force | Fundy Ocean Research Centre for Energy

The Vectron Project: Final Report

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Table of Contents

1 Executive Summary

The in-stream tidal turbine industry requires high-resolution velocity data to inform the design, build, and operation of turbines. In the models used to design turbines and as determined from observations of turbines, turbine loading and power performance are dependent on the high-resolution component of velocity, i.e., turbulence, through the key metrics of streamwise velocity variance, streamwise velocity power spectral density, and streamwise integral length scale (the industry focus is on streamwise (i.e., along stream) velocity), as well as through finer turbulence metrics. The acoustic Doppler current profiler (ADCP) is the standard sensor for measuring velocity, but its divergent beams inherently limit, and limit through dependence of the ADCP on its orientation with respect to the flow direction, the turbulence information it can acquire. The convergent beam Vectron was built to address the need for collecting turbulence at turbine hub height, down to rotor-scale resolution. As a collaboration between Dalhousie University and the Fundy Ocean Research Centre for Energy (FORCE), the purpose of the present Vectron Project was to bring the Vectron to a state approaching industry-readiness.

The key outcomes of this project include:

- The capability to deploy the Vectron and its ("FAST-1") platform (for this project, the platform is O(5 m) in the horizontal and weighs 3.5 mT in air) from a vessel local to the

upper Bay of Fundy and, generally, the capability to deploy from any 'mid-sized' vessel with sufficient deck space and lifting capacity.

- The Vectron is energy efficient, such that there is sufficient on-board power to operate the Vectron and co-located ADCP continuously for 35+ days.
- The Vectron resolves the streamwise velocity to sub-1 metre length scales – a tremendous result.
- The Vectron is verified against turbulence theory and the co-located ADCP as capturing key turbulence metrics for turbine loading and power performance.

It is now proven that the Vectron can be successfully and recovered in high flows and is capable to measure turbulence at turbine rotor scale. Hence, the Vectron is ready for deployment to directly support resource assessment towards determining turbine design parameters and for measurements in support of/during operations.

FORCE would like to thank the following organizations for providing funding to this project: The Atlantic Canada Opportunities Agency (ACOA), the Department of Natural Resources and Renewables (NRR) of Nova Scotia, Research Nova Scotia (RNS), and the Nova Scotia Offshore Energy Research Association (OERA), now Net Zero Atlantic (NZA).

2 Project Objectives

The Vectron Project was focused on bringing the Vectron, a velocity profiler tailored to turbulence characterization in support of the design and operation of in-stream tidal turbines, to a state approaching industry readiness. The Vectron Project was a collaboration between Dalhousie University and FORCE, with the combined objectives of:

a. Modifying the Vectron towards improving its data capture capabilities.
b. Lowering the cost of deploying and retrieving the Vectron sensor platform to industry-sustainable levels.
c. Developing models and software optimally configuring the Vectron for high-flow environments and for post-processing of turbulence measurements geared towards meeting the needs of the in-stream tidal turbine industry.

FORCE was obligated to lead Objective b and the second sub-Objective of c (i.e., turbulence post-processing). This report will summarize the realization of these objectives.

3 Methodology

3.1 Lowering the cost of platform deployment and recovery

The Vectron is mounted on FAST-1, a 6.1 m x 4.0 m x 1.4 m subsea platform with the capacity to support a large and varied sensor suite, including the Vectron. The Vectron consists of five Nortek Signature 1000 ADCPs: four single-beam receivers at the corners of FAST-1 and one 5-beam transceiver located at the centroid of this square configuration of outboard receivers. FAST-1's wide base permits beam convergence, and hence high-resolution velocity profiling, at O(10 m) above the seabed (see Fig. 1). The Vectron has a built-in 'ground-truth' ADCP: for this project, the Vectron and the middle transceiver operating in stand-alone mode were duty-cycled (e.g., 10 minutes Vectron mode, 10 minutes of the 5-beam Signature 1000, 10 minutes Vectron mode,…). In stand-alone mode, the Signature 1000 is a standard ADCP that provides well-established accuracy for profiling of the mean flow (hence providing a degree of verification of the Vectron's capabilities). Turbulence resolution with an ADCP is fundamentally limited by its diverging beams and can be further reduced, through field/deployment operations, by a misalignment of the ADCP's centreline with the principal direction of flow (whereas the accuracy of the Vectron is not dependent on its orientation). Platform orientation is also critical to ensuring stability of the rectangular FAST-1 platform.

