Turbulence measurements in a jet: Comparing the Vectrino and VectrinoII

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

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

***Abstract*—**
Results are reported from an experiment carried out with the newly developed Nortek VectrinoII and the standard Nortek Vectrino in a turbulent axisymmetric jet at a Reynolds number of 5000. The mechanical and acoustic characteristics of these instruments are identical. However, the electronics and signal processing scheme in the VectrinoII represent advancements over those in the original Vectrino (referred to as VectrinoI in this paper). In addition, the VectrinoII provides for profiling over a ca. 3 cm range interval thereby allowing direct measurement of the spatial structure of the flow. The two instruments deliver comparable performance as measured by mean velocity profiles, turbulent kinetic energy spectra, and the derived values of Reynolds stress and dissipation. The Vectrino measurements are compared to the mean and turbulent properties observed by [1] using hot-film and Laser Doppler anemometry. Here, there is good agreement in mean velocity and Reynolds stress measurements. Significant differences are seen in dissipations and velocity variance.

***Index Terms*—Turbulence, velocity, acoustic, Doppler, laboratory, Vectrino.**

I. Introduction

Acoustic Doppler velocimeters (ADVs) have increasingly become a sensor-of-choice for high resolution single-point measurements of flow velocity, especially in field conditions for which rugged probe designs are required. However, turbulence measurements with the early ADVs tended to be contaminated by noise [2]. The Nortek Vectrino, introduced several years ago with turbulent flow measurements in the laboratory as a primary target application, incorporated a 4-transducer orthogonal plane bistatic geometry, rather than the 3-transducer 120-deg geometry of the standard ADVs at the time, and used a slender but more fragile probe design. In principle, the orthogonal geometry should reduce the Doppler noise in velocity estimates [3], [4], and the slender probe design should reduce the possibility of eddies shed by the probe entering the measurement volume. Experiments have been carried out with the Vectrino both fixed in an axisymmetric turbulent jet (Reynolds number ca. 11,000), and translated at constant speed through approximately homogeneous isotropic turbulence with zero mean flow produced by a randomly-actuated jet array (RJA) [5]. The axisymmetric jet results indicated that RMS turbulence levels measured with the Vectrino were 30% greater than expected on the basis of earlier hotfilm and laser Doppler velocimetry measurements. The RJA experiments indicated that the noise was not a function of mean flow speed, and on this basis [5] concluded that the higher RMS levels were not Doppler noise.

So, while the Vectrino and other ADV systems have proven useful, there remain some questions as to their performance in challenging environments. There is therefore room for improvement in system capabilities. The VectrinoII is being introduced by Nortek as an incremental improvement on the existing VectrinoI system [6]. The mechanical and acoustic characteristics of these instruments are identical: both employ the same probe assembly and transducers. However, the VectrinoII provides for profiling over a ca. 3 cm range interval thereby allowing measurement of the spatial structure of the flow. In addition, the electronics and signal processing scheme in the VectrinoII represent advancements over those in the original VectrinoI, and improvements in the accuracy and the effective noise floor of the velocity measurements are expected.

The goal of this paper is to compare the two Vectrinos in the demanding flow environment presented by a turbulent jet. This flow has well defined spatial structure that exhibits self similarity and it has been thoroughly studied ([1], [7]). Importantly, the combination of significant mean velocities with high levels of turbulence provide a challenging environment for coherent sonar based systems [8] and the jet is therefore ideal for the present instrument comparison. The measurements are compared both between the two instruments and with known jet characteristics as reported by [1].

II. Apparatus and Procedure

Experimental data were collected using the Dalhousie University acoustics lab jet tank. Details of this facility can be found in [9] and [8]. The tank is approximately 1 m^3 into which a water jet is directed vertically as shown in Figure 1. The system allows for adjustment of the flow speed, and therefore the Reynolds number of the jet. However, electrical noise generated by the pump controller was found to interfere with the acoustic instruments and so the controller was not used and instead, the flow speed at the nozzle was adjusted by a throttling valve in the circuit. All tests were done with

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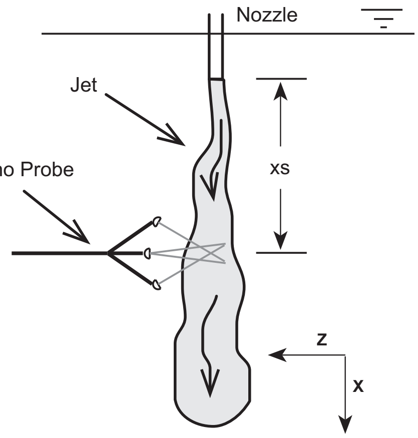

Fig. 1. Geometry of turbulent jet measurements.

