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Effective Use of an Acoustic Velocimeter in a Narrow Water Channel

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Abstract

With the increasing interest in renewable energy production, the study of flow around wind turbines, or submerged objects in general, has expanded as well. For situations in which an analytical solution is difficult to obtain, experimental data is used along with numerically predicted data to solve the problem. Since the collection of data in the field is not always feasible, water channels are equipment commonly used in laboratory settings to study the behavior of fluid flow. Dimensional analysis is used to ensure that the experimental data collected in water channels may be compared to data obtained outside the laboratory. As a part of a larger research project, our experimental team was tasked with the experimental set up of measuring velocity fields around submerged objects. Several methods of measuring fluid flow exist. The measurement method selected was the use of a velocimeter (Nortek's Vectrino velocimeter) which provides three-dimensional velocity readings. The size of the water channel, as well as the method of operation of the Vectrino, provided limitations to the experimental set up that needed to be addressed. The Vectrino operates on the principle of the Doppler Effect which involves the comparison of acoustic signals to measure velocity. Due to the relatively small size of the water channel used, signal interference was a major hindrance in the data collection. The signal interference resulted in an oversaturation of the data. Several methods of signal damping as well as a range of operating conditions were evaluated with the purpose of reducing the signal interference and obtaining reliable data. Higher quality data provides a more accurate representation of flow behavior in conditions outside the laboratory. The paper's conclusions may be expanded and applied to the measurement of the velocity field around an object for other open channel flow applications.

Keywords: Nortek's Vectrino, Narrow Water Channel, Three-Dimensional Velocity

1. Introduction

In the past years, there has been a growing interest in renewable energy production due to "a combination of high energy prices and growing state government support".[1] The U.S. Energy Information Administration predicts the production of renewable energy to increase from 17% in 2018 to 20% in 2020.[2] Wind energy is one of the main components of renewable energy production and is expected to keep growing in the next few years.[2] The optimal placement of vertical axis wind turbines (VAWTs) is a subject of interest since VAWTs can be located in settings (e.g. urban) that are otherwise not accessible to Horizontal Axis Wind Turbines (HAWTs). Numerical models can be used to help determine the placement of VAWTs that yield the highest output by predicting the behavior of flow patterns around surrounding structures under given conditions. Experimental methods must be used in conjunction with the numerical model in order to verify simulation parameters and results. However, it is difficult and time consuming to collect enough field data to encompass a wide range of conditions needed to verify the model. Data collected in a laboratory may be used through application of dimensional analysis to reduce the amount of required field data. As a part of a larger research project studying the optimal placement of VAWTs, velocity data of the flow around a submerged object was collected in a narrow water channel in order to support the numerical model's predictions.

Nortek's Vectrino, an acoustic Doppler velocimeter (ADV), was the main instrument used to measure the flow field. Since the 1990's, ADVs have commonly been used for "the characterization of fluid flow and turbulence".[3] Typical experimental setups utilizing an ADV include "turbulence measurements of the surf zone and estimation of vegetation-induced drag in wetlands".[3] These devices are marketed to perform well in laboratory size open channels as well as in the deep ocean.[4] The advantages of an ADV include that it is "more straightforward to use, more robust, and easier to modify for field work than the other techniques".[5] Alternative noninvasive measurement devices include Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV).[5] However, these systems are expensive and complex to operate.[5]

The investigation of flow fields around submerged objects, in the particular setup used, introduces a situation that is not addressed in the previously mentioned studies. A metal plate was used to fix the objects in the water channel. The plate introduced a new implication into the study: an acoustic environment. This paper summarizes the conditions surrounding the experiment as well as problems encountered in the use of the instrument and the solutions implemented.

2. Conditions Surrounding the Experiment

The collection of the data using Nortek's Vectrino was conducted in a self-contained, recirculating water channel shown in Figure 1.[7] The channel is 18 inches high by 12 inches wide. Its working length is 16 feet and ends with a 358-gallon capacity fiberglass reservoir. The water flows across the channel by means of two circulating pumps. Pump 1 operates with a variable speed motor controller; Pump 2 operates with a non-reversing motor starter. Pump 2 always operates at 60 Hz. The slope is adjustable between +10% and -2%. The user is able to control the flow variables by changing the frequency of Pump 1 or changing the slope of the channel. At a 0% slope, the flow rate can vary from more than 340 GPM down to 2.0 GPM. The water depth may be controlled by raising or lowering the tailgate located at the downstream end of the channel. The tailgate poses an additional constraint. All velocity measurements must be taken at a specific distance away from the end of the channel to avoid back flow caused by the gate.[6]

