Characterization and Testing of a new Bistatic Profiling Acoustic Doppler Velocimeter: The Vectrino-II

Robert G.A. Craig, Chris Loadman and Bernard Clement
Nortek Scientific
1411 Oxford Street
Halifax, NS, B3H 3Z1 Canada

Peter J. Rusello and Eric Siegel
NortekUSA
222 Severn Avenue
Annapolis, MD 21403 USA

***Abstract*—Pulse-to-pulse coherent Doppler sonar systems have been commercially available for almost two decades now. These systems provide non-intrusive, high accuracy, low noise data in difficult environments. Pulse coherent profilers are also capable of measuring very small cell sizes and provide far more details of flow than standard Doppler systems. Multi-beam bi-static profiling systems allow measurements of velocity over a specified range of cells with each beam providing data from closely spaced measurement volumes, thereby removing the need for assumptions of flow homogeneity as required for mono-static systems with diverging beams. While a few bi-static profiling prototype systems have been demonstrated, there have been no commercial platforms available that provide a cost-effective, turn-key solution for providing three component data profiles with accompanying display and processing software tools.**

This paper will describe one such system, the Nortek Vectrino-II. A description of the instrument hardware and software capabilities will be followed by a discussion of some of the novel features and algorithms used by the instrument. Tow tank data and comparisons with a PIV system will be presented.

Keywords-component; acoustic Doppler, coherent, profiler, backscatter, Vectrino, velocimeter, ADV

I. INTRODUCTION

Coherent acoustic Doppler sonar has been in use for several decades now. Commercial systems started appearing in the early 1990s [1]. These commercial systems have been limited to mono-static and single cell bi-static systems. Multi-beam mono-static systems measure different sampling volumes and assume homogeneous flows in order to derive three dimensional representations of the velocity field. Bi-static systems simultaneously sample closely spaced volumes, thereby providing full three dimensional measurements of the velocities.

Profiling Doppler systems sample multiple volumes per measurement cycle thereby providing three-dimensional velocity versus range measurements. While prototype bi-static profiling Doppler systems have been in use in research institutions for quite some time [2][3][4], there have not, to date, been any turn-key commercial systems available.

The challenge with providing a commercial implementation lies in being able to provide a reasonable cost solution which produces good quality data combined with operating software that makes the instrument straightforward to configure and use. The Vectrino-II was designed and implemented with those goals in mind.

II. VECTRINO-II DESCRIPTION

A. *Hardware and Firmware*

The Vectrino-II uses the Nortek Vectrino velocimeter [5] mechanical components (pressure housing, acoustic transducers and probe) combined with completely new electronics, firmware and software. The main data processing engine consists of a high end Field Programmable Gate Array (FPGA) combined with a high-speed Digital Signal Processor (DSP). The FPGA is responsible for the spectral digital down conversion of received backscatter signals, transmit pulse generation and intra-ping timing co-ordination while the DSP performs the coherent Doppler processing, ping interval timing and house-keeping associated with instrument configuration, data formatting, and communications to the host data acquisition system.

Four passive transducers, angled at 30^o towards the center surround the central active transducer producing an intersection point 50mm below the central transducer. This provides a usable profiling region approximately 40-80 mm in height away from the central transducer. The signals from the transducers are input to a highly integrated analog front end chip (commonly used in medical ultrasound) before they are digitized and sent into the FPGA for processing.

The unit generates a continuous train of transmit pulses at 10MHz. The pulses are organized into ensembles with the number of pings per ensemble being determined by the sampling rate (up to 100Hz) and other configuration parameters. Complex data from the FPGA is processed and accumulated for each bin in the range gated profiles for each beam. The accumulated data is subsequently processed to produce average velocity, correlation and amplitude measurements for the sampling period chosen. Contiguous

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pulses are used to provide the data for the coherent Doppler processing meaning that, for N pulses, N-1 pulse pairs of data are averaged together to produce a single measurement. These data (in beam co-ordinates) are converted into instrument XYZ co-ordinates via calibration matrices that have been saved in the instrument probe non-volatile memory (see Section III-C for more information).

