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Programme Area: Marine

Project: PerAWAT

Title: Array Scale Experiment Specification

Abstract:

This document describes the scale model experiments required to investigate array scale blockage and wake effects in order to develop the mathematical models used to predict the influenced flow field in and around tidal turbine arrays. Details of the scaling rationale, the experimental equipment and facilities and the proposed testing programme are described. The purpose of the scale model experiments described here is to provide experimental data to develop and validate the mathematical models that will be developed as part of WG3WP4. This includes measurement of turbine performance and of wake characteristics both downstream of individual devices and downstream of an array of devices. The programme of tests improved understanding of how bounding surface proximity influences both turbine performance and wake structure.

Context:

The Performance Assessment of Wave and Tidal Array Systems (PerAWaT) project, launched in October 2009 with £8m of ETI investment. The project delivered validated, commercial software tools capable of significantly reducing the levels of uncertainty associated with predicting the energy yield of major wave and tidal stream energy arrays. It also produced information that will help reduce commercial risk of future large scale wave and tidal array developments.

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ETI Marine Programme Project
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WG4WP2 D1 ARRAY SCALE EXPERIMENT SPECIFICATION

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CONTENTS

SUMMARY OF NOTATION

Turbine characteristics

D	Rotor diameter (m)
R	Rotor radius (m)
C_T	Thrust coefficient
C_P	Power coefficient
TSR	Tip speed ratio
C_{T0}	Thrust coefficient in boundless conditions
C_{P0}	Power coefficient in boundless conditions
C_L	Coefficient of lift
C_D	Coefficient of drag

Flow Field

U(z)	Mean velocity profile, as a function of depth
$U_{RMS}(z)$	Fluctuation of the velocity profile about the mean, as a function of depth
TI	Turbulence intensity
T	Wave period
H	Significant wave height

A general glossary on tidal energy terms has been provided as part of WG0 D2 – "Glossary of PerAWaT terms". This is a working document which will be revised as the project progresses.

1 INTRODUCTION

1.1 Scope of this document

This document constitutes the first deliverable (D1) of working group 4, work package 2 (WG4WP2D1) of the PerAWAT (Performance Assessment of Wave and Tidal Arrays) project funded by the Energy Technologies Institute (ETI). The project partners of this work package are the University of Manchester (UoM) and Garrad Hassan (GH). This document describes the scale model experiments required to investigate array scale blockage and wake effects in order to develop the mathematical models used to predict the influenced flow field in and around tidal turbine arrays. Details of the scaling rationale, the experimental equipment and facilities and the proposed testing programme are described. This document is the next step for WG4WP2 after the detailed tidal specification WG0D2 [1], in which a high-level specification of WG4WP2D1 is provided. A glossary of terms specific to the PerAWAT project, including summary diagrams showing the key parameters, has been provided as an annex to WGO D2 [2] and should be referred to where necessary.

1.2 Purpose of the scaled model testing

At present there is no available data from prototype or full scale devices and little data from scale model experiments, particularly at array and basin scale. Data is required to aid the development of numerical models both in terms of validating theoretical assumptions and evaluating semi-empirical relationships. Thus as part of the ETI PerAWAT project experimental tests will be undertaken at several geometric scales. WG4WP2 is at the inter-array scale, sitting at the midpoint between the device scale experiments (WG4WP1 and WG4WP3) and basin scales (WG4WP4).

The purpose of the scale model experiments described here is to provide experimental data to develop and validate the mathematical models that will be developed as part of WG3WP4 to describe the flow-field within and around a tidal turbine array. This includes measurement of turbine performance and of wake characteristics both downstream of individual devices and downstream of an array of devices. The programme of tests will improve understanding of how bounding surface proximity influences both turbine performance and wake structure.

The objectives of WG4WP2, as set out in Schedule 5 of the Technology Contract, are to investigate (through physical testing of an array of up to 15 small devices):

1. the effect of bounding surfaces (free surface, seabed and other devices) on device performance and loading
2. the effect of the bounding surfaces, ambient flow field and device performance characteristics on the far wake form
3. the wake interactions within an array including influence of varying ambient turbulence intensities (seabed, waves and large eddies)

1.3 Specific tasks associated with WG4 WP2

Deliverables associated with WG4 WP2 are:

- Test specification (D1) [GH] of sufficient detail and scope to: Evaluate the effect of bounding surfaces and device performance characteristics on the device loading. Evaluate the effect of bounding surfaces, ambient flow field and device performance characteristics on the far wake form. Investigate the wake interactions within an array including influence of varying ambient turbulence intensities (seabed, waves and large eddies). Specification will define the details of: operating points (speeds/torques), instrument type, sample frequencies, acceptable error and experimental programme plan.

- Design of test equipment (D2) [GH & UoM] including: Rotor design, Instrumentation system design and support structure design.

- Construction of test equipment (D3) [UoM] including: Rotor (blades, hub, nacelle, generator), Instrumentation system, Support structure, and Alteration to facility equipment.

- Conduct tests (D4) [UoM] including: Set up test facility, Calibrate instrumentation, Conduct test schedule (measuring rotor thrust, power consumption, and the flow field within and around the array).

- Issue database of experimental data (D5) [GH], including; Data post processing for presentation in experimental database (filtering, quality control etc.), Issue database of experimental data obtained under different current, wave and turbulence conditions

2 FLOW FIELD EFFECTS UNDER INVESTIGATION

This section provides background on the two main topics of investigation: blockage and wakes, with reference to tidal turbines.

2.1 Blockage

Objects within a flow act as an impedance causing the flow to deviate around the object. Blockage effects are generated when bounding surfaces or other objects within the flow restrict the deviation of flow around the object. The Lanchester-Betz's law is the well established theory that predicts how the flow expands around a rotor in a boundless flow as energy is extracted. However, this theory is not applicable when bounding surfaces act to restrict the expansion of flow through the rotor.

Various studies [5] have been conducted into the effects of blockage on turbines including those taking consideration of the free-surface e.g. [4]. The presence of bounding surfaces acts to re-direct the vertical component of the flow into the stream-wise direction, causing an overall increase in the flow through the swept area of the turbine. This leads to:

- increased torque or rotor speed (depending on the rotor control strategy),
- increased loading experienced by the turbine,
- and, potentially, increased power capture.

