Acoustic Doppler Velocimeters (ADV) Performance Curves (APCs) sampling the flow turbulence

Carlos Marcelo García[1], Mariano I. Cantero[1], Yarko Niño[2] and Marcelo H. García[1]

[1] Ven Te Chow Hydrosystems Laboratory, Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 North Mathews Ave., IL 61801, USA. cgarcia2@uiuc.edu, mcantero@uiuc.edu, mhgarcia@uiuc.edu.
[2] Dept. of Civil Engineering, University of Chile, Chile. ynino@ing.uchile.cl

Abstract
The capability of Acoustic Doppler Velocimeters (ADV) to resolve flow turbulence is analyzed by mean of a new tool denoted ADV Perfomance Curves (APCs). These curves can be used to define optimal flow and sampling conditions for turbulence measurements using an ADV. To generate these curves, a conceptual model is developed which simulates both, different flow conditions (flow component) and the instrument operation (instrument component). Different scenarios (ranges of flow conditions and sampling frequencies) are simulated using the conceptual model to generate several synthetic time series of water velocity and corresponding sampled signals. For the sake of comparison, the main turbulence statistics parameters of the synthetically generated sampled and non-sampled time series are plotted in dimensionless form; these plots are called APCs. The performance of the developed tools is validated using experimental results. Using the APCs a new criterion is proposed to perform ADV measurements with good resolution of the flow turbulence. In cases where this criterion can not be satisfied these curves can be used to make the corrections.

Introduction
Acoustic Doppler Velocimeters are capable of reporting accurate mean values of water velocities in three directions (Kraus et al.,1994; Lohrman et al., 1994; Voulgaris et al.,1998) even in low flow conditions (Lohrman et al.,1994). On the other hand, the ability of this instrument to accurately resolve flow turbulence is still uncertain (Barkdoll, 2002). Lohrman et al. (1994) argue that the ADV resolution is sufficient to capture a significant fraction of the flow turbulent kinetic energy (TKE), but they identify the Doppler noise as a problem that causes the TKE to be biased high. Most of the research related to the capability of an ADV to resolve turbulence (specifically TKE and spectra) has focused on the definition of this noise level present in the signal and how it can be removed (Lohrman et al.,1994; Anderson et al., 1995; Voulgaris et al., 1998, Nikora et al., 1998, Lemmin et al.,1999 and Mc Lelland et al., 2000). However, little attention has been dedicated to evaluating the filtering effects of the sampling strategy (spatial and temporal averaging) on the turbulent parameters (moments, spectra, autocorrelation functions, etc.). Only Voulgaris et al. (1998) discusses some issues related with the effects of the spatial averaging.

As an initial approach, it can be argued that the ADV's ability to resolve the turbulence will depend on the flow conditions. The objective of this paper is to introduce novel tools, denoted here ADV Perfomance Curves (APCs), which can be used to define optimal flow and sampling conditions for doing turbulence measurements using an ADV. These tools are validated analyzing water velocity signals sampled with ADVs in 10 different experimental setups and flow conditions at the University of Illinois at Urbana–Champaign, USA.

Description of ADV operation

An ADV measures three-dimensional flow velocities using the Doppler shift principle and consists, basically, of a sound emitter, three sound receivers and a signal conditioning electronic module. The emitter of the instrument generates an acoustic signal that is reflected back by sound-scattering particles present in the water (assumed to move at the water velocity). This scattered sound signal is detected by the instrument receivers and used to compute the signal Doppler phase shift with which the radial flow velocity component is calculated.

The ADV uses a dual pulse-pair scheme with different pulse repetition rates (McLelland et al., 2000). The radial velocities v_i (i=1, 2, 3) are computed using the Doppler relation. This process of sampling the radial velocities for the three receiver is done by ADV as a whole with frequency f_S (equal to $1/T$), which is between 100 and 263 Hz depending on the velocity range and the user-set frequency. Then, the radial velocities computed from each receiver are converted to a local Cartesian coordinate system (u_x, u_y, u_z) using a transformation matrix that is determined empirically (through calibration) by the manufacturer (McLelland et al., 2000).

During the time it takes to make a three-dimensional velocity measurement (T) the flow may vary, however, these *high frequency* variations are smoothed out in the process of signal acquisition and cannot be captured by the instrument. The direct implication of these features is that the Cartesian flow velocity represents an averaged value, over an interval time T, of the real flow velocity. In this sense T can be though as the instrument response time, and the process of acquisition itself can be seen as an analog filter with cut-off frequency $1/T$ (or f_S).

