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Master's Thesis

LARGE TURBULENCE SCALES IN FREE-SURFACE FLOWS

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Abstract

Turbulence in free-surface flows plays a fundamental role in environmental fluid dynamics, governing the transport of sediments, pollutants, and nutrients. A predominant fraction of turbulent kinetic energy and transport is conveyed by coherent structures, known as Large-Scale Motions (LSMs) and Very-Large-Scale Motions (VLSMs), massive turbulent aggregates extending over multiples of the bulk flow depth. Although extensively documented in canonical wall-bounded flows and laboratory channels, their field-scale experimental investigation is limited by operational complexities and instrumental noise. Consequently, the quantitative characterization of these dynamics in natural contexts remains an open research field.

This thesis bridges this gap by investigating the kinematics and energetics of macro-turbulence in a free-surface flows under field conditions. Data were collected at the Cavo Lucca artificial channel. This site was selected following a preliminary investigation to ensure steady, uniform flow within a straight reach; a bathymetric survey mapped the bed to verify the absence of submerged obstacles. The channel, operating in a subcritical regime with a bulk Reynolds number $Re_b \approx 10^6$ (fully developed turbulence, significantly exceeding laboratory scales), was monitored using acoustic Doppler velocity profilers (UB-Lab).

Raw data from Cavo Lucca underwent rigorous pre-processing to isolate surface wave-induced oscillations and remove background acoustic noise. The flow field analysis utilized an advanced spectral algorithm based on the Multi-Resolution Welch method. This adaptive approach allowed the calculation of Power Spectral Densities (PSD) over a broad frequency domain, capturing low-frequency VLSMs while preserving statistical convergence in the inertial range, characterized by the Kolmogorov $k^{-5/3}$ spatial decay.

To make the results universal and directly comparable with datasets acquired under vastly different hydrodynamic and geometric conditions, the pre-multiplied spectra have been rigorously dimensionless. This enabled comparing the energy peaks of turbulent macro-scales across different settings. To validate field results, the analysis was compared against laboratory data (Peruzzi et al., 2020) that had demonstrated these macro-structures in controlled environments, motivating the study of their persistence in real-world contexts. To overcome the statistical confidence limits of these historical data acquired over limited time windows, new long-duration measurement campaigns were conducted using Laser Doppler Anemometry (LDA), thereby significantly reducing the statistical uncertainty of the reference dataset.

The evidence demonstrates substantial topological and energetic consistency between field and laboratory measurements, providing concrete proof of the persistence of VLSMs in the real hydraulic boundary layer, with wavelengths proportional to the bulk flow depth. Although further in-situ investigations are required, the study offers a solid methodological framework. Understanding the energy distribution of such large-scale structures is crucial in environmental engineering for optimizing morphodynamic modeling, allowing for a more accurate evaluation of erosion processes, sediment transport, and pollutant dispersion.

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Introduction

The study of turbulent flows in free-surface flows plays a central role in hydraulics and environmental fluid dynamics, both for the fundamental aspects related to the understanding of mixing mechanisms, and for the direct application repercussions in the engineering field. Among the most relevant macro-structures that characterize the flow field are the Large Scale Motions (LSM) and the Very Large Scale Motions (VLSM), coherent structures of large extension that carry a preponderant fraction of turbulent kinetic energy and momentum transport (Marusic et al., 2010 00; Jiménez, 2018 [II][II]).

In recent years, the topology and kinematics of such structures have been widely documented in confined wall flows, such as boundary layers and pipe flows (Hutchins & Marusic, 2007a [III]; Monty et al., 2009 0).

More recently, experimental investigations have been extended to open channel flows, revealing significant peculiarities. Due to the dynamic boundary condition represented by the free surface, VLSMs are observable even at relatively low values of the friction Reynolds number, extend vertically occupying the entire water flow depth and show a marked dependence on the shape ratio of the cross-section (Peruzzi et al., 2020 136[V]). These characteristics make their study crucial: the understanding of their spatial architecture is in fact crucial for modelling complex environmental processes, such as sediment and pollutant transport, the morphodynamical evolution of riverbeds and energy dissipation in watercourses (Cameron et al., 2019 **Errore. L'origine riferimento non è stata trovata.**).

The present thesis is part of this open line of research, with the main objective of characterizing the kinematic and energetic characterization of VLSMs in real field conditions, thus overcoming the intrinsic scale limitations of experiments in a controlled environment. The monitoring campaign was conducted at the Cavo Lucca artificial canal, operating in fully developed turbulent conditions. The selection of the site was the result of careful preliminary validation: by means of accurate bathymetric surveys, the absence of macro-roughness or submerged obstacles was guaranteed, ensuring the establishment of a stationary and uniform motion, preparatory to reliable measurements.

From a methodological point of view, the flow field analysis focused on the advanced processing of the velocity signal recorded by the Doppler acoustic instrumentation. Through the study of power spectra, the goal was to filter background noise to unequivocally isolate the energy signatures attributable to macro-structures. The results obtained in situ were finally validated through a rigorous comparison with the evidence in the literature, in particular with the recent laboratory datasets of Peruzzi et al., 2020 [V], in order to verify the spatial persistence and phenomenological universality of these turbulent aggregates also in real environmental fluid dynamics.

1. Theoretical foundations of turbulence

1.1 Turbulent flows

Fluid mechanics basically distinguishes two regimes of motion: the laminar regime and the turbulent regime. If the former represents a condition of an almost geometric order, in which the sheets of fluid flow over each other without stirring, the latter constitutes the norm in almost all engineering applications and natural phenomena. Turbulence can be defined as a state of fluid motion characterized by an intrinsic chaotic, high diffusivity and strong three-dimensional rotationality.

Despite more than a century of study, a rigorous and comprehensive mathematical definition of turbulence remains one of the most complex open challenges in modern physics. It is not an intrinsic property of the fluid (as density or viscosity are), but it is a property of motion itself. A turbulent flow manifests as a tangle of overlapping vortex structures, called vortices, that interact with each other by exchanging energy and momentum.

The distinctive features that make turbulence a unique phenomenon are mainly three:

1. Irregularities: The motion appears random in time and space, making it impossible to deterministically predict the trajectories of individual particles; This requires a statistical approach.
2. Diffusivity: Turbulence dramatically accelerates the mixing and transport of mass, heat, and momentum. It is thanks to turbulence that a pollutant is dispersed in a river or that oxygen mixes in the water.
3. Dissipation: Turbulence is a highly dissipative phenomenon. Kinetic energy is transferred from large macroscopic scales to microscopic scales, where viscous forces transform it into internal heat.

Studying turbulence in free-surface flows, the subject of this work, means investigating how these vortex structures interact with solid boundaries (the bottom of the channel) and with the air-water interface. In particular, attention is focused on *large scales*, i.e. those vortices whose dimensions are comparable with the geometric scale of flow. These structures are not simple random fluctuations but are coherent structures that govern the global dynamics of the current, the transport of sediments and the resistance to motion, representing the beating heart of the hydraulic phenomenology.

1.1.1 The Reynolds experiment and the transition to the turbulent regime

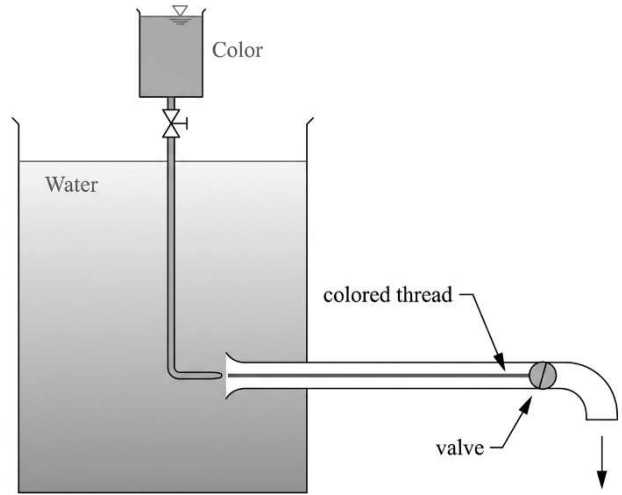
The modern analysis of turbulence finds its historical and scientific foundation in the pioneering work of Osborne Reynolds who, in 1883, conducted a series of experiments to understand the laws governing the motion of fluids. Before Reynolds, there was no single criterion for determining when a flow would behave in an orderly or chaotic manner. His intuition was to identify a dimensionless parameter capable of grouping the geometric and kinematic properties of the current.

The original experiment consisted of a resting water tank connected to a horizontal glass duct. At the mouth of the pipe, Reynolds placed an injector of tracer liquid (actually, a dye such as fluorescein is used) to visualize the flow lines. The velocity of the fluid in the pipe was regulated with extreme precision by means of a valve located at the end of the drain.

Through the observation of the colour filament as the velocity (U) varies, Reynolds identified three distinct regimes:

1. **Laminar Regime ($Re < 2000$):** The dye is maintained as a straight and well-defined line along the axis of the tube. Fluid particles move in parallel trajectories and cross-exchanges are due exclusively to molecular diffusion. In this state, viscous forces are dominant and dampen any disturbance.
2. **Transition Regime ($2000 < Re < 3000$):** As the speed increases, the filament begins to show the first wave instabilities. The motion is no longer perfectly ordered, but it is not yet completely chaotic; intermittent turbulence "bouffées" are observed.
3. **Turbulent Regime ($Re > 3000$):** The colour filament breaks abruptly and the tracer spreads rapidly throughout the tube section. The motion is characterized by three-dimensional fluctuations and the formation of vortices of different sizes that mix the fluid in an extremely efficient way.

Figure 1.1 - Schematic representation of Reynolds' experimental apparatus for characterizing flow regimes. The diagram illustrates the upstream constant-head tank, the axial injection system for the tracer fluid (dye) featuring a control valve, the transparent cylindrical duct equipped with a bell-mouth inlet to minimize entry turbulence, and the downstream outflow valve for controlling the flow rate and varying the Reynolds number.



The parameter introduced, known as the Reynolds Number (Re), is defined by the ratio of inertia forces to viscous forces acting on a fluid volume element:

$$Re = \frac{\text{Inertia forces of the fluid}}{\text{Viscous forces}} = \frac{U \cdot D}{\nu}$$

Where:

- i. U [m/s] is the average velocity of the flow;
- ii. D [m] is the characteristic dimension (in the case of the pipe, the diameter);
- iii. ν [m²/s] is the kinematic viscosity of the fluid.

From a physical point of view, a high Reynolds number indicates that the inertia forces (related to momentum) are so high that they cannot be balanced by the braking action of viscosity. As a result, small disturbances in the flow are not dampened, but amplified, giving rise to the complex structure of turbulence.

It is precisely in the turbulent regime that the large scales that are the subject of this thesis emerge. While Reynolds' experiment visually shows the breakdown of the flow, the underlying physics reveals that energy is fed into the system precisely through these large vortex structures, whose size is comparable with the geometric scale of the domain (in Reynolds' case, the diameter of the tube; in the case of free-surface flows, the depth of the channel).

Although the original Reynolds experiment was conducted inside closed ducts of circular cross-section, the validity of the dimensionless parameter Re is universal, subject to an appropriate choice of characteristic length. In free-surface flows (canals and rivers), which are the subject of this study, the diameter D is replaced by the hydraulic radius (R_h), defined as the ratio between the cross-sectional area and the wetted perimeter, or directly by the hydraulic tie rod (h) in the case of very wide channels. It is crucial to note that critical transition values change dramatically: in a channel, motion is usually considered turbulent for $Re > 500$ (when calculated with

hydraulic radius). This distinction is crucial because the presence of a free surface introduces a dynamic boundary condition that allows the development of surface vortex structures, absent in tubes, which directly affect the large scales of turbulence.

One of the most relevant aspects observed by Reynolds concerns the ability of turbulence to exponentially increase mass transport. While in the laminar regime the tracer moves by pure molecular diffusion (an extremely slow process), in the turbulent regime turbulent diffusion intervenes.

Large scales act as mechanical vectors that grab portions of fluid and transport them transversely to the direction of the flow. This phenomenon, known as mixing, is the reason why turbulence is the main driver of the transport of sediment, oxygen and pollutants in waterways. Without the stirring action of the large vortices, the dynamics of the natural riverbeds would be governed by chemical and physical reaction times incompatible with the observed reality.

Finally, it should be noted that the values of $Re \approx 2000$ and 4000 cited in the literature should not be interpreted as absolute physical constants, but as conventional engineering thresholds. Reynolds himself noted that by minimizing environmental disturbances, machine vibrations, and ensuring perfectly smooth fluid inlet, it is possible to maintain a laminar regime up to much higher Reynolds numbers (even over $10,000$ under extreme laboratory conditions). On the contrary, in a natural riverbed or in an experimental channel, the roughness of the bottom and the geometric irregularities act as "disturbances" that anticipate the transition. This sensitivity to perturbations underlines how turbulence is a phenomenon linked to the interaction between inertia forces and the surrounding environment, making the analysis of large scales even more complex and site-specific.

1.1.2 The statistical approach to turbulence

As observed experimentally by Reynolds, turbulent motion is characterized by an inherently chaotic and apparently stochastic nature. This unpredictability makes a precise deterministic description impossible: although the Navier-Stokes equations govern the phenomenon, the extreme sensitivity to boundary conditions and the overlapping of vortices of different scales make each individual realization of the flow unique and not repeatable in an identical way.

To overcome this complexity, modern fluid mechanics adopts a statistical theory of turbulence. In this context, the physical quantities of the flow field - i.e. the components of instantaneous velocity (u, v, w) and pressure (p) - are treated as random variables.

The goal is no longer to know the exact value of the velocity at any given moment, but to determine its statistical properties through the moments of distribution. Theoretically, if the *Probability Density Function (PDF)* $P(u)$ were known, we could calculate the mean (μ) and variance (σ^2) as follows:

$$\mu = \int_{-\infty}^{+\infty} uP(u)du$$
$$var(u) = \sigma_u^2 = \int_{-\infty}^{+\infty} (u - \mu)^2 P(u)du$$

However, in experimental practice, PDFs are almost never available a priori. The use of statistical estimators, based on a sample of size N (sample of acquired data), is therefore used to approximate the expected value of the quantity:

$$\langle u \rangle = \frac{1}{N} \sum_{i=1}^N u_i$$

This shift from determinism to statistics is fundamental for the study of large scales, as it allows to isolate the average flow behaviour from the turbulent fluctuations that transport energy.

The definition of "average" in a turbulent flow is not unambiguous and depends on the way the system is observed. Two main approaches are distinguished:

a. Ensemble Average

It is the most general and rigorous definition, valid for any type of turbulent flow (stationary or non-stationary). The ensemble average is calculated by considering a large number of independent realizations of the same physical process, measured at exactly the same time point and in the same spatial position. In conceptual terms, imagine having N identical systems and averaging the values measured simultaneously in all systems:

$$\langle u \rangle_{ensemble} = \frac{1}{N} \sum_{i=1}^N u_i(t)$$

b. Time Averaging

In engineering and experimental applications, such as the use of ultrasonic probes or anemometers, it is often impossible to have multiple simultaneous implementations of the system. It is therefore preferable to carry out a prolonged measurement over time on a single realization. If the process is stationary, i.e. if its statistical properties (mean, variance, etc.) do not change over time, the time average is defined as:

$$\bar{u} = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T u(t) dt \approx \frac{1}{N} \sum_{i=1}^N u(\tau_i)$$

The connection between these two worlds is provided by the hypothesis of ergodicity. A system is defined as ergodic when the average calculated over time for a single realization coincides with the overall average calculated on all possible realizations:

$$\langle u \rangle = \bar{u}$$

In statistical terms, ergodicity implies that the system, over time, explores all possible physical states in a uniform manner. This hypothesis is the basis of most experimental data analyses in hydraulics: it allows us to treat a time series of velocities measured at a point in the channel as representative of the entire motion statistics at that point.

Once the media operator is defined, you can apply Reynolds decomposition. Each instantaneous variable is split into the sum of an average (stable) component and a floating (turbulent) component:

$$u(t) = \langle u \rangle + u'(t)$$

$$v(t) = \langle v \rangle + v'(t)$$

$$w(t) = \langle w \rangle + w'(t)$$

Where:

- $\langle u \rangle$ represents the mean component, linked to the global transport of the fluid.
- u' represents the turbulent fluctuation, a zero-mean value that encapsulates all the swirling and chaotic dynamics of the motion.

By the nature of the media operator, the Reynolds decomposition enjoys fundamental mathematical properties (Reynolds rules) that will be used in data analysis:

- The average of the fluctuation is zero by definition: $\langle u' \rangle = 0$
- The average of the average component is the average component itself: $\langle \langle u \rangle \rangle = \langle u \rangle$

This decomposition is the first step towards the analysis of the turbulence structures: while the average component defines the velocity profile in the channel, the energy analysis of the fluctuations u' will allow to identify the size and strength of the turbulent vortices.

Therefore, to quantify how turbulent a flow actually is, it is not enough to know the average speed, but the magnitude of the fluctuations must be analysed. Two main parameters are used for this purpose: variance and turbulent intensity.

The velocity variance represents the average of the square of the fluctuations and is directly related to the turbulent kinetic energy:

$$\sigma_u^2 = \langle (u - \langle u \rangle)^2 \rangle = \langle u'^2 \rangle$$

The square root of the variance is the standard deviation (σ_u), which represents the *RMS value (RMS - Root Mean Square)* of the velocity fluctuations; a fundamental parameter as it expresses the "force" or amplitude typical of the vortices that make up the turbulent motion in a measurement scale consistent with that of the average velocity (m/s). In experimental practice, for a sample of N measurements, the Turbulence Strength is estimated as:

$$\sigma_u = \sqrt{\langle u'^2 \rangle} = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (u_i - \bar{u})^2}$$

However, comparing the strength of turbulence between two flows with very different average velocities can be misleading. The Turbulence Intensity (I) is then introduced, a dimensionless parameter that relates the standard deviation to the average speed:

$$I = \frac{\sigma_u}{\langle u \rangle}$$

The turbulent intensity allows us to understand how much of the motion is "disturbed" compared to the average transport. A signal with high turbulent intensity will have very large fluctuations compared to the average value, a sign of the presence of energetically dominant vortex structures with respect to the main flow.

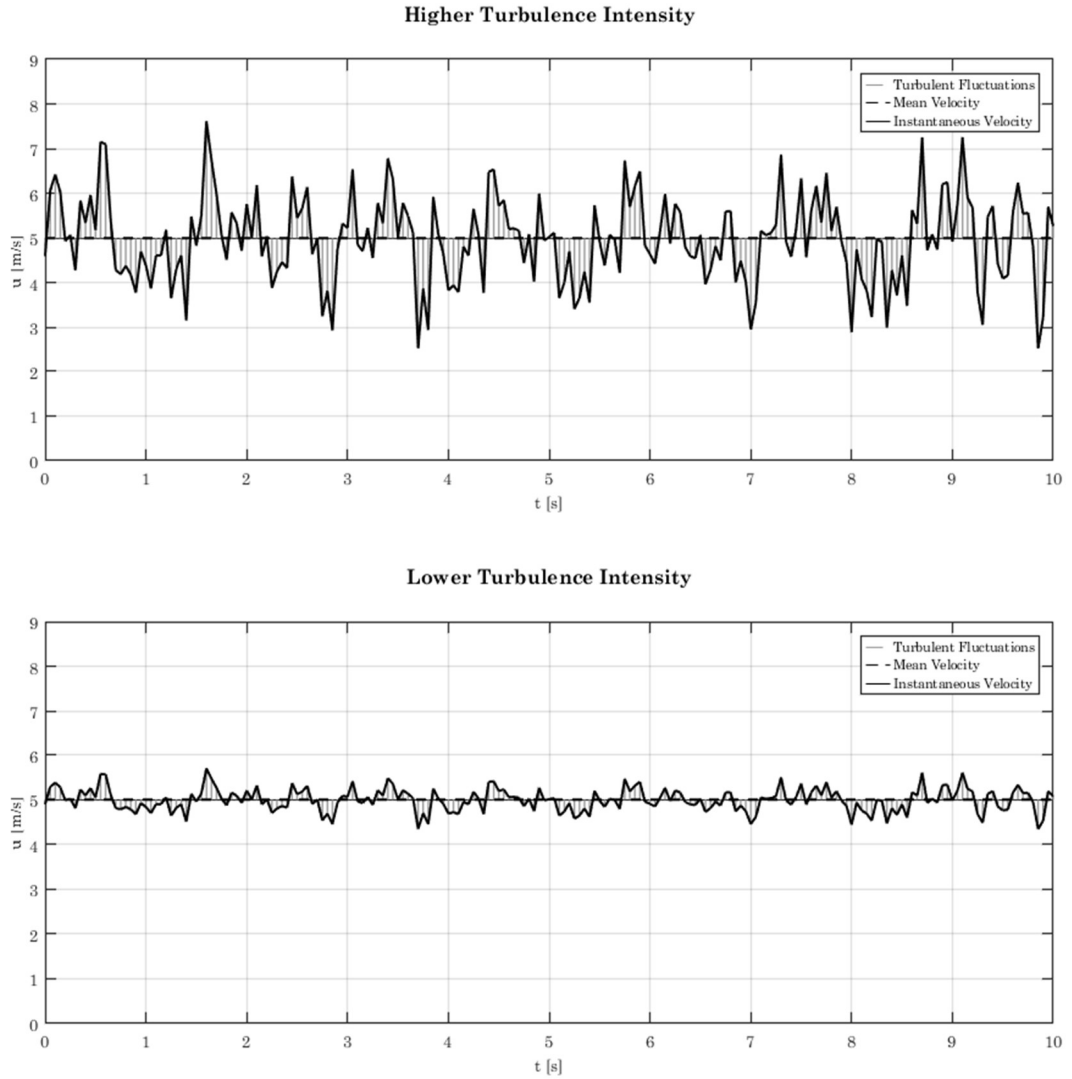


Figure 1.2 — Reynolds Decomposition and Turbulence Intensity: Visual comparison between a high-turbulence (top) and low-turbulence (bottom) flow field, highlighting instantaneous velocity fluctuations around the mean value.

1.2 Turbulent phenomenology

Contrary to the macroscopic perception of a purely chaotic and disordered motion, wall turbulence is configured as a finely structured fluid dynamic field, governed by a complex spatial and temporal superposition of discrete kinematic entities called vortices (or eddies). These coherent structures are fluid regions characterized by intense vorticity and marked phase correlation, which do not remain in a static state but interact continuously: they arise, become distorted by stretching (vortex stretching), aggregate and finally fragment, acting as primary vectors for the transport and mixing of momentum, of passive tracers and kinetic energy within the fluid mass.

The key mechanism that describes the life cycle of these structures and the energy transfer in the flow field is the theory of the "energy cascade", introduced phenomenologically by Lewis Fry Richardson in 1922 [VII][VII].

According to this view, mechanical energy is injected into the system at large scales through external forces or average velocity gradients (main flow instability).

These large vortices are unstable and break up into smaller vortices, which in turn fragment further. This process continues until the vortices become so small that the viscous forces become dominant over the inertia forces, transforming the kinetic energy into heat (dissipation). Richardson poetically summed up this concept:

"Big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls and so on to viscosity."

Richardson's intuitions found their definitive analytic consecration thanks to the formal hypotheses formulated by Andrey Kolmogorov in 1941 [VIII]. Kolmogorov provided a mathematical framework for energy cascade, dividing the turbulence spectrum into three fundamental domains:

1. **Integral Scale (L):** This is the scale of the largest vortices. They contain most of the turbulent kinetic energy and their size is of the order of magnitude of the water tie rod (h) or the width of the channel (W). They are strongly anisotropic structures (they have a preferential direction) and are strictly dependent on the geometry of the site.
2. **Inertial Range:** In this intermediate range, the vortices are too small to be affected by channel geometry but too large to be affected by viscosity. Here the transfer of energy from large to small scales takes place only. Kolmogorov postulated that in this range turbulence was statistically isotropic and followed the famous law of $-5/3$ in the power spectrum.
3. **Kolmogorov scale (η):** It is the microscopic scale where dissipation occurs. Here the local Reynolds number is close to unity, and the energy vanishes by viscous friction.

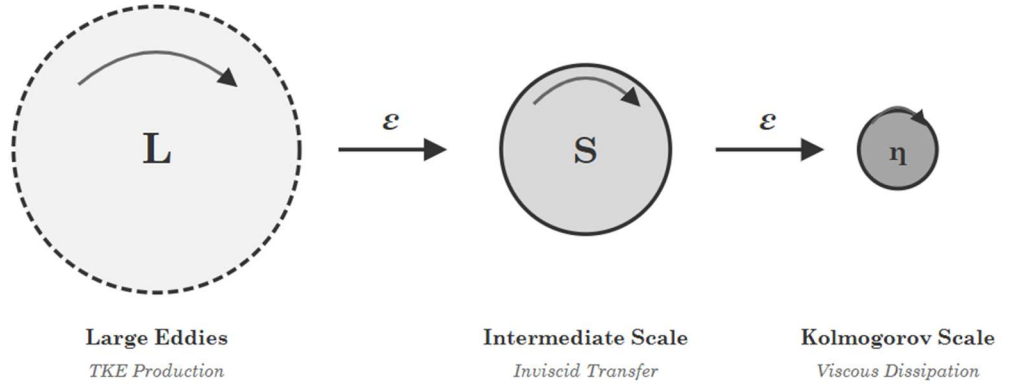


Figure 1.3 – Phenomenological scheme of the energy cascade: fragmentation of macro-vortices (L) into intermediate scales (S) with conservative TKE transfer, up to the dissipative Kolmogorov microscale (η).

To understand the dynamics of energy transfer across the three spectral domains, it is essential to analytically quantify the components involved. Considering a three-dimensional flow field, the instantaneous kinetic energy of the fluid per unit mass $q(t)$ is defined as:

$$q(t) = \frac{1}{2} [u^2(t) + v^2(t) + w^2(t)]$$

Applying the Reynold's decomposition to the individual components of velocity, where each term is expressed as the sum of an average value and a turbulent fluctuation, the equation takes the form:

$$q(t) = \frac{1}{2} [(\bar{u} - u')^2 + (\bar{v} - v')^2 + (\bar{w} - w')^2]$$

Performing the time average of this quantity and remembering that the time average of the fluctuation velocity is by definition zero, the double products cancel each other out. The total average kinetic energy is therefore broken down into two distinct contributions:

$$\bar{q}(t) = \frac{1}{2} [\bar{u}^2 + \bar{v}^2 + \bar{w}^2 + \overline{u'^2} + \overline{v'^2} + \overline{w'^2}]$$

$$\frac{1}{2} [\bar{u}^2 + \bar{v}^2 + \bar{w}^2] \rightarrow \text{MEAN KINETIC ENERGY (MKE)}$$

$$\frac{1}{2} [\overline{u'^2} + \overline{v'^2} + \overline{w'^2}] \rightarrow \text{TURBULENT KINETIC ENERGY (TKE)}$$

This energy is generated entirely at the integral scale L . Large eddies have a characteristic velocity scale U_L of the order of that of the main flow and a Reynolds number much greater than unity ($Re_L = \frac{U_L \cdot L}{\nu} \gg 1$), being their spatial dimension governed uniquely by the physical boundaries of the domain.

Under these conditions, as long as the vortices fragment into structures of intermediate scale (S) such that $Re_S = \frac{u_s \cdot S}{\nu} \gg 1$, the viscous forces are negligible compared to the inertial ones. This implies that the transfer of energy to the lower scales within the inertial range takes place in a purely inviscid regime, without any viscous dissipation. It is precisely in this domain that Kolmogorov's hypotheses find their most rigorous mathematical application. Specifically, the first hypothesis states that there is a range of intermediate scales (S) such that $\eta \ll s \ll L$, within which viscosity does not influence the dynamics of turbulence, identifying the so-called *inertial range*. Furthermore, the second hypothesis postulates that within this inertial scale range, turbulence is isotropic and homogeneous; consequently, the turbulent field can be described using purely statistical terms. Therefore, the velocity associated with the intermediate eddies depends only on:

$$u_s = f(s, \varepsilon)$$

where:

- s is the spatial scale of the eddies;
- ε is the Turbulent Kinetic Energy (TKE) transfer rate.

Since the cascade process is kinematically conservative, the transfer rate of turbulent kinetic energy, denoted by ε , depends exclusively on the large scales that feed it. By applying the principles of dimensional analysis, Kolmogorov deduced that:

$$\varepsilon \sim \frac{U_L^3}{L} \left[\frac{m^2}{s^2} \right]$$

Exploiting the similarity hypothesis, the properties of the vortices in the inertial range depend solely on their spatial dimension (s) and the rate ε . From this dimensional combination, it is analytically derived that the velocity associated with the intermediate vortices, scales according to the relation:

$$u_s \sim (\varepsilon S)^{1/3} [m/s]$$

This self-similar fragmentation stops only when the spatial scale reduces to η , the level at which the TKE is definitively and irreversibly dissipated. This occurs when the local Reynolds number becomes of order unity ($Re_\eta = \frac{u_\eta \cdot \eta}{\nu} \approx 1$).

Assuming that $u_s = u_\eta \rightarrow u_s \sim (\eta \varepsilon)^{1/3}$ and $Re_\eta = 1$, the Kolmogorov length scale can be derived as:

$$\eta = \left(\frac{\nu^3}{\varepsilon} \right)^{1/4}$$

1.3 Spectral analysis and characterization of turbulent scales

1.3.1 Time-domain statistics and characteristic integral scales

In the context of environmental engineering, large eddies play a pivotal role as they dictate mixing phenomena, governing the turbulent diffusion of momentum, heat, and passive solutes. Consequently, the macroscopic mixing coefficients adopted in engineering practice are intrinsically strictly dependent on the kinematics of these macro-structures. To rigorously quantify their influence and characteristic dimensions, it is necessary to move from a phenomenological description to an advanced statistical analysis of the velocity signals.

To statistically characterize the turbulent flow field, the starting point is represented by the covariance, i.e. the relation between simultaneous velocity fluctuations. For the longitudinal (u') and vertical (v') components, their covariance is defined as the time-averaged value of their product:

$$\text{cov}(u', v') = \langle u'v' \rangle = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T u'(t)v'(t) dt$$

While covariance links two different variables, autocovariance correlates a single variable with itself at two time points separated by a delay (τ – *time lag*):

$$R_{uu}(\tau) = \langle u'(t) u'(t + \tau) \rangle$$

This function is the primary analytical tool for quantifying the temporal coherence of turbulent structures. To facilitate the comparison between different signals, it is normalized with respect to the variance of the signal (σ_u^2), thus defining the Autocorrelation Coefficient:

$$\rho_{uu}(\tau) = \frac{R_{uu}(\tau)}{\sigma_u^2}$$

This coefficient varies between 1 (maximum correlation at $\tau = 0$) and 0 (no correlation). From a physical point of view, a signal dominated by macro-structures (*Large Scales*) will have a slow-decay autocorrelation function. Conversely, for a purely chaotic signal (white noise), $\rho_{uu}(\tau)$ would instantly decay to zero for any $\tau > 0$.

In practical experimental measurements, the autocorrelation curve rarely settles perfectly at zero due to inherent statistical noise, but rather begins to oscillate around this null value. The specific time lag at which the autocorrelation coefficient first crosses the zero axis (i.e., $\rho_{uu}(T_0) = 0$) is identified as the *Decorrelation Time Scale*,

also known as the *Large Eddy Turnover Timescale* (T_0). Thus, T_0 provides a direct and practical estimation of the characteristic dimension of the large eddies before they completely lose their coherence.

Furthermore, alongside the zero-crossing time, a more statistically comprehensive metric widely used in turbulence analysis is the Integral Time Scale (T_{uu}). This parameter represents the total area under the autocorrelation curve and is mathematically defined as:

$$T_{uu} = \int_0^{\infty} \rho_{uu}(\tau) d\tau$$

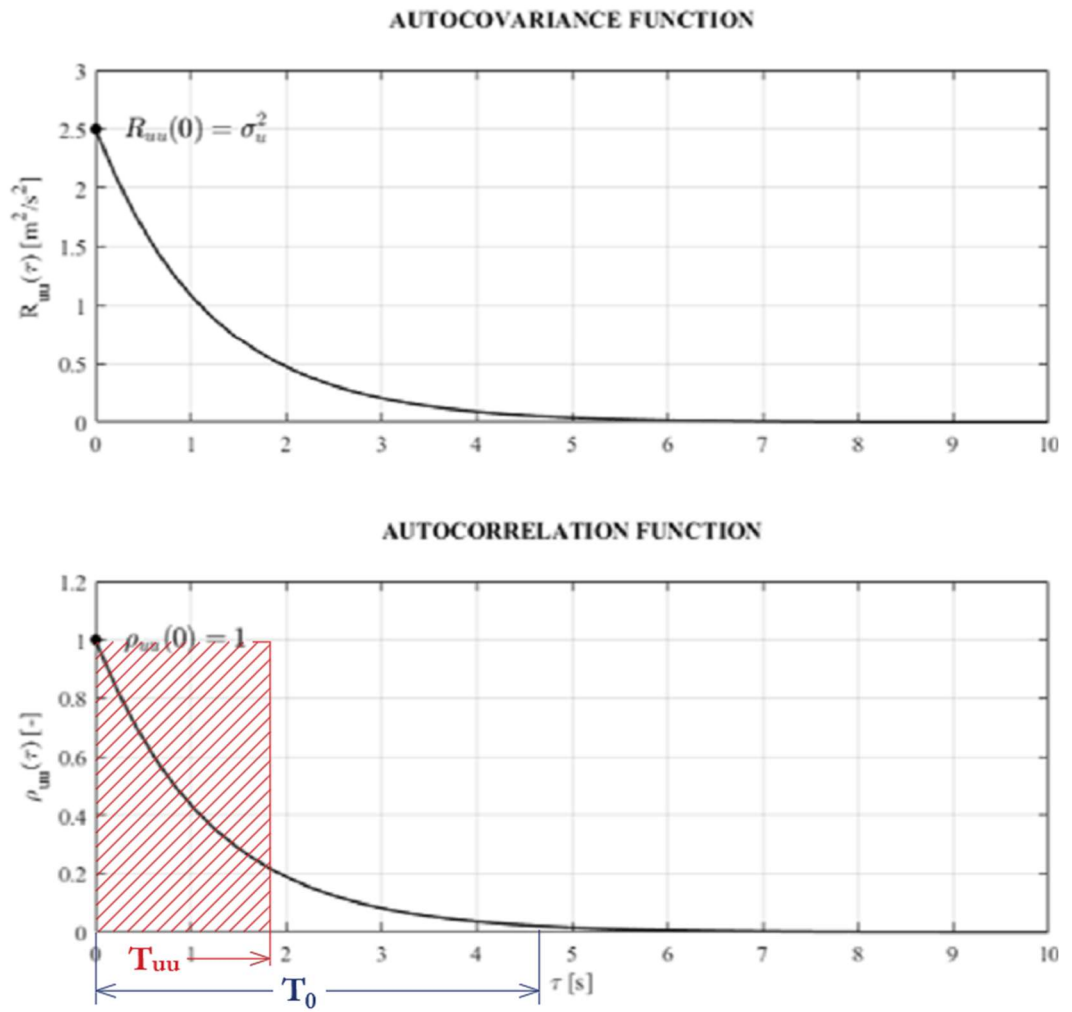


Figure 1.4 – Temporal evolution of the autocovariance function (top) and the normalized autocorrelation function (bottom) for the longitudinal velocity fluctuation. The lower panel highlights the extraction of the characteristic time scales of the macro-turbulence.

While the integral time scale T_{uu} provides a crucial measure of the temporal persistence of large eddies over a fixed sensor, the physical characterization of these macro-structures intrinsically requires their definition in terms of spatial dimensions. Bridging the gap between an Eulerian temporal measurement and a spatial framework relies on a specific kinematic assumption, widely known as Taylor's Hypothesis of "Frozen Turbulence" (1938) [IX].

This hypothesis postulates that if the mean flow velocity ($\bar{u}$) is significantly greater than the turbulent velocity fluctuations (u'), the advection of the turbulent field past the fixed sensor occurs much faster than the internal dynamic evolution of the eddies themselves. Consequently, the turbulent spatial structure can be considered virtually "frozen" and rigidly transported by the mean flow without altering its shape during the passage.

Under this assumption, the temporal coordinate (t) can be directly mapped to the spatial coordinate (x) via the simple kinematic transformation $x = \bar{u} \cdot t$.

This elegantly allows the direct derivation of the macroscopic spatial dimension of the turbulence, the Integral Length Scale (L), from the temporal data:

$$L = \bar{u} \cdot T_0$$

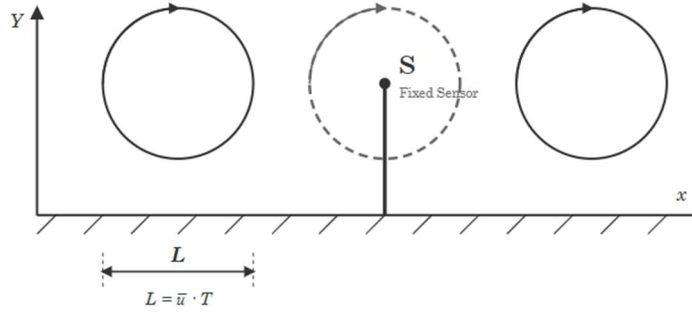


Figure 1.5 – Schematic representation of Taylor's Hypothesis of "Frozen Turbulence".

While mathematically convenient and widely used, Taylor's hypothesis is not universally applicable. Its validity is strictly governed by the local Turbulence Intensity (I), requiring the root-mean-square of the velocity fluctuations to be mathematically negligible compared to the mean flow:

$$\frac{\sqrt{\langle u'^2 \rangle}}{\bar{u}} \ll 1$$

In conventional experimental practice, the frozen turbulence approximation yields reliable spatial conversions only when the turbulence intensity remains below a threshold of approximately 10 to 15% (Tennekes, H., & Lumley, J. L. (1972) **Errore. L'origine riferimento non è stata trovata.**). The hypothesis also assumes that the spatial gradient of the mean velocity is negligible (Lin, C.C. (1953) [XI]). If the flow exhibits a significant mean shear rate ($d\bar{u}/dy$), the upper and lower portions of a turbulent macro-structure are advected at distinctly different speeds. This differential

transport actively stretches and distorts the eddies as they pass the sensor, fundamentally violating the "frozen" field assumption.

1.3.2 Power Spectral Density and Kolmogorov's Spectra

The auto-covariance function provides a fundamental measure of the temporal persistence of large turbulence structures, acting as a global statistical metric. It quantifies the overall duration of the turbulent memory, but does not explicitly reveal how the total turbulent kinetic energy (TKE) is distributed across the various scales of motion. In physical terms, the time domain unable to isolate the energy contribution of the large vortices from the chaotic background of the dissipative microscales. To obtain a complete dynamic characterization of the energy cascade, it is therefore necessary to move from the time domain to the frequency domain.

The transition from a random, chaotic temporal signal to a structured frequency distribution cannot be achieved through a direct Fourier transform of the raw velocity fluctuations, as such a process would not statistically converge. Instead, the mathematical bridge facilitating this transition is the Wiener-Khinchin Theorem, which establishes a fundamental duality for stationary random processes (Pope, 2000) [XII].

According to this theorem, the spectral distribution of energy is intrinsically linked not to the raw signal itself, but to its temporal coherence. Specifically, it dictates that the theoretical two-sided Power Spectral Density, denoted as $\Phi_{uu}(f)$, is exactly the direct Fourier transform of the autocovariance function $R_{uu}(\tau)$. Expressed in terms of the ordinary frequency (f), this theoretical relationship is formally written as:

$$\Phi_{uu}(f) = \int_{-\infty}^{\infty} R_{uu}(\tau) e^{-i2\pi f \tau} d\tau$$

While mathematically rigorous, the two-sided spectrum $\Phi_{uu}(f)$ is defined over both positive and negative frequencies ($-\infty < f < \infty$). In experimental fluid dynamics and practical signal processing, negative frequencies lack a distinct physical counterpart. However, because turbulence is treated as a stationary process, its autocovariance function $R_{uu}(\tau)$ is strictly symmetric (an even function, where $R_{uu}(\tau) = R_{uu}(-\tau)$).

Exploiting this symmetry, the imaginary sine component of Euler's formula cancels out. To conserve the total energy within the physically observable positive frequency domain, the spectral energy from the negative domain is folded over and added to the positive side. This defines the one-sided, physically observable Power Spectral Density, $S_{uu}(f)$, which is typically computed by spectral estimation algorithms:

$$S_{uu}(f) = 2\Phi_{uu}(f) = 4 \int_0^{\infty} R_{uu}(\tau) \cos(2\pi f \tau) d\tau \quad \text{for } f \geq 0$$

The physical profoundness of the one-sided PSD $S_{uu}(f)$ is deeply rooted in its energy conservation properties. By mathematically forcing the integral to cover only the physically meaningful positive frequencies, the total area under the $S_{uu}(f)$ curve yields exactly the initial variance of the velocity fluctuations:

$$\int_0^{\infty} S_{uu}(f) df = \sigma_u^2$$

In an engineering context, the variance σ_u^2 represents the exact amount of turbulent kinetic energy per unit mass associated with the longitudinal velocity component. Therefore, this integral equality proves that the PSD acts as a true energy density function. It visually and mathematically illustrates exactly how the total turbulent energy is partitioned across the continuous spectrum of turbulent frequencies, allowing for the explicit identification of the most energetic macro-structures dominating the flow field.

