Acoustic Doppler Velocimeters for Point Velocity Measurement in Non-Ideal Intakes

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Abstract

Many hydroelectric utilities, including Manitoba Hydro and Hydro Québec, use the current meter method for measuring discharge through low head hydroelectric generating stations featuring short converging intakes. For Manitoba Hydro, point velocities are normally measured across a vertical plane using Ott C31 - Type A current meters, however these instruments are only viable when the flow incident angle is less than 45 degrees from the instrument axis. This paper discusses the use of Acoustic Doppler Velocimeters (ADV's) as an alternative method for determining the three-component point velocities across a non-ideal intake where flow incident angles are expected to exceed 45 degrees, or where we cannot confirm that the requirement will be met.

A series of trials were conducted in 2022 and 2023 through which the suitability of ADV instruments was tested. This included repeat measurements under varying conditions and configurations. The findings from these tests are presented in this paper, including site conditions, instrument configuration and limitations, and uncertainty. In general, the results are favourable indicating that the ADV's functioned well even under high flow angles. Consideration for the handling of random uncertainties was a key finding from these trials, requiring an increased sample size and proper equipment configuration to reduce uncertainties to acceptable levels. This work suggests that these instruments may be a reasonable alternative means of measuring point velocities in non-ideal intake conditions.

1. Introduction

Acoustic Doppler Velocimeters (ADV's) are commonly used in laboratory environments to measure detailed three-dimensional water velocity profiles. Their application in field installations and specifically for turbine performance testing is limited [1, 2], and ADV's are not yet approved for use in code-compliant turbine tests [3, 4]. Despite this, ADV measurements may present a viable alternative means of velocity measurement for the purpose of hydraulic turbine performance testing. This consideration is most important in non-ideal conditions where strong vertical and/or lateral velocity components may prohibit the use of standard propeller type current meters.

A series of trials were conducted in 2022 and 2023 at a Manitoba Hydro facility whereby the suitability of ADV's was tested. This facility features a free-surface intake leading to a bulkhead and wheel pit, as shown on **Figure 1**. The bulkhead introduces strong vertical component velocities near the top of the intake. Based on Computational Fluid Dynamics (CFD) modelling results, the incident velocity vector angles in proximity to the bulkhead are expected to exceed 30-45 degrees relative to the streamline horizontal component. Angles exceeding this range have been found to introduce additional error in water velocity measurements and exceed the stated criteria for Ott C31 - Type A current meters used by Manitoba Hydro.

This paper presents the findings of these trials, focusing on site considerations, equipment, data processing, sensitivities, and uncertainties with ADV applications.

2. Site Considerations

Manitoba Hydro estimates flow within short-converging intakes by measuring point velocities that are normal to a vertical measurement grid spanning each individual water passage. The arrangement of the individual metering points follows guidance from the 'Abnahmeversuche an Wasserturbinen' German test code [5], which typically well exceeds the minimum number of points suggested by ISO 3354 [6]. Integration of the point velocities using the velocity-area method allows for calculation of the total discharge across the measurement plane, considering assumed boundary layer characteristics for all edge and corner elements. The spacing (particularly for edge points) and number of measurement points are both important considerations to reduce the uncertainty of the estimate.

