Die Küste, 69 PROMORPH (2005), 393-407

Effectiveness of Acoustic Profiling for Estimating the Concentration of Suspended Material

By POERBANDONO and ROBERTO MAYERLE

Summary

In this paper the effectiveness of several empirical approaches for converting acoustic backscatter strength into suspended material concentration is investigated. The investigation is based on simultaneous measurements performed using an Acoustic Doppler Current Profiler, an Optical Beam Transmissometer and a Niskin bottle sampler in the main tidal channels of the Dithmarschen Bight on the German North Sea coast. A wide range of conditions regarding water depths and current velocities were covered. The approaches by DEINES (1999) and GARTNER (2002) were also taken into consideration. The effectiveness of the empirical approaches was evaluated by comparing the values estimated from acoustic and optical measurements. The results obtained from both approaches were found to differ by less than a factor of 2. In a range of tests the average relative error was found to be between 20 % and 30 %, with average absolute errors of ≤ 0.08 kg/m^3. The suspended material concentrations determined from acoustic backscatter measurements are presented for a cross-section surveyed at slack water as well as during conditions of maximum current velocity. In the surveyed cross-section it was found that the concentrations of suspended material estimated from acoustic and optical measurements were similar in terms of overall tendency and gradients. The results confirm the acceptability of the investigated empirical approaches for converting acoustic backscatter strength into suspended material concentrations for the conditions in question.

Zusammenfassung

In diesem Bericht wird die Effektivität von verschiedenen empirischen Ansätzen zur Konvertierung der Stärke der akustischen Rückstreuung in Schwebstoffkonzentration untersucht. Die Untersuchung basiert auf simultanen Messungen, die mit einem Acoustic Doppler Current Profiler, einem Optical Beam Transmissometer und einem Niskin Bottle Sampler in den Haupttiderinnen der Dithmarscher Bucht an der deutschen Nordseeküste durchgeführt wurden. Ein weiter Bereich von Bedingungen bezüglich Wassertiefen und Strömungsgeschwindigkeiten wurde abgedeckt. Die Ansätze von DEINES (1999) und GARTNER (2002) wurden ebenfalls berücksichtigt. Die Effektivität der empirischen Ansätze wurde ausgewertet, indem die abgeschätzten Werte der akustischen und optischen Messungen verglichen wurden. Die Ergebnisse aus den beiden Ansätzen unterscheiden sich um weniger als den Faktor 2. In einer Reihe von Tests wurde ein mittlerer relativer Fehler zwischen 20 % und 30 % bestimmt, mit mittleren absoluten Fehlern ≤ 0.08 kg/m^3. Die Schwebstoffkonzentrationen, die durch die Acoustic-Backscatter-Messungen bestimmt wurden, werden für einen Querschnitt zum Zeitpunkt des Stauwassers und der maximalen Strömungsgeschwindigkeiten gezeigt. Es zeigte sich, dass die aus den akustischen und optischen Messungen abgeschätzten Schwebstoffkonzentrationen in dem untersuchten Querschnitt ähnlich in Bezug auf generelle Tendenzen und Gradienten waren. Die Ergebnisse bestätigen die Eignung der untersuchten empirischen Ansätze zur Konvertierung der Stärke der akustischen Rückstreuung in Schwebstoffkonzentrationen.

Keywords

Suspended Material Concentration, Acoustic Doppler Current Profiler, Optical Beam Transmissometer, Tidal Channels, Wadden Sea, North Sea.

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Contents

1. Introduction

Acoustic techniques, e.g. Acoustic Doppler Current Profilers (ADCPs), for estimating suspended material concentration have attracted increasing interest in recent years and now find wide application in practice. In this method the concentrations of solid material in a water column are related to the magnitudes of the acoustic echo intensity of the returned signal, i.e. backscatter. Acoustic devices such as ADCPs are less susceptible to biological fouling, non-intrusive and offer high spatial and temporal resolution. Several corrections are required, however, to account for sound attenuation due to the water body and scattering particles in the water column as well as acoustic energy loss. Due to the interdependency between acoustic propagation and water properties such as salinity and temperature, detailed data processing algorithms and reliable calibration methods are necessary.

The first attempts to obtain qualitative estimates of suspended material concentration using acoustic backscatter were made by SCHOTT and JOHNS (1987), FLAGG and SMITH (1989) and HEYWOOD et al. (1991). Reviews on backscatter theory are presented by LIBICKI et al. (1989) and THORNE and HARDCASTLE (1991). Methods based on a theoretical description of the backscatter from solid particles in suspension were introduced by THORNE et al. (1991). Empirical methods were introduced by YOUNG et al. (1982), VINCENT et al. (1986) and HANES et al. (1988). More recently, a number of empirical methods based on a simplified theoretical approach have been proposed by SONTEK (2002), DEINES (1999), PATINO and BYRNE (2002) and GARTNER (2002), and were tested with a certain degree of success.

