The Vectron

A pulse coherent acoustic Doppler system for remote turbulence resolving velocity measurements

Alex E. Hay
Department of Oceanography
Dalhousie University
Halifax, Canada
alex.hay@dal.ca

Len Zedel
Department of Physics and Physical Oceanography
Memorial University of Newfoundland
St. John's, Canada
zedel@mun.ca

Sven Nylund
Nortek As
Oslo, Norway
sven.nylund@nortek-as.com

Robert Craig
Nortek Scientific
Halifax, Canada
robert@nortekscientific.com

Joel Culina
Fundy Ocean Research Center for Energy (FORCE)
Halifax, Canada
joel.culina@fundyforce.ca

***Abstract*—The Vectron is a new pulse-coherent Doppler sonar system that has been developed to allow remote measurement of turbulent velocities at mid-water depth (O 10 m distant 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 synchronization 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. A prototype system was deployed from a wharf in Parrsboro (Nova Scotia) where turbulent flows with mean velocities up to about 2 m/s were observed. Velocity power spectra are presented and compared to reference observations from a nearby single-point flowmeter.**

Keywords—Doppler Sonar; Velocity; Pulse-to-pulse; Coherent; Bistatic

I. INTRODUCTION

A key – but as yet poorly constrained – design requirement for in-stream tidal energy conversion devices (turbines) is knowledge of the turbulent water velocities that will be encountered. Not only are these measurements needed to estimate power generating potential, they are also required to determine physical loading on turbine structures and thus to better estimate wear and operating life. To be of use for energy conversion device design and operation, these measurements must be made at points in the water column occupied by turbine components, translating to an O(10 m) distance above the seabed or below the surface. While standard Doppler current profilers provide estimates of second-order turbulence statistics via the variance method – e.g. turbulence kinetic energy (TKE), Reynolds stress and dissipation rate – these quantities are necessarily time-averages. Estimates of the 3-component instantaneous velocity cannot be obtained using standard ADCPs because at O(10 m) range the measurement volumes for the different beams are separated by O(10 m) in the horizontal. Given this large spacing between sample points, the intrinsic spatial inhomogeneity of the flow field precludes combining the velocities from the different beams to obtain even a quasi-instantaneous measure of the 3-component turbulent velocity. One alternative is to use single-point velocity sensors, but deploying these instruments at mid-depth in high-speed (exceeding 5 m/s) flow is very challenging. Hence, the goal of the Vectron project is to make turbulence-resolving measurements at mid-depths remotely – i.e. from a bottom- or surface-mounted platform – using acoustic Doppler technology with convergent rather than divergent beams. Our approach is to arrange multiple single-beam Nortek AD2CPs in a bistatic geometry with the acoustic beams intersecting at a sample point O(10 m) from the plane in which the transducers are situated. At the point of overlap, multiple components of velocity are sampled simultaneously. The bistatic geometry addresses the spatial sampling limitations of profiling Doppler

978-1-4799-8419-0/15/$31.00

systems by reducing the length scale of the sampling location to about 0.30 m, a scale comparable to the smallest scale important to turbine design. There is also the challenge of achieving adequate resolution in time. In conventional ADCP systems, state-of-the-art for high performance Doppler sonar is achieved using broad-band processing. Broad-band processing can be used in the Vectron system, but much higher velocity precision can be achieved in principle by using pulse-to-pulse coherent sampling. In profiling systems, pulse-to-pulse coherent processing is restricted to a limited maximum range determined by the time between consecutive acoustic pulses. This time delay also imposes a maximum unambiguous resolvable velocity. For the required 10 m range and 5 m/s maximum velocities of interest here, the pulse-to-pulse coherent approach cannot be used in standard ADCP beam configurations because the O(10 ms) minimum time delay required to avoid range ambiguities along the backscatter path would result in an unacceptably small ambiguity velocity. The bistatic geometry of the Vectron overcomes this limitation because the sample volume is localised at one depth and this raises the possibility of coherent sampling, provided the pulse-to-pulse correlation can be maintained at a sufficiently high level. We describe the Vectron system and report results from preliminary field trials.