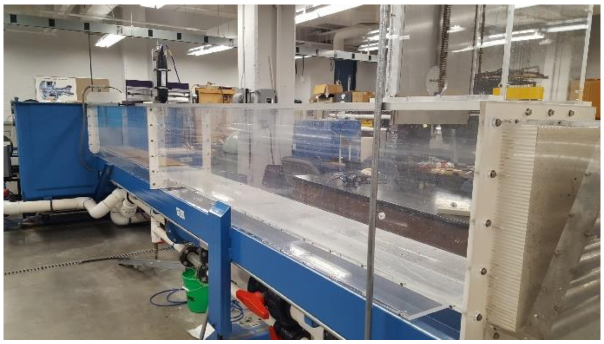


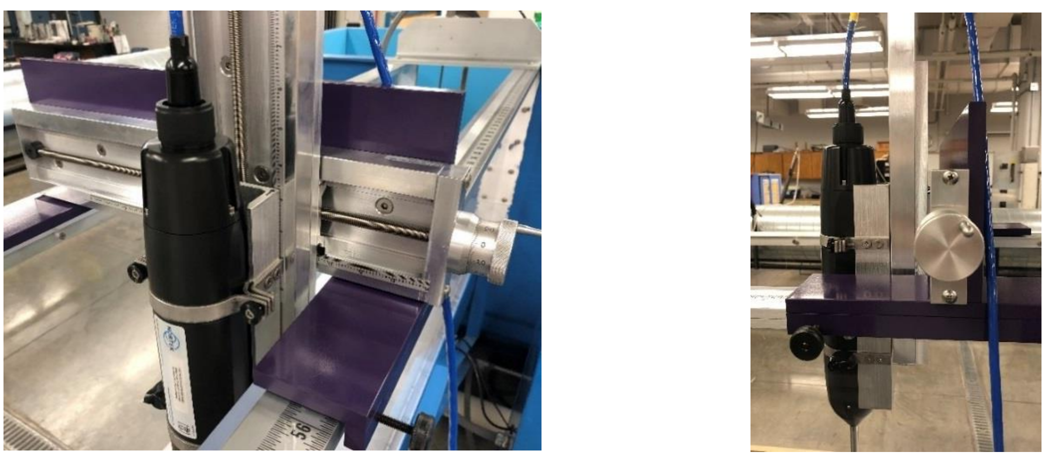
Figure 1. Water channel used to collect data

The Vectrino is a tool commonly used to measure turbulence and three-dimensional velocities in water channels such as the one described above.[8] It operates under the principle of the Doppler effect. The Doppler effect is used to describe the phenomenon in which "waves emitted by an approaching or receding wave source will change frequency in relation to the receiver of the wave whenever the source, receiver, or the wave's carrying medium is in motion relative to the other".[9] The Vectrino probe consists of four receiver beams and a transmitter beam. Each pair of transmitters, composed of two opposing receivers, can measure either an X or Y horizontal velocity component as well as a vertical velocity component. Receivers 1 and 3 measure velocity in the X and Z1 direction and receivers 2 and 4 measure velocity in the Y and Z2 direction.[8] Figure 2(a) shows the beam arrangements where the positive X direction is indicated by the red marking on the beam and positive Y and Z directions may be determined with the right-hand rule.[8] This beam coordinate system does not change depending on the orientation of the Vectrino. The area in which the beams intersect is located 50 mm below the transmitter and is called the sampling volume. This volume, demonstrated in Figure 2(b) has a diameter of 6 mm and its height may be adjusted between 3 and 15 mm in the instrument settings.[8] The transmitter (element in the center) sends out "short acoustic pulse pairs".[8] The pulses travel through the sampling volume and their echo "is recorded in each of the acoustic receiver elements".[8] Using the theory of the Doppler effect, the phase shift between the echoes of each pair of pulses is used to find the 3D velocity in the specified sampling volume of water. Since "the time lag between the transmitted and received pulse determines how far the pulse traveled before it was reflected", the speed of sound in water is a key component of the velocity calculations performed by the Vectrino.[8] Two factors that affect the speed of sound in water are temperature and salinity. The temperature is accounted for using the thermistor embedded in the head of the probe (temperature is sampled every second and reported every ten minutes).[8] The salinity is specified in the instrument settings in the Vectrino software; if the salinity is not specified, a normal salinity of zero ppt is automatically assumed.[8]

(a) (b)

Figure 2. Nortek Vectrino's transmitter and receivers (a) notation convention (b) sampling volume[8]

Since the Vectrino reports velocity measurements in a Cartesian coordinate system, ensuring the correct alignment of the instrument in the laboratory flume is essential. Although aligning everything by eye works well, for a more robust and accurate setup, an "XYZ – Probe Carriage" was built, shown in Figure 3. This carriage allows for movement of the probe in all three directions. The x-direction was chosen to be along the length, y-direction across the width, and z-direction along the depth of the channel.