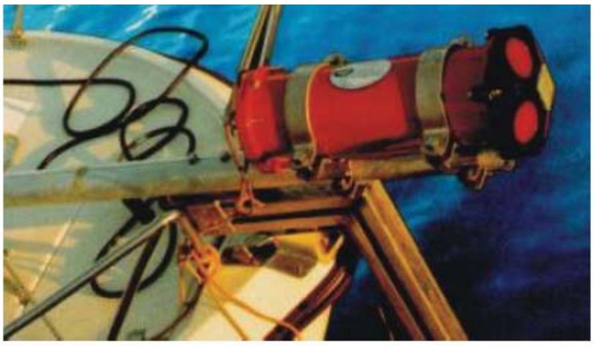
In this paper the effectiveness of the empirical acoustic methods proposed by DEINES (1999) and GARTNER (2001) were verified on the basis of field measurements of suspended material concentration using an optical beam transmissometer. Simultaneous measurements of suspended material concentrations were performed using an ADCP, an optical beam transmissometer and a Niskin bottle sampler in several cross-sections under different conditions within the framework of the research project "Prediction of Medium-scale Coastal Morphodynamics" (PROMORPH). Comparisons of suspended material concentrations obtained by converting the backscatter of optical beam transmissometer measurements were carried out to verify the conversion methods. This paper compiles the results of preliminary investigations summarized in POERBANDONO and MAYERLE (2002, 2003) and further assesses the effectiveness of the empirical methods documented in POERBANDONO and MAYERLE (2004).

2. Field Surveys

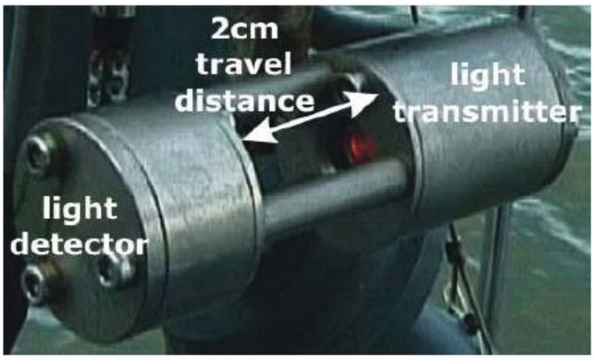
2.1 Measuring Devices

The acoustic backscatter data were obtained using a 1200 kHz Broadband Direct Reading ADCP manufactured by RD Instruments, as shown in Fig. 1a. These data are corrected for loss of intensity due to beam spreading and attenuation, assuming a constant absorption coefficient of 0.618 dB/m. The backscatter value for each bin (measurement layer) is taken to be the average of the values measured by the four transmissometer beams. The instrument was set to record a 0.5 m bin size over a 12 seconds averaging ensemble.

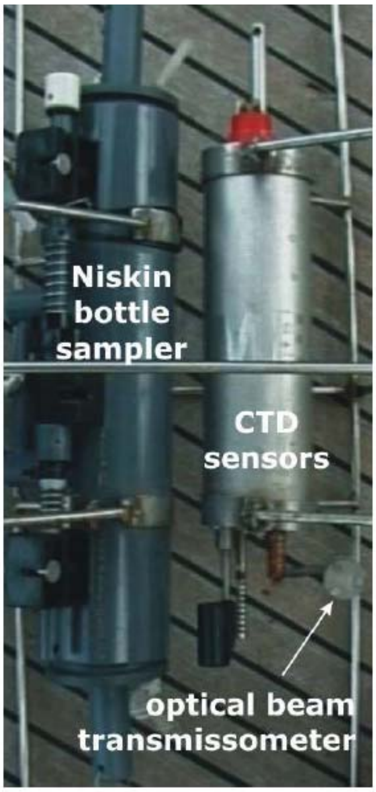
The optical transmission data were measured by means of an optical beam transmissometer (Fig. 1b) mounted in Conductivity-Temperature-Depth (CTD) sensors and equipped with a Niskin bottle sampler (Fig. 1c). The device, which employs visible light with a wavelength of 660 ± 12 nm and a 2 cm travel distance, provides a relative measure of suspended material concentration in terms of the percentage of optical transmission. In order to convert the optical transmission data into suspended material concentrations the device was calibrated against the concentrations determined from direct samples.



