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Formulations for the scattering properties of suspended sandy sediments for use in the application of acoustics to sediment transport processes

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Abstract

Multi-frequency acoustics backscattering has been used for over a decade, to quantitatively measure profiles of suspended sediment particle size and concentration, in the bottom 1–2 m above the seabed. Central to obtaining the sediment parameters from the backscattered signal is a description of the scattering characteristics of the particles in suspension. Therefore, formulations are required for the attenuation and backscattering properties of the suspended particles with size and acoustic frequency. There is no single formulation for these scattering properties and different researchers have used somewhat different expressions. However, these expressions are all based on a variation of sphere scattering, modified to fit available scattering data. Here we bring together all the published data on acoustic backscattering and attenuation by suspensions of sandy sediments. The aim is to provide coastal scientists, who use acoustics for sediment transport measurements, with simple expressions which best represent the observed scattering properties of sandy sediments.

Keywords: Sediments; Transport; Acoustics; Scattering; Attenuation; Instrumentation

1. Introduction

In recent years acoustic instrumentation has been increasingly used to measure non-intrusively, co-located and simultaneously, near-bed profiles of the flow, the suspended sediments and the bed forms (Thorne and Hanes, 2002). Here we highlight the use of multi-frequency acoustic backscattering systems (ABS), for the measurement of particle size and concentration over sandy beds. To extract the suspended sediment parameters from the backscattered signal requires an inversion to be conducted on the signal. At the kernel of this inversion is a description of the scattering properties of the particles in suspension. For suspensions composed of marine sands the individual grains are irregular in shape. At present there does not exist an exact solution to the general problem of scattering by irregularly shaped scatterers. Therefore the approach used to describe the scattering properties of suspensions of sandy sediments has been through direct measurement of their scattering properties and the utilization of sphere scattering models to interpret and represent the observations.

The ABS's currently in use typically operate at three frequencies in transceiver mode; that is the transmit transducers are also used as receivers (Crawford and Hay, 1993; Thorne et al., 2002; Vincent and Hanes, 2002; Green et al., 2004; Dohmen-Janssem and Hanes, 2005). The frequencies are usually in the range 0.5–5 MHz and the aim is to use the differential scattering characteristics of the scatterers with frequency to establish the suspended particle size and concentration. Because ABS's are normally used in transceiver mode, it is the backscattering and attenuating characteristics of the suspended sediment which are required for the acoustic inversion. The relevant acoustic quantities are the backscatter form function, f, which describes the backscattering characteristics of the particles in suspension, and the normalized total scattering cross-section, χ, which describes the attenuating characteristics. Both are non-dimensional parameters and their

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origins and nomenclature come from the acoustic sphere scattering literature (Neubauer et al., 1974). Appendix 1 provides a brief background on f and χ for readers not conversant with the acoustic scattering literature.

The sphere scattering approach, using the f and χ representation, was first adopted by Sheng and Hay (1988) to explain the sediment attenuation observations of Flammer (1962). They used a rigid mobile sphere model which compared reasonably well with the measurements and they also formulated a simple heuristic expression which also provided good agreement with the data. Other publications have adopted a similar approach (Hay and Sheng, 1992; Crawford and Hay, 1993; Thorne et al., 1993; Schaafsma and Hay, 1997; Thorne and Hanes, 2002; Thorne and Buckingham, 2004) and presented similar, though different expressions, related to particular data sets. In this study the objective was to bring together the published literature on acoustic scattering by suspensions of sandy sediments and irregularly shaped particles. The aim was to provide simple expressions for f and χ which compared well with all the data sets available and which can be used with a reasonable degree of confidence in the interpretation of ABS data collected above sandy sediments.

2. Background to *f* and χ

If the phase of the backscattered signal from a suspension of sediments is randomly distributed between 0 and 2π, then for insonification by a piston transceiver, the backscattered signal from a multi-frequency ABS can be converted to concentration, M, and mean particle size, $\langle a\rangle$, (Sheng and Hay, 1988; Hay, 1991; Thorne et al., 1993; Thorne and Hanes, 2002) using

$$M = \left\{\frac{V_{\mathrm{rms}}\psi r}{k_{\mathrm{s}}k_{\mathrm{t}}}\right\}^2 \mathrm{e}^{4r(\alpha_{\mathrm{w}}+\alpha_{\mathrm{s}})}, \tag{1}$$

$$k_{\mathrm{s}} = \frac{\langle f\rangle}{\sqrt{\langle a\rangle\rho}}, \quad \alpha_{\mathrm{s}} = \frac{3}{4r\rho}\int_0^r \frac{\langle\chi\rangle M}{\langle a\rangle}\,\mathrm{d}r.$$

