IMPROVEMENTS IN ACOUSTIC DOPPLER VELOCIMETERY

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ABSTRACT

Acoustic velocimeters have become popular for measuring turbulent and mean flows in fluid mechanics laboratories. A series of tests were conducted to evaluate the performance of several acoustic velocimeters at low signal to noise ratios (SNR) to assess the accuracy of mean flow estimates, and at typical SNR in response to tilting of the velocimeter head with respect to the flow. Tests were conducted in an open channel flow with Particle Imaging Velocimetery (PIV) measurements made for comparison and assessment of flow disturbance around the head. While limited in the scope of its assessment, this study shows large improvements have been made in the performance of acoustic velocimeters since their introduction in the early 1990s.

1. INTRODUCTION

The original Acoustic Doppler Velocimeter was developed to replace the more complex Laser Doppler Velocimeter (LDV) at the US Army Corps of Engineers Waterways Experiment Station in the early 1990s. After their introduction they became standard equipment in fluid mechanics laboratories, offering relatively simple setup to obtain mean and turbulent velocities with high accuracy. Voulgaris and Trowbridge (1998) performed a comparison of the velocity estimates from an acoustic velocimeter with an LDV. They found acoustic velocimeters are capable of measuring both mean and turbulent velocities accurately and report estimates of the error based on velocity range settings, etc.

One major difference between the acoustic velocimeter and LDV is the more invasive nature of the measurement. Acoustic velocimeters require the acoustic transducers to be in contact with the water to measure velocities. This creates a potential flow disturbance as the sample volume is located only a small distance away from the transducer (typically 5 cm), which can impact the accuracy of velocity measurements depending on flow direction and the size of the transducer head.

An additional issue with velocimeter use is the need to seed the water with scattering material to provide adequate return signal strength and signal to noise ratio (SNR) for accurate velocity measurements. Along with correlation, SNR is the main means of judging the quality of velocimeter measurements. Generally, the higher the SNR, the higher the correlation and the more reliable the velocity measurement. However, seeding the flow is not always desirable or practical, as it could interfere with other measurements (optical based techniques for instance), contaminate an otherwise

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clean test tank or simply not be practical when the measurement area is continuously flushed (e.g. a field experiment).

These two problems have led to the development of what can be regarded as the second generation of acoustic velocimeters. While the original Sontek Acoustic Doppler Velocimeter and it's counterpart the Nortek NDV have proven to be two of the most popular and easy to use velocity measurement techniques in fluid mechanics, they are based on technology and electronics from 10 to 20 years ago. Snyder and Castro (1999) found issues with flow disturbance around the original transducer head design and 5%-10% bias errors in the horizontal and vertical velocity estimates when the head was pitched with respect to the flow. These issues uncovered by Snyder, et al.'s work and basic advances in electronics, manufacture, and fabrication have led to an improved velocimeter design.

We conducted a series of tests to compare earlier velocimeters (typical of what are used in many fluid mechanics laboratories) with a newly introduced model which incorporates improvements in electronics, head design, and manufacturing processes. Specific areas of flow disturbance, geometric response (i.e. how the instrument responds to non-horizontal flow fields), low SNR performance, mean flow accuracy, and overall system performance and robustness are examined.

2. EXPERIMENTAL METHODS AND EQUIPMENT DESCRIPTION

Experiments were conducted in a 2 m wide, open channel flume in the Defrees Hydraulics Lab at Cornell University. This flume allows flow depths up to 55 cm with velocities ranging from several cm/s to over 50 cm/s. Two matched pumps circulate water through the main channel, and a passive grid at the inlet section generates turbulent flow throughout the flume. Glass sides and bottom allow the use of optical techniques, including the use of Particle Imagine Velocimetery (PIV) for comparison in this study. A picture of the flume and instrument positioning is presented in Figure 1.

Three velocimeters are used in this comparison. A Sontek LabADV, a 10 Mhz system (transmit frequency) originally manufactured during the mid-1990's and one of the earliest ADV models. A Sontek MicroADV, which has the same head design as the LabADV, but operates at a transmit frequency of 16 Mhz. And a Nortek Vectrino, recently introduced and incorporating many design improvements addressing the issues mentioned in the introduction. The Vectrino operates at 10 Mhz, but has a much smaller, streamlined head with four receivers instead of three found on other systems. The fourth receiver provides redundant information in one velocity component, typically the vertical, depending on orientation. The Vectrino measures 4 velocity components: u, v, w_1 & w_2, where w_1 and w_2 are independent and redundant measurements of the vertical velocity. This redundancy can be used in various processing schemes to improve the accuracy of turbulence measurements as outlined in Blaenkaert and Lemmin (2006).

Figure 2 shows the original ADV head (in this case from a MicroADV) and the new Vectrino head. While similar in size, the overall volume of the Vectrino head is much smaller than the original head design, with more rounded, streamlined receiver arms, and a substantially smaller central transducer. The fourth beam changes the head geometery as well, creating two orthogonal pairs of receivers.

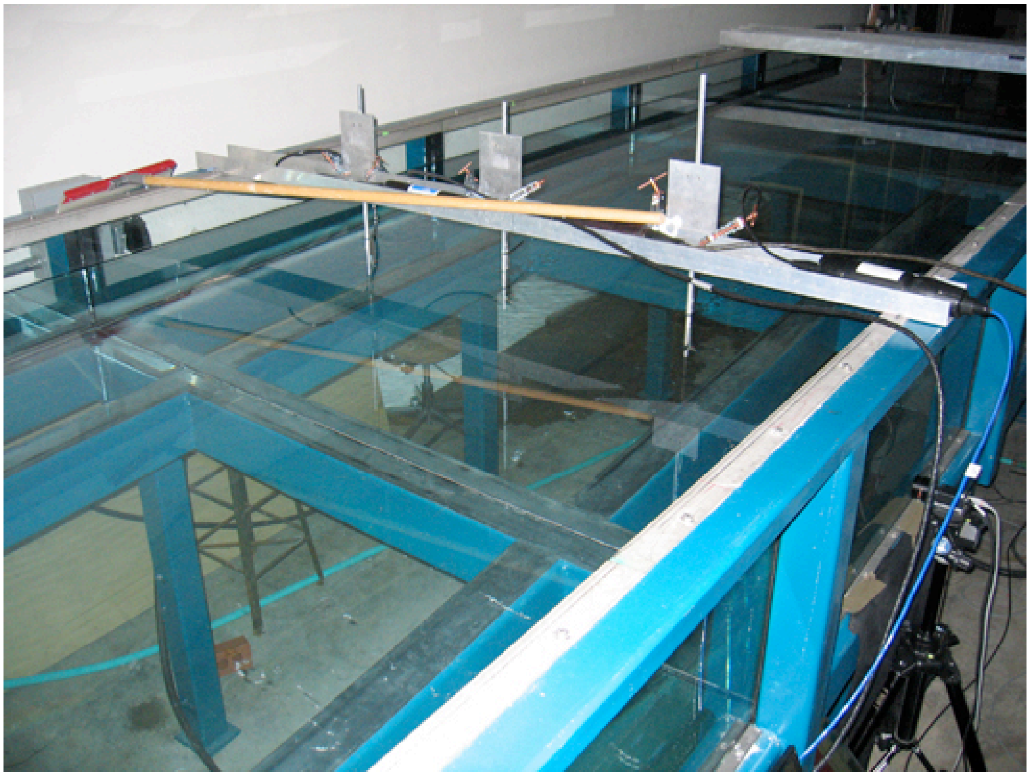

Figure 1. A view of the flume looking downstream. The three velocimeters are mounted on vertical stages. The camera used for the PIV measurements can be seen on the right side of the picture. The image plane illuminated by the laser is aligned with the right hand velocimeter and parallel to the direction of flow.