Two main conclusions can be drawn from the considerations above. The first one is that energy in the signal with frequency larger than f_S is filtered out (acquisition process acts as a low-pass filter). The second one is related with aliasing of the signal. Since the velocity signal is sampled at a frequency f_S the largest frequency that can be resolved by the instrument is $f_S/2$ (Nyquist theorem, see Bendat et al., 2000). This indicates that energy in the frequency range $f_S/2 < f < f_S$ is folded back in the range $0 < f < f_S/2$. The level of aliased energy will depend on the flow characteristics.

After the digital velocity signal is obtained (with frequency f_S), the instrument performs an average of N values of this signal producing a digital signal with frequency $f_R = f_S /N$, which is the ADV's *user-set frequency* with which velocity data is recorded. This averaging process is a digital non-recursive filter (Bendat et al.,

2000; Hamming,1983). The consequences of the digital treatment of the signal are analyzed in the following section.

Conceptual model

A conceptual model is developed here to evaluate the performance of the ADV based on the turbulence characteristics of the flows to be measured with this instrument. The model includes two components, the instrument and the flow components, which simulate both the instrument operation (based on the previous description of how the ADV works) and the power spectrum of flow velocities associated with different flow conditions, respectively. A description of each component is presented next.

Instrument component

For the purpose of our research, the ADV can be conceptually modeled as a two-module linear system. The first module is the data acquisition module (DAM). This module encompasses the sound emitter and receivers, the analog to digital converter (ADC), which works at frequency f_S, and the computation of flow velocities from the acquired signal. The second module is the data preprocessing module (DPM), which encompasses the averaging of the digital velocity signal that produces data at the user-set frequency f_R. The DAM produces a digital signal from the flow velocity, i.e. the input is the flow velocity and the output is a digital signal with frequency f_S. This module is modeled through the sampling of synthetic water velocity series produced in the flow component of the conceptual model. The DPM basically performs a time averaging of the output of the DAM in order to produce data at the user-set frequency f_R. The output is the water velocity digital signal that the ADV users receive. The low-pass filtering of the signal (in the DPM) has implications in the computation of the spectrum and moments from the signal. The quantification of this effect is discussed later in this paper.

Flow component

Synthetic water velocities signals need to be generated to represent different ranges of flow conditions. These signals must have turbulence characteristics that resemble realistic conditions. In order to accomplish that a three dimensional model power spectrum is adopted which include all the turbulence characteristics for specified flow conditions. The model power spectrum used in this paper was proposed by Pope (2000). The input parameters of the model are energy-containing-eddy length scale, L, and Kolmogorov length scale η (which can be estimated from the value of the rate of dissipation of turbulent kinetic energy, ε, of the flow). The three dimensional energy-spectrum function, $E(\kappa)$ predicted by Pope´s model is given by

$$E(\kappa) = C\varepsilon^{2/3}\kappa^{-5/3}f_L(\kappa L)f_\eta(\kappa\eta)$$

where C = constant, κ is the wavenumber and f_L and f_η are shape functions defined as

$$f_L(\kappa L) = \left(\frac{\kappa L}{\left[(\kappa L)^2 + c_L\right]^{1/2}}\right)^{5/3+p_0}$$

$$f_\eta(\kappa\eta) = \exp\left\{-\beta\left\{\left[(\kappa\eta)^4 + c_\eta^{\ 4}\right]^{1/4} - c_\eta\right\}\right\}$$

The function f_L defines the shape of the energy containing eddy part of the spectrum (equal to 1 for large κL) and f_η describes the shape of the dissipation range (equal to 1 for small $\kappa\eta$). Following Pope (2000) the parameters adopted for this model are: p_o =2, c_L = 6.78, c_η =0.40, β =5.2. A one dimensional model spectrum $E_{11}(\kappa_1)$ is required to derive or generate one dimensional water velocity signals. The technique used here to estimate E_{11} is based on a modified version of Pope's (2000) model with the same set of parameters with the exception of C and p_o ($C=C_1$ = 0.49 and p_o = 0 from Garcia et al., 2004). A technique is needed to generate synthetic water velocity signals from the modeled one-dimensional power spectrum with predefined turbulence flow conditions. For that, Shinozuka´s (1972) method is used, which allows generating a 1D water velocity signal as a realization of a turbulent process, using the model power spectrum as a target. Convective velocity U_c is used to transform the power spectrum from the spatial to the time domain. Each point in the time series is computed by summing weighted cosine series with a random phase angle, ϕ, as:

$$x(t) = \sqrt{2}\sum_{q=1}^{N} A_q \cos\left(\omega'_q\, t + \phi_q\right)$$

The generated synthetic signal is only one of the possible realizations of a process with the chosen flow turbulence characteristics because of its random phase angle. The weights A_q are defined from the N numbers of terms of the target spectrum in the time domain. Jeffries et al. (1991), suggested some recommendations regarding Shinozuka´s method, consisting of requirements for N and Nt (number of points in the time series) to avoid undesired periodicity in the synthetic signals. These suggestions were adopted for the present analysis. The method used to generate synthetic velocity series is validated checking that both the model or target spectrum and the spectrum computed from one particular synthetic series compare favorably.

Simulation of different flow conditions using the conceptual model
A set of numerical simulations based on the conceptual model proposed in previous sections was carried out for different values of the parameters in the range that best represents the conditions usually present in laboratory and field turbulence measurements. A number of synthetic turbulent water velocity signals with Δt = 0.0038sec (f_s = 260.8 Hz) were generated as realizations of different flow conditions. The ranges of flow variables used in the simulations are: Convective velocity : 0.01m/s $\leq U_c \leq$ 1m/s; Energy containing eddy length scale: 0.10m $\leq$ L $\leq$ 2m; Kolmogorov length scale: 0.0001m $\leq \eta \leq$ 0.005 m. The range of Kolmogorov length scales proposed here generates a range of 7 orders of magnitude in ε (1.6x10^{-9}m^2/s^3 $\leq \varepsilon \leq$ 1x10^{-2}m^2/s^3), describing conditions prevailing in most of environmental water flows.

It is assumed in the following analysis that both the effects of the analog filter with cut off frequency f_s and the level of aliased energy are negligible (Garcia et al., 2004).

Synthetic signals were generated using the different flow parameters and then sampled according to the sampling strategy described in the instrument component of the conceptual model. The *user-set frequencies* adopted here were f_R = 260.8Hz, 52.2Hz, 26.1Hz, 10Hz, 5Hz and 3Hz. The sampled signals were analyzed in order to compute corresponding turbulent parameters (up to fourth order moments, autocorrelation function and spectrum). Thus, the evolution of these parameters can be evaluated while the flow condition and sampling frequency change.

The effect of different flow conditions on flow statistics is explored in Figs. 1 to 4. The parameters representing flow statistics obtained for values $f_R \leq f_s$ are made dimensionless using the corresponding value of the parameter computed for $f_R = f_s = $ 260.8 Hz (no averaging). Those dimensionless parameters are plotted as a function of the dimensionless parameter defined as: $F = \dfrac{L}{\dfrac{U_c}{f_R}} = \dfrac{f_R}{f_T} = \dfrac{L}{d_R}$ where f_T is the characteristic frequency of large eddies present in the flow and d_R is the diameter of the sampled volume set by the flow and sampling characteristics. The higher the ratio F, the better the description of the turbulence is achieved with a specific instrument. In theory, no turbulence scale could be described from the recorded signal for $F < 1$.

So far, the sampling volume has been considered as a point. However, the spatial averaging performed by ADV should be considered when the value of d_R is smaller than the d = diameter of the measurement volume, d. In those cases d must be used in the parameter F computation instead of d_R because spatial averaging becomes more important than the temporal averaging. This replacement is based on the assumption that the spatial average acts as a low pass filter with wavelength = $1/d$.

The evolution of variances (integral of the spectrum and second order moment of the signal) is shown in dimensionless form in Fig. 1, together with the corresponding fourth order moments. The effects of the averaging on the latter is more important (higher reduction in the sampled moment) than on the variance. A similar analysis was performed for the third order moment but a clear trend could not be detected.
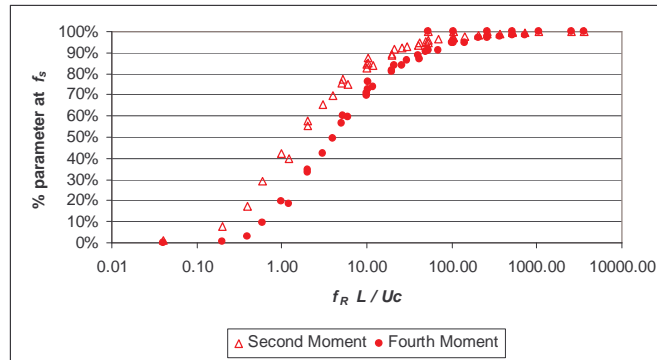

Figure 1: Sampling effect (averaging) on second and fourth order moments.