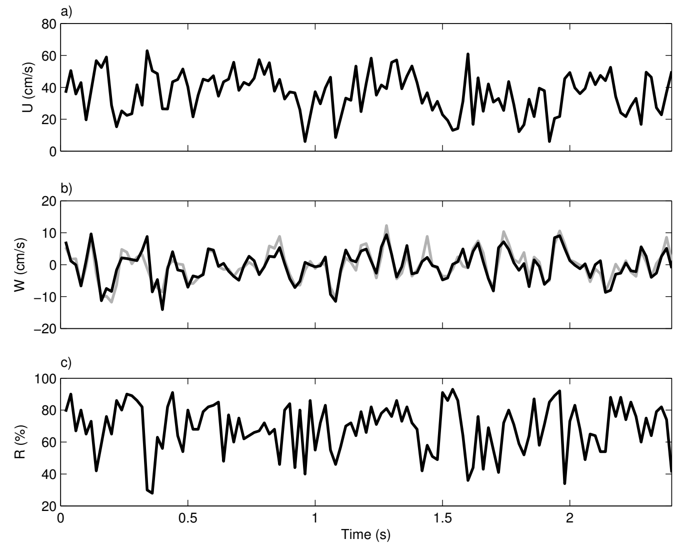

Fig. 2. Example VectrinoI jet axis observations at $xs = 19$ cm. a) axial (u-component) velocities, b) radial (w-component) velocities, beams 1 and 3 (gray), and beams 2 and 4 (black) and c) correlations.

the jet Reynolds number at about 5000. The jet nozzle has a diameter of 1.0 cm.

The jet was seeded with 75 ml of 0.05 mm diameter polyamide particles. High concentrations of scatterers assured high backscatter levels that are known to optimise data quality [10]. Performance of the systems at lower backscatter levels has not been explored.

The VectrinoII was positioned so that the jet axial flow was parallel to the x-axis of measurement (this coordinate system is indicated in Figure 1) and with the jet axis at 6.3 cm from the VectrinoII's central transducer. The instrument was positioned in steps at different distances from the jet nozzle (xs = 13, 19, 25, 31, 37, and 43 cm). Two minutes of data were collected at each position. The VectrinoII was then moved back 2 cm to 8.3 cm from the jet axis and the measurements were repeated. These repeat (overlapping) measurements allow for a consistency test within the profile range of the instrument.

Alignment with the jet axis was verified by positioning a 3/32" (2.4 mm) diameter welding rod coaxial with the jet nozzle and dangling it through the intended sample volume. The location of the rod was then noted in the VectrinoII backscatter profile.

In the case of the VectrinoI, it could be placed into the same mounting jig that had held the VectrinoII and because the physical dimensions of the instruments are identical, the positioning of the sample volume was known. With VectrinoI, velocities were sampled from the jet axis, and then at 1, 2, and 3 cm radially outward from the jet axis. Measurements were made at distances from the jet nozzle matching those chosen for VectrinoII (xs = 13, 19, 25, 31, 37, and 43 cm). Again, 2 minutes of data were collected at each position.

A variety of sample configurations were explored for both instruments but for the purpose of comparison, a "typical" configuration is presented. For the VectrinoI, data were sampled at 50 Hz over a 2.5 mm range interval and a nominal 1 m s^{-1} maximum velocity which corresponded to pulse-to-pulse intervals of 70 and 160 μs. For the VectrinoII, profiles were also acquired at 50 Hz but in 40, 1 mm range cells with a nominal 2 m s^{-1} maximum velocity range with pulse-to-pulse intervals of 150 and 200 μs.

The use of two pulse interval values for the instruments is associated with the use of the dual ping repetition frequency (PRF) method for resolving velocity ambiguities ([11], [12]). In general, longer pulse intervals will result in higher velocity accuracy but potentially degraded signal correlation due to particle advection and turbulence ([13], [14], [15]). In the jet, high turbulence levels indicate the use of the shortest ping interval possible. The VectrinoII pulse intervals are longer (and less optimal than) the VectrinoI intervals because of the need to sample data from farther away when forming the velocity profile.