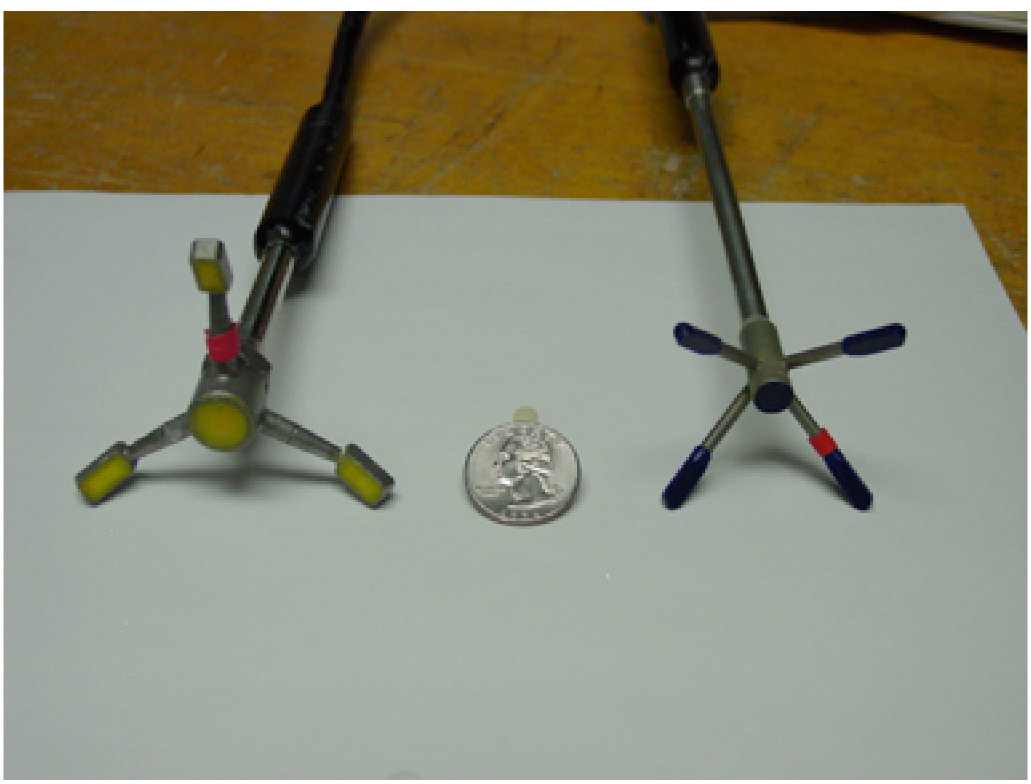

Figure 2 MicroADV (left) and Vectrino (right) head comparison. A quarter is provided for scale.

Several more subtle differences also distinguish the Vectrino from its predecessors. The most notable of these is the non-multiplexed receiver circuitry. Older velocimeters used a multiplexed receiver circuit and amplifier to listen rapidly to each of the three receivers in sequence. The Vectrino uses a non-multiplexed receiver; sampling each of the four receivers simultaneously. In addition, the Vectrino uses smaller pulse elements and smaller spacing between the ping-pairs than the MicroADV, thereby gaining a performance advantage in sampling rate. The higher operating frequency of the MicroADV (16 MHz vs. 10 MHz) allows for increased processing bandwidth and this offsets some of advantages of the Vectrino at the penalty of lower theoretical signal strength (i.e. lower SNR for a given seeding density).

The internal sampling rate for each velocimeter is fixed by the hardware features described above and by the software configuration. The output rate set in the software is partly independent of the internal sampling rate but not fully since it normally reflects the maximum rate at which it is possible to get useful data from the instrument. This rate is 50 Hz for the MicroADV, 25 Hz for the LabADV, and 200 Hz for the Vectrino (with the Vectrino+ firmware). For this study, the LabADV was sampled at 25 Hz and the MicroADV and Vectrino were both sampled at 50 Hz.

The three velocimeters were mounted on vertical stages 50 cm apart in the center of the tank (Figure 3). Using the probe check feature, each velocimeter was set so the sample volume was 15 cm above the bottom (20 cm to the central transducer) and left in this position for the tests. The entire mount was tilted at various angles to examine the geometric response of the instruments as well.

Since a complete examination of the influence of all velocimeter settings would be a massive undertaking and time consuming to perform, and each velocimeter provides varying degrees of control over its sampling setup, only the velocity range setting was altered during the course of this comparison. All other settings were left at their default value, or when applicable altered to create a uniform instrument setup across the three velocimeters. The velocity range, user selectable based on flow speed, controls the time lag between acoustic pulses used to measure velocity. The longer the lag the lower the velocity range as the pulses will be more likely to decorrelate and phase ambiguities can occur, leading to erroneous velocity measurements. However, short lags, which are more robust and allow measurement of more dynamic and higher velocities, introduce more noise into the velocity signal (a consequence of the analog to digital circuitry's resolution). While the specifics of these setting are beyond the scope of this paper, selecting the lowest velocity range applicable to a flow is generally the best option, providing a balance between measurement robustness, accuracy, and minimizing noise.

After acquisition, velocimeter records were processed in MATLAB, removing data points not meeting lower limits for SNR and/or correlation, and eliminating all three (or four for the Nortek Vectrino) velocity estimates when any one component was bad. Lower limits were established for SNR by taking the mean of the entire record and subtracting 3 dB. The correlation lower limit was established in a similar manner, subtracting 15% from the record mean. Each instrument has a different manner of calculating SNR and correlation, so uniform limits across all instruments are not desirable or advantageous to examine system performance at low SNR, one of the principal goals of this experiment. The screening criteria chosen in this study are largely arbitrary, but were partially chosen based on visual inspection of records, user experience, and some amount of trial and error. More rigorous criteria (e.g. a Gaussian filter to establish the lower limit) could be implemented at a later date, but would not likely alter the outcome of this comparison.

PIV, a non-invasive optical technique described by Sveen and Cowen (2004), was used in an X-Z plane at the nearest velocimeter, typically the Nortek Vectrino, to provide a check of mean flow accuracy and examine flow disturbance around the velocimeter's head. The PIV system used a 30 Hz YAG laser (Spectraphysics PIV-400-30) expanded through a cylindrical lens to produce a light sheet directed from below. An 8 bit Basler A602F camera imaged an approximately 10 cm x 10 cm region of the light sheet, including the velocimeter head and sample volume. Timing was controlled to 1 MHz resolution with a National Instruments analog output card (PCI-6711) operated through MATLAB. Images were recorded to a separate computer using Boulder Imaging's VisionNow acquisition software. Image pairs were processed using custom code featuring the advanced subpixel resolution described in Liao and Cowen (2005). Various time differences between images were used, ranging from 5 ms to 15 ms depending on flow speed.

