14th International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering
Kobe, Japan (23.-25. October 2023)

Ultrasonic sediment flux profiling with ACVP Technology: application to sediment-laden Boundary Layer flows

David Hurther[1], and Giovanni De Cesare[2]

[1] Lab. of Geophysical and Industrial Flows (LEGI), University Grenoble Alpes, CNRS, Grenoble-INP, 1009 rue de la Piscine, 38041 Grenoble
[2] Ecole Polytechnique Fédérale de Lausanne (EPFL), Platform of Hydraulic Constructions (PL-LCH), Station 18, CH-1015 Lausanne, Switzerland

Sediment transport in geophysical boundary layer flows has relevance to a broad spectrum of sciences ranging from the physical and chemical, to the biological, ecological and geological. Advances in sediment transport modelling and prediction strongly suffer from lack of space and time-resolved sediment flux measurements due to sediment induced flow opacity hindering the utilization of standard optical flow measurement tools known as LDV, LDA, PIV or PTV technologies. This lack of high-resolution measurements in sediment transport flows strongly limits the identification and quantification of the key boundary layer interaction processes between the (generally highly turbulent) fluid phase, the entrained sediment phase and the underlying flow bed, commonly defined as the dynamic sediment transport process triad [1]. The first part of this study describes the basic measurements principles and methods of (a) ultrasound 1D-2C/3C Doppler velocity profiling, (b) ultrasound spectrometry for sediment concentration profiling. The combination of these two methods into the multi-frequency measurement system as the Acoustic Concentration & Velocity Profiler (ACVP) technology, provides time-resolved profiles of multi-component sediment fluxes across both the suspension and bedload layers at rates resolving small turbulent flow scales. Its application to mean and time-resolved flow quantity measurements is shown in sediment-laden open-channel flow experiments carried out in the LEGI tilting flume facility. Measurement uncertainty in net sediment transport rate is quantified over a wide range of open-channel flow conditions for two sediment sizes.

Keywords: Ultrasound Doppler, Ultrasound spectrometry, Sediment transport, Sediment flux profiling, ACVP

1. Introduction

Reliable predictions of sediment transport flow rate defined as the flow cross-section averaged product of sediment velocity and concentration, remains nowadays a scientific complex and challenging modelling task, particularly for flows in climatic energetic conditions such as during river floods. Concerning the flow velocity modelling, there is still debate on the universality of the value of the von Karman constant κ. [2] argued that the universal value ($\kappa = 0.41$) provides good results, if the wake coefficient due to free-surface flow effects is properly evaluated. However, its reduction in sediment-laden flows has been reported in early studies [3] and more recently based on experimental [4, 5] and numerical evidence [6]. Another challenge concerns the modelling and prediction of sediment concentration profile. Although the Rouse profile for the suspended sediments is a physical process based model, it is often subject to parameter tuning such as for the turbulent Schmidt number value as the ratio between sediment and momentum diffusivities [2].

With the aim of addressing these questions, this study describes a new dataset of sediment transport experiments with two sizes of inertial sediments using the Acoustic Concentration & Velocity Profiling (ACVP) technology as the main flow measurement tool. How sediment flux profiles and net sediment transport rates are measured with this ultrasonic measurement tool is reviewed [7, 8, 9, 16]. Measurement performance is first shown in a mobile bed open-channel flow experiment carrying sediments in the sheet flow regime [4, 5]. Mean and time-resolved profile measurements are presented and discussed revealing the ACVP's potential for in-depth studies of turbulent particle transport processes in energetic boundary layer flows. Second, the accuracy in sediment transport rate measurement is evaluated over a wide range of sediment-laden flow conditions. For this purpose, new experiments and the one of [10] are used covering three hydraulic conditions (low, medium and high bed friction velocity) with two sediment sizes (3mm and 1mm). Conclusions on the potential of ultrasound flow measurements in sediment-laden boundary layer flows are given.