Under Taylor's hypothesis, the temporal Power Spectral Density $S_{uu}(f)$ and the spatial energy spectrum $S(k)$ contain the exact same statistical information, serving as mathematically equivalent representations of the turbulent kinetic energy. However, the temporal spectrum illustrates how rapidly the turbulent structures oscillate past a fixed measurement sensor (an Eulerian perspective), whereas the classical framework of Kolmogorov's energy cascade is formulated in the spatial domain. The physical breakdown of macro-structures into micro-eddies is a process governed by geometric dimensions and spatial dynamics, rather than temporal frequencies. Therefore, to directly align the Eulerian temporal measurements with the universal spatial laws of Kolmogorov's theory, it is customary to map the frequency domain into the spatial wavenumber domain.

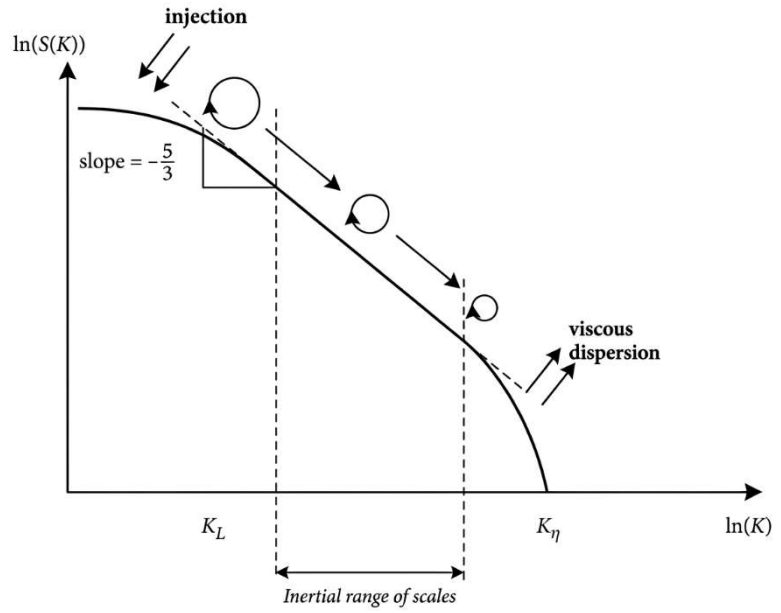
To move from the frequency domain to the spatial domain, the angular frequency of the flow fluctuations ($\omega = 2\pi f$, expressed in [rad/s]) is converted into the spatial wavenumber (k [m^{-1}]). The wavenumber mathematically represents the number of waves (or turbulent structures) contained within a unit of length, effectively acting as the inverse of the spatial wavelength. From Taylor's hypothesis of frozen turbulence, the turbulent structures are assumed to be advected by the local mean velocity $\bar{u}$. Consequently, the wavenumber is defined as:

$$k = \frac{\omega}{\bar{u}} = \frac{2\pi f}{\bar{u}}$$

To conserve the total turbulent kinetic energy per unit mass during this coordinate transformation, the area under the spatial energy spectrum $S(k)$ must strictly equal the area under the temporal spectrum. This enforces the equality $S(k) dk = S_{uu}(f) df$,

leading to the direct derivation of the spatial spectrum from the experimental Eulerian data.

Figure 1.6 – Schematic representation of the Kolmogorov turbulent energy spectrum. The log-log plot shows the three regions of energy transfer as a function of the wavenumber (K): injection at large scales (K_L), the inertial range with a characteristic slope of $-5/3$, and the final dissipative region at microscopic scales (K_η), dominated by viscosity.



As illustrated in Figure 1.6, by plotting the spatial energy spectrum $S(k)$ on a logarithmic scale, it is possible to visualize the fundamental anatomy of the turbulent flow, partitioning the kinetic energy distribution into three distinct wavenumber ranges:

1. **Energy Injection Range** ($k \approx k_L$): This region occupies the lowest wavenumbers (macro-scales), corresponding to the integral length scale L . In this range, turbulent kinetic energy is continuously injected into the system extracted from the mean flow shear. The mechanics of these large eddies are strongly dependent on the specific geometry of the channel and the boundary conditions.
2. **Inertial Subrange** ($k_L \ll k \ll k_\eta$): As the wavenumber increases, the spectrum enters in a universal intermediate region. Here, the turbulent structures are sufficiently smaller than the physical boundaries (thus forgetting the macroscopic geometry) but still large enough to be not affected to viscous effects. The eddies act purely as an inviscid conveyor belt, transferring kinetic energy from larger to smaller scales without any dissipation.
3. **Viscous Dissipation Range** ($k \approx k_\eta$): At the highest wavenumbers, corresponding to the Kolmogorov microscale, the kinetic energy cascade is arrested. The strong velocity gradients within these micro-eddies trigger viscous forces, which irreversibly dissipate the remaining turbulent kinetic energy into heat.

The most profound deduction of Kolmogorov's theory governs the behaviour of the Inertial Subrange. Kolmogorov postulated that, provided the Reynolds number is sufficiently high, the energy spectrum $S(k)$ in the inertial subrange depends exclusively on two parameters:

- The spatial dimension of the eddies, represented by the wavenumber k [L^{-1}].
- The turbulent energy transfer rate ε [$L^2 T^{-3}$].

Through strict dimensional arguments, it is mathematically impossible to formulate a function $S(k)$, which must have the dimensions of energy per unit mass per unit wavenumber [$L^3 T^{-2}$], without explicitly combining ε and k in one unique way. The purely dimensional derivation is:

$$S(k) \propto \varepsilon^{2/3} \cdot k^{-5/3}$$

1.4 Wall flows: confined turbulence

In the study of environmental hydraulics and open channel flows, the presence of a fixed solid boundary (such as the channel bed and banks) radically modifies the fluid dynamics compared to theoretical models developed for free-shear flows (e.g., jets, wakes, or mixing layers). While free-shear flows can often achieve a state of complete similarity where the influence of the macroscopic Reynolds number (Re) becomes negligible, wall-bounded turbulent flows remain inherently strictly dependent on the Reynolds number, as the solid boundary imposes an absolute physical constraint on the length scales of the turbulent eddies (Townsend, 1976 [XIII]).

This behaviour is dictated by the kinematic no-slip condition at the solid interface. Physically, these condition mandate that both the mean velocity and the turbulent velocity fluctuations must be exactly zero at the wall contact. Consequently, the solid boundary acts as a massive sink of momentum, forcing the flow to develop a steep vertical velocity gradient ($d\bar{u}/dz$) to transfer momentum from the faster outer region down to the stationary bed. This crucial region, characterized by a significant momentum deficit and intense shear, is formally defined as the *turbulent boundary layer*.

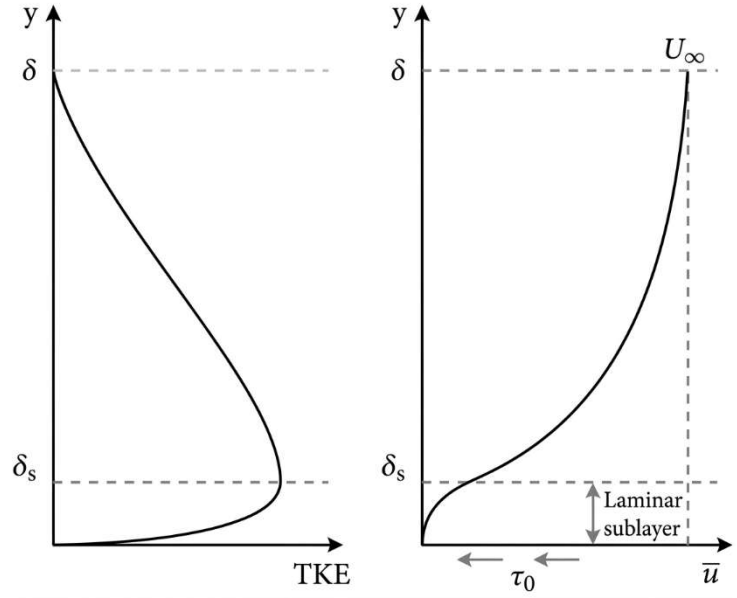
Within the boundary layer, the dynamics of the flow are governed by the continuous interaction between viscous forces and turbulent inertial forces. Because the turbulent fluctuations are suppressed by the presence of the wall, the Reynolds shear stresses ($-\rho\overline{u'v'}$) must vanish exactly at the boundary. Therefore, in the immediate vicinity of the wall, the fluid friction is entirely dominated by molecular viscosity, and the wall shear stress (τ_0) is mathematically described by Newton's law of viscosity:

$$\tau_0 = \mu \left(\frac{d\bar{u}}{dz} \right)_{y=0}$$

Moving far away from the wall, this velocity gradient interacts with the rapidly growing Reynolds stresses. According to the turbulent kinetic energy (TKE) budget equation (Tennekes & Lumley, 1972 **Errore. L'origine riferimento non è stata trovata.**), the mean shear acts as the primary source of turbulence production.

This behaviour is illustrated in Figure 1.7, which highlights the direct spatial correlation between the velocity profile and the distribution of turbulent energy. As shown, the absolute peak of TKE is recorded exactly in coincidence with the maximum value of the velocity gradient, located just outside the laminar sublayer. This highlights how the region adjacent to the wall acts as the primary driver of turbulence generation.

Figure 1.7 — Characteristic vertical profiles in a turbulent wall-confined boundary layer. The graph on the left shows the distribution of turbulent kinetic energy (TKE), and the one on the right shows the mean velocity profile ($\bar{u}$) as a function of height (y).



To universally describe this near-wall dynamic, where the influence of the outer flow depth (H) is negligible and the physics are locally dictated only by the wall shear stress (τ_0) and the kinematic viscosity ($\nu = \mu/\rho$), it is customary to introduce the so-called *inner scaling* variables. The fundamental reference velocity in this region is the friction velocity (u_τ or u_*), defined as:

$$u_* = \sqrt{\frac{\tau_0}{\rho}}$$

It is crucial to emphasize that the friction velocity is not a physical kinematic velocity, but rather the representation of the magnitude of the wall shear stress expressed in units of velocity. Physically, the friction velocity embodies the intensity of the momentum transfer towards the solid boundary. Since the turbulent fluctuations in the near-wall region are generated directly by the wall friction, u_τ dictates the characteristic velocity scale of the turbulent eddies within the boundary layer: the higher the wall shear stress, the higher the friction velocity, and consequently, the more intense the turbulent kinetic energy produced at the bed.

Coupling the friction velocity with the kinematic viscosity yields the viscous length scale (ν/u_τ). This extremely small length scale governs the inner region of the boundary layer, known as the laminar sublayer. In this thin layer, at contact with the fixed wall, typically extending up to a distance of $\delta_s = 5 \frac{\nu}{u_*}$, viscous forces completely

dampen the turbulent motions, making the flow locally laminar despite the extremely high global Reynolds number.

By adopting these inner scales, it is possible to normalize the physical variables, defining the dimensionless distance from the wall (y^+) and the dimensionless mean velocity (u^+):

$$y^+ = \frac{y u_\tau}{\nu} \quad ; \quad u^+ = \frac{\bar{u}}{u_*}$$

The formulation of these dimensionless parameters forms the basis of the classical boundary layer theory, as it allows for a universal mathematical description of the velocity profile extending outwards from the viscous sublayer.

1.4.1 The velocity profile: The Law of the Wall

Based on the inner scaling parameters defined in the previous section, the turbulent boundary layer can be divided into different regions. This division is dictated by the relative magnitude of the viscous shear stress and the turbulent Reynolds shear stress. Plotting the dimensionless velocity profile in a semi-logarithmic graph (refer to what illustrated in *Figure 1.8*) reveals four fundamental regions of flow, collectively describing the entire flow structure from the solid boundary up to the free surface, defining the universal framework known as the Law of the Wall (Pope, 2000 [XII]).

1. Viscous or Laminar sublayer ($y^+ < 5$)

In contact with the solid boundary, the physical presence of the wall completely dampens the turbulent velocity fluctuations in the 3-dimensions. In this extremely thin region, the Reynolds shear stresses are essentially zero and the transfer of the momentum is governed principally by molecular viscosity. By integrating Newton's law of viscosity under the assumption of a locally constant shear stress equal to the value at the wall ($\tau \approx \tau_0$), a strictly linear relationship is obtained between the mean velocity and the distance from the wall:

$$u^+ = y^+$$

2. The Buffer Layer ($5 < y^+ < (50 \div 100)$)

Moving slightly away from the wall, the fluid enters in a highly dynamic transitional zone. Here, neither viscous nor turbulent forces are completely dominant; rather, they are of comparable intensity. This region represents the most chaotic part of the boundary layer, characterized by the violent generation of turbulent instabilities, such as bursting events and fluid ejections. Due to the complex interaction of forces, there is no simple analytical equation to describe

the velocity profile in this region, and continuous transition function functions are generally used to link the linear and logarithmic profiles.

3. The Logarithmic Region ($(50 \div 100) \frac{\nu}{u_\tau} < y^+ < (0.1 \div 0.2) \delta$)

Beyond the buffer layer, the direct effect of molecular viscosity becomes physically negligible, and the flow reaches a fully turbulent state. In this region, the momentum transfer is entirely dominated by the turbulent Reynolds shear stresses. This zone acts as a fundamental intermediate flow region, referred as the overlap layer or logarithmic layer, situated far enough from the wall that the inner viscous length scale ($\frac{\nu}{u_*}$) is no longer relevant, yet close enough to the bed that the outer length scale (the flow depth, H) does not yet influence the flow dynamics.

Because the physics in this overlap layer are independent of both boundary extremes, dimensional analysis (supported by Prandtl's mixing length theory) dictates that the mean velocity gradient must be inversely proportional to the distance from the wall ($d\bar{u}/dy \propto y$). Integrating this relationship yields the logarithmic law (von Kármán, 1930 **Errore. L'origine riferimento non è stata trovata.**):

$$u^+ = \frac{1}{\kappa} \ln y^+ + B$$

Here, κ is the von Kármán constant (universally established $\kappa = 0.37 \div 0.41$), which quantifies the efficiency of the turbulent momentum exchange, and B is an empirical integration constant dictated by the boundary roughness. For hydraulically smooth walls, B assumes a value of about $5.0 \div 5.5$. This equation represents a fundamental milestone in fluid mechanics: it provides a robust and universal mathematical bridge that links the dynamics of the inner wall with the outer free flow, correctly predicting the velocity distribution in this intermediate region. Furthermore, the physical validity of the logarithmic law strictly relies on the assumption of a large scale separation between the inner and outer regions. This condition is structurally satisfied for flows characterized by a high friction Reynolds number ($Re \gg 1000$), where the macroscopic outer length scale (H) is orders of magnitude larger than the inner viscous length scale ($\frac{\nu}{u_*}$).

4. The Outer Region ($y/H > 0.2$)

Moving further away from the bed into the core of the flow, the local inner scaling (y^+) gradually loses its physical relevance. In this outer region, the turbulent boundary layer becomes constrained by the macroscopic outer length scale, which in open-channel flows coincides with the total flow depth (H). Here,

the direct constraining influence of the wall shear stress weakens, and the flow dynamics start to resemble those of a free-shear wake.

Consequently, the measured velocity profile progressively deviates from the theoretical logarithmic law, typically exhibiting a wake-like acceleration towards the free surface. To mathematically capture this deviation, Coles (1956) **Errore. L'origine riferimento non è stata trovata.** expanded the log law by adding an empirical wake function (w), governed by a wake parameter (Π) that depends on the global pressure gradient and the specific geometry of the flow:

$$u^+ = \frac{1}{\kappa} \ln y^+ + B + \frac{2\Pi}{\kappa} \sin^2 \left(\frac{\pi y}{2H} \right)$$

Alternatively, the velocity distribution in this upper zone is classically described by the Velocity Defect Law, which scales the difference between the maximum free-surface velocity ($U_{\max}$) and the local mean velocity ($\bar{u}$) using the friction velocity.

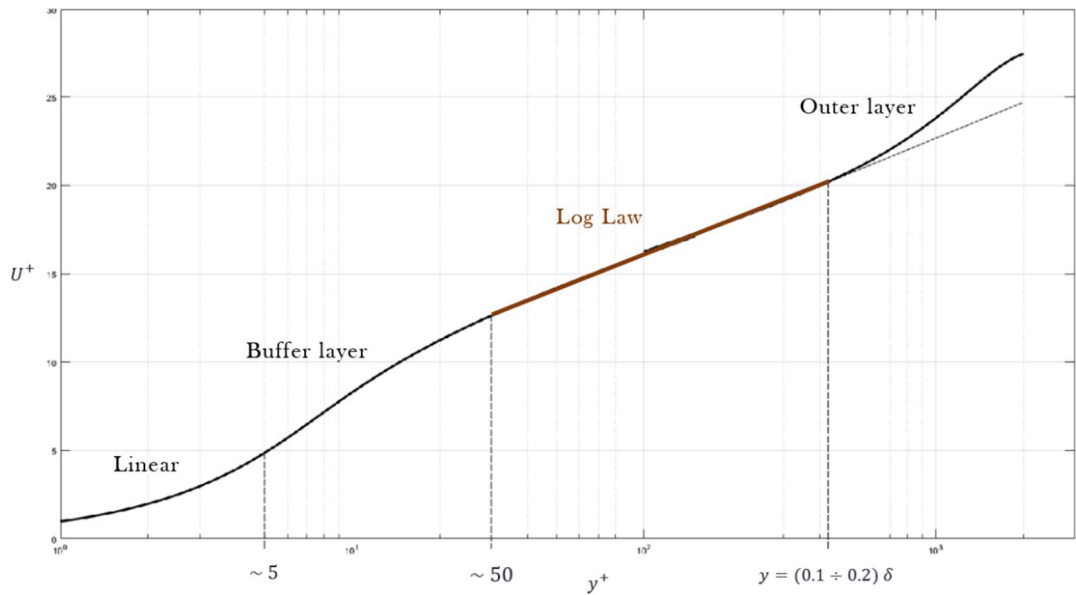


Figure 1.8 — Universal velocity profile in a semi-logarithmic plane, illustrating the subdivision of the turbulent boundary layer into the fundamental kinematic macro-zones.

1.4.2 Effects of surface roughness on the boundary layer

The theoretical framework established in the previous section is based on the assumption of a hydraulically smooth boundary. However, in the field of environmental fluid mechanics, purely smooth surfaces represent a theoretical

abstraction. Natural open channels are characterized by considerable morphological complexity, with boundaries composed of sediments, cobbles, vegetation and other element of disturbance. The presence of these physical asperities radically alters the near-wall turbulence dynamics, requiring a structural adjustment of the universal velocity profile.

To quantitatively evaluate the influence of surface geometry on the flow, it is convenient to rewrite the logarithmic law in a generalized form:

$$u^+ = \frac{1}{\kappa} \ln \left(\frac{y}{y_0} \right)$$

where y_0 is the roughness length, a fundamental parameter that physically quantifies the flow resistance exerted by the solid boundary. For smooth walls, this length is strictly a function of viscosity and shear stress $y_0 = \frac{\nu}{u_\tau} e^{-\kappa B}$. For rough walls, however, y_0 becomes fundamentally dependent on the physical dimensions of the obstacles.

To standardize the immense variety of geometric shapes found in nature (from gravel to urban canopies) and link them to the roughness length, the seminal pipe-flow experiments conducted by Nikuradse provided the essential foundation. Nikuradse introduced the concept of the *equivalent sand roughness height*, denoted as k_s . This parameter represents the theoretical diameter of uniformly packed sand grains that would produce the exact same macroscopic flow resistance as the actual complex surface under investigation. From a fluid mechanics perspective, a surface is not intrinsically "smooth" or "rough" based solely on its absolute physical size, but rather on the ratio between the obstacle height (k_s) and the thickness of the viscous sublayer ($\delta_s \approx 5 \frac{\nu}{u_\tau}$). This ratio is formalized by the dimensionless Roughness Reynolds Number (Re^*):

$$Re^* = \frac{k_s u_\tau}{\nu}$$

Based on the magnitude of this dimensionless parameter, the flow behaviour is dictated by three distinct hydrodynamic regimes. In the hydrodynamically smooth regime ($Re^* \leq 5$), the physical asperities are entirely submerged within the laminar viscous sublayer ($Re^* \leq \delta_s$). The turbulent outer flow never feels the physical roughness; consequently, the roughness effects are completely negligible, and the standard smooth-wall log-law can be applied. As the roughness elements begin to pierce through the viscous sublayer, the flow enters the transitionally rough regime ($5 \leq Re^* \leq 70$), where the flow resistance becomes a hybrid function of both the fluid's molecular viscosity and the physical drag of the obstacles. Finally, in the hydrodynamically rough regime ($Re^* > 70$), the obstacles are significantly larger than the theoretical viscous length scale ($Re^* \gg \delta_s$), causing the complete physical destruction of the viscous sublayer. In this state, molecular viscosity plays no role in momentum transfer near the bed; friction is entirely generated by the form drag (pressure wakes) of the roughness elements, making the roughness length y_0 exclusively a function of k_s .

On these hydrodynamically rough walls, the region near the wall undergoes a profound structural transformation. The area immediately adjacent to and just above the roughness elements is referred to as the roughness sublayer. Within this layer, the flow is highly heterogeneous, dominated by localized separation of wakes from individual obstacles, and the standard principles of spatial averaging in boundary layer theory no longer collapse. As the physical bed is highly irregular, the definition of the absolute vertical origin ($y=0$) becomes ambiguous. To restore the mathematical validity of the logarithmic profile above the roughness sublayer, a semi-empirical parameter called the zero-plane displacement (y_d) must be introduced. This parameter essentially represents a kinematic shift, defining an effective hydrodynamic origin at which the average drag forces act. By incorporating the zero-plane displacement and the equivalent sand roughness, the universal logarithmic velocity profile for a fully rough wall ($Re^* > 70$) is classically expressed as:

$$u^+ = \frac{1}{\kappa} \ln \left(\frac{y - y_d}{k_s} \right) + B_r$$

where B_r is a new integration constant that, for a fully rough Nikuradse-type surface, assumes a universally accepted value of approximately 8.5.

Ultimately, the physical validity of this modified logarithmic layer depends on a strict geometric condition. Just as the logarithmic law for smooth walls requires a large-scale separation dictated by the friction Reynolds number ($Re_\tau \gg 1000$), the existence of a well-defined logarithmic overlap layer on rough walls depends on relative submersion. This is defined as the ratio of the macroscopic external length scale (the flow depth, H) to the microscopic roughness scale (k_s). For the roughness substructure to successfully merge into a logarithmic region without being immediately influenced by the dynamics of the free surface (outer layer), a robust scale separation is required. Although this varies greatly depending on the specific geometry and spacing of the roughness elements, a widely accepted heuristic threshold in open-channel hydraulics requires that the relative submergence must be high:

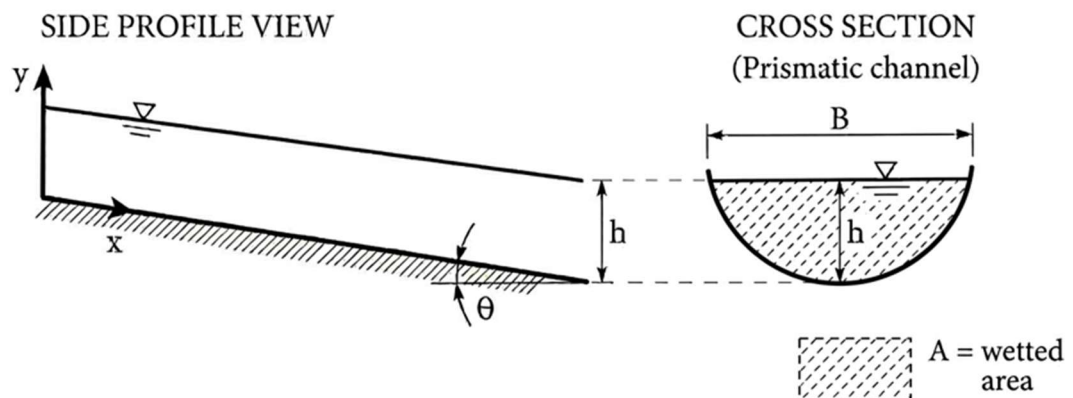
$$\frac{\delta}{k_s} \gg 40$$

If the relative submergence drops below this critical threshold, the flow becomes dominated by macro-roughness interactions, and the classical logarithmic layer may vanish entirely.

1.5 Open channel flow hydraulics (uniform flow)

The hydraulics of free-surface flows differ substantially from motion in pressure ducts due to the presence of a continuous interface between the fluid and the atmosphere. In this physical context, the flow field is not driven by an externally imposed pressure gradient, but rather by the gravitational component of the volumetric force parallel to the slope of the riverbed. The hydraulic analysis of steady and uniform flow represents the fundamental condition of dynamic equilibrium, which is essential for characterising a natural river channel.

The establishment of this specific flow regime is closely linked to the geometry of the cross-section, which not only defines the flow rate but also sets the macroscopic spatial constraints for the development of turbulence. The fundamental hydraulic parameters include the water flow depth (H), measured perpendicular to the bed, the wetted area (A) and the wetted perimeter (P), which quantifies the linear development of the solid-liquid contact interface where tangential stresses are generated. The ratio between these last two quantities defines the hydraulic radius ($R_h = A/P$), i.e. the characteristic length of the flow that governs resistance law. A further critical parameter is the width of the free surface (B), which contributes to defining the aspect ratio of the section (B/H). As evidenced by recent experimental studies on rough-bottomed currents (Peruzzi et al., 2020 [V]), this dimensionless parameter plays a crucial dynamic role: while the wavelengths of the classic turbulent macro-structures (Large-Scale Motions, LSM) scale directly with the flow depth (H), it is precisely the aspect ratio (B/h) that analytically controls the spatial scaling of even larger structures, known as Very Large Scale Motions (VLSM). Moreover, the modulation of the intensity and wavelength of VLSMs along the transverse coordinate suggests a deep dynamic link with secondary currents, whose strength and spatial extension within the cross-section are also dictated by the aspect ratio of the channel.



Within this confined domain, a state of uniform motion is strictly achieved only when the kinematic and geometric parameters of the flow remain unchanged in each cross-section along the longitudinal direction. From a dynamic perspective, this spatial stationarity is established only when there is a perfect balance between the driving forces and the resisting forces: the hydraulic head loss generated by dissipation due to viscous and turbulent friction against the walls is exactly equal to the change in topographic elevation. Consequently, the bed slope (s_0), the free-surface slope (i_w) and

Figure 1.9 – Geometric representation of a prismatic open-channel. The figures highlight the longitudinal side profile view with the cross-sectional geometry, defining the characteristic parameter that represent an open channel flow configuration.

the piezometric and total head difference (H) are perfectly parallel and numerically coincident. In this configuration, the overall convective acceleration of the fluid is zero, and both the velocity profile and the statistical moments of turbulence reach a fully developed flow condition.

By imposing the global equilibrium on the translation of the control volume in uniform motion, the mean boundary shear stress is found to be directly proportional to the hydraulic radius and the energy gradient according to the relation:

$$\tau_0 = \rho g R_h s_0$$

The extraction of the square root of this kinematic stress finally returns the theoretical definition of the frictional velocity:

$$u_* = \sqrt{\frac{\tau_0}{\rho}} = \sqrt{g R_h s_0}$$

This parameter serves as the fundamental inner scaling reference required for the non-dimensionalization of the entire flow field. To establish a solid analytical link between the average flow velocity (U), the geometry of the section and the driving slope, engineering practice relies on constitutive relationships of a semi-empirical nature. The classical treatment refers to the Chézy equation:

$$U = \chi \sqrt{R_h s_0}$$

where χ represents the resistance coefficient, a macroscopic parameter that cannot be derived purely analytically and therefore requires empirical determination. However, the most effective empirical relationship used in environmental hydraulics applications is that proposed by Manning and Strickler:

$$U = \frac{1}{n} R_h^{2/3} S_0^{1/2}$$

In the context of advanced fluid dynamics, it is essential to specify that the Manning coefficient (n) is not a simple intrinsic property of the background material but represents a macroscopic scale parameter that synthesizes the entire turbulent dissipation mechanism.

However, this turbulence generation is not an isolated phenomenon. The spatial evolution of these macroscopic vortices is strictly confined by the physical boundaries of the channel: the lateral walls and the air-water interface. Precisely because of this complex, simultaneous interaction between the bottom boundary layer, the central core, and the free surface, the vertical distribution of the mean longitudinal velocity, while formally following the universal logarithmic law, manifests significant structural deviations in open channels with respect to pressurized pipe flows.

The first macroscopic anomaly is known as the velocity-dip phenomenon: in channels characterized by a low aspect ratio, the maximum velocity peak is not located at the free surface but is depressed at a depth typically between 5% and 25% of the total flow depth. This inflection is kinematically induced by the genesis of strong secondary Prandtl currents of the second kind, originating from the anisotropy of normal Reynolds stresses, which actively convey momentum from the lateral walls towards the symmetry plane and the channel bed.

Concurrently, the presence of the free surface itself imposes a severe thermodynamic and kinematic constraint. Acting as an elastic physical barrier, it suppresses the vertical turbulent fluctuations (w'), forcing a drastic redistribution of the Turbulent Kinetic Energy (TKE) towards the horizontal and transverse fluctuating components. This induced anisotropy profoundly alters the spectral signature of the macro-structures near the top of the water column, making them dynamically distinct from those observed within the bulk of the flow.

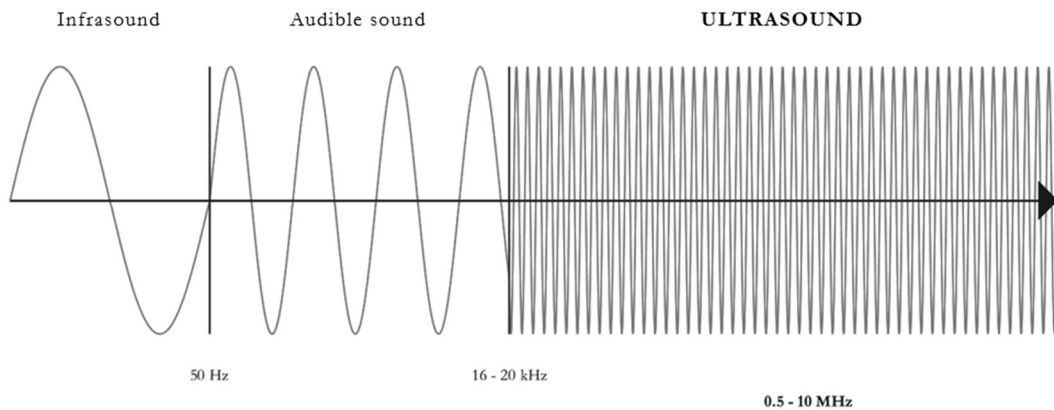
2. Ultrasonic Measurement Principle

2.1 Introduction on the ultrasound

The study of large turbulence scales in free-surface flows requires the use of non-intrusive measurement techniques, capable of guaranteeing a high spatio-temporal resolution without perturbing the flow field. In this domain, ultrasonic velocimetry is one of the most widely used technologies. This technique is based on the emission of high-frequency acoustic waves and the subsequent analysis of the backscattering generated by the interaction between the wavefronts and the tracer particles suspended in the fluid.

This chapter analyses the physical foundations of ultrasonic propagation, culminating in the description of the operating principle of UVP (Ultrasonic Velocity Profiler) technology, with particular reference to the UB-Lab instrumentation used in the present experimental campaign.

Ultrasounds consist of elastic mechanical waves characterized by frequencies above the maximum threshold of human hearing, conventionally set at 20 kHz. Although they are subject to the same physical laws as audible sound waves, their high frequency (which in hydraulic and medical applications typically ranges between 0.5 MHz and 20 MHz) gives them unique properties in terms of directionality and resolution capabilities, making them ideal tools for the non-invasive study of velocity gradients in fluids.



The diagnostic and investigative potential of ultrasound is not a purely human invention but finds its deep foundation in biological evolution. Over the millennia, several species of mammals, in particular bats and cetaceans, have developed sophisticated echolocation systems based on the emission of ultrasonic pulses, using them as primary tools for survival and spatial orientation. However, the translation of this natural phenomenon into a technical application, culminating in the development of today's engineering equipment, is the result of over a century of scientific discoveries. This path, which began in the nineteenth century, has profoundly intertwined the progress of theoretical physics, materials science and military engineering:

1. 1842 - The Doppler Effect: Austrian physicist Christian Doppler formulated the principle that the frequency of a wave perceived by an observer change whether the source or observer is in relative motion. This principle is the beating heart of velocity measurements in fluids.
2. 1880 - Piezoelectricity: Pierre and Jacques Curie discovered that some crystals, such as quartz, generate an electric charge when subjected to mechanical stress and, conversely, vibrate when subjected to an electric field. This discovery has allowed the creation of transducers, the devices capable of converting electrical signals into ultrasonic waves and vice versa.
3. 1916 - SONAR: During World War I, driven by the need to detect submarines, Paul Langevin developed the first ultrasound-based SONAR (Sound Navigation and Ranging) system, demonstrating the practical feasibility of underwater localization using acoustic waves.
4. 1957 - Medical ultrasonography: Tom Brown and Ian Donald applied ultrasound for the first time in medical diagnostics, paving the way for modern ultrasound.
5. 1970 - Flow meters: Technology matured to the point of allowing the creation of the first industrial ultrasonic flowmeters, capable of measuring flow in the pipeline without direct contact with the fluid.

Nowadays, ultrasonic investigation permeates countless industrial and research sectors, ranging from Non-Destructive Testing (NDT) on composite materials to oncological diagnostics, up to micro-welding processes. In the strictly fluid dynamic field, this technology has historically established itself for the non-intrusive measurement of velocity, exploiting the calculation of transit times or the Doppler effect to determine the kinematics, both local and global, of liquid or gaseous flows. However, in the specific context of environmental fluid mechanics, the real leap in

diagnostic quality has been made with the transition from classic flow meters, capable of returning only a single average value quantified over the entire wetted section, to the more sophisticated speed profilers.

It is in this advanced line of research that the UVP (Ultrasonic Velocity Profiler) technology is inserted, the application of which constitutes the methodological core of this thesis. Unlike traditional point sensors, which limit the investigation to a single spatial control volume, the UVP technique allows to instantly acquire an entire velocity profile distributed along the transducer propagation axis (beam axis). Modern profilers, such as the instrumentation developed by Ubertone used in the present experimental campaign, represent the technological synthesis between oceanographic sonar and vascular medical imaging. They operate by exploiting the advanced technique of Pulse-Coherent Doppler, which guarantees a very high precision velocimetric estimation by analysing the phase shift between consecutive acoustic pulses.

In addition to pure kinematics, these tools integrate the fundamental ability to simultaneously record and display the amplitude of the return echo; this parameter not only certifies the acoustic reliability of the recorded data but provides a direct physical proxy to estimate the concentration of suspended particulate matter (sediments) and the turbidity of the fluid. This extraordinary ability to "dissect" the flow field in real time, simultaneously ensuring high spatial and temporal resolution, makes UVP systems the tool of choice for the analysis of turbulence scales. The possibility of capturing the complex spatial-temporal evolution of vortices without introducing any mechanical perturbation within the flow is in fact the essential analytical requirement for the rigorous study of coherent macro-structures.

2.2 Ultrasonic wave

Phenomenological understanding of turbulence requires a thorough understanding of the investigation tool. In the case of ultrasonic profiling, the physical entity that acts as a probe is the high-frequency acoustic wave. This section aims to provide a general overview of the fundamental physical laws governing this phenomenon, introducing the intrinsic nature of the ultrasonic wave, its mathematical formulation, and its dynamic interaction with the fluid domain.

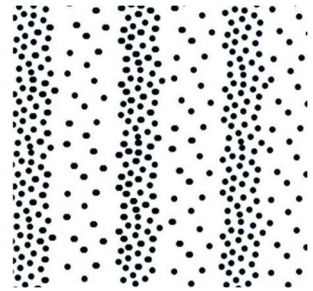
2.2.1 Physical Foundations and Nature of the Perturbation

An ultrasonic wave is fundamentally defined as an elastic mechanical perturbation that propagates through a medium (solid, liquid or gaseous) without inducing any net transport of matter, but with a continuous transfer of energy and momentum. At a microscopic kinematic level, the transit of the wave front forces induces the particles of the medium to perform infinitesimal oscillations around their equilibrium position.

In fluid media, due to the inherent inability to sustain shear stresses, acoustic energy propagation is strictly confined to longitudinal wave modes. In this configuration, the kinematics of the fluid particles are characterized by harmonic oscillations strictly parallel to the axis of wave propagation. This collinear oscillatory motion induces periodic spatial displacements, causing adjacent fluid layers to cyclically converge and diverge.

Consequently, the fluid undergoes continuous localized volumetric deformations, manifesting as a sequence of alternating microscopic regions of enhanced mass density (compressions) and reduced mass density (rarefactions). Through the fluid's thermodynamic equation of state, these cyclic kinematic variations in local density translate directly into macroscopic perturbations of the internal pressure field. This dynamic fluctuation, formally defined as acoustic pressure, constitutes the measurable physical signal that superimposes onto the static hydrostatic pressure of the undisturbed medium.

Figure 2.2 — Two-dimensional schematic representation of the propagation of a longitudinal acoustic wave in a fluid medium, with evidence of compression and rarefaction fronts.



The spatiotemporal evolution of this elasto-mechanical phenomenon is rigorously governed by the acoustic wave equation. This fundamental equation is analytically

derived by applying the acoustic approximation, which assumes the wave to be an infinitesimal perturbation, to linearize the governing laws of fluid dynamics, specifically the continuity and Euler equations (conservation of mass and momentum). By subsequently introducing the thermodynamic equation of state to close the system, the kinematic variables are mathematically eliminated. The result is a single partial differential equation that directly couples the spatial gradients of the acoustic pressure field to its temporal acceleration:

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} = k \rho \frac{\partial^2 p}{\partial t^2}$$

In this mathematical formulation, the acoustic pressure p [N m^{-2}] acts as a spatio-temporal scalar field. The dynamic response of the system is strictly governed by two fundamental physical properties of the fluid:

- Adiabatic compressibility - k [$\text{m}^2 \text{N}^{-1}$]: quantifies the volumetric deformability of the medium, representing its thermodynamic propensity to contract or expand in response to localized pressure variations.
- Mass density - ρ [kg m^{-3}]: defines the local inertia of the fluid, representing its mechanical resistance to the particle accelerations induced by the passage of acoustic waves.

The product of these two state variables ($k\rho$) mathematically defines the inverse square of the acoustic propagation velocity ($1/c^2$). This fundamental relationship underscores a crucial physical principle: the celerity of the ultrasonic wave (c) is not dictated by the source parameters but is exclusively an intrinsic property of the thermodynamic state of medium through which it propagates.

2.2.2 Kinematic description: sinusoidal model

For analytical and experimental purposes, the acoustic pulse emitted by the transducers is modelled as a pure sinusoidal wave. The spatio-temporal evolution of the acoustic pressure field $p(x, t)$ at a given spatial coordinate x and at preestablished time t can be mathematically expressed as:

$$p(x, t) = A_p \sin(\omega t - kx)$$

where:

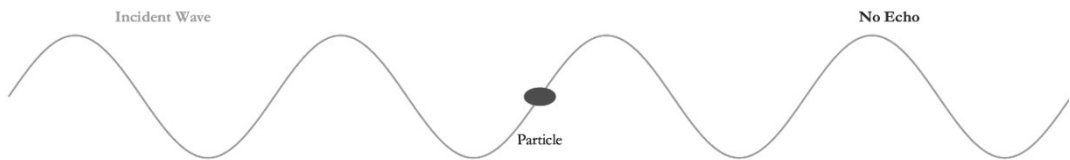
- A_p is the peak acoustic pressure amplitude [N m^{-2}].
- ω is the pulsation (or angular frequency) [$\text{rad} \cdot \text{s}^{-1}$], linked to the emission frequency f by the relation $\omega = 2\pi f$.
- k is the wavenumber [rad m^{-1}], which defines the spatial periodicity of the wave.

From these variables, the acoustic wavelength (λ) is derived, i.e. the spatial distance between two consecutive wavefronts exhibiting the exact same phase:

$$\lambda = \frac{2\pi}{k} = \frac{c}{f}$$

This geometric quantity is of fundamental importance for the instrument's spatial resolution. In the context of ultrasonic velocity profiling, the minimum physical scale of the detectable turbulent structures (eddies) is intrinsically bounded by this parameter. However, the wavelength does not only limit the size of the observable vortices; it also dictates the fundamental requirement for the generation of the measurement signal itself. Effective acoustic interaction, and the subsequent generation of the backscattered echo, requires the incident wave to interact with suspended particles whose dimension and spacing are physically compatible with the wavelength λ . To elaborate on this operational constraint, the Ultrasonic Velocity Profiling (UVP) technique relies entirely on the physical phenomenon of acoustic backscattering. The instrument does not measure the fluid velocity directly; instead, it tracks the kinematics of suspended scatterers (such as sediments, impurities, or microbubbles) that act as fluid dynamic proxies. The efficiency of this backscattering process is strictly governed by the ratio between the equivalent diameter of the scattering particle (D) and the acoustic wavelength (λ). If the suspended particles are significantly smaller than the incident wavelength ($D \ll \lambda$), the acoustic wave predominantly diffracts around the obstacles (approaching the Rayleigh scattering regime). In this scenario, the wave bypasses the particles without being significantly perturbed, resulting in a negligible reflected energy and an undetectable echo. Conversely, when the physical dimensions of the particles approach or exceed the wavelength ($D \gg \lambda$), a substantial portion of the incident acoustic energy is physically intercepted and reflected back towards the active face of the transducer. Therefore, a careful calibration of the emission frequency, and consequently the wavelength of the acoustic waves, is mandatory. It must be selected to ensure geometric compatibility with the naturally occurring or artificially introduced seeding particulate, thereby guaranteeing a high Signal-to-Noise Ratio (SNR) and the acquisition of a valid kinematic measurement.