The tank was initially seeded with a small amount of Sphericell, hollow glass spheres manufactured by Potters Industries Inc. The seed material has a mean diameter of 11 microns and is only slightly negatively buoyant. It provides scattering material for both the acoustic and optical systems. While no direct measure of seed particle density was made, the conditions in this study were typically run at low seed densities, with all acoustic instruments reporting very low to acceptable SNR values as seed density increased. Seed density was controlled through increasing the pump speed and generating higher flow rates, which in turn suspended more seed into the water column.

3. RESULTS

3.1 Low SNR Comparison and Mean Flow Accuracy

One of the principal aims of this comparison was to examine velocimeter performance at low SNR levels. While many natural systems and laboratory facilities provide adequate scattering material, there are many that do not or where seeding is not an option (e.g. because of a desire to maintain a clean facility). Low SNR performance is important to understand so any bias or minimum measurement criteria can be identified and disseminated to the user community.

Instrument SNR vs. seed density (in this case reported as the pump setting; higher pump settings equals higher seed density) are presented in Figure 3. Various velocity ranges were used at each pump speed (typically two to three different ranges) and are distinguished by different symbols. Manufacturer recommendations are typically for a minimum of 15 dB SNR for reliable velocity estimates. A similar plot for correlation vs. seed density (again plotted as pump setting) is presented in Figure 4.

The Nortek Vectrino, especially at low seed density, routinely has the highest SNR of the three instruments. The 16 MHz MicroADV is consistently the lowest, a problem often noted by users of these systems. The LabADV, owing to its frequency and large sampling volume, generally falls in between these two systems. There is little spread in the SNR values based on velocity range for any instrument, although the lowest velocity range setting, 3 cm./s, of the Nortek Vectrino has much lower noise then the next higher setting of 10 cm/s.

Correlation, as expected, generally increases with seed density. Here, the velocity range setting influences the results more with larger spread for a given seed density then evident in the SNR results, although correlation is expressed on a linear scale and SNR on a logarithmic scale. At the lowest seed density (pump setting 4), the velocity range setting greatly influences the reported correlation. As seed density increases, we see declining influence with the velocity range setting until reaching the larger values (2.5 m/s setting). There are two outliers from the Vectrino record worth nothing, at pump settings of 12 and 16. These correspond to a velocity range of 1 m/s. Given proper performance otherwise and the inability to reproduce these results in a separate tank, these two outliers are either instrument or setup dependent and can be safely ignored.

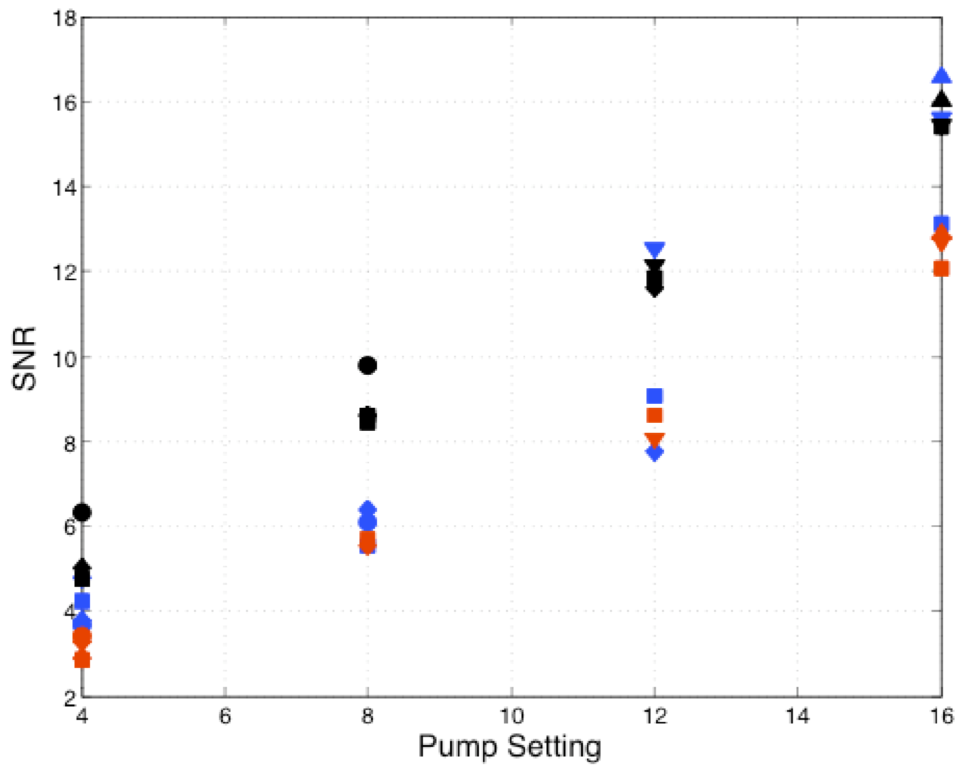

Figure 3 SNR vs. Seed Density (pump setting). The Vectrino is shown in black, MicroADV in red, and LabADV in blue. Velocity ranges are represented by ● - 3 cm/s, ♦ - 10 cm/s, ■ - 30 cm/s, ▼ - 1 m/s, ▲ - 2.5 m/s.

Figure 5 shows the percent error (expressed as a decimal value) from the mean flow estimate obtained from the PIV records as a function of mean SNR. Unfortunately, a secondary circulation in the tank limits the mean flow estimate obtained with PIV so it is only applicable to the velocimeter in its field of view (i.e. the Nortek Vectrino). While the result here is inconclusive in terms of a cross system comparison, the Vectrino is consistently within the accuracy reported by Blanckaert and Lemmin (2006) of approximately 4%. It does this regardless of velocity range or seed density (only the 1 m/s low correlation values mentioned above lie outside of this range). Further testing with a refined setup and sampling scheme could provide more conclusive results in this test.

3.1 Flow Disturbance

Tow tank tests conducted by Snyder, et al. (1999), revealed problems with the original ADV head design. Significant deflection of the flow occurred around the head would affect the accuracy of the velocity measurements. These tow tank tests led to the design of the streamlined head used on the Vectrino. Snyder, et al. Tested a prototype of the Vectrino head and saw significant improvements during subsequent tests.

PIV provides a view of the region immediately around the velocimeter head and sample volume. From the velocity vectors calculated from image pairs, a clear visual representation of the disturbance around the head can be formed. The mean velocity field, ~10 cm/s horizontal, near zero in the vertical, is represented by the scaled arrows overlaid on each image. Shorter arrows represent lower velocities, while the angle from horizontal indicates the larger vertical velocity component.