Full scale tidal turbine arrays are expected to be located in areas where the depth of water varies between 1.5 – 3 D and the lateral distance between rotors varies between 1.5 - 5 turbine diameters (D) (leading to blockage ratios of between 5% and 34% of the cross sectional area). It is therefore important to investigate the effect that bounding surfaces, at similar proximity, have on turbine performance. This is also an area of investigation in other work packages (both numerical - WG3WP1, WG3WP5 - and experimental - WG4WP1 and WG4WP3). Quantitative investigation of lateral bounding is the primary focus of this work package.

In addition to predicting the change in performance due to blockage, a second purpose to the blockage modelling is to predict the altered flow field around the turbine which may impact on the wake recovery and/or other turbines, including the

- ➢ Local flow acceleration in the near wake due to blockage.
- ➢ Wake recovery and expansion: The flow velocity in the bypass region around the turbine (and hence the wake) will be increased due to the restriction of two bounding surfaces. This leads to change in the velocity deficit compared with the

same rotor operating in an unbounded flow, which in turn will have an impact on the rate of mixing between the wake and the bypass flow and the resulting wake recovery length scales.

2.2 Wakes

The wake created by a wind turbine is relatively well understood and established mathematical models correlate well with real wind farm data [5]. These models describe the physical process of wake and free-stream mixing. Any device that extracts energy from a flow causes a reduction in the axial momentum of the downstream flow. The region of reduced flow velocity and static pressure downstream of the turbine plane (that has passed through the turbine plane) is defined as the wake. The specific form of a wake is likely to be complicated and device specific. However, the fundamental physics governing the wake structure and its dissipation can be simplified by considering the wake as two distinct regions:

Near wake

The near wake is the region immediately downstream of the rotor in which the specific properties of the rotor can be discriminated, such as the number of blades, tip vortices and stalled flow. The extraction of momentum from the flow, whilst conserving mass, drives a wake expansion, which also occurs in this region (usually within 1D downstream). The vortical structures which are trailed and shed from the blades and the device support structure comprise the wake and this region is bounded from the outer (faster moving) free-stream fluid by the vortices trailed from the blade tips and shed from the support structure. Typically the near wake transits into the beginning of the far wake at between 2D to 4D downstream (depending on the ambient flow conditions), after which the ambient turbulence in the free-stream flow starts to breaks down the bounding vortices.

Far wake

Once the initial conditions for the far wake are established by the near wake region there are two main mechanisms that drive the wake structure. These are convection and turbulent mixing. If the fluid were completely inviscid then a volume of slower moving flow would just convect downstream at a slower rate than the free-stream flow. However, turbulent mixing is present and acts to re-energise the wake, breaking it up and increasing the velocity until, at a point far downstream, the mean velocity profile across the wake is similar to the free stream.

The mixing process of wakes behind tidal turbines is likely to be very similar to that of wind turbines, although the specific wake structure and decay rate may vary due to the effect of a bounding free surface and flow specific differences, such as turbulence structure. The purpose of the wake model is to represent the recovery of the momentum deficit downstream of the turbine so that both the incident flow velocity and level of turbulence on a downstream turbine can be predicted. The issue of wake interaction is of key importance due to the relatively small lateral spacing between turbines.

Different ambient flow conditions have varied effects on wake recovery, e.g.

- The amount of ambient turbulence intensity in a flow can significantly enhance the mixing process and hence speed up the decay of a wake. Ambient turbulence intensity is prominently governed by the seabed roughness.
- Free-surface waves are another source of flow turbulence. Certain wave states and operating depths may significantly impact on the wake recovery process.
- Large scale eddies are another source of turbulence which have the potential to introduce additional energy to the wake, potentially further aiding recovery.

3 SCALING CONSIDERATIONS

Before designing both the experimental set-up and the experiments themselves, extensive consideration must be given to the representation of a full-scale tidal turbine in its likely operating environment. Three scaling considerations - geometric, kinematic and dynamic - are discussed in Section 3.1. The relative importance of each scaling law is dependant on the processes to be investigated and so the influence of these laws on the dimensionless parameters relevant to rotor design, support structure design and facility scale are detailed in Sections 3.2 to 3.4.

3.1 Similarity requirements

Two issues need to be considered with regard to the similarity requirements. These are the environmental effects on the device and the device effect on the environment. The effect of the environment on the device is twofold. Firstly the incident flow field on to the rotor and secondly the proximity of bounding surfaces both act to alter the rotor performance and loadings (i.e. power and thrust coefficients versus tip speed ratio, C_P & C_T v TSR) compared with the equivalent boundless performance and loadings (C_{P0} and C_{T0}). Both of these effects must be similar to the full scale device in order to make a robust comparison. The effect the device has on the environment (i.e. the form of the wake), is a function of the resistance it presents to the flow, the level of ambient flow mixing and the description surrounding boundaries. The resistance the rotor presents to the flow leads to an extraction of momentum (commonly referred to as operating state of the turbine or C_T). Thus to investigate boundary and interaction effects on wakes at scale similarity of the extracted momentum and the mixing process is required.

Geometric similarity: The depth and lateral spacing between turbines must be similar.

- For blockage modelling the geometric similarity of channel depth to the rotor swept area must be maintained.
- For wake modelling the non-dimensional distance over which flow entrainment occurs must be similar to the full scale system.
- The position of the rotor relative to the seabed and free surface should be maintained.

Kinematic similarity: The velocity profiles through the water column and in the near wake profile should be similar.

- For blockage modelling kinematic similarity is not required.
- For wake modelling the velocity-scale over which flow entrainment occurs must be similar to the full scale system, i.e. the initial velocity deficit must be similar.
- Kinematic similarity must be maintained regarding the spatial and temporal variation in flow onto the rotor, e.g.
  - The free-stream depth velocity profile should be similar to capture the non-uniform mass flow above and below the wake.
  - The effect of seabed shear for a given channel depth, leads to a boundary layer profile and ambient turbulence in the flow. Thus the mean velocity depth profile and level of flow speed fluctuation about the mean velocity must be similar (i.e. $U(z)$ and $U_{RMS}(z)$ must be similar).
  - For tests requiring representative wave states superposed on current, the particle kinematics must be made similar to full scale following Froude scaling (height linearly with scale, period with the square root of the scale).