2. Ultrasonic sediment flux profiling

Sediment flux measurement consists in the simultaneous time-resolved profiling along the streamwise normal flow axis (usually defined as the vertical z-axis direction) of co-located particle velocity and sediment mass (or volume) concentration at a spatio-temporal rate resolving the turbulent flow scales. Standard optical (image and Laser) velocimetry tools known as PIV, PTV, LDA, LDV are not adapted to energetic sediment-laden water flows because of the particle-induced flow opacity. Ultrasonic flow measurements transmitting short acoustic pulses in the MHz frequency range are much better suited to dense sediment-laden flows as long as particle scattering induced attenuation of the pressure signal over the pulse travel-path remains smaller than the magnitude of the flow entering pressure signal.

Co-located profiling of both particle velocity and concentration is still limited worldwide, to very few acoustic measurement systems implementing two technologies in the same instrument: (*i*) the Acoustic Doppler Velocity Profiler (ADVP) technology, for the pulse-coherent Doppler velocity profile measurement. (*ii*) The Acoustic Backscattering System (ABS) technology for sediment size and concentration profiling which applies ultrasonic particle scattering spectrometry [1, 11].

Table 1. Hydraulic parameters

d_p (mm)	w_s (cm/s)	u_* (m/s)	θ (-)	S (-)	Q (m^3/s)	S_0 (-)	U (m/s)	H_f (m)	Re (-)	Fr (-)	Re* (-)	q_s (m^2/s)	C	Experiment type
3	5.59	0.05	0.4	1.1	0.031	0.005	0.53	0.17	0.9×10^5	0.19	375	7×10^{-4}	7×10^{-3}	1 mobile bed run, at full-capacity
3	5.59	0.043	0.33	1.3	0.032	0.0023	0.60	0.15	1.9×10^5	0.49	323	0.0	0.0	8 CW clear-water runs
												6×10^{-5}	5×10^{-4}	3 LOW concentration runs
												2×10^{-4}	2×10^{-3}	3 MED concentration runs
												3×10^{-4}	3×10^{-3}	3 SAT full-capacity runs
3	5.59	0.056	0.56	1.0	0.041	0.0040	0.79	0.15	2.5×10^5	0.65	421	0.0	0.0	8 CW clear-water runs
												7×10^{-5}	6×10^{-4}	3 LOW concentration runs
												2×10^{-4}	2×10^{-3}	3 MED concentration runs
												6×10^{-4}	5×10^{-3}	3 SAT full-capacity runs
3	5.59	0.068	0.81	0.8	0.049	0.0061	0.96	0.15	3.0×10^5	0.80	509	0.0	0.0	8 CW clear-water runs
												9×10^{-5}	6×10^{-4}	3 LOW concentration runs
												3×10^{-4}	2×10^{-3}	3 MED concentration runs
												9×10^{-4}	7×10^{-3}	3 SAT full-capacity runs
1	1.89	0.030	0.48	0.62	0.0186	0.0007	0.37	0.14	1.2×10^5	0.32	105	0.0	0.0	3 CW clear-water runs
												3×10^{-5}	610^{-4}	3 LOW concentration runs
												6×10^{-5}	1×10^{-3}	3 MED concentration runs
												1×10^{-4}	2×10^{-3}	3 SAT full-capacity runs
1	1.89	0.035	0.64	0.54	0.026	0.0016	0.54	0.14	1.7×10^5	0.47	121	0.0	0.0	5 CW clear-water runs
												7×10^{-5}	6×10^{-4}	3 LOW concentration runs
												2×10^{-4}	2×10^{-3}	3 MED concentration runs
												6×10^{-4}	5×10^{-3}	3 SAT full-capacity runs
1	1.89	0.043	0.96	0.44	0.032	0.0023	0.63	0.15	2.0×10^5	0.53	149	0.0	0.0	8 CW clear-water runs
												9×10^{-5}	6×10^{-4}	3 LOW concentration runs
												3×10^{-4}	2×10^{-3}	3 MED concentration runs
												9×10^{-4}	7×10^{-3}	3 SAT full-capacity runs

d_p: sediment median diameter; w_s: still water particle settling velocity; θ: Shields number, S: suspension number; S_0: Slope of the channel; U: bulk mean velocity; H_f: water depth; ν: kinematic viscosity of water; u_*: friction velocity and g is the gravitational acceleration; Re, Fr, Re* are dimensionless bulk Reynolds, Froude, roughness Reynolds numbers; , q_s and C are respectively, the sediment volume transport rate per unit meter flume width and the flow cross-section averaged volume sediment concentration.