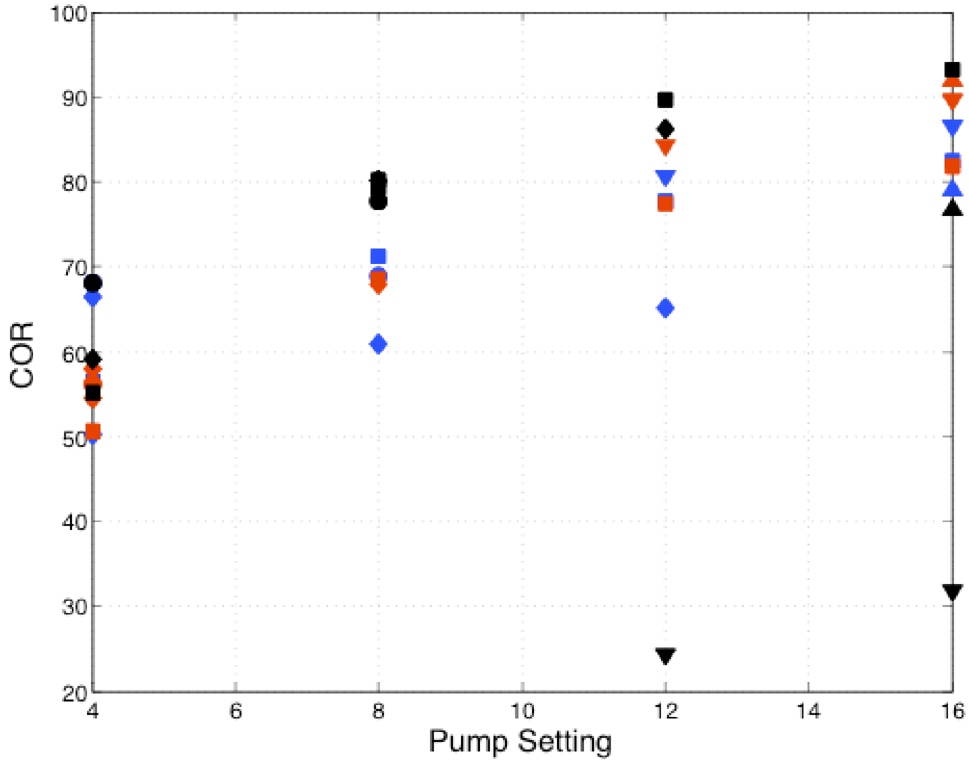

Figure 4 Correlation vs seed density (pump setting). The Vectrino is shown in black, MicroADV in red, and LabADV in blue. Velocity range markers are the same as Figure 3.

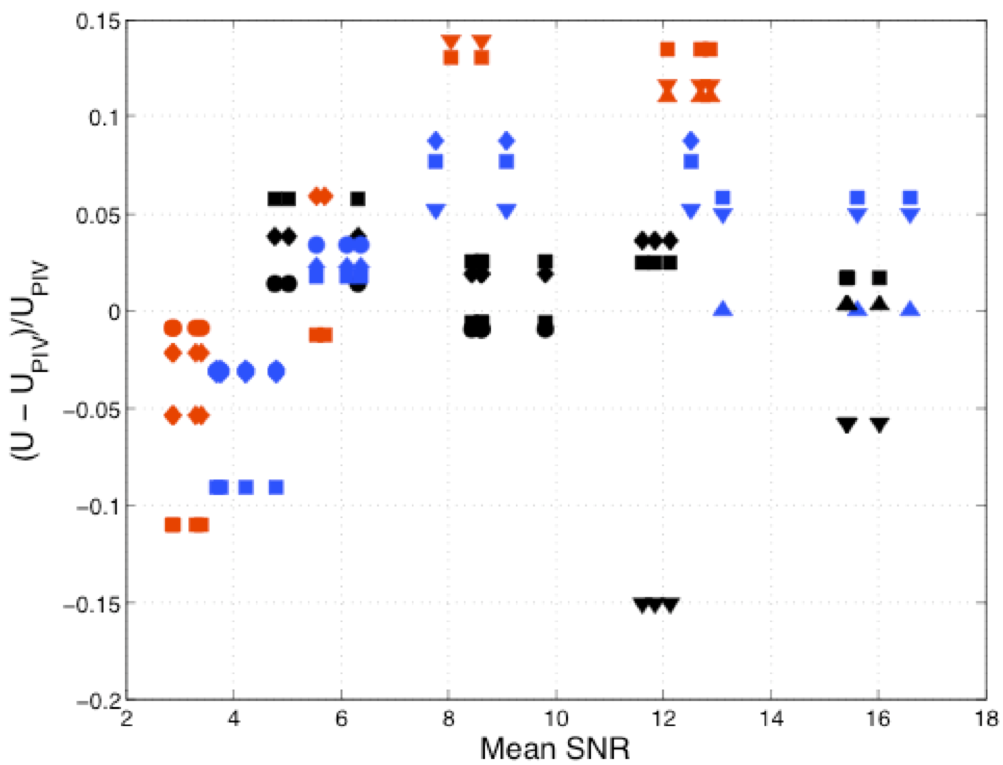

Figure 5 Velocity percent error vs. Mean SNR. The Vectrino is shown in black, MicroADV in red, and LabADV in blue. Velocity range markers are the same as Figure 3.

Figures 6-9 show the wake left by the MicroADV head tilted at various angles. Figure 10-13 show the wake left by the Vectrino head tilted at the same angles. The tilt experiment is designed to simulate the effect of probe wake to non-horizontal flows. The center of the sample volume is marked by a red dot. Note the intense glare around the velocimeter heads (especially in Figures 9 and 13) which limits the region PIV can be applied to.

The region around the sample volume for each head design in all instances appears to be relatively free of contamination from the wake. Because of its larger diameter, the wake left by the MicroADV is larger than the Vectrino. Variations in streamlines can be seen up to half the distance to the sample volume around the MicroADV head in some instances. Visual observations of the MicroADV head showed substantial deflection of the flow near the central transducer. The Vectrino head by contrast showed essentially no deflection near the central transducer.