A thermistor embedded in the probe is used to provide temperature data so that the associated speed of sound can be correctly determined for use in velocity measurement calculation.

Given the volume of data generated (e.g. 40 bins at 100Hz requires ~ 900 kBaud), a high-speed RS-485 serial port is used for communications. This also allows significant cable lengths to be used when connecting to the instrument (a 100m cable is available as an option). A serial-USB converter that is shipped with the instrument allows any PC with a USB port to be used as the controller / data acquisition system.

Signals are provided to assist in the synchronization of the instrument with other instruments or with existing data acquisition systems. The Vectrino-II can either act as a master SYNC pulse generator, generating SYNC signals to other instruments, or as a slave. In slave mode, the Vectrino-II can either be slaved to another Vectrino-II (allowing for synchronized Tx-pulse generation and data collection) or to a different instrument. A variety of synchronization options / file saving options are also available. For existing systems, the option to start Vectrino-II data collection on the reception of a SYNC pulse, collect for a period of time and then re-set the instrument to wait for the next SYNC pulse (with data being saved to a new file) will be the one most commonly used. The SYNC signals are generated using RS-485 differential connections.

The firmware images used in the instrument by both the FPGA and the DSP are fully field-upgradable. This allows bug fixes and new features to be made available to users without requiring the instrument to be returned for servicing.

B. *Acquisition Software*

The acquisition software is used to configure the instrument and to collect, save and display data in real-time. Proper visualization of data as it is being collected greatly facilitates the operation of the instrument, allowing early detection of incorrect configuration parameters or anomalous behavior of the instrument due to external factors.

The acquisition software supports four modes of visualization: textual (for slowly varying data), profile plots, time series plots and real-time 2D contour plots (imaging) .

Profile plots can be display simultaneously with the time series plots and images. Individual data elements can be displayed either separately (Fig. 1 and Fig. 2) or simultaneously (Fig. 3). Re-sizing of plots / images and dynamic zooming of data are also provided.

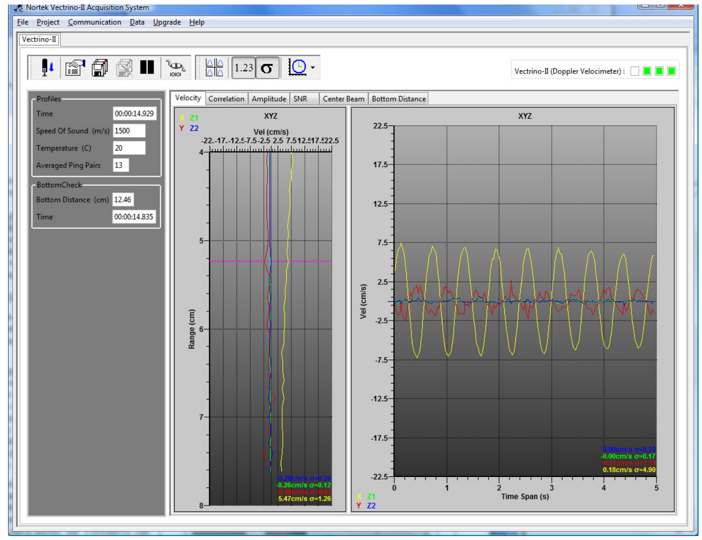

Figure 1. Basic display layout for acquisition software showing tabbed data displays combined with profile and time series plot views

