New methodology to subtract noise effects from turbulence parameters computed from ADV velocity signals

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Abstract

The Acoustic Doppler Velocimeter (ADV) signals are affected by Doppler noise which is intrinsic to the Doppler measurement technique. It has the characteristics of white noise and its integral effects must be subtracted from some turbulence parameters. New tools are introduced in this paper to evaluate the relative importance of the noise energy on the total energy as well as to define the characteristic frequency in the measured energy spectrum where noise energy is more important than turbulent energy (flat plateau). To develop these tools a model for the power spectrum is adopted which allows the analysis of a range of flow conditions. Results show that noise energy can have an important contribution on the total measured energy, mainly in low energy flows. However in those cases, the noise energy level can be defined from the spectrum because the characteristic frequency is smaller than the Nyquist frequency. After the noise energy level is defined, corrections to the rest of the turbulent parameters (length and time scale, convective velocity, etc) must be performed.

Introduction

The presence of noise in water velocity signals obtained using Acoustic Doppler Velocimeter (ADV) and techniques to reduce its effect in the computation of turbulence parameters obtained from these signals have been the focus of several papers in recent years (Lohrmann et al., 1994; Nikora et al., 1998; Voulgaris et al., 1998 and McLelland et al., 2000). Even when all the possible precautions suggested by the manufacturers are taken (correlation ρ and signal to noise ratio SNR within defined ranges) the signal will have a noise level that affects the values of the turbulence parameters. According to McLleland et al. (2000), there are 3 sources of errors in ADV measurements: sampling errors that are hardware controlled, Doppler noise, and errors due to velocity gradients in the sampling volume. Nikora et al. (1998) and Sontek (1997) affirm that the main physical contributor to the error is the Doppler noise which is affected by the finite residence time for suspended particles in the sampling volume (new particles in the sampling volume contribute a phase signal completely uncorrelated to the phase of the other particles), small turbulence scales (at scales smaller than sampling volume, which causes particle scattering) and beam divergence (the angle between the 3D water velocity vector and the propagation direction of the pulse changes slightly since the pulse spreads spherically with distance from the transducer). The Doppler noise has the characteristics of white noise (Nikora et al., 1998; Lemmin et al., 1999 and McLelland et al., 2000) with
a Gaussian probability distribution of its values (Nikora et al., 1998) as well as a flat power spectrum (Anderson et al., 1995). Lemmin et al. (1999) affirm that the spectral density plateau often observed in the high wave number part of the spectrum definitely indicates the presence of uncorrelated noise.

The fact that white noise presents the same energy level for all the frequencies makes it impossible to subtract its effects from the temporal series by using digital filters: however, its integral effects can be subtracted from some turbulence parameters. White noise does not affect the computation of the mean values because it has zero mean. However, the mean value of a fluctuating velocity will vary with each realization. If each individual estimate of the mean is independent and unbiased, then the standard deviation of the estimates of mean velocities, $\sigma(U)$, is related to the standard deviation of the individual estimates $\sigma(u)$ (Gordon et al., 2000 and Newbold, 1991). The higher the noise component in the signal, the higher the standard deviations of the individual velocity estimates and thus, the higher the values of the standard deviation of the estimates of mean velocities. In low turbulence flow, the noise component represent a good portion of the $\sigma(u)$.

Nikora et al. (1998), Voulgaris et al. (1998) and McLelland et al. (2000) showed that Reynolds stress computations are not affected by the presence of the white noise. Lohrmann et al. (1994) considered that the Reynolds stresses can be accurately determined even at levels below the Doppler noise. Besides, Nikora et al. (1998) show that estimates of turbulent kinetic energy are limited by the Doppler noise because the turbulent kinetic energy is biased high. However, Lohrmann et al. (1994), Nikora et al. (1998) and Gordon et al. (2000) affirm that the contributions of noise over the total energy can be considered negligible for flows with high levels of turbulence, such as boundary layers.

