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Suspended Sediment characterization by Multifrequency Acoustics

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Sediment transport, either in natural environment or in sewer systems is of main interest to understand river geomorphology or handle the wastewater regulation and treatment. Knowledge on Suspended Sediment Concentration (SSC) and size distribution leads to a better understanding of sediment transport dynamics. In a wide range of rivers and sewer networks, suspended solids often have a bimodal distribution composed of mineral particles with high diameters and organic matter with smaller sizes. Acoustics methods for the measurement of small-scale sediment processes in water have gained increasing interest over the past decades. Ultrasonic multi-frequency profilers allowing acoustic turbidity profiles measurements at high spatial and temporal resolution which can be linked to the particle presence. The present work will focus on the use of acoustic signals over a wide frequency range to evaluate suspensions with monodispersed sediment distribution and with bimodal distribution of known particle sizes and fractions. Investigations on simple models linking the acoustic signal interpretation and the SSC will be shown, as well as the interpretation of the concentration profile when the granulometric distribution of suspended sediment shows several modes (sand and clay). Results obtained on laboratory test bench will be shown, as well as progress on field measurements.

Keywords: Acoustic, Backscattering, Turbidity, Sediment, Suspended Solids.

1. Introduction

The knowledge of sediment transport characteristics is an important issue in terms of sewer and surface water management. Indeed, the Suspended Solids (SS) transported by the (waste)water are a vector of pollution and they may also be physically damaging [1,2]. A significant sedimentation in structures can lead to progressive silting thereof. Appropriate flow management, in order to limit these phenomena, with high temporal frequency suspended solids data, is needed. Suspended Solids Concentration (SSC) is usually measured either by ad hoc analyzes on samples or continuously by optical turbidity.

Optical turbidity is the most commonly used continuous measurement technology for SSC as well in natural water flows like rivers or in combined sewer systems. Optical turbidity depends on the colour, size and shape of the SS. As widely discussed in [3], optical turbidity can, after adequate calibration, be linearly linked to the SSC. However, it is a point measurement which might not be representative of the whole flow and its sensitivity to biofouling leads to a signal degradation.

Acoustic backscattering or acoustic turbidity is widely used in marine environment and rivers [4]. The use of multi-frequency instruments allows to monitor particle size and concentration. As shown in [5,6] and the references therein, inversion techniques exist and are satisfying in flows with limited particle size and nature. This is unfortunately not the case in rivers and wastewater for which some attempts have been made [7] but no systematic inversion technic exists.

The use of multi-frequency Acoustic Backscattering Systems (ABS) operating at frequencies in the range 0.8 – 8MHz will fit particles in the diameter range 30µm – 300µm. In transceiver mode, the ABS measures the backscattering and the attenuation characteristics of the suspended sediments. The backscattered signal used to estimate concentration depends on the size, the nature and the quantity of particles in the flow. Thus, the concentration estimation is difficult, because of the intertwinement between quantity, shape and density of particles. We will start from the hypothesis that, considering a bimodal distribution with known particle sizes of the fractions, it is possible to determine the proportion of both fractions by the use of acoustic signals over a wide frequency range.

2. Acoustic measurements basics

2.1 Pulsed Measurement Principle

ABS usually works on the pulsed Doppler principle. The emitted signal travels along the beam axis and each encountered particle partly backscatters a part of the acoustic wave. This working principle allows the precise knowledge of the position in the flow of a given backscattered signal amplitude at a given time stamp.

In the same time, due to thermal conduction and viscosity effects, the intensity of the ultrasonic wave propagating in a homogeneous medium decreases. In particle laden flows, an additional attenuation due to the scattering and the absorption by the particles themselves contribute to the intensity decay. This contributes to the decrease of the backscattered signal amplitude.