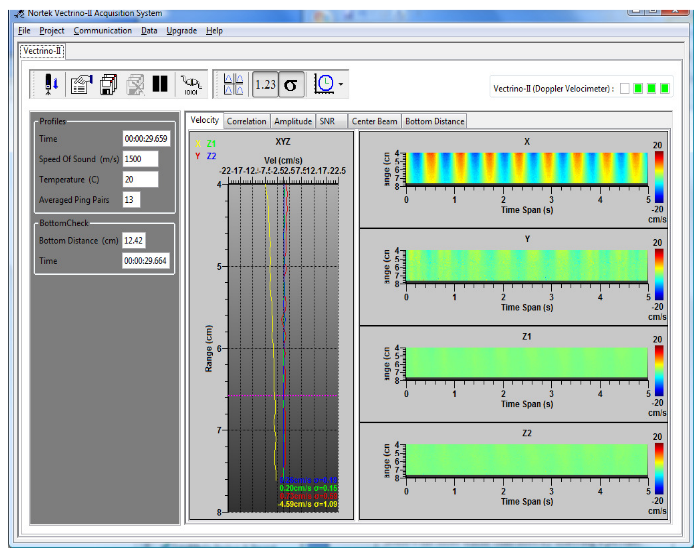

Figure 2. Imaging view enabled

An additional feature included in the software is the ability to display power spectra of velocities as the data is being acquired (Fig. 4). The spectra can be compared with the -5/3 line generally observed when turbulence occurs.

Data files can be saved to disk manually or for a given period of time, size or number of samples. File numbers are automatically incremented. The files are saved in a proprietary self-descriptive format that will be extended to other instrument types in the future. Built-in functions allow these files to be exported directly into ASCII formatted data or Matlab .MAT files for further post processing.

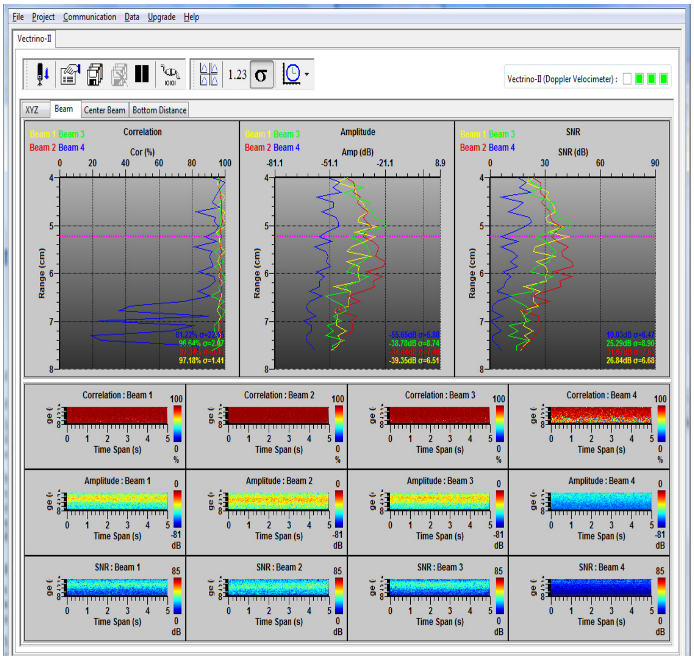

Figure 3. Simultaneous imaging display for several data elements (text view turned off)

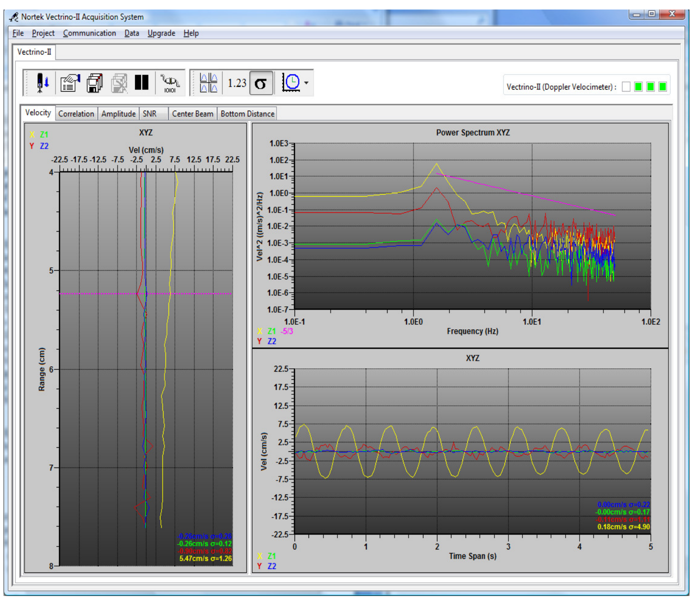

Figure 4. Real-time display of power spectra for velocity data

The software is also capable of supporting multiple instruments simultaneously. The current version provides separate controls for each instrument instantiation. Future revisions will incorporate the concept of "instrument groups" which will allow all instruments in a group to be configured and controlled identically.

