths are 50 *m* to 60 *m* below MSL (bathymetry from numerical modelling of the region undertaken by ABPmer is shown in Figure 5.8).

5.3.2 *Tidal currents*

The currents here are described as a tidal stream type site [28]. There are strong tidal streams which form in this narrow channel, though it is relatively sheltered from wave action [1]. The site can be described as a bounded channel and geologically constrained which causes the acceleration of the flow. The tidal flow is dominantly directed by the topography and channel alignment.

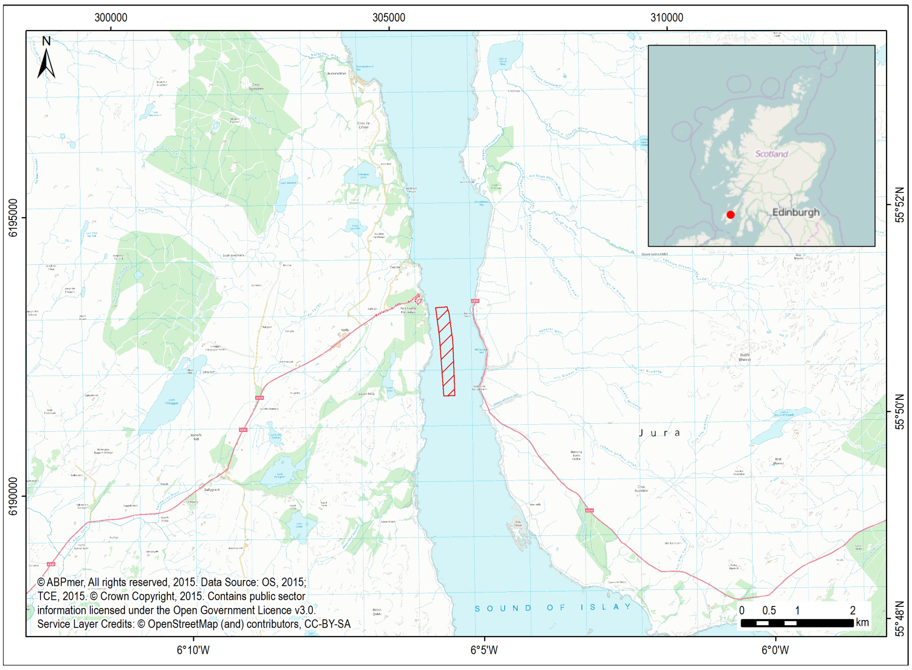

FIGURE 5.7 Location of the Sound of Islay

5.3.3 *Seabed composition*

Sediment type in the Sound of Islay ranges from coarse sediment/gravel dominated areas, to areas of exposed bedrock and boulders and pebbles, where strong flows have swept away smaller particle substrate, and there are also some areas of sand sea bed. Much of the Sound of Islay seabed can be described as a coarse sedimentary environment, with small boulders and sandy gravelly cobbles [1]. Some images of the seabed in the Sound of Islay from the report of Axelsson [1] can be seen in Figures 5.9 and 5.10, showing some of the variety of coarse substrate in this area. The sea bed sediment at the northern and southern entrances to the Sound of Islay tends to be of sandy gravel [3].