The simultaneous analysis of both the evolution of the value of the autocorrelation function at the first lag and the spectrum gives good information about how the sampling technique used by ADV affects the turbulence description
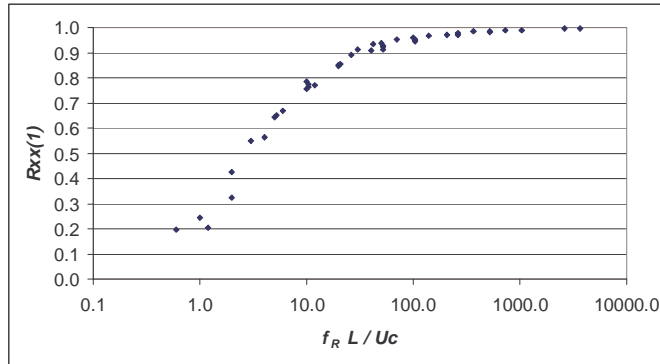

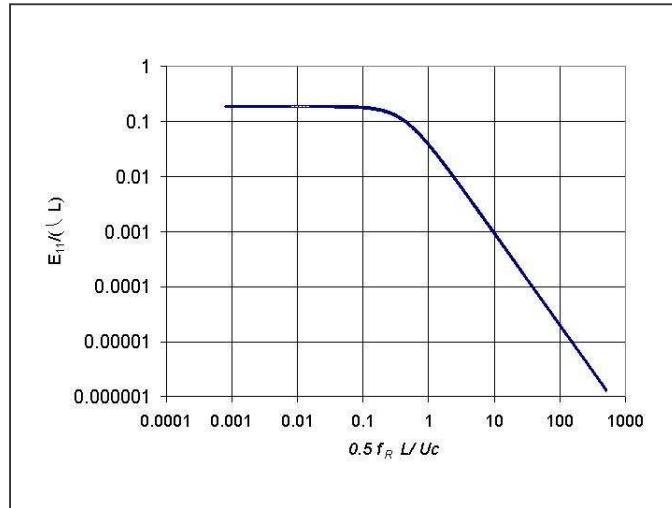Figure 2: Autocorrelation function value at the lag 1.

Figure 3: Non dimensionless power spectrum model.

The first sampled point in the autocorrelation function decreases as the f_R decreases. Smaller values of $Rxx(1)$ means that there is less turbulence sampled in these signals. An analysis for the whole range of flow conditions considered here is included in Figures 2 and 3. The spectrum is made dimensionless in Fig. 3 using the variance of the signal, σ, and the length scale of big eddies, L. The maximum frequency resolved in the spectrum is 0.5 f_R. For 0.5 $F = 0.5 f_R L / Uc < 1$ the inertial range is not resolved and $Rxx(1) = 20\%$. As 0.5 $F > 2$ progressively more of the inertial range gets sampled but the value $Rxx(1)$ is still small unless F gets over a value of about 20. No noise effects are considered in the analysis here which would generate an extra level of decorrelation in the signal.

The averaging technique also affects the autocorrelation function Rxx, increasing the correlation values for the smaller lags when Rxx for equivalent lag times are compared. Thus, the time scales computed from the autocorrelation function (as the

integral of *Rxx* up to the first zero crossing) are high biased. Fig. 4 quantifies this bias, showing the variation of this time scale with F in dimensionless terms.
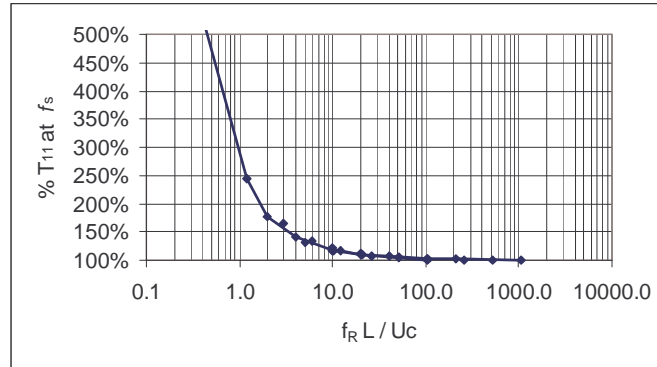