The size and weight of FAST-1 and the precision required for deployment pose a significant operational challenge. An earlier iteration of the Vectron Project brought in a large vessel from Halifax to deploy FAST-1, the mobilization fees for which are not sustainable. The broad plan for achieving cost reduction and sustainability of deployment/recovery of the Vectron entails:

a) Sourcing a vessel local to the upper Bay of Fundy.
b) Applying a graduated field and testing programme towards deployment in high flows.
c) Adapting methodologies for the deployment of smaller platforms in high flows to the deployment of the Vectron.
    - The centrelines of the Signature 1000 ADCP and FAST-1 platform are to be made parallel and aligned with the principal direction of flow.

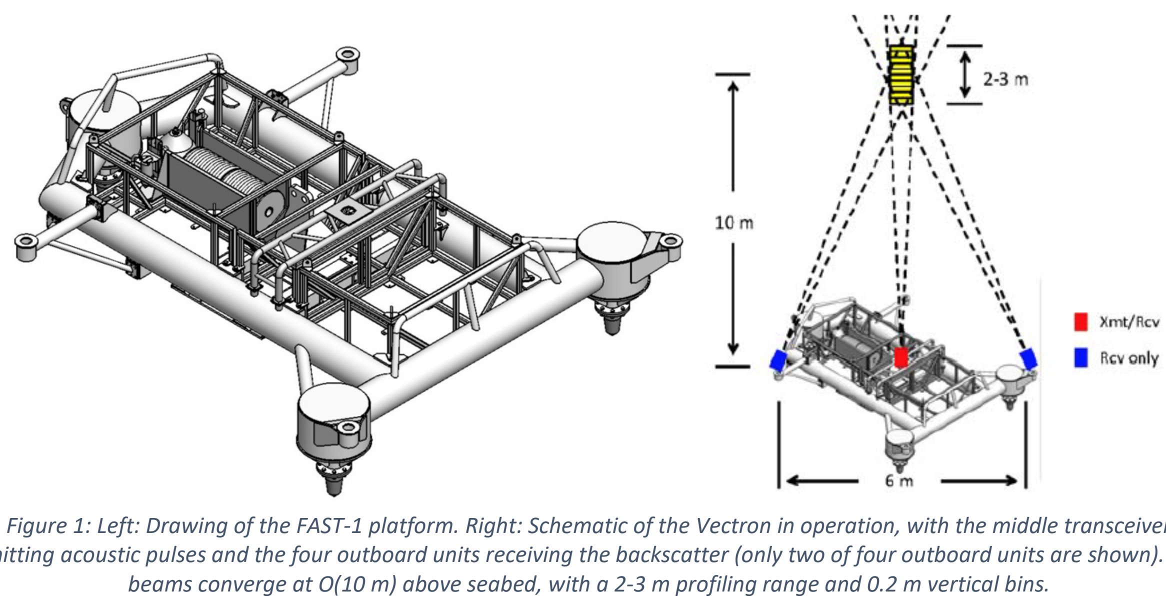

Figure 1: Left: Drawing of the FAST-1 platform. Right: Schematic of the Vectron in operation, with the middle transceiver emitting acoustic pulses and the four outboard units receiving the backscatter (only two of four outboard units are shown). The beams converge at O(10 m) above seabed, with a 2-3 m profiling range and 0.2 m vertical bins.

3.2 Turbulence analysis

The Vectron is compared to the co-located ADCP and against turbulence theory to verify its capabilities to resolve fundamental mean and turbulence properties of high flows. The Vectron is expected to exceed the turbulence resolving capabilities of an ADCP through its measurement region, which is detailed Culina and Hay 2023.

Verification of the Vectron's capabilities to resolve the mean flow is detailed in Hay 2021. The focus here is on turbulence verification. Turbulence verification centres on two metrics that are key to turbine loading and power performance: streamwise velocity power spectra and streamwise velocity variance. For the Signature 1000, variance is calculated by the widely used 'variance method' (Stacey et al. 1999), which can be adapted to calculate the power spectra (McMillan and Hay 2017). By aligning one of the Signature 1000 beam pairs with the principal flow direction, the variance method reduces (but does not eliminate) the loss of turbulence information resulting from beam divergence. For the Vectron, there is no requirement for such a method (nor for a particular platform orientation) since its beams converge. Rather, variance/spectra are calculated by directly applying the appropriate operators (variance/spectra operators) to the beam equations.