2.2 Incoherent backscattering

On the theoretical point of view, the recorded root-mean-square voltage of the backscattered signal can be written [8] at range *r* as follows (Tab.1):

$$V_{rms} = \frac{k_s k_t}{r\psi} M^{1/2} e^{-2\alpha r} \quad (1)$$

Where $$k_s = \frac{\langle f \rangle}{(\rho_s \langle a_s \rangle)^{1/2}}$$

$$\alpha = \alpha_w + \alpha_s = \alpha_w + \frac{3}{4\rho_s r} \int_0^r \frac{\chi_m}{\langle a_s \rangle} M(r')dr'$$

Table 1: variables definition

V_{rms}	Average value of root mean square voltage over a large number of backscattered receptions
k_t	Acquisition system constant
ψ	Near field correction
M	Particle concentration
α_w	Water absorption attenuation
α_s	Particle scattering attenuation
χ_m	Normalized total scattering cross-section
k_s	Particle backscattering properties
$<f>$	Particle averaged form function
ρ_s	Particle density
$<a_s>$	Mean particle radius

Thus, the backscattered signal directly includes information about the particles encountered in the explored medium. If the particles in the medium are well known, in terms of shape, size and density, their acoustic characteristics can be determined. If the content of the flow is unknown, only a qualitative interpretation can be made as the relative behaviour of the suspended sediments concentration for example.

The behaviour of the form function and the normalized scattering cross section of a particle is well-described by the variable $x = k<a_s>$, which is the ratio between the particle circumference and the wavelength of ultrasound in water.

For $x \ll 1$, the so-called Rayleigh regime, the wavelength of sound is much larger than the particle circumference and thus the scattering is considered to be independent of the particle shape. Thereby, the Rayleigh scattering description for a sphere can be kept and this implies that $<f>$ varies with x^2 and χ_m with x^4.

For $x \gg 1$, the geometric regime, the wavelength of sound is smaller than the particle circumference, and the scattering cross-section is directly related to the particle's geometry. In this case, for a rigid sphere, $<f>$ and χ_m tend to a constant value of unity. For irregularly shaped particles $<f>$ and χ_m will tend to a constant value slightly larger than unity.

Thus, the form function $<f>$ and the normalized total scattering cross-section χ_m have both high pass filter behaviour, with cut frequency given by:

$$\nu = \frac{c}{2\pi a_{\min}} \quad (2)$$

The particles with smaller radius will have a lower contribution to backscattering.

2.3 Acoustic characteristics extrapolation

Equation (1) can be rewritten under its logarithmic form:

$$\ln(V_{rms} r\psi) = \ln\left(k_t \langle f \rangle \sqrt{\frac{M}{\rho_s \langle a_s \rangle}} \right) - 2r\left(\alpha_w + \frac{3\chi_m M}{4\rho_s \langle a_s \rangle} \right) \quad (3)$$

For a homogeneous suspension (for which the concentration won't vary with the range), this becomes a linear equation in $\ln(Vr\psi)$ and r, and one obtains:

$$\eta = \ln\left(k_t \langle f \rangle \sqrt{\frac{M}{\rho_s \langle a_s \rangle}} \right)$$

$$\kappa = 2(\alpha_w + \alpha_s) = 2\left(\alpha_w + \frac{3\chi_m M}{4\rho_s \langle a_s \rangle} \right)$$

where η and κ are respectively the intercept and the slope obtained from the plot as expressed in equation (3). This allows the characterization of the behaviour of an insonified particle by specifying its form function $<f>$ and its normalized total scattering cross-section χ_m. In this paper we will focus on the χ_m variable, which present the advantage to be independent on instrument gain and bandwidth.

3. Surrogates characteristics

The present study focuses on the acoustical characterization of different suspensions which models the compounds present in flows like river and wastewater, in order to evaluate their concentration and particle size distribution. Glass spheres (Blanpain) of different sizes and potato starch (Sigma-Aldrich) were used. All these components (listed in Tab.2) are calibrated elements supplied by specialized firms.

Table 2: Particle characteristics used in laboratory experiences

particles	Mean radius (μm)	Density (kg/m^3)
Potato starch	24	1470
Glass spheres	49	2600
Glass spheres	69	2600

4. Measurement bench

To determine the acoustical characteristics of the particles, all measurements were performed at room temperature in a 50 L water tank (figure 1). The suspensions of the particles were obtained by continuous stirring with a propeller whose frequency was adjusted to insure homogeneous slurry.

The measurements were performed with an UB-Lab system (Ubertone, France) and several stand-alone transducers allowing measurements at different frequencies growing from 2.2MHz up to 7.5MHz. Care was taken on the pulse repetition frequency adjustment in order to allow the sound from one emission/reception cycle to dissipate before the following cycle. A temperature sensor completes the test-bench in order to compensate the temperature effects.