II. INSTRUMENT CONFIGURATION

A. *Physical*

The Vectron system consists of a network of Nortek AD2CP units operating at 1 MHz; each of these units can function as an independent instrument but, in order to achieve the Vectron functionality, they are configured to operate as a coordinated system. The Fundy Ocean Research Center for Energy (FORCE) established the Fundy Advanced Sensor Technology (FAST) project to assist in the development of instruments for characterization of tidal sites. A key component of the FAST project has been the development of a large platform on which standard instruments will be inter-compared for the purposes of QA/QC and on which instrument developers will deploy new instruments. The Vectron will be the first such new instrument deployed. As depicted in Fig. 1, outboard units on the FAST platform will form a square with sides of 4 m. The fifth instrument will be centrally located and directed vertically. There is a trade-off between the sampling range and the resolved component of horizontal velocities; the farther away the measurement point, the smaller that resolved component becomes. In order to achieve reasonable velocity resolution the intersection point was chosen to be 7 m above the instrument platform (which is itself 1 m off the seabed). With that intersection position, the instrument measures velocities along a line tilted at about 10 degrees from the vertical in a region that is about 30 cm wide, see the bistatic beam pattern for the Vectron shown in Fig. 2. The beam overlap region will allow a profile over about 2 m in range.

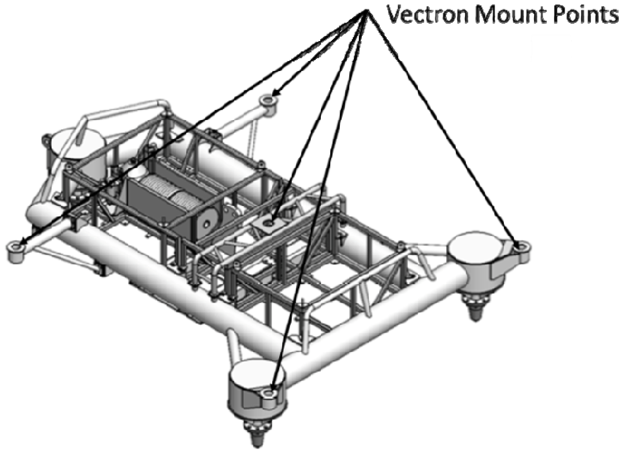

Fig. 1. Vectron physical geometry.

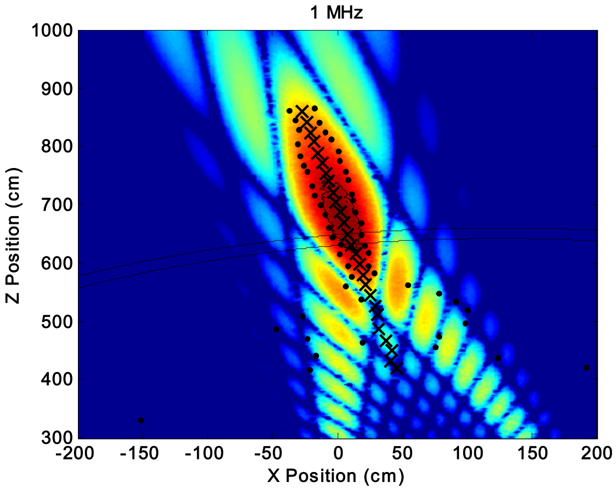

Fig. 2. Bistatic beam pattern for the Vectron system, warmer (red) colors indicate increased scattering contributions, x's identify the mid-point of the sampling position and ·'s identify the 3 dB breadth of the sample: along beam sample widths are of order 20 cm.

B. *Electrical*

The main components of the Vectron are detailed in Fig. 3. Four single beam AD2CP units and a five beam Signature1000 are cabled to an underwater enclosure that houses a low latency Ethernet switch, a power distribution module and a master Precision Time Protocol (PTP) clock. The power distribution module allows the instrument to be powered from either a cabled power supply or an external battery canister. External connectors from the underwater enclosure provide shore connectivity (for power input and Ethernet) for initial testing and on-line deployment and underwater access to power output and Ethernet for any external instrumentation which may be used.

