Continental Shelf Research 31 (2011) 1020–1032

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research papers

Using velocimeter signal to noise ratio as a surrogate measure of suspended mud concentration

Mehrdad Salehi, Kyle Strom *

Department of Civil and Environmental Engineering, University of Houston, Houston, TX, United States

ARTICLE INFO

Article history:
Received 12 October 2010
Received in revised form
25 February 2011
Accepted 17 March 2011
Available online 31 March 2011

Keywords:
Acoustic Doppler velocimeter
Suspended sediment concentration
Mud

ABSTRACT

This study examines the relationship between suspended sediment concentration (SSC) and the signal to noise ratio (SNR) recorded by a 6 MHz Nortek Vector velocimeter in a laboratory water tank using four different synthetic and natural mud mixtures and different combinations of the user-set Vector parameters transmit power level and velocity range. For concentrations less than 1500 mg/l (1.5 g/l), a region of linearity between the logarithm of concentration and time-average SNR was found for all sediment types and transmitter power level settings. Within this concentration range, the experimental data was used to develop calibrated equations of the form, $\log(\mathrm{SSC}) = c_1\mathrm{SNR} + c_2$; R^2 values for all calibrated equations were greater than 0.98, suggesting that properly calibrated relations can yield accurate time-averaged SSC measurements using Vector measured SNR. An analysis of the general calibration equation indicated that the predicted SSC values are sensitive to changes in the coefficient values for c_1 and c_2. Even small (10%) deviations in coefficient values resulted in 20%–65% changes in the predicted SSC. Variation in c_1 and c_2 values among all four mud mixtures were significant enough that the calibrated equations could not be used interchangeably. This was true even among three samples that had similar particle-size distributions. Translation of raw 32 Hz SNR data to 32 Hz SSC time series produced excessively large variation in the SSC time series. Several smoothing and filtering schemes were examined to reduce the magnitude of these fluctuations to more reasonable levels. Of the methods tested, a two-sided moving average functioned best at removing fine-scale variation while retaining larger-scale trends. A 96-point (3 Hz) averaging window brought 98.6% of the Vector estimated SSC time series values to within $\pm 10\%$ of the time-average physical samples. Impacts of turbulent kinetic energy and sampling volume size on instrument recorded SNR were also empirically examined.

1. Introduction

Measurement of suspended sediment concentration (SSC) is a fundamental and important procedure for estimating sediment flux and understanding transport processes in rivers, bays, estuaries, and the marine environment. Three broad methodological categories for collecting SSC data are: (1) direct physical sampling of a suspension; for example, using depth-integrated or point-integrated suspended sediment samplers and various pumping systems (Grey et al., 2000; Diplas et al., 2008); (2) the use of optical backscatter methods which rely on the amount of scattered light emanating from a source submerged in the water, e.g., optical backscatter sensors (OBS) (Downing, 2006; Gray and Gartner, 2009) and Sequoia's LISST (Fugate and Friedrichs, 2002; Thorne et al., 2007); and (3) acoustic backscatter methods, which include dedicated single and multi-frequency acoustic backscatter systems, multi-beam systems, and use of acoustic return strength in single-frequency acoustic Doppler current profilers (ADCPs) and acoustic Doppler velocimeters (ADVs) (Holdaway et al., 1999; Thorne and Hanes, 2002; Gray and Gartner, 2009; Best et al., 2010). Each of these acoustic instruments give varying degrees of information about the suspended matter in the water column. On the upper end, true multi-frequency systems have the ability to determine both concentration and particle-size distribution information through semi-analytic inversion techniques (e.g., Hay and Sheng, 1992; Thosteson and Hanes, 1998; Thorne and Hanes, 2002; Betteridge et al., 2008; Moate and Thorne, 2009). On the lower end, commercially available ADVs and ADCPs record a form of the acoustic backscatter that can be mined to infer concentration estimates. These instruments, however, are designed specifically for measurement of current and turbulent velocity and cannot provide information on suspended sediment particle-size because the instruments only emit at a single frequency.