ADCPs (and the Vectron) have inherent instrument noise, or Doppler noise, that must be accounted for in the calculation of turbulence statistics. Typically, it is assumed that Doppler noise can be modelled as a flow-independent Gaussian white noise process. Following McMillan and Hay 2017, the (constant) spectral density of Doppler noise for a given flow speed is estimated from the flattened (noise floor) portion of the ADCP spectra. Densities so derived are averaged over the lowest speeds (< 0.25 m/s), at which the noise floor is most pronounced, to give an estimation of Doppler noise. This method also serves as the basis for estimation of the Vectron's Doppler noise, but as shown in Section 4.3, this noise must be modelled as flow-*dependent* Gaussian white noise (i.e., state-dependent additive noise). Specifically, for *each* 10-minute record, with which there is associated a current speed, the spectral density is estimated in the above fashion and applied to the computation of turbulence metrics.

For verification of the Vectron, the results are presented from the 2020 deployment at one vertical height – the centroid of the beam convergence region at 7.0 m above the middle unit (approx. 9 m above the seabed).

4 Key Findings and Outcomes

4.1 Deployment cost reduction

For the deployment cost reduction phase, the six outcomes of work packages (WP) WP1 and WP3 were achieved:

a) Appropriate certified vessel identified (i.e., *KIPAWO*)
b) Lift test completed
c) Procedure for cost-effective deployment established and trialed
d) Field proven method for deployment/recovery at high flow sites

e) Provide Dalhousie with sufficient data to validate power consumption upgrades
f) Vectron upgrades (power consumption and beam alignment) are complete

An initial lift test was conducted in Parrsboro on Aug 15, 2019.

A combined lift test and calm water deployment and recovery were conducted on Nov 17, 2019, in a harbour in Grand Passage.

Subsequently, the Vectron was twice deployed in high flows in Grand Passage for 35+ days, for the periods July 31 – September 10, 2020 and May 28 – July 16, 2021, at the locations shown in Fig. 2. No major issues arose during the deployments and recoveries. Based on data from the former deployment, Dalhousie confirmed that the Vectron's upgrades – reduced power consumption and beam alignment – were successful.

Key findings include:

- The necessity of a graduated approach to deployment and recovery.

  As should be standard practice for operations in high flows – and not just for research grade work – a graduated approach was adopted for deployment and recovery. Specifically, key materials and equipment were verified, and the deployment/recovery procedure refined through dry testing and testing in calm waters.

  Equipment verification extended to key components of the vessel. As part of the lift test, it was found that the *KIPAWO*'s winch had much less pull/lift capacity than advertised. This required a reduction of the platform weight (i.e., removal of ballast, to give a platform (dry) weight of 3.5 mT) and relocation to the slower waters of Grand Passage.

  Deployment and recovery in calmer waters verified that the platform could be fit and maneuvered onto and off the deck (see Fig. 3). The short (one day) wet testing revealed water ingress into the platform's tubing. Failure to resolve this would have prevented recovering FAST-1 from a longer (35+ d) deployment. Several smaller issues arose that were successfully addressed before the longer deployments.

- The capability to orient the platform in the streamwise direction

  A platform's orientation is critical for reasons of platform stability, but also for turbulence analysis using ADCPs (by contrast, orientation does not matter in deriving turbulence from the Vectron). As Fig. 4 in Section 4.2 shows (where the variable u is parallel to FAST-1's centreline and v is the cross-axis component), FAST-1 was nearly aligned with the streamwise direction of flow (since velocity was minimal in the v-direction). This was accomplished by deploying that platform into the oncoming tide, as is done in Minas Passage with smaller platforms.

- Redundant and secondary deployment and recovery mechanisms

  The primary deployment and recovery mechanisms are triggered by acoustic releases. Both mechanisms consisted of a redundant acoustic release. Generally (as evidenced from operations in Minas Passage), this redundancy significantly reduces the risk of the mechanism failing (for this project, none of the releases failed).

- Confidence in the capability of a broad range of vessels to deploy and recover FAST-1 and the Vectron

  Although the KIPAWO was used for deployments and recoveries, the deployment and recovery methodology established does not depend on this vessel. There are minimum requirements for deck space and lift capacity, but these can be met by any number of ‘mid-sized’ vessels.