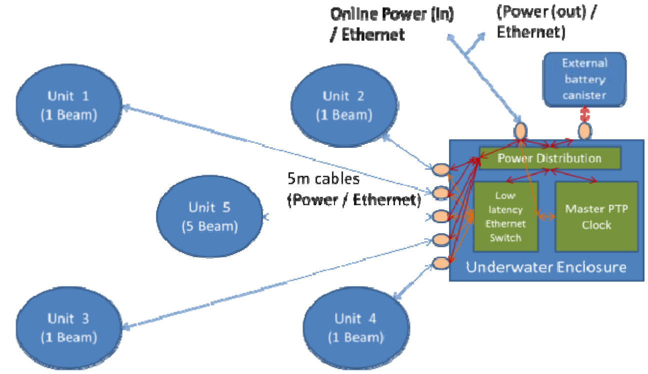

Fig. 3. Vectron system components.

A fundamental challenge in combining bistatic Doppler measurements from independent instruments was finding a way to keep the samples synchronized with the required time resolution. One way would be to share a master high-frequency DAQ clock between instruments but that approach would require additional hardware and cabling requirements. Instead we use the existing Ethernet connections between instruments and implement a PTP clock that provides a precision time stamp at a one second interval. PTP is an IEEE standard (IEEE-1588) that is designed to provide highly accurate (sub-microsecond under optimal conditions) clock synchronization to computer systems using Ethernet. In practice with the Vectron equipment, PTP allows each instrument clock to be synchronized to within ~1µs of the master clock in absolute time. The synchronized clocks are used internally by the instruments to determine the transmit time for the active unit and receive times for the passive units. The absolute time is also used to time stamp data records generated by each instrument, thereby allowing the separately collected data files to be properly collated and analyzed during post-processing.

In applying pulse coherent processing between different instruments, differences in individual clock rates becomes a concern. The internal oscillators used by the individual instruments for transmit and receive signal generation and signal processing have a manufacturing tolerance of ±30 ppm. This tolerance corresponds to a maximum bias in the measurement of about 2 cm/s. The hardware allows correction of the clock rates down to the accuracy of the PTP clock. While this has not yet been implemented, it could in principle enable correction down to 1 ppm or less than 1 mm/s along beam velocity.

The instruments are capable of operating both independently (as standard AD2CPs) or together (as the Vectron). In "Vectron mode", the central instrument is active (both transmitting and receiving) while the others operate passively (receiving only). The central instrument was selected to have five operational beams so that direct comparison with Vectron data could be made to data from the standard divergent-beam Doppler geometry.

III. SIGNAL PROCESSING

The sonars used in the Vectron are based on the Nortek AD2CP hardware platform. The AD2CP platform implements broadband processing through frequency coding by transmitting sequences of identical chirps. It can also switch between alternating configurations so it is possible to alternate between "Vectron" mode and for example "five beam mode" in the same deployment.

In addition to the desire for a single point sample location, the bistatic configuration of the Vectron allows both broadband processing and pulse-to-pulse coherent velocity processing (which has much better velocity precision as will be demonstrated by field data presented later). A pulse coherent system transmits two identical (typically short) transmit pulses at a certain lag interval. The acoustic conditions ideally provide for reception of each transmit pulse in turn without any interference from the previous transmit pulse. The beam pattern in the Vectron (see Fig. 2) allows about 2 m of beam overlap that translates to minimum lag separations between the two pulses on the order of 2-3 ms. Fig. 4 shows anticipated a), and observed b) correlations for the Vectron system. The 1 ms lag correlation curve is clearly lower than the curves for 2 ms and 3 ms. The 2 ms and 3 ms curves are at a comparable maximum correlation level but the 3 ms curve is preferred for two reasons: for a given correlation, the velocity precision will be better for the longer lag since the velocity range is reduced and, since the 3 ms curve is wider, it allows for measuring a longer profile.