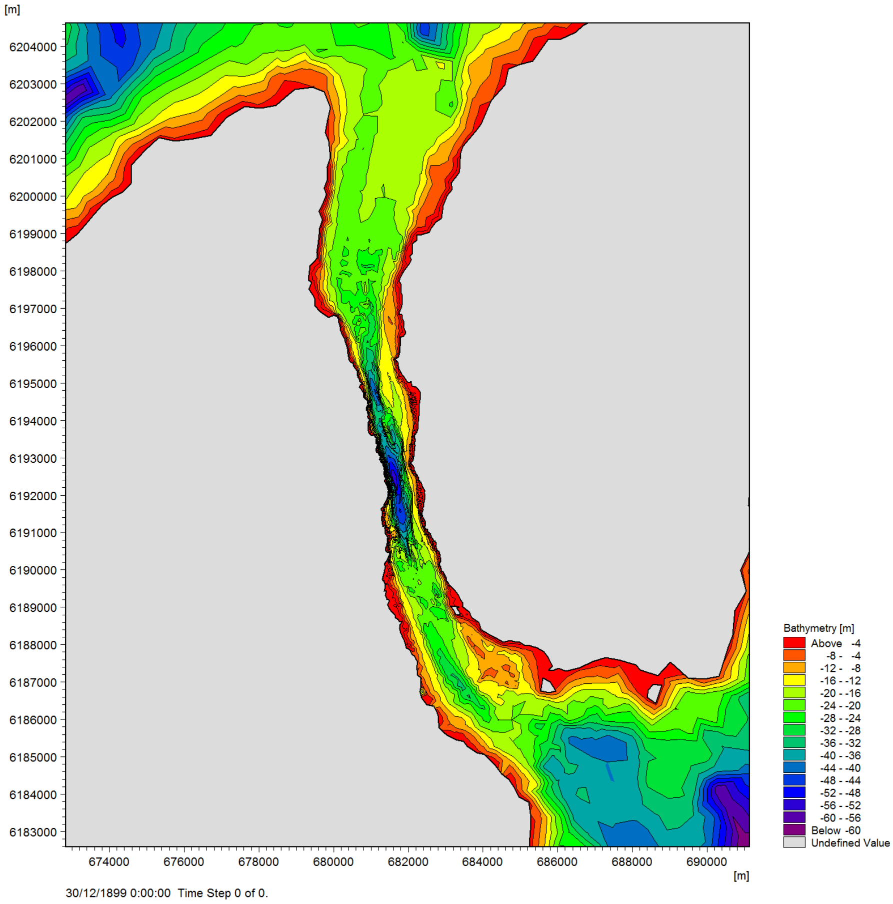

FIGURE 5.8 Model bathymetry of the Islay Sound

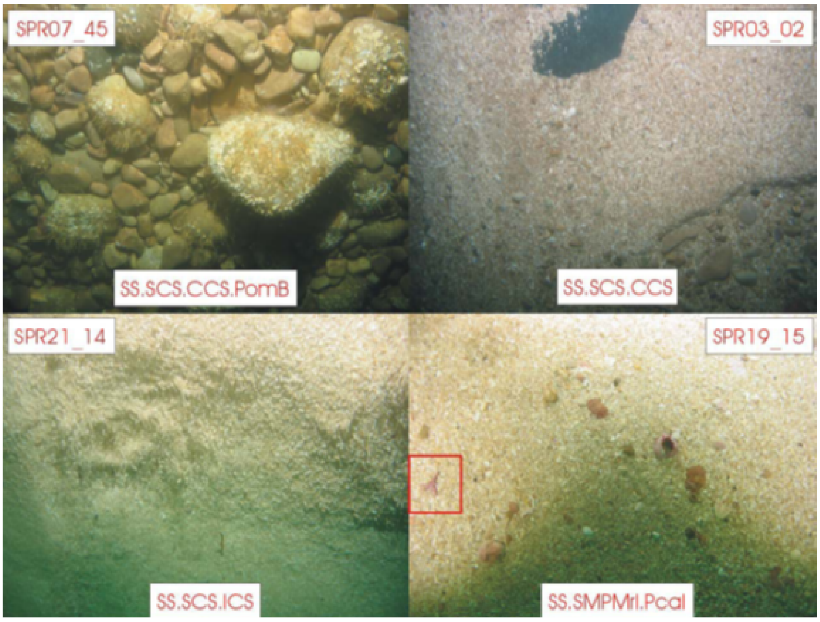

FIGURE 5.9 Photographs of the seabed in the Islay Sound (images from Axelsson [1])

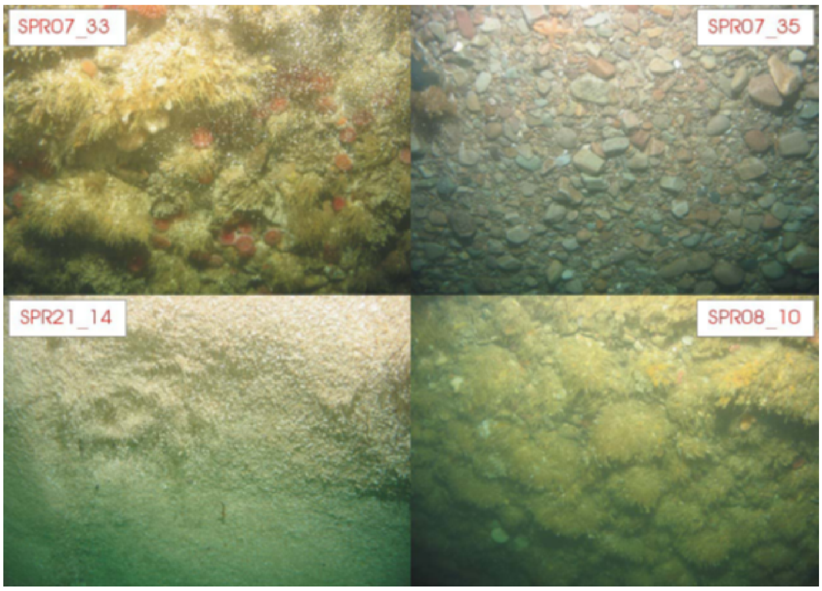

FIGURE 5.10 Photographs of the seabed in the Islay Sound (images from Axelsson [1])