(a) (b)

Figure 3. Mounting of the Vectrino on the water channel

3. Data Quality Checks

Two tools included in the Vectrino software that were used to determine the quality of the data were the Probe Check and the Distance Check. The Probe Check tool allows for the inspection of the region in which the measurements are taken. An example of a typical Probe Check is shown below in Figure 4.[10] Each colored graph corresponds to the four receiver arms, respectively.[10] Point A indicates the start of the sampling volume, Point B corresponds to the peak of the sampling volume, and Point C represents the bed of the sampling environment.[10] The graph should show roughly the same shape for each of the receiver arms.[10] It should also be noted that there is a "signal strength decrease to the noise floor between the measurement volume and the bottom".[10] This dramatic decrease is shown between points B and C in Figure 4. Measures should be taken to ensure that the Probe Check resembles that shown in Figure 4.[10]

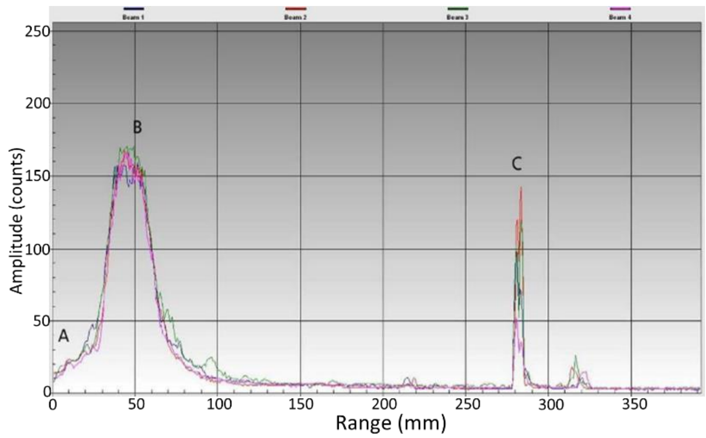


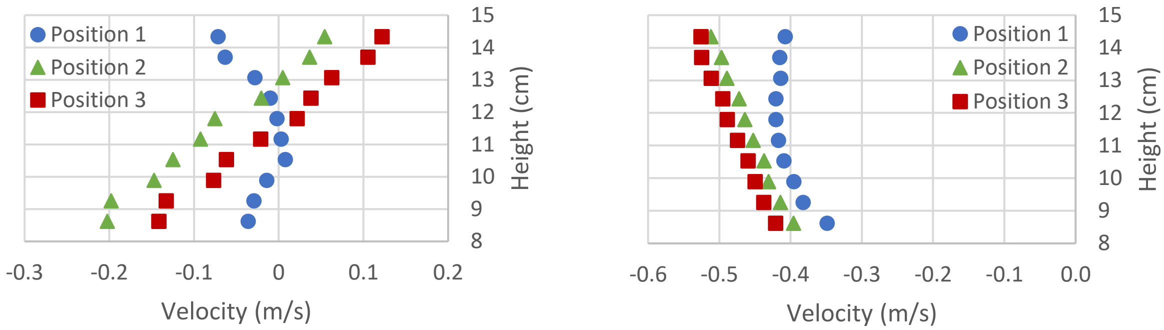
Figure 4. Typical Probe Check indicating quality measurements.[10]

The Distance Check is used to "measure the distance to the bed from the central transducer" through the use of an acoustic pulse that is "sent out separate from the normal velocity sampling pulses".[11] The standard Vectrino firmware does not support the boundary distance mode but does perform a distance measurement immediately preceding the data collection.[11] It is important to ensure that the Distance Check is producing accurate measurements; "odd echoes, grounding problems, and several other things can result in problems with the Distance Check".[12] Problems in the distance measurement can also result depending on the bottom material in the flume; very large return signals can result from "acoustically highly reflective" surfaces and "pollute the water column in such a way that obtaining reliable data is not possible".[12] The additional signals and echoes resulting from the reflective surface alter the distance measurement as the algorithm used to determine the distance searches for the highest return signal peak.[12] In the case of the acoustically noisy environment, it finds the highest peak and reports an incorrect reading[12]. The Distance Check should be used in conjunction with the Probe Check feature to ensure a "clear, sharp peak in the return signal strength at the boundary in all four beams".[12]

4. Parameters Considered

The nominal velocity range, a user-defined setting, is the first factor whose effect on measurement quality was explored. It is the operating range in which measurements are taken in the flume. The Vectrino provides six different options: 0.03, 0.10, 0.30, 1.00, 2.50 and 4.00 m/s. Selecting an appropriate velocity range is a key element in ensuring data quality. The smallest velocity range that encompasses the operating conditions must be selected. Selecting a velocity range that is too large "will result in noisy data because the detected phase shift is very small relative to the ambiguity velocity".[8] On the other hand, too low a velocity range will result in de-correlation of the return signals, or phase wrapping".[8] Phase wrapping is the phenomenon that occurs when the measured phase shift is outside the bounds of zero to 2π. As a consequence, the phase wraps around to zero resulting in a magnitude and sign different from that of the actual value.[8] Phase wrapping may be avoided by selecting the appropriate velocity range using prior knowledge of the flow conditions. While collecting the data regarding flow around a submerged object, the appropriate velocity range was determined with a Pitot-static tube. For example, when the Pitot-tube reported a velocity of 0.35 m/s, the velocity range selected was ± 1.00 m/s. Figure 5 shows the effect of phase wrapping on three velocity profiles taken under the same conditions. Positions 1, 2, and 3 were located along the length of the channel, with Position 3 being closest to the water reservoir. The three positions were approximately the same for Figure 5(a) and Figure 5(b). The phase wrapping was a result of selecting a nominal velocity range of ± 0.10 m/s (Figure 5(a)) instead of ± 1.00 m/s