Dynamic similarity: It is a well know fact that Froude scaling (a measure of inertia to gravitational forces) and Reynolds scaling (a measure of inertia to viscous forces) can not be simultaneously satisfied when scaling free-surface flows (see Appendix 1 for further illustration of this point, in which the highlighted cells correspond to the Froude and Reynolds numbers respectively). Because surface effects could impact on both the performance and loading of a device and the wake structure behind the device, using similar Froude numbers is important (the appropriate wave scaling also follows directly from Froude scaling). The conflict occurs because scaling to the Froude number results in low flow speeds that yield much lower Reynolds numbers. One factor that could be altered to maintain similarity of both Froude and Reynolds number is the type of fluid used in the physical modelling. However, in practice, this can not be easily adjusted and water is used in both cases, so the rotor and support structure used in the physical model must be designed to provide representative momentum extraction at much lower Reynolds number.

Dynamic similarity of the effect of the device on the flow can be achieved by matching the performance characteristics of the rotor in an unbounded flow (i.e. similar C_{P0} and C_{T0} versus TSR curves). The source of rotor loads comes from the blade lift and drag forces (C_L and C_D), which are dependent on Reynolds number. Use of blade sections that are defined by geometric scaling of blade-sections that are designed for full-scale devices would result in (greatly) reduced performance since the ratio of C_L/ C_D reduces with Reynolds number and hence with geometric scale. In order to effect the same change of momentum as a full-scale device, alternative blade sections must be chosen which demonstrate suitable performance (lift/drag ratio) at the Reynolds number appropriate to the experiment. There is limited published information regarding lift and drag coefficients for blade sections at the Reynolds number in question. A detailed investigation into the available data will be performed as part of the rotor design stage [D2].

The dominant forces driving the process of wake recovery in a free-shear flow can be characterised by length and velocity scales (i.e. geometric similarity in the wake shape and velocity deficit). Provided that the wake shear Reynolds number at scale is high enough (or more accurately that viscous terms are small compared to the turbulence diffusions terms) then scaling to shear Reynolds number is not required [6]. The added effect of an ambient shear flow needs to be incorporated. Again, provided the channel shear Reynolds number at small-scale is high enough to avoid adverse effects (which can occur at lower Reynolds numbers), it is sufficient to maintain similarity of velocity and length scales (flow profile and depth).

3.2 Flow scale model

The range of depths at which blockage, array and free-surface effects are likely to be important is 1.5 – 3D. There is a practical minimum limit on the size of a rotor for both instrumentation purposes and in order to meet the similarity requirements (i.e. achieve the same C_T), which is likely to be in the region of D = 0.2 – 0.3 m. In order to investigate free-surface bounding effects in the required range, this suggests a minimum operating depth of 0.4 – 0.5m approx.

The Froude number for tidal flows can vary between 0 – 0.4. It is suggested that Froude number scaling is slightly altered between tests within the bounds of the above range to allow for acceptable levels of Reynolds number where possible. To achieve the desired dynamic similarity the flow speed in the flume is likely to be in the range 0.4 – 0.5 m/s.

To achieve kinematic similarity the seabed roughness can be altered and boundary layer tripping techniques used to yield the required profile and ambient turbulent flow fluctuations. Channel flow bed generated turbulence is governed by the scaling of the bed shear (or friction) Reynolds number. To alter the shear Reynolds number the seabed roughness length scale will not be similar to full scale but a similar boundary layer can be developed.

Real flow depth velocity profiles can vary from almost linear to a 5th power law. A target profile might be a seventh power law but the main issues are generation of high turbulence intensity and development of a fully formed boundary layer. The channel length (distance from inflow) at which the boundary layer becomes fully formed is dependant on the inflow speed and the seabed roughness. Due to the low inflow speeds the turbulent boundary layer may need to be initiated with some upstream roughness or with tripping techniques.

Previous research [3] has demonstrated that four diameters (4D) clearance is required in order to avoid blockage effects from the side walls. Side wall effects are shown in figure 1 (taken from [3]), to become relatively small after z/R = 6 (= 3D) away from the wall.

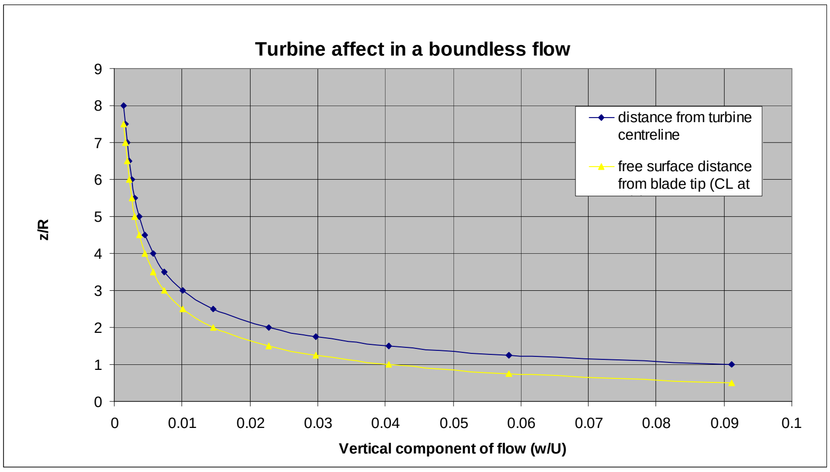


Figure 1: Effect of boundary proximity (from [3]).

3.3 Turbine and support structure scale model

Turbine: Producing measureable power at scales below 1/10th is unlikely due to drive train losses being of an order of magnitude greater than the generated rotor power. It has been standard practice (in the wind industry) to instead drive the rotor at either a constant torque or speed [5]. The power is inferred from measured rotor torque and rpm, coupled with the known losses.

Constant torque: A motor can be used to provide a constant torque (which is proportional to the applied current). Applied current can be accurately measured and modified at a high sampling rate. Using a constant torque approach means that in unsteady flow the rotor speed will fluctuate, but provided the losses are small, the rotor should maintain an approximately constant TSR.

Constant speed: A motor can also be used to provide a constant speed. This may require a closed-loop control system to continually adjust applied torque (applied current) to maintain a steady speed in an unsteady flow. The main argument for constant speed is to allow comparison with CFD results but this data is not used for that purpose. However, this is less preferable to constant torque because a mean TSR and thus C_T will need to be used and it is also not the approach being adopted by the majority of the tidal turbine device developers at present (see section 24 of [1]).

Although a closed-loop control system could be developed to modify applied torque on the basis of measured speed, this would require additional calibration stages and so a constant torque system will be implemented for WG4 WP2 experiments.

The blade design will need to allow several distinct operation points to be emulated. In practise this means operating at three to four specific TSR values. The blade design must ensure different C_T & C_P at these different TSRs. Due to the reduction of maximum lift to drag at low Reynolds number, it may not be possible to design the small scale rotor to produce exactly the same CT(TSR) curve over the range of TSR values of interest. One possibility is to employ different rotor geometries that are designed specifically for a particular operating point (i.e. for a particular combination of CT and TSR). This option will be further investigated during the rotor design stage (D2) and modifications will be made during construction and testing of the experimental equipment (D3).

