2. Measurements of suspended sediment concentrations from ADCP backscatter in strong currents

Lucas M. Merckelbach[1] and H. Ridderinkhof[2]

[1]   Helmholtz-Zentrum Geesthacht, D-21502 Germany, email: lucas.merckelbach@hzg.de

[2]   Royal Netherlands Institute for Sea Research (NIOZ) P.O. Box 59, 1790 AB Texel, The Netherlands

Abstract

Acoustic Doppler Current profilers (ADCP's) have been used to measure currents for over twenty years. Although ADCP's are origianlly not designed to measure acoustic backscatter intensity accurately, several researchers have (successfully) related the backscatter intensity to suspended sediment concentrations (SSC) using a random phase acoustic backscatter model. However, this paper shows experimental evidence that in a tidal inlet during high tidal current velocities, a random phase acoustic backscatter model overestimates the SSC by one or two orders of magnitude, which cannot be explained by a time-varying particle size distribution. An acoustic backscatter model is developed that includes the effect of acoustic backscatter enhanced by coherence in the particles' spatial distribution as a result of turbulence-induced sediment fluctuations. The model results are compared with field measurements, showing a good correspondence between measured and modeled SSC, including the strong high current conditions for which the random phase acoustic backscatter model was shown to fail.

i. Introduction

The Marsdiep is the most southwestern tidal inlet of the Dutch Wadden Sea, a shallow tidal area that is connected to the North Sea (see Fig. B-2.1).
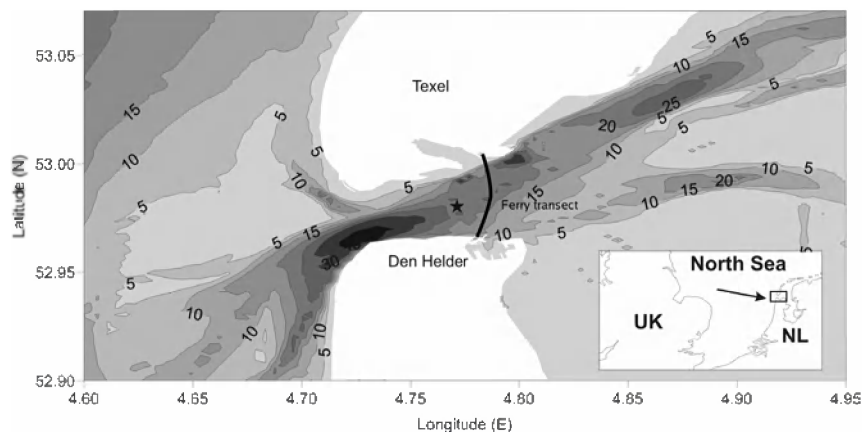

Fig. B-2.1: *Map of the western part of the Wadden Sea. The numbers indicate depth in meters with respect to mean sea level.*

Since 1998 ferry observations have been carried out in this tidal inlet, starting with the ferry *Schulpengat*, which was in service until 2004 and subsequently with the successor ferry *Dr Wagenmaker*. The ferries service the link between the mainland and the island of Texel, making 32 crossings of about 4.5 km each day. A suite of sensors installed in a through-flow system measures water temperature, salinity, fluorescence. For importance of this study is the hull-mounted downward-looking acoustic Doppler current profiler, henceforth referred to as ADCP, which measures three-dimensional velocity profiles. The instrumentation and dataprocessing is described in detail in Ridderinkhof et al. (2002).

The measurement principle of the ADCP is based on acoustic reflection by suspended particles. Therefore, in principle, it should be possible to relate the intensity of the acoustic backscatter to the concentration of the suspended particles. In combination with current velocities, this would provide a unique data set on suspended sediment transport through a tidal inlet. Several researches have tried to exploit the ADCP backscatter intensity to infer suspended sediment concentrations with varying degrees of success (Holdaway et al., 1999). A good review discussing the methodology is given by Thorne and Hanes (2002). Observational data presented in this paper show that the theory as described by Thorne and Hanes overestimates the suspended sediment concentration by orders of magnitude if the current is sufficiently turbulent. A physical explanation for this observation is given and the theoretical model is extended to include this effect.