III. Observations

An example of data collected with VectrinoI sampling at $xs = 19$ cm and at the jet axis are shown in Figure 2. Figure 2a shows the variability of axial (u) velocity associated with turbulence in the jet, the mean value is 36 cm s^{-1} with a standard deviation of 12 cm s^{-1}. The corresponding radial velocities (Figure 2b have a zero mean velocity with standard deviation of 5 cm s^{-1}. The correlations (between successive pings) are shown Figure 2c, they range between 30 and 90%.

Observations made at the same position ($xs = 19$ cm) with the VectrinoII are shown in Figure 3. Axial (u) and radial (w) velocities and correlations are shown in Figures 3a, b, and c respectively. Calibrated velocities are acquired over ranges from 4 to 7 cm, with the jet axis identified by the dashed line. Again, large variability is observed in velocities associated with the jet turbulence. And, with the profile data, coherent axial and radial motions are evident. The correlations also show well defined structures evolving in time.

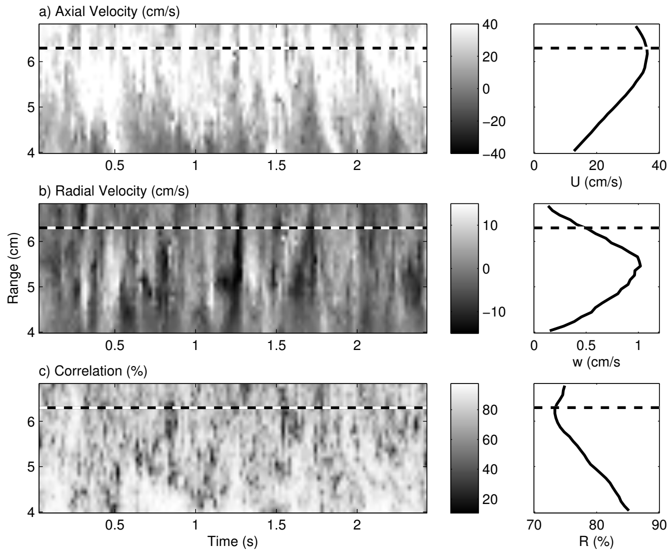

Fig. 3. Example VectrinoII observations at $xs = 19$ cm. a) axial (u-component) velocities, b) radial (w-component) velocities, and c) correlations. Calibrated data were sampled over the interval from 4 to 7 cm range, the jet axis is marked by a dashed line. For each figure, mean profiles are also shown.

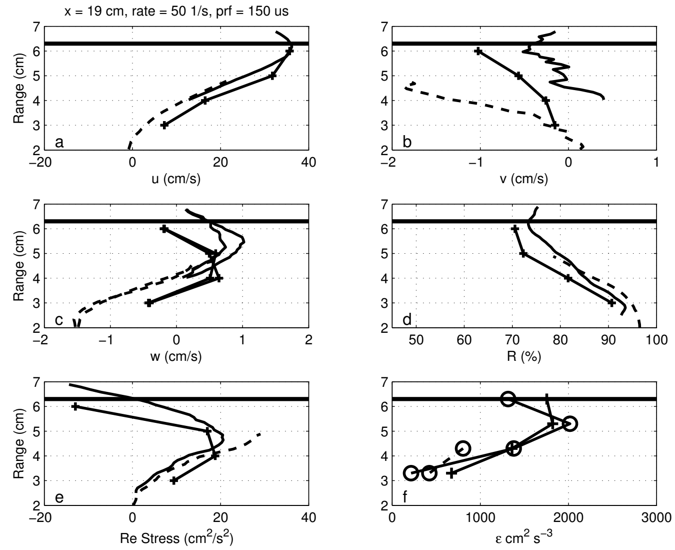

Fig. 4. Mean properties of the jet observed at $xs = 19$ cm. a) mean axial velocity (u), b) mean azimuthal velocity (v), c) mean radial velocity (w), d) mean pulse-to-pulse correlation, e) mean Reynolds stress, and f) mean dissipation (ϵ). The horizontal line indicates the location of the jet axis, VectrinoI data are indicated by $+$'s joined by a solid line, and VectrinoII data are indicated by a solid line (jet axis at 6.3 cm range) and a dashed line (jet axis at 8.3 cm range).