III. PROCESSING ALGORITHMS

A. *Velocity Disambiguation*

The velocity (V) is calculated from the calculated phase difference (Δϕ), speed of sound (c), pulse frequency (f) and the time between pulses (Δt) also known as the ping interval.

$$V = \frac{c}{4\pi f}\frac{\Delta\phi}{\Delta t} \tag{1}$$

An inherent problem with coherent Doppler processing is that of the velocity ambiguity. This arises as a result of the fact that the phase difference can only be determined to within ±π rads.

This makes the ambiguity velocity

$$V = \frac{c}{4f\Delta t} \tag{2}$$

The choice of Δt is crucial to correct operation of the instrument. On the one hand, having a small Δt allows for a large ambiguity velocity. On the other, Δt also determines the range that each pulse is allowed to transit

$$R = \frac{c\,\Delta t}{2} \tag{3}$$

This leads to a minimum ping interval of ~110us for an 8mm range. In addition to the requirement that Δt be large enough to transit the sampling volume, additional per-ping delays are also introduced by the processing chain. In practice the, minimum achievable ping rate is ~150us for the full profiling range meaning that the beam ambiguity velocity is ~0.25m/s which (when the geometry is accounted for) leads to a maximum horizontal velocity of ~1m/s.

A variety of techniques have been used to extend the ambiguity velocity in real-time. These include using two separate pulse pairs, one short to determine the number of phase wraps and one long to determine the actual velocity or using multiple, simultaneous frequencies to produce extended phase measurements [6].

The Vectrino-II uses a technique often used in Doppler radar known as "dual pulse repetition frequency (PRF)" [7]. With this technique, two alternating ping intervals are used to collect a single profile. The velocity calculated using this technique is

$$V = \frac{c}{4\pi f}\frac{(\Delta\phi_2 - \Delta\phi_1)}{(\Delta t_2 - \Delta t_1)} \tag{4}$$

The ambiguity velocity then becomes

$$V = \frac{c}{4f(\Delta t_2 - \Delta t_1)} \tag{5}$$

This technique has the advantage of producing an extended velocity measurement for all cells in the profile (unlike the coarse / fine pulse-pairs technique). Signal noise effectively limits the minimum usable time difference. In practice, a gain of 3 to 5 times the original ambiguity velocity is achievable depending upon the quality of the data available [7]. The Vectrino-II profiler allows measurements of extended velocities up to 3m/s.

An optimized algorithm applied to multi-frequency Doppler and transposed to work with dual PRF data has been implemented in the Vectrino-II [8].

B. Bottom Check

In addition to velocity measurements, the backscatter signal can be used to determine instrument elevation. A high intensity echo is produced when the transmit pulse hits the bottom. The central transducer electronics of the Vectrino-II includes a transmit/receive switch allowing profiles over the full elevation range of the instrument to be collected.

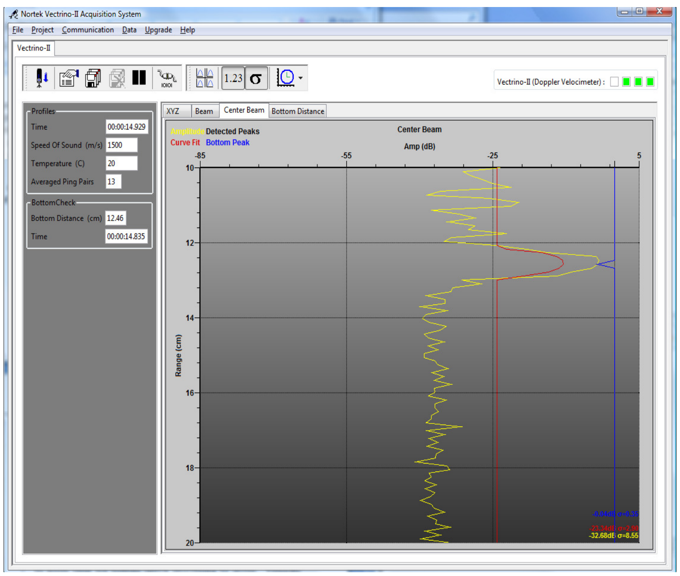

Figure 5. Bottom check data display

The bottom check feature collects a profile over a selected range and finds the maximum peak within this range (Fig. 5). A quadratic fit to the peak is used to determine the associated distance to the bottom. Range attenuation compensation can be turned on to help lock onto peaks which are further away from the probe.