(a) Rayleigh Scattering Regime: $D \ll \lambda$



(b) Backscattering Regime: $D \geq \lambda$

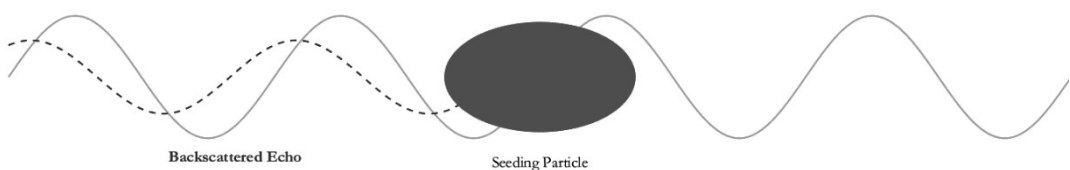


Figure 2.3 — Schematic representation of the acoustic backscattering dependence on the particle-to-wavelength ratio. (a) When the particle diameter is significantly smaller than the wavelength ($D \ll \lambda$), the acoustic wave diffracts around the obstacle with negligible reflection (Rayleigh regime). (b) When the particle dimensions approach or exceed the wavelength ($D \geq \lambda$), the incident wave is effectively intercepted and reflected, generating the backscattered echo required for UVP measurements.

2.2.3 The sound velocity and environmental variables

The propagation velocity of the acoustic wave c [m/s] constitutes the most critical calibration parameter for the ultrasonic acquisition system. In the UVP technology, the spatial coordinate of each measurement volume is not measured directly but is indirectly derived from the acoustic Time-of-Flight (TOF). The distance r from the transducer face to the scattering particle is computed as:

$$r = \frac{c \cdot t}{2}$$

where t is the passed time between the pulse's emission and the reception of the backscattered echo, and the factor of 2 accounts for the round-trip travel of the wave. Consequently, any inaccuracy in the estimation of the acoustic wave velocity translates directly into a systematic distortion of the spatial axis, resulting in a systematic error in the calculation of the velocity profile along the water column.

As previously demonstrated, the celerity of the wave is an intrinsic thermodynamic property of the propagation medium. It varies drastically depending on the physical state of the material crossed, primarily due to differences in molecular spacing and bonding elasticity. For instance:

- Gas (air at 20°C): 330 m/s (high compressibility, low speed).
- Liquids (water at 15°C): 1480 m/s.
- Solids (steel): 5900 m/s (very low compressibility, high speed).

In environmental fluid dynamics, with particular referment for the study of open-channel flows and in general for natural surface water, speed of sound cannot be considered constant. It is a highly dynamic variable depending by different environmental factors: temperature, salinity and hydrostatic pressure. In shallow freshwater environments, where the effects of salinity and pressure gradients are negligible, temperature (T) becomes the absolute dominant driver of acoustic celerity.

Unlike most liquids, water exhibits an anomalous acoustic behaviour: as the temperature increases, its adiabatic bulk modulus increases faster than its density decreases, causing the speed of sound to rise. To account for this non-linear thermodynamic response, modern signal processing interfaces, such as the UB-Lab software, strictly require the continuous input of the fluid's exact temperature. The system then automatically corrects the distance calculations and the spatial positioning of the measuring cells using highly accurate empirical polynomial equations, i.e. the Marczak formulations, that for freshwater can be written as:

$$c = 1402.392 + 5.012285 T - 0.0551184 T^2 + 0.221649 \cdot 10^{-3} T^3$$

This velocity correction it's of fundamental importance to avoid systematic errors in the spatial positioning of the measuring cells along the water tie rod.

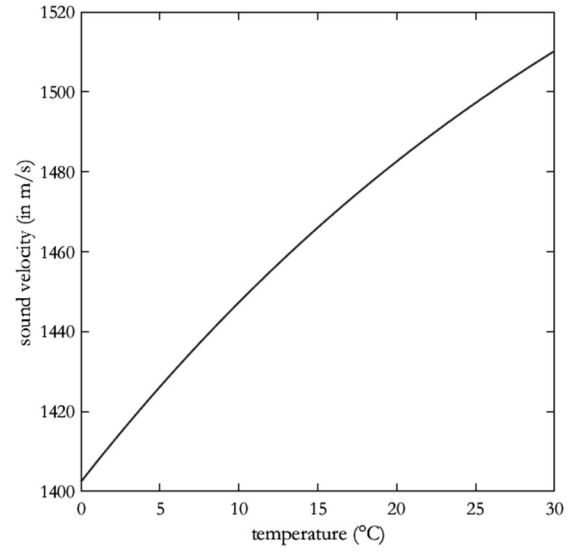


Figure 2.4 — Non-linear relationship between the acoustic speed and temperature in water, computed using the Marczak empirical polynomial formulation.

2.2.4 Acoustic Impedance and Interfaces (Reflection and Transmission)

The specific acoustic impedance (Z) is a material property that defines the ability of the medium to transmit the mechanical energy of the wave, i.e. the resistance imposed by the medium on the passage of the sound wave. Analogous to electrical resistance in electrical circuit, acoustic impedance establishes the behaviour of the signal across different materials, and it is mathematically defined as the product of the medium's density and its acoustic propagation velocity, expressed in Rayls [$kg \cdot m^{-2} \cdot s^{-1}$]:

$$Z = \sqrt{\frac{\rho}{k}} = \rho c$$

This parameter governs the behaviour of the signal whenever it encounters a geometric interface between two different media with different properties, i.e. a change of medium (e.g., transducer-to-water or water-to-sediment boundaries). Typical order of magnitude values highlights the extreme variability of this property:

- Air: 428 Rayl (very low impedance);
- Freshwater: 1.48 MRayl;
- Metal (steel): 46 MRayl (high impedance, highly reflective).

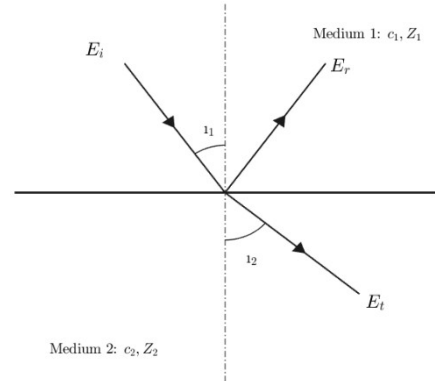
When an incident ultrasonic wave encounters pass through the confine of two different materials, defined by two different specific acoustic impedances Z_1 and Z_2 , the wave undergoes two distinct physical phenomena: reflection and transmission (refraction). If the incident wave strikes the interface at an angle i_1 , the direction of the transmitted wavefront (i_2) is determined by the ratio of the acoustic velocities in the respective media, as defined by Snell's Law:

$$\frac{\sin i_1}{c_1} = \frac{\sin i_2}{c_2}$$

More importantly, the proportion of incident acoustic energy (E_i) that is reflected into the first medium (E_r) is directly proportional to the magnitude of the impedance mismatch. Analytically, the power reflection coefficient (R) is calculated as:

$$R = \frac{E_r}{E_i} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2$$

Figure 2.5 — Schematic representation of acoustic reflection and transmission at an interface between two media with differing specific impedances (Z_1, Z_2). The refraction angle i_2 is governed by the speed of sound ratio according to Snell's Law



This theoretical framework explains several critical operational constraints in experimental acoustic campaigns:

- **Air ↔ Water Interface:** Due to the severe impedance mismatch, the reflection coefficient reaches a value of 0.99, meaning that only the 0.1% of the acoustic energy is transmitted. Practically speaking, this barrier makes it impossible to perform ultrasonic profiling through air. To overcome this issue, even when the transducer is fully immersed in the water, a specific coupling gel (generally provided by the manufacturer) must always be applied to its active face. This protective layer acts as a permanent barrier that isolates the sensor, preventing any direct contact between the transducer and air pockets or adhering microbubbles, thereby ensuring an unattenuated transmission of the acoustic wave into the water.
- **PVC ↔ Water Interface:** In contrast, plastics such as PVC, commonly used for transducer casings and experimental pipe walls, exhibit an acoustic impedance relatively close to that of water. This high degree of acoustic compatibility yields a transmission efficiency of approximately 86%, allowing the ultrasonic pulses to penetrate the active face of the probe and enter the fluid domain without severe energy attenuation.

2.2.5 Energy aspects: Effective Pressure and Intensity

Evaluating the energy content of the propagating wave is essential for determining whether the acoustic signal can emerge clearly above the background noise floor, thus ensuring a high signal-to-noise ratio (SNR). Since a pure harmonic wave fluctuates symmetrically around the ambient hydrostatic pressure, its linear time-averaged value inevitably cancels out to zero. For this reason, the actual physical energy carried by the perturbation is quantified through the root-mean-square (RMS) acoustic pressure, p_{rms} , which integrates the squared pressure field over a complete temporal period T :

$$p_{rms} = \sqrt{\frac{1}{T} \int_0^T p^2(t) dt}$$

For a standard sinusoidal ultrasonic pulse, this relationship simplifies directly to $p_{max}/\sqrt{2}$, yielding a constant scalar value that reflects the effective mechanical stress imposed on the fluid medium.

This energetic framework extends directly to the acoustic intensity (I) which describes the time-averaged rate of acoustic power (P) crossing a unit surface area (S) perpendicular to the direction of wave propagation. Expressed in $W \cdot m^{-2}$, this parameter provides a direct link between the kinematic strength of the perturbation and the intrinsic thermodynamic properties of the fluid, as it depends explicitly on the specific acoustic impedance Z :

$$I = \frac{P}{S} = \frac{p_{rms}^2}{Z}$$

In high-frequency turbulence research, maintaining a sufficiently high acoustic intensity is a strict practical requirement. Because the tracer particles scatter back only a microscopic fraction of the incident energy, the resulting echo must be strong enough to remain distinct from both electronic noise and ambient environmental fluctuations. Ultimately, achieving an optimal SNR through these energy parameters is what allows the system to accurately resolve the rapid, instantaneous velocity fluctuations typical of turbulent structures.

2.3 Wave – Medium interaction

The effectiveness of ultrasonic velocity profiling relies heavily on the complex kinematic and energetic exchanges that occur between the acoustic pulse and the fluid suspension. This coupling goes beyond mere wave propagation; it is the fundamental physical mechanism that encodes the dynamic properties of the flow into the backscattered signal. Within a real fluid, this interaction splits into two simultaneous but opposing macro-phenomena: particle scattering, which redirects the initial energy to create the measurement echo, and progressive attenuation, which dissipates the wave's amplitude and consequently limits the instrument's penetration range along the water column.

2.3.1 Particle scattering mechanisms and acoustic regimes

The Doppler measurement principle depends on capturing frequency shifts reflected by discrete moving targets, typically referred to as tracers or seeding. From a strictly physical point of view, the acoustic response of a particle struck by an ultrasonic field is dictated by the dimensionless size parameter $x = \pi d / \lambda$, where d is the equivalent diameter of the solid and λ is the incident wavelength. Depending on this ratio, the interaction falls into one of four distinct regimes, each characterized by its own directional footprint and energy conversion efficiency:

1. Geometric reflection regime ($d > \lambda$ or $x \gg 1$)

When the suspended solid is significantly larger than the wavelength, the physical interaction closely follows the laws of geometric optics. The particle's surface acts as a macroscopic acoustic mirror, intercepting the wavefront and reflecting the bulk of the energy directly back toward the receiving transducer. While this mechanism ensures a highly favourable signal-to-noise ratio (SNR), it introduces severe kinematic constraints: larger tracer particles possess higher mechanical inertia, meaning they might fail to accurately track the most rapid turbulent fluctuations of the flow.

2. Forward scattering regime ($d \approx \lambda$ or $x \approx 1$)

In conditions of near geometric equivalence, diffraction phenomena around the edges of the particle become dominant. This causes an asymmetrical redistribution of energy, which heavily concentrates in the forward half-space. For monostatic UVP systems, which rely on the same piezoelectric crystal to both emit and receive, this regime represents a critical blind spot. The fraction of energy returning to the source drops drastically, rendering the instrument largely ineffective despite the physical presence of the tracer.

3. Resonant and multidirectional scattering regime ($d < \lambda$)

When the obstacle is moderately smaller than the wavelength, the interaction is no longer purely superficial. The acoustic wave partially penetrates the elastic structure of the solid, triggering its natural vibrational modes. If the pulse frequency happens to match one of these natural frequencies, the scattering

cross-section experiences a significant amplification due to structural resonance. The resulting effect is nearly isotropic, scattering energy in all spatial directions while still preserving a sufficient backscattered signal for Doppler decoding.

4. Rayleigh scattering (Acoustic transparency) regime ($d \ll \lambda$ or $x \ll 1$)

In the limit where the particle is infinitesimal compared to the spatial period of the wave, the scattering efficiency decays with the fourth power of the frequency, strictly following Rayleigh's law (where the scattered intensity is proportional to d^6/λ^4). Under these conditions, the fluid behaves as a perfectly homogeneous and acoustically transparent continuous medium. The wave passes through the suspension without undergoing any measurable deflection, and the reflected energy falls well below the thermal and electronic noise floor, making it impossible to extract any instantaneous velocity data.

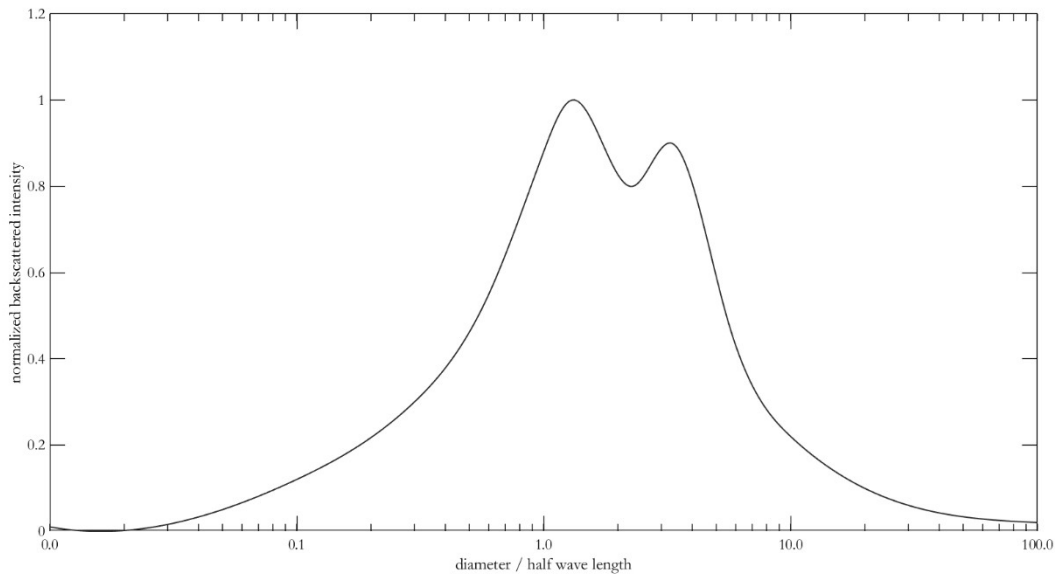


Figure 2.6 — Normalized acoustic backscattered intensity as a function of the ratio between the tracer particle diameter and the acoustic half-wavelength. The non-linear distribution visually summarizes the transition across the fundamental scattering domains: the steep decay on the left ($d < \lambda$) illustrates the severe signal loss typical of the Rayleigh transparency regime, whereas the central amplification peaks highlight the maximum energy reflection occurring within the resonant scattering regime.

Understanding these regimes imposes strict operational criteria when designing experimental setups. Selecting the operating frequency of the transducers must always involve a preliminary analysis of the tracer's particle size distribution, as maximizing the SNR depends entirely on deliberately placing the measurement system within the optimal scattering range.

2.3.2 Attenuation phenomena

Attenuation represents the cumulative loss of acoustic intensity experienced by the wave as it propagates through the fluid medium. This continuous energy depletion fundamentally restricts the maximum penetration depth of the instrument and must be carefully modelled to preserve the integrity of the acquired velocity data. The residual acoustic intensity $I(z)$ at a given spatial distance z from the acoustic source is governed by a standard exponential decay law:

$$I_{att}(z) = I_0 e^{-2\alpha z}$$

where I_0 represents the initial intensity transmitted at the transducer interface, and α is the global attenuation coefficient of the medium (expressed in m^{-1}). Rather than being a single isolated mechanism, this macroscopic decay is the synergistic result of three distinct physical processes: molecular absorption, particle scattering, and geometric beam divergence.

The primary driver of energy loss is acoustic absorption, a dissipative process in which the organized mechanical energy of the wave is irreversibly converted into internal heat. This thermodynamic conversion is triggered by two main factors: the viscous friction generated between adjacent fluid particles during their acoustic oscillation, and molecular relaxation effects, which represent a slight delay in the medium's thermodynamic response to rapid pressure variations. In pure water, the absorption coefficient (α_a) is highly sensitive to the operating frequency f of the transducer, strictly following a quadratic relationship:

$$\alpha_a = K f^2$$

The parameter K is not a universal constant; it exhibits a strong dependence on the fluid's temperature T [$^{\circ}\text{C}$], reflecting significant thermodynamic shifts in the dynamic viscosity and molecular structure of the water:

$$K = [2.4 \cdot 10^{-3}(T - 38)^2 + 1.5] \cdot 10^{-14}$$

This rigid frequency dependence introduces a fundamental engineering trade-off in UVP applications: while selecting a higher emission frequency significantly improves the spatial resolution of the measurement, it inevitably triggers a severe escalation in signal attenuation, thereby drastically reducing the instrument's effective profiling range.

Alongside this thermal dissipation, the main beam energy is further depleted by the scattering process itself. Although a certain degree of particle scattering is strictly necessary to generate the Doppler return echo, an excessive concentration of suspended tracers, or the presence of irregular geometric boundaries, forces a substantial fraction of the acoustic energy to deflect away from the main measurement axis, exacerbating the overall signal decay.

Independent of these medium-induced losses, the wave also experiences a purely spatial intensity drop due to geometric beam divergence. Because the ultrasonic source is not perfectly collimated, the acoustic wavefront naturally spreads out as it travels away from the active face of the sensor. Even in an ideal, completely non-dissipative fluid, the acoustic intensity would still decrease with distance simply because the initial acoustic power is forced to distribute over a progressively expanding surface area, an effect that becomes particularly dominant in the far-field region of the transducer.

2.3.3 Historical perspective and signal optimization in environmental flows

An interesting conceptual parallel can be drawn between modern ultrasonic profiling and classical flow visualization techniques, specifically, the seminal experiment conducted by Osborne Reynolds in 1883. While Reynolds used a liquid dye to visually trace streamlines and identify the onset of the transition to turbulent flow, ultrasonic measurements employ suspended scattering particles as an acoustic equivalent to his colored tracer. Unlike traditional optical methods, which offered a purely qualitative description, often restricted to the free surface or transparent laboratory conduits, wave-medium interaction allows researchers to acoustically illuminate the fluid's interior regions. By analyzing both the backscattered echo intensity and its spatial persistence (accounting for attenuation), UVP technology provides a high-resolution quantitative map of coherent turbulent structures, effectively overcoming the inherent limitations of direct optical observation.

In practical environmental applications, particularly when monitoring free-surface flows and artificial channels, this delicate balance between acoustic scattering and attenuation determines the effectively feasible measurement range. An excessively low tracer concentration yields a weak return echo, rendering the signal virtually indistinguishable from background noise. Conversely, excessive turbidity significantly amplifies scattering-induced attenuation, preventing the acoustic pulse from penetrating the deeper regions of the water column. A rigorous interpretation of the physics governing wave-medium interaction is not merely a theoretical exercise, but a fundamental prerequisite for any subsequent spectral analysis of velocity fluctuations. Ensuring an optimal acoustic balance guarantees that the acquired time series faithfully reflect the actual fluid dynamics, providing clean, artifact-free input data that are essential for robust power spectral density estimates.

2.4 Ultrasonic Beam

Contrary to the idealized concept of an infinitely thin, one-dimensional ray, the acoustic field generated by a piezoelectric transducer expands into a complex three-dimensional volume. The spatial configuration and intensity of this acoustic beam do not remain constant but evolve continuously along the axis of propagation. Rather than projecting as a perfect cylinder, the geometry of the sampling volume is strictly governed by the laws of diffractive optics and is fundamentally determined by two physical constraints: the operating frequency of the emission (f) and the geometric dimensions of the active transducer face, typically characterized by its radius R_t .

To physically describe the generation and subsequent spatial evolution of this beam, the Huygens-Fresnel principle serves as the primary theoretical framework. This principle postulates that every point on the vibrating surface of the transducer acts as an independent, secondary source of elementary spherical waves. As these elementary waves propagate forward into the fluid, they inevitably overlap. It is precisely the intricate pattern of constructive and destructive interference among these countless spherical wavefronts that ultimately shapes the resulting acoustic field.

Mathematically, this spatial distribution is computed through the Rayleigh integral, which evaluates the resultant wave function (f_r) at any specific spatial coordinate by integrating the contributions of the entire vibrating surface:

$$f_r(x, y, z) = \left| \iint \frac{\exp(-jk d_{0x})}{d_{0x}} \cos(\vec{x}, \vec{d}_{0x}) dS \right|$$

where:

- S is the active area of the transducer;
- k is the acoustic wavenumber;
- d_{0x} is the absolute distance between the elemental vibrating surface (dS) and the specific point of observation.
- $\cos(\vec{x}, \vec{d}_{0x})$ represent the obliquity factor, defining the angular directivity of the elementary spherical waves propagating from the surface.

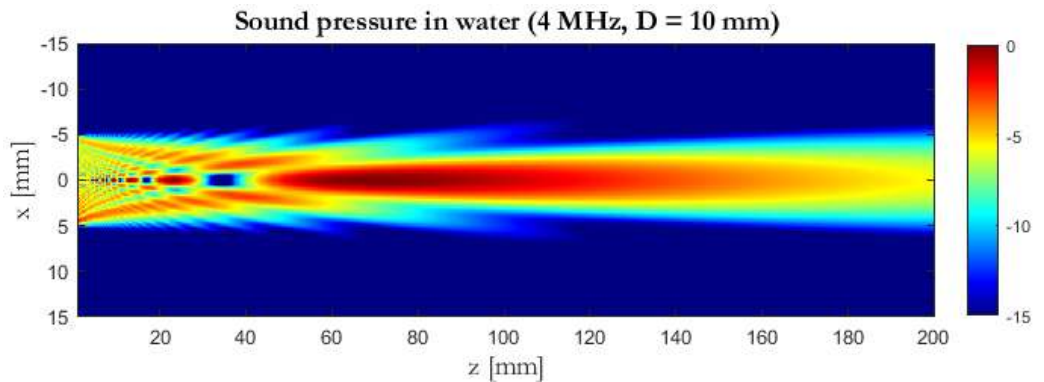


Figure 2.7 — Sound pressure in water (4MHz, D=10mm). Numerical simulation of the spatial pressure distribution for a 10 [mm] diameter transducer operating at 4 [MHz] in a freshwater medium.

The solution to the Rayleigh integral reveals that the acoustic energy radiated by a transducer does not propagate as a uniform, collimated beam. Instead, the pressure field is structurally organized into two distinct propagation regions, each characterized by fundamentally different geometric and energetic properties. This transition is determined by the interference patterns of the elementary spherical waves, and its precise location serves as a critical constraint for the configuration of any ultrasonic velocity profiling system.

The region immediately adjacent to the transducer face is defined as the Near-field or Fresnel zone. Within this domain, the acoustic pressure field is dominated by complex constructive and destructive interference resulting from the phase differences between elementary source points. Consequently, the pressure map exhibits intense spatial oscillations both along the beam axis and across the transverse cross-sections. From an experimental point of view, measurements performed within the Fresnel zone can be inherently unstable, as the local pressure is extremely sensitive to micro-variations in the transducer-target alignment. The characteristic length of this zone (x_{CP}) marks the limit of the Fresnel region and is analytically defined by the transducer geometry and frequency as:

$$x_{CP} = \frac{R_t^2 f}{c}$$

with:

- R_t the active surface radius [m];
- f the emission frequency [Hz];
- c the sound speed [m/s].

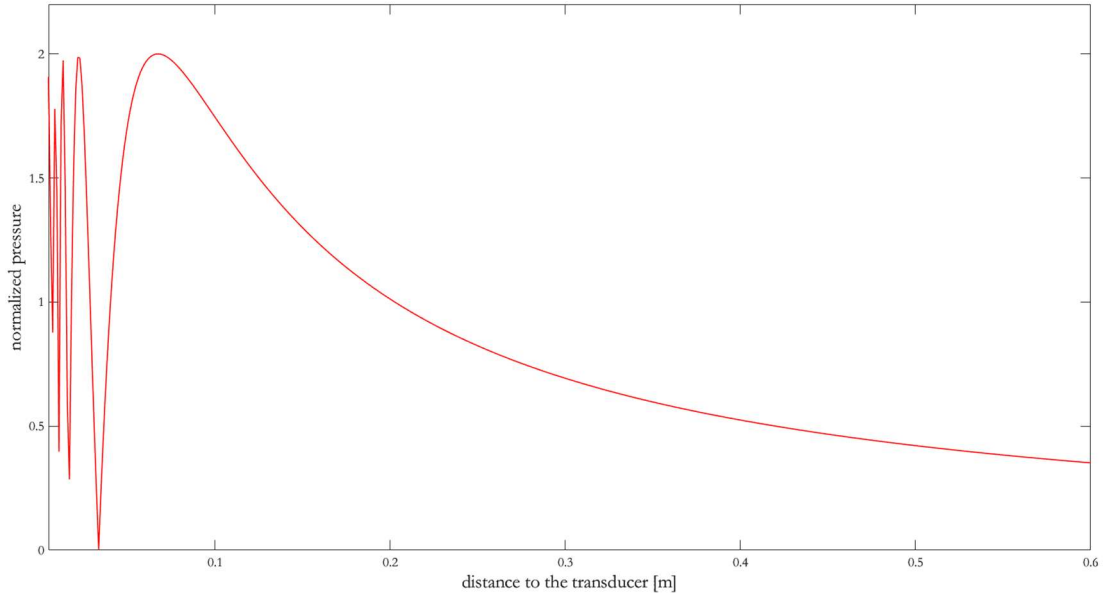


Figure 2.8 – Normalized axial acoustic pressure distribution for a circular transducer. The plot illustrates the transition from the near-field region, dominated by high-frequency spatial oscillations due to constructive and destructive wave interference, to the far-field region, where the pressure amplitude exhibits a smooth, monotonic decay. The final maximum peak corresponds to the Rayleigh distance, which marks the geometric boundary beyond which the acoustic beam stabilizes into a well-defined far-field lobe.

Beyond the distance x_{CP} , the acoustic field transition into the Far-field, or Fraunhofer zone. In this region, the wave interference stabilizes, causing the acoustic pressure to decay in a predictable and monotonic manner. The beam begins to diverge, assuming a characteristic conical geometry. The spatial extent of this divergence is quantified by the half-angle of aperture (θ) which defines the angular width of the main lobe where the acoustic pressure drops by a reference threshold (typically -3 dB):

$$\theta = \frac{0.61 c}{R_t f}$$

In this region, the system achieves its maximum directivity. However, a significant operational trade-off emerges: while the beam propagation becomes highly stable and predictable, the transverse spatial resolution gradually diminishes as the distance from the sensor increases. Understanding this spatial evolution is essential for data interpretation, as the signal captured in the far-field is effectively a spatially integrated representation of the velocity fluctuations, whereas the near-field requires a more cautious approach to account for the localized interference artifacts inherent in the pressure field.

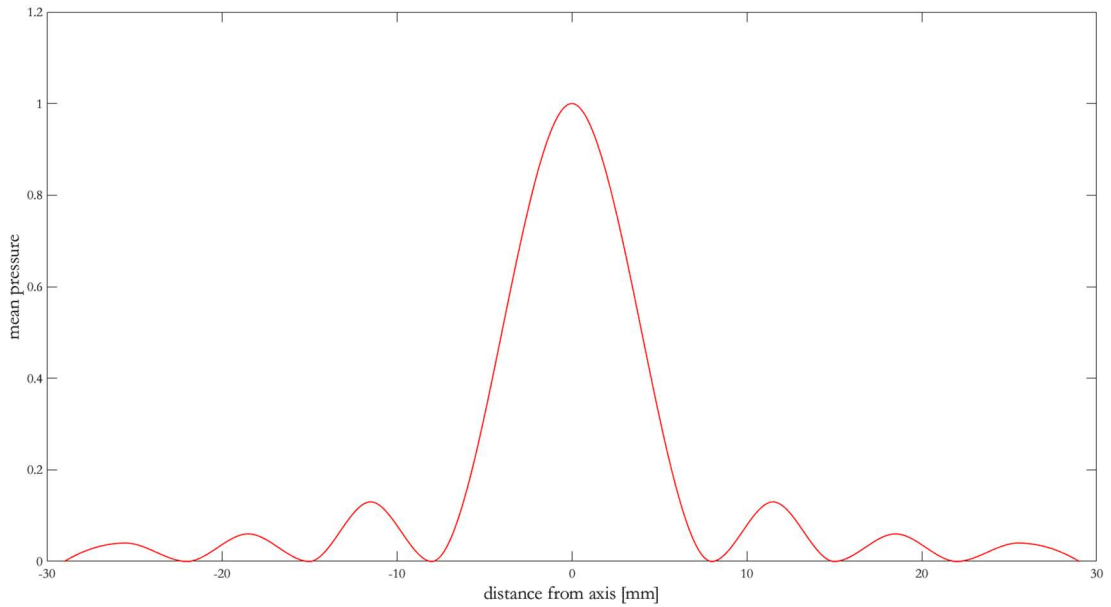


Figure 2.9 — Transverse mean pressure profile in the far-field (Fraunhofer) region. The distribution shows that the acoustic energy is concentrated within a dominant central lobe, flanked by secondary lobes of significantly lower amplitude. The width of this central lobe determines the lateral resolution of the ultrasonic profiling system; as the distance from the transducer increases, the main lobe broadens, leading to a natural trade-off between the depth of investigation and the ability to resolve fine-scale turbulent structures.

To facilitate the design of experimental measurement cells and accurately estimate the effective sampling volume of the UVP system, the complex pressure field is frequently approximated by the so-called cylinder-cone model. This geometric abstraction provides a pragmatic framework for calculating the spatial region from which the backscattered signal is collected, assuming a deterministic energy distribution within

the acoustic beam. The model assumes that, within the near-field region, specifically up to a distance of approximately $1.6 \cdot x_{CP}$, the beam maintains a perfectly cylindrical geometry with a constant radius equivalent to that of the transducer active surface (R_t). Beyond this threshold, the beam transitions into a conical expansion, where the divergence is governed by the previously derived half-angle of aperture (θ). This simplified geometry is constrained by the physical requirement that this idealized volume must contain approximately 90% of the total radiated acoustic energy.

By adopting this approach, the complexity of the Rayleigh integral is reduced to a tractable geometric problem, allowing for the precise determination of the spatial resolution along the measurement axis. In practical laboratory campaigns, this model proves indispensable for defining the resolution of the velocity profiles, particularly when assessing the influence of wall proximity or the spatial integration of coherent turbulent structures. By mapping the transducer's acoustic footprint onto this cylinder-cone volume, one can anticipate the spatial averaging effects inherent in the Doppler shift processing, ensuring that the detected velocity fluctuations are correctly correlated with the actual physical location within the flow domain.

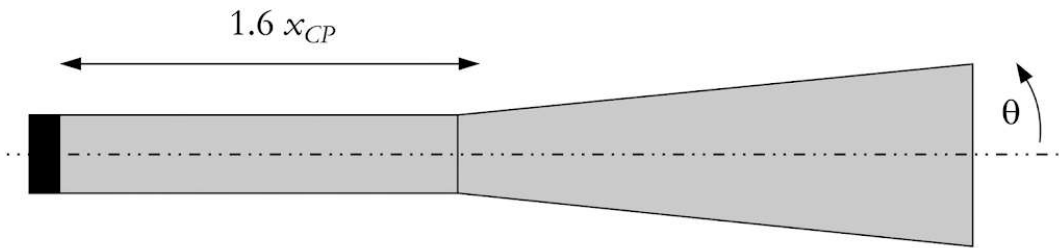


Figure 2.10 – Geometric representation of the cylinder-cone beam model. This schematic illustrates the two-stage approximation used to define the transducer's acoustic sampling volume.

Frequency	Diameter	Near field length	Half-angle aperture	Beam diameter
1.0 MHz	20 mm	6.8 cm	5.2°	3.4 cm at 30cm distance
1.5 MHz	20 mm	10 cm	3.4°	12 cm at 1m distance
3.4 MHz	7 mm	2.8 cm	4.3°	15 cm at 1m distance

Table 2.1 – Summary of standard transducer beam characteristics. The provided data highlights the strong dependency of the acoustic beam geometry on the operating frequency and the transducer diameter. These specifications demonstrate the inherent trade-offs in ultrasonic instrumentation, where higher frequencies generally offer tighter focusing capabilities but different divergence patterns in the far-field region.

2.5 Hardware architecture and signal processing chain

The hardware architecture of an ultrasonic velocity profiler is designed to handle a demanding dual-functionality: the generation of high-energy acoustic pulses and the precise detection of extremely weak backscattered echoes. The system typically operates through a closed-loop coupling between a central control unit and a piezoelectric transducer, which serves as the physical interface between the electronic signal chain and the fluid medium.

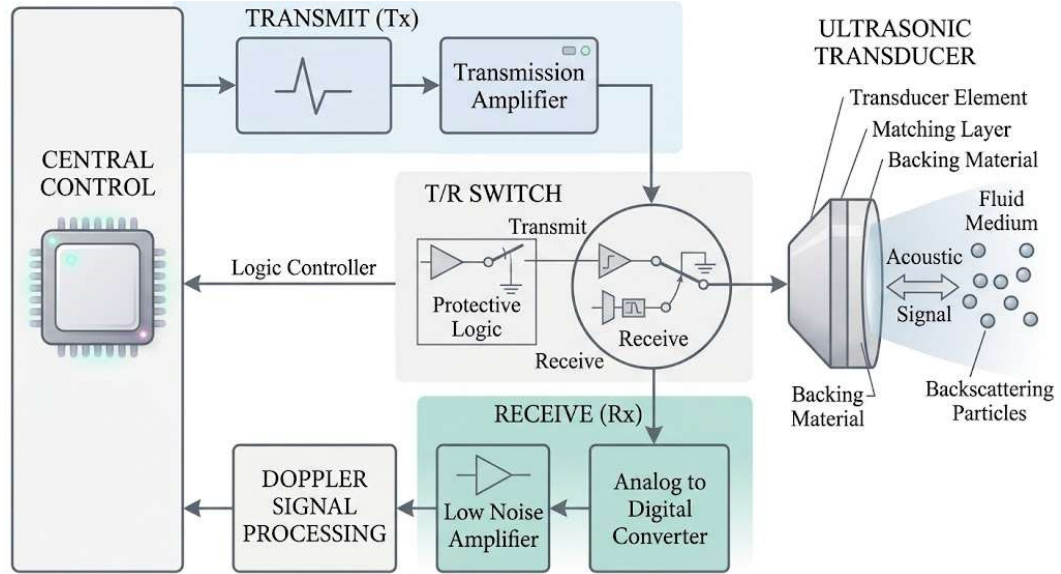
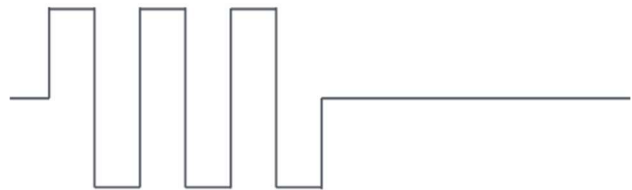


Figure 2.11 – Block diagram of the UVP hardware system. The process starts in the transmission (Tx) branch, which generates the electrical pulse that the transducer converts into an acoustic wave. During this emission, the T/R (Transmit/Receive) switch protects the sensitive receiver from high voltages, which directly creates the near-field blanking zone. Once the emission stops, the system enters the listening phase. The reception (Rx) branch captures the weak echoes returning from the fluid, and a Low Noise Amplifier (LNA) boosts these faint signals before they are digitized and processed to calculate the flow velocity.

2.5.1 Emission dynamics and the transient response limit

The measurement cycle initiate with the generation of an acoustic burst, often referred to as a pulse train, which consists of a precise sequence of sinusoidal or square-wave oscillations. These electronic signals are driven to the piezoelectric element, where they are transduced into mechanical vibrations that propagate into the fluid.

Figure 2.12 – Schematic representation of a typical ultrasonic emission sequence. The waveform illustrates a finite pulse train (burst) consisting of multiple square-wave cycles generated by the transmission electronics.



The integrity of this process is inherently constrained by the electromechanical response of the crystal, leading to a phenomenon known as the relaxation time. Upon the cessation of the emission burst, the transducer element does not stop vibrating instantaneously due to its structural inertia, a phenomenon characterized as ringing. To protect the sensitive reception circuitry from this residual energy, the hardware employs a temporary electronic decoupling phase. This protective interval creates a blanking zone (or dead zone), a spatial region immediately adjacent to the transducer face where no valid velocity data can be acquired, as the receiver is temporarily inhibited to prevent signal saturation.

The extent of this near-surface blind zone is physically coupled to the operational frequency of the sensor. Higher emission frequencies enable a faster damping of the crystal vibrations and a more precise control of the pulse train, thereby reducing the blanking zone. For instance, sensors operating at 1 MHz typically exhibit a blanking distance of approximately 20 mm, whereas 4 MHz systems can minimize this footprint to roughly 5 mm.

This hardware limitation is of significant concern for experimental fluid mechanics; in near-wall measurement campaigns, the blanking zone often coincides with the region of maximum turbulent production and high velocity gradients. Consequently, minimizing this blind zone is not merely an equipment specification, but a fundamental requirement for accurately capturing the viscous sublayer and the onset of the turbulent boundary layer. Beyond this initial dead zone, the system transitions into an active reception mode, where the electronics must maintain a high dynamic range to amplify the exponentially decaying return signal while filtering out ambient acoustic noise and electronic interference.

2.5.2 Wideband transducer technology

Modern ultrasonic profiling depends largely on the physical properties of the piezoelectric crystal. Currently, most UVP systems are equipped with wideband transducers. Unlike older sensors restricted to a single specific frequency, wideband models can operate over a flexible spectrum, typically spanning from 50% to 80% around their nominal center frequency. This feature represents a significant advantage for the study of turbulent flows.

From a practical point of view, this frequency flexibility helps optimize signal quality. The intensity of the acoustic backscatter relies heavily on how the sound wavelength matches the physical size of the seeding particles suspended in the water. A wideband sensor allows the user to fine-tune the operating frequency to better interact with the specific particles present in the channel, thereby naturally improving the signal-to-noise ratio.

However, the most significant advantage of wide bandwidth is its direct impact on spatial resolution. Based on fundamental signal processing principles, generating an

extremely short, sharp acoustic pulse in the time domain requires combining a wide range of frequencies. A traditional narrow-band sensor can only produce a long, drawn-out pulse. A wide-band transducer, on the other hand, possesses the spectral capability to emit very short, abrupt pulses.

This time-domain feature translates directly into physical space. Since sound travels through water at a relatively constant speed (approximately 1480 m/s), the time duration of the electronic burst dictates the physical length of the acoustic “packet” traveling through the flow. A long pulse creates a large physical sound packet in the water, while a very brief pulse generates a remarkably thin acoustic packet. This distinction is crucial for turbulence analysis. The UVP instrument calculates flow velocity by averaging the movement of all particles caught within that specific acoustic packet at a given moment. If the packet is physically large, the instrument averages a large volume of water, artificially smoothing out the data and masking small-scale turbulent eddies. By keeping the burst short, the measurement cell shrinks to a thin slice of fluid. This drastically reduces spatial averaging, allowing the system to capture the fine, small-scale details of the turbulence that would otherwise be lost.

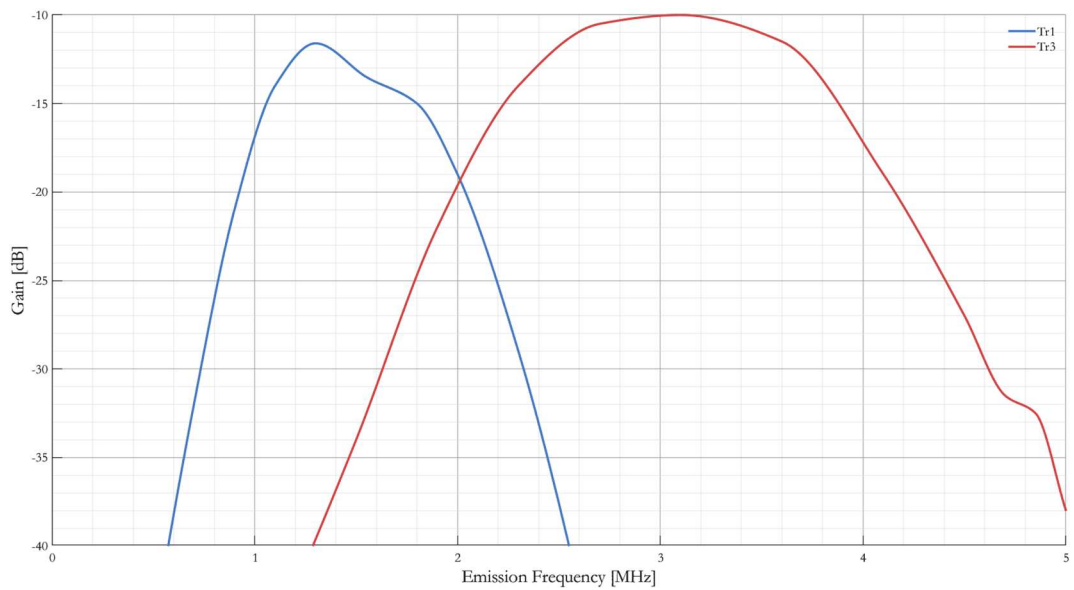


Figure 2.13 — Frequency response spectra of two standard ultrasonic transducers (Tr1 and Tr3). The plot illustrates the signal gain as a function of the emission frequency. The blue curve (Tr1) represents a transducer with a nominal center frequency of 1.25 MHz, whereas the red curve (Tr3) corresponds to a sensor optimized for higher frequencies, with a nominal center frequency of 3 MHz. The broad, bell-shaped profile of both curves visually highlights the wideband nature of these devices.