IV. Instrument Comparison

In the first instance, the two Vectrinos were compared by considering profiles of mean velocity characteristics: Figure 4a, b, and c show velocity sections of u (axial), v (azimuthal), and w (radial) velocity respectively. In Figures 4a, b, and c, VectrinoI data are indicated by $+$ joined by straight lines, VectrinoII data are indicated by a solid line (jet axis at 6.3 cm range) and a dashed line (jet axis at 8.3 cm range). In general, agreement between the two instruments here is good, some offset in the axial velocities (Figure 4a) suggests that the positioning of the instruments with respect to the jet axis was slightly different. Jet azimuthal velocities (Figure 4b) are generally weak as would be expected. Radial velocities (Figure 4c) are near zero at the jet axis then show outward flow increasing to a maximum at about 1.5 cm from the jet axis and then decreasing with an inward flow beyond about 3 cm from the jet axis associated with the entrainment of fluid into the jet (see [8]).

The standard measure of data quality for pulse-to-pulse coherent systems is the signal correlation. Mean values for both VectrinoI and VectrinoII correlations are shown in Figure 4d. Values are lowest at the jet axis due to the higher mean velocity and greater turbulence. The correlations increase with increasing distance from the jet axis. VectrinoI correlations tend to be slightly less than those for the VectrinoII in this trial.

A. Derived Quantities

Both instruments can be used to estimate Reynolds stress as $\overline{u'w'}$ and example values are shown in Figure 4e. Here both instruments provide comparable values with differences likely explained by a slight difference in jet position relative to the two instruments. What does stand out is that the VectrinoII observations from the $r = 8.3$ cm position are high at the 4 - 5 cm range: a bias likely introduced from calibration errors and would suggest that measurements over the corresponding interval of 6 - 7 cm collected with the instrument at the $r = 6.3$ cm position may similarly be incorrect.

The character of the turbulent flow can be explored by considering kinetic energy spectra. Spectra could be constructed for the velocity components (u, v, and w), but less noise is present when using the directly measured individual beam velocities. As an example, spectra for a single beam (beam 1) are shown in Figure 5 at the $xs = 19$ cm position. For the VectrinoI, spectra can only be shown at the four sampled positions ($r = 0$, 1, 2, and 3 cm), and for comparison purposes, data from these positions were also selected from the VectrinoII profile. There is generally good agreement between the form and level of the spectra: levels at $r = 0$, and 1 cm are comparable and levels at $r = 2$ and 3 cm decrease as they are farther from the jet axis. Slight changes in level between instruments (or trials) could easily be caused by alignment offsets. There is the hint of a noise floor close to the Nyquist frequency of 25 Hz in the VectrinoI data at $r = 0$. Both instruments see a noise floor at the $r = 3$ cm position associated with smaller velocity signals farther from the jet.

All of the spectra show evidence of a well defined inertial subrange at frequencies beyond about 5 Hz; the straight line in Figures 5 indicates a -5/3 slope. The spectral level can then be used to infer the energy dissipation (as described by [16]). Dissipation estimates based on spectral levels between

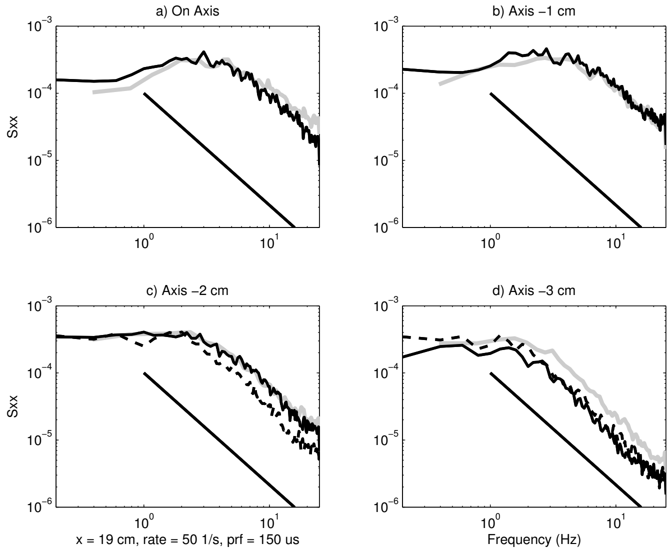

Fig. 5. Spectra of beam 1 velocity measurements for both VectrinoI (gray) and VectrinoII (black) at $xs = 19$ cm at jet radial positions of 0, 1, 2, and 3 cm (a, b, c, and d respectively). For VectrinoII, solid line is for instrument at $r = 6.3$ cm and dashed line is for the instrument at the $r = 8.3$ cm position. The straight line indicates a -5/3 slope.