The ADVP technology as implemented in the present ACVP system was originally developed by [15] for multi-bistatic velocity profiling at turbulent flow scales.

The first sediment flux profiling system was proposed by [12] as the Acoustic Sediment Flux Profiler (ASFP) followed by the development of the Doppler Profiler (Dopbeam) by [13]. Both systems offered the first direct measurement of time-resolved sediment flux profiles at turbulent flow scales, with different piezo-electrical sensor setups, slightly different vertical resolutions (6mm for the ASFP, 6.9mm for the dopbeam), profiling ranges (40cm for the ASFP, 50cm for the dopbeam), similar temporal resolutions (1/25Hz), different acoustic intensity inversion methods (Least Mean Square compensation method for the ASFP and iterative implicit method for the dopbeam) and the same pulse-coherent Doppler velocimetry method (pulse-pair algorithm of [14]. The most important limitation of both systems concerned the measurable sediment concentration range. For the ASFP and dopbeam systems, a maximal volumetric sediment concentration of 10% and 20%, respectively, could be reached before particle scattering induced attenuation of the acoustic signal hindered reliable concentration estimation. This limitation restricted the application of both instruments to suspended sediment transport studies. Nevertheless, this technology offered unprecedented possibilities in experimental sediment transport research both in fluvial flows and coastal ocean flows.

A considerably improved sediment flux profiling technology was developed by [7] as the Acoustic Concentration & Velocity Profiler (ACVP) technology. Compared to the original ASFP and dopbeam instruments, this system offered increased spatial (1.5mm) and temporal resolutions (1/80Hz) allowing typically the resolution of the Taylor micro-scale in boundary layer open-channel flows with bulk Reynolds numbers up to $0(10^6)$. Furthermore, the instrument's multi-frequency performance was designed to transmit acoustic pulses between 500KHz and 5MHz. This capability allowed the most important measurement improvement compared to the original ASFP and dopbeam instruments, the vertical profiling across both the suspension and the dense bedload layer down to the undisturbed granular flow bed. This required the development of a new dual-frequency inversion method [7] avoiding the data inversion instability encountered with the standard iterative implicit and explicit inversion methods [1]. Furthermore, the implementation of a novel Acoustic Bed Interface Tracking (ABIT) method [8, 9] in the ACVP system permitted for the first time, to decompose the measured total sediment transport rate (as the vertically integrated sediment flux profile) into bedload and suspended load transport rates. These unprecedented sediment transport rate measurement performances initiated the deployment of the ACVP technology in many fluvial and coastal sediment transport process studies.

3. Experimental setup & flow conditions

In the present study, sediment-laden open-channel flow experiments using low density (1192kg/m3) plexiglas (PMMA) particles with median diameters d_p=1mm (dp1) and d_p=3mm (dp3) were carried out in the LEGI tilting flume. The flume is 10m long, 0.35m wide and 0.5m deep.

Two types of experiments were carried out, the first type (first row in Table 1) corresponds to a full capacity sediment transport flow over a thick (15cm) granular flow bed subject to erosion and transport by the overflowing water current. Only dp3 sediments were used for this type of experiments. All other experiments in Table 1 (second to last row) use a standard conveyor belt injection of a sediment load falling into the water flow at 1m downwards the flume inlet. Details of the experimental protocols can be found in [4] and [10].

For all experiments, the flow regime was highly turbulent, hydraulically rough and subcritical (Table 1). To assure the full development of the turbulent shear boundary layer, a honey comb at the flume inlet is used and the test section was placed 7m downwards the flume inlet.