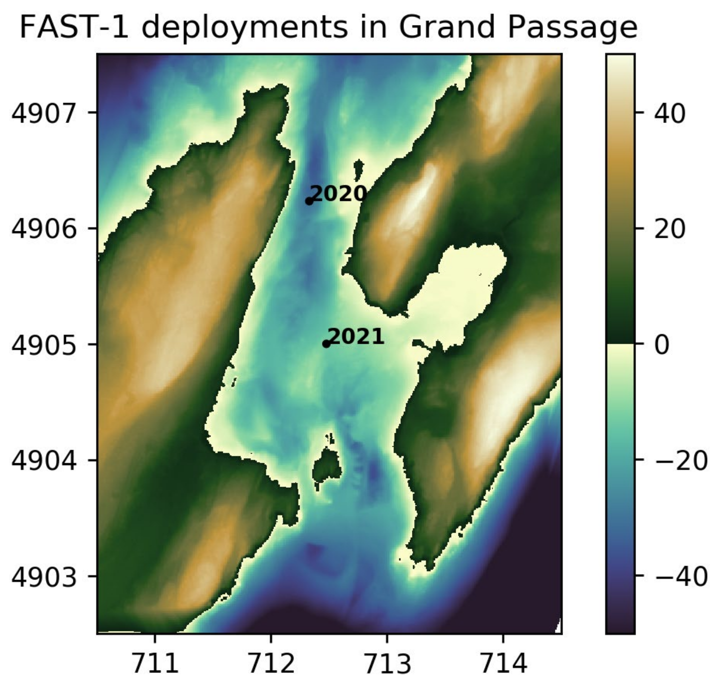

Figure 2: Locations (WGS84 UTM19 (km)) of the two FAST-1 deployments of 35+ d duration, overlaid onto the bathymetry field (MSL).

Figure 3: Calm water testing of the deployment and recovery procedure for FAST- 1 from Nov. 19, 2019, in Grand Passage.

4.2 Vectron validation: Mean flow

Figures 4-5 shows the streamwise mean velocity at 7 metres above the middle (Signature 1000) unit. Fig. 5 shows a snapshot of the excellent agreement between the three components of velocity (streamwise, spanwise, and vertical velocities). Fig. 6 quantifies this excellent agreement: there is approximately 1% difference between streamwise velocities from the Vectron and Signature 1000. Further results for the mean flow are presented in Hay 2021.

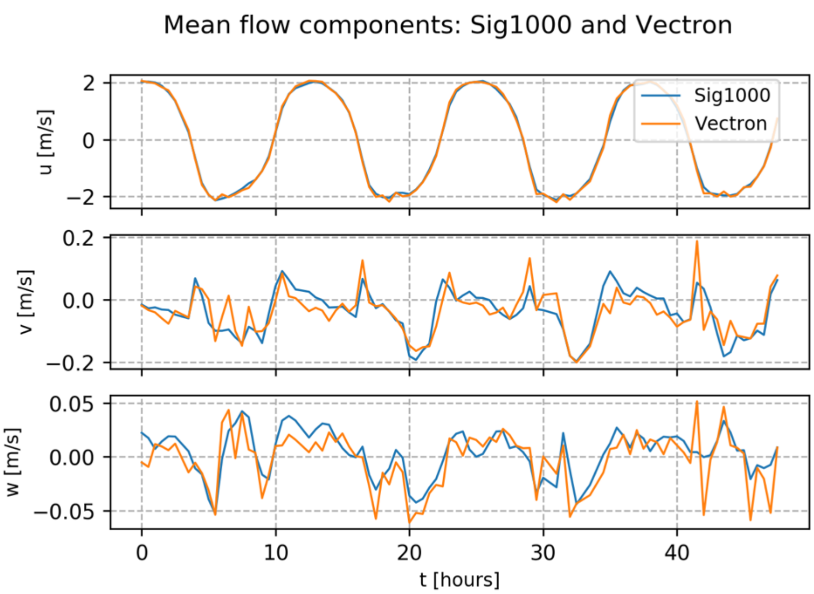

Figure 4: Time series over 48 hours of streamwise (u), spanwise (v), and vertical (w) mean velocities at 7 m above the Sig1000.