The Doppler noise produces decorrelation of the signal and hence the autocorrelation function reduces its value to zero faster than in signals without noise. Consequently, the temporal scales obtained from this function are biased low. On the other hand, velocity spectra for horizontal velocity components are biased high due to the presence of the Doppler noise while for the vertical velocity the noise is negligible small (Lohrmann, 1994 and Nikora et al., 1998). Assuming that the noise and the turbulent fluctuations are decorrelated, it can be shown (Nikora et al. 1998) that the spectrum of the resulting measurement is the sum of the turbulent spectrum plus the noise level. Nikora et al. (1998) identified the Doppler noise as a flattening of the spectrum as they approach to the Nyquist frequency. They found that in the worst case the flattening may take place around 4-5Hz for the horizontal velocity but more typically in the range of 5-10Hz.

**Doppler noise detection**

The first step in the analysis of signals that have intrinsic noise consists of detecting the energy level of the white noise for each velocity component.
In low energy flow, the energy level of the white noise can be identified in a power spectrum as a flat plateau at high frequencies. Nikora et al. (1998) suggested that empirical spectra of the Doppler noise can be replaced by straight horizontal lines whose ordinates are equal to the average of noise spectral ordinates. The first method to detect noise levels discussed here is called “spectral analysis” by Voulgaris et al. (1998). They calculate the noise energy as the variance using the noise energy level detected in the tail of the spectrum (frequency range is chosen so that there are 10 estimates for the calculation of the statistically significant average, i.e. 11.5-12.5Hz for sampling frequency = 25Hz).

Nikora et al. (1998) defined a characteristic frequency $f_n$ that defines a boundary in the power spectrum between two regions. The first region corresponds to frequencies smaller than $f_n$ where the turbulence energy is much larger than the noise energy. In the other region, for frequencies higher than $f_n$, turbulence energy is weaker than the noise energy. If the frequency $f_n$ is smaller than the Nyquist frequency ($f_R/2$), the flat plateau in the spectrum would be visualized. In those cases, the spectral analysis technique to estimate the noise energy level could be applied. This method becomes a very good approximation to determine the noise energy level, however, for high-energy flows, the plateau cannot be distinguished in the spectrum, yet it does not imply that the signal does not have intrinsic noise. In these cases, different methodologies were suggested to estimate the noise level (Nikora et al., 1998; Voulgaris et al., 1998 and McLelland, 2000), which have an inconvenience. They mainly assume that the noise level of signal is the same if the instrument configuration and flow conditions do not change. It implies that the users are recording the same signal quality each time that the instrument with the same configuration (sampling frequency, velocity range, etc) is sampling the same flow conditions. However, there are certain conditions which cannot be controlled by the users during the measurement (i.e. level of seeding particles, bubbles, etc.) which strongly affect the quality of the signal (Nikora et al., 1998, and Lemmin et al., 1999), and thus, the noise level. Sontek (1997) suggested that estimation of the Doppler noise from a pulse coherent system (as Voulgaris et al., 1998 and McLleland et al., 2000 do) is a complicated function and that for practical systems it provides at best a lower bound for instrument noise level.

**Evaluation of the Doppler noise effect on the total turbulent energy**

**Conceptual framework**

Some issues must be discussed based in the information cited before. The most accurate methodology presented before to detect the noise energy level which is recognized by different authors (Nikora et al., 1998, Voulgaris et al., 1998) is the “spectral analysis”. This technique does not work for cases where the noise plateau in the spectrum is not clearly developed (highly turbulent flow). However, the noise Doppler effects are not important for these flow conditions (Lohrmann et al., 1994, Nikora et al., 1998, and Gordon et al., 2000). Some tools are introduced here to evaluate the relative importance ($E$) of the noise energy over the real turbulent energy for the different flow conditions.
$E = \frac{\left(\sigma^2_n\right)}{\left(\sigma^2_m-\sigma^2_n\right)}$

Here $\sigma^2_n$ is the noise energy, $\sigma^2_r = \sigma^2_m - \sigma^2_n$ is the real turbulent energy and $\sigma^2_m$ is measured turbulent energy. The ratio $E$ allows quantifying the importance of estimating the noise effects in high energy flows where spectral analysis technique does not work.