Support structure:

Where possible the support structure geometry should be kept similar to a representative full-scale geometry as this is a potential source of flow disturbance. At scale it is not practical to mount turbines from the bottom of the flume (which is the proposed mechanism for mounting of full-scale devices), due to the requirement for trailing instrumentation cables underwater. Instead a surface piercing structure is likely to have to be adopted. The support structure drag should be minimised to reduce flow disturbance e.g. by the use of hydrofoil sections. For practical reasons the support structure lever arm must be of suitable size so that the thrust force experienced on the rotor is sufficient to be measured to the required accuracy, hence a compromise is required.

3.4 Scaling summary

The selection of an appropriate test facility and hence physical scale of the array tests is driven by the scaling considerations discussed in Sections 3.1 to 3.3. The main requirements are:

- Kinematic similarity of the ambient flow to full-scale.
- Geometric similarity must be maintained where possible, although Reynolds number effects at model scale will lead to altered rotor geometry.
- Similarity of the interaction of the flow with each turbine in the array, For representative wake modelling the momentum extraction by the turbine must be similar i.e. similar C_T.
- Sufficient dimensions to install arrays of devices without lateral blockage.

In addition:

- Free- surface effects need to be similar to the real situation, i.e. similar Froude numbers.
- Care must be taken to minimise drag from the support structure.

Thus the flume employed must have sufficient length and depth-Reynolds number must be sufficient to allow development of bed-generated turbulence (depth-Reynolds number > 1e5). To allow study of realistic sea-states, the facility should also allow superposition of waves on current. As detailed in Section 3.1, kinematic and dynamic similarity of the small-scale and full-scale rotor can be maintained by appropriate selection of the rotor geometry. This requires that the blade Reynolds number is sufficiently large for lift- and drag- characteristics to be available. A lower bound of 2e4 has been used for the basis of selecting the scale of the facility since limited data is available to this range. Finally, the flume width and length must be sufficient to allow investigation of the effect of lateral blockage on turbine performance without influence of the flume sidewalls. To study a row of three turbines at 3D centre-centre spacing with 4D wall separation requires a width of at least 12D. Based on these requirements and considering the facilities summarised in Section 25 of [1], the University of Manchester wide flume has been identified for these tests. Further details of the facility are given in Section 5.1.

4 TESTING PROGRAMME

The objectives of WG4WP2, detailed in section 1.2, will be investigated via an incremental testing procedure. This section details the considerations taken in the design of the testing programme, paying particular attention to the requirements for making useful comparisons with numerical modelling methods. The section concludes with a table summarising the tests planned for the arrays in section 4.4. The next deliverable of this work pacakge (WG4WP2 D2) will contain the next level of detail down.

4.1 Calibration tests

Initially, a variety of calibration tests are required. These include:

- Flume characteristics in the absence of rotors i.e. measurement of in-flow conditions characterising the mean velocity and ambient turbulence intensity depth and lateral profile and how these characteristics develop downstream.
- Evaluation of the required sampling period and frequency at which data is statistically stable. This will be different dependent on the intended analysis of the data, which includes mean flow characteristics, TI and Reynolds Stress analysis.
- Calibration of individual instruments including ADVs, strain gauges and turbine scale models.

4.2 Blockage tests

This work stream is a key interface for WG3WP4. The model which is being developed in this workpage contains a method of accounting for blockage. In order to make useful comparisons with this and other numerical models, the following information is required:

- The unbounded rotor characteristics so that the effect of blockage can be quantified and used to validate the blockage correction models. This will be achieved via one of the following options:
    - Measurement of the C_L & C_D of the foil section (followed by use of GH Tidal Bladed to predict C_T & C_P of a range of operating states).
    - Measurement of the rotor C_T & C_P over a range of operating states directly, under effectively unbounded flow conditions (blockage ratios of below 5%). This can be achieved in a wind tunnel or water flume with larger cross sectional area such as will be used in WG4WP1.
    - Initial interrogation of unbounded performance can be conducted using one small rotor in the flume being used in this work package, however depth effects will be present here which must be considered.
- The effect of blockage on the turbine operating point and the wake structure. This should include the influence of free surface proximity and of lateral spacing on turbine operating point and wake structure.
- Measurements of the flow field at several locations outside of the turbine streamtube to provide a check for the mathematical modelling of the effect of blockage on the surrounding flow-field. Locations to include:
    - Upstream
    - Lateral positions
    - Immediately downstream (because accelerating the flow around the turbine increases the speed of the flow around the wake and thus affects the mixing process)

4.3 Array wake tests

In addition to the blockage model, there are several parts to the GH wake model (WG3WP4 for which this work stream is a key interface):

1. A semi-empirical model is used to predict the near wake velocity profile.
2. An eddy viscosity model predicts the centreline decay as a function of the near wake profile, the ambient flow mean flow and turbulence intensity.
3. And wake interaction models which estimate the effect of wake merging.

The near wake model will be validated via WG3WP1, however, in order to compare the eddy viscosity model with the WG4WP2 experiments the near wake profile of the rotors needs to be measured to ensure it is properly represented in the GH eddy viscosity model.

The eddy viscosity model has been shown to represent the far wake recovery behind both a lab scale rotor and porous discs. However, to gain confidence in the model, a basic parametric study would be useful to initiate the more detailed experimental campaign. This should comprise:

- Single wake mapping from the near to far wake with sample duration sufficient to evaluate Reynolds Stress (it is of particular interest to find the distance downstream where the shear layer meets the centreline). The wake structure (sectional shape) and velocity deficits also to be measured.
- Ideally the above test is repeated for different operating states (i.e. different CT) and for each ambient flow condition (i.e. different bed generated turbulence and wave states).
- Investigate the effect of boundaries on the far wake structure, i.e. repeat the above test, but at a different channel depth.

Further studies that are required in order to make useful comparisons with the model developed in WG3WP4 include:

- Investigations to understand the effect of wake boundary conditions on the wake structure. Turbine configurations studied should include a turbine whose wake is constrained on one- and both- sides by the wake of an adjacent device.
    - Variation of lateral spacing
    - Variation of longitudinal spacing
- Increasing array size, laterally and then adding additional rows
- Investigation of staggered array layouts in which downstream device is partially within the wake of an upstream device.
- Comparison of ambient flow affects for different layouts
- Flow speed effect: One of the scaling assumptions is that the wake shear Reynolds number is high enough not to affect the wake recovery process. If this is truly the case, then changing the inflow, whilst maintaining rotor C_T & C_p and boundary layer profile, should not affect wake recovery. This assumption is investigated as part of the numerical simulations conducted in WG3 WP1.