Bottom check data is interleaved with the velocity data and can be sampled at a rate of up to 10 Hz (dependent upon velocity sampling rate). In order to provide an uninterrupted flow of velocity data, the number of ping pairs averaged per velocity sample is reduced to allow time for bottom check processing to occur. This maintains a constant velocity sample rate with only a slight degradation in signal to noise for each velocity sample taken adjacent to bottom check samples.

C. Probe Calibration

Probe geometry calibration is a significant issue for a bi-static profiler. Small variations in the manufacturing process can result in variations in geometry that can greatly influence the transformation coefficients used to translate from beam to XYZ co-ordinates [1]. The transformation of beam velocities, $\vec{v}_{beam}$, to a velocity vector referenced to the XYZ coordinate system is straightforward and assumes that the XYZ velocities, $\vec{v}_{xyz}$, can be derived through a linear combination of the velocities measured in beam space on all four transducers through a transformation matrix, T (6).

$$\vec{V}_{xyz} = T\,\vec{V}_{beam} \tag{6}$$

The job of the calibration procedure is to derive the matrix T by measuring beam velocities while constraining the XYZ velocities to known values. For the Vectrino-II, the calibration procedure is carried out on a cell by cell basis at the smallest possible cell size so that a unique transformation matrix is derived for every possible spatial position in the profile. Because of shifts in the speed of sound or desired profiles that are different from those used at calibration times it is possible to measure points in space that do not have an exact calibration. For these points the transformation matrix is derived through interpolation.

The initial calibration routines were performed in a manner similar to that used for the single point Vectrino [1]. This procedure, while certainly appropriate for a single point measurement at the intersection volume of the beams, appears to suffer from small systematic errors as the sampling volumes move away from this intersection region, especially in the region closer to the transducers. This results in a small but noticeable rounding of the profile in this region. Work is currently under way to enhance the calibration methodology to remove these errors.

D. Acoustic Interference Detection and Removal

Acoustic coherent Doppler systems can suffer from data degradation due to reflections from previous pulse(s) interfering with the current pulse (Fig. 6 and Fig. 7).

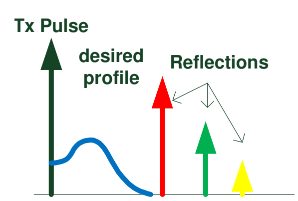

Figure 6. Single acoustic ping with multiple reflections from the initial transmit pulse occurring after the profiling region.

Detection and removal of these so-called “weak spot” regions within a Doppler system can be notoriously difficult given that the environmental geometry plays a significant role in how these weak spots manifest. This interference may (for example) be seen in amplitude data as unexpected sharp peaks in an otherwise smooth profile. Since reflection interference as low as 20 dB below the in-profile scattering amplitudes can cause significant velocity errors, the detection of these weak spots in typical data sets can be extremely difficult. In current systems, it is common for the user to have to recognize these undesired effects and modify the configuration (sampling volume, ping interval, power, etc.) to remove them.

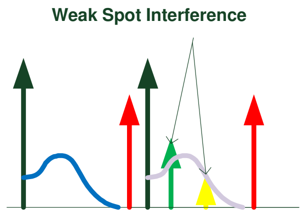

Figure 7. Reflections from the first acoustic pulse interfere with the sampling region of the second acoustic pulse

The Vectrino-II uses adaptive ping interval algorithms to help alleviate these issues. To accomplish this task the instrument attempts to measure the channel impulse response between the transmit transducer and all four receive transducers by taking deep profiles down each receiver beam. These profiles are then scanned to determine the temporal position of the relevant energy in the backscatter. In environments which exhibit large amounts of acoustic interference, ping rates are chosen that are long enough to avoid all reflections by constraining the ping rates to values larger than the duration of the channel impulse response.