The sediment-injected experiments (2nd to last row in Table 1) are performed in sequences of at least two runs, consisting of one clear-water flow for reference, followed by 1 to 3 sediment-laden flow runs, each with a duration of 300s, to guaranty low statistical bias of the measured mean flow quantities. Three flow conditions for each particle diameter were studied for the sediment-injected experiments. For each forcing condition, one clear-water and three solid transport conditions are investigated. This is repeated three times for experiment repeatability purposes. The full-capacity conditions were defined empirically, when a thin sediment layer was deposited over the flume's rigid bed. The two other transport conditions were fixed as a function of the mean sediment concentration C=qs/Q where qs corresponds to the sediment rate injected by the conveyor belt.

4. Results

Figure 1 shows vertical profiles of mean flow quantitites measured with the ACVP for the mobile bed experiments (first row in Table 1). Figure 1a and the panel below are pictures taken in these energetic sediment-laden open-channel flows. As expected, the sediment concentration is seen to increase with vicinity to the granular flow bed. Figure 1b represents the vertical profile of mean horizontal velocity. The solid black curve reveals the presence of a logarithmic profile shape starting above the top of the bedload layer. Inside the bedload layer, the profile deviates strongly from a log profile and vanishes to zero over a height of about 5 *dp*. The interface between the (dense) bedload layer and the above lying (dilute) suspension layer is defined at the height where the time-averaged sediment concentration profile (Figure 1c) is equal to 8%. Below this height the mean concentration increases rapidly until a fairly constant value around 55% which corresponds well to the typical value of a packed granular bed at rest. Furthermore, the position where this saturation value is reached corresponds well to the height where the flow velocity becomes negligibly low. The black solid curve in the suspension layer corresponds to a best-fitted Rouse profile supporting the turbulent mixing controlled transport of sediments in this layer. Figure 1d shows the

