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An overview on the use of backscattered sound for measuring suspended particle size and concentration profiles in non-cohesive inorganic sediment transport studies

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ABSTRACT

For over two decades, coastal marine scientists studying boundary layer sediment transport processes have been using, and developing, the application of sound for high temporal–spatial resolution measurements of suspended particle size and concentration profiles. To extract the suspended sediment parameters from the acoustic data requires an understanding of the interaction of sound with a suspension of sediments and an inversion methodology. This understanding is distributed around journals in a number of scientific fields and there is no single article that succinctly draws together the different components. In the present work the aim is to provide an overview on the acoustic approach to measuring suspended sediment parameters and assess its application in the study of non-cohesive inorganic suspended sediment transport processes.

1. Introduction

It is readily acknowledged that one of the most important processes in the coastal environment is the movement of sediments; they impact on habitats, water quality, turbidity, biogeochemistry and morphology (Davies and Thorne, 2008; Amoudry and Souza, 2011). Therefore improving our capability to monitor and model sediment transport in the marine environment is an essential component of sustainable development and management. In particular as detailed physics based process models have developed, there has been the requirement to measure sediment dynamics with increasing temporal–spatial resolution (van der Werf et al., 2008). This has led to the development of new technologies and the utilisation of acoustics has been one of the competitors in this field (Thorne and Hay, 2012).

On the larger scale acoustic Doppler current profilers, ADCP, have been around for three decades measuring flow profiles (Gordon, 1996) and more recently the amplitude of the backscattered signal has been used to estimate suspended concentration (Holdaway et al., 1999; Moore et al., 2012, 2013). Further in the last year or two there has also been the application of using swath bathymetry systems to measure suspended sediments (Simmons et al., 2010). On the smaller scale significant advances have been taking place in the application of sound to the study of near-bed sediment transport processes (Vincent et al., 1999; Hurther and Thorne, 2011; Bolanos et al., 2012; Hay et al., 2012). Acoustics has and is being developed for near-bed studies because it is recognised as having the potential to measure non-intrusively, co-located, simultaneously and with high spatial–temporal resolution, suspended sediment and flow profiles and provide information on bedforms. This has lead to the development of multi-frequency acoustic backscatter systems, ABS, to measure suspended particle size and concentration (Crawford and Hay, 1993; Thorne and Hardcastle, 1997), high resolution acoustic Doppler velocity profilers, ADVP, for turbulent and intra-wave observations (Hurther et al., 2007; Hay et al., 2012), combined systems for high resolution acoustic concentration and velocity profiles, ACVP, (Hurther et al., 2011) and two and three dimensional acoustic ripple profiles, ARP, to provide detailed bedform measurements with sub-centimetric resolution (Traykovski, 2007; Hay, 2011; O'Hara Murray et al., 2012). Developments using acoustic near-bed systems have been presented in the literature (Thorne and Hanes, 2002; Hurther et al., 2011).

The present work focuses on the near-bed application and forms the third part of a trilogy on ABS systems in which the first part described the system calibration using suspensions with known scattering characteristics (Betteridge et al., 2008), the second centered on acoustic scattering properties of suspended