ii. Field observations

For calibrating the method outlined by Thorne and Hanes, we carried out several 13-h measurement campaigns near the ferry transect, indicated by the star in Figure B-2.1. Each campaign consisted of measuring suspended sediment concentration profiles with 20-minute intervals using an optical backscatter (OBS) mounted to a CTD frame. The OBS was calibrated with water samples taken from three different depth levels concurrently with the CTD casts. Concurrently, a downward-looking Nortek 1 MHz ADCP collected velocity profiles with a vertical resolution (bin size) of 1 m. The ADCP recorded profiles of velocity vectors in three dimensions as well as acoustic backscatter intensities. Due to the divergence of the acoustic beams and the attenuation of acoustic energy due to water (and to some extent sediment), the acoustic backscatter intensity for a given bin depends on the distance from the ADCP device. Herein, the acoustic backscatter intensity, when corrected for these effects, is referred to as echo intensity, *EI*. For the mathematical formulation of this correction procedure, the reader is referred to Thorne and Hanes (2002) or Merckelbach (2006).

The model described by Thorne and Hanes (2002) assumes the backscattered signal to be an ensemble of backscattered signals with random phases. The mathematical formulation of the random phase backscatter model boils down to

$$EI = K_i \cdot 10 \log_{10} \left(c / \rho_s \right), \tag{1}$$

where EI is the echo intensity (in dB), c the sediment concentration, ϱ_s the density of solids, and K_i a coefficient of proportionality. Figure B-2.2 shows a scatter plot of the logarithm of the suspended sediment concentration, derived from OBS, and the echo intensity, expressed in dB. According to (1) this should result in a (more or less) linear relation. It is seen that *i)* only a part of the data conforms to this linear relationship, and *ii)* the deviating data are consistently biased towards high echo intensities.
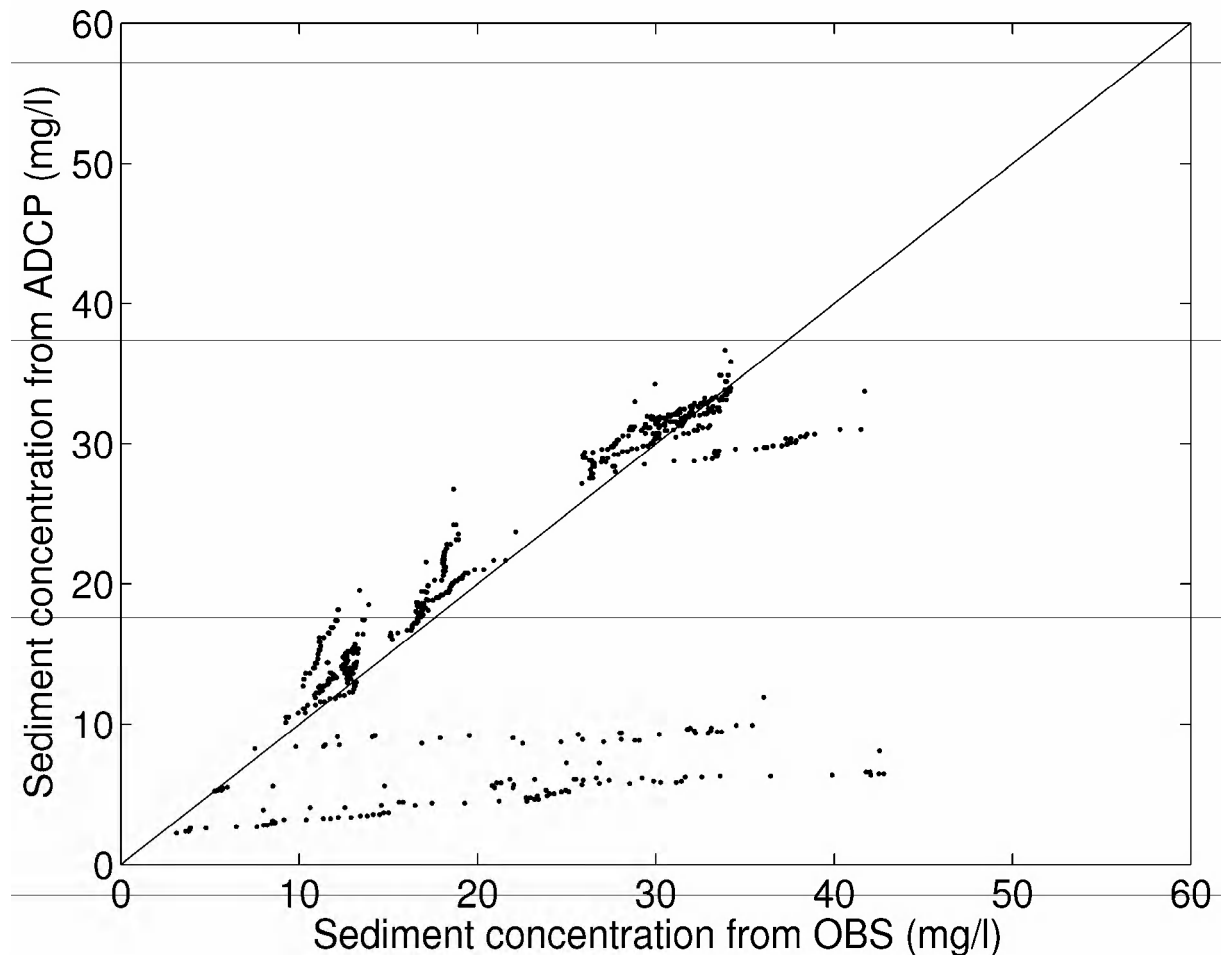