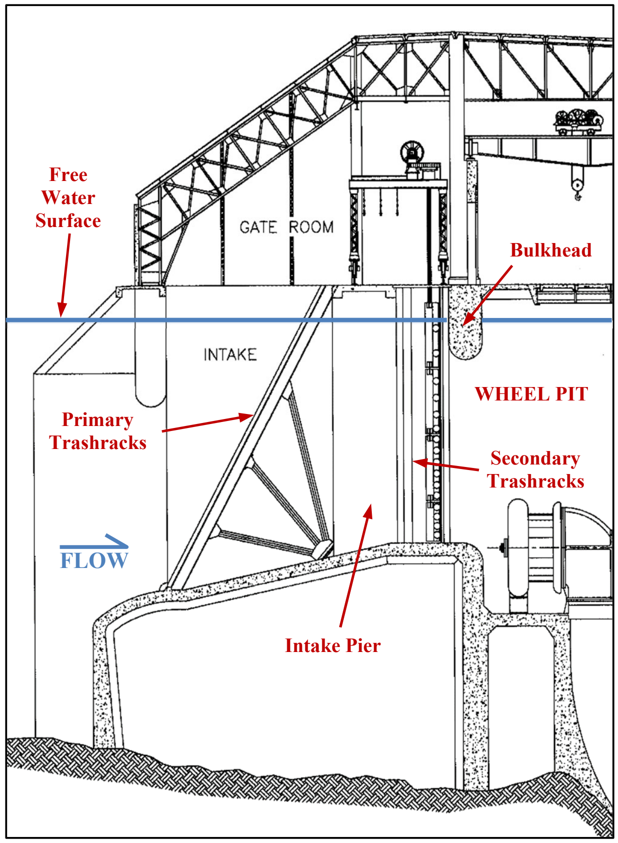


Figure 1. Profile view of intake configuration for ADV trials

For the ADV trials, the method noted above was adapted in consideration of the non-ideal configuration of the intake, most notably the presence of a bulkhead near the top free water surface boundary. The grid configuration included 7 metering points distributed laterally across the intake and 13 (or more) levels distributed vertically, totalling a minimum of 91 point velocity measurements for each test. The spacing between the wall and edge points was ~0.17 m along the side and bottom boundaries. In addition, a consistent vertical spacing of ~0.37 m was used for each level above the bottom of the bulkhead up to the free water surface. The boundary layer assumptions for the top elements were also modified to assume a uniform vertical flow profile in the top-most cells (i.e. the surface velocity was assumed to be the same as the upper-most point velocity measurements). The orientation of the metering grid is shown in Figure 2.

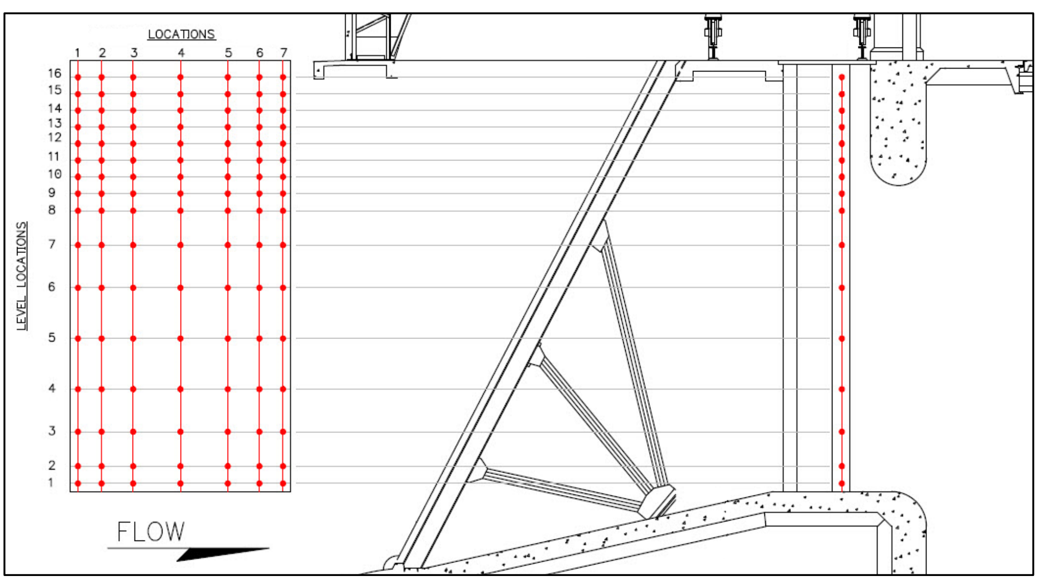


Figure 2. Point velocity metering grid for ADV trials

To facilitate the measurements, the instruments were mounted to a steel frame and lowered through the intake stopping at each level for two minutes, during which stationary readings were collected. Trials testing the sensitivity to sampling frequency and duration were also conducted and are discussed herein. The two tests, the first conducted in 2022 and the second in 2023, differed primarily in that the secondary trashracks were removed prior to the 2023 test. The intent of this trial was to reduce the turbulence and overall disturbance introduced by the trashracks, especially given their proximity (approximately 0.6 m) to the metering plane.

3. ADV Instrumentation

The devices used for these trials were Sontek FlowTracker2 Lab ADV's with the three receiver configuration. The instruments capture three-dimensional component water velocities and have a stated velocity range of ±0.001 to 4.0 m/s, with a stated accuracy of ±1% of the measured velocity. An ADV's high single ping accuracy allows for measurements in normally hard-to-measure conditions including turbulence, rapidly changing flows, near boundaries and high shear regimes, making it well-suited for the intake section where the trials were performed.