Figure 1: Water tank and instrumentation

For all the measurements, the following common procedure was applied. The tank was filled with water from the main supply, and the propeller was activated in order to allow the air bubbles to leave the water. This procedure was monitored and lasted until the signals recorded by the instrument reduced to background levels. The particles were then added at concentrations of 0.1g/l and 0.2g/l for mineral matter and 1g/l and 1.5g/l for organic matter. The propeller velocity was adjusted to make sure that all the particles are in suspension. After homogenization of the suspension, a run of six hundred profiles was realized, each one composed of sixty-four samples. This procedure was applied for the nine used ultrasound frequencies.

5. Measurements and analysis

5.1 Laboratory experiences

In a first step a run of measurements was carried out with a single compound. Figure 2 represent a typical recording, here for a suspension of glass spheres with a radius of 49μm. To obtain the information about the total scattering cross section χ_m, the expression in Eq. (3) was used. The figure shows the variation of $\ln(r\psi V)$ as a function of the range r from the transducer, after suppression of the near field.

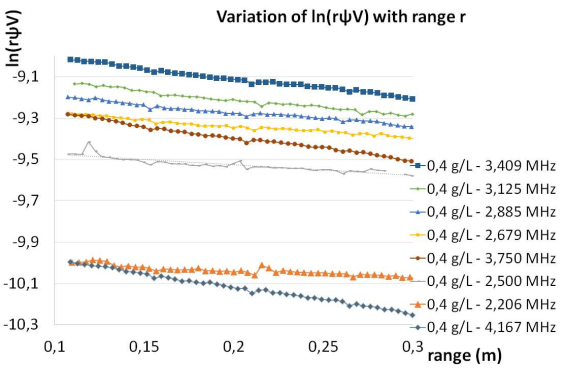

Figure 2: $\ln(r\psi V)$ as a function of range at different frequencies.

The slope of the curves at all frequencies gives the attenuation due to the suspended particles. Considering that the density, the mean size and the concentration for the different suspended materials is well known in our tank, we can evaluate the normalized total scattering cross-section χ_m at the different ultrasound frequencies [9].

5.2 results and discussion

Figure 3 present the theoretical curves of the normalized total scattering cross-section χ_m versus frequency for the potato starch and the glass spheres of radius 49μm [8].

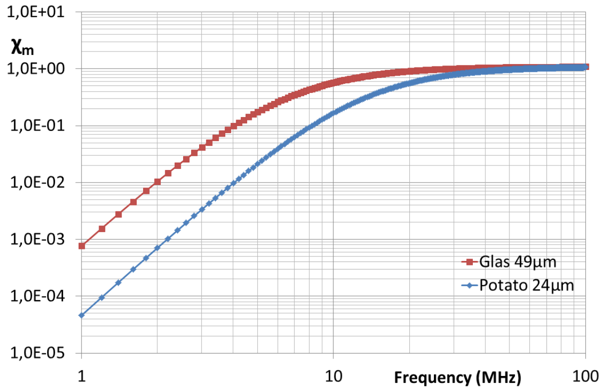

Figure 3: Theoretical χ_m versus frequency.

The frequencies available on the UB-Lab allow only measurements in the Rayleigh regime and in a part of the intermediate regime. Results obtained for very small frequencies (*x<<1*) might have a high degree of uncertainty because in this case the attenuation is mainly due to water. Nevertheless, significant measurements were done on frequencies growing up from 2.2MHz to 7.5MHz.

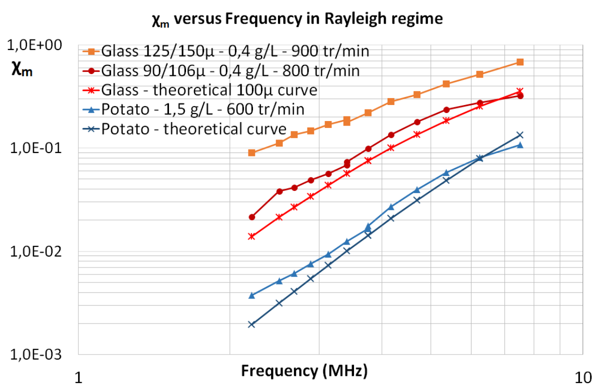

Figure 4: X_m versus frequency for potato starch and glass spheres from two different sizes, comparison with theory

Figure 4 shows the measured normalized total scattering cross-section χ_m as a function of frequency for potato starch and two types of glass spheres. We can observe that the ratio between the values for the mineral particles and the organic one change in a meaningful way when the frequencies increase: at frequencies under 3MHz, the χ_m factor for potato starch is even 20 times smaller as the χ_m factor for glass. At frequencies over 6MHz, this ratio falls to 6.