Fig. B-2.2: OBS derived suspended sediment concentration against echo intensity.

This means that if echo intensities were to be used to infer suspended sediment concentration, a significant part of the suspended sediment concentration data would be overestimated by at least one or two orders of magnitude. Figure B-2.3 shows measured and modelled suspended sediment concentrations using (1), at 17 m below the water level for data from the measurement campaign AS27 (5 November, 2003).
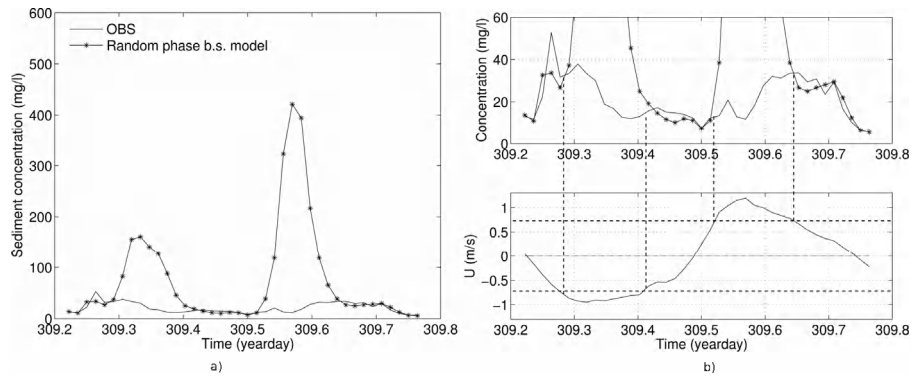
Fig. B-2.3: Panel (a) shows measured and modeled suspended sediment concentration based on random phase backscatter at 17 m below sea level. Panel b) shows the modeled and measured concentrations clipped at 50 mg/l and the corresponding depth-averaged current velocity.

The model is seen to overestimate during two phases of the (semidiurnal) tide (panel a), namely where the depth averaged velocity U exceeds 0.7 m.s^{-1} (panel b). This observation is consistent with the observations from other measurement campaigns.