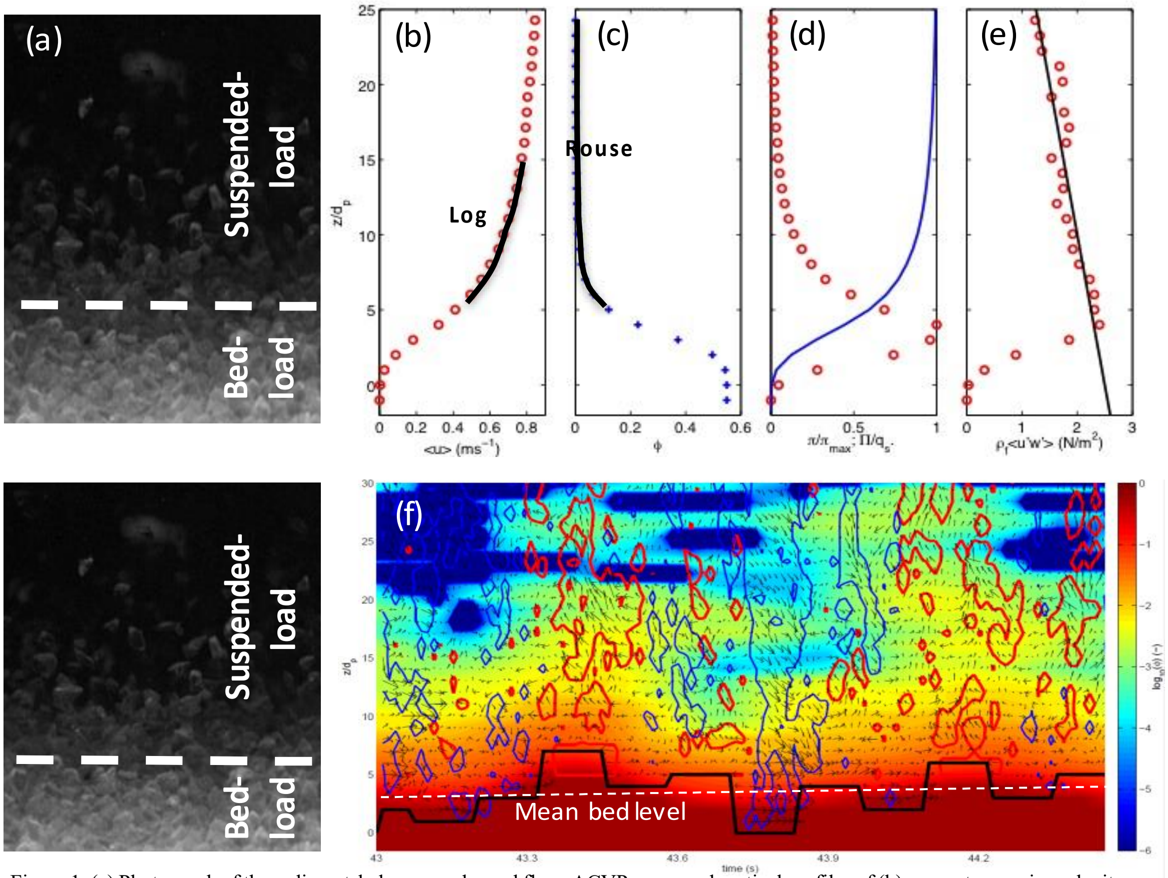

Figure 1: (a) Photograph of the sediment-laden open channel flow. ACVP measured vertical profiles of (b) mean streamwise velocity, (c) mean sediment concentration, (d) mean streamwise sediment flux, (e) mean Reynolds shear stress. Grey zones demarks the bedload layer. (f) Time-resolved sediment concentration colormap, 2C-xz turbulent velocity vector field and coherent flow structures as ejection- and sweep-type events. The black solid and white dashed curves represents the time-resolved and time-averaged flow

horizontal sediment flux as the time-averaged product of time-resolved velocity and sediment concentration profiles. It can be seen that a maximum in sediment flux is found inside the bedload layer. The blue curve in this Figure shows the cumulative transport towards the free-surface. It can be deduced that at the top of the bedload layer, more than 50% of the transported sediment load is reached revealing the dominant contribution of bedload transport for this flow condition (condirmed by the suspension number value S=1.1 in Table 1). Figure 1e represents the vertical profile of mean Reynolds shear stress as the relevant flow quantity for sediment transport. As expected under uniform steady open-channel flow conditions, the profile follows a linear trend with height (solid black curve) in the suspension layer. The maximum value is found inside the bedload layer below its top end. Inside the bedload layer, fluid Reynolds stress gradually decreases towards a zero-value reached at the non-moving granular flow bed. This supports the gradual transfer to grain stresses inside the granular rheology controlled bedload layer.

Time-resolved measurement performances of the ACVP technology is shown in Figure 1f. by the representation of the two-component (xz) turbulent velocity vector field $\boldsymbol{V'}(u'w')$, the sediment concentration colormap and the turbulent coherent flow structures as ejection-type (red contours) and sweep-type (blue contours) flow eddies. Time averaged and time-resolved flow-bed position is represented by the dashed white and solid black lines. It can beseen that sediment entrainment into the suspension layer are associated with turbulent ejection-type flow structures and that bed erosion sequences are due to turbulent sweep-type events. The quality of these high-resolution ACVP measurements open new perspectives in the study of turbulent transport processes in energetic sediment-laden flows.

Figure 2 compares the ACVP measured sediment transport rate to the injected sediment load rate used a ground truth reference values in the sediment-injected experiments. Blue circle and black square symbols represent the dp3 and dp1 data, respectively. Mean relative error over the 27 different experiments are 4.7% and 10% for dp3 and dp1 experiments, respectively.

