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Acoustic backscatter by suspended cohesive sediments: Field observations, Seine Estuary, France

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ABSTRACT

Observations of suspended sediment size and concentration, flow and acoustic backscatter intensity collected on the Seine Estuary (France) are used to study the acoustic response in cohesive-sediment dominated environments. Estimates of suspended sediment concentration based on *optical* backscatter sensors and water samples are used to calibrate the *acoustic* backscatter intensity. The vertical structure of suspended sediment concentration is then estimated from acoustic backscatter information. To our knowledge, this is the first field application of the recently proposed model of acoustic scattering by flocculating suspensions based on the variation of particle density (floc-scattering model). The estimates of sediment concentration reproduce well the observations under different tidal (neap/spring) conditions, confirming the applicability of the new model in the field when detailed particle size measurements are available. When particle size measurements are not available, using estimated floc sizes based on the turbulence intensities may provide reasonable SSC profiles. During spring tide events (associated with strong currents, small flocs and large concentrations), the performances of the new floc-scattering model and the previous models given for solid particle-scattering are comparable. The floc-scattering model increases the quality of the SSC estimates especially during low-energy conditions characterized with larger flocs.

1. Introduction

Suspended sediment concentration (SSC) information is essential for understanding sediment transport dynamics in estuarine and coastal environments. Acoustic profiling devices are widely used to measure both current velocity and SSC profiles since, unlike the point measurements by optical systems, they can provide information about the vertical structure of SSC. In sandy environments, where backscattering occurs from individual particles, acoustic techniques have been used intensively to estimate the vertical distribution of suspended sediment concentration and size from the backscattered signal (acoustic inversion) (e.g., Urick, 1948; Sheng and Hay, 1988; Downing et al., 1995; Crawford and Hay, 1993; Thorne and Hanes, 2002). Transferring these techniques to cohesive sediment environments such as estuaries is challenging, because cohesive sediment characteristics (size, shape, density, etc.) and flocculation are highly sensitive to flow conditions (e.g., Dyer and Manning, 1999; McAnally and Mehta, 2000; Winterwerp, 2002; Voulgaris and Meyers, 2004; Verney et al., 2011; Safak et al., 2013; Wang et al., 2013; Sahin, 2014). As a consequence, the use of acoustic backscatter systems to study sediment transport processes in fine-grained, cohesive environments is generally considered less accurate. All of the few studies published so far (e.g., Gartner, 2004; Hoitink and Hoekstra, 2005; Ha et al., 2011; Sahin et al., 2013; Sahin, 2014) acknowledge the difficulty and uncertainty of interpretation of the acoustic observations when sediment flocculation is present.

Acoustic and optical backscatter show a distinct sensitivity to flocculation. Vincent and MacDonald (2015) showed that there are small but systematic decreases in the optical backscattered signal between the primary and flocculated particles typically between 9% and 20% depending on the concentration. This small change in backscattered signal suggests that the size of particles scattering the light (sub-particles constituting the flocs) may increase a little as the degree of flocculation increases, given that the optical backscatter is inversely proportional to the particle diameter for a given mass concentration (Fugate and Friedrichs, 2002, Ha et al., 2009). They conclude that the changes in the optical backscatter that occur between

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primary (unflocculated) and flocculated particles are relatively small, from the point of view of a marine scientist wishing to measure concentrations of fine sediment. Accordingly, optical instruments are commonly used to measure sediment concentration in environments dominated with flocculated particles (e.g., Kineke and Sternberg, 1992; Safak et al., 2013; Sahin et al., 2013; Verney et al., 2013; Sahin, 2014). In contrast, acoustic backscatter intensity increases with the growth of particle (or floc). Although the signal intensity increases as the floc size increases, the intensity is much smaller for flocs than that for the solid particles of same size (MacDonald et al., 2013; Vincent and MacDonald, 2015). In previous studies, acoustic backscatter sensitivity to flocculation was related to low density of the aggregates and their porous nature (Ha et al., 2009, 2011; MacDonald et al., 2013; Rouhnia et al., 2014). In ADV-based (ADV: Acoustic Doppler Velocimeter) measurements of floc growth, Rouhnia et al. (2014) observed that the backscattered signal intensity increases rapidly with floc size up to certain value, then the rate of increase significantly slows down for larger flocs.

