Velocímetros acústicos Doppler: Caracterización de flujos turbulentos en ingeniería hidráulica

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Outline

1. Turbulent flows
2. Experimental characterization of turbulent flows
3. Acoustic Doppler velocimeter (ADV)
4. Sampling, signal processing and turbulence parameters computation

The nature of turbulent flows

The flow is unsteady, irregular, random and chaotic.

(http://www.davis.k12.ut.us/)

The nature of turbulent flows

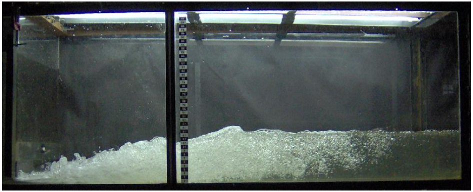
Turbulent motions of many scales.

(http://fuckyeahfluiddynamics.tumblr.com/)

More detailed observations in laboratory experiments

Breakup of an aircraft engine turbulent liquid fuel jet injected into a compressed turbulent gaseous cross-stream.

Courtesy of M. Herrmann



Hydraulic jump formed downstream a sluice gate.

Courtesy of E. Trierweiler

The study of turbulent flows (Pope 2000)

Navier-Stokes equations (1845)
(laminar or turbulent fluid flows)

- Modelling: theoretical studies, aimed at developing tractable mathematical models that can accurately predict properties of turbulent flows.
- Discovery (the process of finding information): experimental (or simulation) studies aimed at providing qualitative or quantitative information about particular flows.

Experimental characterization
of turbulent flows

The study of turbulent flows

Experimental characterization of turbulent flows

Flow visualizations

Flow measurements

Flow measurements

Defining the optimun...

- Measurement technique.
- Sampling configuration, signal processing and turbulence parameters computation (including confidence intervals).

...in order to accurately characterize turbulent flow.

Measurement technique

| PIV | Hot-wire | LDA | ADV | UVP | PTV | ADCP |

⟶

Laboratory → Field

(scale of experimental facilities)

Sampling, signal processing and data analysis techniques.

Requirements for making the water velocity signal representative of the turbulent process in the water.

- Sampling strategy (sampling frequency and sampling time).
- Error analysis (adequate signal post-processing).
- Computation of turbulence parameters (including confidence intervals).

Flow measurements

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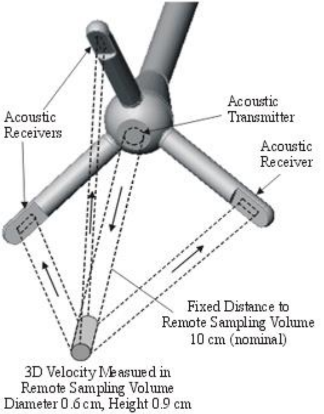
Acoustic Doppler velocimeter (ADV)

Courtesy of Sontek®

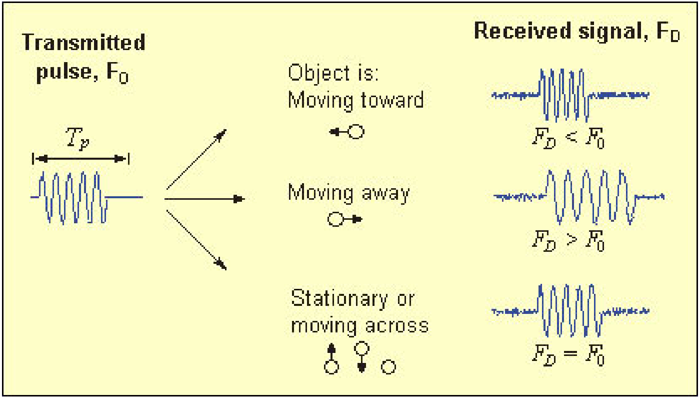
Acoustic Doppler velocimeter (ADV)

ADV measures 3-D water velocity components in a remote sampling volume using the shift Doppler principle.