Acoustic backscatter due to turbulence

The mechanism that is proposed to explain this discrepancy accounts for enhanced acoustic backscatter intensity due to the ensemble of backscattered signals to be composed of signals with phases that are not entirely random. Figure B-2.4 explains this schematically. Incoming acoustic waves, represented by the dashed horizontal lines, travel from top to bottom. Particles within a bin, indicated by dots inside gray trapeziums cause the incoming waves to be reflected. Backscatter waves, resulting from the incoming wave drawn by the solid line, travel bottom to top.
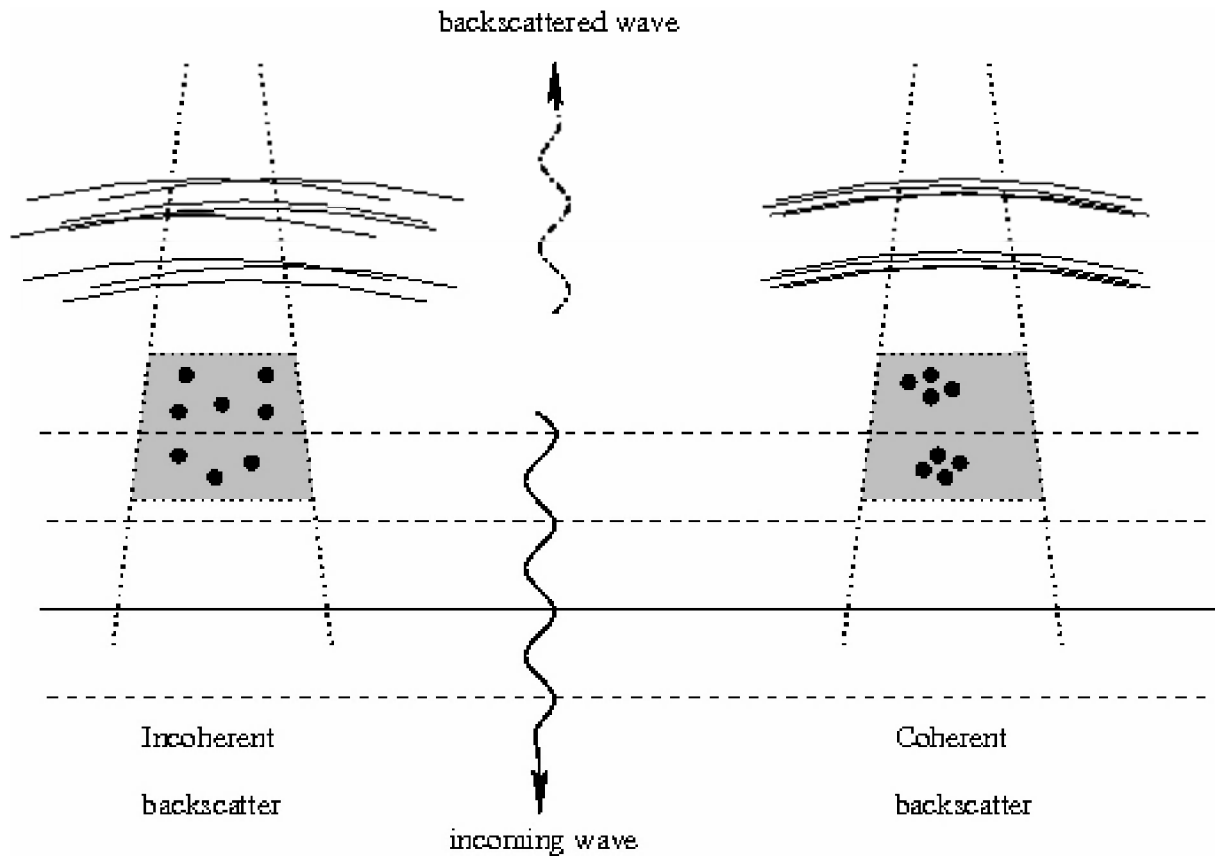
Fig. B-2.4: *Schematic representation of incoherent and coherent backscatter. See text for explanation.*

On the left, the scattering particles randomly positioned, causing backscattered signals to have random phases, or to be incoherent. On the right, particles are grouped in space. The resulting backscattered signals are not random any more and have (to some extent) coherent phases. In the case of incoherent signals, some signals are counter-phased and cancel each other, but not so in the case of coherent backscatter. Therefore the ensemble intensity of a given number of scatterers in a bin is stronger if the backscatter is coherent. This effect is most efficient for particles that are equally spaced (in the direction of the acoustic wave) at a distance of half the acoustic wavelength, the Bragg wavelength λ_B. For a 1 MHz ADCP the Bragg wavelength is about 0.8 mm.

Turbulence provides a mechanism to cause scattering particles (sediment) to be non-randomly distributed within a bin. Consider a constant sediment concentration gradient. A turbulent eddy of a given scale will mix water parcels with different concentration, resulting in a fluctuation in sediment concentration, superimposed on the original constant gradient. The scale of the sediment fluctuation is then the same as the scale of the mixing eddy. Turbulent eddies can appear over a broad range of scales, as large as the dimensions of the flow (water depth, for example) down to centimeter or even millimeter scale, the Kolmogorov scale at which the energy is dissipated by viscosity. The stronger the flow, the smaller the Kolmogorov scale must be to be effective enough to dissipate the turbulent energy. Can the current in the Marsdiep be that strong that the Kolmogorov scale is smaller than the Bragg wavelength, so that turbulence causes