2.5.3 Reception electronics and dynamic gain management

Once the acoustic wave interacts with the suspended seeding particles, the backscattered echoes returning to the transducer face possess extremely low energy levels. The amplitude of these acoustic reflections is typically minute, ranging from a few millivolts down to fractions of a microvolt. To successfully digitize these faint signatures and extract meaningful kinematic data, the hardware relies on a highly specialized, low-tolerance amplification stage. Central to this reception chain is the Low Noise Amplifier (LNA), a critical component engineered to push the system's sensitivity threshold down to approximately -100 dBm. This extreme sensitivity is an absolute prerequisite for detecting the microscopic acoustic footprints of small tracers caught within fine turbulent structures, ensuring that intrinsic electronic noise does not bury the physical data.

However, capturing these echoes presents a secondary, strictly physical challenge: as discussed in the context of acoustic propagation, the signal intensity decays exponentially as it travels further from the sensor due to fluid attenuation and geometric spreading. If the receiver maintained a constant amplification factor, the echoes returning from the deeper regions of the channel would be completely lost or indiscernible. To counteract this spatial decay and ensure a uniform signal strength along the entire velocity profile, the system architecture incorporates a Time-Gain Control (TGC) mechanism.

This compensation strategy can be tailored to the specific constraints of the hydraulic campaign. Under steady and highly predictable conditions, researchers can impose a manual, fixed amplification curve designed around the expected attenuation limits. Conversely, in complex environmental, the system typically operates in an automatic gain mode. In this configuration, the hardware dynamically scales the amplification factor as a function of the acoustic travel time, which directly correlates to the distance from the probe. This dynamic adjustment continuously optimizes the signal-to-noise ratio across the entire measurement window, carefully balancing the need to magnify distant echoes while strictly preventing the saturation of the analog-to-digital converters in the near-field.

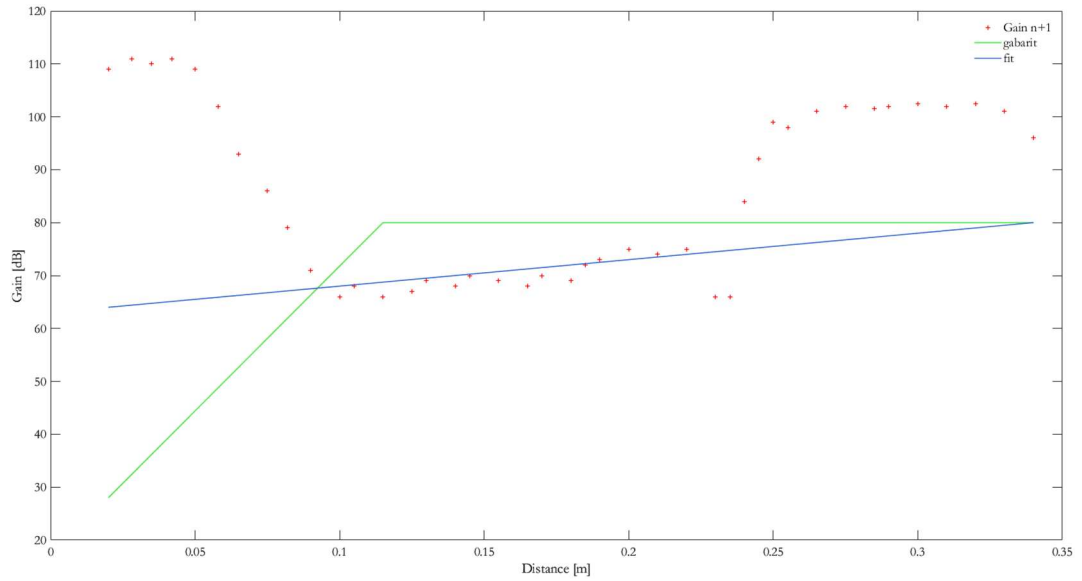


Figure 2.14 – Spatial distribution of the Time-Gain Control (TGC). The plot illustrates the dynamic amplification applied by the receiving hardware over distance. Red markers (gain $n+1$) show the actual instantaneous gain, which progressively increases to compensate for the acoustic attenuation in the fluid. The green line (gabarit) acts as a safety threshold to prevent near-field saturation, while the blue line (fit) represents the theoretical linear compensation trend. At greater distances, the high gain inevitably amplifies background noise, degrading the Signal-to-Noise Ratio (SNR) and defining the maximum measurable depth of the profile.

2.5.4 Data output

Following the analog-to-digital conversion and the initial onboard signal conditioning, the hardware unit transfers the acquired acoustic data to a dedicated computational system. In the context of Ubertone instrumentation, the device systematically records the entire measurement campaign utilizing a proprietary binary structure, designated as the raw UDT format. This uncompressed file acts as a comprehensive repository of the acoustic survey. Rather than just storing final numbers, it meticulously logs the raw echo amplitude profiles alongside the computed Doppler velocity vectors. Furthermore, it strictly embeds all configuration meta, such as the nominal emission frequency (f_0), the pulse repetition frequency (PRF), and the exact spatial dimensions of the measurement cells.

2.6 Velocity Measurement by Ultrasound

The non-intrusive quantification of fluid velocity via ultrasonic waves relies on the fundamental interaction between acoustic propagation and the kinematic state of the carrying medium. While the underlying physics remain consistent, engineers have developed several distinct methodological architectures to extract velocity data, each presenting unique trade-offs regarding spatial resolution, measurable range, and overall accuracy.

In the specific context of analyzing turbulent structures, the strict requirement is the ability to highly resolve velocity gradients across a continuous vertical profile. Consequently, while techniques exploiting transit-time differentials or continuous frequency shifts are widely employed in industrial macro-metering, Pulsed Doppler technology emerges as the most suitable ultrasonic method capable of providing the necessary spatial discrimination without the constraints of single-point or path-averaged measurements.

To establish a rigorous analytical foundation, the following sections examine the operating principles of these various technological approaches, evaluating their specific capabilities to determine the most effective solution for the targeted field of application.

2.6.1 Transit-Time Velocimetry (Time of Flight method)

The transit-time method evaluates the total flow by measuring the time difference of an acoustic pulse propagating along a defined path. In a typical configuration, two piezoelectric transducers (Probe A and Probe B) operate alternately as transmitter and receiver, positioned diagonally relative to the main flow axis.

When the fluid is in motion, the acoustic wave propagating downstream is naturally accelerated by the convective transport of the fluid itself. Conversely, the pulse traveling upstream against the current experiences a proportional deceleration. By defining L as the physical distance between the sensors, c as the speed of sound in the fluid, and θ as the angle between the acoustic path and the flow direction, the respective travel times can be expressed as:

$$T_{AB} = \frac{L}{c + v \cos \theta}$$

$$T_{BA} = \frac{L}{c - v \cos \theta}$$

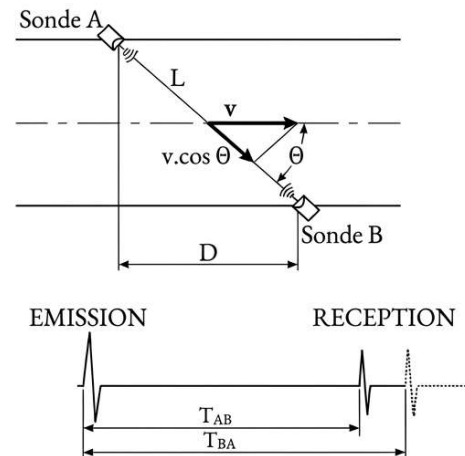


Figure 2.15 – Operating scheme of the Time of Flight (ToF) method.

By combining these two measurements, the system can isolate the fluid velocity (v) algebraically, effectively rendering the final calculation independent of the local speed of sound (which can fluctuate with temperature or salinity):

$$V = \frac{L^2}{2D} \left(\frac{1}{T_{AB}} - \frac{1}{T_{BA}} \right) = \frac{L^2}{2D} \left(\frac{\Delta T}{T_{AB} T_{BA}} \right)$$

From a macroscopic perspective, this approach is remarkably robust for determining the mean discharge in closed pipes or wide-open channels. However, it suffers from a critical theoretical constraint: the resulting velocity v is an integrated average along the entire acoustic chord between the two probes. This inherent spatial integration completely obfuscates local velocity fluctuations. Consequently, the ToF method is structurally unsuited for capturing the localized, small-scale turbulent eddies and steep velocity gradients that dictate boundary layer mechanics, rendering it ineffective for detailed turbulence profiling.

2.6.2 Continuous Wave Doppler (CW)

The *Continuous Wave* (CW) Doppler technique represents a measurement architecture that differs significantly from pulsed paradigms, relying on the uninterrupted emission and reception of an ultrasonic signal.

In this configuration, the instrumentation typically consists of two distinct transducers: an emitter, which propagates a sinusoidal wave at a constant frequency f_1 , and a receiver, positioned to intercept the radiation backscattered by suspended particles within the fluid.

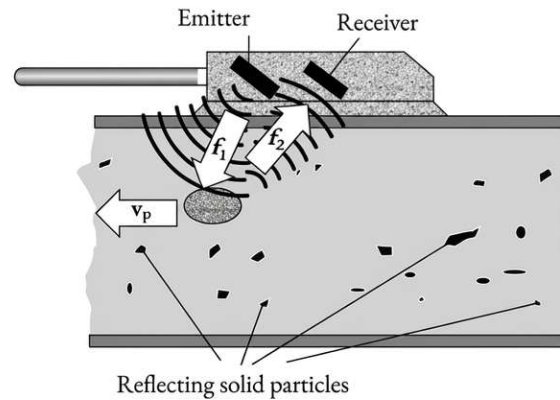


Figure 2.16 –

Schematic representation of the continuous-wave (CW) Doppler principle.

The frequency shift $\Delta f = f_1 - f_2$ detected in the received signal is directly proportional to the particle velocity along the acoustic axis, defined by the classical Doppler relationship:

$$v = \frac{c (f_1 - f_2)}{2 f_1 \cos \theta}$$

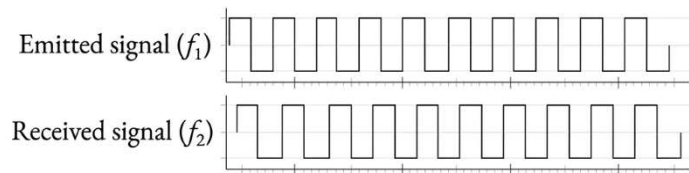


Figure 2.17 – Graphical representation of the Doppler frequency shift.

While this methodology ensures high frequency sensitivity and is particularly effective for monitoring high-velocity flows, its fundamental limitation lies in its inherent lack of spatial resolution. Because the transmitter operates continuously, the system is unable to utilize time-of-flight information to discern the depth of the captured particles. Consequently, the processed signal is merely the vector integration of all velocity contributions present within the entire area of intersection between the emitted and received beams. This sampling volume, extending along the entire acoustic path, precludes the reconstruction of a local kinematic profile, effectively relegating CW Doppler technology to integrated measurement tools that are inadequate for the detailed analysis of turbulent gradients in confined systems.

2.6.3 Pulsed Doppler Method

The spatial resolution limits inherent to continuous-wave (CW) systems are definitively overcome through the implementation of the Pulsed Doppler technology. This approach shifts the measurement strategy from a purely frequency-based domain to a spatiotemporal paradigm, relying on the transmission of discrete acoustic bursts rather than a continuous signal. Consequently, the transducer operates in a monostatic configuration, alternating between active emission cycles and passive listening intervals to capture the backscattered radiation from the suspended tracers.

Unlike CW architectures, which directly detect frequency modulations over an uninterrupted acoustic stream, the pulsed configuration interrogates the flow field by extracting three fundamental physical properties from the echo of each discrete burst. The time elapsed between emission and reception acts as a precise acoustic chronometer, uniquely identifying the radial position of the sampling volume. Simultaneously, the amplitude of the return signal provides a proxy for the acoustic scattering cross-section and tracer concentration. Finally, rather than measuring a raw frequency shift, the system registers the instantaneous phase of the acoustic wave upon reception, which constitutes the critical parameter for the kinematic evaluation

To reconstruct a continuous vertical velocity profile, the acoustic beam is subjected to a strict spatial discretization process known as range gating. The continuous return signal is systematically sliced into contiguous measurement cells, whose individual spatial extents are dictated by the temporal duration of the emitted pulse. By enabling the receiver exclusively during specific temporal windows, the instrument isolates the acoustic feedback originating from precise radial distances.

Within each discrete control volume, the local fluid velocity cannot be physically derived from the absolute frequency or phase of a single burst, as the pulse duration is vastly insufficient for classical spectral analysis. Instead, the measurement methodology relies entirely on the principle of phase coherence. The system evaluates the microscopic displacement of the scattering particle cloud by comparing the phase of the echoes returning from the exact same spatial cell across two or more consecutive emissions. Separated by a strictly designated listening interval T_e , which corresponds

to the reciprocal of the Pulse Repetition Frequency ($T_e = 1/\text{PRF}$), any movement of the fluid induces a variation in the acoustic travel distance. This spatial translation manifests electrically at the transducer as a measurable phase shift ($\Delta\Phi$) between the successive backscattered signals.

The spatiotemporal correlation between the phase variation and the temporal interval allows the computational unit to analytically derive a virtual Doppler frequency (f_D). This relationship is mathematically expressed as:

$$f_D = \frac{\Delta\Phi}{2\pi \cdot T_e}$$

Once the local Doppler frequency has been extracted through this phase-shift analysis, the scalar velocity of the fluid (v) within the specific control volume is calculated using the classical Doppler equation:

$$v = \frac{f_D \cdot c}{2f_0 \cos \beta}$$

where f_0 represents the nominal carrier frequency of the emitted burst, c is the local speed of sound in the fluid medium, and β is the oriented angle between the primary direction of motion and the acoustic measurement axis. This sophisticated reliance on phase correlation allows the Pulsed Doppler method to function effectively as a microscopic spatiotemporal ruler, granting the unique capability to resolve steep velocity gradients and capture highly localized turbulent structures.

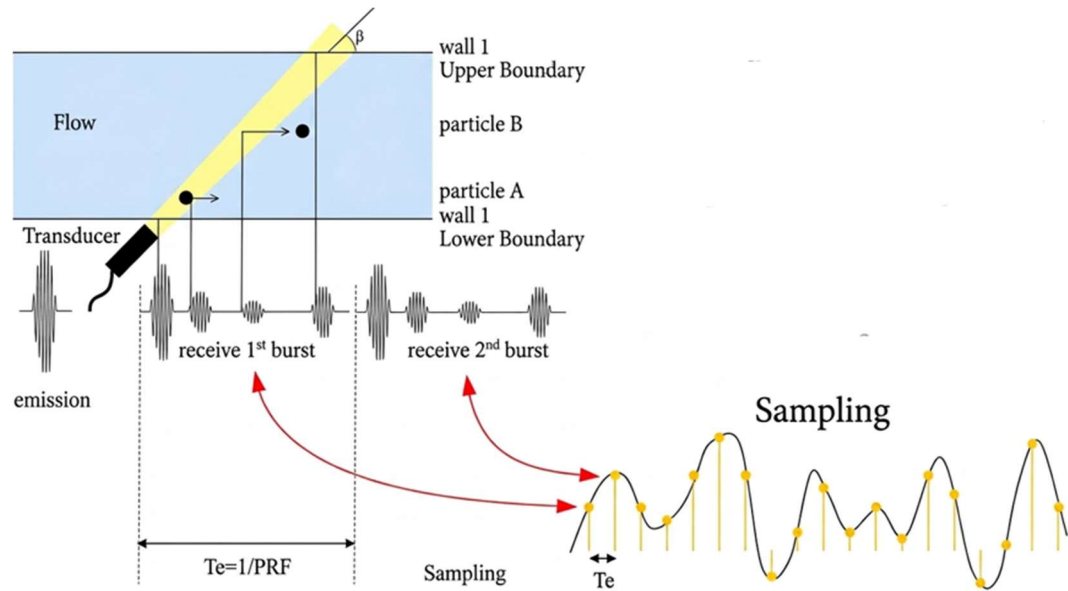


Figure 2.18 — Operational principle of the Coherent Pulsed Doppler technique in a monostatic configuration. The schematic illustrates the range-gated spatial discretization, where the acoustic beam is sliced into distinct measurement cells, and the temporal sampling mechanism. The right-hand inset demonstrates the reconstruction of the velocity signal through phase coherence analysis, obtained by sampling the backscattered echoes at a fixed interval defined by the Pulse Repetition Frequency (PRF).

2.7 Range – Velocity Ambiguity and Nyquist Constraints

The operational efficacy of monostatic Pulsed Doppler systems is inherently governed by a fundamental trade-off between the maximum interrogation depth and the highest detectable velocity. This constraint, formally known as range-velocity ambiguity, arises because the measurement relies on the periodic transmission of discrete acoustic pulses rather than a continuous wave. Consequently, the Pulse Repetition Frequency (PRF) emerges as the primary control parameter, dictating both the spatial discretization of the measurement volume and the temporal sampling rate of the backscattered signal.

2.7.1 Sampling Criteria and Shannon Theorem

The determination of the local fluid velocity relies on the accurate extraction of the Doppler frequency shift (f_D) within each specific range gate. Since the phase of the backscattered echoes is sampled at discrete time intervals defined by the PRF, the reconstruction of the Doppler signal is strictly governed by the Nyquist-Shannon sampling theorem. To ensure the unambiguous recovery of the velocity data, the theorem dictates that the maximum measurable Doppler frequency (f_{max}) must not exceed half of the sampling frequency:

$$f_{max} < \frac{PRF}{2}$$

When the actual fluid velocity generates a Doppler shift that exceeds this theoretical boundary (the Nyquist limit), the system fails to sample the signal at an adequate rate, leading to the phenomenon of aliasing. Physically, the phase variation between consecutive echoes is mathematically misinterpreted as a lower frequency shift, or one of opposite sign.

This introduces a critical operational compromise: setting a lower PRF allows for a deeper exploration range, providing the system with sufficient time to receive echoes from distant targets, but it simultaneously lowers the Nyquist limit, substantially increasing the risk of aliasing. Conversely, a higher PRF safely accommodates faster flows but inherently restricts the maximum measurable depth. When aliasing occurs, the misinterpretation of the high-frequency components translates into severe non-physical artifacts, which typically manifest as abrupt, erroneous jumps or artificial inversions in the reconstructed velocity profile.

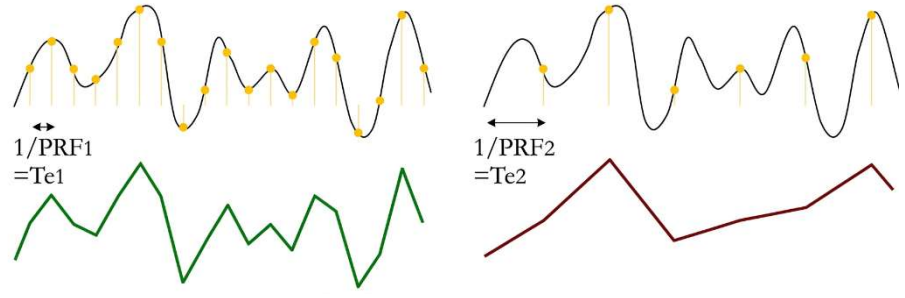


Figure 2.19 – Schematic representation of the Pulse Repetition Frequency (PRF) effect on Doppler signal sampling. (Left) High sampling frequency (PRF1) with a short listening interval (T_{e1}) satisfies the Nyquist criterion, enabling accurate reconstruction of the original signal (green waveform). (Right) Low sampling frequency (PRF2) with an extended interval (T_{e2}) fails to capture high-frequency variations, inducing aliasing artifacts and generating an erroneous, lower-frequency reconstructed signal (red waveform).

2.7.2 Spatiotemporal Constraints and Analytical Range-Velocity Ambiguity

This discrete sampling framework directly establishes a coupled dependency between the maximum accessible measurement depth and the upper velocity threshold. To maintain spatial certainty along the acoustic axis and prevent range ambiguity, where an echo from a preceding pulse is erroneously superimposed onto a subsequent emission cycle, the instrument must allow sufficient time for the acoustic burst to propagate to the maximum depth and return before the next pulse is transmitted.

Given a flow domain characterized by a water height (h) and an acoustic beam inclined at a beam-flow angle (β), the maximum path length along the measurement axis is geometrically defined as $h/\sin(\beta)$. The round-trip travel time over this distance must remain strictly lower than the pulse repetition interval ($T_e = 1/PRF$), which establishes the spatial range boundary as:

$$\frac{h}{\sin \beta} \leq \frac{c}{2 \cdot PRF}$$

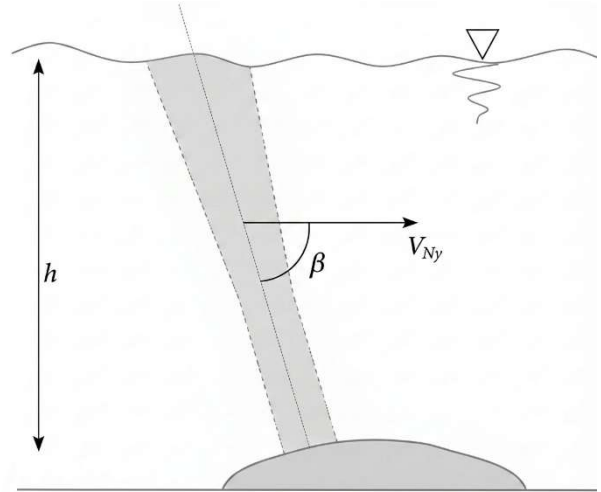


Figure 2.20 – Geometric representation of the hydrodynamic domain and acoustic beam pointing configuration in an open-channel flow.

Concurrently, the temporal sampling frequency dictates the maximum unaliased Doppler shift that can be resolved, mapping directly to the upper limit of measurable fluid motion. By substituting the Nyquist frequency limit into the classical Doppler

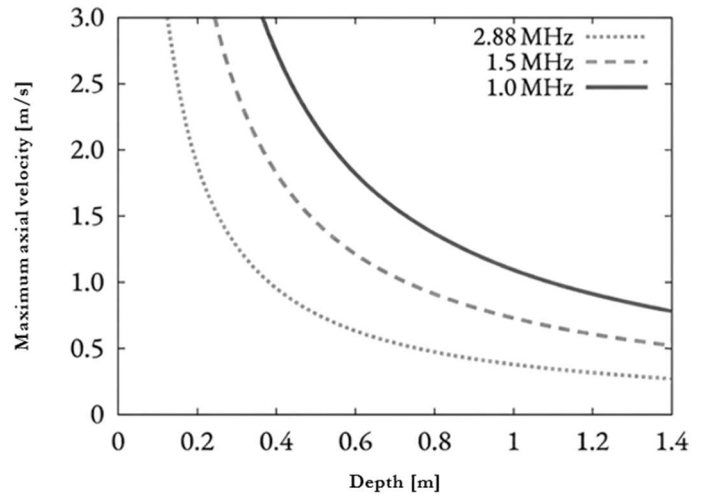
relationship, the boundary velocity, formally defined as the Nyquist velocity (v_{Ny}), marks the threshold beyond which the true velocity vector $\mathbf{v}$ falls into ambiguity, dictating that the valid velocity field must reside within the stable interval $-v_{Ny} < v < v_{Ny}$. By extracting the operational PRF from the spatial constraint and substituting it into the Doppler limit, the two opposing physical requirements can be analytically combined to yield the fundamental range-velocity ambiguity equation for monostatic architectures:

$$v_{Ny} = \frac{c^2 \cdot \tan \beta}{8f_0 \cdot h}$$

This mathematical framework reveals that the product of the maximum measurable velocity and the water height is an invariant property determined solely by the local speed of sound (c), the nominal carrier frequency (f_0), and the orientation angle (β). Consequently, any operational expansion of the vertical interrogation range inherently compresses the maximum detectable velocity threshold, forcing a strict experimental compromise. The total unaliased velocity span, or velocity range (R_{vp}), available to the system before encountering phase wrapping is thus strictly bounded by the operational setup parameters according to the relation:

$$R_{vp} = \frac{c \cdot PRF}{2 \cdot f_0}$$

Figure 2.20 – Hyperbolic trend of the maximum axial velocity (m/s) as a function of depth (m) for three different carrier frequencies (f_0), showing the expansion of the kinematic range as the frequency decreases.

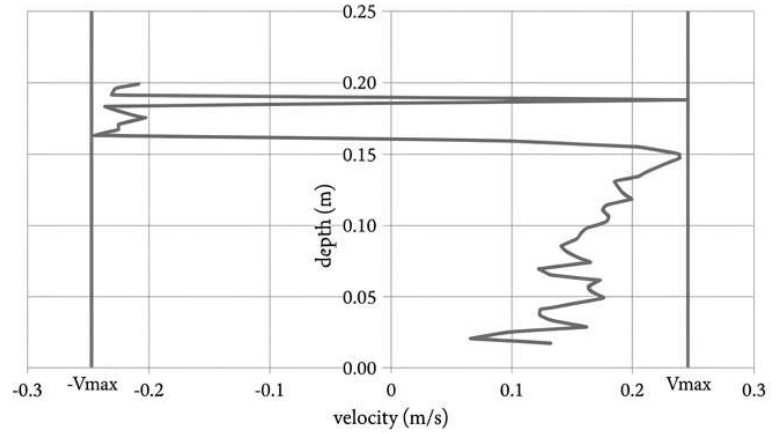


2.7.3 Phenomenological impact of Aliasing on Velocity Profile

When the physical flow conditions within the channel exceed these analytical boundaries, the failure of the phase-coherence estimation manifests as distinct, non-physical distortions within the reconstructed vertical velocity profile. The most prominent artifact is the appearance of velocity jumps, which are a direct consequence of phase wrapping. When the localized fluid motion induces an inter-pulse phase shift exceeding $\pm\pi$ radians, the periodic nature of the phase function causes the tracking algorithm to misinterpret high-velocity components as lower-frequency inputs or motions of an opposite sign, causing the velocity profile to undergo sharp, instantaneous discontinuities where the data abruptly transits from the positive to the negative boundary limits.

This kinematic inversion is empirically exemplified in *Figure 2.22*, where the continuous fluid velocity profile undergoes an unphysical, abrupt truncation upon reaching the positive Nyquist boundary ($V_{\max}$), immediately re-emerging at the negative extreme of the velocity axis ($-V_{\max}$) and introducing critical discontinuities in the identification of localized velocity gradients.

Figure 2.22 — Experimental vertical profile of flow velocity (m/s) versus depth (m), showing a spectral aliasing artifact (phase wrapping) at a depth of approximately 0.16 m.



Furthermore, if the system setup is heavily biased toward capturing high-velocity components via an elevated pulse repetition frequency, the corresponding reduction in the listening window introduces severe range limitations. In such scenarios, the backscattered energy from the deepest layers of the water column fails to return to the transducer within the designated time frame, resulting in either a total truncation of the profile near the channel bed or the improper temporal wrapping of deep-water reflections onto superficial range gates, thereby distorting the velocity measurements in the lower regions of the flow where boundary-layer dynamics and bed-shear phenomena are most critical.

To mitigate these distortive effects and stabilize the profile reconstruction, the instrumental setup must be dynamically optimized by balancing the pulse repetition frequency or, when environmental conditions allow, shifting to a lower nominal carrier frequency f_0 to expand the velocity range while preserving the required exploration depth.

2.8 Parasite Echoes Suppression by Pulse Coding and Static Echo Filter

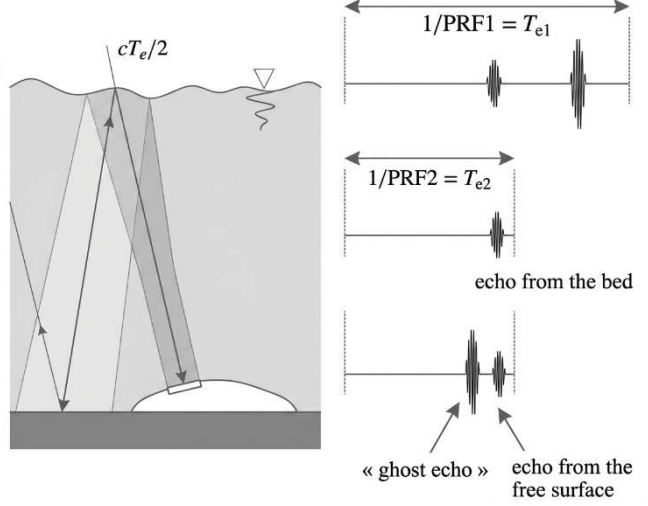
The operational precision of monostatic pulsed Doppler systems is often compromised by impure acoustic phenomena, which superimpose interfering energy onto the weak backscattered signals from tracers carried by the fluid. To preserve the thermodynamic and kinematic integrity of velocity profiles, modern instrument architectures employ sophisticated mitigation strategies at both the hardware and software levels. These algorithms target two distinct classes of acoustic interference: dynamic reflections subject to range ambiguity and stationary boundary-induced clutter.

2.8.1 Ghost Echoes and Multipath Propagation

The periodic, phase-coherent nature of pulsed ultrasound interrogation inevitably introduces ghost echoes, artifacts that distort the velocity field and map non-existent kinematic structures. These disturbances arise from two primary physical mechanisms:

1. **Range Folding (Inter-pulse Spatial Overlap):** When operating at a high Pulse Repetition Frequency (PRF), the inter-pulse period ($T_e = 1/\text{PRF}$) is shorter than the round-trip acoustic time-of-flight required for waves to completely attenuate. Consequently, highly reflective boundaries situated beyond the nominal maximum range ($h_{\max}$), such as the concrete bed in a channel or the free-water surface, can backscatter sufficient energy from pulse N-1 (or earlier pulses) that returns to the transducer face simultaneously with the near-field echo of pulse N. The receiver, being temporally synchronized to the current emission cycle, mistakenly attributes this delayed far-field echo to a near-field measurement volume, causing severe spectral contamination.
2. **Multipath Reverberation (Multiple Interface Reflections):** The complex geometry of confined hydraulic channels, bounded by the free surface and the solid boundaries, acts as an acoustic waveguide. An emitted wavefront can undergo successive specular reflections between the water-air interface and the channel bed before returning to the transducer. These prolonged, secondary acoustic pathways arrive at the sensor with significant temporal delays. The instrumentation interprets these late-arriving reverberations as signals originating from fictitious depths, producing phantom profiles that mask the real velocity distribution.

Figure 2.23 — Mechanisms of secondary acoustic interference within a confined free-surface channel. The left diagram traces the multipath reverberation pathways between the channel bed and the water-air interface ($c^*T_e/2$). The right-hand signals show the temporal mapping of the echoes as a function of the Pulse Repetition Frequency; an operational reduction in the inter-pulse window (from PRF1 to PRF2) causes the late-arriving boundary reflections from previous cycles to overlap with the current measurement window, generating a false "ghost echo" artifact alongside the legitimate free-surface return.



2.8.2 Mitigation via Phase-Coded Excitation (Pulse Coding)

To decouple the range-folded ghost echoes from the current-pulse reflections, advanced instruments utilize pulse coding techniques (e.g., orthogonal pseudo-random noise sequences or binary phase-shift keying).

Instead of emitting identical sinusoidal bursts, the system modulates the phase of each transmitted pulse N according to a unique mathematical code:

$$x_N(t) = a(t)e^{j(2\pi f_0 t + \theta_N)}$$

where θ_N represents the phase-coding state of the N -th burst.

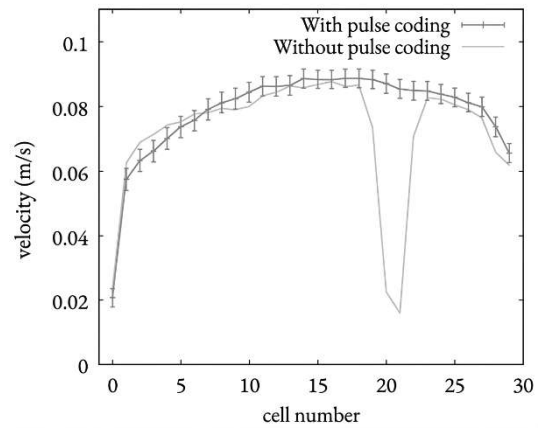
Upon reception, the digitized echo profile is processed through a hardware correlator that performs a real-time cross-correlation between the incoming raw signal and the specific phase code of the current emission. Due to the orthogonal properties of the selected pseudo-random sequences, the correlation output yields a sharp, high-amplitude peak only for the echoes physically originating from pulse N . Conversely, any range-folded contributions from pulse $N-1$ or earlier emissions, possessing uncorrelated phase histories, are spread out as low-level, zero-mean white noise in the spectral domain. This phase-coherent coding effectively suppresses range ambiguity without requiring an operational reduction in the PRF.

In the Ubertone configuration environment, this firmware-level routine is activated and managed via the JSON configuration file through the parameter flag "phase coding": true.

From an experimental perspective, while phase-coded excitation successfully suppresses ghost profiles, it introduces distinct metrological trade-offs:

- **Reduction of the Signal-to-Noise Ratio (SNR):** The phase-spreading of uncorrelated signals mathematically increases the broadband white-noise floor of the acquisition system, which inherently degrades the effective SNR of the weak backscattered tracer signals.
- **Increased Statistical Variance:** Due to the heightened complexity of the modulated signal, the computed velocity estimates exhibit a higher statistical variance. This manifests as increased fluctuations in the velocity time-series compared to non-coded sinusoidal emissions, requiring longer averaging windows to achieve comparable statistical convergence.

Figure 2.24 — Experimental velocity profiles reconstructed with and without phase-coded application. The unmodulated signal (light grey line) exhibits a localized ghost corresponding to cell n.21, resulting in a severe, non-physical drop in measured velocity. The implementation of phase coding (dark grey line) successfully isolates and suppresses the range-folded interference, restoring the physical consistency of the profile. The overlay of error bars denotes the increased statistical variance inherent to the demodulation of the coded pseudo-random noise sequence.



2.8.3 Static Echo and Clutter Filtering

While pulse coding isolates dynamic range-folded interferences, the system must also address high-amplitude reflections originating from stationary obstacles (such as structural walls, stagnant boundary layers, or the transducer mounting bracket). This clutter signal possesses an amplitude that is often several orders of magnitude higher than the weak backscattering from microscopic tracers.

Because solid boundaries, such as the channel bed or lateral walls, are stationary, the acoustic energy backscattered from these structures exhibits a Doppler frequency shift of exactly zero ($f_D=0$).

In the digital processing stage, the reflected echo is mathematically decomposed into two components phase-shifted by 90° , known as In-phase (I) and Quadrature (Q). When plotted together, these components form a two-dimensional coordinate system called the complex I-Q plane, where the signal is represented as a vector.

Within this geometric representation, the massive stationary reflection from a wall does not rotate; instead, it manifests as a large, motionless displacement from the origin, known as a severe DC offset. Because the energy reflected by a solid wall is orders of magnitude stronger than the weak scattering from microscopic fluid tracers, this static vector risk to saturate the analog-to-digital converters (ADC). If clipping occurs, the dominant static signal completely blinds the receiver, masking the delicate, dynamic phase variations generated by the turbulent flow.

To isolate the velocity of the moving tracers, the demodulated I-Q signals must be routed through a digital Static Echo Filter (or Clutter Filter). This is typically implemented as a high-order high-pass filter, utilizing either an Infinite Impulse Response (IIR) or a Finite Impulse Response (FIR) architecture. The primary objective of this filter is to act as a sharp frequency boundary: its transfer function is designed with an extremely steep transition band centered precisely around zero frequency. Defined by a normalized cut-off frequency (f_c), the filter selectively attenuates and discards the massive, near-static signals representing the stationary boundaries, while allowing the higher-frequency phase shifts of the moving fluid particles to pass through unadulterated.

The operational efficiency of this high-pass architecture depends heavily on the precise calibration of the normalized cut-off frequency (f_c). In practical hydraulic laboratory applications, configuring f_c involves a critical optimization problem: setting the threshold too high inadvertently filters out the low-velocity fluid components, particularly within the viscous sublayer near the channel bed where velocities naturally approach zero. Conversely, an insufficiently low f_c fails to damp the stationary clutter, allowing residual wall-reflection energy to corrupt the velocity estimation.

Furthermore, the mathematical efficacy of this digital filtering sequence is strictly bounded by the physical dynamic range of the Analog-to-Digital Converter (ADC). In boundary-dominated environments, such as smooth metallic flume walls or highly reflective concrete beds, the amplitude of the static echo can exceed the maximum voltage threshold of the instrument's pre-amplification stage, causing severe hardware saturation (clipping). When clipping occurs, the continuous wave-shape is permanently distorted, resulting in an irreversible loss of the tracer phase information before the signal even reaches the digital processing unit. Under these saturated conditions, the digital Static Echo Filter becomes entirely ineffective.

Consequently, within the instrument's configuration framework, the optimization of the receiver gain must be paired with the careful adjustment of the filter coefficients. In the Ubertone control environment, this sub-routine is governed via the execution parameters under the "static echo filter" JSON structure. Proper management of these parameters is paramount for capturing accurate logarithmic velocity profiles and resolving high-shear turbulent structures in the immediate proximity of solid boundaries.

3. Field Monitoring and Instrumentation Architecture

3.1 Selection and Characterization of the Acoustic Interrogation Site

The transition from idealized laboratory flumes to real-world anthropogenic channels represents one of the most critical challenges in experimental fluid mechanics. In controlled environments, boundary conditions are strictly regulated, allowing for the isolation of specific kinematic phenomena. Conversely, field measurements in open-channel flows are inherently subjected to environmental forcing, geometric irregularities, and spatial heterogeneities. Consequently, the choice of the sampling site is not merely a geographical preference, but a fundamental metrological prerequisite. The quality and physical representativeness of the acquired velocity data strictly depend on identifying a cross-section where the flow exhibits robust conditions of longitudinal uniformity and statistical stationarity.

To obtain a representative sample, the ideal sampling point must be carefully selected. Naturally, this requires a rigorous, step-by-step approach that consider multiple factors simultaneously. It is therefore mandatory to jointly evaluate the hydrodynamic, morphological and logistical requirements of the points selected during the preliminary survey, so as to minimize the discrepancy between the theoretical principles underlying the turbulent open-channel flow studies and the real condition of an artificial channel.

The selection process of the optimal location for the sampling of velocity data consists of three consecutive phases, with the aim of progressively narrowing the initial list of potential sites. The investigation starts with the knowledge that a network of irrigation canals, built in the early 20th century, exists in the Piedmont region, which carried water to the flatlands of the Lombardy region, where rice cultivation land can still be found today. These are man-made channels that don't follow natural courses and have probably the geometrical characteristics required for our purpose, which will be described than, and must be verified. The first two stages involve a preliminary remote analysis, using a Geographic Information System (GIS) software to examine the canals, based on a pre-existing map of the entire water network, cited before, created by the regional authorities; this step allows for the immediate exclusion of sections that doesn't respect the morphological and geometric criteria established. Subsequently, the second stage entails a more in-depth study of the sites selected in the previous phase using high-resolution satellite image, allowing for the identification of local geometric and morphological features that are not captured in the regional map. Finally, the third stage involves the carrying out of field inspections that permit us to verify physically that the sections of interest meet the theoretical criteria at the base of our study and to ensure there aren't inconvenient structures or recent structural modifications that have not been recorded in the past. In fact, geographical data digitalized on the regional geographic information systems are only a general maps that doesn't provide the level of geometric detail or the updating of information required for this study.

3.1.1 Theoretical Constraints and Physical Prerequisites

At the base of the choice of an optimal site, it is essential to ensure uniform water flow, for which there must be no obstacles upstream of the chosen sampling section that may cause flow instability. When water passes through or near to these hydraulic structures such as siphons, weirs or bridge columns, or in the presence of sudden geometric variations in the channel cross-section, the fluid equilibrium is broken due to the generation of strong turbulence, vortices, and flow separation, all of which deeply alter the velocity profile. After passing through such discontinuities, the fluid requires a certain distance to return to its initial state and dissipate the energy introduced by these elements. To ensure that flow has stabilized and become uniform again, the acoustic measuring instrument must be positioned at a specific longitudinal distance from the last obstacle upstream. However, the exact numerical value for this distance remains a subject of academic debate, as the presence of numerous influencing factors, that are amplified in number in real-world field applications.

Recent studies, focusing on the behavior of free-surface flows, have demonstrated that, for large-scale coherent structures, a significantly longer longitudinal distance is required for the flow to lose the memory of upstream element of disturbance. Experimental laboratory studies indicate that turbulence statistics and energy spectra exhibit transient patterns up to a distance of $x/h \sim 150$ downstream of the initial discontinuity (Zampiron et al., 2022 **Errore. L'origine riferimento non è stata trovata.**). However, this distance value requirement increases further when we talk about of VLSMs (Very Large-Scale Motions), i.e. larger coherent structures characterizing the outer region of fully developed free-surface flows, which require an undisturbed boundary layer to reach a stable equilibrium state.