Figure 4: Sampling effect (averaging) on integral time scale (T_{11})

Figures 1 to 4 are called Acoustic doppler velocimeter Performance Curves (APCs). From them, criteria for sampling turbulence in water flows with ADV technology can be readily defined. From the present analysis it is concluded that a good sampling criterion should consider values of $F > 20$, as such range yields reasonably small losses in the moments and at the same time resolve important portions of the spectrum. The limit $F = 20$ means, for instance, that when using an ADV with $f_R = 25$Hz for an experiment with $L = 20$ cm, turbulence cannot be accurately resolved in flows with velocities higher than 25 cm/s.

Validation of the conceptual model.
The assumptions used to develop the conceptual model are validated using experimental data of an open channel flow, obtained in a flume of width B = 0.91m at the Hydrosystems Laboratory – UIUC. Firstly, a set of 11 velocity time series were sampled with a Sontek Micro Acoustic Doppler Velocimeter (ADV) at the same location, with the same flow conditions and same ADV velocity range, but with different sampling frequencies, up to 50 Hz, which is the maximum value permitted by the apparatus. The sampling volume of the ADV was located at y = 4cm from the bottom of the flume. The flow condition analyzed consisted of a water depth h = 0.282m, a flow discharge Q = 0.12 [m^3/s], and a local value of the shear velocity at this vertical u* = 4.82 cm/s. The size of the energy containing eddy scale, L, corresponding to this flow is estimated to be equal to 0.282 m (h), and the associated convective velocity is determined to be equal to Uc = 0.58m/s from the three-dimensional velocity vector data using the relation proposed by Heskestad (1965). Following Nezu et al. (1993), the dimensionless parameter $\epsilon h/u*3$ is estimated to have a value equal to 16 for y/h = 0.142. Thus the rate of dissipation of TKE at the measurement point is about 6.35 10-3 m^2/s^3 and the corresponding Kolmogorov length scale is 0.00011m, which agree with the typical values for open channel flow. The minimum observed value of the signal to noise ratio (a signal quality parameter) for all the measured velocity time series was 17.9, a high enough value that ensures the good quality of the data. Water velocity signals were recorded during 2 minutes for each ADV configuration.

The effect of the temporal averaging of the ADV (for values of f_R = 50; 30; 25; 20; 10; 5; 2; 1; 0.5; 0.2; 0.1Hz) on the recorded velocity signals is well predicted by the present conceptual model. The observed evolution of the odd moments when f_R changes is included in Figures 5 and 6.
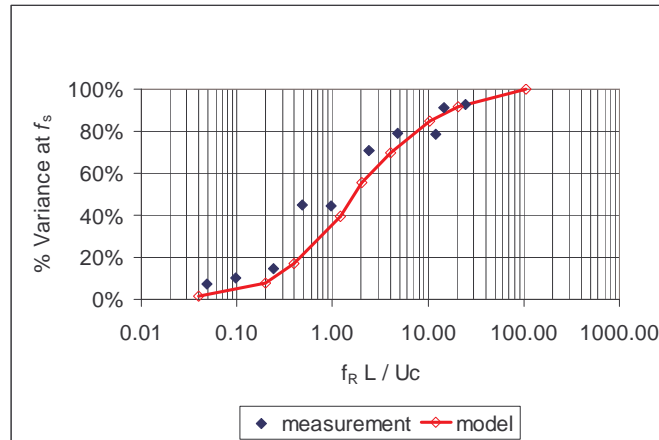