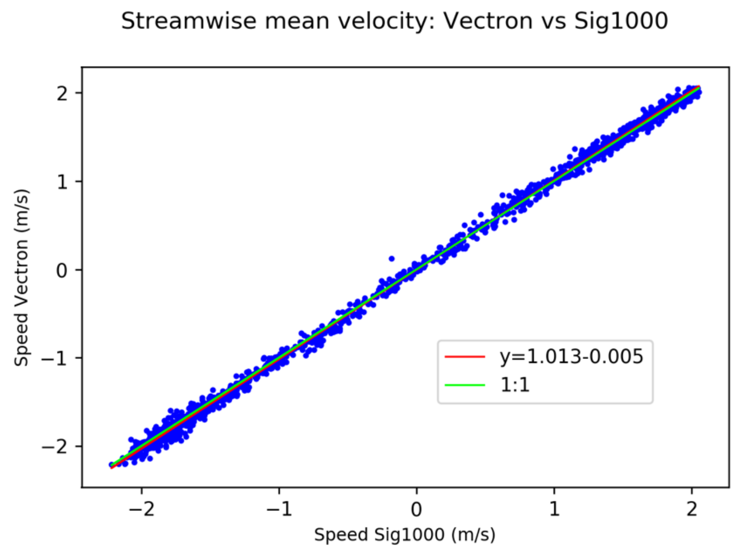

Figure 5: Streamwise mean velocities for the Vectron against the co-located Signature 1000 ADCP. There is excellent agreement between the two sensors.

4.3 Vectron validation: Turbulence

Figures 6-8 show power spectral density (PSD) as a function of spatial frequency for the streamwise velocity, binned by the fastest speeds. This metric shows (Fig. 6) that the Signature 1000 resolves velocity to a length scale of only 5 meters, with no clear evidence of the inertial subrange of frequencies. This range is key to verifying the turbulence resolving capabilities of a sensor, since the theory indicates it has universal properties (i.e., common to high flows) including PSD slopes of -5/3. By contrast, the PSDs for the Vectron with flow-dependent Doppler noise (Fig. 7) show resolution to sub-1 m length scales and the clear presence, from the excellent fit to the -5/3 slope, that the Vectron captures the low-frequency end of the inertial subrange. This is a tremendous result, demonstrating the Vectron's ability resolve turbulence to turbine blade length scales. With flow-independent Doppler noise, the Vectron PSDs are a poor fit to theory, also demonstrating a dependence on flow conditions (Fig. 8). Given the excellent results using flow-dependent noise, the flow dependence of the PSDs is not due to turbulence but to machine/Doppler noise.

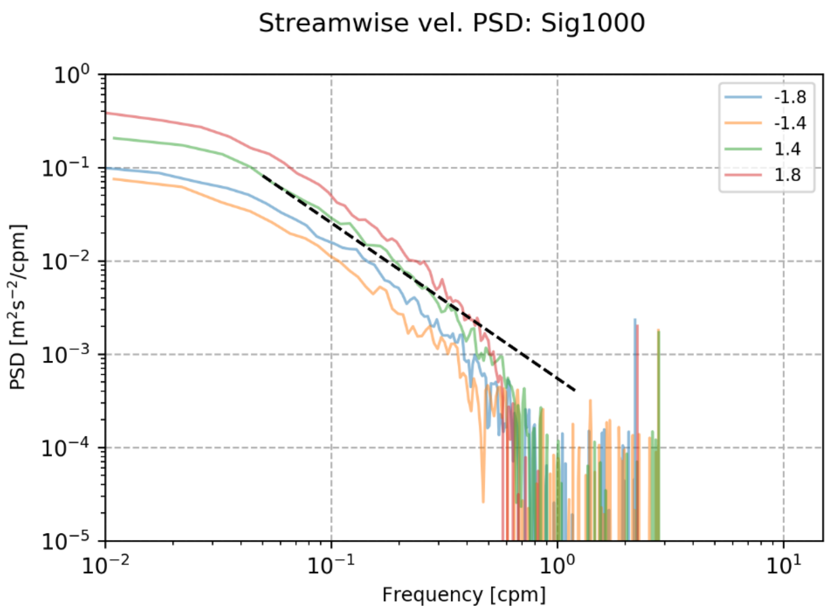

Figure 6: Streamwise velocity power spectral densities, binned and averaged by the fastest speeds, for the Signature 1000 ADCP. The black dotted line has a slope of -5/3, corresponding to the theoretical slope through the inertial subrange. The spatial frequency is in units of cycles per metre.