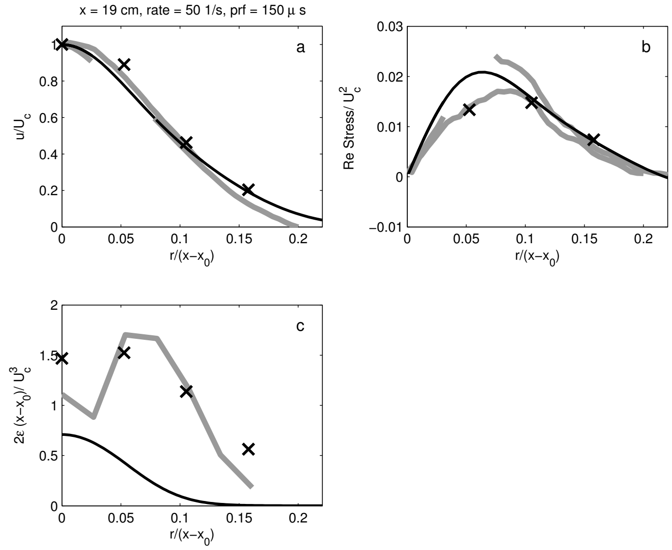

Fig. 6. Comparison of VectrinoI (×), VectrinoII (gray), and observations of [1] (black): a) axial velocity, b) Reynolds stress, and c) dissipation. Results are shown with non-dimensional units, but data are taken from the $xs = 19$ cm position.

5 and 15 Hz in Figure 5 are shown in Figure 4f (VectrinoI +, VectrinoII ○) and there is good consistency between the two instruments.

V. Comparison with Independent Observations

The comparisons presented so far show that the VectrinoI and VectrinoII return comparable quality data. However, since these instruments operate on the same fundamental principles, agreement should be expected. A more complete test of their abilities in turbulent flow is a comparison with independent measurements. For that purpose, the comprehensive set of observations reported by [1] are considered. Those observations are made using Laser Doppler Velocimetry and hot-wire anemometry in a turbulent air jet. Importantly, because of the self-similar nature of the turbulent jet, these observations from different turbulent jets can be directly compared when non-dimensionalized.

Figure 6a shows the profile of axial velocities from the present VectrinoI (×) and VectrinoII (gray) observations, and fits from observations by [1] (black). Data are taken from the $xs = 19$ cm position but results from other ranges are consistent with observations at this position. Observations are normalized by the non-dimensional scales characteristic of the jet: length by distance from the virtual nozzle position $(x-x_0)$ and velocity by the axial velocity at a given distance from the nozzle $U_c(x)$: for these observations, the virtual nozzle position is a small correction ($x_0 \simeq -0.4$ cm as determined from the evolution of the axial velocity with xs). The present data show a slightly broader core to the jet with a suggestion of recirculation at greater ranges.

Figure 6b shows Reynolds stress again from the $xs = 19$ cm position and again in non-dimensional units. Agreement with [1] is very good showing a Reynolds stress of 0 on axis as expected and then rising to a peak at $r/(x-x_0) \simeq 0.08$ before decaying back towards 0: a pleasing result.

Dissipations are shown in Figure 6c. For this comparison, [1] provide several possible dissipation measurements and the only one shown is based on the assumption of local axial symmetry in the turbulence. The agreement here is generally poor with the present observations double those reported by [1]. The cause of the difference is not known although a possible difficulty is that the spectral estimates of dissipation have assumed isotropy which may not be valid in the jet.

The Vectrinos (and most ADV type instruments) provide very accurate measurements of w, and much poorer measurements of u and v because of their sampling geometry. Given that this is a known weakness, it is important to consider the behaviour of these measurements. Unfortunately [1] do not provide sections of mean velocity other than the jet-axial component (already shown in Figure 6a), what they do provide are sections of the variance terms $\overline{u'^2}$, $\overline{v'^2}$, and $\overline{w'^2}$. These values (non-dimensionalized) are plotted as sections across the jet at $xs = 19$ cm in Figure 7. As with the dissipation estimates, the present observations are approximately a factor of 2 greater than the values reported in [1] for $\overline{u'^2}$ and $\overline{v'^2}$ (Figures 7a, and b). In contrast, for the radial component $\overline{w'^2}$ (Figure 7c), the values are low again perhaps by a factor of two. In addition, the present observations show significant axial structure not seen by [1].