The analysis of acoustic backscatter data from muddy environments is hampered by the fact that the main features of scatterers are essentially unknown. It is still unclear in which form (i.e., primary particles, microflocs or macroflocs) the cohesive sediment should be considered as scatterers. Most of the previous studies suggest that scattering characteristics of a suspension of flocculated particles are controlled by the floc properties, rather than constituent primary particles. Theoretically, the marginal value of ka (where k is the wave number of the acoustic signal and a is the mean radius of scattering particle in suspension) for detection of suspended sediment particles may be roughly about 0.05, suggesting that acoustical devices operating at MHz frequencies would not be capable to resolve SSC well for grain sizes of order of 1 μm, a typical primary particle size constituting flocs in muddy environments (Lynch et al., 1994; Ha et al., 2011). Gartner (2004) successfully estimated concentration profiles by using flocs as scatterers with 1,200 kHz and 2,400 kHz acoustic Doppler current profilers (ADCP). Ha et al. (2011), using a 1,500 kHz pulse-coherent acoustic Doppler profiler (PC-ADP), suggested that the acoustic signal responds to compacted and robust flocs as a whole, rather than to the primary constituent particles. With a 1,500 kHz PC-ADP, inversion calculations by Sahin et al. (2013) using alternatively flocs and primary particles as scatterers consistently showed a better agreement for flocs, with a marginally significant correction due to primary-particle viscous effect. In contrast, a study by Fugate and Friedrichs (2002) suggests that the acoustic signal may penetrate the pores of flocs, and therefore the acoustic response for resuspended aggregates depends mostly on the constituent grains rather than the floc characteristics. Vincent and MacDonald (2015) recently speculated that the acoustic signal is sensitive to the sub-particles within the larger particles (flocs), referred to as flocculi, and that the flocculi could be treated as elastic spheres with density and acoustic wave propagation speeds equal to primary particles. However, the lack of field measurements of SSC and floc size with high spatial and temporal resolution may have precluded previous efforts from drawing a clear conclusion. A careful examination evaluating both views is warranted.

In the absence of a theoretical framework to describe the interactions between flocculated sediments and sound, previous applications involving possible scattering by mud flocs have defaulted to using expressions derived for solid (primary-particle) scatterers. Recently, MacDonald et al. (2013) carried out the first experimental study to investigate the interaction of sound with a suspension of flocculated sediments under controlled conditions, i.e., in a homogeneous suspension with known primary and flocculated sediment size and concentrations. Their results show significant differences between sediment backscattering properties before, and after aggregation, suggesting that the scattering characteristics are not solely controlled by the primary particles, but are also influenced by the presence of the flocs. The order-of-magnitude difference between the values of scattering parameters (e.g., form function, total scattering cross-section) obtained for flocs and for quartz primary particles is significant and casts doubt on the applicability of expressions previously derived for solid scatterers in applications involving flocculated particles. In a complementary study, Thorne et al. (2014) proposed the first model for the modification of scattering characteristics as the sediment flocculates, transitioning from separate primary particles to large low-density aggregates. The approach models primary particles as solid elastic spheres, and large, low-density flocs as fluid elastic spheres. This leads to a new model, so-called a hybrid model, that uses a variable particle density to represent the processes of flocculation. The model captures well the general behavior observed by MacDonald et al. (2013).

Here, we investigate the backscattering of the acoustic signal in a cohesive sediment environment under different hydrodynamic conditions. The field observations used here include optical and acoustic backscatter, as well as floc-size measurements throughout the water column, providing a detailed synchronous picture of floc variability, hydrodynamic conditions, and acoustic backscatter characteristics. This study aims to test the acoustic backscatter model for flocculates of Thorne et al. (2014) and its applicability under field conditions. We invert acoustic backscatter data in an estuarine environment to derive profiles of sediment concentration. The implications of the results are discussed in relation to importance of floc size measurements and improvements made by the new model over the previous solid-scatterer based models.

2. Method

2.1. Acoustic inversion

The backscatter intensity of an acoustic profiler can be converted to the vertical distribution of suspended concentration, M, using (see Appendix)

$$M(r) = \left\{\frac{10^{I_{dB}/20} r\psi}{k_s k_t{''}}\right\}^2 e^{4r\alpha}. \tag{1}$$

with

$$k_t{''} = \left\{\frac{3\tau c}{16}\right\}^{1/2} \frac{0.96}{ka_t}\frac{p_0}{p_{ref}}, \quad k_s(r) = \frac{\langle f_f(r)\rangle}{\sqrt{\langle a(r)\rangle \rho(a)}} \tag{2}$$

where M is the mass concentration of suspended scatterers (kg m^{-3}), r is the range from the transceiver along the acoustic beam (m), ψ is the dimensionless near-field correction factor describing the departure from spherical spreading in the near-field of the transducer, k_s embodies the scattering properties of sediment (kg$^{-1/2}$ m), $k_t{''}$ is a system constant (V m$^{3/2}$), α denotes the attenuation coefficient (Nepers m^{-1}), f_f is a form function describing the backscattering characteristics of a particle relative to its geometrical size (dimensionless), a is the radius of sediment in suspension (m), and $\rho(a)$ denotes sediment density (kg m^{-3}). The dependency of scatterer density on particles size is used to introduce the process of flocculation into the suspension scattering characteristics. The angular brackets indicate an average over the particle number size distribution (mean value) present in the sample volume. In the expression for k_t'', p_0 is the pressure at the reference distance r_0, which is normally defined as 1 m; the parameter τ is the acoustic pulse duration, c is the speed of sound in water, k is the acoustic wave number and a_t is the radius of the active area of the transducer. The range dependence of the parameters is not shown in the subsequent equations for simplicity.

The commercial instruments used in this study (ADCP) only provide access to the processed output signal in the manufacturer specified unit (counts) of received signal strength indicator. This is not a physical unit, but rather a relative measure of intensity for which the reference pressure is 1 μPa at 1 m. If the ambient noise intensity, E_r, is known, then the received signal intensity, E, can be converted to signal