Courtesy of Sontek®

The Doppler effect



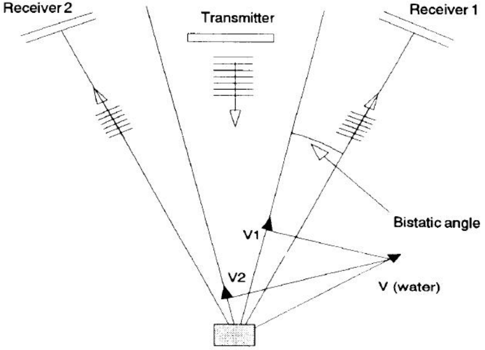
Courtesy of Sontek®

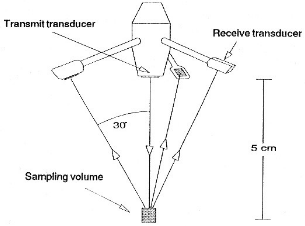
ADV acoustic operation

Single-Pulse (ADCPs)	• Measures shift in frequency between emitted and reflected pulses. • Spatial resolution is a function of the frequency of the emitted pulse (3m-3MHz and 100m-500KHz).
Pulse-to-Pulse Coherent (ADVs)	• Measures the phase shift between the reflected pulses at time t and $t + \tau$. • Higher spatial resolution (1cm-10MHz). • Introduces ambiguity errors (aliasing).

Determination of bistatic velocity

$$v_i = \frac{C}{4\pi f_{ADV}} \frac{d\phi}{dt}, \quad i = 1, 2, 3.$$

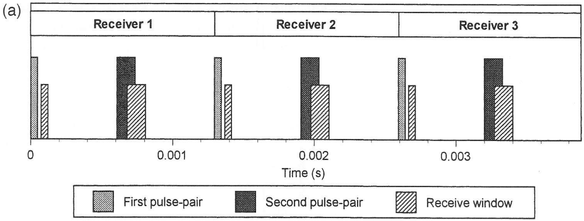




Courtesy of C. Kraus

Dual pulse repetition rate

Unequal pulse repetition rates, τ_1 and τ_2, separated by τ_D.



Courtesy of S. McLellands

$$T_s = 3(\tau_1 + \tau_D + \tau_2 + \tau_D)$$

Cartesian coordinate system transformation

Bistatic velocity $(v_i) \rightarrow$ Cartesian coordinate system (u_i).

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix}$$

the transformation matrix a_{ij} is provided by the manufacturer.

ADV computes velocity u_i at $f_s = 1/T_s$

Sampled and recorded velocity

Filtering effects due to the sampling strategy used by ADVs.

- ADV samples velocity at f_s.
- User records velocity at f_R.

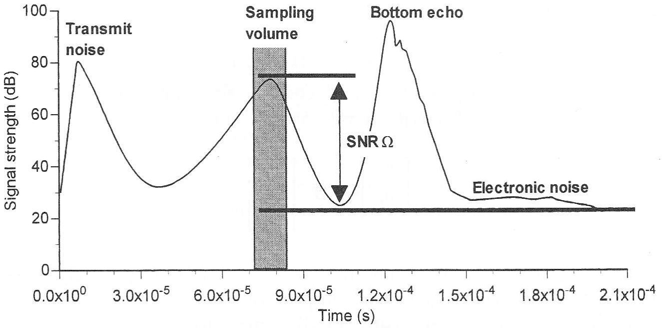
Instrument velocity range (cm s^{-1})	Dual pulse-pair spacing ($\times 10^{-6}$ s)		Velocity measurement time T ($\times 10^{-3}$ s)	Number of dual pulse-pairs measured during sample period M		
	τ_1	τ_2		1 Hz	25 Hz	100 Hz
250	40	104	3·792	263	10	2
100	48	128	3·888	256	9	2
30	112	240	4·416	226	8	1
10	240	480	5·520	180	7	1
3	400	800	6·960	143	5	1

Courtesy of S. McLellands

User records velocity u_i at f_R

ADV data validation

Signal-to-Noise Ratio (SNR) > 15dB.

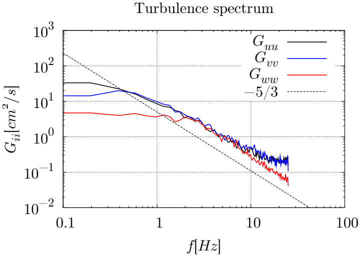


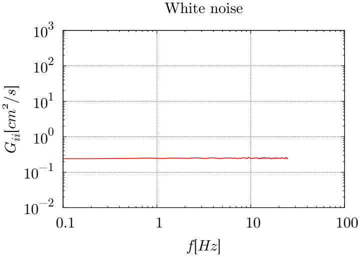
Courtesy of S. McLellands

ADV data validation

Correlation (COR) > 70%.

Low COR values indicates loss of coherence during pulse propagation through the fluid (Doppler noise).





to keep in mind...