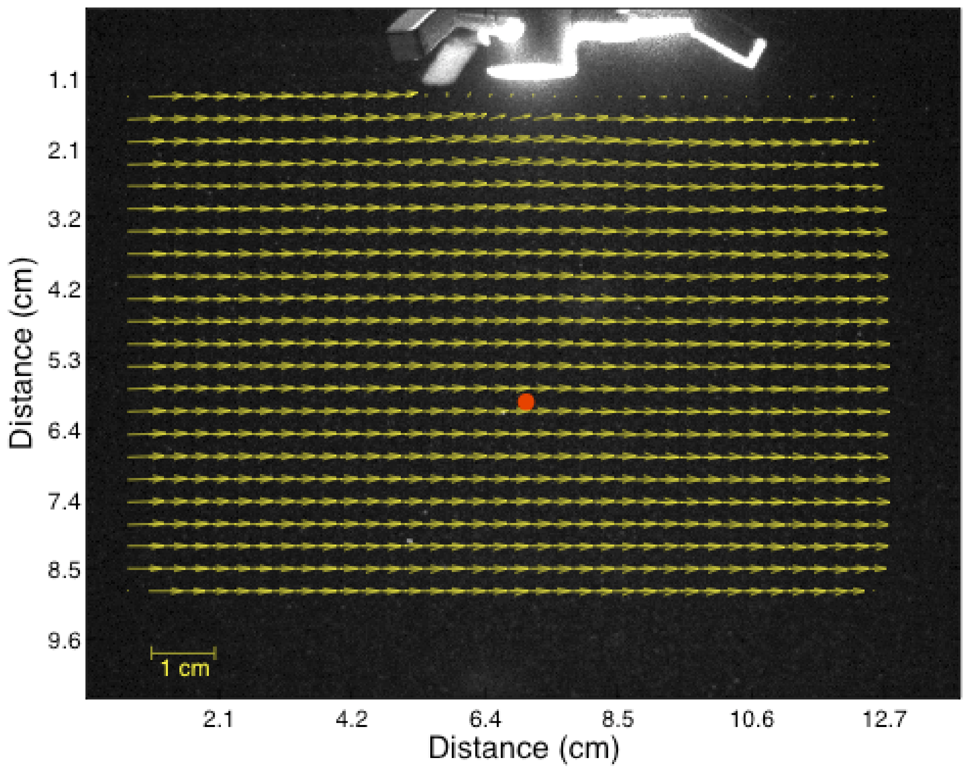

Figure 6 PIV velocity vector overlay with MicroADV head level.

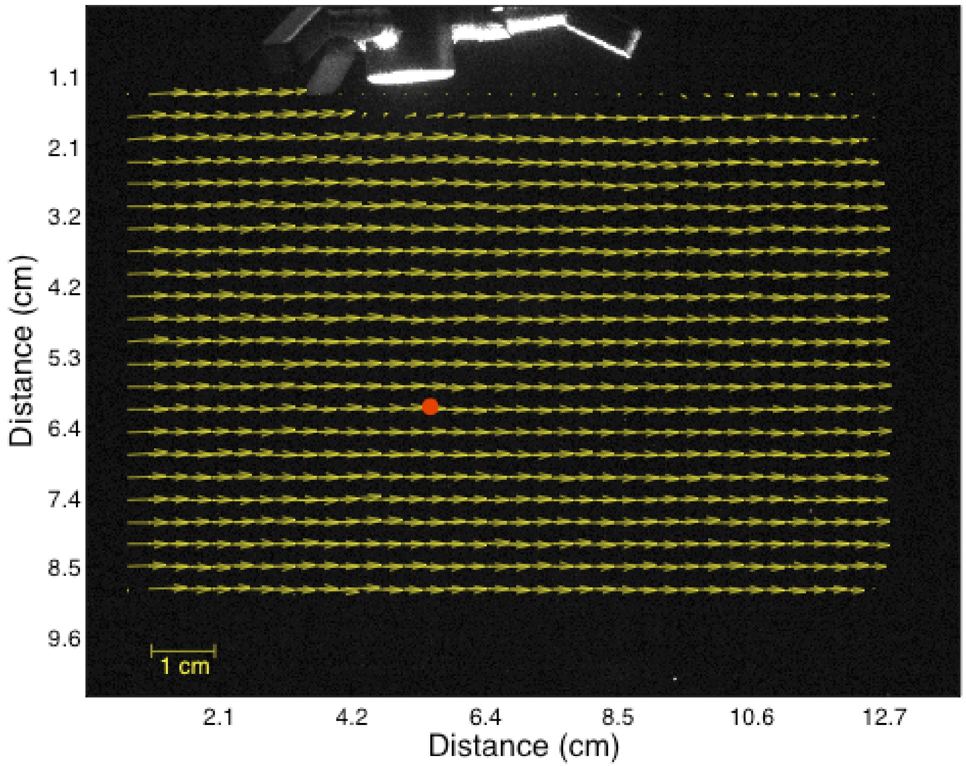

Figure 7 PIV velocity vector overlay with MicroADV head tilted ~4.5°.

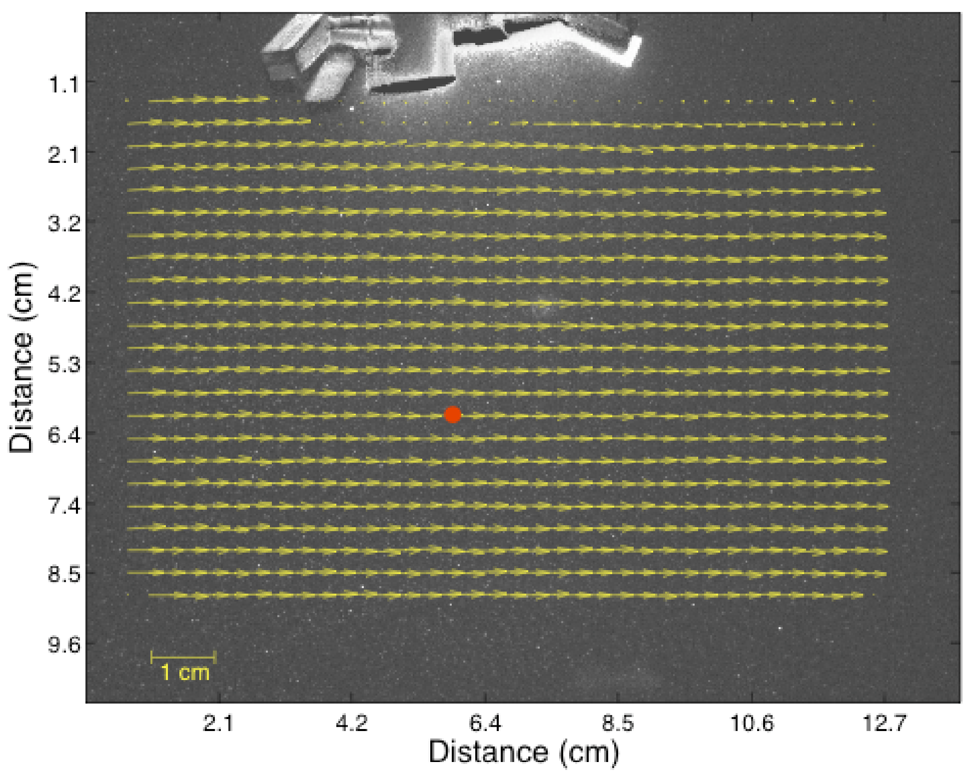

Figure 8 PIV velocity vector overlay with MicroADV head tilted ~9°.