(Figure 5(b)). Note that when the correct nominal velocity range was selected, the water flowed in the negative x-direction, as expected based on the orientation of the probe in the channel with respect to the water flow. On the other hand, when a nominal velocity range that was too small was selected, the velocity profiles show a change in flow direction, which was not the case.



(a) (b)

Figure 5. Effects of phase wrapping that resulted from improper nominal velocity range selection (a) incorrect nominal velocity range (b) correct nominal velocity range

The Vectrino poses a few limitations regarding where it can collect measurements. It is not capable of measuring velocities close to the surface, or too close to the bottom or sides of the water channel. Velocities near the surface may not be collected because the transducer must be submerged at all times while collecting data.[13] In addition, there is a distance of approximately 50 mm below the transducer in which no measurements may be collected, shown in Figure 2. Velocity measurements near the walls of the water channel were difficult to collect due to the geometry of the probe. As shown in Figure 2, the Vectrino's probe has four arms that extend outwards. These arms, although necessary for collecting the return signals, limit the proximity of the sampling volume to the channel walls. Finally, weak spots, as the result of pulse interference, are of concern when measuring near boundaries in flumes with a hard bottom.[8] Weak spots occur when "the first pulse hits the bottom and the reflected signal of the first pulse reaches the sampling volume at the same time as the second pulse goes through the sampling volume".[8] Typically, "low SNR and correlation values, as well as noisy velocity traces" are key indicators when identifying weak spots.[8] The signal-to-noise ratio (SNR) is a measure of signal strength and is reported in decibels.[8] Correlation provides a statistical measure of similar behavior between the received signals with respect to time.[8] The correlation is represented as a percentage, where 100 percent indicates perfect correlation between the signals.[8] If a weak spot is identified, there are several ways to correct the problem. The first way is to adjust the nominal velocity range up or down to increase SNR and correlation values. An alternative approach is to avoid the weak spots altogether by moving the instrument away from the boundary. Even moving just several centimeters away from the boundary can eliminate the problem.[8] The trade-off seen in this option is the reduction in workspace within the flume. Under the given conditions, it was determined, with the help of Nortek technical support, that measurements taken below a height of 3.375 in above the channel bed did not yield accurate results and would not be collected. The reason for choosing the minimum height of 3.375 in and the measures taken to avoid signal interference may be seen through the analysis of probe checks. No matter which approach is selected, a minimum distance of five cm must be maintained between the central transducer and the channel bed to avoid the intersection of the sampling volume with the bottom of the flume.

The data collected concerning the optimal placement of VAWTs also required measurements to be taken above a metal plate, thus producing an acoustic environment. The magnetic plate resulted in stronger reflections than those that would result in a water channel with a base of a different material. In order to dampen these signals, a thin layer of cork was used to cover the magnetic plate. The power level is another parameter that affects measurement quality. It indicates "how much acoustic energy the instrument transmits to the water".[8] The Vectrino may operate at four different power levels: LOW, LOW +, HIGH -, and HIGH +.

When the default parameter settings were used in the specified water channel, while still adjusting for nominal velocity range, a series of Probe Checks were obtained to ensure measurement quality. The initial set of Probe Checks was collected using the following parameters as constants: sampling rate of 10 Hz, nominal velocity range of +/- 1.00 m/s, and the Field Probe setting. All other parameters were left at the default states. The three parameters that were allowed to vary were the distance from the bed of the channel to the sampling volume (height), power level, and the channel bed material. Two different materials were investigated: the metallic plate, as well as a 0.0625 in layer of gasket material (cork) that covered the metallic plate. The two different materials were compared to display the influence a noisy environment has on the quality of measurements. The Probe Check was collected with the velocimeter mounted in the center of the water channel at two different heights to illustrate the importance of remaining an appropriate distance from the bed of the channel. The measurement heights were selected to be 2.145 and 3.395 inches above the bed of the channel. These two heights were chosen to be below and above the minimum height previously determined, respectively. The two heights were selected to emphasize the effect of the proximity to the channel bed on measurement quality. The power was allowed to vary at the two different heights for both of the bed materials. Figures 6-9 contain the Probe Check for the two heights and two materials at the four different power levels. The shape of the Probe Check, as well as a built in "Distance Check" were used to analyze the results.