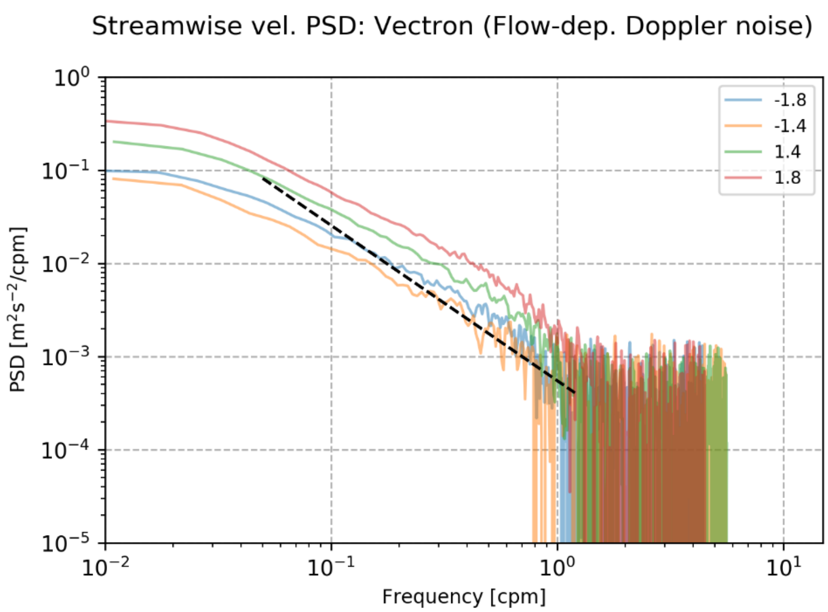

Figure 7: Same as Fig. 6 but for the Vectron with a flow-dependent model of Doppler noise.

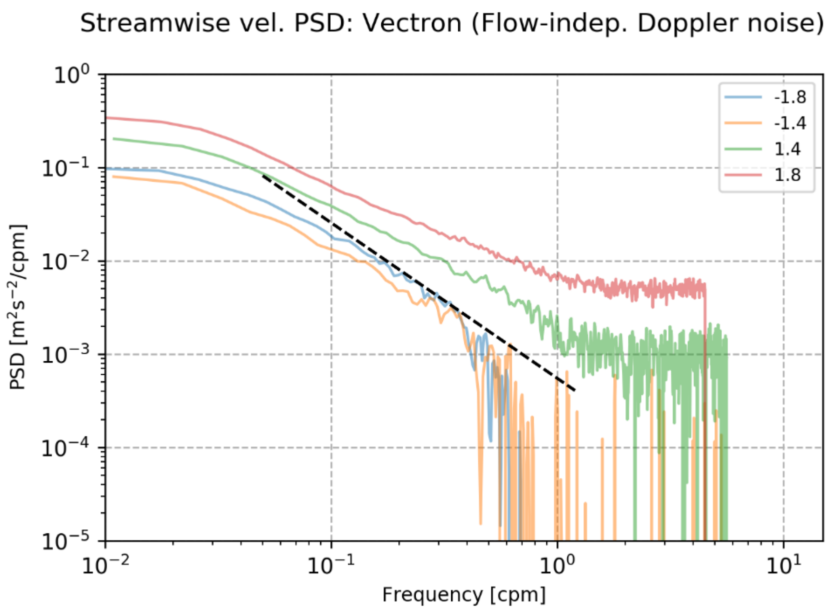

Figure 8: Same as Fig. 7 but with a flow-independent noise model of Doppler noise.

Figures 9-10 show results for streamwise velocity variances. With flow-independent Doppler noise, the Vectron's streamwise variances includes negative values and compare poorly with those from the Signature 1000 (not shown). With flow-dependent Doppler noise, there is reasonable agreement between the Vectron and the Signature 1000 (Fig. 9), but the Vectron's streamwise velocity variances exceed those of the Signature 1000 by 18% on average (Fig. 10). An examination of the streamwise-vertical velocity covariance, which is not dependent on Doppler noise, indicates differences of a similar magnitude (not shown). These results are further explored in the forthcoming paper.