* Corresponding author.
E-mail address: kbstrom@uh.edu (K. Strom).

0278-4343/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.csr.2011.03.008

Commercially available acoustic Doppler velocimeters are common tools for measuring time varying turbulent velocity signatures in both field and laboratory settings (Voulgaris and Trowbridge, 1998; Nikora and Goring, 2000; Maddux et al., 2003; Strom and Papanicolaou, 2007). Since Doppler systems measure the fluid velocity using acoustic reflections from small particles, they also inherently record a form of information concerning the suspended particulate matter in the water column (Lohrmann et al., 1994; Lohrmann, 2001a; Nikora and Goring, 2002; Hosseini et al., 2006). If a usable and physically meaningful form of this information can be extracted, then ADV systems can be used to simultaneously measure velocity and suspended sediment concentration. This is an attractive option and has led to several studies which use the strength of the acoustic return in ADV data as a surrogate for suspended sediment concentration once a suitable calibration curve has been developed (e.g., Fugate and Friedrichs, 2002; Nikora and Goring, 2002; Voulgaris and Meyers, 2004; Hosseini et al., 2006; Chanson et al., 2008; Ha, 2008; Salehi and Strom, 2009). Several of these studies have observed a linearity in the logarithm of SSC and the time-averaged acoustic backscatter strength (Fugate and Friedrichs, 2002; Nikora and Goring, 2002; Voulgaris and Meyers, 2004; Chanson et al., 2008; Ha, 2008). This information has then been used in field settings to make estimates of in-situ settling velocity (Fugate and Friedrichs, 2002; Voulgaris and Meyers, 2004; Ha and Maa, 2010) and suspended sediment flux (Andersen et al., 2007; Trevethan et al., 2007; Chanson et al., 2008). Of these studies, the results of Fugate and Friedrichs (2002) and Voulgaris and Meyers (2004) are particularly encouraging because they suggest that estimates of SSC made with their ADV system were as good, if not better in some cases, than those made with an OBS and a LISST-100x. The broad goal of this paper is to further explore the use of ADV instrumentation for simultaneous measurement of turbulent-scale velocity and SSC time series.

1.1. Acoustic backscatter and SSC

A foundation for linking ADV recorded acoustic information to suspended sediment concentration can be built by assuming that the suspended sediment particles generate acoustic scattering in the Rayleigh regime and that this can be modeled with the sonar equation (Urick, 1983). Within the Rayleigh regime ($kr<1$ where k is the acoustic wave number, $k=2\pi/\lambda$, λ is the wavelength, and r is the particle radius), scatter theory implies that the volume backscatter strength of the signal, S_v, takes the following functionality with SSC (Hoitink and Hoekstra, 2005) for uniform sized suspensions,

$$S_v = 10\log\left(\frac{3\phi k^4 r^3}{\rho_s}\text{SSC}\right) \tag{1}$$

where ϕ is a material property, ρ_s is the sediment density, and SSC is the suspended sediment concentration (sediment mass/volume of the mixture). For a given emitted frequency and sediment type and size, Eq. (1) shows that,

$$S_v \propto 10\log(\text{SSC}) \quad \text{or SSC} \propto 10^{S_v/10} \tag{2}$$

when $kr<1$. It should be noted that the above relation is for uniform sized suspended spheres and that the strength and form of the backscatter also depends on the shape of the particle-size distribution and the shape of the particles themselves (Moate and Thorne, 2009). For our purposes it is sufficient to say that the strength of the backscatter should be proportional to the logarithm of the suspended sediment concentration.