Each ADV measures the velocity of water using the Doppler effect and is built as a bistatic system consisting of the central acoustic transmitter and three receivers. The transmitter generates sound with energy concentrated in a narrow cone, while the receiver is most sensitive to sound coming from a very narrow angular range. The transducers are mounted such that their beams intersect at a volume of water located a precise distance away, nominally 10 cm from the transmitter. This beam intersection determines the location of the sampling volume. Figure 3 shows a schematic of the FlowTracker2 probe head (with two receivers) and sampling volume location.

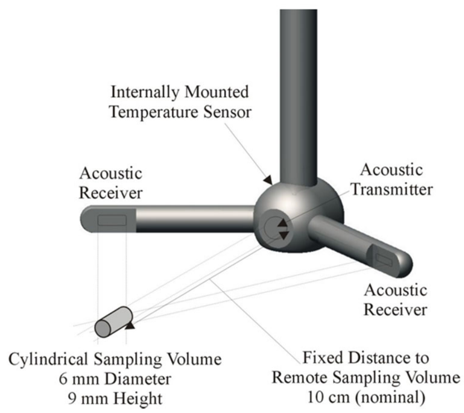


Figure 3. FlowTracker2 Lab ADV probe showing cylindrical sampling volume

The transmitter generates a short pulse of sound at 10 MHz, which propagates through the water along the axis of its beam. As the pulse passes through the sampling volume, the acoustic energy is reflected in all directions by particulate matter (sediment, small organisms, bubbles, etc.). Some portion of the reflected energy travels back along the receiver axis, where it is sampled by the ADV and the processing electronics measure the change in frequency. The Doppler shift measured by each receiver is proportional to the velocity of the particles along the bistatic axis of that receiver and the transmitter.

3.1 Pulse-coherent Signal Processing Theory

The pulse coherent technique was first introduced by Lhermitte and Serafin [7] and consists of a sequence of two short pulse pairs, typically with the time between pulses in a pair much longer than the length the actual pulse. This "coherent" method allows for a high accuracy, low noise velocity calculation based on the phase shift between the two pulses, and works best for resolving fine-scale motions.

In pulse coherent systems, the phase shift, $\Delta\Phi$, is calculated from the two signals, and is related to Δf, the Doppler Shift, by:

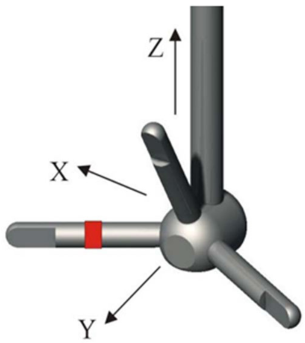
$$\Delta f = \Delta\Phi / 2\pi\Delta t \quad (1)$$

where Δt is the time difference between pings. The actual detection and calculation of $\Delta\Phi$ uses signal processing techniques involving covariance functions. The velocity, v, is then calculated using Δf:

$$v = c\Delta f / 2f \quad (2)$$

where f is the principle frequency of the instrument (f =10 MHz in the case of the FlowTracker2 ADV probe), and c is the speed of sound in water.

3.2 ADV Calibration Methods
Each ADV underwent a factory calibration by towing the instrument through a seeded tow tank using precise stepper motors at independently verified speeds. Using sampling rates of 5 Hz at 50 pings per sample (250 Hz effective ping rate), a transformation matrix is calculated to shift in-line beam coordinate velocities to an XYZ coordinate system (shown in Figure 4). Because ceramic transducer elements are moulded and placed manually into the probe, there are slight geometric variations from probe to probe; the factory transformation matrix calibration takes these variations into account and transforms the received signal to XYZ coordinates based on each probe's specific transducer geometry and noise. The transformation matrix is then applied to the velocity calculations, and then verified with post-calibration verification tows.



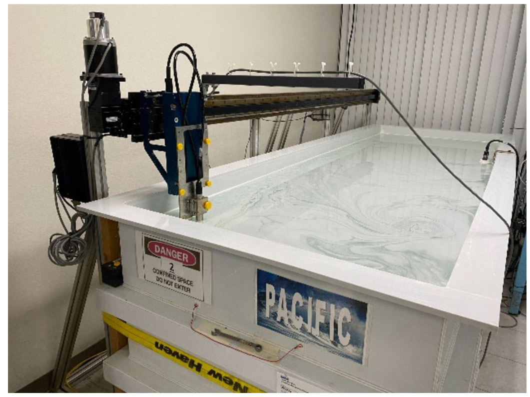


Figure 4. Left: XYZ axis of FlowTracker2 probe. Right: Tow tank used to calibrate FlowTracker2 probes.