4.4 Summary of experiments

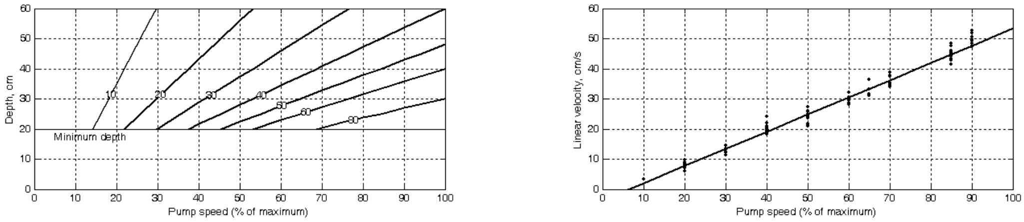
For all experiments, measurements will be taken of thrust, power (angular speed x torque) and the velocity field. The extent of velocity field measurements varies with the type of test. For detailed tests, measurements of the 3-dimensional wake-structure are required (i.e. multiple 2D sections in the vertical plane each taken at a different streamwise ordinate). For investigative tests, velocity measurements will be limited to either 1-dimensional (i.e. centreline variation) or 2-dimensional variations (i.e. a vertical plane) depending on the subject of the investigative test. Previous involvement in an experimental testing programme of tidal turbines (TSB project #200018) and prior studies in the wind turbine industry ([5] and [7]) have been used to inform the choice of variables and ranges.

Test description	**Variables And ranges**	**Constants**	**Measurements**	**Type of test**	**Blockage Test (Y/N)?**	**Wake Test (Y/N)?**
Isolated device baseline data						
Operating point beneath free-surface	Operating point (TSR & C_{T0})	U(z), Depth, TI	Thrust and power, Flow field, Reynolds stresses	Detailed	Y	Y
Effect of blockage on performance & wake structure (Tests with 2 - 3 turbines)						
Operating point	TSR, C_{T0} 0.3 – 0.9	U(z), Depth, TI	Thrust and power, Rotor speed, Flow field measurements			
Lateral spacing	~0.5D increments	U(z), Depth, TI		Detailed	Y	Y
Yaw angle	~10 degree increments.	U(z), Depth, TI		Investigative	N	Y
Depth / Diameter ratio (will consider making a smaller diameter rotor)	Depth ~1.5D-3D	U(z), TI		Investigation	Y	Y
Flow speed	Flow rate	Depth, TI		Investigation	Y	Y
Multi-row arrays in currents (up to 3x5)						
Operating point	TSR & C_{T0}	U(z), Depth, TI	Thrust and power, Rotor speed, Flow field measurements	Detailed	Y	Y
Longitudinal spacing	~2D increments			Detailed	Y	
Lateral spacing	~0.5D increments			Detailed	Y	Y
Depth / Diameter ratio	Depth ~1.5D-3D	U(z), Depth, TI		Investigative	Y	Y
Effect of unsteady ambient flow on arrays (at selected operating set points) – sea state Repeat selection of detailed tests for “Arrays in currents”						
Wave-forcing	Irregular waves, H & T representative of full scale	U, Depth	Thrust and power, Rotor speed, Flow field measurements	Detailed	N	Y
Ambient TI (bed-generated)	Flow rate /profile	Depth		Investigative	Y	Y
Large Eddy Structures	Bed form	U, Depth	Thrust and power, Rotor speed, Flow field measurements	Detailed	N	Y

5 EXPERIMENTAL EQUIPMENT AND FACILITIES

5.1 General description of the experimental facilities

Experiments will be conducted in the University of Manchester wide wave-current flume. An explanation for the selection of this facility is given in Section 3.4. The flume is 5 m wide with a flat test section of 18 m between inlet and outlet. An overhead crane is available for installation of test equipment. Current generation is provided by 2 No. 50 kW pumps which develop mean flow velocities of up to 0.5 m/s at typical operating depths of 450 mm. Tests can be run in water depths of up to 600 mm as indicated by Figure 1. Wavemaking is provided by eight Edinburgh Designs piston-type wave paddles allowing generation of irregular waves conforming to standard spectra with peak frequencies in the range 0.5 to 1.5 Hz (roughly equivalent to 5 to 15 s at full-scale) and significant wave heights up to 50 mm (roughly equivalent to 5 m at full-scale).



Variation of mean velocity (cm/s) with water depth and pump speed (by flow-rate)

Velocity measurements taken in water depth of 0.45 m using propeller probe

Figure 2 – Indicative range of attainable flow speeds for specified depth and pump speed.

5.2 Experimental equipment

5.2.1 Instrumentation

Measuring the flow field is critical in analysing wake characteristics. To measure the flow field the three velocity components are taken at specified positions. Measuring the velocity of the flow is not easily achieved due to the effect the measuring devices have on the flow. The most appropriate type of device, due to its versatility in measuring flow velocities at different locations, is an Acoustic Doppler Velocimeter (ADV). PC run, specialised data logging software is used to capture the flow measurements. As discussed in detail in a report from an earlier study (Appendix 2) the sample duration required depends on the flume employed, the target signal to noise ratio (SNR), the target correlation coefficient (COR) and the flow parameter under consideration (e.g. mean velocity or Reynolds stress). The sample duration will be quantified in WG4 WP2 D2. Sample quality and duration should be sufficient to allow filtering at a minimum SNR of 15 % and a minimum correlation coefficient of 50 % without significant loss of samples. The format of the data files has been specified in WG0. In addition, individual turbine performance characteristics need to be monitored to correlate the turbine loading with its effect on the flow. The instruments used for measuring the principal parameters are;

Measurement parameter	**Device**	**Measurement range**	**Raw data sampling frequency/data set**	**Raw data accuracy**
Spatial position in domain	Carriage position	0 – 4 m lateral 0 – 10 m longitudinal	n/a	n/a

Mean Velocity. Velocity time-history or spectra adequate to obtain turbulence intensity	Acoustic Doppler Velocimeter (ADV).	0 - 1 m/s	200Hz Min 5000 samples per location	SNR > 15 dB (Appendix 2)
Reynolds-Stress	Acoustic Doppler Velocimeter (ADV).	0 - 1 m/s	Min 10000 samples per location	SNR > 15dB (Appendix 2)
Turbine thrust	Load cells or strain gauges.	0 – 10 N	200 Hz	5%
Rotor angular speed (from angular position)	Optical encoder	0 – 40 rad/s 0 – 2π rad	200Hz	Position to π/50 rad
Applied torque or equivalent	Applied current	0 – 2A	200Hz	2mA

5.2.2 Instrumentation calibration

ADV are supplied with a certificate of calibration from the manufacturer. The key issue to ensure is that there are sufficient numbers of suspended particles in the flume flow to allow a high signal to noise signal.