To conciliate this scientific discussion and to consider also the presence of these uncertainties, which are often amplified in real-world experimental campaigns, an highly conservative distance value is adopted as a reference. This approach is in line with the fundamental studies based on Direct Numerical Simulation (DNS) of turbulent boundary layers, which demonstrate that a downstream distance (fetch) of at least 300 times the initial boundary layer thickness is necessary for the fluid to lose memory of those localized perturbations defined before (Jiménez et al., 2008 **Errore. L'origine riferimento non è stata trovata.**; Simens et al., 2009 **Errore. L'origine riferimento non è stata trovata.**). Therefore, for our experimental campaign, we have decided to adopt, at preliminary phase, a value of distance that ranges between 300 and 400 times the local flow depth (h).

However, this is not the only relevant characteristic that the channel must possess. In fact, the channel's cross-sectional geometry is supposed to be equally crucial, and to define this characteristic the fundamental parameter generally adopted in academic studies is the aspect ratio, i.e. the ratio of width to flow depth (W/h). Recent academic studies on open-channel flows, conducted in laboratories on smooth-bed channels, have confirmed that Large-Scale Motions (LSM) depend fundamentally on the local

depth (h), while the presence and dimension of Very Large-Scale Motions (VLSM) are supposed to be directly linked to channel aspect ratio, as clearly confirmed by the study of Peruzzi et al. (2020) [V]. The results of this research highlight that channels with a low aspect ratio are not suitable to detect the presence in the flow boundary layer of such coherent structures. This is because, when sidewalls are too close each other, secondary currents, i.e. spiral vortices generated by the presence of the banks, intensify to the point that they can occupy the entire section channel flow. This secondary structure present into the flow prevents VLSM from elongating freely, reducing their dimension, and locking them into the centerline of the flow section. Conversely, choosing a very wide channel makes it possible to move these secondary currents away from the center confining them to the edges, leaving the central part of the flow completely free from any interference and so allowing the VLSMs to grow, develop, and move undisturbed.

In addition to the cross-sectional geometry requirements defined before, it's essential that the physical nature of the walls remains unchanged along the entire length defined by the distance between the sampling point and the last upstream discontinuity, as previously defined.

The stability of the turbulent flow field depends on channel wall roughness, for which any sudden variation in construction materials or the degree of bank degradation significantly compromises flow uniformity. When the flow passes through a section at which can be denoted a change in the physical state of the boundaries, and so a drastic shift in bed friction value, the fluid starts to adapt to the new boundary conditions imposed by this change. This discontinuity at the flow boundary impose the formation of what, in fluid dynamics terms, is defined as Internal Boundary Layer (IBL), i.e. a turbulent flow layer characterized by mean flow statistics profoundly distinct from those of the layer above. This change of statistical property of the flow present in this layer starts at the exact point of the roughness change, and it gradually thickens and propagates along the vertical direction as it moves downstream. This entails into a split of fluid statistical property into two distinct regions described by profound different kinematic statistics. Within the IBL, which expands gradually downstream, the kinematics is established by the presence of the new surface roughness, while the upper portion of the water column keep the characteristics of the upstream conditions, originating a complex transition phase, that require a large longitudinal space to so that the fluid recover a uniform state condition along the entire flow depth. If velocity data are recorded at or near this bed discontinuity, the formation of this internal layer causes a discontinuity in the measured velocity profile. To avoid errors in reconstructing the real velocity profile under uniform flow conditions, the selected measurement site must exhibit material continuity and a consistent level of maintenance along the entire length from the last discontinuity detected upstream.

In addition to the characteristics defined in the previous pages, when selecting the section of a channel for the local velocity measurements, we have also to take into account the planimetric trend. During the selection phase of the sampling location, it's necessary to discard sections in proximity of sharp curves and tortuous paths, as these determine the configuration of complex fluid-dynamic phenomena that invalidate the scaling laws and velocity profiles, consistent with uniform flow condition, as established in the previously theoretical chapters.

In fact, as the fluid pass through a sharp curve, it is subjected to a centrifugal acceleration, which generates a transverse pressure gradient along the channel width, for which the faster fluid that flow near to the free surface is pushed toward the outer side, while the slower fluid present near to the bed is pushed toward the inner side of the channel; in this way, a large-scale secondary circulation patterns is generated, containing a sufficient energy to profoundly alter the vertical distribution of longitudinal velocity.

Beyond the hydraulic and geometric constraints of the channel cross-section, the final choice depends on the logistical feasibility of installing the acoustic profiling instrumentation. First, it must be noted that this type of equipment, used to record and measure local flow velocity, is highly sensitive to external mechanical noise, for which any vibration or oscillation of the transducer during the data acquisition must be minimized. These precautions are essential to prevent the contamination of the acquired velocity time series, which otherwise introduce artificial low-frequency energy. Furthermore, easy access to the chosen sampling point must be ensured, with the necessary safety conditions for conducting long-term measurements that require the continual presence of an operator that control periodically the proper continuation of the sampling. For these reasons, the ideal location is identified into a pedestrian bridge or, alternatively, low-traffic road bridge, that offers suitable anchor points for the installation of the acoustic profiler equipment instrumentation.

3.1.2 Progressive Screening Methodology

The idea behind the inception of the project described in the present work, born from the knowledge of the existence of an extensive irrigation water network that pass through the plains of Piedmont and Lombardy. This irrigation channels originally was designed to transport water drawn from the high-volume alpine rivers to the lands in the Vercelli area, that are still used for agriculture purpose.

As those are human-made infrastructures designed to minimize head loss during the path for the optimization of water transport over the long distances spanning over the entire region and also, from an economic point of view, to reduce the onerous linked to the building phase, these canals was constructed with a geometry that correspond with what we have defined before for the optimal characteristic that the channel must be possess. This is because the construction of this imposing project was driven by the need to maximize energy efficiency in terms of transport for which long and perfectly straight path were built, avoiding excessive curves except where necessitated by the presence of insurmountable natural or artificial obstacles. For this reason, the linearity that characterizes them makes them, in principle, ideal candidates for the analysis of wall turbulence under uniform flow conditions.

In this context, our initial attention naturally turned to the Cavour Canal, which is the largest and most famous hydraulic infrastructure of the entire irrigation framework, built at the end of the 1800s as a monumental engineering project to completely transform agriculture in the Vercelli area, for which it can be considered essentially as a big artificial river.

The Cavour canal represent the ideal cases for the sampling of local velocity and the study of large-coherent turbulence structure. It had incredibly high flow rates and impressive water speeds, which can be translated into a real high Reynolds number (Re) and, even more importantly, a massive friction Reynolds number (Re_τ), that combined with a very high cross-sectional aspect ratio, it positions itself as the ideal site for our purpose. The goal in this field is to reach high Reynolds numbers, as this creates a clear separation between the turbulent flow near the bottom of the channel and the flow in the outer region. Under these strong flow conditions, which aren't affected by viscosity like they are in smaller models, Very Large-Scale Motions can develop fully and be easily seen in the energy spectrum. This is important because it allows scientists to study these motions without any interference from viscous effects.

Although, as previously highlighted, this channel possesses unique geometric and hydraulic characteristics, from the preliminary field survey it has been noted certain logistical challenges associated with such a large-scale infrastructure. Indeed, the primary issues derive properly from its role as the main channel, the central artery, of the interrogation system; in fact, its course is signed by the presence of a large number of diversion points that feed the secondary network, as well as the presence of siphons, even if in a smaller number.

However, the GIS analysis had anyway allowed to identify and select some straight stretches, between one bridge and the next, geometrically impeccable for the purposes pre-established by us, capable of guaranteeing a sufficiently long stretch that permits the stabilization of the flow.

The main problem, which has led to the definitive discarding of the various sites preliminarily selected from the regional database, is not of a fluid dynamic nature, but is linked to logistics, and therefore to the structural characteristics of the chosen sampling points. In fact, the road bridges that cross these straight stretches, selected during the first phase of investigation, are located at considerable heights with respect to the free surface, and immersing the acoustic profiling instrumentation in a channel with such fast currents and massive flow rates involves a series of problems.

First of all, this notable hydrodynamic thrust on the sensor support, in contact with the moving water, leads to the generation of strong vibrations and oscillations of the entire slender support structure, which would have introduced a high mechanical noise, detected in the low-frequency spectra, totally corrupting the velocity series sampled over time. Furthermore, a simple telescopic rod or other slender structure, under the effort of this notable solicitation imposed longitudinally by the thrust of the water, would have bent or broken. The technical solution to this problem would have been the design and anchoring to the bridge of a real and proper steel reticular structure, massive and aerodynamic, to which would have been hooked, from a lower height from the free surface of the current, a rod lowered in depth that would have allowed to obtain a greater rigidity of the sensor and of the entire structure.

However, it is necessary to take into account also the realization and installation costs that the realization of such a structure would have entailed, completely out of measure for a single experimental campaign, in addition to requiring very long timelines and the intervention of specialized personnel for the assembly of the same. Without ignoring also the fact that simple anchor points doesn't exist, but it is necessary to design a structure that is anchored to the enormous pillars, requiring assembly work directly from a boat by specialized personnel or the realization of a reticular structure that rests on the sides of the channel itself.

To this economic barrier is added also the bureaucratic problem, due to the necessity to obtain the authorizing permits from the managing entities for a fixed installation so complex and invasive, which would have inevitably hindered the traffic and the normal maintenance operations of the channel.

As highlighted also in the subsequent reported images, made during the preliminary inspections on the cited channel, these constraints of hydraulic and logistic character, together with the limitations of accessibility in safety, have made impossible the use of the Cavour Canal, forcing the research to orient itself toward sites hydraulically similar but logistically more manageable.



Image 3.1 – View of the Cavour canal taken from the centerline of a pedestrian bridge, which highlights the notable linearity of the stretch towards upstream, with respect to the direction of the water flow, and the wide cross-section of the canal. Although such uninterrupted geometric regularity initially seemed ideal for the purpose of sampling velocity time series, evidence gathered in the field revealed the presence 50 meters further downstream of a water intake directed towards a secondary parallel branch.



Image 3.2 – Comparative photographic survey between two different points along the Cavour canal, from which is highlighted the presence of various discontinuities, which have compromised the hydrodynamic suitability of the inspected site. (A) A clear variation of the material along the banks of the canal at about 50-70 meters from the bridge, on which it was intended to mount the anchoring structure of the Doppler sensors. Such sudden variation in the surface roughness inevitably triggers the formation of an internal boundary layer (IBL), which alters the uniform flow conditions required for the purposes of the scope of the present study. (B) A view towards upstream of the Cavour canal, which shows a significant linearity optimal for the present study. However, following a field inspection, there emerged the presence of a lateral water intake located at a distance comprised between 50 and 100 meters from the chosen sampling point. Such distance results completely insufficient to guarantee the complete dissipation of the structural wake and the full stabilization of the turbulent flow field before reaching the measurement section.



Image 3.3 – Lateral view of a historical brick arch bridge that crosses the canal, for the crossing of the Cavour canal. From the present image is clearly evident the dimension of these structures that impose constraints of a logistic type: the enormous structure does not offer easy or safe anchor points for the rigid fixing of the instrumentation for the acoustic profiling.



Image 3.4 – Lateral view of a crossing work on the Cavour canal characterized by the presence of a continuous structure in concrete and by a simple metal railing. The image highlights how the support structure of the bridge enters directly into contact with the free surface of the current, which notably alters the stationary structure of the flow.

Following the exclusion of the main artery of the irrigation system, it is decided to pass from an approach based on simple a priori selection to a step-by-step approach, as outlined in the previous paragraph, making it necessary considering the enormous extension and the notable ramification of the irrigation network, which would make extremely onerous, both in economic and temporal terms, proceeding to the physical inspection of every single canal.

The first phase of investigation was therefore based on a large-scale spatial analysis conducted through the use of the open-source software QGIS. In order to be able to work on concrete and updated data, the starting point was the importation inside this virtual environment of the official vector cartography provided by the SIBI (Reclamation and Irrigation Information System), in its most recent version dating back to January 2025. Once loaded the entire conformation of the state-owned irrigation water canals, the software was not used as a simple passive viewer of maps, but it became an essential tool to filter all the canals that did not respect the fluid-dynamic and geometric constraints discussed in the previous paragraphs. Exploiting the digital measurement tools provided by the program itself, the search for the optimal sections for the sampling begins from the identification of the canals with favourable geometries, going to exclude overly tortuous paths, points located in proximity of sorting nodes, where the water is introduced into secondary branches through the use of sluice gates, and, above all, those stretches blatantly fragmented by an excessive presence of bridges or other works of artificial disturbance, such as siphons. This preliminary skimming operation permits to drastically reduce the zone of investigation, eliminating all those unusable canals, making reference to what was said on the necessary characteristics defined previously, and making emerge only a restricted number of sections in which the canals guarantee the presence of suitable geometric structures, therefore widths sufficiently large with respect to the flow depth and the long stabilization distances necessary for the study of the turbulence spectra. The result of this preparatory procedure is shown simply in the thematic map reported in the following figure, where the coloured boxes enclose exactly the chosen points at which we have to carry out the subsequent evaluations, having passed the checks of a geometric character.

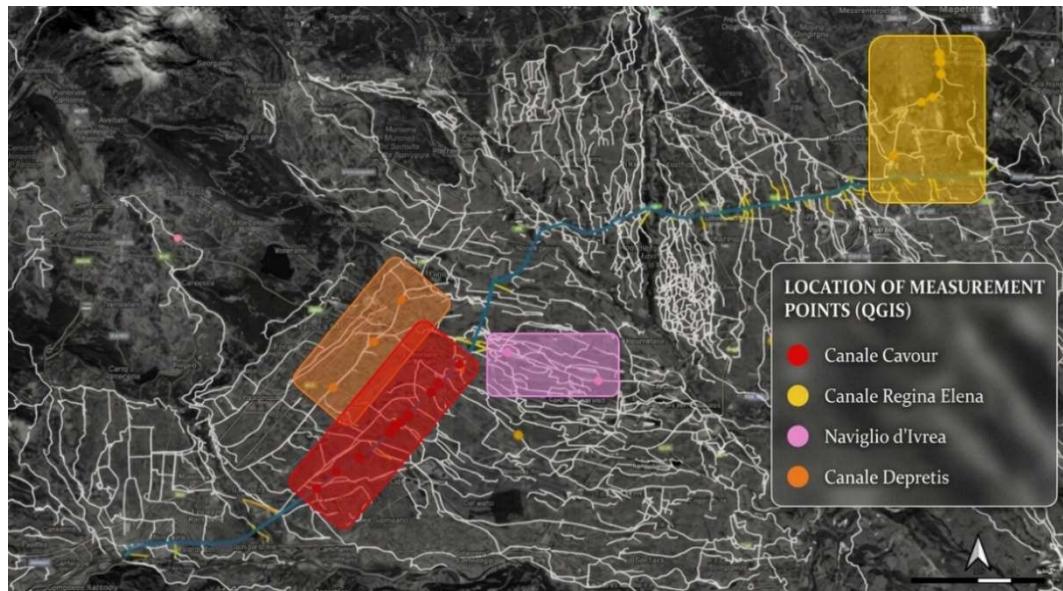


Figure 3.1 – Thematic map generated using QGIS software, illustrating the results of the initial large-scale spatial analysis conducted on the regional irrigation network. The highlighted macro-areas, enclosed within colored boxes, identify selected groups of potential measurement points that passed the initial geometric and structural assessment. As indicated in the legend, the candidate sampling sections are distributed along four main hydraulic arteries: the Cavour Canal (red), Regina Elena Canal (yellow), Naviglio d'Ivrea (pink), and Depretis Canal (orange).

The second phase of screening, aimed at decreasing even more the potential sampling points, foresees the execution of the specific analysis of the points already identified in the previous phase with the high-resolution satellite images, obtained from the use of web mapping services, such as Google Earth and Google Maps.

This step allows a first visual check, very useful for identifying those morphological or structural irregularities that cannot be uncovered by the analysis of the official regional mapping databases, such as the presence of secondary small bridges, as well as the thick vegetation present at the edges of the channel that could enter into contact with the superficial layer of water, or again small lateral derivations – even not really recognized by the control entities. In this way it is possible to immediately discard the blatantly unsuitable stretches, drastically reducing the number of candidates, without going on site.

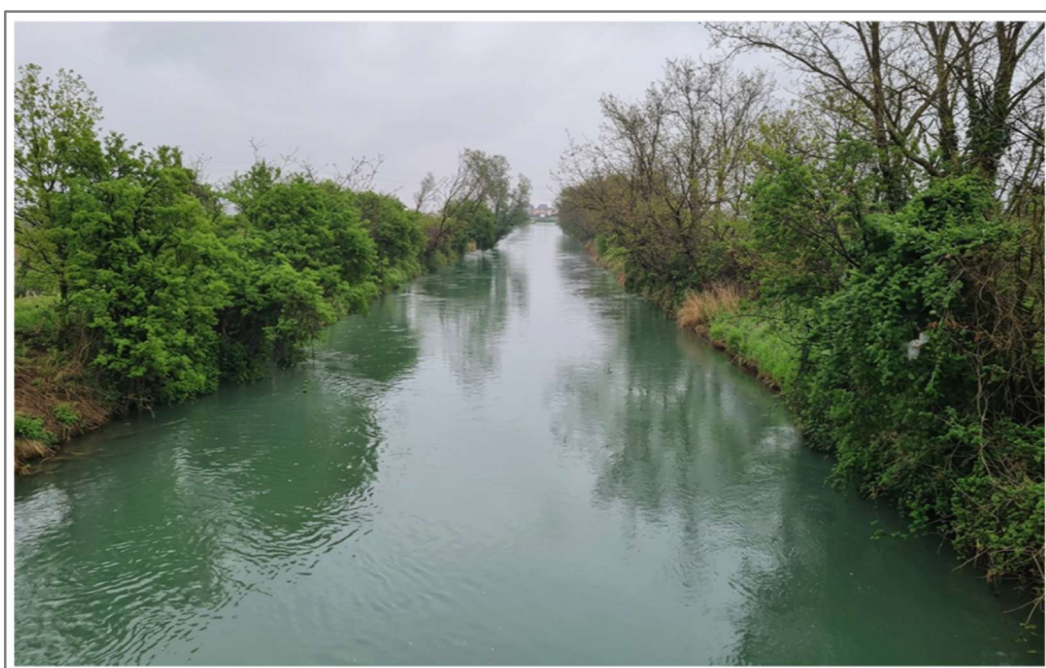


Image 3.6 – Photographic documentation of the Depretis Canal that illustrates a discarded sampling site, since, as one can easily deduce, characterized by the presence of dense and uncared for vegetation along both the banks of the canal. The bushes and the protruding branches extend themselves beyond the edges of the canal, coming into direct contact with the free surface of the water, causing superficial perturbations that alter the conditions of uniform flow, rendering the section unsuitable to an accurate sampling of the temporal series of the local velocity.

At this point, even before the field evaluation, the process requires an intermediate step born from the necessity of confronting oneself with the managing entity of the irrigation network under examination, that is the Est Sesia Consortium, which administers the canals of that area. This dialogue is made in fact necessary in that it permits us to obtain updated information on the real hydraulic and maintenance conditions of the various stretches, in such a way as to have a real practical feedback, to definitively confirm or exclude the potential sections remained in the list at the previous steps.

Finally, the last step naturally consists in the direct on-site inspection, essential to ascertain that the sites identified by the previous remotely carried out analyses truly respect all the requested conditions. This operation of investigation in presence, allows in fact to evaluate a series of details that from the previously acquired images are not clearly deducible, in that they do not allow to have the flexibility requested in the movements treating themselves however of images acquired by predominantly secondary systems for the management of the roads; nor much less the information provided by the control and management entity can return such information with sufficient precision, not knowing well the matter in question.

Such inspection allows therefore to fully evaluate the requested logistic procedure, linked to the ease of access for the transport of the instrumentation, as well as other parameters like the characterization of the banks and the absence of invisible obstacles from above or from scarcely updated maps, like submerged vegetation or debris along the edges; for which going physically on site is, in any case, an obligatory passage, necessary also to execute with precision the necessary metric survey. During the in-situ reconnaissance, after having verified first of all the respect of the upstream section of the hydraulic and geometric conditions, one must measure with the maximum accuracy the actual width of the canal and, even more critical datum, the exact distance that intervenes between the walkable plane of the bridge and the free surface of the water. Contextually, the first-person observation of the architectural and structural elements present makes itself necessary to understand if the geometries of the bridge or of the walkable stretch possess safe structural elements to exploit as anchor points for the instrumentation. Collecting these specific constructive details and the design quotas makes possible, through the use of the hydraulic laboratories of the Polytechnic of Turin, to design and realize to measure the entire support framework. On the basis therefore of the elements present is determined the ad hoc structure necessary to reach the exact point of immersion of the sensor in the flow, for which extremely important it results to know also the difference in height of the walkable plane with respect to the free surface of the water to correctly define the length of the rigid rod to immerse in the current; on the basis of this distance must be defined furthermore the contraption necessary to the end of stabilizing as much as possible the entire structure, avoiding very slender solutions, but one proceeds to the design of an articulated structure by the whole of multiple elements rigidly constrained among themselves.

Applying in sequence the various steps described, which unites remote analysis, satellite observation, comparison with the managing entity and direct inspection, one manages to progressively decrease the list until isolating the ideal stretch. Among all the watercourses taken into examination, the Cavo Lucca revealed itself the only one capable of satisfying at best all the imposed requirements, even if with some limitation, not presenting particular hydraulic interruptions upstream, it has an aspect ratio entirely comparable to those utilized in the studies of laboratory channels, so as to permit a comparison of the obtained results, and possesses regular and homogeneous banks, besides not being disturbed by the presence of intrusive vegetation. Furthermore, it offers an easily accessible road bridge, not trafficked, perfect to install the instrumentation in a rigid and simple way to the metallic structure, and to execute the samplings in total safety.

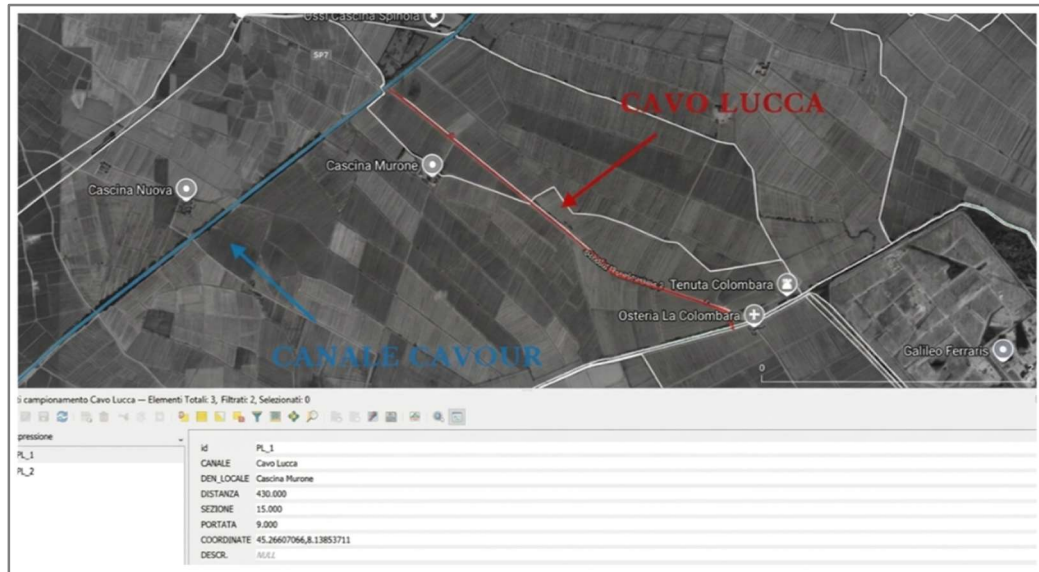


Figure 3.2 – Graphical interface of the workspace of QGIS that shows the geographic localization and the relative acquired data of the selected sampling site. The reported map visually defines the position of the site on the Cavo Lucca (indicated by the red arrow) with respect to the main artery (Cavour Canal - indicated by the blue arrow). The summary table reported below reports the data of spatial definition and of the basic geometric characteristics of the present canal, extracted at the specific measurement section near Cascina Murone (among which width of the section, expected flow rate and exact geographic coordinates).

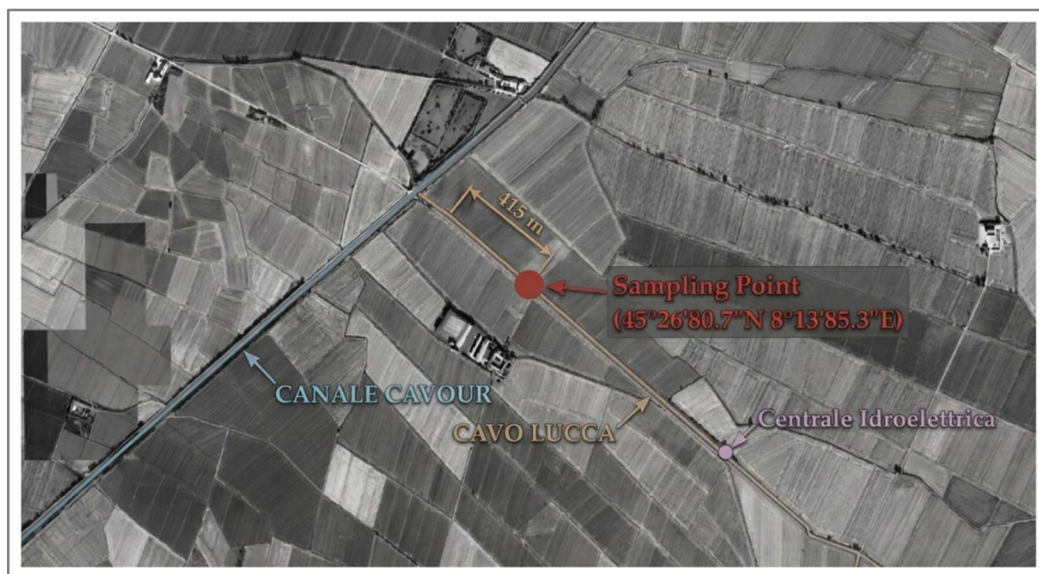


Figure 3.3 – Satellite image, extracted from digital mapping environment Google Earth, that shows the exact location of the selected sampling point along the Cavo Lucca. The map highlights the essential characteristics of linearity of this canal, putting into evidence the straight stretch upstream, devoid of interruptions, of the total length of 415 meters. Such extended linear development guarantees the spatial distance necessary so that the turbulent boundary layer develops itself completely and the flow stabilizes itself before reaching the measurement section. The cartographic map provides furthermore a spatial context, showing the main artery from which this branch draws the water (Cavour Canal) and indicates downstream the presence of a hydroelectric power plant, which requires constant flow rates for its functioning.

The Cavo Lucca is one of the main irrigation canals in the Novara plain, managed by the Est Sesia Consortium, with the primary function to distribute water for agricultural purposes, specifically for the cultivation of rice, which withdraws the latter directly from the Cavour Canal in correspondence of the territory of Galliate (NO), through a historical withdrawal sluice gate built approximately at the half in the nineteenth century, in order to feed the irrigation network of the lower plain and ensure constant flow rates even during the periods of maximum agricultural demand. The hydraulic regime of the Cavo Lucca is characterized by a sustained flow during all the year, due to the presence downstream of a hydroelectric power plant that requires a constant minimum flow rate for its functioning. However, the highest flow rates are typically recorded in the period between May and July, due to the greater demand of water to utilize for the phase of submersion, and therefore, the season of maximum irrigation of the rice fields. For this reason, the experimental campaign was planned precisely in coincidence of such season of sustained irrigation, with measurements executed on data 18 June 2025.



Image 3.7 – Photographic image of the Cavo Lucca taken during the inspection in the field, which highlights the linearity of the stretch upstream of the sampling section. The image clearly evidences the geometric regularity of the irrigation canal, with the flow delimited by extremely regular vertical concrete banks and characterized by the absence of intrusive vegetation in direct contact with the free surface of the water.

The choice of the sampling point fell, therefore, from the last analysis executed on the field, on the site denominated PL1 (see *Figure 3.2*), situated at Cascina Murone (SP7). From a hydraulic and geometric point of view, in correspondence of the sampling section the flow of water has an average depth of 1.72 m and a width of 5.30 m, for a total wetted area of 9.12 m². The aspect ratio is equal to about 3.08, compatibly with one of the values defined in the laboratory study by Peruzzi et al. (2020) [V], which allow to do a direct comparison of the obtained results, making the section particularly suitable for the spectral investigation. From the first reconnaissance and the comparison with the managing regional entity, it is estimated furthermore a maximum flow rate, in the aforementioned period, equal approximately to 9 m³/s, with an average velocity, actually registered during the campaign, of 0.88 m/s, while the hydraulic radius, equal to 1.04 m, confirms conditions of well-developed flow similar to an indefinite flow, without significant local disturbances.

From a morphological point of view, the bottom and the banks are made of concrete, recently subjected to maintenance in the quarter period preceding the sampling, condition that guarantees uniformity of the boundary conditions, stability of the geometries and reduced incidence of erosion phenomena that can develop in time. The distance from the first significant discontinuity upstream is of about 415 m, a value coherent with the minimum distance requested by the scientific literature so that the flow returns stable (300-400 times the height of the water), which ensures a statistically stationary turbulent development.

From a logistic point of view, the site offers good accessibility to the sampling point due to the presence of a pedestrian bridge that crosses the canal, generally used uniquely for the vehicles transit of the managing entities. This is of fundamental importance, in that it allows the safe installation of the acoustic profiling instrumentation, and the safe transit of the operators during the long recording campaign. In particular, the bridge permits the sensors to be positioned in the centerline and lowered to the predetermined depth without too much difficulty, maintaining at the same time stable and safe conditions for the operators, simplifying the design of the support and anchoring structure (subsequently described in paragraph 3.3.2).

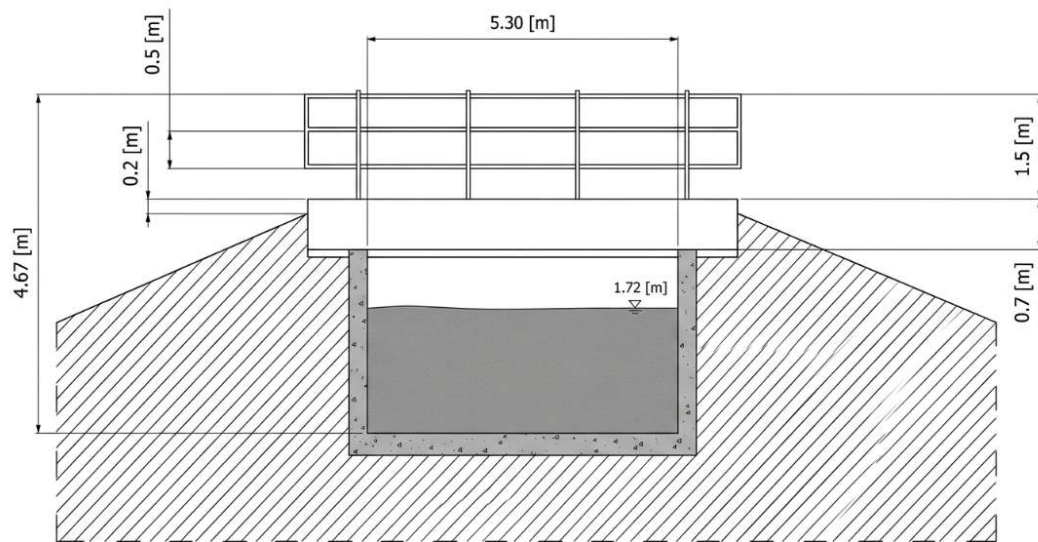


Figure 3.4 – Technical drawing of Cavo Lucca cross-section in correspondence of the selected sampling site (PL1), with the reported dimensioning of the various geometric and structural elements surveyed during the field inspection. Such accurate metric surveys are fundamental for the subsequent design and the custom-made realization, in the laboratory, of the rigid anchoring structure necessary to safely immerse the acoustic sensors in the flow.

Criterion	Requirement	Field verification	Outcome Cavo Lucca
Distance from discontinuity	$> 300 \div 400 \delta$	Absence of significant works upstream	SATISFIED
Aspect ratio	Comparable to laboratory cases	Wide and shallow section, with a value of 3.08 (minimum acceptable threshold per Peruzzi et al. (2020))	SATISFIED
Bank/Bed materials	Homogeneous	Regular banks and bottom, no alternation	SATISFIED
Planimetric trend	Straight	Straight, curvature-free section upstream	SATISFIED
Logistical accessibility	Presence of low-altitude bridge	Stable and easily accessible pedestrian bridge	SATISFIED
Vegetation	Absent	No vegetation in contact with the free surface	SATISFIED

Table 3.1 – Summary matrix of the principal geometric, hydrodynamic and logistic parameters adopted as evaluation criteria for the selection of the site. The table puts into system the specific theoretical requirements, the relative verifications conducted during the field surveys and confirms the overall suitability of the sampling section identified on the Cavo Lucca for the execution of the experimental campaign.

3.2 Bathymetric Survey and Boundary Geometry Reconstruction

To establish the final suitability of the chosen site (Cavo Lucca – Galliate (NO)) and guarantee the reliability of the temporal measurements of velocity, it is necessary to verify, in a preliminary measure, the absence of obstacles or submerged materials, which naturally cannot be identified with the naked eye during the previously described inspection verification. For such reason it is necessary to conduct a preliminary bathymetric survey for the stretch upstream of the chosen sampling section, in order to verify what defined; furthermore, this additional analysis allows, besides acquiring a detailed knowledge of the morphology of the bottom of the canal, also to record in precise absolute value the flow rate values and the height of the free surface of the flow immediately upstream of the sampling point.

Therefore, a detailed bathymetric analysis was executed along a stretch of about 150 meters upstream of the sampling section, value of distance established on the basis of the compromise between the theoretical investigation necessities and the logistic and safety needs. From a scientific point of view, linked to the study of the uniformity of the flow object of study, this value guarantees an area sufficiently wide for the bathymetric investigation for which even in the eventuality of small elements of disturbance on the bottom present beyond this spatial distance from the sampling point, the flow has in fact all the necessary space to stabilize itself completely before reaching the sensor. Under the practical profile instead the prolongation of the survey on greater distances or until the successive discontinuity in the canal would have entailed the deferment of the execution times in a disproportionate manner and, above all, would have compromised the safety of the personnel in the field, due to the presence of raised banks of about 50 cm with respect to the ground level. These physical limitations of transit at the edges would have impeded the operators from walking in safety in proximity of the banks of the canal, forcing them to descend to the level of the surrounding land, which would have made much more difficult the maintenance in perfect tension of the tow rope connected to the instrument (whose operative modality will be detailed after).

The sampling is conducted adopting a rigorously non-invasive approach, based on the technique of the moving boat method, for which the acoustic monitoring instrumentation is housed on a small and manually movable floating support, designed by the manufacturer to maintain a stable trim during the bathymetric survey. The instrumentation is governed by the use of a tow rope stretched transversally between the two banks of the canal, maneuvered by the operators on the ground. The manual manoeuvring of the operators allow to make slide in a constant manner, during the longitudinal advancement, the instrument from one bank to the other, pulling the rope more from one side with respect to the other and trying, at the same time, to maintain it always taut.

Once a first transversal scan of the section is therefore completed, the float is made to advance longitudinally by a few meters in opposite direction to the flow direction, to then repeat in reverse sense the operation of crossing and monitoring of the corresponding section. This movement scheme permits the instrument to scan progressively, section after section, the entire volume of water in the space defined before upstream of the bridge, acquiring a dense and regular spatial grid of measurement points inside the sampled volume. Interpolating the recorded data the real morphological conformation of the bottom is reconstructed and this permits also to map in an incredibly detailed way the velocity field inside the entire area of investigation.



Figure 3.4 – Aerial section of the mapped field derived directly from the QGIS worksheet, in which the bathymetric data are processed, which shows the spatial trajectory of the acoustic profiler during the bathymetric survey along the Cavo Lucca. The yellow dots represented in the figure represent the points of the grid where the profiler effectively performed measurement, defining the scanning grid that guarantees a complete and high-resolution three-dimensional mapping of both the morphology of the bottom of the canal and of the internal velocity field.

To monitor the stretch preceding the sampling point, an acoustic profiler (SonTek RiverSurveyor M9 [i]) mounted directly on a floating structure was used, which allows to move easily the sensor along the various sections, determined by the rather constant movement of the operators from the sides.

The choice of the profiling instrumentation falls on this multibeam technology with respect to the classic single-beam echosounders precisely for its capacity to generate high-definition 3D models, necessary to determine even the minimal irregularities of the bottom of the canal object of investigation. The instrument adopted exploits the Doppler effect for monitoring, basing its functioning on the physical theory previously described in chapter 2, through the generation of 9 acoustic beams: eight transducers arranged in "Janus" configuration, which work on two distinct frequencies (3.0 and 1.0 MHz) to cover different depths, and a further vertical echosounder, functioning at the frequency of 0.5 MHz, which provides us a depth datum independent and much more precise, used to monitor canals with larger depths thanks to the lower working frequency which permits to reach wider distances. In practice, the system measures the flight time of the acoustic pulses reflected from the bottom and, knowing the speed of sound in water, which is calculated following correction in real time thanks to the use of an integrated temperature sensor, calculates the elevation of every point of the grid with millimetric precision.

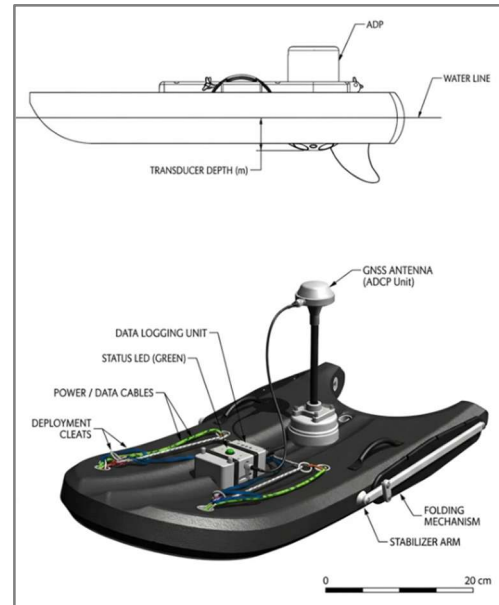


Figure 3.5 – Technical scheme of the floating support on which the acoustic profiler is mounted. The figure illustrates the arrangement on the support of the main on-board components, among which the GNSS antenna, the data recording unit, and the anchoring system for the tow rope.

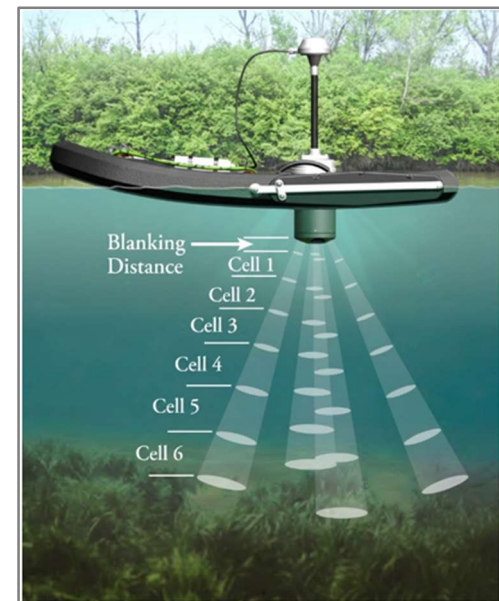


Figure 3.6 – Schematic representation of the functioning of the bathymetric analysis system (SonTek RiverSurveyor M9). The image defines the blanking zone immediately below the 9 transducers and the acoustic beams pulsed by each of them, which allow to monitor the velocity along the entire water column down to the bottom.

The instrumentation and the associated software exploit the use of an algorithm (SmartPulseHD) which adapts the sent pulses based on the hydrodynamic flow conditions, allowing to obtain velocity data with better resolution, inside the measurement cells. The floating structure hosts on itself a high-precision GPS receiver, which allows to define the position in real time with an extremely reduced margin of error, of only 3 centimeters. The system, furthermore, allows to track and maintain constantly updated the position in real time even in case of temporary loss of the GPS signal, thanks to the use of the “Bottom-track” function, which exploits the Doppler effect to calculate the displacement speed of the float with respect to the canal bottom, subtracting it from the detected movement.

The adopted instrument allows to measure and record constantly the volumetric flow rate, basing itself on the same Doppler effect; by calculating, first of all, the point velocity on a grid of points arranged according to a rigid scheme, these are averaged to define the mean velocity inside the section in question, and from the simple multiplication of this value by the wetted area the real-time water flow rate that flows through the section in question is obtained. Furthermore, all the calculation is performed directly in the hardware of the instrument, allowing us not to lose any data even in case of loss of connection with the computer on the shore.

In field practice, the overall operation, which includes the assembly, the acquisition of the data, and the preliminary checks on the correct functionality of the analysis instrument, required about 2 hours. In practice, the analysis operation itself requires very little time, as the emission of the pulses, as defined previously, is modulated on a very high frequency. The total time, therefore, is defined in large part by the time necessary to perform the preliminary functionality test and the calibration of the internal compass of the RiverSurveyor. On the other hand, this step results to be of fundamental importance to eliminate magnetic interferences. In practice, it is necessary to rotate the instrument slowly for two complete circles, making it perform slow pitch and roll oscillations, to be repeated until the position of the instrument is acquired.

Performed the analysis and the verification of the data subsequently in the laboratory, the certainty was obtained that there are no anomalies in the runoff and elements of disturbance on the bottom of the canal, for which the chosen site (Cavo Lucca) results to be suitable, in definitive, to proceed with the assembly of the instrumentation and proceed with the acquisition of the temporal series of velocity.