3.3 SNR and the Importance of Sufficient Scatterers
All acoustic Doppler systems require a sufficient amount of acoustic scattering material in the water in order to return a proper signal. These systems measure the velocity of the scatterers, and the assumption is made that the scatterers move at the velocity of the water. Signal strength, recorded for each ADV receiver, is a measure of the intensity of the reflected acoustic signal. The signal is then converted to a signal-to-noise ratio (SNR) in dB. The main function of signal strength data is to verify there is sufficient particulate matter in the water. If the water is too clear, the return signal may not be stronger than the ambient electronics noise level. Without sufficient signal strength, the ADV is unable to make accurate velocity measurements. As SNR decreases, the noise in ADV velocity measurements will increase. When the SNR reaches a nominal threshold of 3dB or below, a reliable velocity calculation is generally difficult to achieve. While this is not normally a concern in field applications, it can produce problems in natural spring-fed mountainous sites with very clear water.

3.4 Ambiguity Velocity and Wrapping
The phase, Φ, is defined on a 360° (or 0 to 2π) circle for any sinusoidal signal. There is a range of the phase shift, $\Delta\Phi$, where there exists an 'ambiguous' velocity. Figure 5 depicts different phase shift examples for (a) phase shift +90 degrees away from original signal; (b) phase shift -90 degrees toward original signal; (c) phase shift +180 degrees away from original signal; and (d) phase shift ambiguity showing either a +270 degree shift away or -90 degree shift toward original signal. The grey box outlined in (b) and (d) shows the same perceived phase shift despite a possible reversal in shift direction, resulting in an ambiguity.

The maximum velocity measurable corresponds to when $\Delta\Phi$ enters an ambiguous state and is determined by how the ping timing is configured for a given instrument. This maximum velocity (often called "ambiguity velocity") is used to guide the selection of instrument velocity range. If the probe encounters velocities beyond this maximum ambiguity velocity, a phenomenon called "wrapping" will occur. The resulting wrapped velocity is usually the opposite sign compared to the expected velocity. It is thus critical for a pulse coherent system to be set up to for a certain maximum velocity of the flow in order to get proper velocity measurements. When using the 'Auto' range setting, the FlowTracker2 may be able to resolve the ambiguity automatically to mitigate against wrapping. However, when using a manually set velocity range, care must be taken to ensure that measured velocities do not exceed what is expected given a chosen range setting.

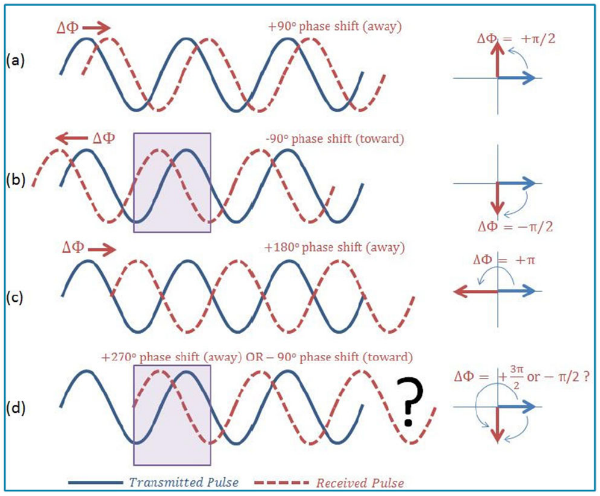


Figure 5. Illustration of phase shift and ambiguity

4. Findings

As previously noted, the 2022 trials were conducted with the secondary trashracks in place, which produced considerable turbulence and aeration across the measurement section and caused data quality issues within the ADV readings including data spikes and wrapping. For the 2023 trials, the secondary trashracks had been removed which resulted in a significant reduction in turbulence and aeration, and a notable improvement in data quality. A comparison of the raw data signals for a similar location measured in each of the two years is provided in Figure 6. The effect of removing the trashracks is clearly evident with a general increase in velocity and overall reduction in turbulence and noise. The remainder of this paper will focus on the 2023 trials.