The calibration of load cells/strain gauges should be conducted by applying known loads to the rig. The full range of operational loads should be applied and at least five experimental data points shall be gathered to evaluate the calibration curve. Five experimental points are sufficient here, for confirmation of a linear phenomenon. Instrument calibration willl be elaborated on further in WG4WP2D2.

5.2.3 Data logging system

All real time data series shall be collected using a modular data logging system based on the National Instruments Labview system. A logging interface will be developed to allow specification of:

A number of co-ordinates at which velocity samples are required (defined in plane perpendicular to the flow)
Duration of each sample
Number of devices

The following data will be recorded directly to file for post-processing:

3-component velocity signals from each ADV probe
Angular position from each turbine model to calculate angular speed
Applied current from each turbine model
Signal proportional to measured thrust

It will be convenient to display summary data during each test to facilitate evaluation of data-quality during data collection. Key parameters are: position of measurement probes (spatial co-ordinates), streamwise and transverse velocity, angular speed, applied current and signal to noise ratio.

Time-series of test-data will be saved on the logging PC (a standalone device to minimise the risk of virus infection and software update problems) and copied to a separate workstation for analysis. A copy of all data will be stored on an independent flash-drive after each test and written to permanent media (DVD) at regular intervals.

5.2.4 Experimental measurements

There should be sufficient measurement/data points to enable the wake width/shape to be established for comparison to the empirical wake model developed in WG3WP4. As detailed in Section 2.1, the nearwake form is studied in more detail in other work packages (WG3WP1, WG4WP1) and the objective of this package is to understand the effect of blockage on far-wake structure. The centreline velocity should be measured at a minimum of 1D spacing starting at no more than 2D behind the rotor and continue until the velocity deficit is small. If possible, closer It is acknowledged that design of the experiments may not provide representative velocity measurements within 1D of the rotor plane (due to the dimensions of the nacelle which will need to be large relative to the rotor).

The accuracy in measuring turbine thrust and inflow speed should be sufficiently high to ensure the error in C_T is less than 5%. The likely overall accuracy in measuring the flow field is difficult to estimate precisely, however it is an objective to make this less than 5%. More detail is included in Appendix 2 on how the error will be evaluated. As a matter of course with any experimental programme, repeatability of the tests will be thoroughly investigated.

6 SUMMARY

The purpose of the scale model tests is to provide a data set of experimental measurements that are directly comparable to the mathematical model developed in WG4 WP3. These models are used to predict the influenced flow field in and around tidal turbine arrays. Such a flow field is affected by both blockage and wake structure, and these form the objectives of the investigations to be conducted in WG4 WP2, as set out in the Schedule 5 of the Technology Contract. The purpose of this report is to define the scope of an experimental study and the required accuracy of measuremed data that will be compared to mathematical models. This report provides background on array scale blockage and wake effects. The scaling rationale has been discussed in detail and a suitable facility identified. An outline of the experiments that are required to meet the work package objectives is given, and appropriate operating points (speeds/torques), instrument type, sample frequencies and acceptable error are specified. The report concludes with specification of the experimental equipment and facilities that are necessary to achieve such a testing programme.

The next stages of work include the following tasks:

- Detailed design of the rotor.
- Detailed design of the instrumentation system.
- Detailed design of the support structure.
- Detailed design of the flow measurement system.

All of these tasks will form the second deliverable of this work package, WG4WP2D2 (due to be submitted at the end of February 2010). After this deliverable has been accepted construction of the test equipment will commence (due to be completed by October 2010).

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APPENDIX 1: ROTOR SCALING CALCULATIONS

		Channel depth	Channel width	Diameter	rotor Swept area		chord length	U rated		TSR	Possible Cp	Possible Ct	Power		Thrust		Froude No		Reynolds No	
																				Rechord
scale	ratio	m	m	m	ratio	m^2		ratio	m/s				ratio	W	ratio	N	ratio	value	ratio	value
Full size	1.00	36.00	550	18.00	1.0000	254.47	0.400	1.00	2.573	4.5	0.45	0.80	1	1.00E+06	1	690862	1	0.14	1	2.4E+06
1/10th scale - 158 W	0.100	3.60	55.00	1.80	0.0100	2.54	0.040	0.35	0.895	4.5	0.40	0.80	4.21E-04	3.65E+02	1.00E-03	816	1.1	0.15	0.035	8.4E+04
1/15th scale - 38 W	0.067	2.40	36.67	1.20	0.0044	1.13	0.027	0.31	0.797	4.5	0.30	0.80	1.32E-04	8.60E+01	2.96E-04	288	1.2	0.16	0.020	4.8E+04
1/20th scale - 14 W	0.050	1.80	27.50	0.90	0.0025	0.64	0.020	0.29	0.748	4.5	0.30	0.80	6.14E-05	3.99E+01	1.25E-04	142	1.3	0.18	0.014	3.4E+04
1/50th scale - < 1W!	0.020	0.72	11.00	0.36	0.0004	0.10	0.008	0.20	0.509	4.5	0.30	0.80	3.10E-06	2.02E+00	8.00E-06	11	1.4	0.19	0.004	9.3E+03
1/70th scale	0.014	0.51	7.86	0.26	0.0002	0.05	0.006	0.18	0.461	4.5	0.30	0.80	1.18E-06	7.65E-01	2.92E-06	4	1.5	0.21	0.002	6.0E+03
1/90th scale	0.011	0.40	6.11	0.20	0.0001	0.03	0.004	0.17	0.434	4.5	0.30	0.80	5.92E-07	3.85E-01	1.37E-06	2	1.6	0.22	0.002	4.4E+03
1/100th scale	0.010	0.36	5.50	0.18	0.0001	0.03	0.004	0.17	0.437	4.5	0.30	0.80	4.91E-07	3.20E-01	1.00E-06	2	1.7	0.23	0.002	4.0E+03
1/110th scale	0.009	0.33	5.00	0.16	0.0001	0.02	0.004	0.17	0.442	4.5	0.30	0.80	4.18E-07	2.72E-01	7.51E-07	2	1.8	0.25	0.002	3.7E+03
1/130th scale	0.008	0.28	4.23	0.14	0.0001	0.02	0.003	0.17	0.429	4.5	0.30	0.80	2.74E-07	1.78E-01	4.55E-07	1	1.9	0.26	0.001	3.0E+03

NB. The highlighted cells correspond to the Froude and Reynolds numbers respectively. Decreasing the scale of the experimental test whilst maintaining geometric similarilty leads to increased Froude number and significantly decreased Reynolds numbers.