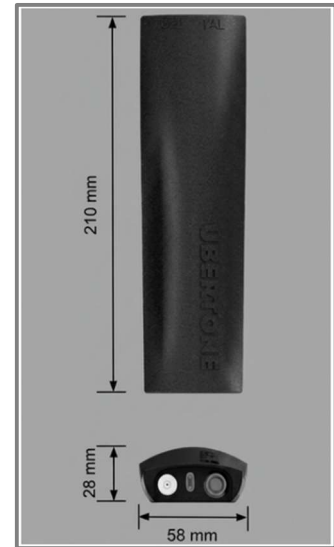
3.3 Acoustic Profiling System: Hardware and Software Architecture

3.3.1 Hardware Architecture and Transducer Specifications

The acquisition of the temporal series of the velocities inside the flow of the Cavo Lucca is performed through the acoustic profiler UB-Lab P, produced by the company Ubertone. The portable instrument adopted in this experimental campaign was conceived, in the design phase by the parent company, precisely to be used in field conditions outdoors, given its versatility and simplicity of use in these applications.

The delivered instrument is equipped with several elements that will be briefly described in this section in order to fully understand its application. Constructively speaking, the signal acquisition electronics are entirely contained inside a rigid water-proof structure, called "chassis", which ensures adequate protection against water splashes and humidity, in addition to being extremely compact; which guarantees optimal adaptability to the operating conditions of this campaign.

Figure 3.7 – Chassis of the UB-Lab P profiler, showing overall dimensions (210 x 58 x 28 mm).



The same is equipped with an internal rechargeable battery capable of guaranteeing, in standard laboratory usage conditions, a continuous operation of the profiling activity of about four and a half hours. However, the necessity to conduct sampling sessions longer than the maximum duration of autonomous operation defined by the manufacturer, as regards the study in question, makes the use of power banks or a fixed charger mandatory; the latter, however, generally cannot be used during in situ sampling sessions if an external generator is not available. The acquisition of very long temporal series arises from the necessity to stabilize the measurements and decrease the statistical uncertainty in the subsequent data processing, for which the use of a support battery is indispensable. Furthermore, the severe environmental conditions imposed by the summer season, as in the case in question, tend to accelerate the discharge rate of the internal battery, and moreover exposes the electronics contained inside to the risk of overheating. The sensor autonomously imposes an operational limit of functioning when a temperature inside of 45°C is reached, after which the hardware enters an automatic blocking state to prevent damage to the internal circuits. For these reasons, in contexts characterized by the constant presence of solar radiation

on the sensor, it becomes necessary to ensure together with the auxiliary power supply system a shading and cooling strategy of the instrument, through forced ventilation or through the use of insulated containers in which the chassis will have to be placed.

The device furthermore is equipped with a Wi-Fi communication module integrated on the motherboard that allows to avoid wiring between the instrument and the computer on the ground, which furthermore allows to obtain data in real time and perform monitoring, to check the actual functioning of the acoustic profiling instrument, even at a distance; in this way it is avoided that the operator be blocked in proximity of the instrument, but can operate the control operations in total safety from a remote location.

Regarding the operational modalities of the UB-Lab P profiler, it is designed to operate in monostatic mode, whereby the same transducer acts both as emitter of the ultrasonic wave pulses and as receiver of the backscattered signal from the seeding in suspension (see paragraph 2.6.3). The hardware block is equipped with two dedicated connectors that allow the connection and the synchronous functioning of two different transducers, which can be therefore used simultaneously to obtain measurements at the same time from two different positions.

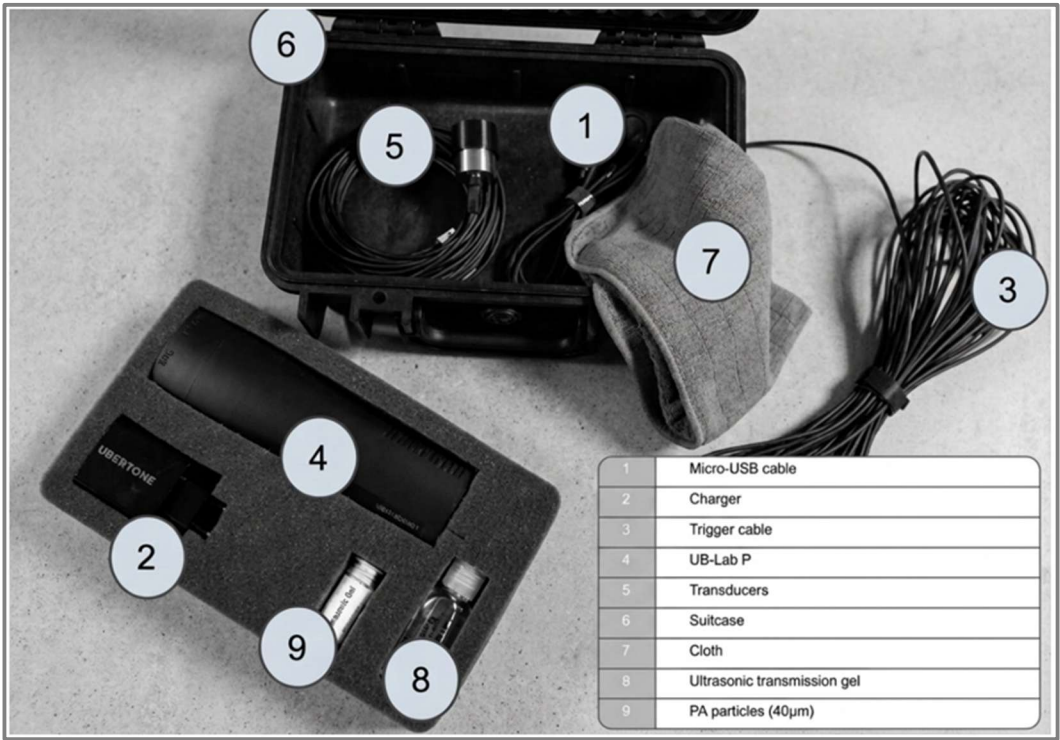


Figure 3.8 – Overview of the equipment included with the UB-Lab P profiler instrumentation, which components are shown and shortly described in the photo.

Measurement Performance	
Sampling range	From 0.005 to 4 m
Number of cells	From 2 to 200
Cell size	From 0.73 mm to 30 mm
Speed range	From -10 to 10 m/s (under Nyquist conditions)
Speed accuracy	From 0.2% to 1%
Speed resolution	15 ppm of velocity range
Sampling rate	Up to 15 Hz
Signal Processing	Phase-coded coherent Doppler
Number of configurations	8
Trigger IN/OUT	Yes (Lemo connector for FFA.00.250)
Acoustics	
Measurement Mode	Monostatic
Transducer Connectors	2 for emission/receive transducers
Type of connectors	Lemo per FFA.00.250
Frequency range	From 0.025 to 3.6 MHz
Beam width	2° - 5° semi-angle (depending on transducer and frequency)
Emission voltage	50V (typical)
Physical characteristics	
Dimensions	28 x 58 x 210 mm ³
Weight	0.2 kg
Connection	Wireless (Wi-Fi)
Data Management	
Communication	Wi-Fi
Internal data logger	Up to 1.2 GB
File format	Binary Data File (.udt)
Speed	Profile data (relative to the beam axis) by beam and cell
E _o	Backscattered echo RMS amplitude per beam and cell
Data quality	Speed data quality indicator for beam and cell
Power supply	
Input	5V
Consumption and Autonomy	Typical: 2.5 W
LED ON/OFF	Yes, integrated into the power button

Table 3.2 – Summary of the technical specifications and of the operational parameters of the UB-Lab P instrumentation. The table reports the hardware characteristics, the acoustic functioning parameters and the performances of the acoustic profiling instrument.

3.3.2 Mechanical Deployment and Software Configuration

First of all, before the beginning of the sampling, it must be specified that, in order for there to be the correct propagation of the ultrasonic wave pulse and therefore the correct reception of the return signal, the active face of the transducer must be constantly in contact with the water. As already specified in the previous chapters, it is necessary to avoid that the transducer comes into contact with air, which can be present inside the fluid even in the form of microbubbles; for this reason, before immersion inside the flow, a coupling gel directly supplied by the manufacturing company is applied on the transmission face of the transducer (for the technical reasons refer to paragraph 2.2.4).

In the specific applied context of the present study, the geometric configuration of the transducers (operating at a frequency of 3 MHz) adopted for the measurements foresees the mounting of both in a direction perfectly parallel to the flow direction of the water in the channel, with the active face pointing upstream. Such a configurational choice is dictated by the compliance with some constraints emerged in the design phase of the analysis, that is from short-duration measurement tests that were carried out in a preliminary phase during the inspection and in the laboratory, in order to verify the optimal configuration of the parameters required by the software. First of all, it must be specified that the use of acoustic profiling instrumentation with such a high frequency certainly guarantees a very high spatial resolution, but at the expense of the maximum useful sampling distance, since, from the theory of acoustic signals, we know that the acoustic beam is subject to a greater attenuation of energy. Therefore, the vertical installation of the transducer would certainly not have allowed analysing the flow along the entire depth, but only for a few centimeters of distance from the active face. It must be further specified that the in-situ sampling conditions diverge greatly from controlled environments; the main reason consists in the non-use of artificial tracers, whereby the intensity of the return signal depends exclusively on the level of turbidity of the water, which cannot be managed a priori.

Based on these reasons, as confirmed by preliminary evaluations on the signal, it is found how the quality of the received data varies absolutely along the measurement axis. In fact, the first cells, placed at a lesser distance from the active face of the transducer, generally show to be profoundly disturbed by the very presence of the transducer, whereby much noise is recorded. While the more distant cells return an excessively weak signal, due to the acoustic phenomena of dispersion. Ultimately, the choice fell on the horizontal mounting, in order to bypass these limits, whereby the instrumentation acquires data at a constant elevation. In this way, the data analysis proceeds through an examination of the data obtained for the single measurement cells,

proceeding to discard those deriving from the aforementioned cells and extracting the velocity values exclusively from the cluster of central cells, that is the control volumes that are characterized by the highest signal-to-noise ratio (SNR), making sure to analyse only the clean signal.

Regarding the practical phase of implementation, and, therefore, of the immersion of the transducers in the flow of the Cavo Lucca, this configuration necessitates the design and subsequent realization of a support structure, on which the transducers will be mounted, which will be firmly anchored to the designated bridge in correspondence with the optimal section.

The anchoring and support system was conceived as a trellis frame, constituted by a grid of interwoven steel tubes held together by a series of orthogonal adjustable cross joints tightened by screws. The structure was purposefully designed for the conditions required by the specific selected sampling point, since the structural characteristics of the bridge highlighted the presence of an overhang between the railing and the edge of the bridge and a vertical distance between the free surface of the water and the base of the bridge considerable enough not to allow using solely a telescopic tube to be lowered inside the channel, since it would not have been sufficiently constrained to support the imposed hydrodynamic loads.

Through the use of the structure designed and then implemented in the field, as is evident from figure 3.9, this problem is largely contained, creating a support base that allows, first of all, to overcome the overhang between the railing and the boundary of the bridge and, being much more stable and integral also thanks to the direct contact between the edge and the structure, capable of distributing the loads and discharging the forces directly onto the fixed structures of the bridge.

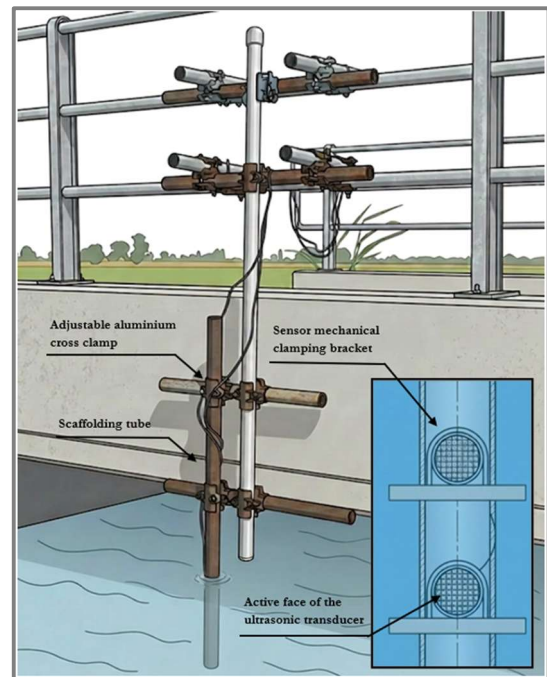


Figure 3.9 – Illustrative scheme of the mechanical anchoring and support system realized in correspondence with the sampling section identified as optimal. The image shows the trellis frame constrained to the parapet of the bridge through orthogonal joints and the vertical rod lowered into the flow. In the bottom right box is reported the detail of the horizontal arrangement of the two ultrasonic transducers and the annexed locking modality.

Through the central nodes of this frame the support rod is lowered vertically, at whose extremities the two transducers are anchored at a different height, thanks to the use of two small plates on which they are rested and subsequently blocked with two adjustable metal bands with screw fastening. The vertical rod extends for about 3.10 m, a condition established by the limits imposed for transport in a van, whereby the structure was conceived also in reason of the maximum allowed length of the tubes, allowing to block the tube that will be immersed in the channel at a lower height compared to the height from the bottom of the channel, in such a way that the sensors can be immersed up to the pre-established sampling height. In this way the use of a slender structure is avoided and notable flexural rigidity is conferred to the entire scaffolding, a necessary condition to counteract the thrusts exerted by the current in transit. This configuration allows, therefore, to minimize the vibrations induced on the body of the rod, since any induced mechanical oscillation would be recorded by the instrument and interpreted as a parasitic water velocity fluctuation, to the detriment of the quality of the spectral analysis of the turbulence.

Once the mechanical arrangement has been defined and before the transducers are correctly positioned at the pre-established heights, the UB-Lab P requires the input of some parameters, which must be configured to optimize the acoustic signal and, therefore, the sampling, based on the specific hydrodynamic conditions of the flow in the Lucca channel. Following laboratory tests and preliminary tests carried out directly following the immersion of the transducers in the channel, the best possible configuration is determined, with the parameters imposed in the software summarized below in the table.

UB - Lab P Software Configuration parameters		
Key string	Description	Value
PRF	Repetition frequency of the ultrasonic pulses	5000 [Hz]
f_0	Frequency of the ultrasonic wave sent into the medium	3 [MHz]
Cell size	Thickness of each measuring cell along the radius	$5,93 \cdot 10^{-3}$ [m]
Intercell	Distance between the centre of one cell and the next	$8,89 \cdot 10^{-3}$ [m]
Number of cells	Total number of active measuring cells	15
Sample number	Number of samples acquired for each profile	20
Profiles per block	Number of speed profiles acquired in a block	5
Block duration	Time duration of an acquisition block	0,020 [s]

Table 3.3 – Configuration parameters set in the UB-Lab P software for the optimization of the sampling on Cavo Lucca. The table summarizes the values defined following the preliminary tests in the laboratory and in-situ.

During the sampling, the bulk of data generated during the acoustic profiling activity in water, is continuously recorded in the internal data logger of the instrument (momentary maximum capacity of 1.2 GB) in binary format, proprietary to the manufacturing company, identified by the .udt extension.

The present file cannot however be read by common calculation software, therefore an intermediate step is needed; the data are directly uploaded onto the Ubertone Cloud2 web architecture, which subsequently allows to extract the raw files without any difficulty, and generates text files in CSV format that can be directly read and imported into the MATLAB calculation environment, through which they will subsequently be processed.

4. Data Processing and Turbulence Analysis

4.1 Data Pre-processing and Hydraulic Characterization

Before proceeding to the elaboration of the data acquired through the UB-Lab P acoustic sensor, it is necessary to detain an overall framing of the hydrodynamic state of the flow at the chosen sampling section of the Cavo Lucca. The global parameters have been derived from the geometry of the channel bed, following the inspection on field, which presents a perfectly rectangular section with a width equal to 5.30 m and hydraulic depth equal to 1.72 m, traversed by a flow rate, provided to us directly by the managing body of the irrigation system at the start of the sampling operations, equal to $8 \text{ m}^3/\text{s}$. Such flow rate value is monitored by the manager at the entrance of the water in the Cavo Lucca, through sensors positioned downstream of the floodgates, that allow the withdrawal of the water from the Cavour Canal to feed this secondary channel. The managing body monitors and maintains this flow generally constant over time, except in case of exceptional operational anomalies, in such a way as to guarantee a continuous and stable flow to the hydroelectric power plant situated downstream of the sampling point, as well as to constantly feed the irrigation system. For such reasons the flow is maintained constant for the whole arch time of the day and becomes an important advantage for our measurement campaign, assuring steady state conditions for the entire duration of the measurement.

From the data collected in the field are therefore derived the geometric quantities, such as wetted area ($A=9.12 \text{ m}^2$), the hydraulic radius ($R=1.045 \text{ m}$) and the aspect ratio ($W/h = 3.08$), as well as the global mean velocity equal to 0.877 m/s . Further such measurements, particular importance assumes the exact position of the sampling point, necessary in order to determine the dimensionless parameters, previously defined, necessary to make comparisons with studies carried out in other measurement contexts. From the satellite coordinates one can easily deduce the distance from the entrance of the Cavour Canal ($x_c = 587 \text{ m}$) and, even more important, the distance from the first upstream discontinuity ($x = 414.5 \text{ m}$), from which is deduced a dimensionless distance equal to 241.02 (considered to be suitable for the stabilizing of the hydrodynamic flow conditions).

The transducers have been mounted and positioned along the tube so that they were positioned respectively at a height of 10 and 18 cm from the bottom of the channel. This specific geometric configuration of the acquisition element responds to theoretical constraints linked to the structure of the turbulent flow in a free surface channel; specifically, having determined the value of the hydraulic depth equal to 1.72 m, the non-dimensionalized vertical installation elevations (y/H) correspond exactly to 0.06 and 0.10. As defined in the previous theoretical chapters, this region of the motion field is defined logarithmic region, which extends up to $y/H = 0.20$. Furthermore, for uniform open-channel flow the logarithmic law of the wall is generally assumed to be valid, with a good approximation, over the entire water column above the bed, due to the negligible wake effect compared to closed boundary layer flows.

Inside this region the velocity profile follows exactly the law of the wall, whereby the positioning of the two transducers at different height allows to be able to apply the differential method for the calculation of the friction velocity (u_*).

Defined, therefore, the boundary conditions one proceeds to the extraction of the data in CSV format, previously exported in the cloud of Ubertone, which are, again, imported in calculation environment MATLAB to execute the data analysis, isolating the recorded data of the longitudinal velocity for each of the 15 active measurement cells along the acoustic beam. Since the transducers have been oriented in direction parallel to the direction of outflow of the water in the channel, the center of gravity of the control volumes is found at the same elevation, defined previously. Consequently, the variation that is observed among the registered velocity data corresponding to the different measurement cells depends, therefore, exclusively on the distance with respect to the active face of the transducer; for such reason, the methodological choice of analysis of all the measurement cells has been carried out exactly to the end of verifying the effectiveness of sampling in the various points and quantifying the influence of the noise on the acquired data series.

Making reference to what written in paragraph 2.4, keeping in mind that the active face of the piezometer crystal has a measured diameter of 20 mm, one calculates a length of the near field (Fresnel zone) equal to about 0.20 m. Since the spatial window from which the instrument obtains the data extends for a maximum radius of 14 cm, it is deduced that all the cells fall inside this region; this allows us to have a great advantage for the analysis of the data, inasmuch as inside this zone we know that acoustic beam does not widen, but follows rather a stably cylindrical shape with constant diameter, equal to that of the active face of the transducer. This geometry guarantees a uniform spatial resolution for all the cells and allows to reduce the effects of energetic attenuation due to the geometric dispersion of the beam.

However, the preliminary analysis of the data provided to us directly from the interface of Ubertone Cloud2 shows that the quality of the acquired data is not univocal along the whole profiling radius (see Figure 4.1 reported below), rather the cells immediately in proximity of the sensor show a return signal of the velocity completely altered, showing a drastic decrease of the Signal-to-Noise Ratio (SNR), which assumes negative values. This worsening of the signal is linked probably to the phenomenon of the transducer ringing, whereby following the sending of the acoustic pulse, the piezoelectric material continues to vibrate by inertia even without sending any signal, rendering the receiver momentarily blind and incapable to interpret the signal of the first return echoes from the suspended material (reference is made to chapter 2 for in-depth analysis). For what concerns the most distant cells, the decrease of the SNR is due to the acoustic attenuation of the signal in the water, which corresponds to a decrease of the amplitude of the energetic return signal.

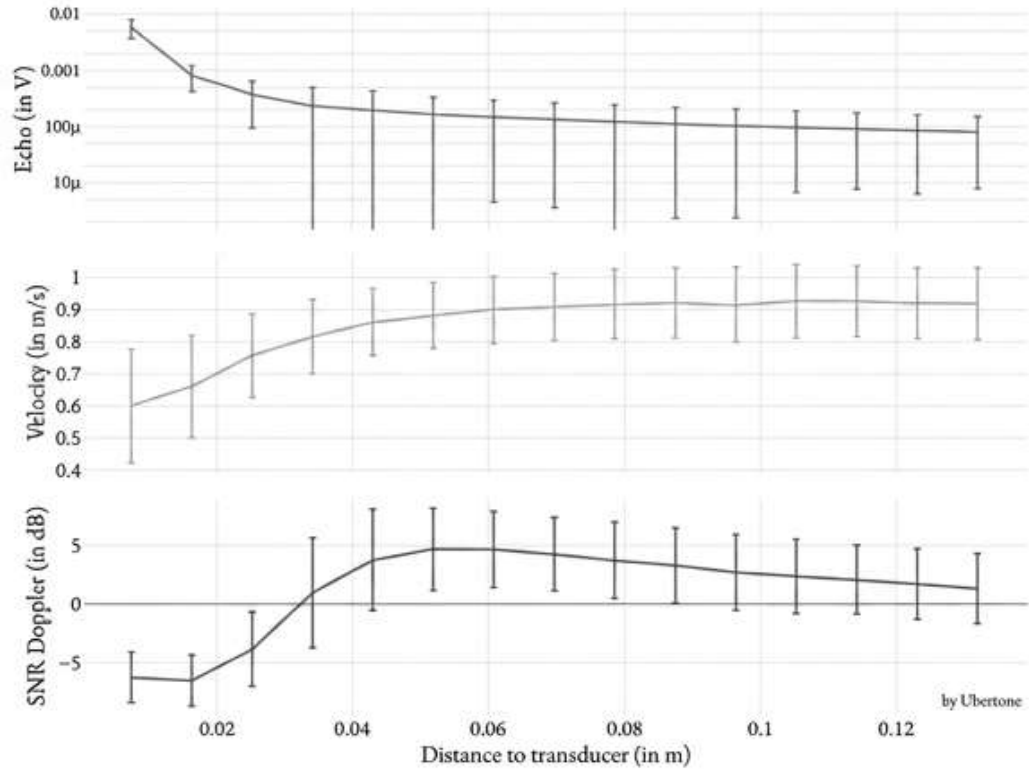


Figure 4.1 – Averaged profiles of echo amplitude (top), mean velocity (middle), and Signal-to-Noise Ratio (bottom) defined along the acoustic beam axis. Data provided directly from the Ubertone Cloud2.

From what is shown by the Ubertone interface, one can already identify the ideal reference cells for the subsequent validation of the data, corresponding to cell number 6 and 9. The first positioned at a distance from the transducer interface of about 5 cm, is found just beyond the blind region defined before, given that it shows the greatest Signal-to-Noise Ratio (SNR = 5 dB), while the second positioned at a distance of about 8 cm, even though showing a certain attenuation of the energetic amplitude of the return signal, corresponds with the first cell after which the calculated mean velocity data becomes stable. Subsequent evaluations regarding this will be carried out, analyzing personally all the velocity values registered in every control volume.

Proceeding at this point with the elaboration of the data in the MATLAB environment, the instantaneous velocity signals, acquired at a constant frequency equal to 12.51 Hz, are elaborated following the approach of the Reynolds decomposition, in such a way as to eliminate the mean value of the velocity corresponding to the mean convective contribution of the flow and allow to isolate the fluctuating component associated to the vortical motions of the turbulence. The time series of the fluctuations are subsequently analyzed in such a way as to eliminate the outliers, that is those punctual velocity signals that deviate by much from the remaining values, resulting in fact unrealistic. These are generally attributable to the presence of macro-debris in the flow, just

as they can be due to momentary interferences of electronic character. Naturally, from a methodological point of view, they must be eliminated in order not to corrupt the subsequent statistical calculations, manifesting themselves as unexpected peaks of fictitious energy associated to the high frequencies in the pre-multiplied spectrum.

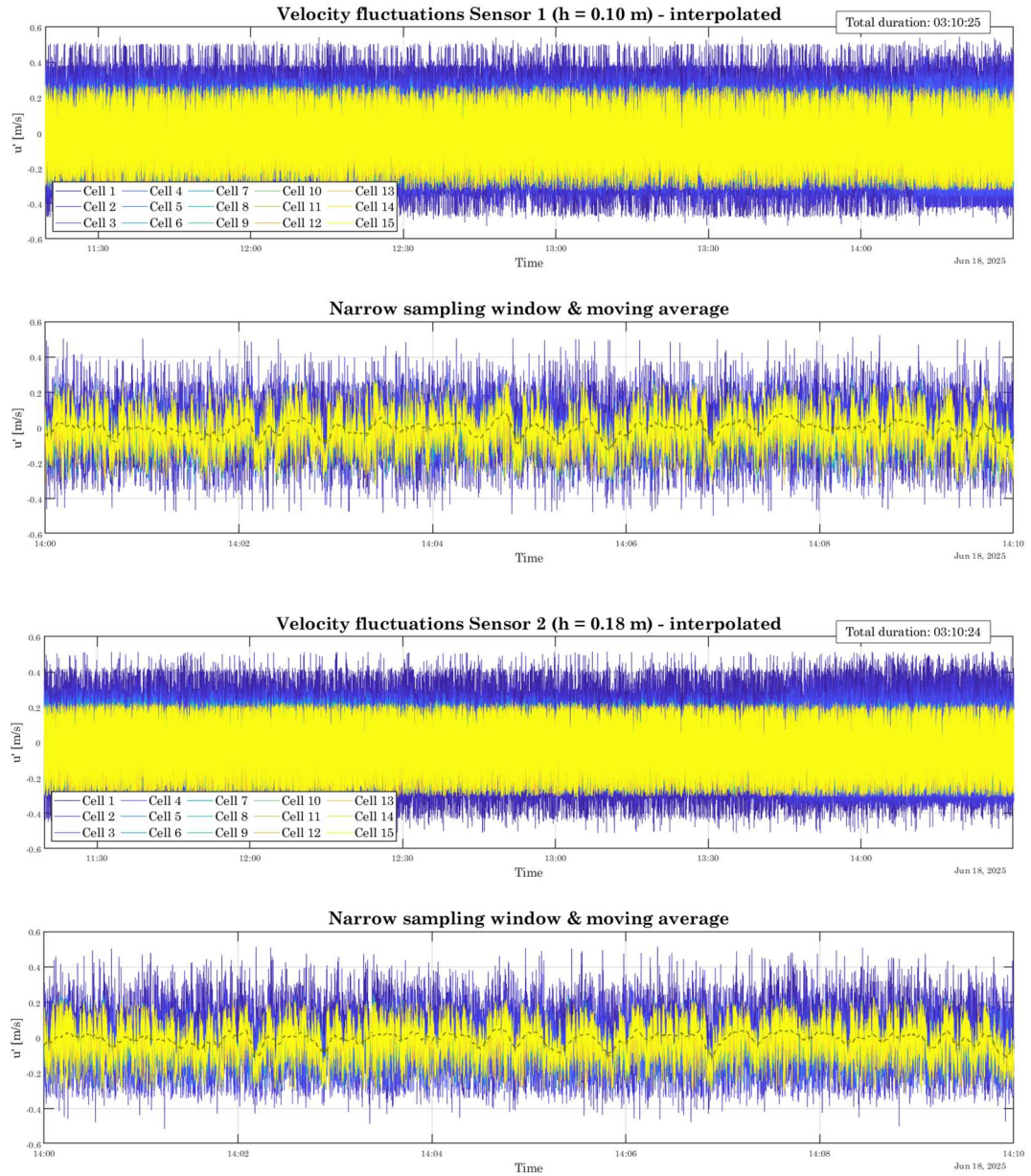


Figure 4.2 – Temporal trend of the fluctuations of the longitudinal velocity (u') for Sensor 1 (top, $h=0.10$ m) and Sensor 2 (bottom, $h=0.18$ m). For each sensor are shown the complete signal over the entire duration of the sampling (global view) and an enlargement on a time window of 10 minutes.

In order to proceed with the exact spectral analysis one must determine the friction velocity which represents the fundamental parameter in the study of turbulent motions, as defined in the theoretical phase. To quantify exactly the value of this magnitude, in such a way as to reduce the associated uncertainty, 3 different calculation methods are compared. As we have said before, the positioning points of the transducers are found without a shadow of a doubt inside the logarithmic region, in such way we can exploit the theoretical considerations linked to the development of the velocity profile inside this section of the fluid.

The first approach is based on the local discretization of the velocity gradient in the logarithmic zone, whereby using the mean velocity difference calculated thanks to the positioning at two different elevations of the sensors one can easily calculate the friction velocity. The second calculation method is based on the intersection of the mean velocity data, calculated at the two established heights, through the use of the formula of the law of the wall.

$$u_*(1) = \frac{\overline{u_2} - \overline{u_1}}{\Delta z} \kappa \bar{z} = 0.0387 [m/s]$$

$$u_*(2) = \frac{\kappa(\overline{U_2} - \overline{U_1})}{\ln\left(\frac{y_2}{y_1}\right)} = 0.0377 [m/s]$$

Although the application of the law of the wall would be the most rigorous method to apply from the theoretical point of view, the values calculated through this approach result to be extremely sensitive to the kinematic difference between the measurement heights, inasmuch as, specifically to the case study in examination, the velocity gradient results to be very small and this is due to the elevated velocity of the water flow in the channel, but above all because of the relative proximity between them of the sensors. For this reason, the calculation is heavily affected by the presence of the background noise of the acoustic signal, due exactly to the low registered velocity difference. At this point, it results more suitable to adopt a global scale approach for the calculation of the friction velocity, in order to avoid such described limitation; for this reason, one resorts to the empirical approach established by the Manning equation.

This third adopted method is no longer based on the punctual estimation of the velocity, but rather on the global mean velocity of the flow, or on a magnitude weighted over the whole water column, mathematically more stable and robust not being influenced by the velocity fluctuations. For the application of the formula one must calculate first of all the slope of the energetic line (S_f), which requires the knowledge of the value of roughness of the wall; this latter cannot, however, be established a priori, without carrying out in situ tests directly on the wall of the channel — highly unfeasible given the condition of continuous outflow, imposed by the needs of irrigation supply for agricultural purpose and of the hydroelectric plant, whereby the necessity would arise to wait for maintenance periods of the channel in which there is not the outflow of water.

To compensate for this impracticability of the experimental determination a parametric type approach is adopted, whereby, making reference to the literature, four different values of the Manning coefficient have been established included in the range $n \in [0.015, 0.018]$, identified by Ven Te Chow (1959) as the typical interval of the roughness values for concrete walls. In this way one must consider the uncertainty of the calculation, whereby the confidence interval is determined for the value of the friction velocity:

$$u_*(3) = \sqrt{gRS_f} = 0.0409 \div 0.0491 \text{ [m/s]}$$

Given the elevated uncertainty of the calculation of the first two approaches, due to the presence of the background noise in the data registered by the sensor, the estimate obtained through the empirical method of Manning will be assumed as reference value for the subsequent analyses of the measured punctual velocity data, taking into account always the uncertainty of the data.

Having defined the friction velocity one proceeds to the calculation of the characteristic scale of the viscous layer ($\delta_v = \frac{\nu}{u_*} \approx 2.4 \cdot 10^{-5} \text{ [m]}$), that is the dimension of the geometric region in contact with the wall of the channel where the viscous forces prevail over the turbulent fluctuations. From the determination of this parameter, one calculates the friction Reynolds number, or Von Karman number, defined as the ratio between the hydraulic depth and such wall length, whereby one obtains $Re_\tau \approx 58000$. This parameter is of crucial relevance for the studies of characterization of the turbulence; it quantifies the amplitude of the spectral separation between the external macro-scale and the internal micro-scale which, as amply demonstrated by the scientific literature on the studies of turbulent structures in free surface flows, allows to define the degree of spectral separation between the large scales object of study, that is between the LSM and the VLSM. From recent scientific studies on the matter a threshold value of 1700 is indicated in order to be able to guarantee a clear spatial separation between these structures, even if the recent laboratory studies of Peruzzi et al. (2020) [V] demonstrate the presence of VLSM for values of the von Karman number in the surroundings of 725. Such calculated value certifies in an absolute way that the motion field does not suffer the confinement effects typical of low values of Re_τ .

Finally, one determines the value of bulk Reynolds ($Re_b = 9.16 \cdot 10^5$) and the Froude number ($Fr = 0.213$). The obtained value, amply below the unitary value, defines clearly a state of subcritical motion, whereby such condition indicates that the convective velocity of the flow in the channel is inferior to the propagation celerity of the wave motion. In such conditions, the hydrodynamic perturbations can propagate towards upstream, guaranteeing us that the outflow is effectively controlled by the downstream conditions and this justifies the stationarity of the hydraulic depth over the total duration of the sampling.

Table 4.1 – Summary of the hydrodynamic parameters calculated for the measurement section on the Cavo Lucca.

Geometry and Development	
Wetted cross-sectional area	9.12 [m ²]
Hydraulic radius	1.045 [m]
Aspect ratio	3.08
Non-dimensional distance	241.02
Kinematic Parameters	
Global mean velocity	0.877 [m/s]
Friction velocity (Manning - Ref.)	0.0409 - 0.0491 [m/s]
Roughness height	4.77 10 ⁻⁶ [m]
Viscous length scale	2.4 10 ⁻⁵ [m]
Dimensionless Groups	
Bulk Reynolds number	9.16 10 ⁵
von Kármán number	58000
Froude number	0.213

4.2 One-Point Statistics and Data Validation

Before facing the exploration of the coherent structures of large-scale turbulence and of the spectral analysis, it is necessary to determine the quality of the acquired dataset in order to validate the experimental methodology described previously.

This procedure is conducted through the analysis of the single-point statistics, focusing mainly on the first and second order statistical moments of the punctual motion field. of the obtained results with the consolidated evidences in the scientific literature relatively to the free-surface turbulent flows, considering the use of analytical models for high Reynolds number flows (conditions extremely different from those of laboratory), allowing to verify in an absolute way the quality of the data acquired by means of the acoustic profiling instrument UB-Lab P, though, therefore, the proof of the absence of significant deviations of the calculated variables due to the effect of the elevated instrumental background noise and verifying the correctness of the values calculated in the preceding section.

As already said in first analysis, in order to represent at best the obtained results, one will take into account the uncertainty of the calculations where it is not possible to determine with certainty the analytical values of the various statistics, whereby the measured punctual value will always be provided accompanied by its uncertainty band. For the calculation of this latter one relies on the theory of error propagation, specifying that they are due to the uncertainty of the roughness value assumed as reference in first analysis belonging to the range $n \in [0.015, 0.018]$, used for the estimation of the wall velocity.

Naturally, it must be highlighted, that all the single-point statistics presented in the present paragraph will not be analyzed in their absolute values, but rather adimensionalized resorting to the normalization generally adopted in the antecedent literature studies in inner scale and in outer scale. This methodological procedure is essential to decouple the calculated quantities from the specific geometry of the flow in the channel in question, thus allowing to compare with the data of the scientific literature.

The analysis of the single-point statistics focuses on the study of the longitudinal velocity fluctuations acquired in correspondence to the previously defined measurement quota determined by the positioning of the two transducers. In a first phase, the values of velocity fluctuations adimensionalized through the inner scaling normalization are analyzed, whereby the value of the distance from the channel bed is adimensionalized with respect to the characteristic length of the viscous zone (y^+),

while the value of the variance is adimensionalized with respect to the square of the friction velocity (σ_u^2/u_τ^2).

It is known from the literature that the turbulent kinetic energy scaled in wall units does not present a univocal trend for all free-surface flows, but rather a strict dependence on the Friction Reynolds number is found. To this end, we can compare the values acquired from the data of Peruzzi et al. (2020) [V] and the data obtained during this experimental campaign with the theoretical trends hypothesized by the predictive analytical model proposed by Marusic and Kunkel (2003) [XIX].

The model defined by this study allows to definitively establish the relationship of what happens inside the boundary layer with the Friction Reynolds number. It is based on the attached eddy hypothesis, initially proposed by Townsend [XIII], and suggests that the boundary layer varies in a significant way as the von Karman number varies, with an influence of the outer flow that propagates down to the viscous sublayer; whereby increasing the Reynolds value, the spatial and energetic dimension of the turbulent macro-structures enlarges notably.

In physical practice, this demonstrates that the large eddies that are part of the outer region of the boundary layer manage to have an influence on the entire water column, down to the bottom. These structures generate movements, defined inactive motions, that literally sweep the water layers near the wall, completely modifying its motion field at the contact in the viscous zone, demonstrating that the energy of these scales of magnitude is transmitted downwards and, therefore, the turbulence in proximity to the bottom does not depend solely on the wall friction, but is strongly influenced by the evolution of the phenomenon in the upper layers. Whereby, having amply understood that the spatial dimension and the intensity of the LSMs and VLMS depends mainly on the Reynolds number, one can easily understand how the footprint of these on the bottom varies based on this parameter.

For the experimental validation of the data acquired in the field, these have been compared with the data calculated according to the analytical model proposed by Marusic and Kunkel (2003) [XIX], calculating the theoretical trends at different Friction Reynolds values; furthermore, the values obtained from the laboratory studies of Peruzzi et al. (2020) [V] have also been reported, in such a way as to confirm the validity of these as well. The results are shown in Figure 4.2 on the following page, reporting the trends of the parameters calculated from the velocity fluctuations recorded in all the measurement cells.

Normalised streamwise turbulence intensity - Marusic & Kunkel (2003)

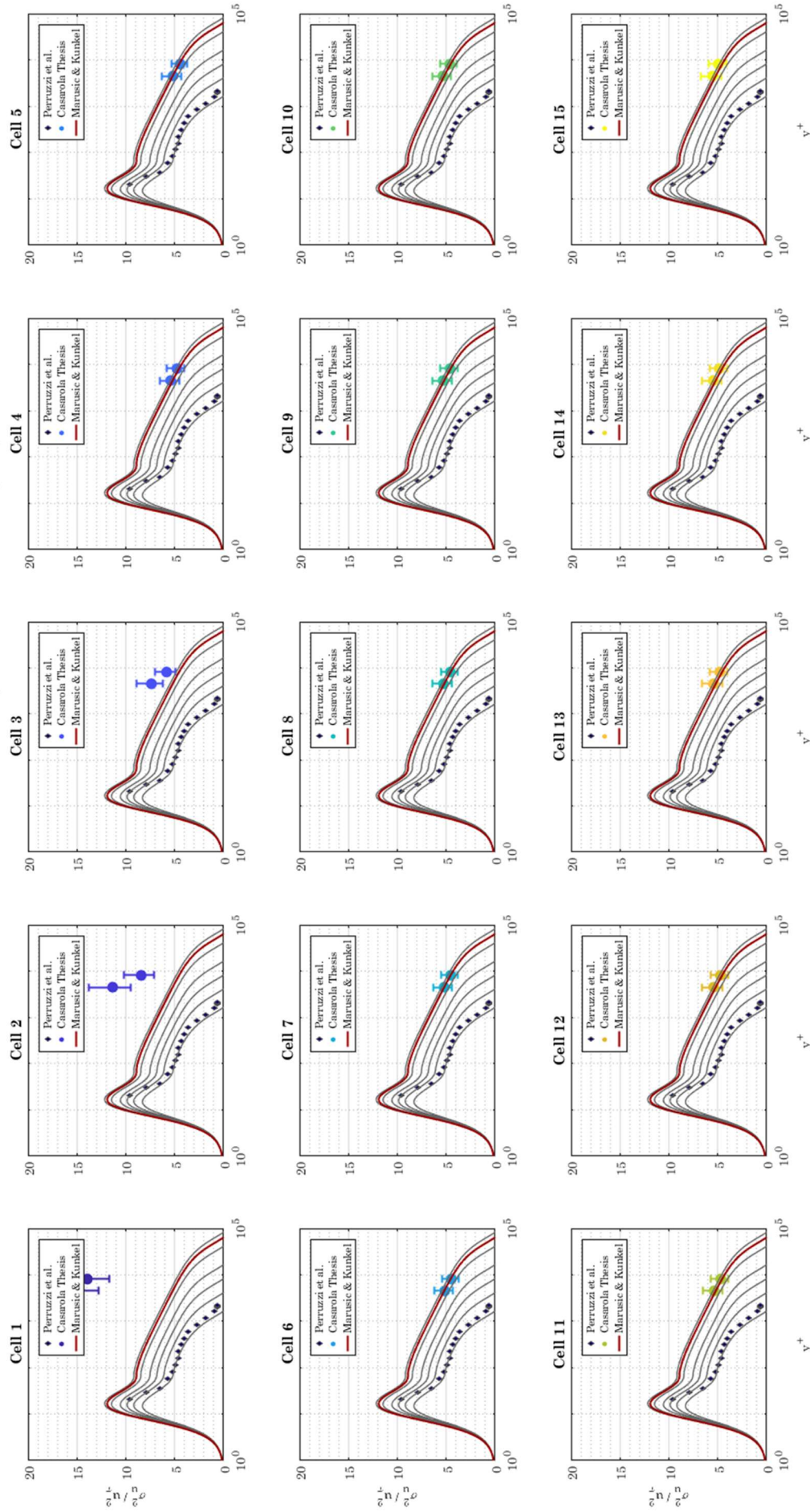


Figure 4.3 — Normalised streamwise turbulence intensity in inner scaling. The graphs describe the hydrodynamic conditions monitored in the 15 acquisition cells of the UVP and show: the experimental data of the Cavo Luca (coloured points with confidence band), the literature data of Perruzzi et al. (2020) (dark blue diamonds) and the theoretical curves derived from the predictive model of Marusic and Kunkel (2003). The trend of the theoretical model is reported for various increasing Reynolds numbers, while the continuous red line identifies the theoretical trend calculated at the Reynolds number coinciding with that of the present case study.