The Probe Checks in Figures 6-9 were compared to that in Figure 4 in order to find the combination of variables that yielded the most accurate results. Figure 6 contains probe checks collected at two different heights with the two different water channel bed materials and power level on HIGH. All of the probe checks with these power level differ from the ideal case (Figure 4) at all heights and channel bed materials. Not enough separation was seen between the sampling volume and the channel bed, and all of the probe checks appeared oversaturated. It was evident that further adjustments needed to be made. Figure 7 shows the probe checks collected with the power level on HIGH -. The Probe Checks collected with this power level show more separation between the sampling volume and channel bed signals than those collected with the HIGH power level. This separation between the signals was not yet enough, however, and the data still appeared oversaturated. Please note that there was an improvement when the channel bed material was changed; the probe checks collected over the cork are less saturated than those collected over the metallic plate. Figure 8 and Figure 9 show the probe checks collected with the power level on LOW+ and LOW, respectively. The probe checks collected with both of these power levels show no oversaturation and enough separation between the sample volume and channel bed signals. Both bed materials closely resemble that of the ideal case shown in Figure 4. Although the probe checks collected above the cork and metal under both the LOW+ and LOW power levels (but at different heights) have very similar shapes, the decision on the height and material above which accurate data could be collected was made based on the Distance Check results discussed below. Table 1 contains a summary of these observations.

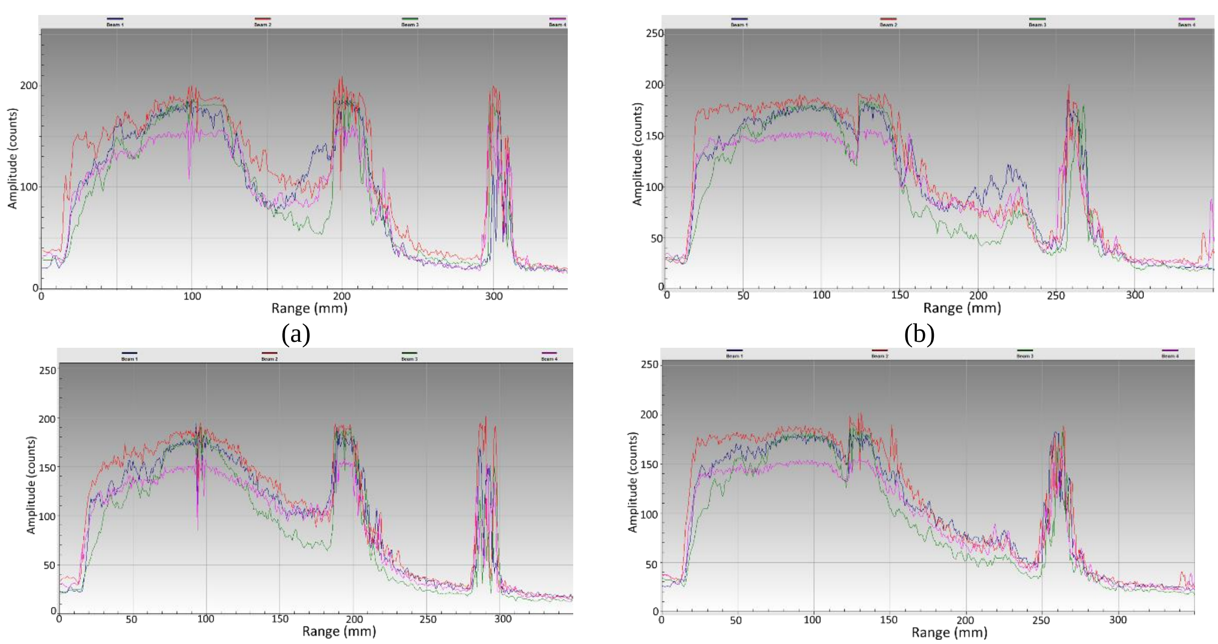


Figure 6. HIGH power level (a) metal plate, height of 2.145 in (b) metal plate, height of 3.395 in (c) cork, height of 2.145 in (d) cork, height of 3.395 in