A problem with a pulse coherent approach is the limited velocity range as dictated by the associated ambiguity velocity [1]. Velocity precision improves with longer pulse lags but the

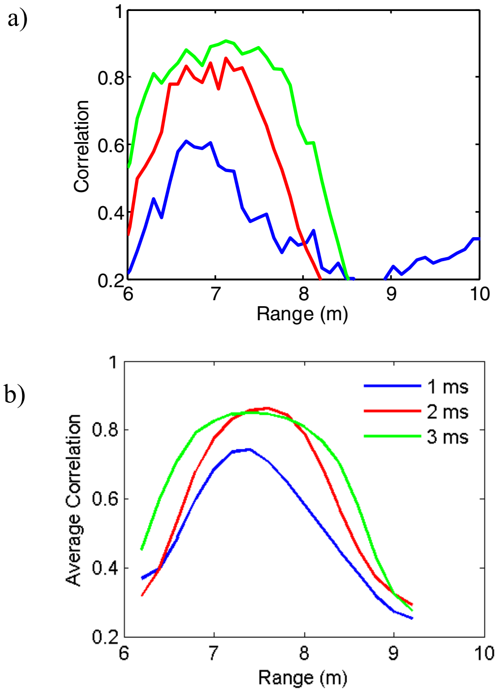

Fig. 4. Modelled a) and observed b) correlations from the Vectron. Modelled data was generated using the Doppler backscatter model described in [2]. Observations were collected during the field trials.. The slight offset in location of peak correlations suggests a slight error in beam alignment.

velocity range is also reduced. The velocity range for the desired lag of 3 ms here is only ± 0.125 m/s at nominal speed of sound. Even with the small bistatic angle of 10° the resulting horizontal velocity is only ±0.72 m/s. Going down to the 2 ms lag is also an option to increase the velocity range, but ambiguity wraps will still occur at ±1.08 m/s horizontally. This is much less than velocities commonly encountered in areas of interest (for example Minas Passage in the Bay of Fundy where horizontal velocities can exceed 5 m/s).

To increase the velocity range in pulse coherent systems, one needs to resolve the ambiguities that occur. Several methods have been developed typically where another pulse coherent measurement is taken at a shorter lag which has low precision but an adequate velocity range. This second estimate is in turn used to resolve the ambiguity of the more precise estimate measured at the longer lag. [3]. This approach cannot be used in the Vectron for several reasons. With the anticipated horizontal velocities in the Bay of Fundy the required lag would have to be so short that the resulting precision would not be adequate to resolve the ambiguity of the long lag sample. Furthermore, these methods do not work well at above two to three ambiguity wraps of the precise estimate. Added to that, it is desirable to have a high sampling rate in turbulence experiments and using another pulse pair at a shorter lag would decrease the maximum sampling rate by a factor of two. Finally, the shortest lag that the beam overlap will allow and still permit coherent processing is limited to about 2 ms. Instead, a completely different scheme is implemented in the Vectron.

The Multi Correlation Pulse Coherent method was invented by Nortek AS during the development of a single point current meter in 2013. The discovery that led to the completely novel scheme came from calculating the correlation at lag intervals to each side of the nominal lag interval. When calculating the correlation spaced at a whole number of periods of the system frequency, to each side of the nominal lag, the resulting curve has a parabolic shape around its maximum value. Furthermore, the position of the maximum value of the curve shifts with the velocity due to the compression and dilation that originates from the Doppler effect. The Multi Correlation Pulse Coherent method (MCPC) involves calculating discrete points of the correlation curve and making a coarse estimate of the velocity by parabolic interpolation around the maximum value of the correlation curve. This velocity estimate is then used for ambiguity resolution. Another important aspect of the MCPC method is that the precise phase estimate between the two receive signals is calculated at the point where the maximum correlation is found. This maintains the precision of the regular velocity estimate through more than 2-3 ambiguity wraps. Finally, since the shape of the correlation curve is crucial, the bandwidth of the transmit pulses must be sufficiently large to achieve adequate precision of the velocity estimate from the correlation curve. This is ensured in the Vectron by transmitting a chirp in each of the two transmit pulses at a bandwidth of 25% (250 kHz for the Vectron system frequency of 1 MHz).