The above expression assumes the attenuation over a range bin is not substantial (see Hay, 1991). V_{rms} is the root-mean-square backscattered signal; this is an ensemble average over a number of backscatter returns. The ensemble is required because the individual backscattered signals are Rayleigh distributed (Libicki et al., 1989; Thorne et al., 1993). r is the range from the transceiver, ψ accounts for the departure from spherical spreading within the transducer nearfield, k_{s} represents the scattering properties of the sediments, ρ is the density of the sand grains in suspension, k_{t} is a system constant (see preceding companion paper, Betteridge et al., 2007, for its measurement), α_{w} is attenuation due to water absorption and the other terms are given below.

$$\langle a\rangle = \int_0^\infty aP(a)\,\mathrm{d}a, \tag{2}$$

$$\langle f(x_0)\rangle = \left\{\frac{\int_0^\infty aP(a)\,\mathrm{d}a, \int_0^\infty a^2 f(x)^2 P(a)\,\mathrm{d}a,}{\int_0^\infty a^3 P(a)\,\mathrm{d}a}\right\}^{1/2}, \tag{3}$$

$$\langle\chi(x_0)\rangle = \left\{\frac{\int_0^\infty aP(a)\,\mathrm{d}a, \int_0^\infty a^2 \chi(x) P(a)\,\mathrm{d}a,}{\int_0^\infty a^3 P(a)\,\mathrm{d}a}\right\}, \tag{4}$$

where a is the radii of the sediment grains in suspension, $P(a)$ is the probability size distribution of the grains and $x = ka$, where k is the wave number, $k = 2\pi/\lambda$, λ is the wavelength of the sound in water and $x_0 = k\langle a\rangle$. The variable x is non-dimensional and as will be seen below is an appropriate choice for describing the dependency of f and χ. As a step towards the evaluation of Eq. (1), Eqs. (3) and (4) need to be calculated and this requires expressions for f and χ. The purpose of the present paper is to provide these expressions using all the presently available published data, so that coastal scientists can use them in a straightforward manner in the interpretation of ABS data.

Although there is no general solution to the scattering properties of irregularly shaped particles we can make some reasonable estimates for $x \ll 1$ and $x \gg 1$. For $x \ll 1$, the Rayleigh regime, the wavelength of the sound is much greater than the particle circumference and scattering is considered to be independent of the shape of the scatterer. Therefore one might anticipate spherical and irregularly shaped scatterers may have similar scattering characteristics. Rayleigh scattering for a sphere is given by (Clay and Medwin, 1977)

$$f = 2x^2\left[\frac{e-1}{3e} + \frac{g-1}{2g+1}\right], \tag{5a}$$

$$\chi = 2x^4\left[\left(\frac{e-1}{3e}\right)^2 + \frac{1}{3}\left(\frac{g-1}{2g+1}\right)^2\right], \tag{5b}$$

$e = E_1/E_0$ is the ratio of elasticity of sand grains (quartz) to water, $e = 39$, and g is the ratio of density of the sand grains to water, $g = 2.65$. Putting the values for e and g into Eq. (5) gives $f = 1.17x^2$ and $\chi = 0.26x^4$; these are particularly simple expressions. For $x \gg 1$, the geometric regime, the scattering cross-section is the particle's actual cross-section. There is a theorem (Van de Hulst, 1981; Chinnery et al., 1997) that states that the geometric cross-section of a convex particle, averaged over all orientations, is equal to a quarter of the surface area of the particle. This is obviously the case for a sphere where the surface area is $4\pi a^2$ and the cross-sectional area is πa^2. Since a sphere has the minimum surface area to volume, then it is expected that a particle of irregular shape, having a similar volume to a sphere, would have a larger surface area and hence a higher geometric and scattering cross-section. For a rigid sphere f and χ tend to a constant value of unity for $x \gg 1$ and therefore it might be reasonable to anticipate that for irregularly shaped particles f and χ would tend to a constant value somewhat greater than unity.