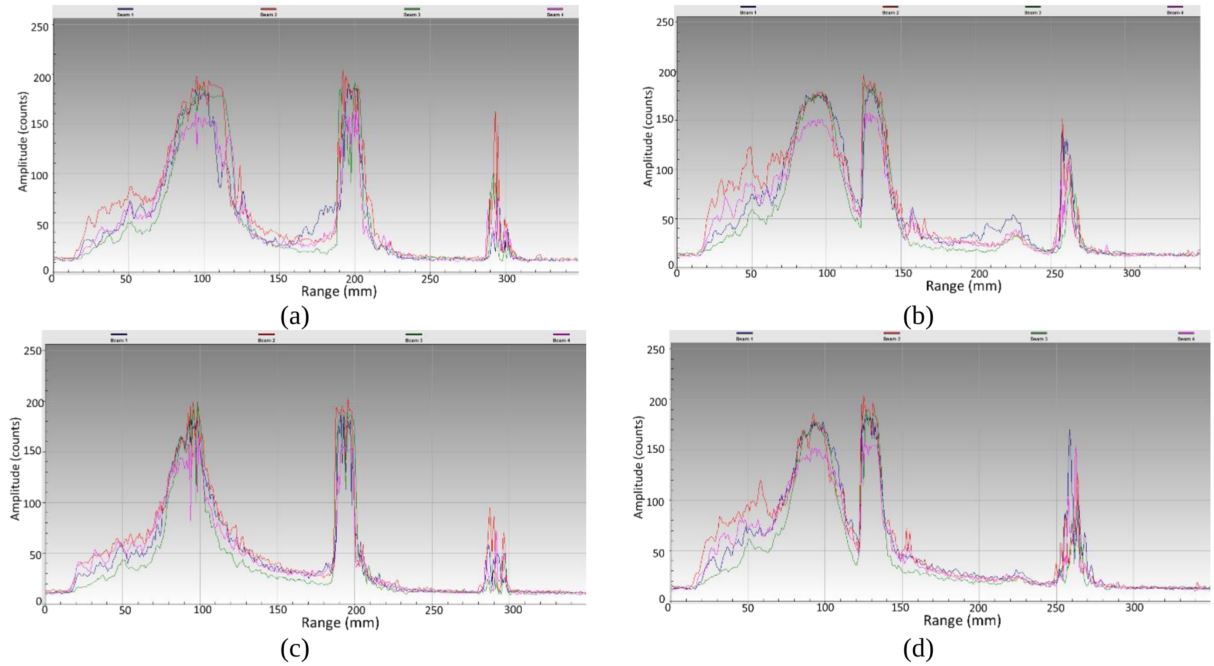


Figure 7. HIGH - power level (a) metal plate, height of 2.145 in (b) metal plate, height of 3.395 in (c) cork, height of 2.145 in (d) cork, height of 3.395 in

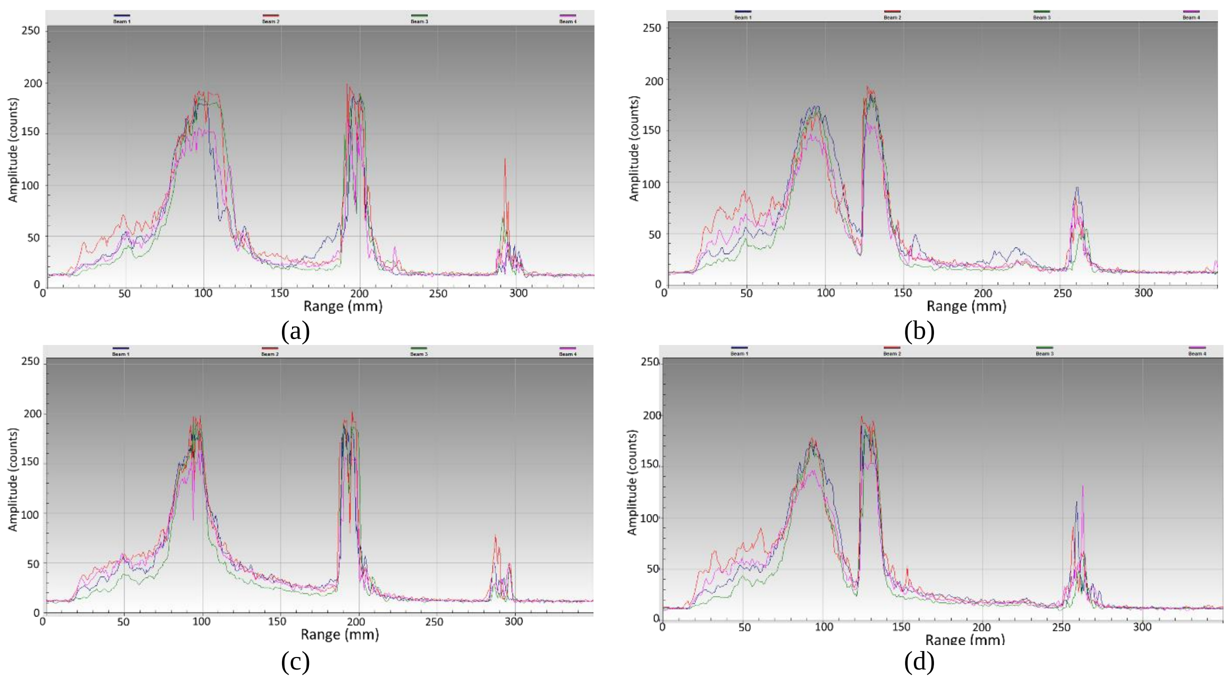


Figure 8. LOW + power level (a) metal plate, height of 2.145 in (b) metal plate, height of 3.395 in (c) cork, height of 2.145 in (d) cork, height of 3.395 in