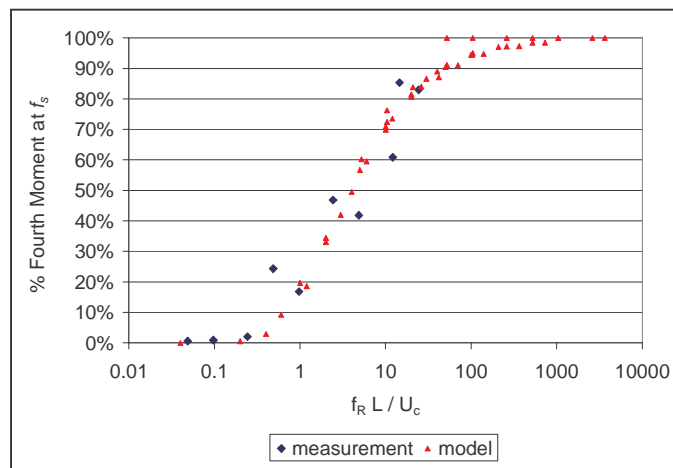Figure 5: Observed sampling effect (averaging) on the variance

Figure 6: Observed sampling effect (averaging) on the 4th order moment

The values of the moments corresponding to the real sampling frequency f_s of the instrument are needed to make the plot dimensionless; however, this information cannot be obtained from the ADV. To overcome this problem, the value of the ratio between the corresponding moments obtained at f_R and f_s for the higher sampling frequency (f_R =50Hz and F = 24.31) is assumed to be the same as that predicted by the conceptual model (92.5% for the variance and 83% for the fourth order moment). Then, the trend obtained from the measurements agrees very well with that predicted by the model.

Likewise, a good agreement is obtained in Figure 7 between ADV measurements and the predictions of the conceptual model for the variation with the dimensionless frequency F of the correlation value at the first lag, Rxx(1).
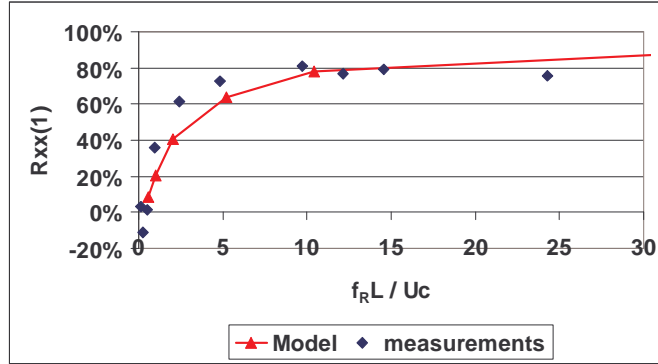
Figure 7: Observed Rxx(1) for different averaging frequency.

Figure 8 shows the observed variation of the integral time scale with F. A good agreement is obtained between the prediction of the conceptual model and the observations, with exception of the behavior at dimensionless frequencies lower than about unity.
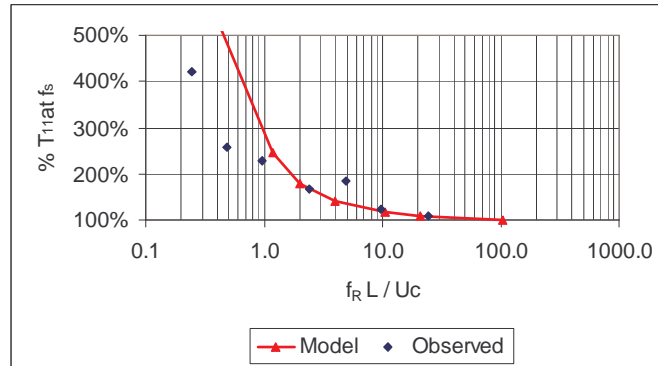

Figure 8: Observed sampling effect (averaging) on integral time scale (T_{11})

Conclusions

Acoustic Doppler velocimeters (ADV) have proved to report a good description of the turbulence when certain conditions are satisfied. These restrictions are related to the instrument configuration (sampling frequency) and flow conditions (convective velocity and turbulence scales in the flow). In general, the ADV produces a reduction of all the even moments in the water velocity signal due to the low pass filter of the sampling strategy used by this technology. Besides, this sampling affects the autocorrelation function (increasing Rxx for small lag times), the time scales computed from them (which result to be high biased) and the power spectrum (less resolution of the inertial range). However, the present analysis indicates that all these effects are rather negligible in cases where a value of the dimensionless frequency (F = f_R L/Uc) higher than 20 is used. This result provides a new criterion to analyze the validity of the ADV measurements as a good representation of the turbulence in any flow with known convective velocity and length scales. In cases where this criterion cannot be satisfied (i.e., F results lower than about 20) a set of curves, denoted here APC curves, are proposed to estimate the values of the necessary corrections.

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