sediment fluctuations at a scale equal to the Bragg wavelength? To answer that question, we can estimate the Kolmogorov length scale η by (Tennekes & Lumley, 1972)

$$\eta = \left(\frac{v^3}{\varepsilon}\right)^{1/4},$$ (2)

where v is the kinematic viscosity and ε the dissipation rate. The kinematic viscosity for water is about $1*10^{-6}$ m²/s and the dissipation rate can be estimated from

$$\varepsilon = \frac{u_*^3}{h\kappa},$$ (3)

where $u_* \approx 1/20\,U$, h the water depth (about 22 m) and $\kappa = 0.4$ (von Karman constant). From (2) and (3), and $U = 0.7$ m.s⁻¹ (see Fig. B-2.3) it follows that the Kolmogorov length scale is 0.7 mm, which is close to the Bragg wavelength of 0.8 mm. It is indeed plausible that in the Mardiep the Kolmogorov length scale becomes smaller than the Bragg wavelength if the depth-averaged current velocity exceeds 0.7 m/s.

iii. Model formulation and results

A rigorous mathematical derivation of an acoustic backscatter model for (sediment) particles to cause coherent backscatter is beyond the scope of this paper. Instead, the reader is referred to Merckelbach (2006). Here we suffice by sketching the line of thoughts.

In Merckelbach (2006) it is explained in detail how the echo intensity can be formulated in terms of the fluctuation spectrum of the scatterers (sediment particles), evaluated for the Bragg wavelength. This formulation allows for particles to be randomly distributed (white noise) as well as the distribution of particles to have fluctuations at particular wavelengths. Furthermore, as argued above, the turbulent range, or more precisely, the inertial subrange may extend to scales smaller than the Bragg wavelength for currents exceeding 0.7 m.s⁻¹. Drawing upon the analogy with salinity or temperature, we can formulate a theoretical spectrum of sediment concentration fluctuations. Assuming the theoretical spectrum is representative for the real spectrum, we arrive at a formulation for the coherent backscatter regime that is expressed in terms of the suspended sedimentation concentration gradient

$$EI = K_c \cdot 10\log_{10}\left(\rho_s^{-2}\left(\kappa z \frac{h-z}{h}\right)^{2/3}\left(\frac{dc}{dz}\right)^2\right),$$ (4)

where z is the vertical ordinate, taken positive in upward direction with the origin at the sea bed and K_c is a bulk coefficient accounting for all parameters not discussed herein. (see Merckelbach, 2006) for a break-down of Kc)

Summarizing the results so far, we have the incoherent backscatter regime (random phase) for $\eta < \lambda_B$, for which the suspended sediment concentration can be solved for directly from (1), and a coherent backscatter regime for $\eta \geq \lambda_B$, for which the suspended sediment concentration is given by the (first-order) differential equation (4). Solving for the sediment concentration from (4) requires exactly one boundary condition or integration constant.

In order to verify the model extension for the coherent backscatter regime with measurements, the boundary condition is provided by an independent OBS measurement near the surface (about 3 m below sea level, corresponding to the first usable acoustic bin). In this way, (4) defines the shape of the profile, whereas the OBS measurement pinpoints the profile. Fig. B-2.5 shows a scatter plot of OBS versus ADCP inferred suspended sediment concentration, limited to data of the coherent backscatter regime. The solid line represents the line of perfect agreement. Profiles are discernible as "strings" of points.
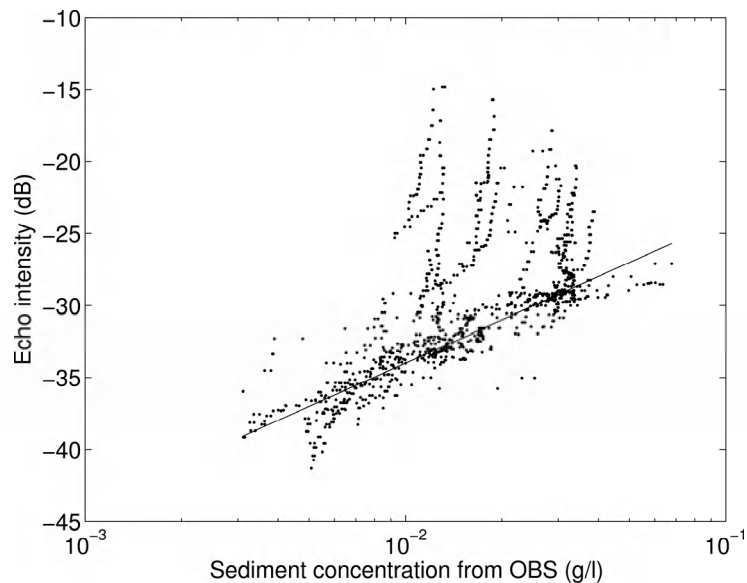