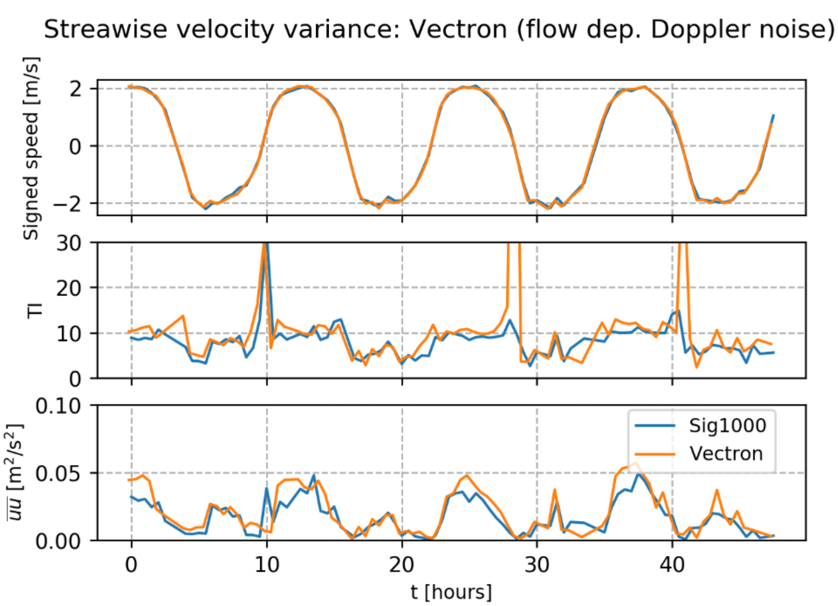

Figure 9: Snapshot of streamwise variance and its normalization (Turbulence Intensity), with a flow-dependent model of the Vectron's Doppler noise.

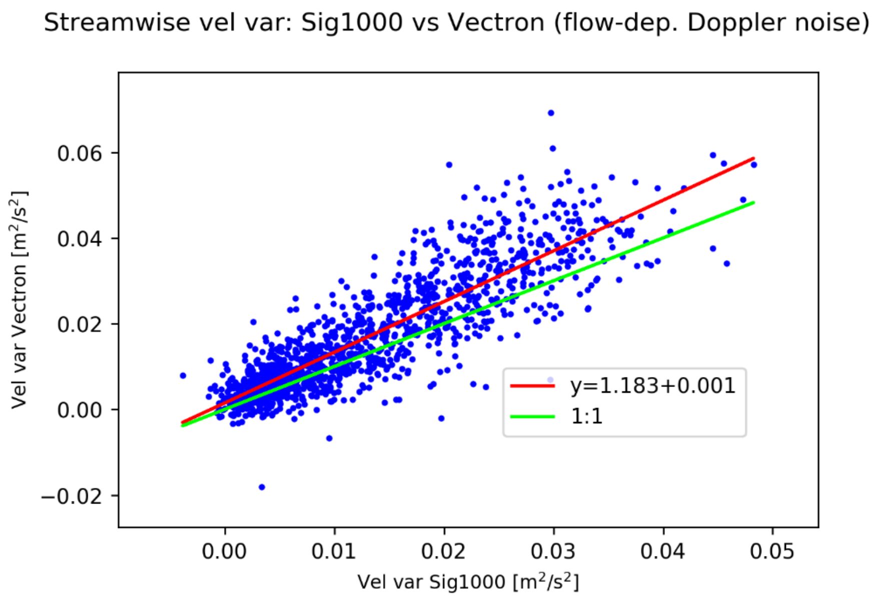

Figure 10: Streamwise velocity variance for Vectron with flow-dependent Doppler noise vs. Signature 1000, using data over August 2020.

5 Conclusions and Impact

The acoustic Doppler current profiler (ADCP) is the standard sensor for velocity profiling but cannot provide the high-resolution/turbulence data required to build and operate in-stream tidal turbines at competitive costing. Furthermore, there is a lack of understanding of turbulence at high flow sites and its impact on turbines. The Vectron Project aimed to advance resolution of these issues by bringing the Vectron to a state approaching industry-readiness, for direct utilization at high flow sites.

By these standards, the Vectron Project was successful. Half the project focused on sensor upgrades and improving costing and proficiency of marine operations. On the latter front, which was FORCE's responsibility, there was great success given the constraints of operating in the upper Bay of Fundy. Testing and deployments occurred in Grand Passage to accommodate the limitations of the sole vessel (the *KIPAWO* motorized barge) capable of completing the project at the desired costing. Following a systematic, graduated field programme of dry and calm water testing, FAST-1/Vectron was twice deployed and recovered for 35+ d in high flow conditions, at the desired orientation, without significant problems. Importantly, the method of deployment and recovery is not dependent on the *KIPAWO*; rather, Vectron/FAST-1 can be deployed/recovered by any vessel with sufficient deck space and lifting power. These are expected to become readily available with an increase in activity related to turbine deployments.

The Vectron proved able to resolve streamwise turbulence to sub-1 meter length scales. This is the first time this has been proven for a bottom-mounted acoustic Doppler profiler. This demonstrates the capability of the Vectron to resolve velocity/turbulence to the length scale of a turbine blade, compared to the standard divergent-beam ADCP that cannot resolve better than the length scale of the full turbine rotor/swept area.