Referring to Figure 4.3, the grey curves identify the application of the theoretical model of Marusic and Kunkel, clearly showing the strong dependence of the results on the von Karman number. As the Reynolds value increases, the curves translate upwards, following the same trend, certifying the effects described above.

The theoretical models adapt perfectly to the trend of the experimental data extracted from Peruzzi et al. (2020) along the entire profile, characterized by ($Re_\tau = 2240$), showing a coherent trend on the lower curves; behaviour aligned with the limited spatial dimensions of the turbulent structures that can develop inside laboratory channels. As regards the punctual data acquired in the Cavo Lucca, they position themselves perfectly on the red theoretical curve calculated with the same von Karman number recorded in the current experimental conditions ($Re_\tau = 58000$). This overlap between the statistics of the data recorded in the field and the theoretical model allows one to be sure that the acoustic instrument has recorded values effectively associated with the turbulent structures and that the time series of the velocity fluctuation values are not dominated by the presence of background noise.

Subsequently, the mean velocity profiles are calculated and printed adopting the normalization in outer scale, verifying if the distribution of the velocity profile follows the trend established by the velocity defect law along the entire water column. By means of this procedure one evaluates the behaviour of the total flow in the channel interpolating the data by means of the logarithmic equation:

$$\frac{U_{max} - U}{u_*} = -\frac{1}{\kappa} \ln\left(\frac{y}{H}\right) + B_1$$

where U_{max} coincides with the maximum velocity measured in proximity to the free surface, $\kappa = 0.41$ is the von Kármán constant and B_1 is a constant, defined by the wake effect in the outer region, where the trend of the normalized velocity profile separates from the trend established by the logarithmic law.

The constant B_1 is directly correlated to the wake parameter established by the studies of Coles (II), which for free-surface flows is approximated to a constant value, which justifies the use of a fixed value adopted by Peruzzi equal to 0.5. However, in uniform free-surface flow conditions the deviation from the logarithmic law due to the wake effect can be neglected, therefore a null B_1 value is assumed.

At methodological level, it is necessary to specify that, due to the acquisition of the velocity data only at specific heights defined earlier, the maximum velocity term along the profile does not represent an experimentally measured datum, but rather it has been estimated through the application of the log-law assuming it valid up to the elevation coinciding with the free surface of the flow. This assumption represents anyway an engineeringly accepted and rigorous approximation to fill the gaps of the measurements carried out in the field.

Therefore, despite the effective alignment of the experimental points with the data acquired by Peruzzi et al. (2020) [V] and with the theoretical curve of the velocity defect modelled starting from these data (see Figure 4.4), it is nevertheless necessary to take these results with a grain of salt. In fact, the estimation of the maximum velocity from the theoretical model added to the uncertainty deriving from the calculation of the friction velocity, does not allow us to assume this result as an absolute validation of the kinematics of the studied flow.

To compensate for this uncertainty due to the mathematical assumption on the calculation of the maximum velocity and conclude this section of validation of the one-point statistics, the turbulence intensity in outer scaling is analyzed. In the plotting plane, one places on the abscissa the vertical elevation adimensionalized through the water depth and on the ordinate the standard deviation of velocity normalized with the friction velocity. This approach allows to evaluate the progressive decay of the turbulent energy as one move away from the bottom of the channel and approaches the free surface.

Observing the graphs reported in Figure 4.5, one immediately notes that the turbulence intensity is maximum near the wall and as one move away from the bottom the turbulence intensity decreases in a regular manner. This shown trend is perfectly coherent with the theoretical considerations defined previously.

Naturally, also in this case it is not possible to trace the continuous profile up to the free surface given the geometric limitations of positioning of the transducers in a real environment. However, the marked points fit perfectly into the decreasing trend of the data acquired in the laboratory by Peruzzi et al. (2020) [V]. Furthermore, also the uncertainty interval associated with this statistic, calculated from the values of the friction velocity, keeps Peruzzi's values within the confidence bands.

Normalised streamwise mean velocity - Outer Scaling Validation

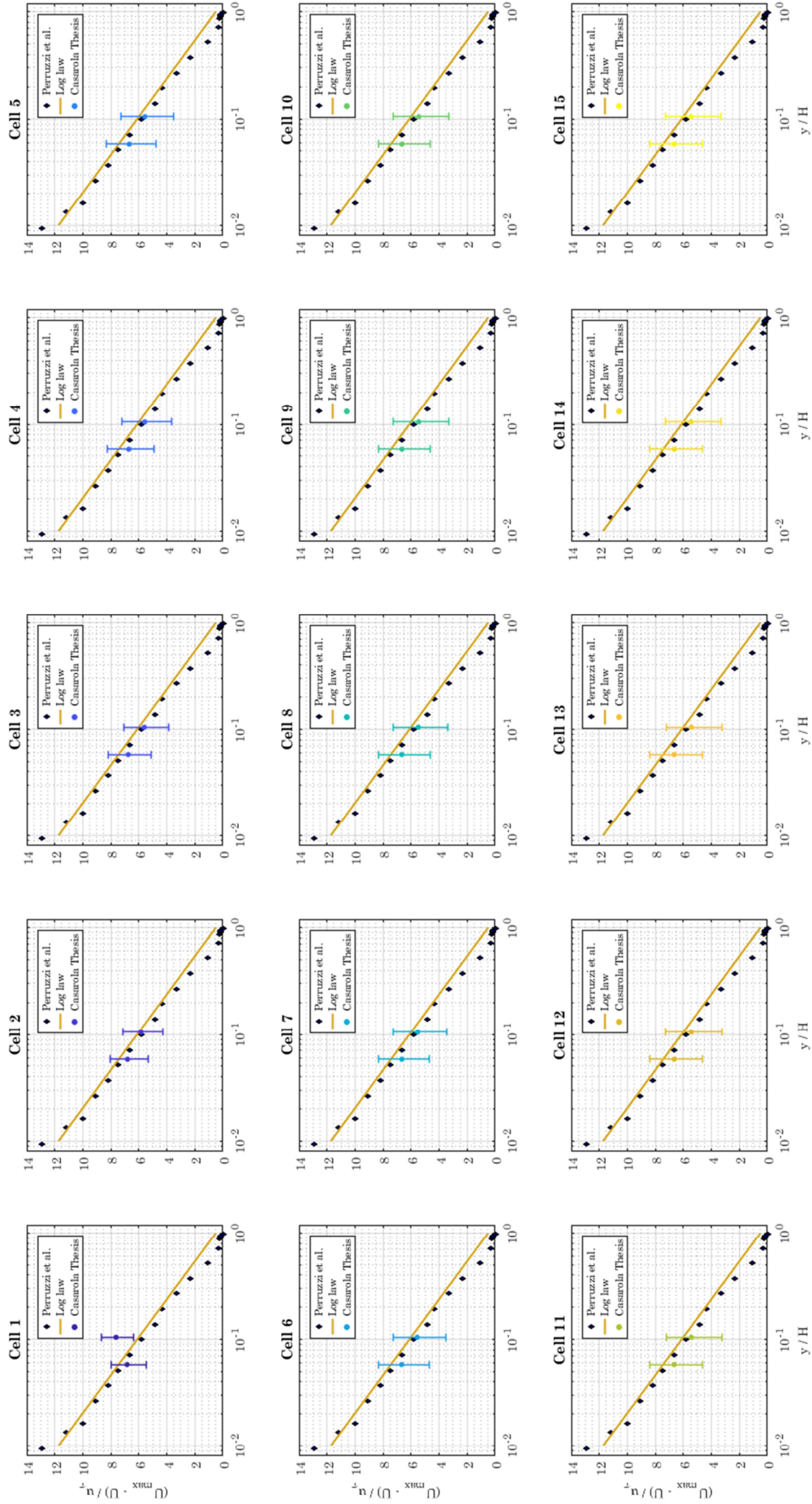


Figure 4.4 — Experimental profiles of the mean velocity defect normalized in outer scaling. The graphs show the statistic calculated for the 15 measurement cells of the acoustic profiler UB-Lab P, comparing the experimental data acquired in the Cavo Lucca (coloured points with relative confidence interval) with the laboratory data extracted from Peruzzi et al. (2020) (dark blue diamonds). The continuous yellow line identifies the theoretical trend defined by the logarithmic law, adapted to the laboratory data.

Normalised streamwise turbulence intensity - Outer Scaling Validation

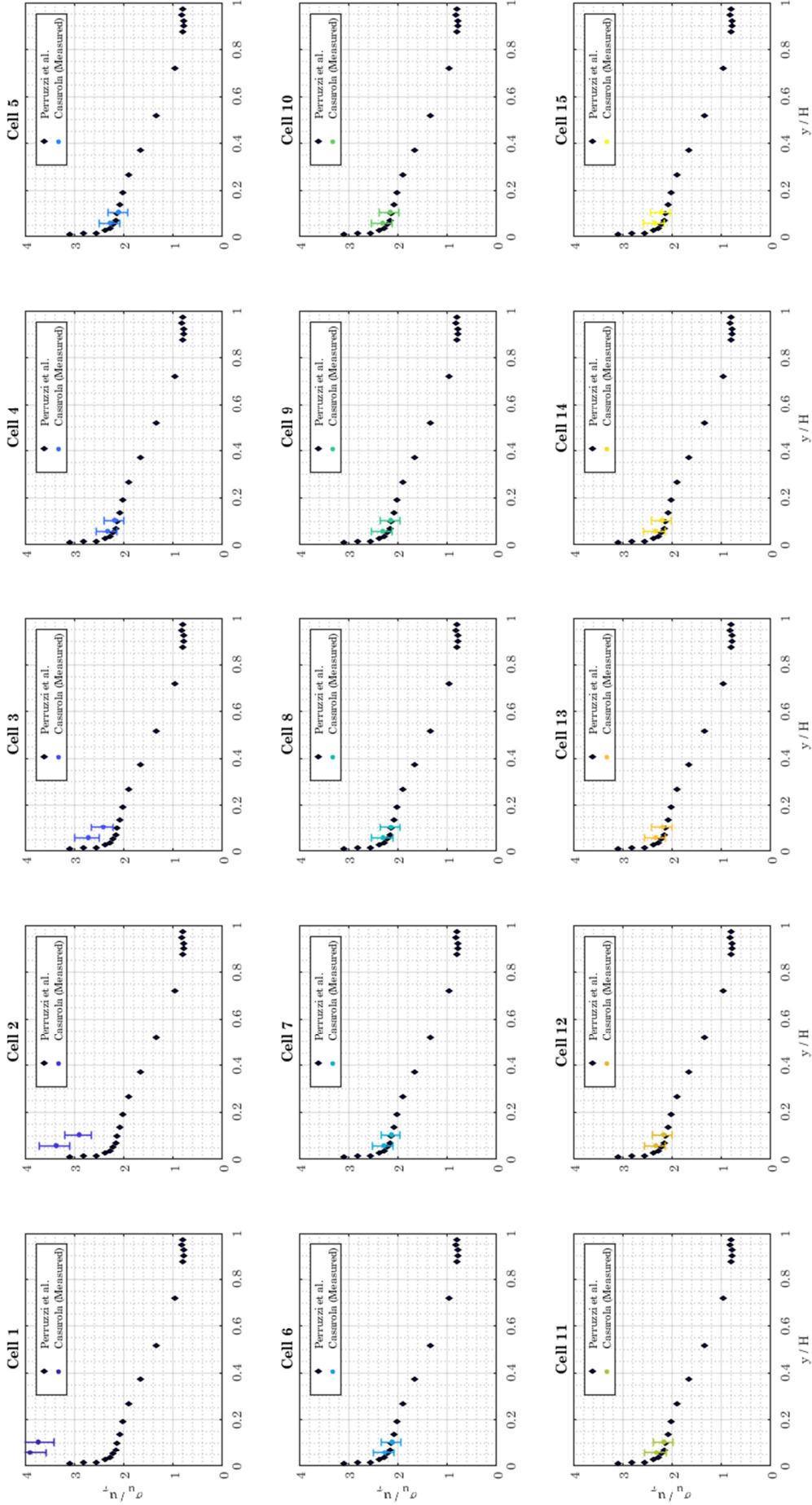


Figure 4.5 — Experimental profiles of longitudinal turbulence intensity normalized in outer scaling. The graphs illustrate the progressive decay of the turbulent energy towards the free surface for the 15 acquisition cells of the acoustic profiler UB-Lab P. The data measured in the field (coloured points with the relative confidence bands) are validated through the direct comparison with the decreasing trend of the laboratory data of Peruzzi et al. (2020) (dark blue diamonds).

4.3 Spatial Resolution Limits and Time Scales

In order to proceed with the processing of the energy spectra for the identification of the large turbulence structures, it is necessary to define the domain of validity of the signal measured by the UB-Lab P sensor in terms of temporal scale, in order, therefore, to define the limits of spatial resolution. The ultrasonic sensor returns point velocity time series, whose characteristics in temporal terms define the physical limits of the coherent structures identifiable by the ultrasonic sampling.

In the transition to the frequency domain, the resolution range is directly determined by the set-up parameters of the acoustic profiler. Specifically to the study in question, the signal was sampled by the profiler with a frequency equal to 12.51 Hz, which parameter defines the Nyquist frequency, equal to half of the signal sampling one, beyond which it is not possible to resolve the fastest fluctuations. As regards the lower limit, instead, this is determined by the total duration of the in-situ sampling ($f_{min} = \frac{1}{T_{tot}} = 8.75 \cdot 10^{-5} [Hz]$).

As regards the maximum detectable scale in spatial terms, these require high transit times through the measurement cells given their longitudinal extension, therefore it is necessary to have to sample over a sufficiently extended temporal window so that they can be identified, and moreover this becomes necessary also to be able to resolve these scales a number of times at least sufficient to be able to decrease as much as possible the uncertainty of the energy associated with the latter in the energy spectra.

For the purposes of the correct spectral processing of the data sampled in-situ, one must take into account the spatial resolution limit imposed by the geometry of the ultrasonic beam emitted into the flow by the transducers. The geometric dimension of the sampling cells identified by the spatial dimension of the ultrasonic beam acts as a low-pass filter, for which the smallest turbulent structures, having a spatial dimension smaller than half of the smallest dimension of the cell, cannot be resolved. This constraint of a geometric nature translates into the maximum frequencies sampleable by the sensor, for which one obtains limit values equal to 29.09 Hz for sensor 1 and to 27.38 Hz for sensor 2; both values have been calculated for the first measurement cell of the ultrasonic beam. Theoretically the lowest frequency value should correspond to the largest cell, this only at parity of measured mean velocity, but, as said previously, the signal in the first cells results extremely influenced by noise and does not allow to carry out realistic measurements.

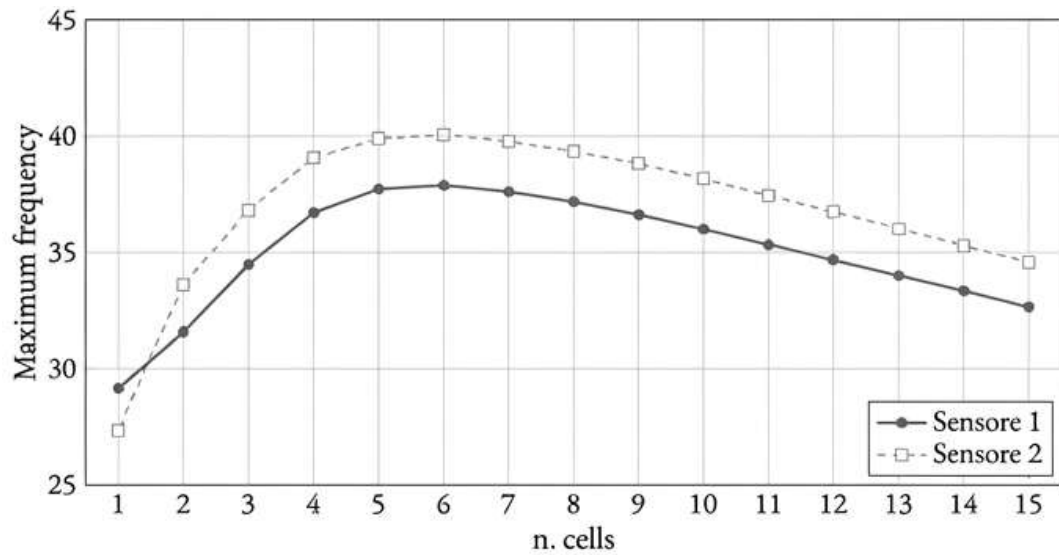


Figure 4.6 – Maximum resolvable frequency as a function of the measurement cell contained in the acoustic beam emitted by the two transducers (Sensor 1, continuous line; Sensor 2, dashed line). The graphs illustrate the theoretical limit imposed by the effect of the geometric low-pass filter.

Comparing the frequency values of maximum resolution reported in Table 4.2, corresponding to the small geometric scales of the turbulence, it clearly emerges that they are distinctly higher than the sampling frequency. Consequently, it is demonstrated in this way that the minimum resolvable turbulent scale corresponds to the sampling frequency, therefore in the subsequent analyses such maximum limit value will be adopted.

4.4 Power Spectral Density (PSD) and Signal Filtering

The analysis of the point velocity data measured in the Cavo Lucca properly begins through the processing of the Power Spectral Density (PSD), which represents the decomposition of the variance of the acquired velocity signal, that correspond to the turbulent kinetic energy, in the frequency domain.

In this initial phase of the investigation of the turbulent structure that characterizes the flow, the calculation of the PSD is not strictly aimed at the identification of large-scale turbulent vortices, but serves as a tool suited to verify the compliance of the data sampled in-situ with the physical principles determined by the theoretical laws established by Kolmogorov. Secondly, the analysis of the PSD allows to identify the validity limit of the sampled signal, that is, used to quantify the entity of the background noise in order to then be able to filter it, obtaining a clean and valid signal for the subsequent mathematical elaborations.

To estimate the power spectral density (PSD) of the sampled signal in the time domain, the Welch method is adopted, which represents a step forward compared to the classical method based on the Fourier Transform (FFT). Such method is conceived to reduce the noise in the estimation of the PSD and to improve the quality of the analysis, adopting specific expedients in the calculation phase.

The Welch method foresees the subdivision of the temporal signal into a predetermined number of segments, or rather windows, of equal length, each of which partially overlaps the next one. In the implementation of the algorithm in the MATLAB environment, the estimation of the PSD is executed, at least in a preliminary phase, by subdividing the time series of the point velocity data into a number of windows for which each one contain 500 value, with an overlap percentage of the latter of 50%; these values have been defined following a preliminary graphical evaluation, seeking the best compromise, through the observation of the obtained results, between the reduction of the variance and at the same time the maintenance of an adequate resolution of the spectrum.

For each window the Fourier Transform (FFT) is calculated and the PSD estimates obtained for the individual segments are then averaged to obtain a more stable final estimate. This windowing operation allows to gently attenuate the amplitude of the signal towards its extremities, decreasing those that in scientific jargon are identified as the edge effects caused by the fragmentation of the time series. In this way the generation of fictitious frequency components is prevented and the spectral leakage is

minimized, that is a mathematical artifact due to the assumption of infinite periodicity implicit in the calculation of the FFT that in reality cannot be realized.

The estimates obtained for the individual windows are averaged among themselves based on the data overlap defined previously, which allows to obtain a final estimation of the PSD more accurate and less sensitive to the random fluctuations of the signal, guaranteeing the statistical robustness necessary for the calculation purposes.

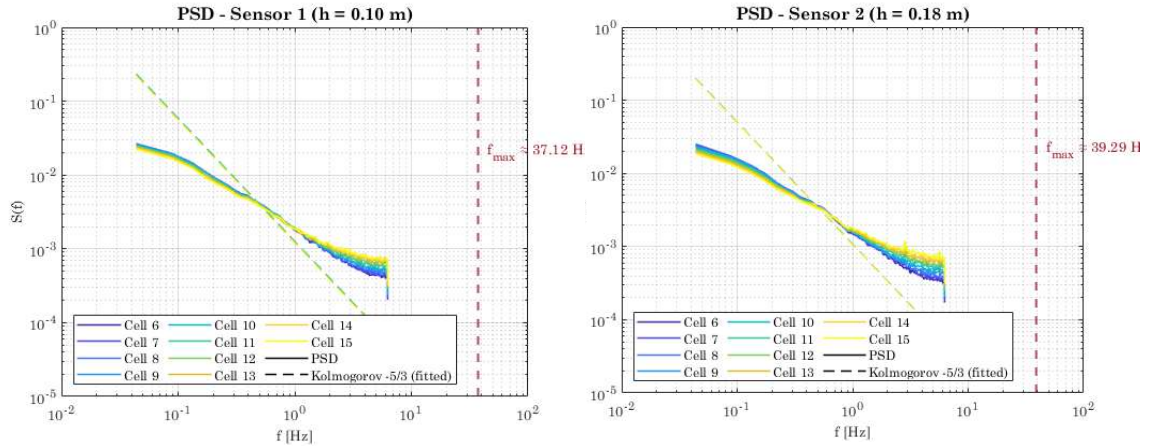


Figure 4.7 – Power Spectral Density (PSD) graphs defined through the implementation of the Welch method for the signals acquired in the Cavo Lucca by Sensor 1 ($h=0.10$ m, left) and by Sensor 2 ($h=0.18$ m, right). The log-log graphs show the PSDs relative to the measurement cells from 6 to 15, excluding the first control volumes in the acoustic beam generated by the two transducers, since the data recorded in them suffer from the phenomenon of transducer ringing. In the two graphs are identified, furthermore, the theoretical decay lines hypothesized by Kolmogorov and the maximum resolvable frequency determined by the minimum spatial limits of the acoustic beam.

Observing the obtained spectra shown in Figure 4.7, one distinguishes the presence of two clearly distinct regions in the frequency domain, denoted with respect to the trend of the calculated PSD. In the region at intermediate frequencies, visually identified in the range $f = 0.1 \div 1-2$ Hz, the experimental curves highlight a linear trend in the log-log plane, clearly identifiable as the theoretical energy decay established by Kolmogorov's law; the values, however, do not align precisely with the line calculated from the theoretical model since the spectrum is probably affected by the presence of noise.

Moving towards the high frequencies, for $f > 2$ Hz, the curves relative to the different cells stop following the slope relative to the energy decay hypothesized by Kolmogorov and show a marked flattening in the graph, which constitutes the horizontal plateau generally assimilable to the presence of background noise in the data recorded by the acoustic profiler. Such divergence from the theoretical trend, identifiable in the

frequency domain, manifests itself as white noise, characterized by a constant energy level that results independent of the frequencies.

The assumption that the instrumental noise identified by the plateau in the energy spectrum is widely demonstrated in the literature and justified by the Wiener-Khintchine Theorem **Errore. L'origine riferimento non è stata trovata.** [XXI]. According to such analytical supposition, the noise originated by the acoustic instrument is linked to a purely random stochastic process, for which there is no temporal correlation between the recorded noise values. This is represented mathematically in the fact that the autocorrelation function can be approximated with the Dirac function, for which a unitary value is obtained for a null time delay while subsequently the function assumes a null value; consequently, the Fourier transform applied to such function thus determined, by definition, returns a constant value that results independent of the frequency value.

For this reason, the analysis of the spectra reported in Figure 4.7 requires the application of a correction linked to the nature of the functioning of the adopted acoustic instrumentation, in order, therefore, to remove the identified background noise. Based on the previously made considerations on the mathematical properties of the signals on the additive assumption of the noise on the energy spectrum, one proceeds by filtering such signal over all frequencies. To this end, the energy level associated with the plateau identified in the high frequency region is determined, estimating the mean value of the spectral density associated with the instrumental noise (PSD_n), implemented in the algorithm based on the identification of the approaching of the slope of the experimental curve to the null value. In this way, such constant value associated with the instrumental disturbance is uniformly subtracted from all frequencies of the spectrum, according to the relation:

$$S_{corr}(f) = \max[S(f) - PSD_n, 0]$$

The imposition of the null value allows to avoid that at the high frequencies the power spectral density values assume negative values in which the real energy calculated with the Welch method results lower than the uncertainty defined by the instrumental noise.

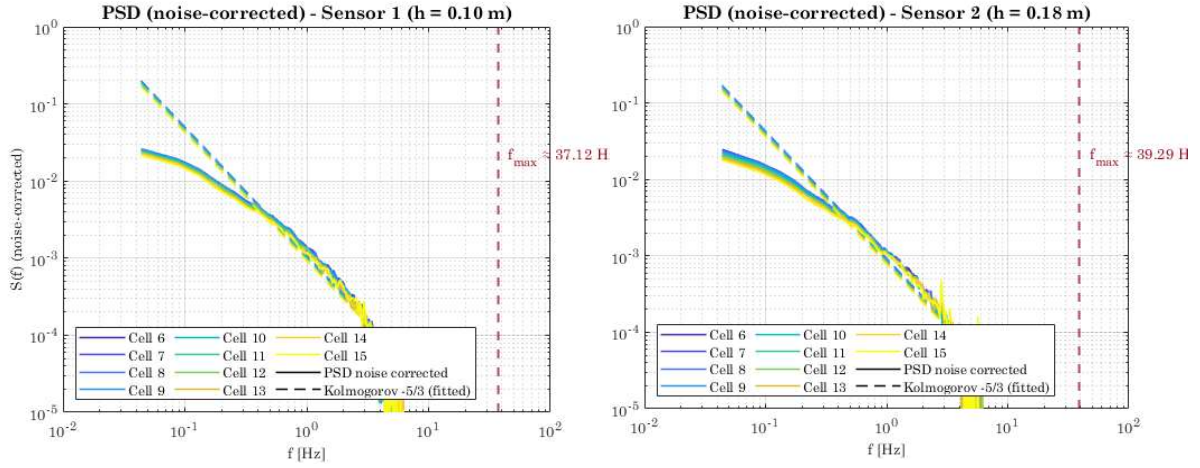


Figure 4.8 – Graphs of Power Spectral Density corrected from the experimentally determined white noise (noise-corrected PSD), justified by the Wiener-Khinchine theorem, for the signals acquired by Sensor 1 ($h = 0.10$ m, on the left) and by Sensor 2 ($h = 0.18$ m, on the right). The graphs, represented in logarithmic scale, illustrate the purified spectra for the measurement cells from 6 to 15 downstream of the analytical subtraction of the instrumental noise. In the two graphs are identified, furthermore, the theoretical decay lines hypothesized by Kolmogorov and the maximum resolvable frequency determined by the minimum spatial limits of the acoustic beam.

Being the PSD values now purified from the background noise, the investigation moves to the spatial domain of the wavenumbers, adopting the mathematical formulations described in the previous theoretical treatment, through Taylor's frozen turbulence hypothesis. From the spectra obtained for all the measurement cells determined in the acoustic beam (Figures 4.9 - 4.10), two distinct regions characteristic of the turbulent flow are clearly identified.

The first of these corresponds to the intermediate range of the wavenumbers, identified in the literature as the inertial range, in which the kinetic energy is transferred from the large scales towards the dissipative scales, denominated as Kolmogorov scales, for which the trend of the theoretical spectrum defines that the energy decay is proportional to $k^{-5/3}$.

The second region is identified in correspondence with the low wavenumbers, that is in the region of the spectrum dominated by the large turbulent structures that are directly responsible for the extraction of the kinetic energy from the mean motion of the flow. These structures, unlike the isotropic behaviour observable at the smaller scales of the spectrum, are anisotropic and their evolution in space is strongly linked to the interaction with the physical boundaries of the channel. According to the literature, and in particular the studies of Townsend (1976) [XIII] and the developments of Perry et al. (1986) **Errore. L'origine riferimento non è stata**

trovata., in flows near the wall at high Reynolds number, there exists an overlap zone of the spectrum where the energy follows a k^{-1} power law. This spectral energy decay at the low wavenumber values constitutes the analytical signature of the large turbulent structures, giving proof of what is explicated in the literature whereby it indicates the presence of coherent structures whose dimension grows scaling with the distance from the bed, testifying to the dynamics with which the velocity gradient along the vertical profile injects energy into the system through increasingly larger vortices.

From the analysis of the results reported in the following figures, a clear separation emerges between the signal processed for the different measurement cells. As previously specified and emerged from the analysis of the data measured in the field, the cells closest to the emission of the beam show an extremely irregular and distorted trend compared to what is expressed by the aforementioned theoretical models. Such discrepancy from the theoretical trends has no significance in physical terms but clearly represents the influence of the acoustic reverberation phenomenon in proximity to the active face of the transducer inserted in the flow. On the contrary, regarding the data acquired in the successive measurement cells, there is full validation of the data, since the regression line overlaps perfectly with the theoretical Kolmogorov slope for both sensors in the inertial region. Also moving towards the lower wavenumbers, the spectra clearly show a change in slope, settling on values comprised between -0.83 and -0.87, highlighting the correct transition towards the large scales of turbulence, which will be subsequently better studied through the employment of the calculation of the pre-multiplied spectra.

Spatial spectrum $S(k)$ - Sensor 1 ($h = 0.10$ [m])

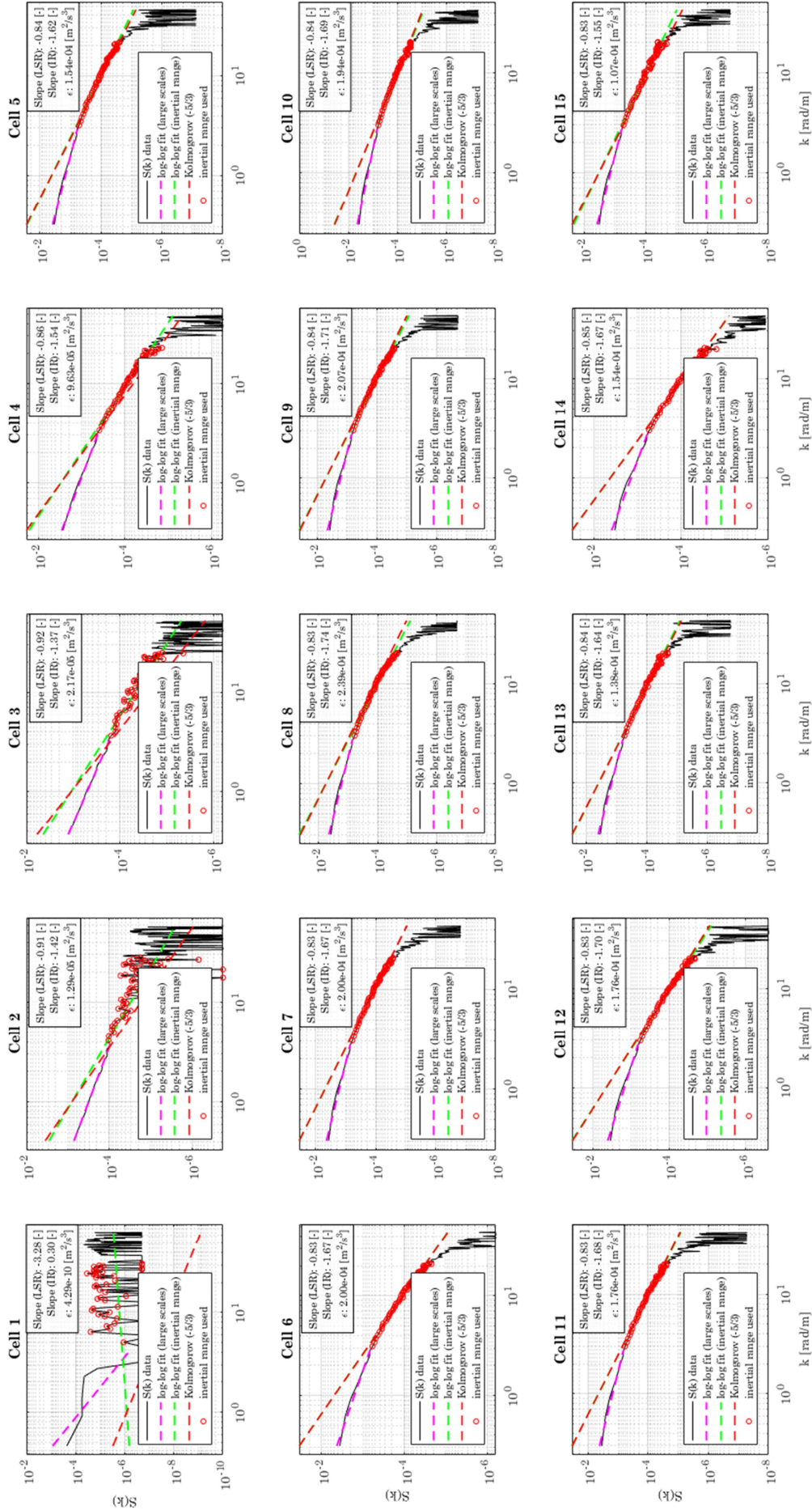


Figure 4.9 — Spatial spectra $S(k)$ defined for the 15 measurement cells relative to Sensor 1 ($h = 0.10$ m). The graphs illustrate the trend of the experimental signal (solid black line) following the subtraction of the instrumental noise. Inside each spectrum are highlighted: the linear regression line calculated for the inertial range (dashed green line) based on the experimental points identified in the intermediate region (red circles), the theoretical energy decay of Kolmogorov (dashed red line) and the interpolation for the Large-Scale Range (dashed magenta line) based on the analytical modelling proposed by Townsend (1976).

Spatial spectrum $S(k)$ - Sensor 2 ($h = 0.18$ [m])

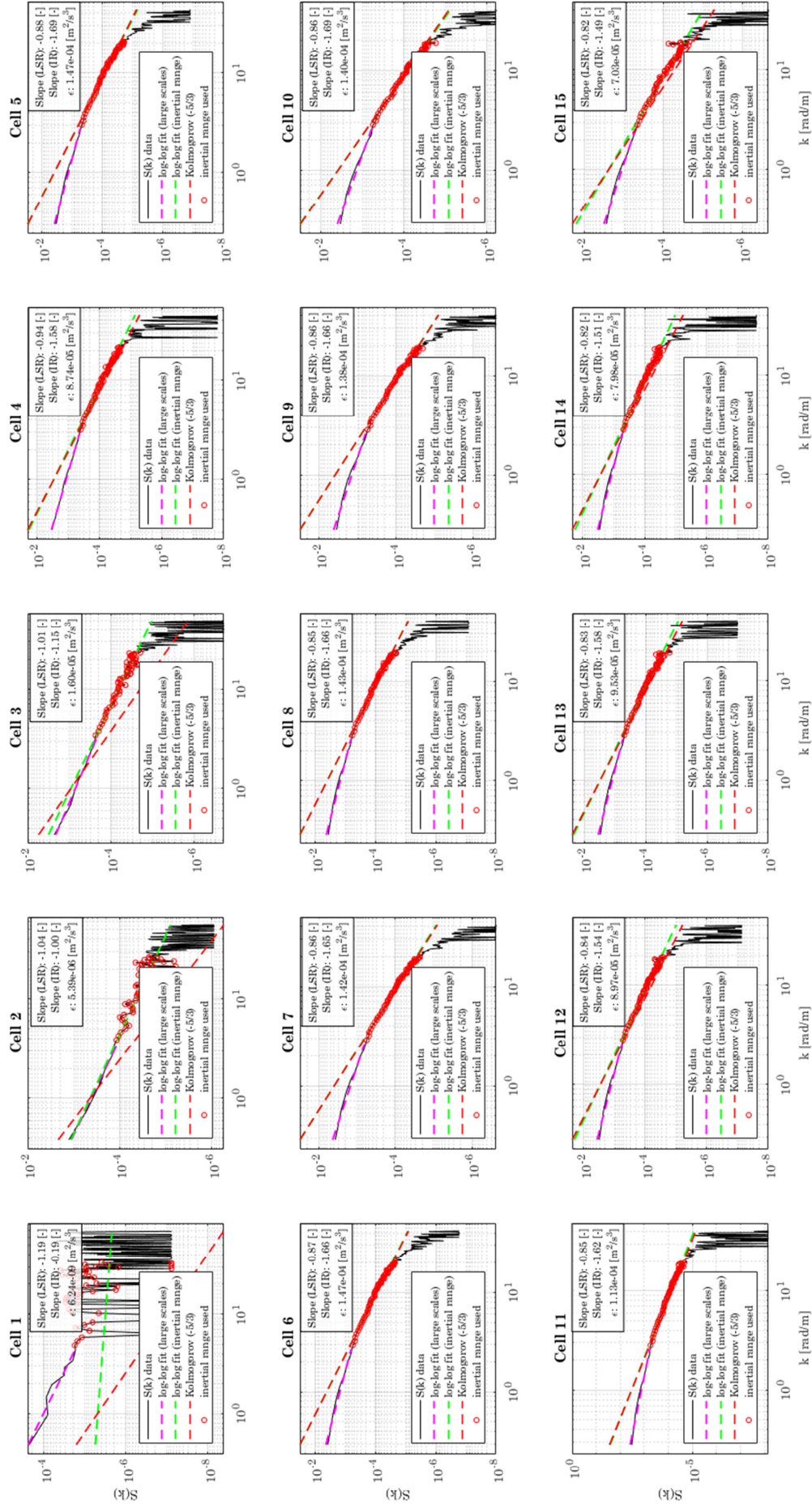


Figure 4.10 – Spatial spectra $S(k)$ defined for the 15 measurement cells relative to Sensor 2 ($h = 0.18$ m). The graphs illustrate the trend of the experimental signal (solid black line) following the subtraction of the instrumental noise. Inside each spectrum are highlighted: the linear regression line calculated for the inertial range (dashed green line) based on the experimental points identified in the intermediate region (red circles), the theoretical energy decay of Kolmogorov (dashed red line) and the interpolation for the Large-Scale Range (dashed magenta line) based on the analytical modelling proposed by Townsend (1976).

4.5 Advanced Spectral Analysis and Multi-Resolution Approach

The energetic characterization of the large turbulent structures requires an investigation tool that allows to identify the effective energy associated with the various scales. In the energy spectrum $S(f)$ just shown, the spectral density tends to diverge upwards as the frequency decreases, masking the real distribution of the turbulent kinetic energy, which does not allow to identify the dominant energetic structures; to this end, one proceeds to the calculation of the pre-multiplied energy spectra ($f \cdot S(f)$).

Let us now recall some theoretical notes for the purpose of the correct interpretation of the results. The integral of the newly calculated spectrum defines the variance of the measured signal, that is the total turbulent kinetic energy; for this reason, adopting the logarithmic abscissa axis ($\ln f$) in order to be able to visualize a wider interval of scales, so that the area subtended by the curve still represents the energy of the flow, the integrand function must be multiplied by the frequency, that is:

$$\int S(f)df = \int f \cdot S(f)d(\ln f)$$

Consequently, representing the pre-multiplied spectrum in the semi-logarithmic plane, the area subtended by the curve coincides with the total turbulent kinetic energy. This approach, generally adopted by the scientific literature, avoids the visual distortions characteristic of the PSD and highlights the energetic peaks of the flow, in order to determine the energetically dominant scales.

However, the application of Welch's method with a fixed number of windows for which $nfft=500$, previously applied, introduces a physical limit when analysing the large-scale turbulent structures, coinciding with the very low frequencies. Such segmentation of the time series of the measured pointwise velocity data heavily limits the spectrum by defining the minimum resolvable frequency, drastically reducing the number of calculated points in the low-frequency region.