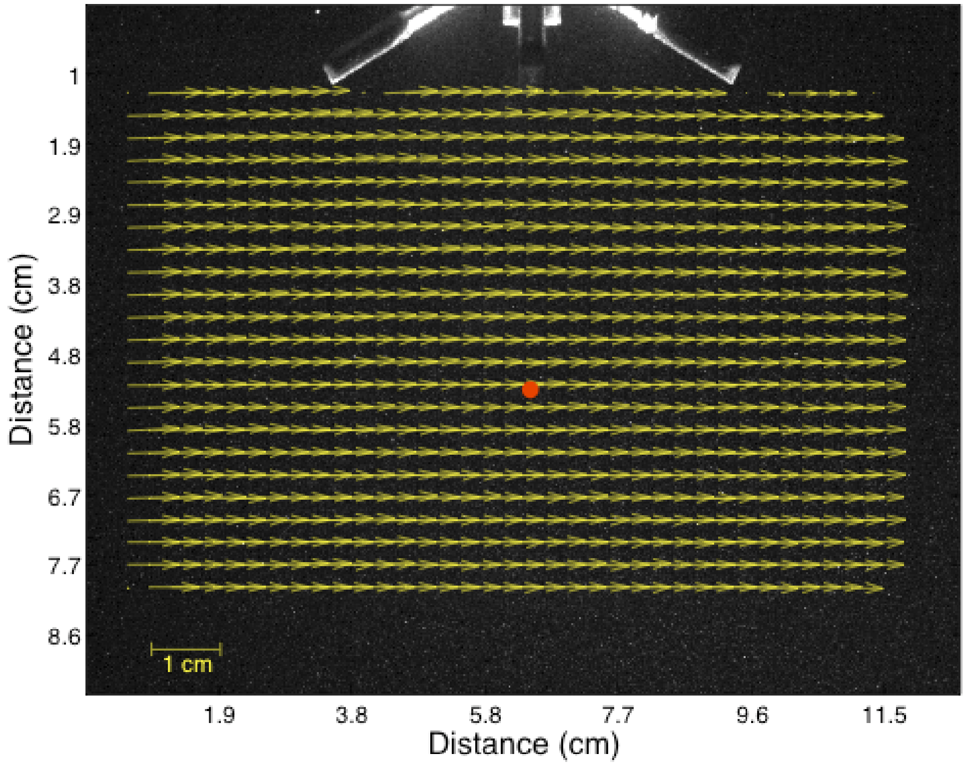

Figure 9 PIV velocity vector overlay with Vectrino head level.

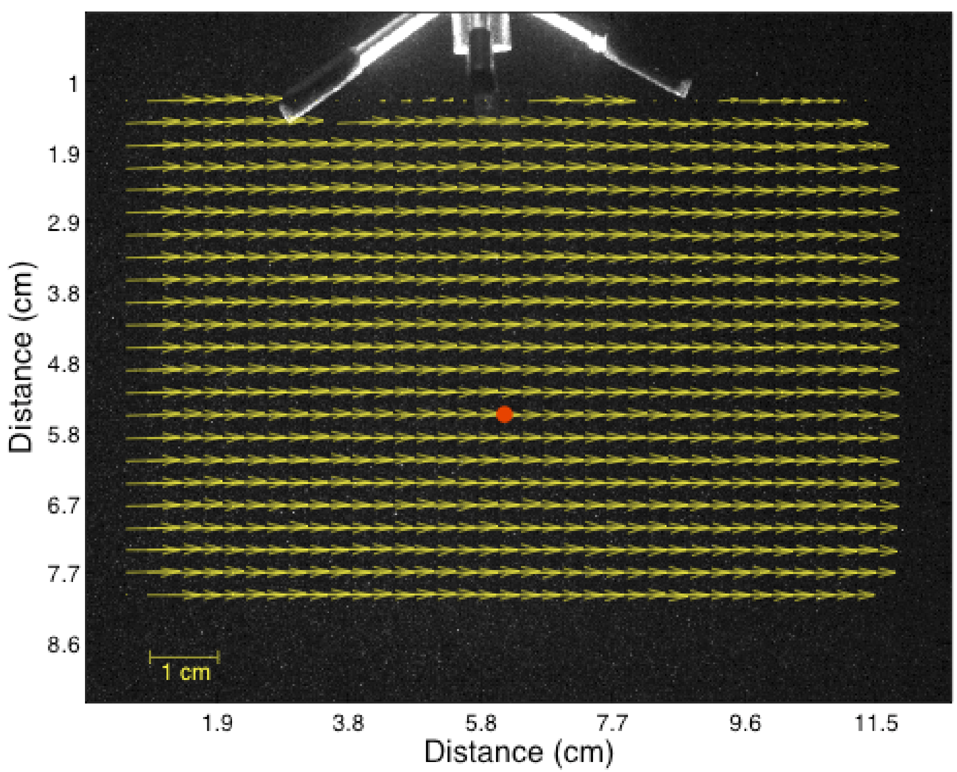

Figure 10 PIV velocity vector overlay with Vectrino head tilted ~4.5°.

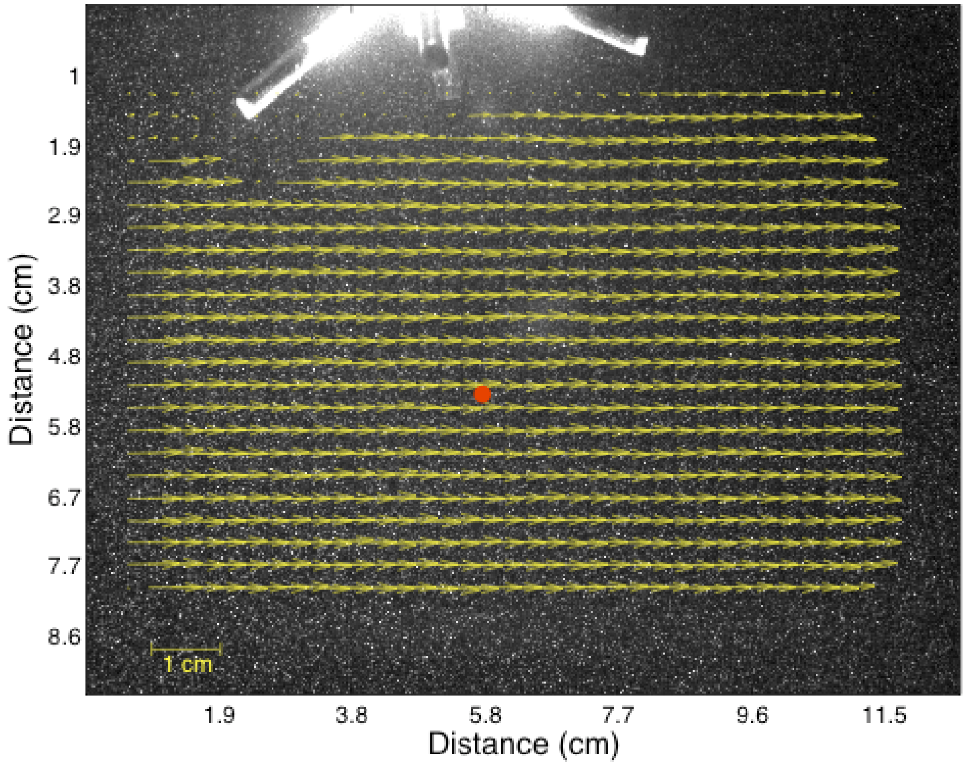

Figure 11 PIV velocity vector overlay with Vectrino head tilted ~9°.