VI. Summary/Conclusions

The objective of this paper has been to compare the ability of the VectrinoI and the new profiling VectrinoII to make

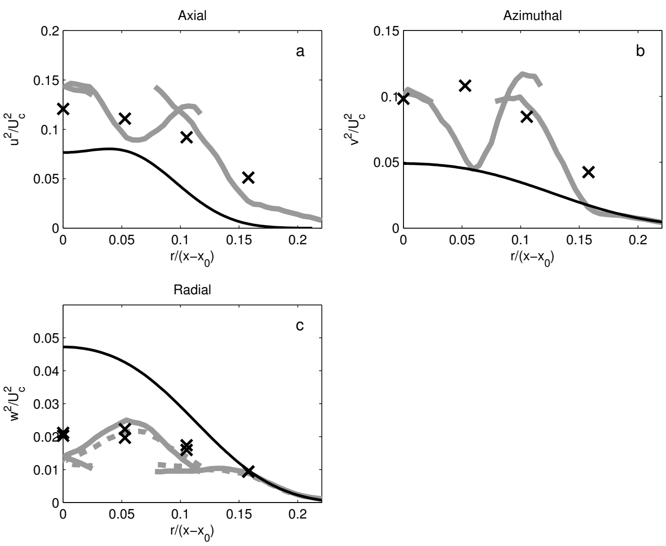

Fig. 7. Comparison of VectrinoI ($\times$), VectrinoII (gray), and observations of [1] (black): a) $\overline{u'^2}$, b) $\overline{v'^2}$, and c) $\overline{w'^2}$. Results are shown with non-dimensional units, but data are taken from the $xs = 19$ cm position.

measurements in a turbulent flow. For this purpose, both instruments were used to make observations of flow in a turbulent jet for which the flow properties are well understood ([1], [7]). The jet Reynolds number was 5000, and measurements were made at various positions downstream of the nozzle. At each downstream position, measurements were made at four jet-radial positions with the point measuring VectrinoI and at two (overlapping) positions with the profiling VectrinoII.

The two instruments provide similar values for mean velocities, computed Reynolds stress, and energy spectra. When considering this agreement it is important to realize that the VectrinoII is sampling a range cell of length 1 mm compared to the 2.5 mm cell sampled by the VectrinoI so that the VectrinoII is working with less signal to provide a given measurement. As well, the VectrinoII provides velocities simultaneously at 40 range bins as compared with the single point sample provided by the VectrinoI.

Certain characteristics of the comparison do raise questions about calibration. For both instruments, non-zero azimuthal velocities were observed (Figure 4b) and in particular, the VectrinoII shows substantial structure with axial range that is not expected. Another area where calibration shows up as a concern is the failure of the two overlapping VectrinoII profiles of Reynolds stress to coincide at ranges between 4 and 5 cm (compare the dashed and solid lines in Figure 4e). In contrast, the mean axial and radial velocities (shown in Figure 4a and c) show very nice consistency between the two VectrinoII profiles.

Comparisons were also made between the present observations and independent measurements of flow parameters in a turbulent jet [1]. Good agreement was seen in profiles transverse to the jet axis of axial velocity and Reynolds stress (Figure 6a and b) but dissipations (Figure 6c) calculated using the Vectrinos were comparatively high (by a factor of two). In comparisons of velocity variances (Figure 7), the $u-$ and $v-$ components were consistently a factor of two higher than those in [1] while the $w-$ component was consistently low. Some part of this difference could be associated with the sampling geometry of the Vectrinos that makes $w-$ component velocity estimates more accurate than the $u-$ and $v-$ components and it is possible that the high readings are caused by measurement noise. The detailed profile of variance provided by the VectrinoII suggested structure in the variance not seen by [1] and not reproduced by the VectrinoI. These differences again might suggest calibration problems with the VectrinoII.

What did stand out with these measurements was the convenience of collecting a profile of data with the VectrinoII as compared to single point VectrinoI measurements. The collection of data was much faster: in the present study it basically took four times as long to collect the VectrinoI data as it did to collect the VectrinoII data. Also, the availability of a profile allowed accurate positioning of the jet axis while with the single point measurements, the alignment of instrument positioning had to be trusted.

The VectrinoII is still being developed: even as we were collecting this data Nortek were making firmware updates available that visibly improved data quality. Also, revised calibration schemes are being developed so that the concerns identified here should be addressed in future instruments.

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