Preliminary results on a combination between glass and potato particles show a coherent behaviour. At low frequencies the contribution of the potato starch is not significant in the ultrasound measurements. By increasing the frequency, the backscattered signal shows more like a concentration combination of the two components. More investigation has to be done on this subtraction approach, in order to define the selection rules between mineral and organic particles. Nevertheless, these results shows that low frequencies allow to identify mineral particles and higher frequencies are more sensitive to combination of mineral and organic particles. Field measurements presented below shows consistent results.

5.3 Field measurements

The measurements were undertaken in the entry chamber of the wastewater treatment plant of Greater Nancy (250 000 p.e.) from May to November 2014. Its reference flow is 120 000 m3/day and 65% of the wastewater comes from a combined sewer system.

An UB-Flow 315 from Ubertone was mounted on an articulated arm. Therefore, the device was floating on the water surface and looking down at the chamber bottom. Measurements were taken at different frequencies to be sensitive to different particle sizes and compositions. In parallel to the acoustic measurements, optical turbidity was continuously recorded by a turbidimeter (Solitax, Hach Lange) which was mounted on the articulated arm, next to the profiler. According to the weather conditions, specific series of wastewater samples were collected every hour by dry weather and every 15 minutes during a rain event.

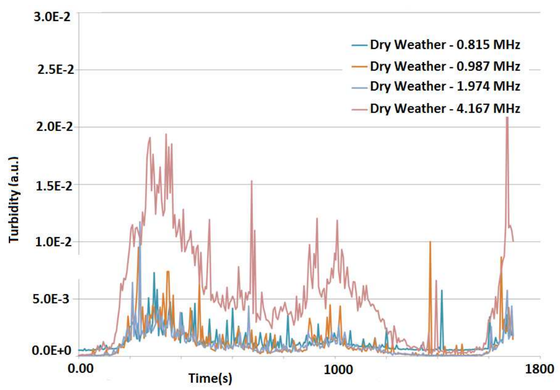

Figure 5: Acoustic turbidity evolution with time and frequency for dry weather.

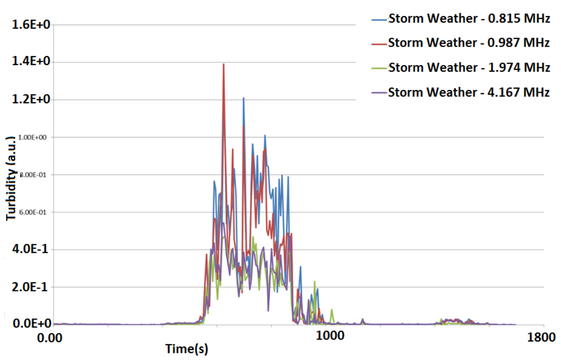

Figure 6: Acoustic turbidity evolution with time and frequency for storm weather.

Figure 5 shows the change in the acoustic turbidity (similar to amplitude but with instrument corrections) versus time at different frequencies for dry weather and figure 6 for a storm event. Whatever the weather, the evolution of the acoustic turbidity is similar at the different frequencies. During dry weather, a maximum intensity is observed for the highest frequency, 4.167 MHz, foreshadowing the preponderance of particles less than 60 microns radius. During storm events, the maximum turbidity is observed for both lower frequencies; this suggests a majority of mineral suspended solids with radius less than 300 microns. Furthermore, the comparison of the turbidity shows that there is a factor of 100 between measurements in dry weather and those in rainy weather.

6. Summary

The present study focused on the scattering properties of suspension of potato starch and glass spheres, and application on field measurements. It is a part of a larger work which includes the evaluation of <f> and χ_m in both Rayleigh and geometric regimes for particles which models the compounds present in flows like river and wastewater. The goal is to classify suspensions in particle sizes and classes by the use of several different ultrasound frequencies.

Measurements carried out in a wastewater flow shows that discrimination between high mineral and smaller organic particles can be operate. This tendency is observed on different measurement sites, and the work presented on this paper must be carry on in order to create a merge between laboratory estimations and field measurements.

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