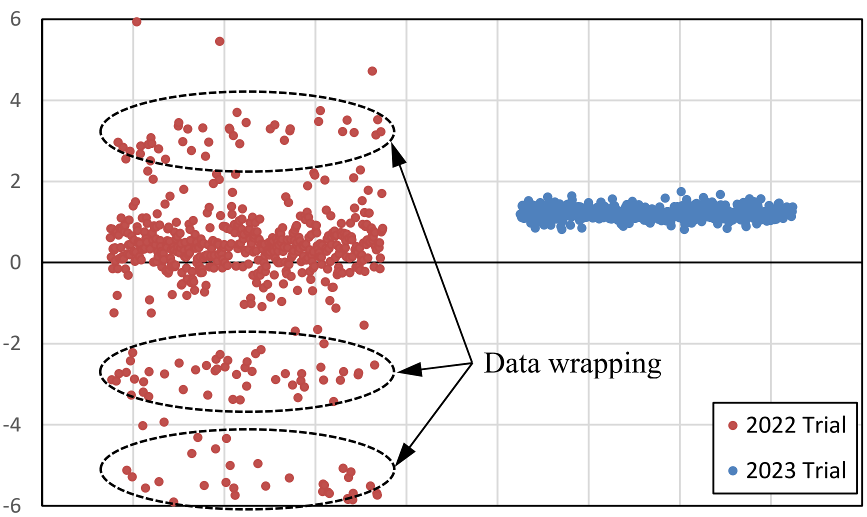


Figure 6. Raw data comparison with (2022) and without (2023) secondary trashracks in place

The measured average point water velocities ranged from 0.06 to 1.81 m/s across the intake. Minimal data wrapping or other anomalies were noted and removed through a simple outlier analysis on the component velocity data. No further data processing was completed prior to determining the total velocity vector. A representative dataset for a single ADV velocity profile measurement in the streamline (X) direction is presented in Figure 7.

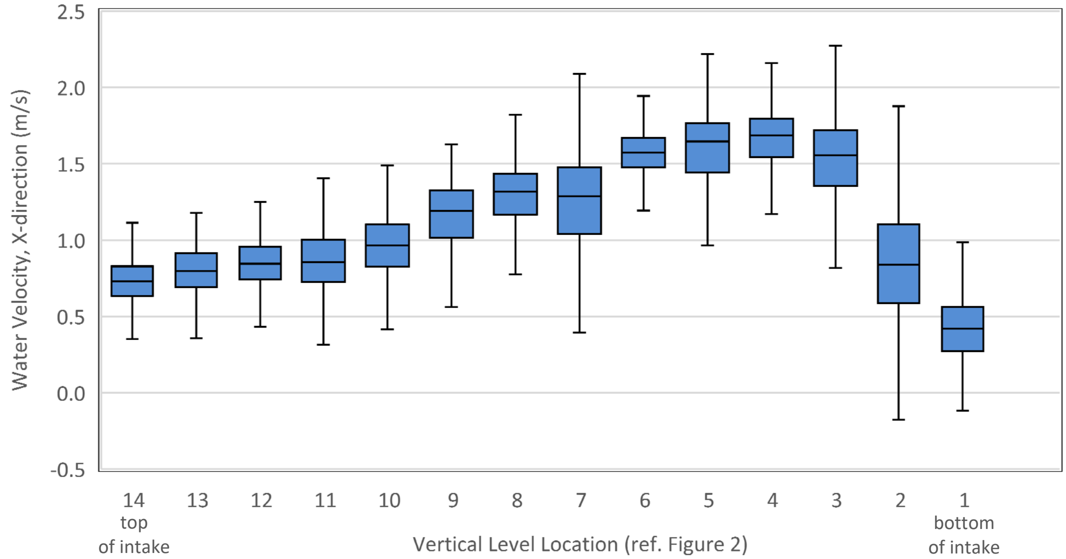


Figure 7. Streamline water velocity measurement for a single ADV sample dataset (~1200 samples per level)

Overall, the instruments produced reliable and stationary, albeit highly variable, readings. The inherent nature of ADV sampling with instantaneous pings and small sample volume means that even small turbulence effects influence the results. This has benefits in that the turbulence magnitude is measured with high temporal resolution [8], however it also requires that many samples are taken such that the data can be accurately reduced to an average point velocity for flow estimation. This, in turn, has the effect of extending the sampling duration and potentially risking data and operational stationarity. One possible means of mitigating this risk and reducing sampling duration is by increasing the sampling frequency. In comparison, turbulence fluctuations are not a major consideration when using Ott C31 - Type A current meters as the large propellers inherently average out variations across the relatively large sampling volume.