To define the real flow parameters, a three dimensional power spectrum model (Pope, 2000) that resemble realistic conditions including all the turbulence characteristics for specified flow conditions was used. The input parameters of the model are energy-containing-eddy length scale, $L$, and Kolmogorov length scale $\eta$ (which can be estimated from the value of the turbulent kinetic energy dissipation rate, $\varepsilon$, of the flow). The three dimensional energy-spectrum function, $E(\kappa)$ predicted by Pope’s model is given by

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

where $C$ is a constant, $\kappa$ is the wavenumber and $f_L$ and $f_\eta$ are shape functions defined as

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

$$f_\eta(\kappa \eta) = \exp\left\{ -\beta \left[ (\kappa \eta)^4 + c_\eta^{4/3} \right]^{1/4} - c_\eta \right\}$$

The function $f_L$ defines the shape of the energy containing eddy part of the spectrum (equal to 1 for large $\kappa L$) and $f_\eta$ describes the shape of the dissipation range (equal to 1 for small $\kappa \eta$). Following Pope (2000) the parameters adopted for this model are: $p_o = 2$, $c_L = 6.78$, $c_\eta = 0.40$, $\beta = 5.2$.

A one-dimensional model spectrum, $E_{11}(\kappa_1)$, is required in this analysis (it is the spectrum which can be obtained for a ADV time signal of each velocity component). 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 García et al., 2004).

To evaluate the relative importance of the noise energy on the real turbulent energy, each of the model spectra obtained from the simulation of different flow conditions is integrated up to the Nyquist frequency to compute the turbulent flow energy for the specified flow conditions. Then, this energy value is compared with a noise energy computed using the white noise characteristics of the Doppler noise. Thus the noise energy is obtained as the product of the noise energy level $E_{11n}$ and the Nyquist frequency $f_R/2$.

A set of numerical simulations based on the model proposed before 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. The variables used in this part of the analysis are: $U_c$, $L$, $\eta$, $E_{1/n}$ and $f_R$. The last is defined by the instrument configuration and $U_c$ is the convective velocity used to convert from the spatial domain (model spectrum) to time domain (spectrum obtained from ADV time signal). A number of synthetic turbulent water velocity signals with $t = 0.0038$ sec were generated as realizations of different flow conditions. The ranges of flow variables used in the simulations are: $0.01 \text{m/s} \leq U_c \leq 1 \text{m/s}; 0.10 \text{m} \leq L \leq 2 \text{m}; 0.0001 \text{m} \leq \eta \leq 0.005 \text{ m}$. The range of Kolmogorov length scales proposed here generates a range of 7 orders of magnitude in $\varepsilon (1.6\times10^{-9} \text{m}^2/\text{s}^3 \leq \varepsilon \leq 1\times10^{-2} \text{m}^2/\text{s}^3)$, describing conditions prevailing in most environmental water flows. A range of noise energy level typical of ADV measurements is considered here based on the writers experience and previous research (Nikora et al., 1998). Here, $10^{-5} \text{m}^2/\text{s} \leq E_{1/n} \leq 10^{-7} \text{m}^2/\text{s}$

A complementary analysis is related to the definition of the characteristic frequency $f_n$ for the flow conditions and instrument configuration cited before. Values of $f_n$ smaller than the Nyquist frequency indicate that the flat plateau in the power spectrum can be detected. Thus the spectral analysis technique to define the noise energy level can be used. Using the fact that the measured energy power spectrum is the sum of the real energy spectrum and the noise spectrum (Nikora et al., 1998), a set of measured energy spectra was built for the different flow conditions and noise energy level. The frequency $f_n$ is defined as the frequency where the real flow energy is equal to the noise energy. Above this frequency, noise is the more important component in the measured power spectrum.

**Results**

The energy ratio $E$, is plotted in Figures 1 to 4 as a function of the Kolmogorov length scale $\eta$ and the energy containing eddy length scale $L$ for different flow convective velocities $U_c$. The ratio $E$ decreases as the energy-containing-eddy length scale increases and $E$ increases as $\eta$ increases, i.e. noise is less important for energetic flows.

Figures 1 and 2 represent the same set of variables but different convective velocity. It can be concluded from these figures that $U_c$ is not a relevant parameter describing the behavior of $E$.