Fig. 5 shows example correlation curves for four different acoustic pulse lags. By applying slight offsets and computing multiple correlations, the correlation curves are produced and coarse estimates of the along-beam velocity can be computed. The measured velocities were comparable for all lag settings. A velocity estimate would need only one pulse lag, multiple lags are shown in Fig. 5 for comparison purposes. At similar velocities as presented here, the correlation peak shifts with increasing lag interval. One ambiguity (wrap) corresponds to one period at the system frequency so each microsecond of offset here represent one ambiguity jump of the precise velocity estimate. The velocity for the 4 ms pulse lag interval shows that the velocity is just between three to four ambiguity wraps. Also notice that a traditional pulse coherent approach would estimate this phase at the 0 µs correlation offset where the correlation is below 0.2 and the velocity estimate would be very noisy if useful at all.

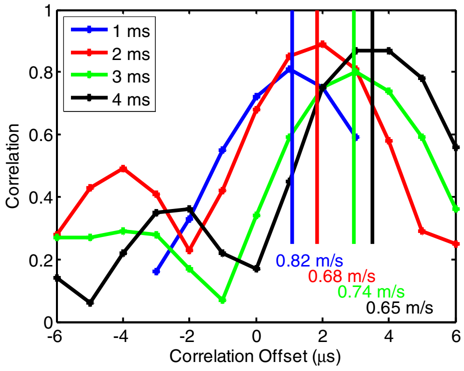

Fig. 5. Correlation curves for four different pulse lag values. The coarse estimates of velocity originating from the parabolic fit of the correlation curve are shown by vertical lines, coarse along-beam velocity estimates are indicated below.

IV. FIELD TRIAL

The setup for the field trial is presented in Fig. 6 and 7. As indicated in the photograph (Fig. 6), the individual Doppler sonars were arranged in a linear horizontal array on an aluminum I-beam bolted to the corrugated steel protective facing on the seaward end of the Parrsboro wharf. The acoustic beams were thus in a horizontal plane, the outermost slant beams (1 and 2) intersecting the centre beam (5) at about 7 m range from unit 5. Beams 3 and 4 intersected the centre beam at ca. 3 m range. An ADV (Nortek Vector) was mounted on a tripod at 9 m range. The Vectron data presented here are from the outermost slant beams and beam 5 -- i.e. from the

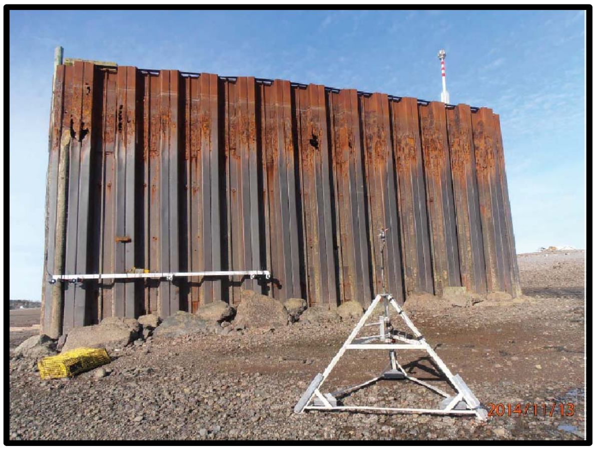

Fig. 6. Photograph of the experimental setup, taken at low tide, showing the ADV frame in the foreground, and the Vectron array and wharf face in the rear. The aluminum I-beam is 6.4 m long, for scale. Communications and power for the Vectron were via cable to a truck on the wharf. The ADV was autonomous.

farther of the two beam axis intersection points, which is the range planned for future FAST platform deployments. An ADV (Nortek Vector) was mounted on a tripod at a range of 9 m, to avoid contamination with the tripod, and at point to the side of the beam 5 axis as determined by the flow direction. The 7 m beam intersection point was about 3 m above bottom, so as to be roughly equidistant between surface and bottom during the strongest flows at mid-tide. Similarly, the ADV measurement point was 2.6 m above bottom. The sampling rate for both the Vectron and the ADV was 32 Hz. The Vectron range bin width was 20 cm.