6 Recommendations and Future Considerations

Recommended future actions, next steps, and additional research and recommended changes that could improve on future research and initiatives:

- Use of a smaller, more portable, modular Vectron platform and mount.

  Due to the size of FAST-1, it was difficult and costly to achieve the surveying and machining accuracy required for convergence of the Vectron's beam. Towards the project conclusion, conceptual drawings were made of a Vectron mount that would sit atop a smaller platform owned by FORCE (see Fig. 11). The trade-off is beam convergence at O(5 m) from the platform vs. O(10 m) achieved by FAST-1, but the benefits would include duplicability of the platform/mount, beam convergence at the highest precision, ease of transport, and the ability to deploy from virtually any vessel. It could be adapted as a floating platform or mounted to a floating turbine to provide near-surface velocity measurements, which bottom-mounted ADCPs cannot provide.

- Deployment in Minas Passage.

  Due to vessel constraints, it was practically necessary to deploy FAST-1/Vectron in Grand Passage. With the promise of larger vessels to support the industry in Minas Passage, the Vectron/FAST-1 can be readily deployed at many sites of interest in Minas Passage.

- Further exploration of turbulence and its impacts on turbine loading and power performance.

  The turbulence models used in turbine design are borrowed from the wind turbine industry and apply relatively simple turbulence metrics. It is critical to lowering the cost of turbines to better understand and model how turbulence interacts with turbines. In this regard, observational data, e.g., from the Vectron, is critical.

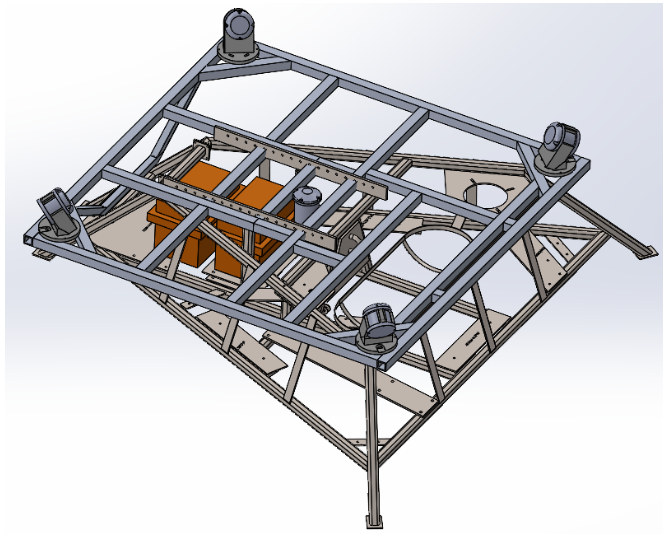

Figure 11: Conceptual drawing of a smaller, removable, portable mount for the Vectron, that sits atop a standard FORCE subsea platform.

7 Highly Qualified Personnel (HQP) Summary

a) Jeremy Locke: Co-led operations planning for FAST-1 deployment and recovery and contributed to FAST-1 preparation.

b) Chuck Taylor: Contributed to FAST-1 preparation, operations planning, and deployment and recovery.

8 Dissemination

Refereed publications:
Turbulence resolution to turbine blade length scale with a seabed-mounted convergent beam acoustic Doppler profiler (in preparation, with Alex Hay, Dalhousie)
Abstracts:
Quantifying the errors on turbulence measurements made by ADCPs at tidal turbine sites (accepted by ICOE-OEE 2022; with Alex Hay, Dalhousie)
Invited national and international presentations
Awards:
Other:

9 References

Culina, J.D. and A.E. Hay. 2023. Turbulence resolution to turbine blade length scale with a seabed-mounted convergent beam acoustic Doppler profiler. Manuscript in preparation.

Hay, A.E. The Vectron Project: Final Report. Submitted to the Nova Scotia Offshore Energy Research Association on Dec. 19, 2021.

McMillan, J.H. and A.E. Hay. 2017. Spectral and structure function estimates of turbulence dissipation rates in a high-flow tidal channel using broadband ADCPs. J. Atmos. Ocean Technol. **34(1)**:5-20.

Stacey, M.T., S.G. Monismith, and J.R. Burau. 1999. Measurements of Reynolds stress profiles in unstratified tidal flow. J. Geophys. Res. Oceans **104**: 10933-10949