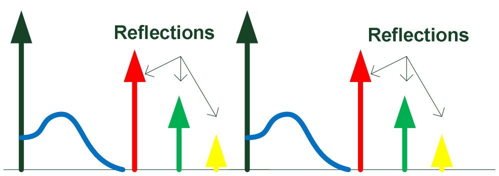

Figure 8. Ping rate chosen such that interference region dissipates before the next acoustic pulse is transmitted.

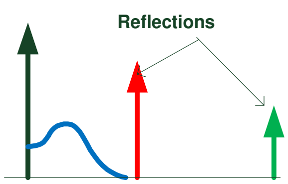

Figure 9. Signal showing more widely spaced acoustic interference.

In environments that exhibit less acoustic interference a more sophisticated approach can be employed to avoid weak spots while at the same time allow fast ping rates for the measurement of faster and more turbulent flows. In this case, the instrument predicts the temporal position of all relevant interferers for a large number of ping intervals though use of the convolution operator. A minimum ping rate is then selected that satisfies the conditions of range, ambiguity velocity and weak spots. In this case, every attempt is made to place the profiles between relevant reflections rather than after all of them.

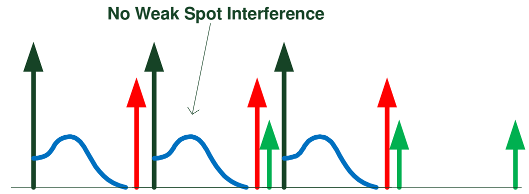

Figure 10. Ping interval selected such that sampling region occurs between reflections.

IV. RESULTS

A. *Tow Tank*

The Vectrino-II was towed in a tow tank at the Dalhousie University Department of Engineering facility (Halifax, Nova Scotia). The tow tank has calm water with a depth of nominally 0.75 m and the Vectrino probe was positioned nominally 0.25 m below the surface of the water. Once the tow carriage was up to full speed, the tested tow path was 7.0 m long. Mean tow carriage speed was calculated by using a hand-held stopwatch to measure the time it took the carriage to move over the 7.0 m range.

Fig. 11 shows two replicate tows at a nominal speed of 0.33 m/s. The blue lines represent replicate profiles of mean speed calculated using a constant calibration transformation matrix (from the 50 mm range cell) applied to all range cells. The transformation matrix from cell range 50 mm is the standard matrix that is supplied with single-point Vectrino velocimeters that have a measurement volume centered at 50 mm. It is evident that the constant transformation matrix is not adequate for use over the full velocity profile. The measurements are nearly correct and show the expected vertical trend near the center of the profile range (50-55 m), but errors are quickly apparent at the top and bottom of the profile.

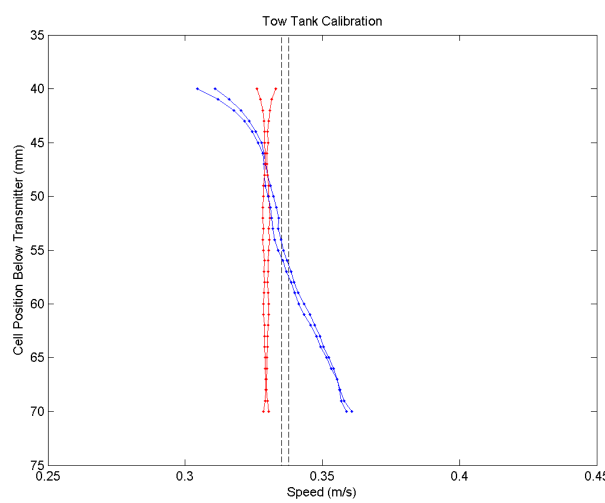

Figure 11. Tow tank data for Vectrino-II (two replicate tows). The blue line is a single matrix correction. The red line is a full profile correction.