Although not indicated in Fig. 7, the end of the I-beam to which module 1 was mounted was damaged during shipment to the site by what must have been very rough treatment by the transportation company. As a result, the beam 1 intersection point – based on the range of maximum average amplitude -- was located at ca. 8 m range.

The wharf trial was carried out over a 4 day period, November 11-14, 2014. The main data collection period was during the day of the 13th and the night of the 13th and 14th. During the day, the Vectron was controlled from a data acquisition truck, which allowed us to implement different configurations, including both the broadband and multi-correlation modes. During the night, we left it to operate autonomously under battery power, both as a check on noise levels compared to being powered by a DC power supply, and because autonomous operation will be required for the FAST platform deployments. No noticeable change in noise level was observed.

The comparisons presented here between the two Vectron operating modes, and between the Vectron and the ADV, are in the frequency domain, time series comparisons being comparatively less germane because the measurements were either not simultaneous or not co-located. The metrics of interest are: (a) the Vectron noise levels in the two operating modes, and in comparison to the ADV noise level; (b) the presence of an inertial subrange during high flow; and (c) evidence for spatial filtering of the spectrum by the ca. 20 x 30 x 30 cm dimensions of the Vectron detected volume compared to the ca. 1 cm^3 scale of the ADV detected volume. The spectra were computed using 1024 point Hanning-windowed data segments, 16 segments, and 50 % overlap.

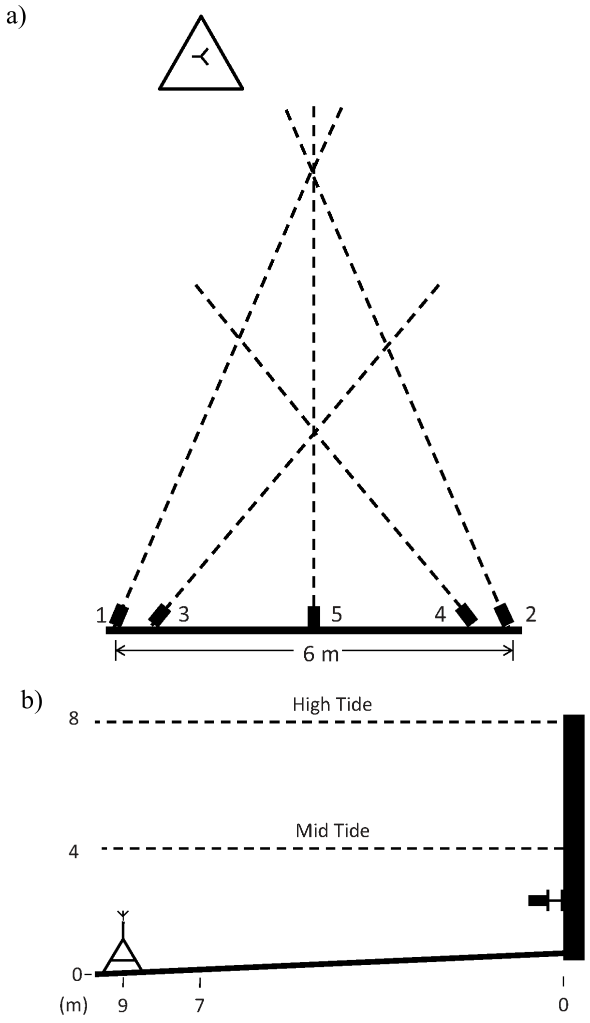

Fig. 7. Schematics of the setup in plan a) and view b) perspectives. The dashed lines in a) indicate the beam axes for the Vectron array. Except for the I-beam, the Vectron modules, and the ADV transducer assembly, the drawings are roughly to scale.

Representative results from broadband operation for the experiment are presented in Fig. 8 during ebb, and Fig. 9 during flood. A -5/3 range is present in both sets of results, and the noise level is consistently close to 1 x 10^{-3} $m^2/s^2/Hz$, as indicated by the black dashed line. These data are from the autonomous battery-powered operation during the night of Nov. 13-14.