5.4 Differences in typology

Both the Inner Sound Pentland Firth and the Sound of Islay sites experience fast tidal streams and are therefore potential sites for renewable tidal energy developments. However, the sites differ in their resource typology in a number of ways. The Sound of Islay is a much narrower and longer channel, fairly sheltered from wave action and geologically constrained by the islands of Islay and Jura. The channel is also fairly straight which directionally aligns the flow. This makes the flow fairly rectilinear with ebb and flood directions being around 180° apart. Conversely, in the Inner Sound Pentland Firth misalignment of the ebb and flood flow directions has been reported in previous studies [8, 14]. The Inner Sound Pentland Firth is comparatively wider and more exposed to the influences of the open sea. The locations of some example cross-sectional transects are shown in Figure 5.11 for both sites. The cross-sectional depth profiles at these transect locations are then presented in Figure 5.12 to demonstrate the differences in cross-sectional width and area between the Inner Sound Pentland Firth and the Sound of Islay.

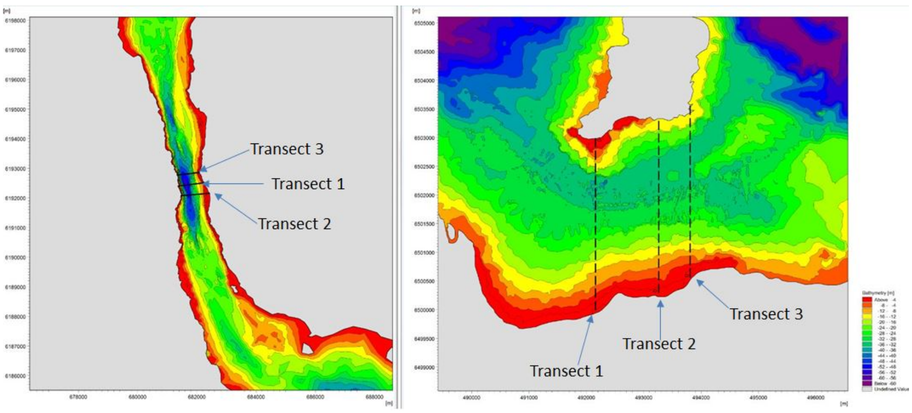

FIGURE 5.11 Locations of cross-sectional transects, Sound of Islay (left), and Inner Sound Pentland Firth (right)

For most of the area of the Sound of Islay, the depths are generally shallower than the depths of the Pentland Firth Inner Sound, with the exception of the deepest section of the Sound of Islay which reaches depths of around 60 m. The bathymetry of the Inner Sound Pentland Firth and Sound of Islay can be seen in Figures 5.4 and 5.8 respectively.

The seabed in the Pentland Firth Inner Sound tends to be exposed bedrock which can be of a very steep gradient and irregular (see Figures 5.5 and 5.6), and there are also shallow rocky outcrops such as the Stroma Skerries [9]. This

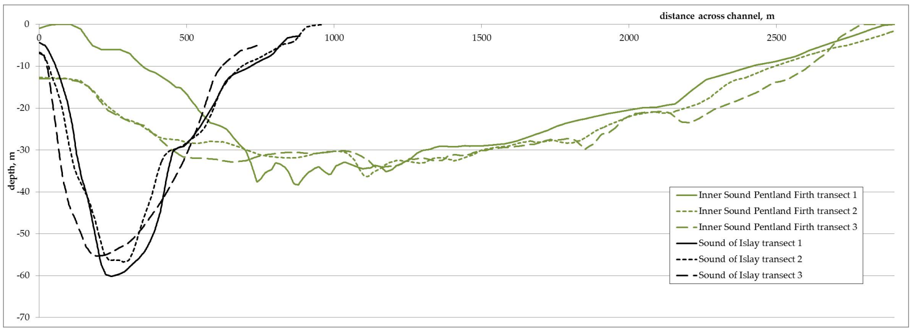

FIGURE 5.12 Cross-sectional transect profiles (from numerical model bathymetry). Across-channel distance is north to south for Inner Sound Pentland Firth, and west to east for the Sound of Islay.

indicates that the site is likely to be very rough bathymetrically, and could therefore give rise to very turbulent flow conditions. Bedforms are known to be related to the roughness of the flow, and complex heterogeneous beds can lead to greater Reynolds numbers, and therefore an increase in likelihood of fully-rough turbulent flow regimes [5].