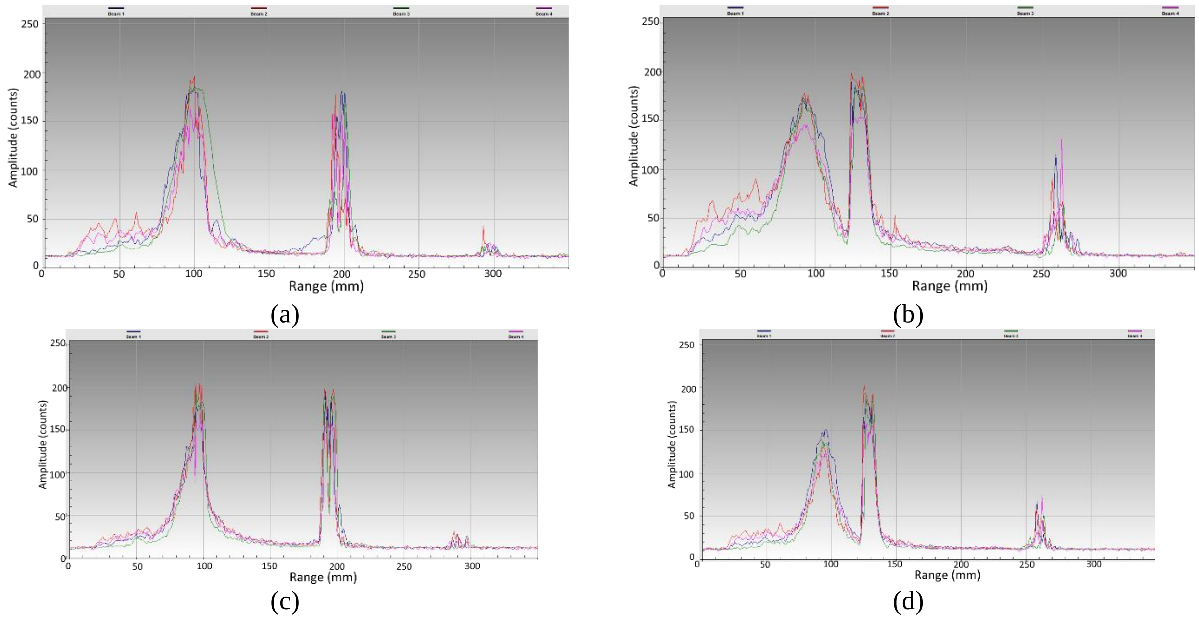


Figure 9. LOW power level (a) metal plate, height of 2.145 in (b) metal plate, height of 3.395 in (c) cork, height of 2.145 in (d) cork, height of 3.395 in

Table 1. Observations of effect of channel bed material, measurement height above channel bed and power level on Probe Checks.

<table>
<tr><td colspan="2">Channel Bed Material:</td><td colspan="2">Metal Plate</td><td colspan="2">Cork</td></tr>
<tr><td colspan="2">Measurement Height:</td><td>2.145 in</td><td>3.395 in</td><td>2.145 in</td><td>3.395 in</td></tr>
<tr><td rowspan="5">Power Level</td><td>LOW</td><td colspan="4">Not oversaturated. Distinct separation between sampling volume and channel bed. Resembles ideal probe check.</td></tr>
<tr><td>LOW +</td><td colspan="4">Not oversaturated. Distinct separation between sampling volume and channel bed. Resembles ideal probe check.</td></tr>
<tr><td rowspan="2">HIGH -</td><td colspan="4">Oversaturated, but less than HIGH+. Not enough separation between sampling volume and bed.</td></tr>
<tr><td colspan="2">More oversaturated than cork.</td><td colspan="2">Less oversaturated than metal.</td></tr>
<tr><td>HIGH</td><td colspan="4">Oversaturated. Not enough separation between sampling volume and channel bed.</td></tr>
</table>

Table 2 displays the Distance Check results for the same conditions in which the Probe Checks were collected. The height indicated in the table represents the distance from the sampling volume to the bed of the channel, in inches. The distance to the transducer is the distance from the central transducer to the bed of the channel; this is the distance provided by the Distance Check, in centimeters. Based on the results of the Distance Check, all measurements taken above the metal plate should not be used. The results indicate that the measurements taken at 2.145 in should not be used as erroneous signals are affecting the results; the difference in actual and measured distance to transducer are evidence of this. The power levels of HIGH– and HIGH+ were indicated by the Probe Checks to be unusable as they showed sign of oversaturation and signal interference. After examining the Probe Checks and Distance Checks, the measurements taken at the actual height of 3.395 in can be safely used with confidence in the quality of the data at the LOW and LOW+ power levels. Additional Probe and Distance Checks were performed to maximize the work space in the channel and determine the lowest possible height in which accurate measurements can be taken. All measurements taken below 2.645 in are fully interfered and cannot be used to measure velocities. Measurements taken at a height between 2.895 and 3.145 in are questionable and should be subject to extra scrutiny. The results of the probe and distance checks were discussed with Nortek Technical Support, and it was concluded that the measurements taken at (and above) 3.395 in can be safely used as the sampling volume is unobstructed by the boundary.