A region can be defined in Figures 1, 3 and 4 (darker area) which is disregarded in the analysis because of the requirements suggested by Garcia et al. (2004) through the analysis of the Acoustic Doppler Velocimeter Performance Curves (APCs), where a dimensionless number $F = \frac{f_R L}{U_c} > 20$ is required to obtain a good description of the flow turbulence because of the ADV filtering techniques used in the processing of the recorded signal (Garcia et al., 2004). For $F > 20$ and the conditions represented in figures 1, 3 and 4 ($f_R = 25 \text{Hz}$ and $U_c = 0.5 \text{m/s}$), turbulent energy in flows with $L < 0.4 \text{m}$ will not be well represented. Following, only flow conditions and instrument configuration which allow a good representation of the flow turbulence will be analyzed. For that reason, the dark area in Figures 1, 3 and 4 is not going to be included in the analysis.
Figure 1 shows that the highest ratio $E$ predicted for $\eta \leq 0.0005$m (which is representative of most of the laboratory and field experiments) and the noise energy level $E_{11n} = 10^{-6}$ m$^2$/s is 7%. For flows with $L > 0.7$m, this ratio $E$ is lower than 5%. Figure 4 shows that the ratio $E$ is lower than 5% for all the possible flow conditions and instrument configuration which satisfy the APC requirements at $E_{11n}=10^{-7}$ m$^2$/s. However, Figure 3 ($E_{11n} = 10^{-5}$ m$^2$/s) deserves special attention because for most of the conditions the ratio $E$ remains with values higher than 10% which indicates that noise energy must be subtracted in these conditions because of its importance.

The detected values of the frequency $f_n$ are plotted in Figures 5 to 6 as a function of the Kolmogorov length scales ($\eta$), for three different convective velocities ($U_c$). In this analysis the eddy-containing-eddy length scale is found to be not a relevant parameter. The plots show that the higher the value of $\eta$ the smaller the frequency where the noise is detected. Recall that higher $\eta$ implies lower energy flow. Besides, it can observed that the faster $U_c$, the higher the value of the frequency $f_n$.

Figures 5 shows the case which deserve more attention according to the analysis performed before ($E_{11n} = 10^{-5}$ m$^2$/s) because it presents the highest ratio $E$ (Figure 3). For all the flow conditions where $\eta > 0.00025$m, the frequency $f_n$ is lower than Nyquist frequency ($f_R/2$) if a user-defined sampling frequency $f_R = 25$Hz is used. It can be observed in Figure 3 that flow and sampling conditions which satisfy the requirements imposed for the APC (resolving the flow turbulence) with $\eta < 0.00025$m present values of ratio $E < 10%$. In cases where the ratio $E$ is higher than 10% ($\eta > 0.00025$m) the noise floor can be detected from the measured spectrum, and thus the spectral analysis technique to estimate the noise energy level can be used.

For the value of noise energy level, $E_{11n} = 10^{-6}$ m$^2$/s, the ratio $E$ is lower than 10% for Kolmogorov length scales $\eta \leq 0.0006$m (Figure 1). Therefore, two regions can be defined in Figure 6: for one of them ($\eta > 0.0006$m) the noise energy is important and it must be corrected. For this entire region, $f_n < 12.5$Hz. Thus using a defined user sampling frequency $f_R = 25$Hz, the noise plateau will be observed in the spectrum.

In the cases where the noise energy is important in relation to the real turbulent energy of the signal, the noise energy level can be computed using the analysis spectral method because the white noise plateau is observed in the power spectrum (Figures 3 and 5). In cases of very high energy flow (or very small noise energy level), this method can no be used, however the noise energy is smaller than 10% of the real total energy.

**Validation**

The proposed tools includes in Figures 1 to 6 are validated using water velocity signals recorded at several facilities by researchers of the Hydrosystems Laboratory of the University of Illinois at Urbana – Champaign. Because it is very difficult to set a priori a defined noise energy level, instead of comparing just one curve, a pair of curves is used to define a range of values of $E_{11n}$. The results are included in Figure 7 and 8. For the Figure 7, the ranges of variables observed in the experiment: 0.05m/s<\(U_c<0.21\)m/s, 4.46E+4m < $\eta$< 6.29E+4m and 1.21E-6m$^2$/s<$E_{11n}$<7.7 E-6m$^2$/s. In this figure, the lower
bound curve represent $E$ ratio obtained for $\eta=0.0005m$, $E_{11n}=1E-6m^2/s$ and $Uc = 0.5m/s$. The upper curve represent the $\eta=0.0005m$, $E_{11n}=1E-5m^2/s$ and $Uc = 0.01m/s$ conditions.