Although there are areas of exposed bedrock in the Sound of Islay, most of the area can be described as a coarse sedimentary seabed of sandy gravelly cobbles and small boulders [1]; Figures 5.9 and 5.10). The lower area percentage of exposed bedrock in the Sound of Islay than in the Inner Sound Pentland Firth, indicates that the seabed here is likely to be bathymetrically smoother and less irregular, and therefore less likely to cause turbulence in the flow. Further seabed surveying would be required to accurately quantify the roughness length of the seabed at the two locations. A summary of the general characteristics of the two sites is shown in Table 5.1.

	Inner Sound Pentland Firth	Sound of Islay
Channel length	6 km (approx.)	20 km (approx.)
Channel width	2.5 km (approx.)	700 m in the narrowest section
Depths	Generally shallower than 40m below MSL	Deepest section in the middle of the Sound is around 60 m below MSL
Tidal current type	Tidal stream combined with hydraulic current	Tidal stream
Tidal range	Around 1 m during a neap tide Over 4 m during a spring tide	Around 0.5 m during a neap tide Around 2 m during a spring tide
Site exposure	Fairly open, exposed location	Generally sheltered from wave action geographically by islands of Islay and Jura.
Seabed types	Exposed bedrock. Areas of boulders, cobbles, coarse sediment.	Generally coarse sediment, cobbles and boulders, gravels. Some areas of exposed bedrock.

TABLE 5.1 Summary table of general characteristics of Inner Sound Pentland Firth and the Sound of Islay

6 Data Management and Quality Control

The process of quality control is a key component underlying the provision of good quality data to the tidal energy sector. There are currently no regulated standards for quality controlling current velocity data sets, but otherwise it should be a matter of Good Practice to develop, establish or obtain a Data Quality Management System (DQMS) which summarises the various aspects relating to the control of quality (from pre-collection to delivery) for turbulence data. The following sections provide detail on the considerations which may form part or all of an appropriate DQMS.

6.1 Data backup and management

Prior to quality checking the raw data from any instrument, there should be an established protocol for data management, which includes raw data backup procedures, quality check procedures and quality checked data backup procedures. All data must be backed up onto a remote server/hard disk before any raw data are cleared from the memory of the instruments. Data is very expensive to collect, and it is critical that loss of data through poor management is avoided. A generic overview of the data management process is shown in Figure 6.1. We recommend a similar data management process to this is adopted for turbulence projects.

6.2 Data quality control

The fundamental objective of the DQC procedure is to generate a dataset for which all the data points are considered to be real, although a dataset which contains noise, together with description of a systematic approach to the data editing process. In the first instance one should use the specific manufacturer's custom software, although it should be highlighted that these packages are designed for general usage and may remove too many data due to the extreme environment from where they were collected. As such, many researchers in this area have developed custom QC routines. However, these are not widely available and often not quality assured using best practices for software development.

6.2.1 ADCPs and ADVs / current sensors

Pre-processing of ADCP and ADV data sets invariably requires a multi-stage QC process. Stage 1 involves the relatively easy removal of data known to