Figure 14 shows the streamwise and vertical velocities measured by the velocimeters as well as the ideal response when tilted at various angles to the flow. The ideal response is proportional to the cosine of the pitch angle for the streamwise component, and proportional to the sine of the angle for the vertical. The ideal response is plotted in green, and the same color system used before to distinguish the velocimeters is used (Vectrino – black, MicroADV – red, LabADV – blue). There is an offset in the MicroADV and LabADV velocities due to the secondary circulation mentioned before. This does not affect the result however, as we are interested in the shape of the curve, not it's relative position. The Vectrino, as would be expected given the results presented in Figures 9-11, performs almost ideally, a similar result to what Castro et al. found when testing the prototype Vectrino head. The MicroADV and LabADV, which share the same head design, show similar performance to each other, with a relatively flat response between +/- 10°. This can lead to significant errors (> 10%) in the reported velocity for not purely horizontal flows.

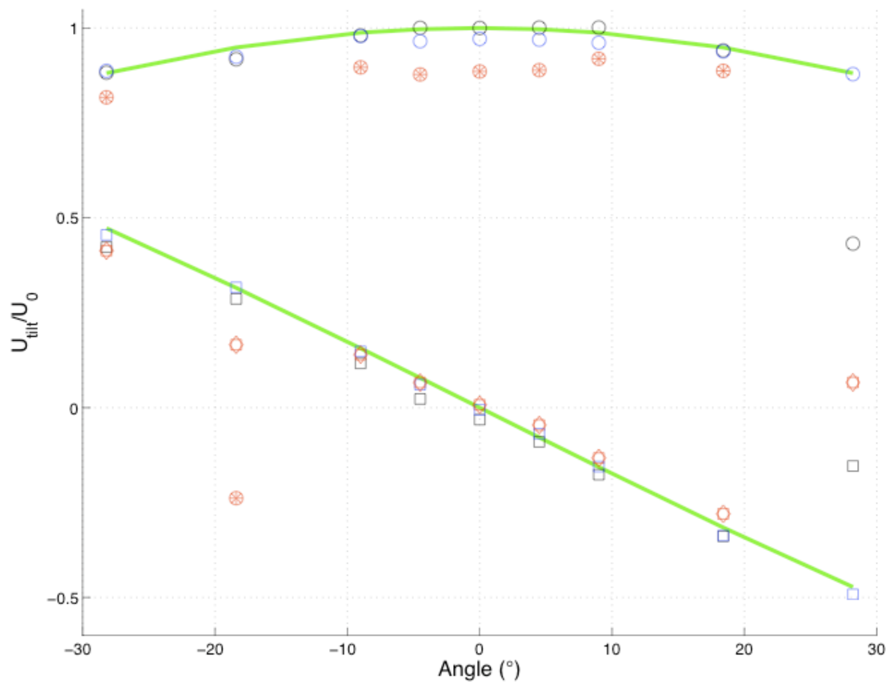

Figure 14 Tilted probe velocity response. Negative angles are tilts into the flow. Nortek Vectrino – Black, Sontek LabADV – Blue, Sontek MicroADV – Red.

3.3 System Noise

After screening for data quality, power spectral densities were computed from each velocity record, averaging over 4 windows, typically around 1000 points in each window. Results for select velocity ranges are presented in Figures 15 and 16. Results are consistent across all velocity ranges tested. Owing to its newer circuit design and improvements in manufacturing and quality control, the Vectrino has a lower noise floor across all velocity ranges. The most striking result is at the 2.5 m/s velocity ranges, where the LabADV produces almost no inertial sub range despite the high flow rate. The MicroADV and Vectrino do not introduce significant noise until well into the inertial sub range, with the Vectrino clearly dominating this comparison. Prior work at higher sample rates show the noise floor of the Vectrino is not typically reached until approximately 50 Hz.

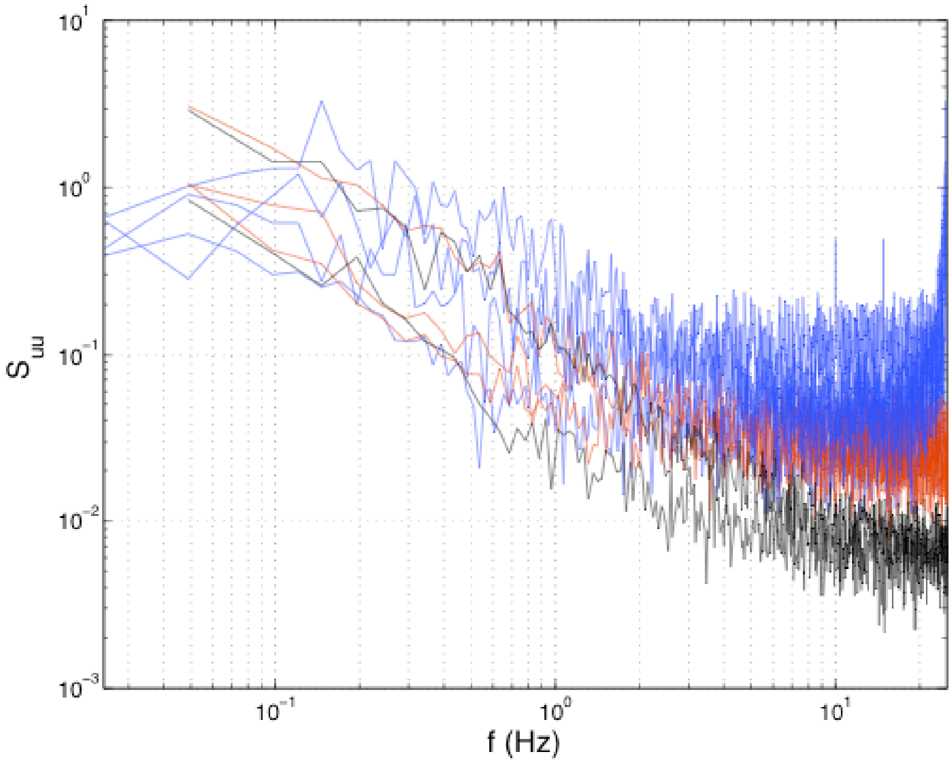

Figure 15 PSD for each velocimeter at the 10 cm/s velocity range. Nortek Vectrino – Black, Sontek LabADV – Blue, Sontek MicroADV – Red.