Table 2. Summary of the Distance Checks performed at different power levels for two different flume bed materials at two different heights.

	Metal Plate		Cork	
Actual Height:	2.145 in	3.395 in	2.145 in	3.395 in
Actual Distance to Transducer:	10.45 cm	13.62 cm	10.45 cm	13.62 cm
Power Level	Measured Distance to Transducer (cm)		Measured Distance to Transducer (cm)	
LOW	20.3	26.5	19.9	13.2
LOW +	20.3	26.6	19.9	13.2
HIGH -	20.3	26.6	19.9	13.2
HIGH +	20.3	26.6	19.9	13.2

5. Application of Parameter Changes

Figure 10 contains a field plot of the data collected with the Vectrino in the water channel. The purpose of collecting this data was to observe the flow behavior around differently-shaped items in various arrangements. In order to create the plots, close to 192 data points were collected at one-inch increments across the magnetic plate covered in cork. 600 hundred samples were collected at each data point location at a frequency of 10 Hz. A MATLAB code was written to process the large quantities of data and produce the plot in Figure 10. The figure contains the magnitude of the velocity along the channel length (x-direction) and across the channel (y-direction) as well as a vector plot illustrating the two-dimensional flow direction. Note that, as discussed, measurements could not be collected too close to the channel walls, as demonstrated by the lack of data between the y-coordinates of -2.5 and 0 and 6.5 and 9 (across the channel). For the same reasons, data could not be collected directly next to the submerged items. Nevertheless, the plots provide a detailed description of the flow behavior. In addition, the data was collected at a height of 4.945 inches which is above the minimum height required for accurate data collection.

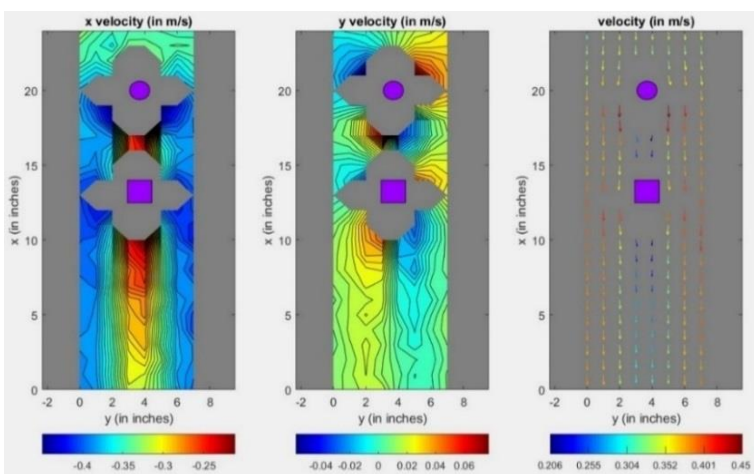


Figure 10. Velocity field plots collected with Nortek's Vectrino in a laboratory flume

6. Conclusion

This paper discussed the use of Nortek's Vectrino to obtain three-dimensional velocity measurements in a narrow water channel as part of a larger project regarding wind energy. It was shown that factors such as water salinity and temperature, the power level, the nominal velocity range, the proximity to the channel bed and the material of the channel bed have significant effects on the measurement accuracy. Probe Checks and Distance Checks were found to be useful instruments in the determination of the ideal combination of parameters under the given conditions. Salinity may be accounted for within the parameter settings; a normal salinity of zero ppt is typically used (default setting), but it may be adjusted if it differs significantly from the default. Adjusting the nominal velocity range using previous knowledge of flow characteristics avoids phase wrapping. In the experimental conditions discussed, a Pitot-static tube was used to determine the nominal velocity range. Lowering the power level, as appropriate, reduces the signal saturation sometimes seen in probe checks. If the material at the bed of the laboratory flume results in strong signal interference, dampening materials may be used to reduce the noise level and signal oversaturation. A minimum distance from the channel bed at which velocity measurements could be collected was determined in order to avoid the effects of weak spots. Finally, examples of the data collected with the Vectrino under the specified conditions with the changes in the parameters discussed were included to show an application of the instrument in a laboratory setting. The techniques used may be expanded to research projects in a wide range of applications.

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