To test the effect of sampling frequency on the data quality, additional trials were conducted at a set operating point and sampling elevation by changing only the sampling frequency between 1, 2, 5, and 10 Hz. An equivalent sample size of 600 data points was collected for each of the four frequencies, and the data was plotted for comparison as shown in Figure 5.

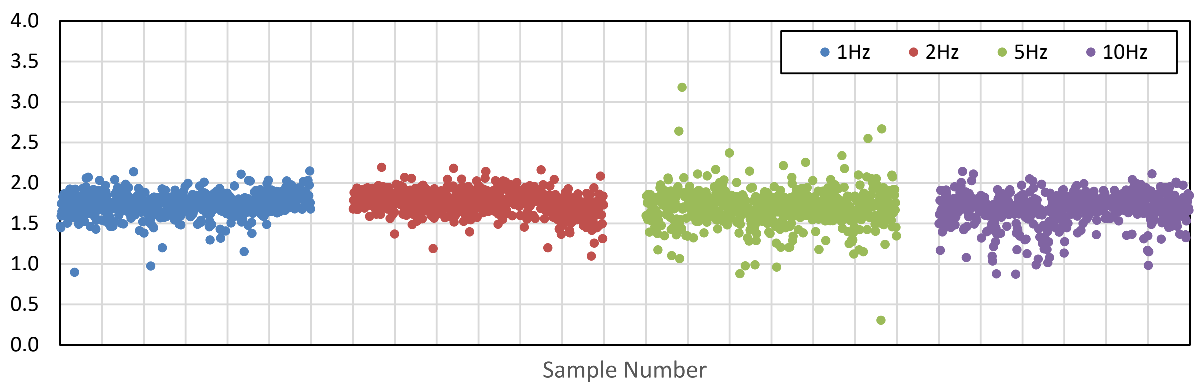


Figure 8. Comparison for different sampling frequencies, 600 samples each, raw data

Visually, the data looks similar for all four sampling frequencies. While the datasets were statistically different – the Kruskal-Wallis test rejected the null hypothesis that the samples came from the same distribution – this is likely attributed to small non-stationarities in unit operations (i.e. wicket gate drift), and not data processing on the instrument side. Fundamentally, the ADV's collect and process data using the same methods regardless of sampling frequency. Faster sampling does allow for the resolution of phenomena occurring at smaller time scales and may lead to the introduction of additional measurement noise, as is visible within the 5Hz and 10Hz signals. The significance of the resultant increased random uncertainties should be considered in relation to the potential for increased systematic uncertainties when decreasing the sampling frequency and extending the collection time.

One notable advantage of ADV technology is in its ability to resolve boundaries across the measurement section. Based on equipment orientation, bottom/top and left/right boundaries may be measured using Signal-to-Noise Ratio (SNR) response, which clearly identifies nearby boundaries. This is evident on Figure 9 showing a single peak at approximately 12 cm (sampling volume) and 29 cm (bottom boundary) – indicating that the sampling volume was located 17 cm away from the floor of the intake. This may help resolve systematic errors related to conduit dimensions and measurement locations.