APPENDIX 2: POST-PROCESSING OF DATA

The following is a report undertaken during the GH led TSB project (TSB project #200018) on the performance characteristics and optimisation of marine current energy converter arrrays (2007-2009). The experiments referred to in this appendix were carried out in both the Chilworth Research laboratory, University of Southampton and the circulating water channel at IFREMER research facility in Boulonge sur Mer, France. The purpose of this appendix is to provide background on the post-processing of data from ADVs and experimental error. Once the instrumentation is finalised (in WG4WP2D2) the permissible bounds of experimental error will be decided based on these guidelines. This appendix does not relate to the tests detailed in this document.

Post-processing of ADV data

Problems with the accuracy of ADV velocity measurements can be caused by relatively high levels of ambient noise and spikes in the data due to a phase shift between the outgoing and incoming pulse. For this reason data should not be used without suitable post-processing. In addition to velocity measurements the ADV provides signal to noise ratio (SNR) and correlation (COR) parameters which can be used to filter the data improving the quality of the measurements.

SNR is an indication of the strength of received signal compared to the noise level of the instrument; as ambient noise increases, SNR decreases. It is defined as follows:

$$SNR = 20\log_{10}\left(\frac{\text{Amplitude}_{\text{signal}}}{\text{Amplitude}_{\text{noise}}}\right) \qquad \text{(Nortek, 2004)}$$

The generally accepted SNR threshold is recommended to be at least 5dB when measuring average flow velocities (Wahl, 2000) and a minimum of 15dB when measuring instantaneous velocities and turbulence quantities (Wahl, 2000; Rusello *et* al, 2006; Ciochetto, 2007) but there is no theoretical or experimental evidence to support these rule of thumb limits (Ciochetto, 2007). Low SNR values can be a result of inadequate scattering material being present in the flow (Blanckaert, 2006; Rusello *et al*, 2006).

The correlation parameter, is an indicator of the relative consistency of the behaviour of the scatterers in the sampling volume during the sampling period. ADV's collect data at a higher sampling rate than the reporting period, and the COR parameter indicates the consistency of the multiple measurements that take place within each sampling period (Wahl, 2000).

Manufacturers have typically recommended filtering to remove any samples with correlation scores below 70% (Wahl, 2000; Ciochetto, 2007) and even if the data is considered poor in only one beam the whole sample should be discarded (Ciochetto, 2007). However, samples with correlation values much less than 70% can sometimes still provide good data, particularly if the signal to noise ratio is high and the flow is relatively turbulent (Wahl, 2000). Low correlation values can be an indication of high levels of turbulence (Wahl, 2000; Ciochetto, 2007) and in cases of high turbulence the reduction in correlation will be independent of SNR. If turbulence are not strong then correlation is a function of SNR (Ciochetto, 2007).

Most spikes can be removed at the time of processing by adjusting the instrument velocity range. Remaining spikes may correspond to reductions in SNR and correlation values but as this is not always the case an additional procedure to remove spikes should be employed (Wahl, 2000). In some cases spikes may look similar to natural fluctuations in the velocity. Goring & Nikora (2002) developed an algorithm *Acceleration Threshold Method* which considers maximum possible instantaneous acceleration values and this method is used widely.

Accuracy of the ADV data, particularly when considering turbulence characteristics, can be significantly reduced if the sample size is too small. Chanson *et al* (2007, citing García *et* al 2005) suggest the the sampling record should contain more than 5,000 samples to yield minumum errors for turbulence measurements and that records in excess of 50,000 samples are required for accurate determination of Reynolds stresses. However, Voulgaris & Trowbridge (1997) using 9,000 samples showed that an ADV sensor can measure mean velocity and Reynolds stress within 1% of the estimated true mean value.

Post processing of porous disc experimental data

Between two and six thousand measurement records were produced at each datapoint for each experiment run. The ADV's velocity range was reduced until the number of spikes in the data was minimal. Spikes were removed where downstream velocity differed by more than 50% of the mean. In addition, measurements were discarded where the lateral and vertical velocity components were greater than three standard deviations from the mean.

Goring & Nikora (2002) state that "almost any spike replacement method is preferable to spike elimination" but in this case the spikes were few and the effect of elimination not considered to be significant. Future work could be improved by introducing a more refined method for spike removal and replacement.

Data produced in the smaller Chilworth flume was filtered by setting minimum correlation to 70% and minimum SNR to 15%. The effect of filtering at this level produced a minimal reduction in data. Figure 1 shows the decrease in sample size for 7 typical datapoints.

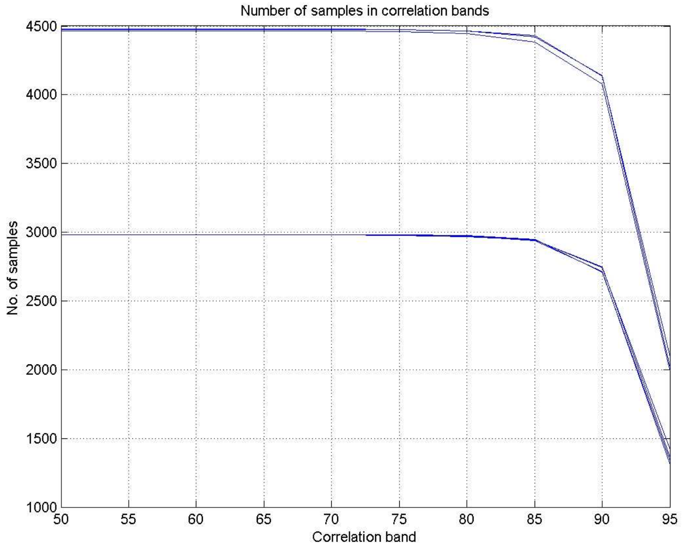


Figure 1. Reduction in number of data samples with increase in correlation filter (7 datapoints)

Experiments carried out in the flume at Ifremer produced records with comparatively low correlation values. Setting the correlation filter to around 45% would cause around 10% of the data to be discarded; at 70% more than half the data would be eliminated (see Figure 2).