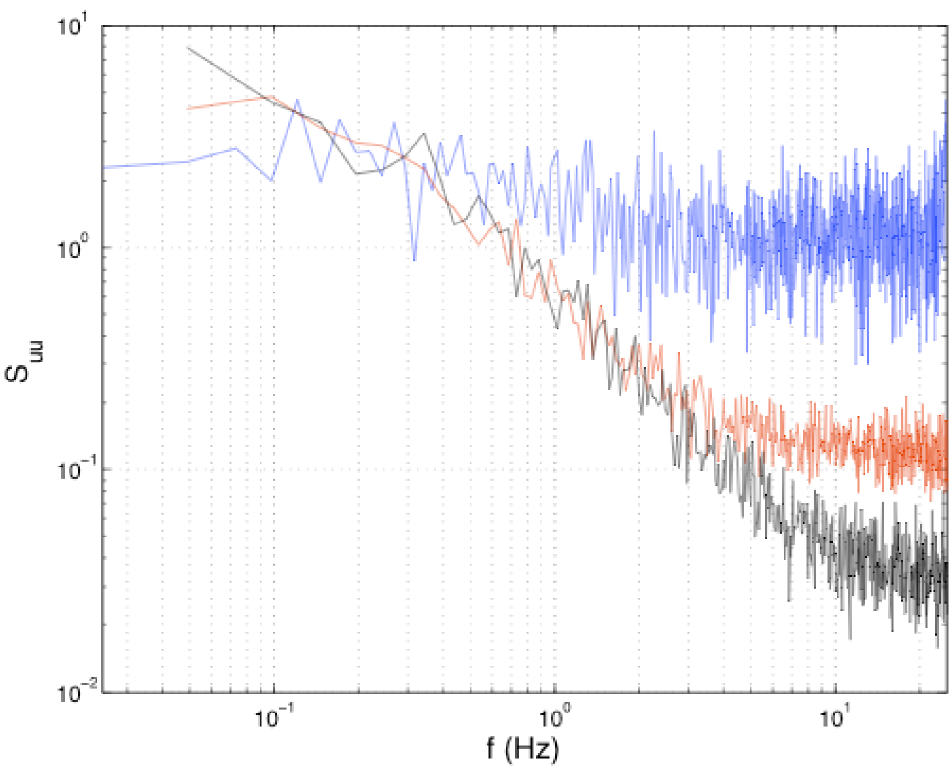

Figure 16 PSD for each velocimeter at the 2.5 m/s velocity range. Nortek Vectrino – Black, Sontek LabADV – Blue, Sontek MicroADV – Red.

4. DISCUSSION

4.1 Low SNR Performance

The Vectrino consistently reported among the highest SNR of the three systems. The MicroADV, as expected from user experience, typically had what would be considered low SNR compared to seed density when compared to 10 MHz systems. The LabADV was generally between these two systems, again as expected due it's older design and lower operating frequency.

Typically, users expect to see correlations above 70% and SNR around 15 dB to ensure data quality. These values are based on user experience with the early Sontek ADV and not necessarily applicable to all systems. Specifically, since each system has varying methods for calculating SNR, there are a wide range of acceptable values that are dependent on the instrument being used. Correlation as a data quality indicator should be relatively independent of the instrument, although variations in processing schemes will affect it. If we assume 70% is an acceptable lower limit to ensure data quality, we can say something about system performance and provide some general guidelines for instrument use.

For instance, the LabADV doesn't consistently report acceptable correlations until the pumps are set to 12 (corresponding to an SNR of ~10). However, the mean correlation is still low, as most users typically look for a mean correlation value in the 90s. To reach this value, SNR must increase to 15 dB, as specified in manufacturer recommendations. The MicroADV reflects similar performance, with the SNR values for 70% and 90% correlations shifted down to 8 and 12 dB, accounted for by its higher operating frequency and the expected loss in SNR because of this. The Nortek Vectrino has similar limits in terms of SNR for its performance (e.g. 8 and 12 dB for 70% and 90% correlations), but reaches them at lower seed densities.

The lower system noise of the newer hardware, coupled with its lower operating frequency, extend the range of conditions in which reliable velocity estimates can be obtained. For a given seed density, the Nortek Vectrino will generally report higher SNR and correlation, the two indicators commonly used to judge data quality. More importantly, when seeding density is low, the Vectrino will produce valid data more reliably.

While inconclusive as cross system comparison, the mean flow accuracy check for the Vectrino agrees well with what other researchers have found. It is expected the MicroADV and LabADV will both achieve similar accuracy in terms of mean flow estimates, although the range of conditions over which this occurs will be narrower as per the discussion above. More testing, with a more capable PIV system, specifically an improved camera in terms of bits per pixel and overall resolution, would allow better assessment of mean flow accuracy for all systems. Timing improvements would allow synchronization of samples between the PIV system and the velocimeter, allowing for a more detailed comparison rather then just mean flow comparisons.

Overall, the LabADV was the most robust and forgiving of the three instruments with respect to instrument setup. The MicroADV exhibited more phase wrapping of the velocity signal than the other two velocimeters, indicating smaller maximum horizontal velocities for a given velocity range. This could prove to be problematic when large jumps occur in the velocity range setting, such as between 1 m/s and 2.5 m/s as the system noise will increase dramatically. The Vectrino in this experiment had some performance oddities which don't appear to affect the older systems, evidenced by the poor performance at the 1 m/s velocity range. Since further testing did not reproduce these performance problems, they currently remain unexplained, but appear to be flow or instrument specific. Changing the velocity range eliminated the low correlations, indicating it is easy to correct if a problem such as this arises.

4.2 Flow Disturbance and Geometric Response

One of the critical areas where the Vectrino shows an improvement is its interaction with the flow. There will always be slight offsets in the mounting and orientation of a velocimeter, and purely horizontal flow is rarely expected. These conditions can affect the measurement accuracy to a large degree. Snyder, et al. assumed initial offsets of 2° in their velocimeter mountings which had a major influence on their comparisons with theory. Given their results and the response of the older head design to pitch in this study, even small misalignments in the vertical can impact measurements beyond the aliasing that would occur in a rotated coordinate system.

The new head design employed on the Vectrino helps to minimize this source of error, and it's near ideal response in the range +/- 10° pitch indicates any presumed bias should be easily corrected for. Care should still be taken when mounting a velocimeter to ensure it is as level as possible.

One area not addressed in Snyder, et al.'s or this study is the implications for a multidimensional flow. The region where these measurements were made is essentially 1-D. While this is a common situation in the lab, it is less likely in the environment or in more complex lab flows. A small vertical component of velocity would easily introduce the smaller angles examined here for pitch, and the error introduced by this small change in flow direction could be significant, especially for the older head designs.

5. CONCLUSSIONS

A series of tests were conducted to evaluate the performance of acoustic velocimeters in low seed/SNR conditions, the system noise levels, accuracy of mean flow estimates, and response when tilted with respect to the flow. The systems evaluated represented the first generation of velocimeter hardware and an improved design in terms of transducer head and electronics. Overall, the new design showed increased performance at low SNR values, with lower seed density required to achieve similar results to older systems. System noise has been reduced, increasing the range of seed conditions over which a velocimeter can be used reliably, and also permitting the use of higher sample rates internally and for data output. The new velocimeter hardware also utilizes a new head design which improved its response to being pitched with respect to the mean flow and it's overall flow disturbance. While some questions remain, such as mean flow accuracy at low SNR, velocimeter performance has been shown to improve with each generation of hardware.

ACKNOWLEDGEMENTS

The primary author would like to thank Evan Variano and Todd Cowen of the Defrees Hydraulics Lab for their assistance with the PIV setup and processing. Without their knowledge and experience this project would not have been possible.

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