For the acoustic Doppler system, the strength of the backscatter can be modeled using the following version of the sonar equation in dB units (Lohrmann, 2001a; Gartner, 2004; Hoitink and Hoekstra, 2005),

$$S_v = K_c(E-E_r)+20\log(R)+2\alpha R+c \tag{3}$$

Here, E is echo strength (counts), E_r is the reference receiver noise (counts), K_c is a conversion factor (dB/counts), α is a water and sediment absorption factor, R is the range to the sampling volume (for an ADV, R is a constant), and c is a constant with units of dB. The last two terms in Eq. (3) are known as the major contributors to the two-way transmission loss, 2TL, in acoustic energy as a wave travels from the emitter to the sampling volume and back,

$$2\text{TL} = 20\log(R)+2\alpha R \tag{4}$$

The first and second terms of Eq. (4) account for loss due to spreading and absorption, respectively. The absorption coefficient, α, can be decomposed into sound absorption due to the water and absorption due to sediment, $\alpha=\alpha_w+\alpha_s$. α_w is a function of pressure, salinity, and frequency. However, for the fixed frequencies used with ADVs, α_w can be taken as a constant that does not vary with salinity; for the Nortek Vector used in this study (f=6 MHz) α_w can be taken as $\alpha_w=9$ (dB/m) over the range of typical fresh and salt water salinities (Lohrmann, 2001b). α_s is a function of sediment concentration, density, radius and size distribution as well as the emitter acoustics. For uniform sized particles, the relationship for α_s is defined as (Urick, 1983; Hoitink and Hoekstra, 2005),

$$\alpha_s = \left[\frac{k^4 r^3}{96\rho_s} + \frac{ks(SG-1)^2}{2\rho_s(s^2+[SG+\delta]^2)}\right]\frac{20}{\ln(10)}\text{SSC} \tag{5}$$

where $s=[9/(2\beta r)][1+2/(\beta r)]$, $\beta=\sqrt{\pi f/\nu}$, f is frequency, ν is the kinematic viscosity of water (m^2/s), SG is the specific gravity of the sediment, $\delta=[1+9/(\beta r)]/2$, and SSC is the mass concentration (kg/m^3). It should also be noted that the particle-size distribution of the suspended matter also impacts the exact form of the attenuation.

For an ADV, R and α_w are constants (R is ≈ 0.15 m for the Vector used in this study), and combining Eqs. (2) and (3) gives,

$$\log(\text{SSC}) = \frac{K_c(E-E_r)}{10}+c'+c''\alpha_s \tag{6}$$

where c' and c'' are constants for fixed R and α_w values, and $\alpha_s=\alpha_s(\text{SSC})$. For reasonably low concentrations (SSC less than approximately 1000 mg/l), $c''\alpha_s$ is small compared to the other terms in Eq. (6) and can be neglected. Taking $K_c(E-E_r)/10 \cong c_1\text{SNR}$ and taking $c_2=c'$, results in a linear relationship between the signal to noise ratio, SNR (dB), and the logarithm of SSC,

$$\log(\text{SSC}) = c_1\text{SNR}+c_2 \quad \text{or SSC} = 10^{(c_1\text{SNR}+c_2)} \tag{7}$$

The coefficients c_1 and c_2 are sediment and velocimeter dependent parameters that can be found through linear regression applied to measurements of SSC and the corresponding time-averaged SNR values. It should be noted that due to the theory, assumptions, and simplifications used to arrive at Eq. (7), the values of c_1 and c_2 are a function of particle size, particle-size composition, sediment mineral and organic composition, absorption, and instrument dependent conversions. As such, they should be thought of as calibration coefficients in the SSC–SNR relationship which are only valid for the sediment conditions and instrument settings for which they were developed.

1.2. Study objectives

Investigation into the nature of the relation between backscatter strength and SSC with Doppler-based velocimeter systems has been ongoing since the instruments inception (Thevenot and Kraus, 1993; Kawanisi and Yokosi, 1997). Much of the work in this vein has focused on measuring concentration with profiler-based instruments (e.g., Thevenot and Kraus, 1993; Gartner, 2004; Hoitink and Hoekstra, 2005) and has benefited from the extensive development