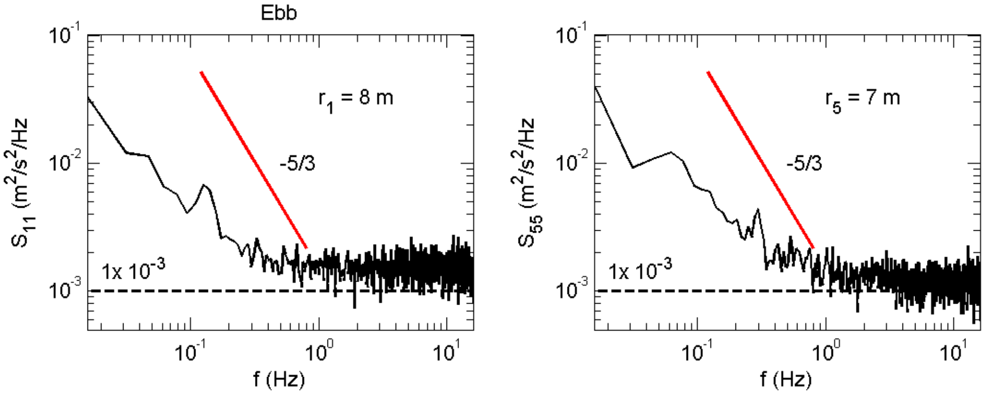

Fig. 8. Beam velocity spectra (beams 1 and 5) from the Vectron in broadband mode during ebb at the ranges indicated (r_1 = 8 m, r_5 = 7 m). The ranges are different for the reasons indicated in the text.

Representative spectra from the Multi Correlation Pulse Coherent mode are presented in Fig. 10. The approximate noise floor – 1 x 10^{-5} m^2/s^2/Hz – is 2 orders of magnitude lower than the level in broadband mode, and consequently the inertial subrange is more distinct than in the broadband results, despite the spectral densities being comparable (compare Figs. 10 and 9 at 0.1 Hz, for example).

Also shown in Fig. 10 are spectra computed from the ADV data, after projecting the ADV velocity onto the module 1 and 2 directions. The Vectron and ADV spectra are very comparable, even with respect to the apparent noise level, which is very encouraging. In the inertial subrange at frequencies above about 1 Hz, the Vectron spectra roll off more steeply than -5/3. We suggest that this is likely the result of the spatial filtering associated with the 30 cm effective size of the Vectron detected volume given the beam width, 7 or 8 m range, and 20 cm range cells. The mean flow speed registered by the ADV during the 8.5 min interval (corresponding to the spectra) was 68 cm/s. The corresponding advection frequency for a 30 cm effective measurement volume size would be 0.5 Hz.

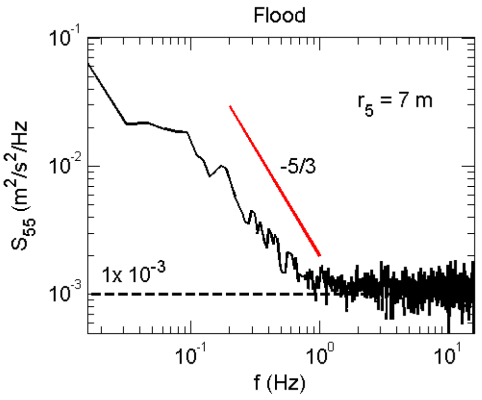

Fig. 9. Beam velocity spectrum (beam 5) from the Vectron in broadband mode at the range indicated during flood.

V. SUMMARY/CONCLUSIONS

We have described the design and performance of a new Doppler sonar measuring system called the Vectron. The system has been developed in order to obtain measurements required by the in-stream tidal energy conversion industry. The requirement is to provide turbulence resolving velocity measurements at O(10) m distance from the sampling instrument in areas where flow speeds are as high as 5 m/s. These measurements are required to predict transient loads on turbine components.