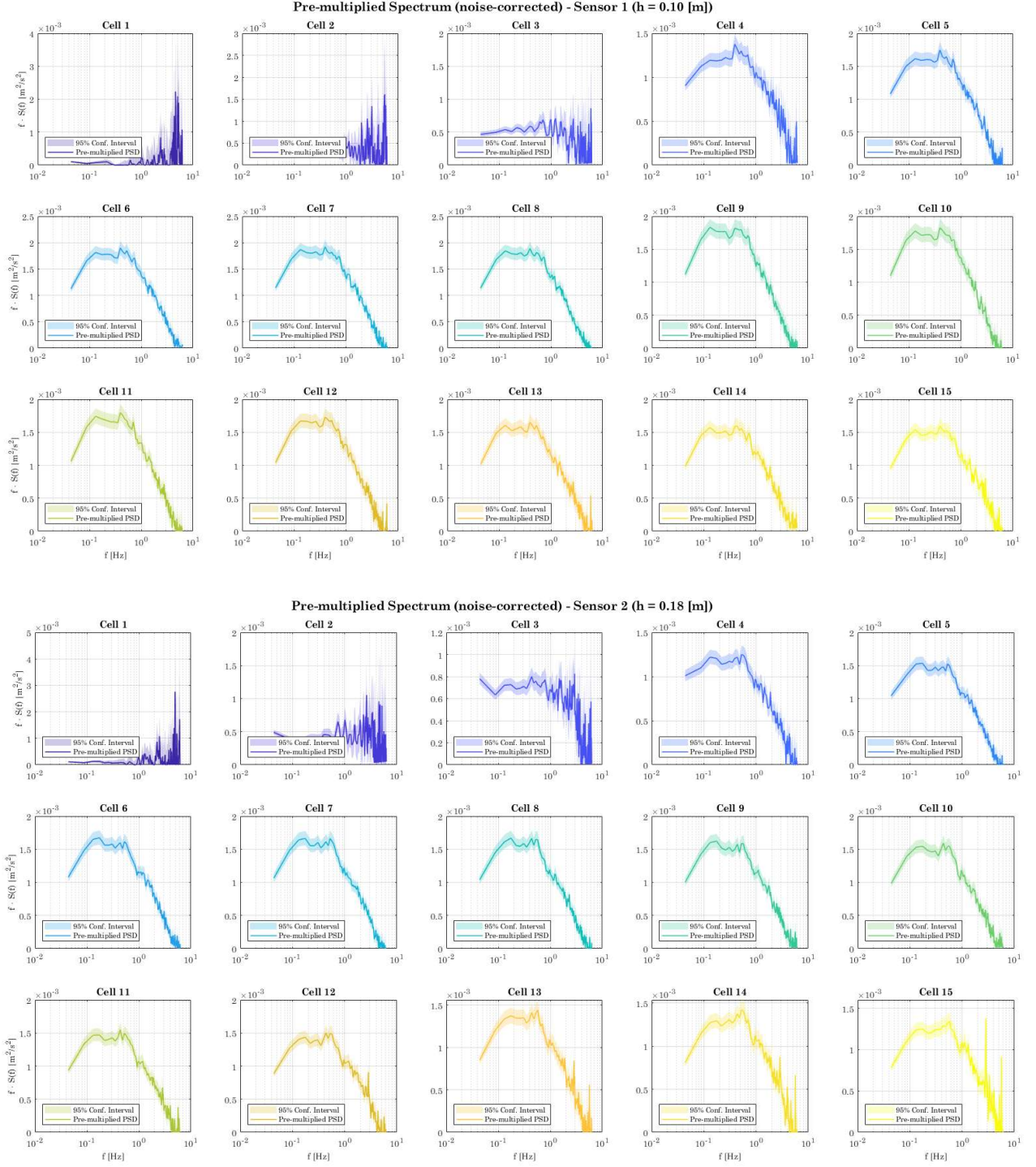


Figure 4.11 – Pre-multiplied energy spectra in the frequency domain for the 15 measurement cells of Sensor 1 (h=0.10 m, top) and of Sensor 2 (h=0.18 m, bottom). For each cell, the trend of the pre-multiplied spectrum is plotted (solid line) together with the respective confidence interval calculated at 95% (light band).

The computational approach previously adopted is therefore not suitable for the identification of the larger turbulent structures that dominate the flow, as it is based on the spectral resolution of windows of fixed temporal length. To overcome this constraint, it is necessary to calculate the FFT over a signal length suitable for identifying the macroscales that compose the studied domain; to obtain this result, without losing resolution capacity and avoiding what are the noise effects produced by the calculation of the simple Fourier Transform, an algorithm based on an adaptive multi-resolution approach was implemented.

This calculation methodology foresees the separation of the frequency domain into two regions, imposing a frequency value equal to 0.5 Hz that separates them, whereby one proceeds to the calculation of the spectrum with Welch's method going to dynamically modulate the length of the analysed time window (T_{win}).

In practice, for the low-frequency values, the algorithm was written with an adaptive logic, whereby the length of the window on which the FFT is applied is modulated and defined for each single frequency, according to the relationship:

$$T_{win}(f) = \frac{n}{f}$$

Where n represents the number of repetitions, that is the minimum number of complete cycles of the wave associated with the specific frequency, for which $n=8$ is assumed.

The length of the window is thus determined by the multiplication with the sampling frequency; through this calculation procedure it is possible to resolve the spectrum even at the very low frequencies, and the imposed number of repetitions results in the right compromise to obtain a good resolution in this region of the frequency domain, reducing the uncertainty associated with the calculation.

For the high-frequency regime ($f > 0.5$ Hz), in which the oscillations are rapid and do not require extended observation intervals, a constant time window equal to 16 [s] was adopted. This methodological setting allows optimizing the calculation procedure by adopting a single operation of spectral vectorization, guaranteeing at the same time a high number of averages and, consequently, an effective reduction of the calculation uncertainty associated with the high frequencies.

In order to correctly interpret the energy spectrum, one must always take into account the uncertainty of the measurements, which is why the statistical calculation of the 95% confidence intervals is integrated into the processing; such calculation exploits the chi-square theory associated with the averages of the data series in each window, estimating the upper and lower uncertainty bands, also purified from the instrumental noise level previously identified, for each frequency and sampling cell of the acoustic instrument. The integration of these spectral bands allows to identify with scientific rigor the real energetic peaks associated with the turbulent structures, separating them from the purely random fluctuations that compose the turbulent motion.

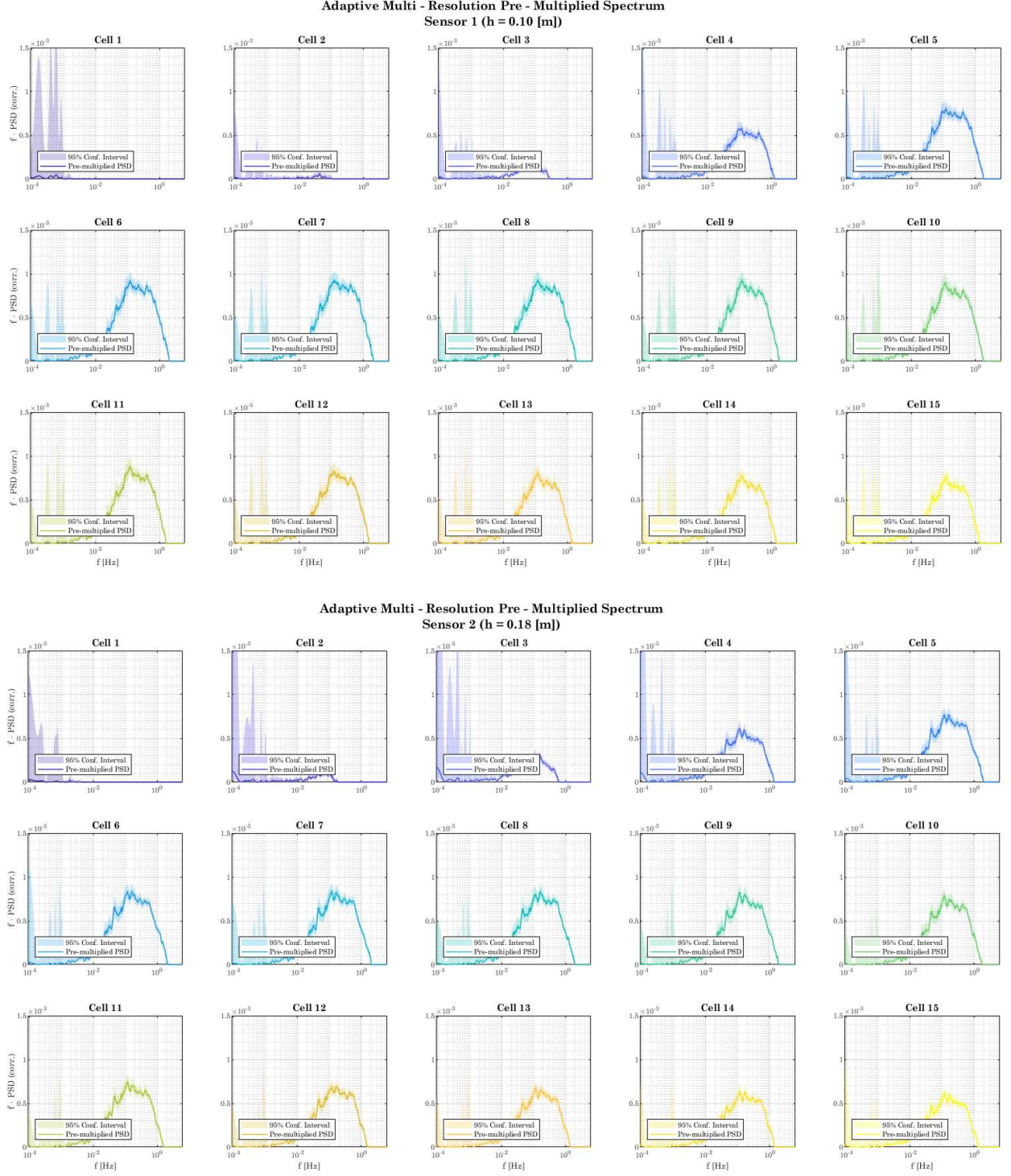


Figure 4.12 — Adaptive Multi-resolution Pre-multiplied energy spectra in the frequency domain for the 15 measurement cells of Sensor 1 ($h=0.10$ m, top) and of Sensor 2 ($h=0.18$ m, bottom). For each cell, the trend of the pre-multiplied spectrum is plotted (solid line) together with the respective confidence interval calculated at 95% (light band).

4.6 Reference Laboratory Data and Instrumentation

The validation of what was observed from the processing of the pointwise velocity data in field conditions is not enough to define the behaviour of the large turbulent structures, but rather it is necessary to understand if these energetic scales characteristic of the motion in a real environment coincide or not with what is observable in a controlled environment, that is in the laboratory. The main objective of this section, therefore, does not consist in the mere validation of the results obtained from the processing of the signals in the field, but rather in a phenomenological comparison of the energy spectra, aimed at evaluating whether the same turbulent structures develop both in the Cavo Lucca and at the laboratory scale.

For the comparison with the laboratory investigation, reference is made to the studies conducted by Perruzzi et al. (2020) [V], as they have already conducted studies on the large turbulent structures in free-surface flows, analysing their behaviour under various hydraulic conditions at the laboratory scale. Specifically, the comparative analysis is focused on the collected dataset identified by the author as "Test 1", for which an aspect ratio equal to 3.05 is identified, that is a condition analogous to the present case study; such analogy is of fundamental importance, since this parameter constitutes the main hydrodynamic condition that governs the development and the spatial confinement of the VLSMs.

In order to fully understand the results obtained in the energy spectra determined by Perruzzi and to be able to interpret the reasons why the results acquired in the Cavo Lucca are analogous or divergent compared to those of the laboratory, it becomes indispensable to analyse in detail the hydrodynamic and experimental execution conditions of the reference literature experiment.

The laboratory measurements were carried out at the hydraulics laboratories of the Polytechnic of Turin, through the use of a large-scale recirculating channel with a flat bed, which implies that the flow is not uniform along the entire track.

The channel used is rectangular, 50 m long and 0.61 m wide, with glass side walls and a bed consisting of smooth concrete blocks positioned along the entire length, for which a Nikuradse equivalent sand roughness of 0.25 mm is estimated. The inlet section, instead, is equipped with a steel ramp and a fine-mesh screen that allows the recirculation of the water.

The horizontal conformation of the bottom defines the conditions of non-uniformity of the flow, therefore it is necessary to carry out the hydrodynamic characterization specifically for each measurement section. In this context, for the reasons defined earlier, the comparative analysis focuses on the data set identified as “Test 1”, whereby the hydrodynamic characteristics of this experimental configuration are reported in the following table.

Table 4.2 – Hydrodynamic and geometric parameters characterizing "Test 1" of the reference experimental campaign (Perruzzi et al., 2020).

Hydraulics condition - TEST 1	
h (cm)	20.0
U_b (m/s)	0.2195
U_τ (m/s)	0.00985
δ_v (μm)	89.3
l^+	9
Re_b	30 150
Re_τ	2 240
Fr	0.157
W/h	3.05
x/h	150
z/W	0.00

The laboratory measurements were conducted employing a Laser Doppler Anemometry (LDA) technology, generally used in controlled environments as it is a non-intrusive type of technology, which does not alter the flow conditions in the slightest, and offers the advantage of having a control volume, from which the useful data are recorded, of almost microscopic dimensions, allowing to record the very small dissipative scales that make up the spectrum.

The instrument employed adopts the use of two pairs of laser beams having different wavelengths for the measurement of the vertical and longitudinal velocity component; in this treatise, we will refer, naturally, only to the longitudinal pointwise velocity data. The intersection of the pair of beams generates a very small control volume, within which a grating of light and dark bands is determined, whereby the passage of the seeding in this microscopic volume backscatters the laser light producing a signal with a frequency dependent on the instantaneous velocity of the particle itself, based on the considerations of the Doppler effect.

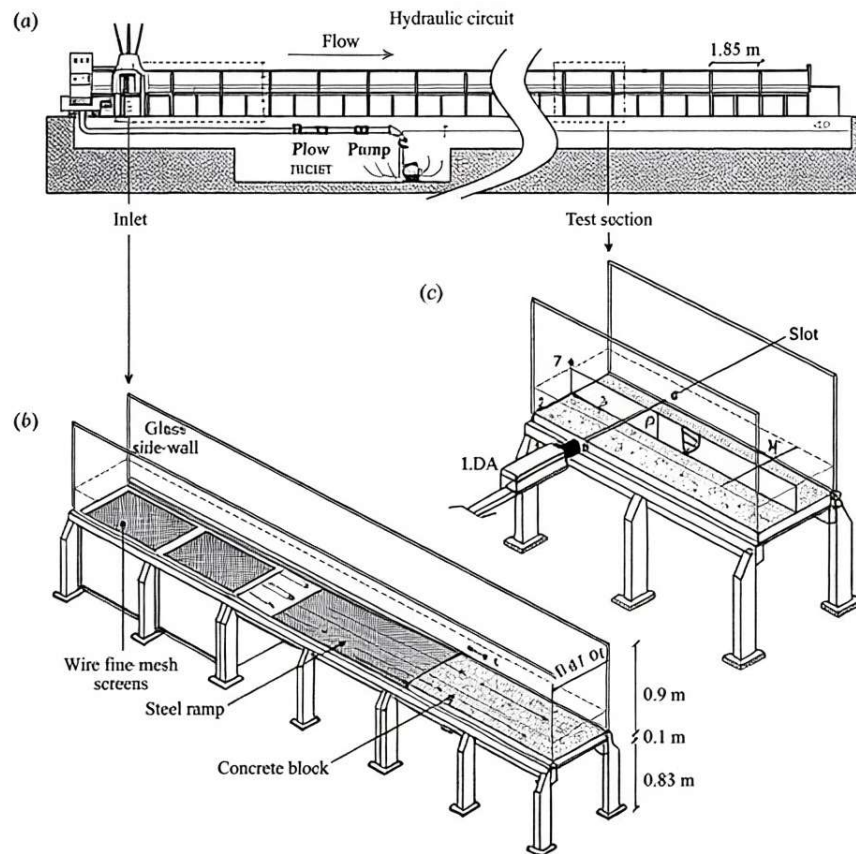


Figure 4.13 – Scheme of the experimental instrumentation employed for the acquisition of the reference data by Perruzzi et al. (2020), in a laboratory environment. (a) Longitudinal view of the entire hydraulic circuit. (b) Detail of the inlet flow conditions. (c) Detail of the measurement section, characterized by glass side walls that allow the non-intrusive implementation and positioning of the Laser Doppler Anemometry (LDA) system. (Source: adapted from Perruzzi et al., 2020).

Before proceeding with the processing of the spectra from the data obtained in controlled conditions and in order to carry out the comparison between these and the spectra obtained from real conditions, there is the need to highlight a fundamental methodological difference in the calculation phase.

This procedural difference arises from the fact that the LDA instrumentation acquires the pointwise velocity signal as a function of the arrival of the seeding particles in the control volume, unlike the UVP instrumentation which guarantees an equally spaced temporal sampling determined by the fixed frequency of emission of the acoustic pulses from the transducers.

The LDA system, therefore, acquires the velocity data as a function of the random arrival of the particles inside the measurement volume, whereby it returns a time series of the velocity values sampled non-uniformly in time. Consequently, the calculation algorithm, previously described for the processing of the UVP data, for the calculation of the FFT cannot be directly applied to the data obtained in the laboratory, for which a temporal regularization operation of the acquired signal is required.

To this end, once the average sampling frequency has been calculated (Sensor 1: $F_s(1) = 168.59$ [Hz], Sensor 2: $F_s(2) = 224.91$ [Hz]), one proceeds to the reconstruction of the signal through linear interpolation on a regular temporal grid previously established as a function of this value. Having obtained, therefore, the signal regularized in time, one proceeds to the processing of the spectra with the approach defined previously, through the implementation of the Welch method applied with a multi-resolution approach (see the following figure for results).

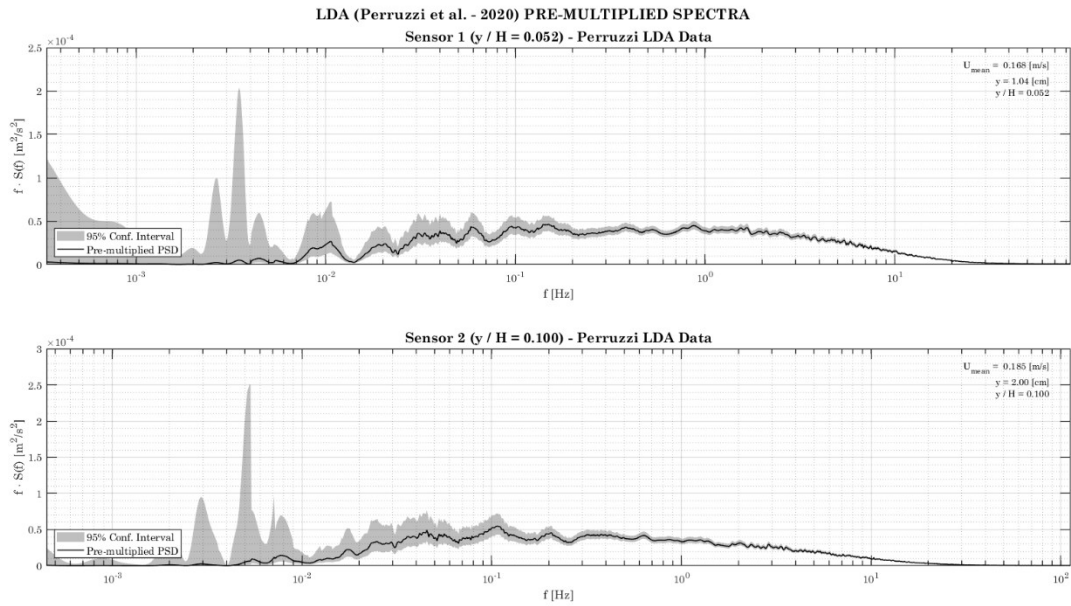


Figure 4.14 – Pre-multiplied energy spectra relative to the longitudinal velocity data acquired with LDA instrumentation (Perruzzi et al., 2020). The upper graph shows the results for Sensor 1, positioned at a dimensionless height from the bed $y/H = 0.052$, while the lower one refers to Sensor 2 at $y/H = 0.100$.

The pre-multiplied spectrum shown in Figure 4.14 clearly shows uncertainty intervals that increase as the frequency decreases, whereby the result at low frequencies cannot be taken as certain data. In the experimental laboratory data acquisition campaign, for each test, samples were extracted in 40-minute time windows, which, although sufficient to guarantee statistical stability for the medium scales and dissipative

structures, results penalizing for the identification of the large turbulent scales. This sampling window introduces excessive statistical uncertainty in the low-frequency region, whereby the trend of the spectral curve does not allow the identification of the largest turbulent structures with absolute certainty.

This limit, however, cannot be overcome by means of other expedients in the calculation procedure as it is constrained by the methodological structure of the measurement campaign itself; for this reason, it becomes necessary to carry out a new measurement campaign under the same conditions, but with sampling times suitable for the correct resolution of the frequencies, relative to the large turbulent structures, identified by the previous spectrum.

To this end, the new measurement campaign was conducted by exactly replicating the hydraulic and geometric conditions previously defined, with a water depth equal to 20 cm and positioning the control volume at a distance of 2 cm from the bottom of the channel ($y/H = 0.100$), for a total duration of the test of 6 hours and 37 seconds. This procedure has allowed to reduce the uncertainty associated with the calculation of the energy spectrum at low frequencies, providing the correct trend over the entire frequency domain, allowing us to obtain an optimal term of comparison to identify the energetic characteristics of the large turbulent structures.

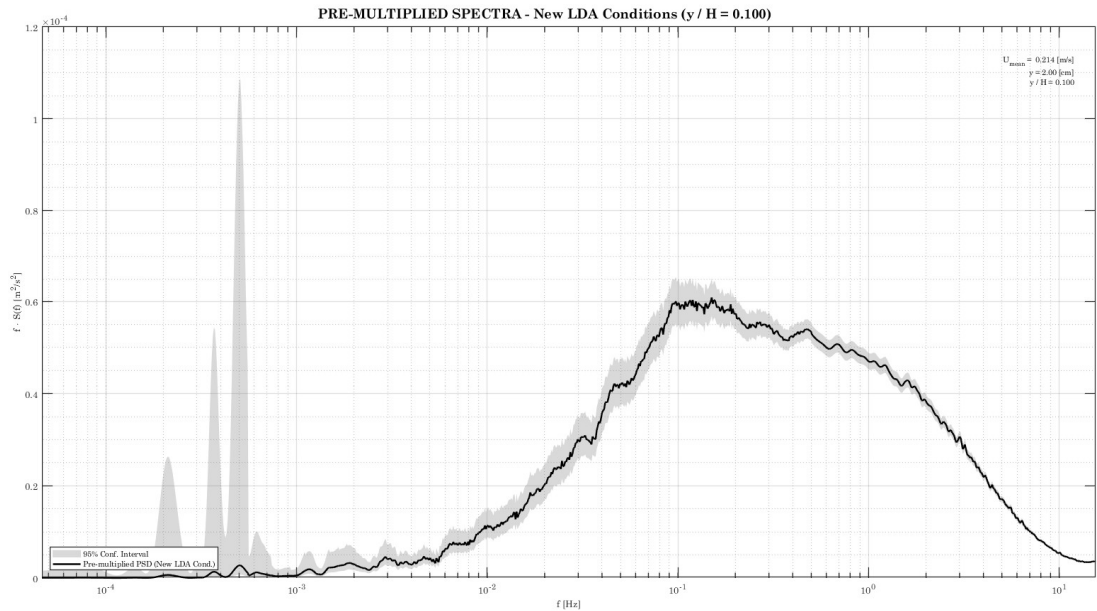


Figure 4.15 — Pre-multiplied energy spectra relative to the longitudinal velocity data acquired using LDA instrumentation in the laboratory during the new, extended experimental campaign. The signal was recorded at a dimensionless height of $y/H=0.100$ for a total duration of 6 hours and 37 seconds.

4.7 Spectral comparison and Identification of Macro-Structures

The concluding phase of the spectral analysis aims to characterize the large-scale turbulent motions by directly comparing the field measurements acquired in the Cavo Lucca with the reference laboratory data. As previously argued, for the purposes of graphical comparison and interpretation of the results, exclusively the spectrum obtained from the new experimental LDA campaign conducted for this research is utilized; it was therefore decided to exclude the data obtained by Perruzzi et al. (2020) [V] since, due to the reduced sampling time windows, the low-frequency region was dominated by excessive statistical uncertainty that would have compromised the reliability of the results in the identification phase of the large turbulent structures.

To ensure a rigorous comparison between two hydrodynamic systems characterized by different levels of turbulent kinetic energy, dictated by the different flow scales, the energy spectra require an appropriate normalization. By dividing the pre-multiplied spectrum by the total variance of the respective signal, the effect of the absolute energetic magnitude is eliminated, forcing the area under the curves to be exactly unitary. This scaling operation transforms the spectrum into a true probability density function, allowing the exclusive and one-to-one evaluation of the turbulence morphology, namely the percentage fraction of energy carried by each spatial scale independently of the total flow magnitude. For the acoustic field data, this normalization is performed with respect to the variance of the true turbulent fluctuations ($\sigma_{u,\text{clean}}^2$), calculated by systematically subtracting the estimated white noise variance from the raw signal variance ($\sigma_{u,\text{clean}}^2 = \sigma_{u,\text{raw}}^2 - \sigma_{\text{noise}}^2$), thus guaranteeing strict compliance with the energy balances.

Before proceeding with the physical interpretation of the structures, it is mandatory to validate the robustness of the identified spectral peaks against the intrinsic instrumental noise characterizing the UVP profiler. Figure 4.16 illustrates a sensitivity analysis conducted on a representative measurement volume, identified in Cell 6. The choice of this specific cell derives from its excellent acquisition quality: presenting the highest Signal-to-Noise Ratio (SNR) of the entire profile, it constitutes the intrinsically most reliable measurement of the dataset. The spectral behavior is therefore evaluated following the subtraction of different noise variance thresholds, ranging between 3.00×10^{-4} and $4.00 \times 10^{-4} \text{ m}^2/\text{s}^2$. These limit values were visually extrapolated from the analysis of the previously plotted Power Spectral Density (PSD), identifying the upper and lower extremes of the high-frequency plateau associated with white noise. This interval effectively defines the operational margin of uncertainty in the computation of the corrected spectra.

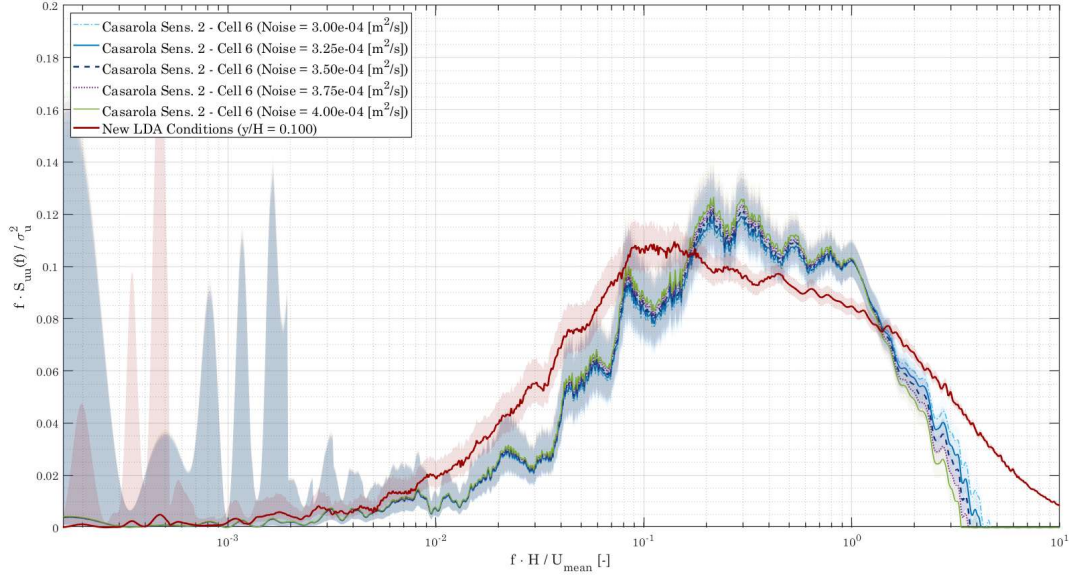


Figure 4.16 – Sensitivity analysis of the variance-normalized pre-multiplied energy spectrum in outer scaling with respect to instrumental noise subtraction. The data refer to Cell 6 (Sensor 2, $y/H=0.105$). The different curves (in shades of light blue) illustrate the spectral behaviour as the subtracted noise threshold varies (from 3.00×10^{-4} to $4.00 \times 10^{-4} \text{ m}^2/\text{s}^2$). In red is reported the reference curve acquired in the laboratory using LDA technology ($y/H=0.100$).

The sensitivity analysis leads to two fundamental conclusions. Firstly, in the low-frequency region ($f \cdot H/U_{mean} < 10^{-1}$), the spectral curves are strictly invariant with respect to the magnitude of the subtracted noise. This insensitivity unequivocally demonstrates that the dominant energetic peaks observed in this region are real physical entities, representative of the turbulent macro-structures, and not instrumental artifacts. Secondly, observing the high-frequency tail ($f \cdot H/U_{mean} > 1$), a physiological divergence emerges between the field data and the LDA reference curve. Although the UVP instrumentation operates with sampling frequencies amply sufficient to investigate such spectral region, the corrected spectra undergo an abrupt decay, vanishing for normalized frequency values close to $3 \div 4$. Such discrepancy is the direct consequence of the different Signal-to-Noise Ratio that characterizes the two technologies. In the high-frequency dissipative regime, the kinetic energy of the small eddies drastically reduces, ending up being entirely masked by the background acoustic noise typical of the Doppler acoustic profiler; the mathematical operation of subtracting the nominal noise level therefore nullifies the residual signal. Conversely, the laser technology (LDA) is characterized by a background noise orders of magnitude lower, guaranteeing a sufficient SNR to track the energy cascade down to the micro-scales.

This evidence confirms that the UVP instrumentation in the field is highly reliable and energetically accurate for the complete resolution of the macro-structures, while for the investigation of the dissipative microscopic scales the limit of investigation is dictated solely by the natural noise threshold of the acoustic transducer.

Having validated the physical consistency of the spectral curves, the analysis proceeds with the direct comparison between the variance-normalized spectra obtained from the extended laboratory LDA campaign and the field data. For the latter, the investigation focuses exclusively on the measurement volume comprised between Cell 6 and Cell 9, located in the inner region of the flow ($y/H \approx 0.105$). The selection of this specific spatial interval is not random, but rather dictated by stringent reliability criteria of the acoustic signal. The first cells of the profile are indeed markedly affected by the ringing phenomenon, namely the interference linked to the oscillation transient of the piezoelectric transducer; conversely, proceeding beyond the ninth cell, a progressive attenuation of the return echo is observed, attributable to the natural energetic dispersion of the ultrasonic beam. Consequently, the range comprised between cells 6 and 9 isolates the portion of the profile characterized by the maximum stability and fidelity of the data.

In order to objectively compare the dimensions of the turbulent structures developed in two hydrodynamic systems of intrinsically different scales, an appropriate normalization of the abscissa domain — outer scaling — is carried out. Since it is physically unavoidable that a larger-scale flow generates, in absolute terms, proportionally more extensive macro-structures, a simple comparison of absolute frequencies or wavelengths would be completely misleading. Using the flow depth as the reference length scale and the local mean velocity for the necessary spatio-temporal conversion, the size of the eddies is non-dimensionalized, expressing it in purely relative terms with respect to the depth of the current. This procedure allows for the understanding of the true proportion of such structures with respect to the flow geometry, guaranteeing a rigorous morphological and phenomenological comparison between the laboratory model and the real environment, completely independent of their absolute dimensions.

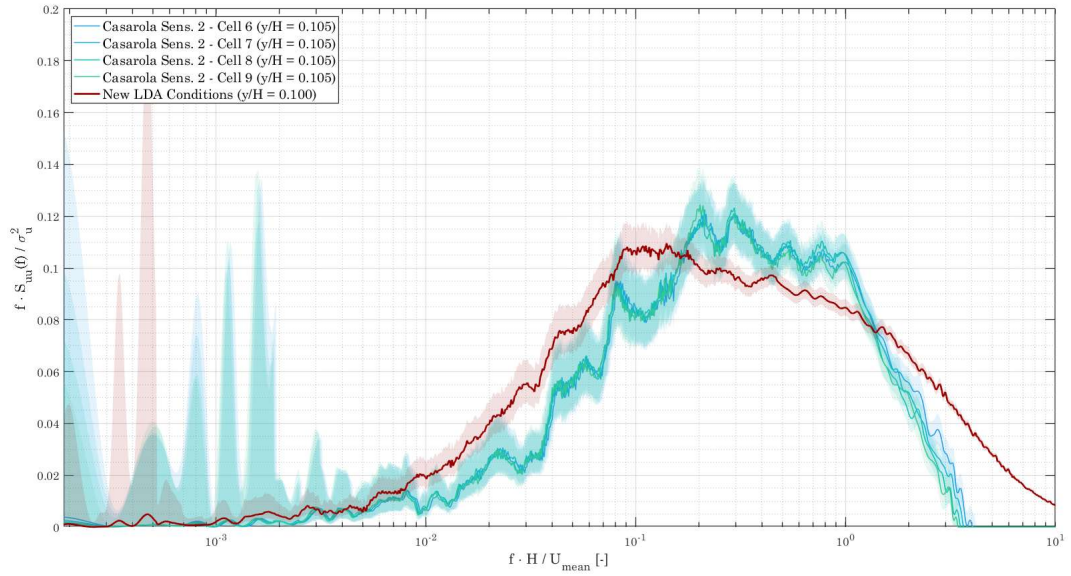


Figure 4.17 – Comparison of the variance-normalized pre-multiplied energy spectra in the non-dimensionalized frequency domain in outer scaling. The field data acquired via UVP acoustic profiler, relating to the measurement volume comprised between Cells 6 and 9 ($y/H=0.105$, shades of blue), are superimposed on the reference curve obtained in the laboratory via LDA technology ($y/H=0.100$, red line).

As illustrated in Figure 4.17, the graphical superimposition highlights a marked divergence precisely in the region characteristic of large-scale turbulent structures. Specifically, the dominant energetic peak relative to the ideal laboratory condition resides at lower normalized frequencies compared to what was recorded by the acoustic profilers in the field. Such a spectral shift to the left evidently suggests the presence of intrinsically more extensive and spatially persistent turbulent structures within the controlled flume compared to those that actually manage to develop in the real environment.

To fully understand the physical dimensions of these energy-containing eddies, the transition from the temporal to the spatial domain becomes necessary, as explained in the previous paragraphs. As illustrated in Figure 4.18, the pre-multiplied and normalized spectra are consequently plotted as a function of the dimensionless wavelength (λ_x/H). This specific spatial representation, which is based on the principles of outer scaling, adopts the flow depth as the geometric reference parameter: in this way, the analysis is decoupled from the absolute physical dimensions of the channel, allowing to directly and unequivocally quantify the proportion and the relative spatial footprint of such macro-structures with respect to the overall depth of the current.

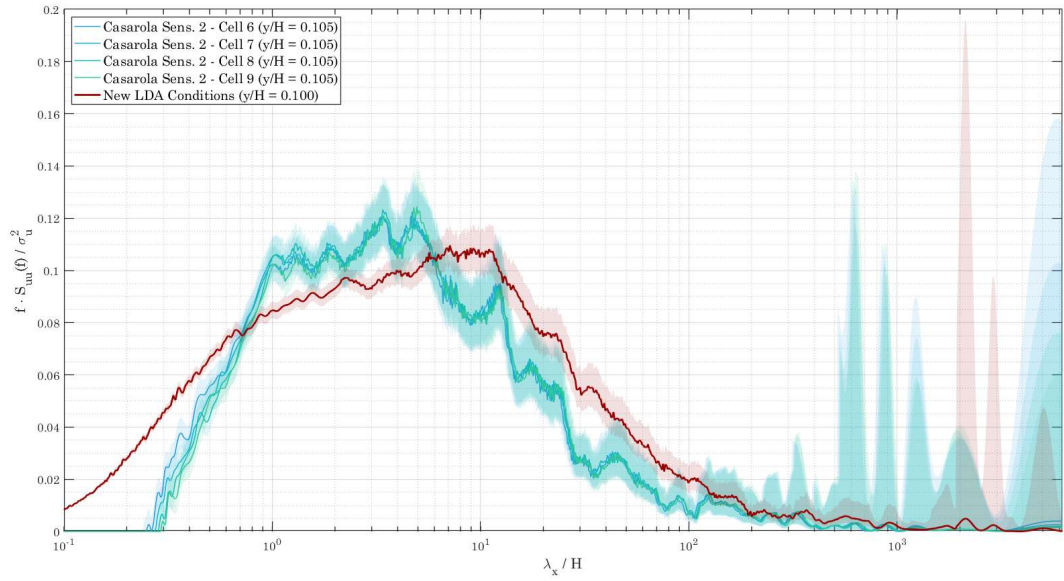


Figure 4.18 – Comparison of the variance-normalized pre-multiplied energy spectra in the spatial domain, plotted as a function of the longitudinal wavelength non-dimensionalized in outer scaling. The field data acquired via UVP profiler (Sensor 2, cells from 6 to 9, shades of blue) are compared with the reference measurements obtained in the laboratory via LDA (red line).

The adoption of such spatial representation allows the objective identification of the macro-structures governing the flow dynamics. Specifically, the laboratory measurements (red line) exhibit an absolute energetic maximum centred around $\lambda_x/H \approx 10$. In the context of free-surface flows, this notable spatial coherence constitutes the unequivocal signature of Very Large-Scale Motions (VLSM). Such macro-structures originate from the fluid dynamic mechanism of longitudinal concatenation of primary eddies; in the specific hydrodynamic setup reproduced in the laboratory flume, such spatial alignment process is clearly prevalent, allowing the turbulent kinetic energy to accumulate massively on scales of the order of ten times the flow depth.

Conversely, the field measurements acquired in the Cavo Lucca (light blue lines) highlight a substantially different energetic distribution. The dominant spectral peak results in this case shifted to shorter spatial scales, localizing at $\lambda_x/H \approx 5$. This dimensionless value coincides with the theoretical definition of Large-Scale Motions (LSM), namely the turbulent structures whose extension scales in a directly proportional manner with the flow depth.

From the phenomenological comparison between the two environments, a clear shift of the energetic centre of gravity evidently emerges: under field conditions, the turbulent kinetic energy migrates towards lower wavelengths compared to the

laboratory case. Nevertheless, the spectra relative to the Cavo Lucca highlight a secondary and clearly distinguishable energetic peak in the region corresponding to $\lambda_x/H > 10$. This experimental evidence objectively demonstrates that VLSMs actually populate the boundary layer of the real free-surface flow as well, although their energetic footprint results subordinate and strongly mitigated compared to the ideal case.

Consequently, a lack of universal collapse is observed between the spectra measured in the laboratory and those characteristic of the real environment. Under the operating conditions of the Cavo Lucca, the energy remains predominantly confined within the LSM motions, which assume to all intents and purposes the role of dominant structures of the flow. The inhibition of the massive development of VLSMs in this natural context results particularly interesting if analyzed in light of the friction Reynolds number (Re_τ). The canonical literature on smooth-wall flows typically associates an increase in Re_τ with a greater scale separation, which guarantees a wider physical space for the genesis and concatenation of the macro-structures. The experimental field data show however an opposite behaviour, with a clear mitigation of the VLSMs. This evidence demonstrates that in the Cavo Lucca the potential spatial development guaranteed by the high Reynolds number is drastically inhibited and overpowered by factors of a morphological and topological nature.

Among the disturbance factors that could have mostly influenced such dynamics, the limited extension of the fetch in the real channel is primarily included: the distance from the first upstream morphological discontinuity is presumably insufficient to guarantee the complete spatial development and the concatenation of the turbulence structures. A further crucial element is represented by the transition of the wall roughness regime. While the reference experimental data are placed in a hydrodynamically smooth regime ($k_s = 0.25$ mm), the field section operates in a transitional regime ($k_s = 1.45$ mm). The increase in the bottom macro-roughness destructively interferes with the near-wall turbulent interaction mechanisms, fragmenting the primary eddies and hindering their constructive process (bottom-up) towards the wider spatial scales.

These elements physiologically concur to the shift of the energetic centre of gravity towards shorter wavelengths. The rigorous parameterization of the joint impact of fetch, roughness, and Reynolds regime on the dynamics of natural macro-structures represents, therefore, an open question of primary importance, which necessitates further and specific future in-depth studies.

5. Conclusion and Future Outlook

A set of experimental velocity data was collected in real free-surface flow conditions at the artificial irrigation channel Cavo Lucca, acquired through the use of an ultrasonic acoustic profiler (UB-Lab P). In order to validate the experimental methodology and evaluate the data quality, the classical single-point statistics were calculated and compared with the literature, confirming the reliability of the signal and demonstrating that the recorded velocity fluctuations were not dominated by background instrumental noise.

The key results of the present work were obtained from the spectral analysis of the velocity time series, calculated in the outer scaling normalized spatial domain to allow the direct identification of the size of the energetically dominant structures. The pre-multiplied energy spectra were compared with a reference dataset, obtained by Laser Doppler Anemometry (LDA) in a laboratory channel characterized by a comparable aspect ratio. The comparison revealed a lack of universal collapse and a substantial phenomenological divergence between the two environments. While the laboratory data showed a massive accumulation of turbulent kinetic energy at wavelengths consistent with Very Large-Scale Motions (VLSM, $\lambda_x/H \approx 10$), the dominant spectral peak obtained from the data measured in the Cavo Lucca resulted clearly shifted towards shorter spatial scales ($\lambda_x/H \approx 5$), coinciding with the signature of the LSMs. Although the observation of a secondary peak confirmed the presence of the VLSM even in the real free-surface flow, their energetic footprint resulted strongly mitigated compared to the laboratory case.

This inhibition of the energetic footprint of the VLSMs in the real context is particularly interesting by virtue of the fully developed turbulence regime that characterizes the flow. Such a condition is evidenced by a friction Reynolds number ($Re_\tau = 38000$) of over an order of magnitude higher compared to the laboratory case ($Re_\tau = 2240$). At the moment, the exact causes of this mitigation of the energy possessed by the VLSMs in field conditions cannot be uniquely established and constitute an open scientific question. Among the possible disturbing factors hypothesized in the first analysis, which could have influenced such dynamics, are included the limited extension of the undisturbed straight upstream reach (fetch), potentially insufficient to guarantee the complete development and longitudinal concatenation of the turbulent structures, and the transitional roughness regime of the real channel wall. The increase of the bottom roughness could in fact negatively interfere with the near-wall interaction mechanisms, fragmenting the primary vortices before they can effectively align on wider spatial scales. However, the rigorous quantification and parameterization of the impact of the fetch, the roughness and the Reynolds regime on the dynamics of the macro-structures in real condition remain open questions, which require further and specific future investigations.

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