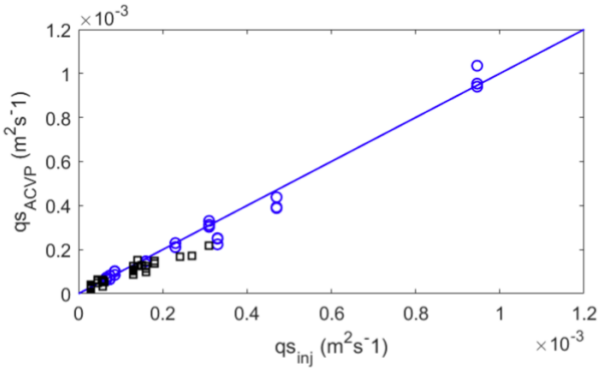

Figure 2: ACVP measured sediment transport flow rate versus flow injected sediment transport rate

5. Conclusion

ACVP profiling performance was shown for mean and time-resolved velocity, Reynolds shear stress, sediment concentration and sediment flux in energetic sediment-laden boundary layer flows generated in gravity-driven tilting flume experiments. Measurement accuracy in sediment transport flow rate was found to remain below 10% over a wide range of sediment-laden open-channel flow conditions. ACVP flow measurement technology offers new potential in process-oriented studies and modelling of sediment transport in highly turbulent flows.

References

[1] Thorne, P. D., & Hanes, D. M. (2002). A review of acoustic measurement of small-scale sediment processes. Continental shelf research.

[2] Cellino, M., and W. H. Graf. (1999). Sediment-Laden Flow in Open-Channels under Noncapacity and Capacity Conditions. J. Hydraul. Eng.

[3] Vanoni, V. A. E. J. 1946 Transportation of suspended sediment by running water. Trans. Am. Soc. Civ. Eng. 111, 67–133.

[4] Revil-Baudard, T., Chauchat, J., Hurther, D. and Barraud, P.-A. (2015). Investigation of sheet-flow processes based on novel acoustic high-resolution velocity and concentration measurements. Journal of Fluid Mechanics.

[5] Revil-Baudard, T., Chauchat, J., Hurther, D. and Eiff, O. (2016). Turbulence modifications induced by the bed mobility in intense sediment laden flows. Journal of Fluid Mechanics.

[6] Cheng, Z., Hsu, T. J., & Chauchat, J. (2018). An Eulerian two-phase model for steady sheet flow using large-eddy simulation methodology. Advances in Water Resources.

[7] Hurther, D., Thorne, P. D., Bricault, M., Lemmin, U., & Barnoud, J. M. (2011). A multi-frequency Acoustic Concentration and Velocity Profiler (ACVP) for boundary layer measurements of fine-scale flow and sediment transport processes. Coastal Engineering.

[8] Hurther, D., & Thorne, P. D. (2011). Suspension and near-bed load sediment transport processes above a migrating, sand-rippled bed under shoaling waves. Journal of Geophysical Research: Oceans.

[9] Fromant, G., Mieras, R. S., Revil-Baudard, T., Puleo, J. A., Hurther, D., & Chauchat, J. (2018). On Bedload and Suspended Load Measurement Performances in Sheet Flows Using Acoustic and Conductivity Profilers. Journal of Geophysical Research: Earth Surface.

[10] Guta, H., Hurther, D., & Chauchat, J. (2022). Bedload and Concentration Effects on Turbulent Suspension Properties in Heavy Particle Sheet Flows. Journal of Hydraulic Engineering.

[11] Thorne, P. D., and Hurther, D. (2014). An overview on the use of backscattered sound for measuring suspended particle size and concentration profiles in non-cohesive inorganic sediment transport studies. Continental Shelf Research.

[12] Shen, C., & Lemmin, U. (1997). A two-dimensional acoustic sediment flux profiler. Measurement Science and Technology, 8(8), 880.

[13] Zedel, L., & Hay, A. E. (1999). A coherent Doppler profiler for high-resolution particle velocimetry in the ocean: Laboratory measurements of turbulence and particle flux. Journal of Atmospheric and Oceanic Technology.

[14] Lhermitte, R., & Serafin, R. (1984). Pulse-to-pulse coherent Doppler sonar signal processing techniques. *Journal of Atmospheric and Oceanic Technology*.

[15] Lemmin, U., & Rolland, T. (1997). Acoustic velocity profiler for laboratory and field studies. Journal of Hydraulic Engineering.

[16] Saugy J.-N., Amini A. and De Cesare G. (2022). Flow structure and grain motion assessments of large river widening in a physical model using ultrasonic Doppler velocity measurements, Experiments in Fluids.