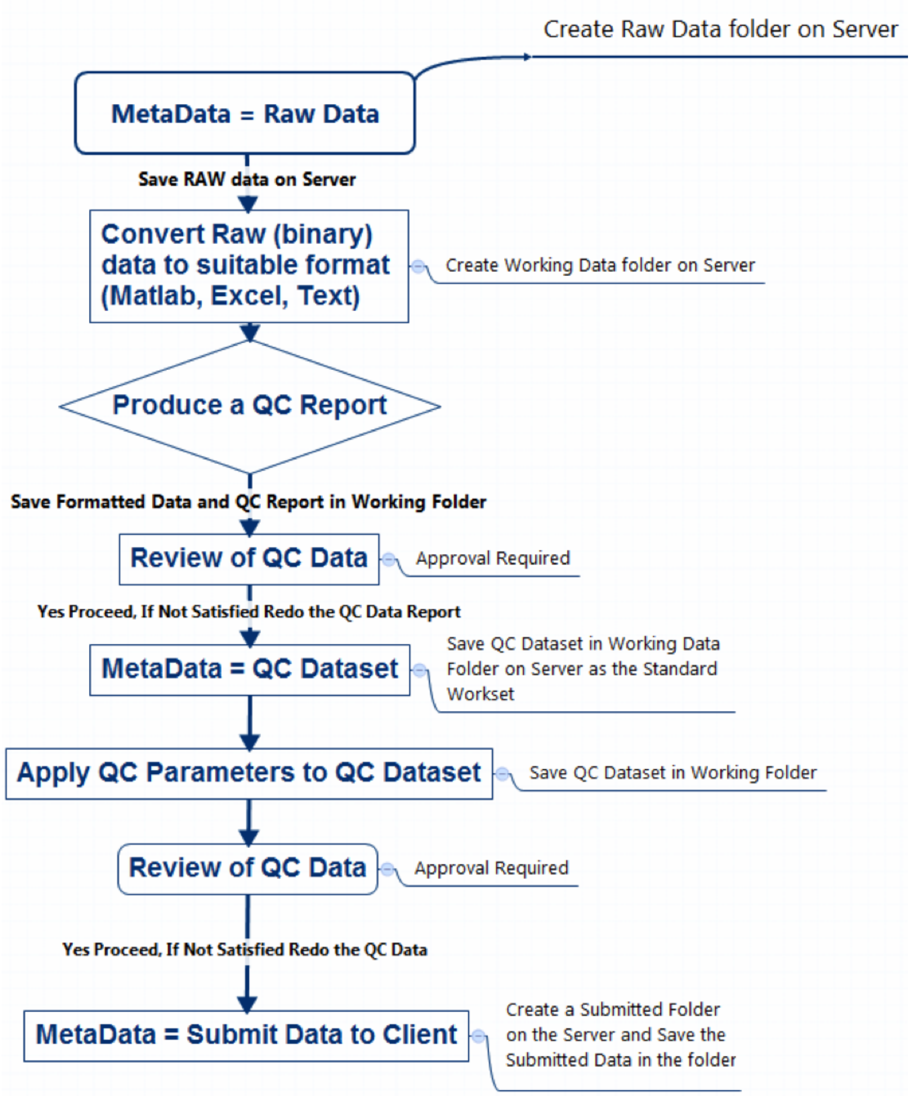

FIGURE 6.1 Data management process overview.

be poor, such as data collected during deployment/recovery and bins outside the optimal profile range (blanking distance etc.). Areas where data may be compromised can be highlighted for Stage 2 QC such as:

- **Vibration effects.** The internal compass may not be able to accurately resolve rapid changes in pitch/roll and can introduce errors. Note that this vibration is best resolved at site.
- **Correlation magnitude and echo intensity** The nature of tidal races can mean that the there are few particulates from which an ADCP signal can scatter off. This will be highlighted by poor echo intensity and may mean that the signal is too low at the extremities of the range to provide reliable data. Correlation magnitude (the difference between velocities recorded by the pairs of bins) may be low, which would ordinarily be a marker for unreliable data. In this case, the flow may be so turbulent that correlation between beams is unlikely to be high. Caution should be applied to avoid removing valid data.
- **Magnetic correction** It is assumed that a compass calibration has been undertaken with the instrument in its frame, complete with charged batteries. However, the alignment may be affected by iron in the vicinity (considering that the frame will likely be deployed on bed rock) and should be quantified and corrected where possible prior to final processing.

Figure 6.2 provides a recommended, high level, generic approach to data quality control and which may be applied to any current profiler or current meter data type.

6.2.2 Shear probes (Microrider)

The signals reported by the shear probes can be compromised in several ways that are itemised below. All of these unwanted contributions to the shear probe signal bias the dissipation estimates high and should be removed in the quality control process.