For the Figure 8, the ranges of variables observed in the experiment are: $0.05m/s<Uc<0.21m/s$, and $1.06E-6m2/s<E_{11n}<7.7 E-6m2/s$. In this case, the upper bound curve represent $E$ ratio obtained for $E_{11n}=1E-6m^2/s$ and $Uc = 0.5m/s$. The lower curve represent the $E_{11n}=1E-5m^2/s$ and $Uc = 0.01m/s$ conditions.

The observed behavior of the experimental results (dots) in both figures agrees well with predictions from the theory.

**Doppler noise correction on the turbulent parameters**

Using the noise energy level determined before, the following step consists of subtracting the noise effects from the hydraulics parameters. For that, the hypothesis that noise and velocities fluctuations are uncorrelated is used. It can be proved experimentally that the electronic related component of the noise is independent of the flow characteristics. The flow related component depends of the mean flows characteristics but even in this case it can be shown that the velocity fluctuations and the noise are uncorrelated.

The noise effect can be removed firstly from the spectrum using energy noise level defined before. It consists simply of subtracting this level for the measured spectra. Thus the corrected spectra for each velocity component are obtained. The area below the power spectrum in the frequency domain is the variance. Using the corrected power spectra, the corrected variances for each component are computed, and from those the turbulent kinetic energy is obtained. Because, the signal can not be filtered after the noise level is detected, alternatives methodologies to compute corrected estimators of the autocorrelation function and the time scales related to it must be developed. The methodology proposed here consists of computation of autocorrelation function using the inverse fast Fourier transform of the power spectrum corrected previously corrected. Thus, the white noise effect can be removed and the time scales derived from this function will have more realistic values.

**Conclusions**

Doppler noise constitutes the main error source in ADV measurements and its effects on the turbulent parameters computed from these signals must be quantified and removed in certain cases. The spectral analysis method provides the most realistic energy Doppler noise level. However it cannot be used in high turbulent energy flows where the characteristic frequency $f_n$ (where the noise is detected as a flat plateau in the spectrum) is higher than the Nyquist frequency. It is proved here that in those cases that the technique can not be applied the Doppler noise contribution to the total measured energy is lower than 10%. After the noise energy level is detected, noise effects must be subtracted from estimators of the autocorrelation function, convective velocity, length and time scales and rate of dissipation of turbulent kinetic energy.
References


Figures

Figure 1: The ratio $E$ for $U_c = 0.5 \text{ m/s}$, $f_R = 25 \text{Hz}$ and $E_{11n} = 10^{-6} \text{ m}^2/\text{s}$

Figure 2: The ratio $E$ for $U_c = 0.01 \text{ m/s}$, $f_R = 25 \text{Hz}$ and $E_{11n} = 10^{-6} \text{ m}^2/\text{s}$

Figure 3: The ratio $E$ for $U_c = 0.5 \text{ m/s}$, $f_R = 25 \text{Hz}$ and $E_{11n} = 10^{-5} \text{ m}^2/\text{s}$

Figure 4: The ratio $E$ for $U_c = 0.5 \text{ m/s}$, $f_R = 25 \text{Hz}$ and $E_{11n} = 10^{-7} \text{ m}^2/\text{s}$

Figure 5: The characteristic frequency $f_n$ for $f_R = 25 \text{Hz}$ and $E_{11n} = 10^{-5} \text{ m}^2/\text{s}$
Figure 6: The characteristic frequency $f_n$ for $f_R=25\text{Hz}$ and $E_{11n} = 10^{-6} \text{ m}^2/\text{s}$

Figure 7: Validation of the ratio $E$ curves

Figure 8: Validation of the characteristic frequency $f_n$