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Nomenclature

a	particle radius (m)
a_o	mean radius based on $n(a)$ (m)
a_c	mean radius of the suspension field based on n(a) (m)
a_m	mean radius based on $m(a)$ (m)
a_M	acoustic estimate of the suspended particle radius (m)
a_r	reference value for a_c at z_r (m)
a_{50}	median mass radius based on $m(a)$ (m)
A_t	transducer radius (m)
C	suspended concentration field (kg m^{-3})
C_r	reference value for C at z_r (kg m^{-3})
d_{50}	median mass diameter based on $m(a)$ (m)
f_i	intrinsic backscatter form function (-)
f	ensemble density normalised backscatter form function (kg$^{-1/2}$ m$^{3/2}$)
j	frequency counter used in the inversion.
k	acoustic wavenumber, $2\pi/\lambda$ (m^{-1})
K	sediment backscattering property (kg$^{-1/2}$ m)
m(a)	particle mass radius probability density function (-)
M_o	initial acoustic estimate of the suspended concentration (kg m^{-3})
M	acoustic estimate of the suspended concentration. (kg m^{-3})
n(a)	particle number radius probability density function (-)
N	number of frequencies used in the inversion.
r	range from the transducer (m)
r_n	transducer nearfield $\pi A_t^2/\lambda$ (m)
$\Re$	the system constant (V m$^{3/2}$)
V	backscattered signal (V)
u*	bed friction velocity (ms^{-1})
V_m^2	mean-square backscattered signal (V^2)
$x{=}ka$	(–), $x_o{=}ka_o$ (–)
z	height above the bed (m)
z_r	reference height, z_r=0.005 (m)
α_w	attenuation due to water absorption (Nepers m^{-1})
α_s	attenuation due to sediment scattering (Nepers m^{-1})
γ_o	random error introduced into the backscattered signal (-)
δ	normalised standard deviation (-)
ε	systematic error introduced into the backscattered signal (-)
η	number of independent samples (-)
λ	wavelength of sound (m)
ξ	sediment attenuation constant (kg^{-1} m^2)
ρ	sediment grain density (kg m^{-3})
σ	standard deviation (units depend on parameter)
σ_e	standard error (units depend on parameter)
τ	time lag (s)
τ_o	decorrelation time lag (s)
Φ	parameter used to estimate acoustical particle radius (-)
χ_i	intrinsic normalised total scattering cross-section (-)
χ	ensemble density normalised mean normalised total scattering cross-section (kg^{-1} m^3)
ψ	Transducer nearfield correction (-)
1	parameters in the text with subscript 'b' refers to bed sediments.
2	$\overline{X}$. Overbar represents a time averaged parameter.
3	$\overline{X/Y}$. Overbar represents a time and height averaged parameter.

marine sediments (Thorne and Meral, 2008; Moate and Thorne, 2012) and here the study focuses upon the extraction of suspended sediment parameters from the backscattered acoustic data. The literature associated with the application of acoustics to the measurement of suspended sediment measurements is distributed amongst journals in the fields of acoustics (Sheng and Hay, 1988; Thosteson and Hanes, 1998; Moate and Thorne, 2009), engineering (Thorne et al., 1994; Hurther et al., 2011), sedimentology (Vincent et al., 1991, 1999; O'Hara Murray et al., 2012; Pedocchi and Garcia, 2012) and geosciences (Hay and Sheng, 1992; Hurther and Thorne, 2011) with no single article providing an overview of the approach. It was therefore considered timely, given the expanding use of sound for measuring suspended sediments, that an article providing such an overview of the topic would be of value to coastal marine scientists who are using, or beginning to use acoustics, in bottom boundary layer sediment transport studies.

Examined here is the inversion of acoustic data backscattered from inorganic non-cohesive suspended sediments and its application to the measurement of suspended particle size and concentration profiles. The intention is to provide a description of the commonly adopted inversion approach used with contemporary ABS deployed in sandy marine environments. To this end a series of formulations are described which cover a range of inversions from simple to more complex approaches. Depending on the availability of independent information on the suspension, the inversion may be more or less subject to uncertainty. Here an assessment is made of the inversion process and how different factors impact on the calculated acoustic estimates of suspended particle size and concentration. The relationship between the measured acoustic parameters and those commonly used in sediment transport models is discussed. The influence of the system calibration accuracy, the uncertainty in the scattering properties of the sediments, the effect of the particle size distribution, the frequencies to use and the impact of signal averaging are all considered in the assessment. The specific impact of extraneous scatterers such as bubbles, organic particles and living organisms on the acoustic inversion is not explicitly investigated in this study, although the extraneous scatterers could be considered as contributing to the systematic and random errors introduced into the backscattered signals used in the study.

To carry out the inversion assessment, a suspension field is simulated, sound propagated through the field and the backscattered signal calculated. It is this backscattered signal which is inverted using a number of formulations, from simple to more complex in a number of scenarios. The suspension field used is based on observations collected in coastal environments. The time-averaged vertical profile of suspended sediment concentration corresponds to a standard Rouse profile. In the absence of a general theory for vertical grain size sorting a time-averaged vertical profile based on a power law is employed. This formulation comes from observations collected in a wave dominated rippled bed environment (Thorne et al., 2011a). Although this size profile is not necessarily appropriate to highly turbulent suspension flows when size sorting may be ignored, it does offers a flow regime for testing the full performance of the acoustic profiling of both sediment concentration and grain size. Superimposed upon the mean profiles are temporal fluctuations to represent turbulence and wave motion and assessment is made as to how well these fluctuation are represented in the acoustic inversions.

The software underpinning the results presented in the paper can be found at http://noc.ac.uk/using-science/products/software/csr-acoustic-inversions. The software consists of MATLAB programs which calculate the suspension field, the sediment