- Pulse-to-pulse coherent method and ambiguity errors (spikes).
- Acoustic technique and loss of coherence during pulse propagation through the fluid (Doppler noise).
- Sampling strategy and f_s and f_R (filtering effects).

Flow measurements

Defining the optimun...

- Measurement technique.
- Sampling configuration, signal processing and turbulence parameters computation (including confidence intervals).

...in order to accurately characterize turbulent flow.

Definition of the optimum sampling configuration

Determination of the sampling time T_{serie}.

$$T = L/U_c$$

- T is the turbulence time scale.
- L is the energy containing eddy length-scale.
- U_c is the convective velocity.

$T_{serie} \geqslant 20T$ for mean velocity ($\varepsilon < 10\%$).

$T_{serie} \geqslant 400T$ for variance and power spectrum ($\varepsilon < 5\%$).

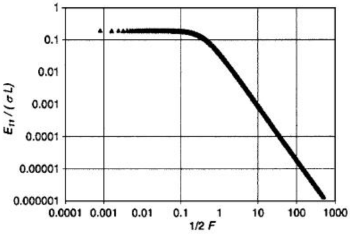
Definition of the optimum sampling configuration

Determination of the sampling frequency f_R.

Dimensionless frequency

$$F = f_R L / U_c > 20.$$

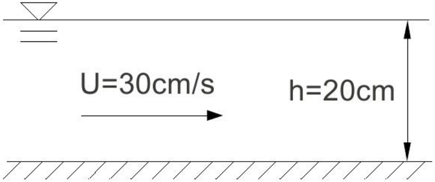
- f_R is ADV recording frequency.
- L is the energy containing eddy length-scale.
- U_c is the convective velocity.



Courtesy of C. M. García

Example - Open Channel flow

Sampling time T_{serie} and sampling frequency f_R?.



Signal processing and turbulence parameters computation including uncertainty analysis

Sources of error in ADV's turbulence measurements.

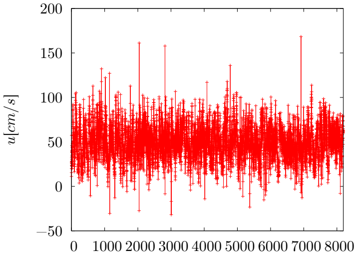
- Spikes.
- Doppler noise.
- Filtering effects.

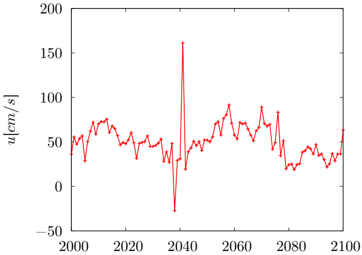
Uncertainty analysis for defining confidence intervals.

- Moving Block Bootstrap method (MBB).

Sources of error - Spikes

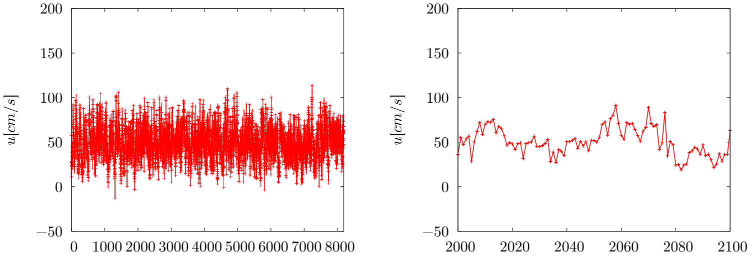
Raw turbulence water time signal (open-channel flow laboratory).





Sources of error - Spikes

Identification and replacement of spikes using PSTM algorithm (Goring and Nikora 2002).



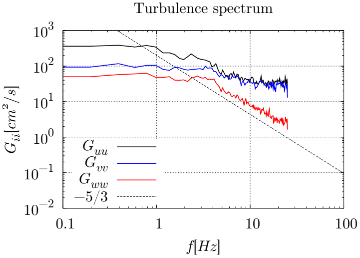
Sources of error - Doppler noise

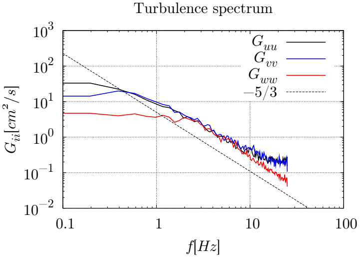
White noise characteristics (Voulgaris and Trowbridge 1998).