- **Vibration effects.** Caused by vibration of the platform holding the shear probes. It is recommended that a vibration-coherent noise removal algorithm is used to eliminate the degradation. The algorithm is effective up to 200 *Hz*.
- **Plankton.** Collision of plankton with the shear probes can be another source of anomaly that needs to be removed from the data. A collision

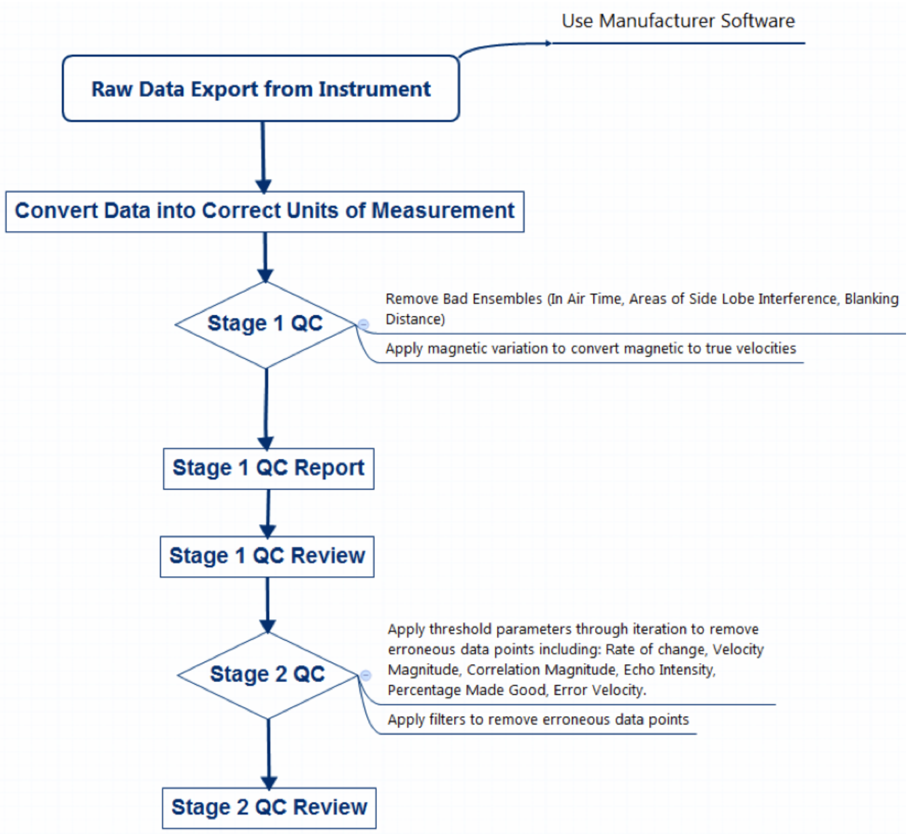

FIGURE 6.2 ADCP and ADV Recommended quality control procedure.

will result in a large-amplitude spike followed by a few tenths of milliseconds of damped oscillation. Spikes in the shear probe data should be eliminated with an algorithm that detects these anomalies and replaces them with a local mean. One such algorithm is the 'despike' function in the Rockland Scientific ODAS Matlab Library (www.rocklandscientific.com). A good choice is to remove about 40 $m\ s$ after and 20 $m\ s$ before a spike.

- **Snagging of Seaweed.** It is recognised that snagging of seaweed on the shear probes can cause anomalously large and elevated spectrums at high wave numbers. It is recommended that snagging anomalies is eliminated by sorting the estimates of the four probes into ascending order. If the ratio of the largest to the smallest exceeds a critical value, then the largest one is eliminated. This process should be continued until the ratio of the largest to the smallest is below critical. There is no accepted standard for eliminating estimates based on the ratio of values. However, a value of 2 to 2.5 is considered to be effective at removing anomalies. Snagging, like all other forms of signal contamination, always increases the estimate of the rate of dissipation.

- **Angle of attack.** The angle of attack of the flow past the shear probe must be less than 20° for the proper functioning of the shear probe. The angle can be estimated from the concurrently collected ADV data.
- **Speed.** Experience so far, (45 days of deployment) indicate that the MicroRider mounted on a Nemo float gives good results for speeds greater than 0.75 $m\ s^{-s}$, although often speeds as slow as 0.5 $m\ s^{-s}$ also give good data. The lower limit of speed may be site dependent and must be determined during data processing.
- **Pitch.** The pitch of the Nemo depends on how closely it is balanced in static water and on the speed of flow, which levels the Nemo by hydrodynamic forces. Data quality is good for pitch in the range of $+/-7°$.

