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Suspended sediment assessment by combining sound attenuation and backscatter measurements – analytical method and experimental validation

Massimo Guerrero*, Vittorio Di Federico

DICAM, University of Bologna, viale Risorgimento 2, Bologna 40136, Italy

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ABSTRACT

The use of acoustic techniques has become common for estimating suspended sediment in water environments. An emitted beam propagates into water producing backscatter and attenuation, which depend on scattering particles concentration and size distribution. Unfortunately, the actual particles size distribution (PSD) may largely affect the accuracy of concentration quantification through the unknown coefficients of backscattering strength, k_s^2, and normalized attenuation, ζ_s. This issue was partially solved by applying the multi-frequency approach. Despite this possibility, a relevant scientific and practical question remains regarding the possibility of using acoustic methods to investigate poorly sorted sediment in the spectrum ranging from clay to fine sand. The aim of this study is to investigate the possibility of combining the measurement of sound attenuation and backscatter to determine ζ_s for the suspended particles and the corresponding concentration. The proposed method is moderately dependent from actual PSD, thus relaxing the need of frequent calibrations to account for changes in k_s^2 and ζ_s coefficients. Laboratory tests were conducted under controlled conditions to validate this measurement technique. With respect to existing approaches, the developed method more accurately estimates the concentration of suspended particles ranging from clay to fine sand and, at the same time, gives an indication on their actual PSD.

1. Introduction

Reliable data regarding suspended sediment in water environment serves a variety of environmental and engineering practices. These include inland navigation (Guerrero et al., 2013a; Paarlberg et al., 2015), sea shoreline protection (Archetti and Romagnoli, 2011; Carniel et al., 2011), erosion hazard mitigation during flood (Elhakeem et al., 2017), irrigation water supply (Guerrero, 2014), habitat and river morphology preservation (Nones and Gerstgraser, 2016; Haimann et al., 2016; Guerrero et al., 2015), and environmental sustainable hydropower development (Guerrero et al., 2016; Felix et al., 2016). The direct sampling of the mixture of water and sediment is a challenging task especially during rough climate conditions, such as storms and waves in the sea and high discharges and rough water-level conditions in a river. In addition, the continuous monitoring of suspended sediment in a fixed position is hardly achievable by means of physical samples because of the time and effort required for sampling and subsequent laboratory analyses. Hence indirect methods for the quantification of suspended sediment have been noticeably improved in the last decades, focusing on acoustic and optical techniques.

As to the acoustic methods, the assumptions made regarding the actual particle size distribution (PSD) of the suspended sediment (Guerrero et al., 2016) eventually enable an accurate inversion of the sonar equation (Thorne and Hurther, 2014). Therefore, the reliability of acoustic methods largely depends on the validity of these assumptions.

Two main approaches exist: the backscatter method and the attenuation method. For the first, the suspended sediment concentration was successfully correlated to the measured backscattering strength (i.e., a logarithmic form of the backscatter) that may be corrected by considering attenuation processes due to suspended particles. Indeed the acoustic backscatter depends in addition on PSD (Guerrero et al., 2016; Thorne and Meral, 2008). This occurrence may undermine the mentioned correlation; however using a multi-frequency approach, the indetermination related to the actual PSD may be solved (Guerrero et al., 2013b; Thorne and Hanes, 2002; Thosteson and Hanes, 1998) to some degree, although this may not be feasible when using few frequencies for poorly sorted sediment (i.e., wide PSD). Even so, the multi-frequency approach was validated for the investigation of suspended sand from riverbed or in the nearshore region.

The second approach (attenuation) is based on scatter attenuation that spreads energy out of the incident beam and the viscous dissipation as result of the friction produced by particles to fluid relative motions.

* Correspondence author.
E-mail address: massimo.guerrero@unibo.it (M. Guerrero).

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This approach was developed for a prevailing attenuation effect due to suspended fine fractions (i.e., clay and silt) which dominates the acoustic beam propagation into a homogenous concentration. In this case, the measured attenuation was correlated to sediment concentration, the backscatter gradient along the beam being negligible. This attenuation method was successfully applied for the monitoring of fine sediment concentration during flood events in rivers (Wright et al., 2010; Moore et al., 2012) by relaying on the fact that suspended sediment are homogenously distributed along horizontal alignments. Unfortunately, the sound attenuation depends on PSD too, which again raises questions on the reliability of acoustic methods when using a single frequency in case of changing PSD during the monitored period, although the ensonified volume may be limited to a region where homogenous concentration is expected, eventually resulting in a "punctual" measurement.

Whatever the method used, the obtained correlations between sediment concentration and measured backscatter and attenuation are site and time specific. For example, the attenuation effect due to clay-silt fractions should be calibrated when trying to correlate sand concentration to single and multi-frequency backscatter. For the attenuation approach, the correlation between attenuation and concentration should be validated in the field that accounts for the actual PSD. These facts may require frequent and dense sampling to keep the assessed calibration validated accounting for PSD change and the actual distribution of concentration along the acoustic beam; this, in turn, makes the use of acoustic methods tricky, interfering with the objective of substituting the physical sampling with indirect methods.