The Vectrino-II probe calibration procedure calculates unique transformation matrices at 1 mm range cells over the length of the velocity profile (see section III.C). The red lines in Fig. 11 represent the same replicate tows with the profile transformation matrix applied. The straight vertical line that is apparent in the mean profile indicates a uniform velocity measured from the top to the bottom, as expected in a tow tank with still water.

The black vertical dashed lines provide the estimates of tow carriage speed for the two replicate tows. The difference between the two replicate tow carriage speeds and the difference in speed measured between the tow carriage and the Vectrino-II are both about 0.005 m/s. This represents the error bars of the experimental set-up (stopwatch, carriage speed, speed of sound measurement, etc.) and is equivalent to ~1.5% of the actual speed.

B. Boundary Layer and PIV Comparison

The Vectrino-II was mounted on a vertical stage in the 8 m Research Flume at the DeFrees Hydraulics Laboratory at Cornell University. This stage allowed precise positioning of the system above the smooth acrylic bottom. Two centrifugal pumps generated a free stream velocity of approximately 200 mm/s.

Two data sets were taken, one to assess near bed performance by positioning the Vectrino-II 70 mm above the bed, and a second positioning the Vectrino-II 85 mm above the bed during which a particle image velocimetery (PIV) data set was obtained. The same instrument setup was used for both data sets, including a profile range of 40 - 70 mm and a velocity range 0.4 m/s.

The same flow conditions were used for all three datasets and they are plotted here for comparison, with the expectation the PIV data provides an accurate, unbiased measurement of the flow. The PIV data was processed using custom software based on the cross-correlation of image pairs [9].

Fig. 12 shows the mean un-normalized stream-wise velocity profiles. A portion of the deviation from the PIV mean profile is believed to be attributable to calibration error. The bottom 10 mm of the flow features high shear rates. Compared to the 1 mm cell size used for the Vectrino-II, the PIV data set sub-window size is 2.8 mm, so shear is not expected to be a major problem for the Vectrino-II in the near bed region. The vertical velocity is essentially zero (+/- 2 mm/s).

One of the advantages of measuring in the turbulent flat plate boundary layer is the existence of an analytical solution for the velocity profile and the availability of accurate direct numerical simulation (DNS) results when measured velocity profiles are plotted in wall coordinates. Wall coordinates are defined as:

$$U^+ = \frac{U}{u_*} \tag{7}$$

$$z^* = \frac{z^* u_*}{\nu} \tag{8}$$

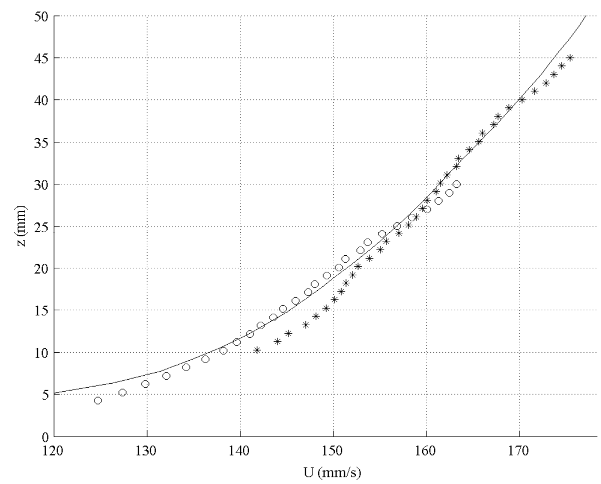

Figure 12. PIV (–) and Vectrino II positioned at 70 mm (o) and 85 mm (*) mean stream-wise velocity profiles

Where ν is kinematic viscosity and u_* is the friction velocity

$$u_* = \sqrt{\tau_w/\rho} \tag{9}$$

For further details on the turbulent boundary layer, the reader is referred to [9] and [10] and references therein. Prior measurements in this facility have shown good agreement with the smooth formulation Log Law boundary layer velocity profile and direct numerical simulation results [10]. The Log Law is defined as

$$U^+ = \kappa^{-1} * \log(z^+) + \beta \tag{10}$$

Where κ = 0.41 (von Kármán's constant) and β was taken to be 5.5 for this flow.