6.2.3 Shear probes (Vertical Microstructure Profiler)

Two key kinematic parameters that determine if a profile provides good quality data are the fall rate (pressure derivative dP/dt) and the inclination angle of the instrument θ_x. The shear probe, like all velocimeters, is a relative velocity sensor it measures the vector difference of the water velocity and the profiler velocity. This makes the shear probe sensitive to vibrations of the profiler. The two horizontal components of the vibration are measured with two piezo-ceramic accelerometers for frequencies in the band of 0.1 Hz to 200 Hz. It is recommended that any vibrational contamination is removed using the 'coherent noise removal' technique described by Goodman et al. [15].

7 Conclusions

This document provides information to guide and assist groups interested in the acquisition of turbulence data at tidal race settings. It is clear that acquisition of high quality turbulence data from these tidal race environments is both complex and challenging, requiring consideration of a range of factors across a number of areas. This document addresses the following:

i **Definition of project goals and objectives:-** accurate, and in-advance, definition of the project requirements in terms for turbulence is key to collection of turbulence data which will meet the characterisation, modelling and engineering requirements. The project objective(s) should take into consideration temporal and spatial aspects of flow turbulence, specific turbulence metrics required, and length scales, for example.A vague definition of project goals and objectives may result in the collection of turbulence data which may not be wholly useful.

> Key Lessons:
>
> - Understand which turbulence parameters are relevant or required before deciding survey methodology.
> - Understand the limitations of the instruments and methods used to collect turbulence data.

ii **Background site hydrodynamic and morphological characterisation:-** this is a process which collates and reviews all available pre-existing data sources. This may include mean flow and other metocean information (e.g. wave dynamics), site bathymetry data, surficial sediment cover, and coastline morphology. Insofar as marine turbulence can often, typologically, reflect site specific characteristics (e.g. boulder fields at the seabed will generate localised wall turbulence), it is critical that all available information is inspected in detail. The information review is also critical and useful to survey planning and design, in particular micro-siting of bed mounted sensor frames and clump weights of moored instruments.

> Key Lessons:
>
> - Turbulence is site specific so careful planning of proposed deployment sites is recommended over impromptu data collection.

iii **Instrumentation available commercially for the collection of turbulence data:-** this document presents acoustic (Doppler devices, including recent 5 beam units) and non-acoustic (shear probes) instruments which are available commercially for the measurement of marine turbulence. It also covers the platforms, both common and innovative, used to date to deploy the instruments in the sea. A technical description of both types of instruments is provided at a level to enable interested groups to understand the advantages and limitations of the differing instrument options.

Key Lessons:

- ✓ ADCP profilers are suited to provide general long term vertical profiles of turbulence data.
- ✗ ADCP profilers can only resolve large scale eddies > 1 *m* (dependant on bin size and beam separation).
- ✓ ADVs are suited to provide high resolution data and can resolve eddies across the spectrum (> 0.01 *m*).
- ✗ ADV data is single point and can be limited by memory constraints (although can be used as part of an array).
- ✓ VMPs can provide high resolution profiles and can resolve small scale eddies (> 0.01 *m*) over a wide spatial coverage (with repeated deployments).
- ✗ VMPs are limited to structures < 1 *m* (the length of the instrument) and are labour intensive relative to the data return.
- ✓ Buoy-mounted shear probes (Nemo) can provide long term time series of high resolution data at hub height.
- ✗ Retrieval of a high quality dataset is more uncertain due to movement of the buoy along all axes and relative to the seabed with potential data loss if pitch $> 20°$. Where motion compensation is used, the Inertial Motion Unit must be of sufficient accuracy and sampled at sufficient frequency (preferably in sync with the instrument sampling frequency) to robustly process for motion compensation.

iv **Instrument selection considerations:-** selecting the correct instrument to meet the project objectives is key. Choice of instrumentation is driven by a range of factors dictated by the overall project objective(s), the scale of turbulent motions of interest, the spatial aspects of the project (e.g. single or multiple sites), and the specific nature of the turbulent effects from an engineering standpoint. These in turn govern the turbulence metric(s) required to be measured. A table is presented in this report which offers a useful starting point in terms of which instrument to select for site specific turbulence data acquisition. Some consideration has been given to novel instrumentation platforms and arrangements. Given the capabilities of ADVs in capturing the required range of turbulent lengthscales (provided that sufficient motion compensation is possible or that they are fixed in space), the idea of [19] to distribute multiple ADVs on a single mooring (overcoming the one limitation of single-point measurement) shows great promise.