The Vectron provides these measurements by utilizing a bistatic geometry that allows pulse-to-pulse coherent velocity measurements with (horizontal component) ambiguity velocities of O(1) m/s (a monostatic system would provide ambiguity velocities an order of magnitude lower at these distances). Ambiguity issues are still a concern and these are addressed through a new approach developed by Nortek AS known as the Multi Correlation Pulse Coherent MCPC method. The MCPC method computes correlations at multiple offset values allowing an estimate to be made of the actual correlation function. The location of the correlation peak in (lagged) time provides a coarse estimate of the actual velocity that is not subject to ambiguity errors. A pulse coherent velocity estimate can then be made at the lag of peak correlation providing the required high precision velocity estimate.

The Vectron system is not a fixed package but rather a modular system configured from individual Nortek AD2CP single beam units. Critical time synchronization between the essentially independent instruments is achieved through a low latency Ethernet switch with a master Precision Time Protocol

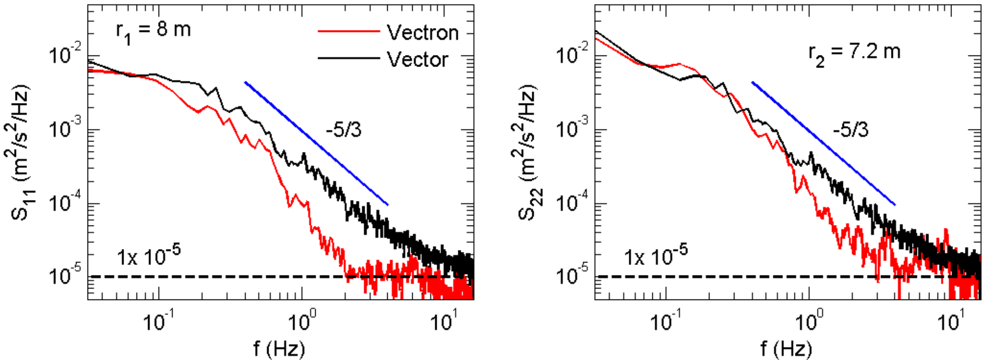

Fig. 10. Vectron beam velocity spectra in pulse-coherent mode with mulit-correlation processing (red) compared to spectra computed from the Vector ADV after projection onto the Vectron beam 1 and beam 2 directions. The dashed line indicates the approximate Vectron noise floor.

(PTP) clock. Individual units have clock rates that are stable to ±30 ppm and allow overall accuracy to about 2 cm/s; in future we intend to apply available hardware corrections that improve the clock accuracy down to the limit of the PTP clock and all but eliminate any velocity errors associated with clock drift.

Field trials of the system were undertaken from the wharf in Parrsboro NS; here 2 m/s tidal turbulent currents occur under conditions where comparison observations could be obtained using a Nortek Vector ADV. We have used velocity spectra as a measure of data quality. When operating the Vectron AD2CPs in broadband Doppler mode, a configuration that is known to provide reliable velocity measurements under high speed flow conditions, clear -5/3 inertial spectra are recovered and a noise floor of 1 x 10^{-3} m^2/s^2/Hz m/s is realized (Figs. 8 and 9). In comparison, when using the MCPC approach, a substantially lower noise floor is achieved (1 x 10^{-5} m^2/s^2/Hz) and the computed spectra compare favorably with independent ADV measurements (Fig. 10).

Future deployments of the Vectron are anticipated within the year with the system to be deployed in Minas Passage as part of the site evaluation for a planned in-stream tidal generation facility.

ACKNOWLEDGMENT

The authors should like to recognize Mr. Richard Cheel for significant contributions assembling system components and managing both lab and field trials of the Vectron.

REFERENCES

[1] Brumley, B., R. Cabrera, K. Deines, and E. Terray, 1990: Performance of a broadband acoustic Doppler current profiler. Proc. IEEE Fourth Working Conf. on Current Measurement, Clinton, MD, IEEE, 283–289.

[2] Zedel, L. "Modelling Doppler Sonar Backscatter", Proc. IEEE/OES Eleventh Current, Waves and Turbulence Measurement Workshop, St.. Petersburg, FL, IEEE.

[3] Zedel, L., and A.E. Hay, 2010: Resolving Velocity Ambiguity in Multifrequency Pulse-to-pulse Coherent Doppler Sonar. IEEE Journal of Oceanic Engineering. 35, 2010.