Therefore, despite the recent advancements in acoustic methods for suspended sediment assessment, further research efforts in this area are justified by the objective of improving the reliability of these methods for poorly sorted PSDs, lowering at the same time the need of calibration on the basis of frequent and dense samples. In this regard, this paper reports on the possibility of simultaneously characterizing particles size distribution and concentration by combining attenuation and backscatter measurements. A novel acoustic method significantly reducing the estimation sensitivity to actual PSD is proposed for the estimation of suspended sediment concentration. The method is based on attenuation to backscatter ratio at a single frequency, which straightforwardly defines the acoustic parameter correlating the measured attenuation to sediment concentration for a wide range of PSDs ranging from clay to sand and with changing width (i.e., variable standard deviation). In addition, the ratio of backscatters at two well-spaced frequencies is used to further extend the range of applicability of the method toward wider PSDs. The method exhibits a modest dependence on the actual PSD, therefore providing two benefits, as it (i) lowers the need of case specific calibrations; (ii) offers a reliable estimation of concentration and an indication regarding the size distribution of suspended sediment.

In sum, a combination of theoretical and experimental approaches is proposed to advance the fundamental understanding of the interaction of suspended sediment with ultrasound in water environment. The measure of ultrasound intensity within water is used to indirectly quantify the concentration of suspended sediment, an issue which is relevant in a variety of basic processes and applications regarding water resources. In particular, the method is novel in that the ratio of acoustic attenuation to backscatter is applied for the first time to estimate the sediment concentration for different PSDs. Advancements are achieved is a two levels: first, different PSDs are simulated and tested in the laboratory, exploring a variety of combinations of mean sizes and standard deviations to represent the most likely conditions typical of actual rivers. Secondly, further steps are taken towards the complete validation of an integrated theoretical-experimental approach to measure suspended sediment in rivers, paving the way for field applications. The proposed method will be useful to both practitioners and theoreticians who work in the field of hydroacoustics, thus contributing to the advancement of knowledge regarding fluvial processes and related water resources.

The structure of the paper is as follows. Section 2 summarizes the background for acoustic methods and describes the proposed methodology for a reliable assessment of concentration using the attenuation to backscatter ratio at a single-frequency and the dual-frequency backscatter ratio; Section 3 describes the laboratory setup and tests conducted to validate the method; the results obtained are presented and examined in Section 4. Section 5 presents a general discussion on the proposed method, its advancements and limitations, focusing on the possibility of extracting information regarding the PSD and on the use of multifrequency to further enlarge the method applicability. A set of conclusions and perspectives for future work closes the paper (Section 6).

2. The acoustic method

In this Section, the basic aspects regarding the underwater propagation of sound are firstly presented by introducing the sonar equation (Section 2.1). Then the physical meaning of the attenuation to backscatter ratio at given frequency is presented (Section 2.2), and the effects of PSD changes on coefficients of backscattering strength, k_s^2, and normalized attenuation, ζ_s, are described. The use of the attenuation to backscatter ratio at 0.5 MHz for the inversion of the sonar equation is illustrated in Section 2.3; the method consists of three steps: (i) The determination of the most likely PSD affecting the sound propagation, (ii) the quantification of ζ_s, and (iii) the assessment of corresponding sediment concentration. Finally, an alternative approach to evaluate the sediment concentration in case of low ζ_s at 0.5 MHz is explored in Section 2.4. The method employs a higher frequency (i.e., 8 MHz) to infer the ratio between backscattering strength coefficients at 8 MHz and 0.5 MHz.

2.1. Acoustic scattering and attenuation

For readers' convenience, only the basic aspects are reported here regarding the theory of sound scattering from a water-particles mixture. Exhaustive studies may be found in technical-scientific books (Medwin and Clay, 1998; Urick, 1997; Urick, 1948) and in more recent review papers (Thorne and Hurther, 2014; Thorne and Meral, 2008; Thorne and Hanes, 2002).

The sound intensity received by an acoustic system, I, depends on: (i) The reference pressure p_0 at unity distance r_0, and the acoustic system settings (i.e., amplifier gain, transmit power and pulse length), that may be represented with a constant value, k_t, for a given system setting; (ii) the ability of suspended particles to scatter sound back to a mono-static transducer (i.e., backscattering strength) at a distance r; (iii) the two-way round-trip attenuation; (iv) the geometrical spreading. This relationship is expressed by Eq. (1), which is derived by e.g. Thorne and Hanes (2002) and is usually referred as the sonar equation:

$$I = p_0^2 \cdot r_0^2 \frac{k_t^2 \cdot k_s^2 \cdot M_s}{r^2 \cdot \psi^2} e^{-4(\alpha_w + \alpha_s)\cdot r}, \qquad (1)$$

where (i) the backscattering coefficient k_s^2 times the mass concentration M_s is the backscattering strength; (ii) α_w and α_s are the water viscosity and suspended sediment attenuation coefficients, respectively; (iii) $r^2\psi^2$ is the geometrical spreading that includes the near field correction coefficient ψ (Downing et al., 1995), in the far field $\psi = 1$.

It is worth noting that much of the existing acoustics literature reports logarithmic forms of the sonar equation, including the target strength or an equivalent decibel expression of the backscattering strength that is ten times the common logarithm of $k_s^2 M_s$. This is because the echo intensity level, E, spans a wide range of orders of magnitude and an hydrophone usually gives the received sound intensity in a dB scale, I_{dB}, (Guerrero et al., 2017; Latosinski et al., 2014; Szupiany et al., 2016) as reported in Eq. (2):

$$I_{dB} = C + 10log(k_s^2 \cdot M_s) - 20log(r \cdot \psi) - 20log(e) \cdot 2(\alpha_w + \alpha_s) \cdot r \qquad (2)$$