Key Lessons:

- ✓ Turbulence data resolution is limited to the sampling volume of the instrument.
- ✓ Collection of turbulence data at tidal sites generally pushes the limits of acoustic instrumentation. Optimisation of the programme to record high resolution data must be balanced with limitations of the instrument's interaction with site characteristics.
- ✓ Simultaneous measurement of water depth / wave height aids post processing for turbulence by allowing wave and turbulent motion to be decoupled straightforwardly.
- ✓ Selecting increased frequency or resolution decreases the effective range of an ADCP, which may limit ability at deeper water sites.
- ✓ Turbulence data have been successfully collected using TRDI ADCPs running at 1 Hz. As such, there is a small but significant literature library detailing the finer points of collection, Quality Control and further analysis of TRDI-derived data.
- ✓ Consider using ADVs distributed onto a moored array for high-quality, high resolution turbulence data (such as the x-wing configuration).
- ✓ Consider operational restrictions and economies when deploying instruments. ADCPs are subject to very tight weather windows, and may be deployed at slack water in neap tides only. Instrument platforms or moorings deployable in a wider range of sea states, weather conditions and tides may dramatically reduce operational risk.

v **Programming and setup of this equipment:-** Software provided by the manufacturer enables interfacing with the instrument and the ability to upload individually tailored programmes that optimally collect velocity and turbulence data. The TiME project tested the major acoustic and non-acoustic instrumentation in various configurations at two commercially active TEC sites, and the experience gained from those studies in terms of instrument programming and setup together with other published work is captured herein.

Key Lessons:

- Liaise with experience. Communicate with the relevant manufacturer in regard to the programme set up as a minimum. Consider using an experienced survey team to provide the data. Experience gained during this study suggests the following programming settings:
  - ✓ ADCPs should run at 1 Hz with 1 m bins for a standard 30 day deployment.
  - ✓ ADVs run optimally at 4 Hz before noise and memory become limitations.
  - ✓ ADCPs and ADVs should ideally be deployed in a bottom-mounted frame.
  - ✓ VMP deployments should be repeated over a tidal cycle to provide a time series, and used in 'curtaining' mode to map the spatial characteristics of turbulence.
  - ✓ Test runs of the Nemo system to ensure neutral buoyancy is advised.

vi **Survey planning, Risk Assessment and QHSE:-** Data collection operations in tidal races are particularly challenging, and a systematic, comprehensive and adaptive approach to planning a survey to collect turbulence data is necessary to minimise risks to both the collection of good quality turbulence data and to personnel, vessels, equipment etc. The guidance herein combines Good Practice developed and adopted by the report authors (borne out of their commercial professional involvement in the northern European tidal energy sector) with other, published work. The report aims to provide sufficient detail to the reader across areas which include site selection and characterisation, vessel attributes and audits, mooring configuration, health and safety processes (RAMS Risk Assessment and Method Statements and SWP safe working practices), and (domestic) Regulations to enable an appreciation of this important aspect of the data acquisition process.

Key Lessons:

- ✓ Use local skippers/vessels for knowledge of the survey site.
- ✓ Ensure all personnel are aware of the proposed survey work and risks and mitigation that are undertaken as a result.
- ✓ Create a system to ensure that ADCP frames are level on deployment and that all equipment is sufficiently robust enough to survive the effects of maintained strong current flow.
- ✓ Get sufficient insurance. If recovery systems fail then return of data and equipment can be costly and lengthy.

vii **Data Management and Pre-Processing:-** The process of quality control is a key component underlying the provision of good quality data to the tidal energy sector. The data are expensive to collect and must be managed and backed up through an established data management protocol, which should include the addition of metadata, to avoid loss. Pre-processing of the data must be performed with the understanding that noise and turbulence are not easily distinguishable so useful data may be removed using general QC algorithms.

Key Lessons:

- ✓ The size of the dataset requires robust back up methods.
- ✓ Control the dataset through use of metadata.
- ✓ Since datasets can occupy considerable memory, adoption of a unified standard binary file format for data exchange (e.g. HDF5) is preferred. Modern binary files are partially readable, improving convenience, speed and eliminating risk of data loss by splitting large datasets for transfer.

A framework connecting these areas has been developed (figure 1.1). This provides guidelines for a safe, fit-for-purpose and quality assured survey practice for the tidal industry, allowing measurement of tidal flows including turbulence. It is anticipated that adherence to items within this, notwithstanding future progress and technological and other developments, will ensure that future data collection will be conducted in a consistent, reproducible and accurate manner across the tidal power sector. The improved understanding of turbulence and the ability to make useful, quality measurements will significantly de-risk upcoming and future tidal projects.

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