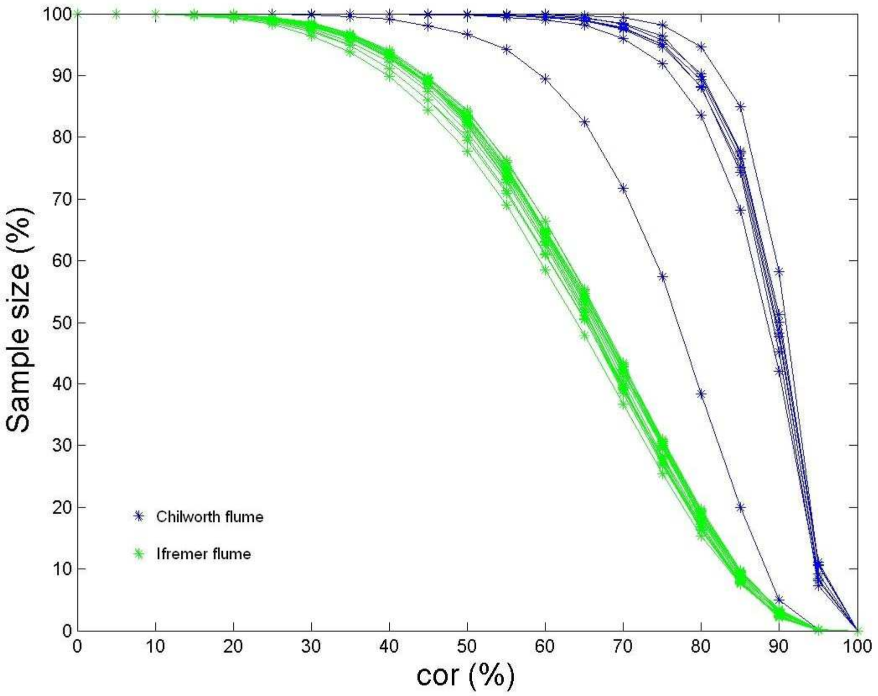


Figure 2. Percentage decrease in sample size with increase in correlation filter for base runs 'Ct' and 'Boundless'

SNR values from the Ifremer flume were extremely low compared to those from Chilworth. Water in the channel was very clean and it was not normal procedure to use ADVs at this site. The lack of suspended particles in the water is likely to have been the main factor causing the SNR readings to be low.

Filtering the data with an SNR threshold of 15 would eliminate almost all of the data and a threshold of 5 would reduce the sample size by nearly two thirds (see Figure 3).

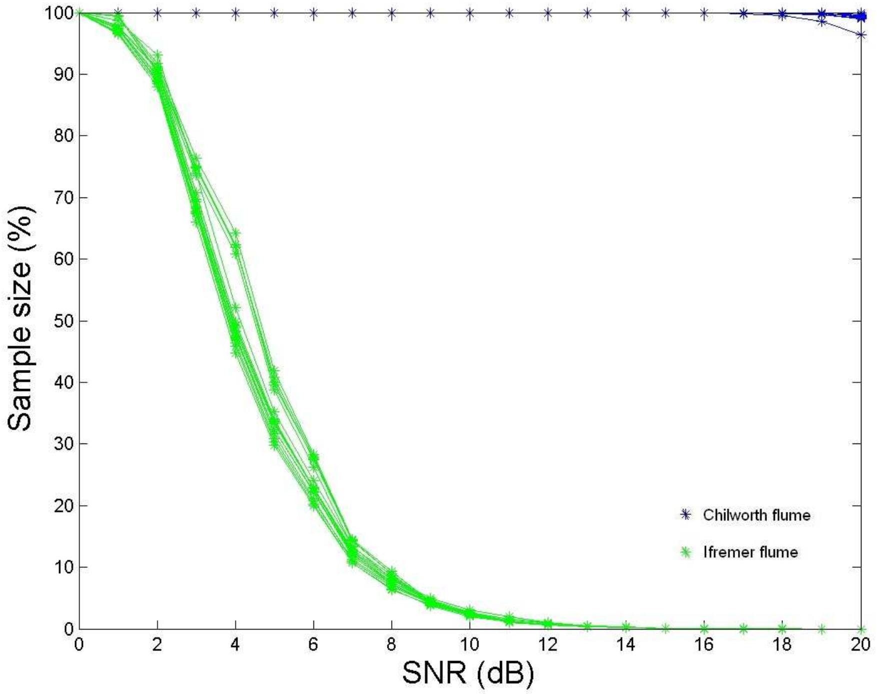
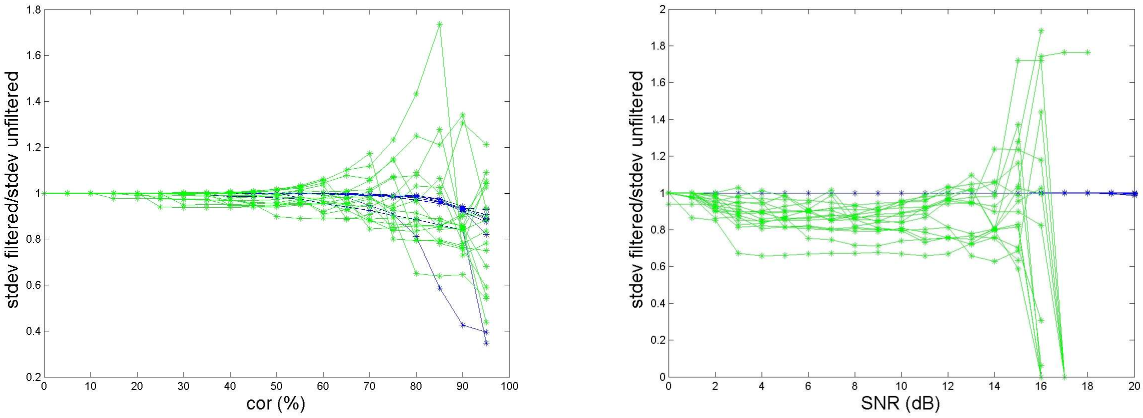


Figure 3. Percentage decrease in sample size with increase in SNR filter for base runs 'Ct' and 'Boundless'

The increase in standard deviation from mean velocity



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