Fig. B-2.5: *ADCP estimated versus OBS derived sediment concentrations for the coherent backscatter regime only.*

As an OBS value is used as boundary condition, all profiles have their origin close to the solid line. The criterion is, however, to what extent the strings remain close or parallel to the line of perfect agreement. The results show that indeed most profiles remain within ± 5 mg.l^{-1} from the line of perfect agreement. Four profiles, appearing as two, clearly stick out by concentrations inferred from acoustic backscatter that are too low. In Merckelbach (2006) it is shown that these profiles are measured at the onset of the coherent backscatter regime, but would match well with OBS data if treated as incoherent backscatter. The most likely explanation for this is that turbulence needs time to develop when the current is quickly accelerating, but the estimate of the Kolmogorov length scale assumes steady-state conditions, or instant adjustment. Therefore the Kolmogorov length scale estimated for the onset of the coherent backscatter regime would be too small, resulting in the regime to be incorrectly identified as coherent backscatter.

iv. Disscusion and conclusions

Observational data presented herein clearly shows that if the depth-averaged current velocity exceeds a certain threshold value, the classical acoustic backscatter model as described by Thorne and Hanes (2002) fails to yield a reasonable estimate for the suspended sediment concentration. We have argued that this is caused by particles being rearranged in more organised distribution

by the effects of turbulent stirring, so that the phases of the backscattered signals are not entirely random anymore, but show some degree of coherence. This in turn yields stronger backscatter intensity, in accordance with the observations.

Particle size may also play a role as for a given concentration, fewer, but larger particles cause stronger backscatter. Although we have not considered this hererin, it is conceivable that during stronger currents larger particles can be kept in suspension. However, evidence shown and analysed in Merckelbach (2006) shows no support for changing particle size distributions as explanation of the results observed. In fact, measured particle size distributions support the method described herein, if used to break down the fitting coefficients K_i and K_c (see Merckelbach, 2006) for details).

Nevertheless, unsolved issues remain. As argued before, solving (4) requires a boundary condition. Ideally this extra information is provided by an independent measurement, such as an OBS measurement somewhere in the water column, however, in practice such measurements are not always possible or available, as is the case with the ferry based measurements. Merckelbach (2006) proposes two methods as workarounds if no independent measurement is available. The first method assumes that the concentration profile can be represented by a Rouse profile. The second method is semi-empirical, in which the effect of coherent backscatter is included in (1) by a term proportional to $\log(c^2)$. Results show that the semi-empirical method outperforms the method based on the Rouse profile, but still falls short if a OBS measurement is used as boundary condition. To improve the applicability of the proposed model, and, indeed of ADCP derived suspended sediment concentration estimates in general, the boundary condition problem requires more investigation.

References

Holdaway, G., Thorne, P., Flatt, D., Jones, S., Prandle, D. (1999). Comparison between adcp and transmissometer measurements of suspended sediment concentration. Continental Shelf Research 19: 421–441.

Merckelbach, L.M. (2006). A model for high-frequency acoustic Doppler current profiler backscatter from suspended sediment in strong currents. Continental Shelf Research 26:1316–1335.

Ridderinkhof, H., Haren, H.V., Eijgenraam, F., Hillebrand, T. (2002). Ferry observations on temperature, salinity and currents in the marsdiep tidal inlet between the north sea and wadden sea. In: Operational oceanography: implementation at the European and regional scales, Proceedings of the second international conference on EUROGOOS. Vol. 66. Elsevier Oceanography Series, pp. 139–148.

Tennekes, H., Lumley, J. (1972). A first course in turbulence. The MIT Press, Cambridge, Massachusetts, USA.

Thorne, P., Hanes, D. (2002). A review of acoustic measurement of small-scale sediment processes. Continental Shelf Research 22:603–632.