Results of this scaling, using u_* determined by a least squares fit to the Log Law and the PIV determined velocity profile are shown in Figs. 13 and 14. These are two different views of the same data, with Fig. 14 providing a semi-logarithmic version, highlighting the structure of the Log Law region of the flow.

Results of this comparison are very promising. The PIV data, as expected, does an excellent job of measuring the mean velocity profile, and when plotted in wall coordinates matches the Spalart DNS data extremely well. The two Vectrino II profiles show similar agreement to the Log Law profile and Spalart DNS data. Their scaled values are slightly larger than expected and some deviations from the shape of the profile are evident. These deviations are attributed primarily to the calibration of the probe.

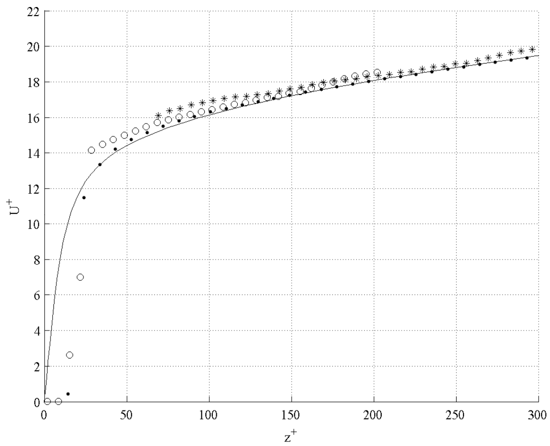

Figure 13. PIV (•) and Vectrino-II positioned at 70 mm (o) and 85 mm (*) mean streamwise velocity profile plotted in wall coordinates. Spalart's DNS data is the solid line.

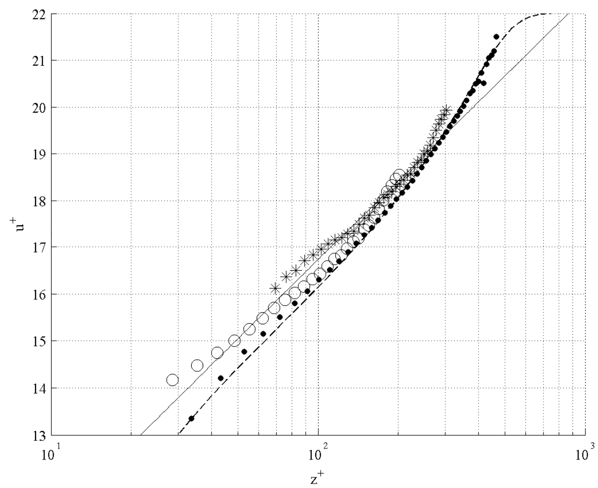

Figure 14. PIV (•) and Vectrino-II positioned at 70 mm (o) and 85 mm (*) mean streamwise velocity profile plotted in semi-logarithmic wall coordinates. Spalart's DNS data is the dashed line while the Log Law (10) is the solid line.

V. CONCLUSIONS

A newly developed, commercially available profiling acoustic Doppler velocimeter has been demonstrated. This system offers a turn-key solution with both hardware and software improvements that will allow users to easily configure and operate the instrument. Experimental data obtained with the Vectrino-II exhibited good agreement with both PIV and tow tank data. Information on the improved capability to measure turbulent flows in a jet tank as well as comparison to a standard Vectrino is described in [11].

While there appear to be small systematic errors in the probe calibration, particularly in the cells closest to the transmitter, enhancements to the existing calibration routines are expected to remove these errors.

Notable innovations in measurement capability include profiling three-component velocity with 1 mm range cells at up to 100 Hz, real-time (interleaved) distance check at up to 10 Hz, adaptive ping intervals to reduce weak-spot interference, increased dynamic range and improved SNR. New software features include the ability to run multiple instruments from the same control window, displays of velocity time series and vertical profiles, real-time contour plots, real-time energy spectra plots, enhanced synchronization options, and direct output to Matlab structured arrays. These features will make the instrument easier to configure while producing better quality data.

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