- Doppler noise do not affect mean velocities (its mean is equal to zero).
- Reynolds Stresses are not affected by Doppler noise.
- Doppler noise produces decorrelation of the signals. Thus, temporal scales are low biased.
- Turbulent kinetic energy is biased high.

Sources of error - Doppler noise

Identification and quantification (plateau at high frequencies).





Sources of error - Filtering effects

Due to ADVs digital averaging (García et al. 2005).

- $f_s = 1/\Delta t_x$ ADV sampling frequency.
- $f_R = 1/\Delta t_y = f_s/N$ recording frequency.

Conceptual model

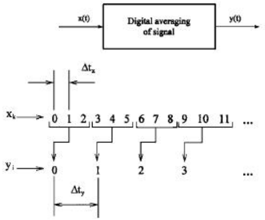


Fig. 1. Digital averaging of water velocity signal for $N=3$. Acoustic Doppler velocimeter acquires a water velocity signal x at frequency f_S and then processes it (digital averaging) into y which is the velocity signal recorded at frequency f_R ($f_S=N\,f_R$, $\Delta t_x=1/f_S$, and $\Delta t_y=1/f_R$).

Courtesy of C. M. García

Sources of error - Filtering effects

On variance.

- $F = f_R L / U_c \approx 20$, filtering is about 10% (variance at f_R is 90% of the variance at f_s).

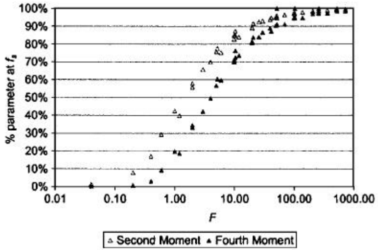


Fig. 5. Effects of digital averaging on second- and fourth-order moments of the water velocity signals. For $F = f_R L / U_c = 20$, the second- and fourth-order moments of the signal sampled at frequency f_R are about 90 and 80%, respectively, of the values of the parameters of the signal sampled at frequency f_S.

Courtesy of C. M. García

Uncertainty analysis - confidence intervals

Statistical errors due to sampling a random signal
Moving Block Bootstrap method (García et al. 2006).

- Block length and turbulence integral time scale.

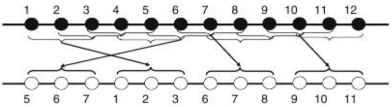
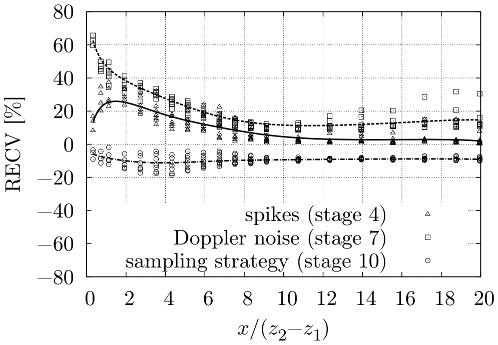


Fig. 1 A schematic diagram of the MBB for time series using a block length equal to three samples. The *black series* represents the original time series and the *white circles* denote one of the bootstrap realizations using MBB. *Numbers indicate* the sample order in the original signal (Adapted from Efron and Tibshirani 1993)

Courtesy of C. M. García

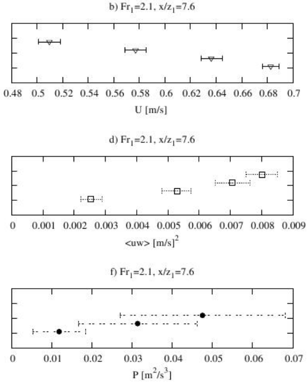
Sources of error - Variance computation

Romagnoli, García and Lopardo (2011b) "Signal post-processing technique and uncertainty analysis of ADV's turbulence measurements on free hydraulic jumps" Journal of Hydraulic Engineering, ASCE.



Confidence intervals

Romagnoli, García and Lopardo (2011a) Discussion of "Energy dissipation and turbulence production in weak hydraulic jumps" by E. Mignot and R. Cienfuegos. Journal of Hydraulic Engineering, ASCE.



- U is lower than 3% of measured values.
- $< uw >$ between 15% and 60% of measured values.
- $< uw > dU/dz$ between 40% and 200% of measured values.

Collaboration

- Universidad Nacional de Córdoba, Facultad de Ciencias Exactas, Físicas y Naturales.
- Universidad Nacional del Litoral, Facultad de Ingeniería y Ciencias Hídricas.
- Instituto Nacional del Agua.

Research group UNR

Thanks!