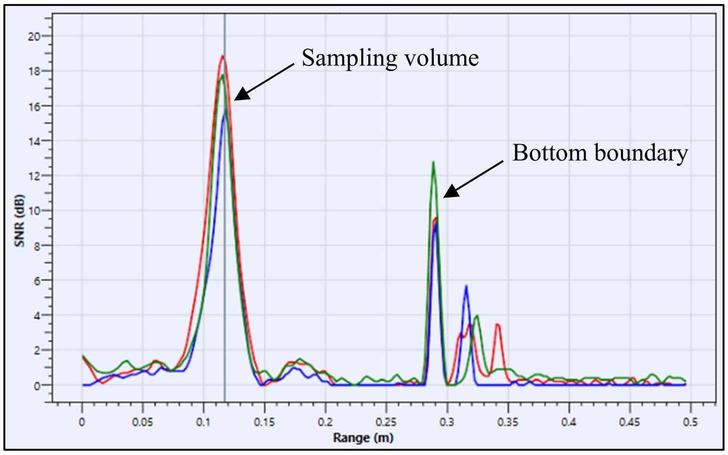


Figure 9. ADV SNR plot showing wall boundary

4.1 Comparison to CFD

Part of the reason for conducting these ADV trials was to confirm the initial assumptions that incident angles near the top of the intake would exceed the specifications of Ott C31 - Type A current meters. The trials did confirm this assumption, with incident angles approaching and exceeding 45 degrees at several metering locations near the top-middle portion of the grid. These angles are attributed to a predominant vertical velocity component near the surface as water gets drawn below the intake bulkhead and into the wheel pit. A comparison was made against CFD results, focusing primarily on flow angle agreement between the measured and modelled data, as shown in Figure 10.

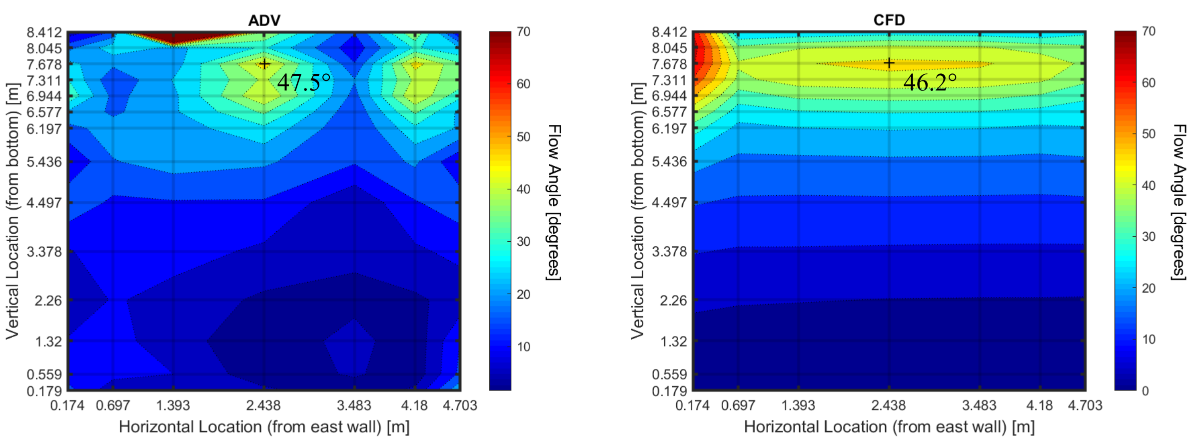


Figure 10. Flow angle comparison - measured vs. CFD

It is evident that, although the CFD results were idealized and did not resolve specific details within the flow patterns observed during the trials, they did accurately reflect the high incident angles present at the top of the intake. The maximum flow angle that was measured with ADV's near the lateral mid-section (location 2.438 m, 7.678 m) was 47.5 degrees, compared to 46.2 degrees for CFD. Both methods support the assumption that conditions within the intake exceed the specifications of the propeller type current meters. Also note that both the measured and modelled angle profiles show anomalies near the top left of the intake – the cause for this has not yet been evaluated.

5. Uncertainties

Manitoba Hydro uses methods for evaluating uncertainties that consider both systematic and random errors within the measurement, typically consistent with the procedures outlined in ISO 3354 [6]. The focus of this section is limited to considerations specific to the use of ADV's for velocity measurement in conduits.

5.1 Systematic

The accuracy of the ADV probe geometry, with factory calibration, is specified to ±1.0% of the measured velocity. This represents the limits of the calibration procedure to determine the angular alignment of the acoustic transmitter and receivers to account for the physical probe geometry and the total uncertainty from measurement noise mentioned earlier. The ADV specifications state a maximum zero offset velocity of ±0.25 cm/s. With Doppler processing, there is no potential for zero offset in velocity measurements; this specification is included because of the difficulty in generating calibrated velocities at low speeds. In addition, since the instruments have no moving parts, recalibration of the probe is not necessary unless the transmitter or receivers are damaged.

5.2 Random

All Doppler systems have an inherent measurement noise that is a result of the physical process by which the sound waves are scattered from particles in the water. This is referred to as Doppler noise. Doppler noise is purely random and can be assumed to follow a Gaussian distribution. Averaging multiple data points converges to the true value without introducing bias. The total observed noise within a sample considers the effects of Doppler noise, as well as other sampling errors and electronic noise from the analog-to-digital converter to resolve the phase shift.

A number of test runs were conducted at high frequencies (10 Hz) for long durations (10 mins) in an effort to determine the minimum sample size needed to reduce individual instrument random uncertainties to acceptable levels under varying conditions. All of the tests were conducted with the expected velocity range set to ±200 cm/s. In the first test, the average velocity was measured to be 0.69 m/s, with a standard deviation of 0.30 m/s. A relatively noisy signal was observed which required a minimum of 1800 samples to reduce random uncertainties to below 2%. In the second test (mean velocity = 1.39 m/s, standard deviation = 0.13 m/s), meeting the 2% random error target required only 84 samples, whereas random uncertainties below 1.0% were achieved with 350 samples and 0.5% with 1350 samples. A visualization of how random uncertainties decreased with sample size for both trials is provided in Figure 11.

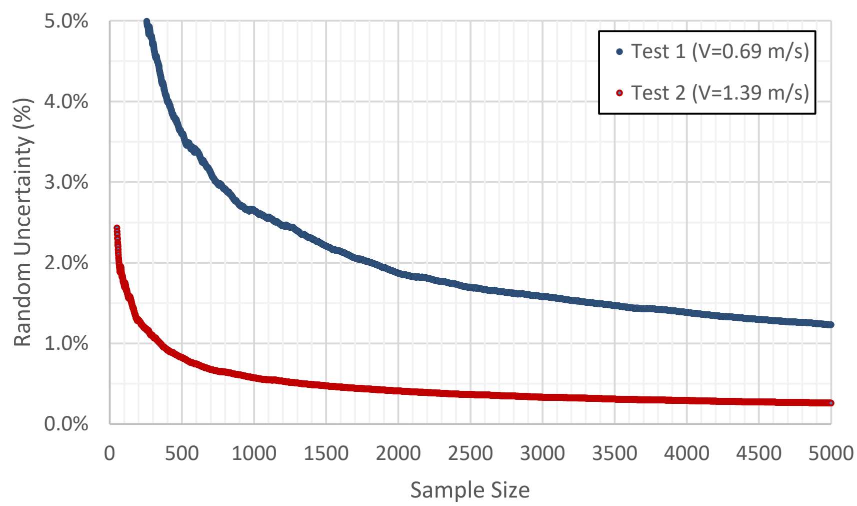


Figure 11. Random uncertainty estimates with increasing sample size, velocity range = ±200 cm/s

While the above figure provides information on the random uncertainty for a single sample, it does not consider the effect of uncertainty propagation when averaging readings from multiple instruments and levels as would be necessary for flow estimation across the metering grid. The combined uncertainty taking many readings into consideration (assuming similar magnitudes) should decrease as the number of non-correlated readings increases. In addition, it is known that setting the velocity range higher than what is necessary may result in increased sample noise, which is the likely cause of the high random errors experienced in Test 1. These trials exemplify the importance of ensuring the instrument configuration is in-line with expected conditions to reduce random uncertainties to acceptable levels.

6. Conclusion

The trials conducted in 2022 and 2023 showed that ADV's may provide a reasonable alternative means of measuring point velocities in non-ideal intake conditions, however they also exemplify the importance of site consideration and instrument configuration in ensuring that a reliable and accurate measurement is collected. The key considerations are 1) to ensure relatively stable hydraulic conditions free of excessive turbulence and aeration, and 2) to properly understand the theory and configure the instruments to reduce the potential for excessive signal noise and data wrapping. Selecting the appropriate maximum velocity range and sampling frequency is important towards optimizing data quality. Maximum velocity range is particularly important – too low a range increases the likelihood for data wrapping, and too high a range increases signal noise. With proper configuration and under the right conditions, it is possible to collect an adequate sample size to reduce overall random uncertainties to acceptable levels.

ADV's are shown to be well suited for velocity measurements in non-ideal intakes where incident flow angles exceed the specifications for Ott C31 – Type A current meters. While the random uncertainties exceed those of propeller type instruments, they can be treated through statistical means and reduced through proper instrument configurations. In addition, the ability to measure individual component velocities helps offset the potentially high systematic uncertainties that would be present if using current meters, especially at high flow angles. Further to this, the component velocities can also be used to assess the suitability of code compliant current meters for flow measurement. CFD is also shown to generally provide a reasonable approximation of flow angles for the purpose of planning the flow measurement.

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