(a) Acoustic Doppler Current Profiler



(b) Optical beam transmissometer



(c) Niskin bottle and CTD

Fig. 1: Measuring devices used in the study

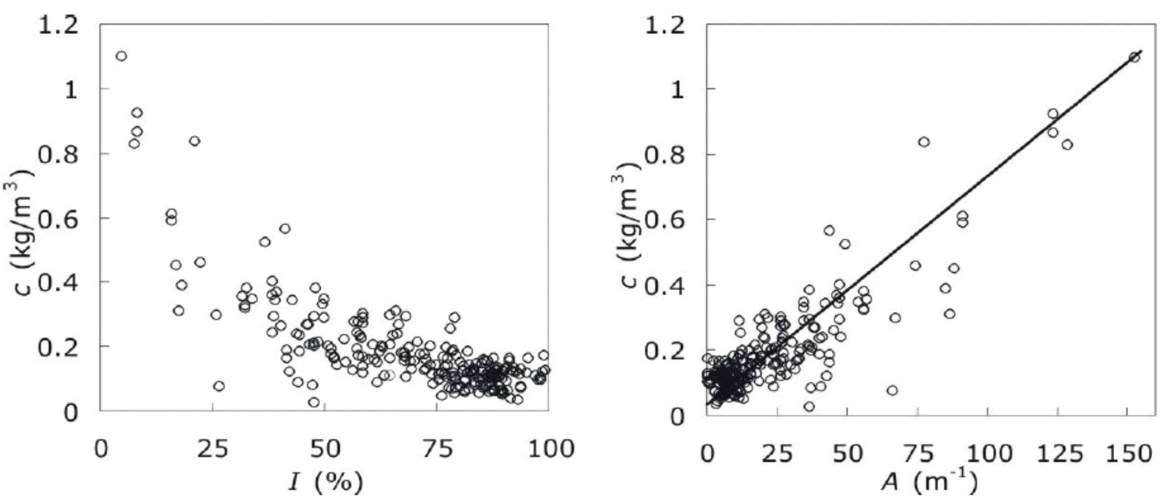
The Niskin bottle sampler was used to collect water samples of approximately 2 litres of volume. The CTD probe was mainly used to provide information of depth where optical transmission measurements and sampling of water were executed. The suspended material concentration is determined by filtering the water sample and performing a gravimetric analysis following a standard protocol resumed by VAN DER LINDE (1998). A GF/F type filter was used for the filtration. The suspended material concentration of the sample is defined as the difference in the dry weight of the filter before and after filtration divided by the sample volume.

The optical transmission data were calibrated against the suspended material concentrations determined from 200 Niskin bottle samples according to the method described by OHM (1985) and RICKLEFS (1989). The concentrations were found to vary between 0.03 and 1.10 kg/m^3. Fig. 2a shows the measured optical transmission (I) and the corresponding direct sample concentration (c). The following relationship was obtained between the suspended material concentration and optical attenuation:

$$c = (7A + 33)10^{-3} \tag{1}$$

with c = the suspended material concentration [kg/m^3]
A = the attenuation coefficient [$-L^{-1}\ln(\mathrm{I})$]
L = the transmissometer path length [cm]
I = the optical transmission as a decimal fraction.

Linear correlation of the optical attenuation and suspended material concentration data resulted in the regression line (Eq. 1) shown in Fig. 2b. A correlation coefficient $r^2 = 0.9$ was obtained for this regression analysis. Further data sets (approx. 250 data pairs) with concentrations varying between 0.02 and 1.62 kg/m^3 were used for validation purposes. In 80 % of all cases the difference between estimated and measured concentrations was less than twofold. The accuracy of optical measurements was estimated on the basis of agreement with concentrations determined from physical samples. It was found that the representative relative agreement between optical and direct sampling measurements is about 30 % POERBANDONO (2003). The optical estimation is limited to concentrations above approx. 0.03 kg/m^3. This is due to an insufficient sensitivity of the optical beam transmissometer with a path length of only 2 cm for detecting low concentrations.



(a) Concentration (c) vs. transmissibility (I) (b) Concentration (c) vs. optical attenuation (A)

Fig. 2: Calibration of optical concentration measurements

2.2 Field Measurements

Field measurements were carried out in the tidal channels of the Dithmarschen Bight. The locations of the measurement station S1 and cross-sections T1–T4 are shown in Fig. 3. In the study area the mobile bed sediments consist mainly of fine to very fine sands. Recent grab sampling surveys along the main channels indicate that the median grain size of bed sediments in the uppermost layer varies between 80 to 230 µm. The grain size of material transported in suspension is much smaller than that of bed material, with median values ranging between 10 and 90 µm. The distribution of suspended material concentration over the water column is fairly uniform (POERBANDONO et al., 2003).

Most of the field data used in this study were collected from moving vessels under calm weather conditions over the investigated cross-sections in different tidal channels. Measurements of acoustic backscatter and optical transmission profiles as well as the sampling of suspended material concentration were carried out along the cross-sections as shown in Fig. 4. The ADCP was directed downwards from the bow of the vessel and deployed for the continuous measurement of acoustic backscatter profiles over the cross-section. Measurements over the water column were made from about 1.6m below the free surface (due to the effects of transducer draught and blanking distance) down to the last 6 % of depth above the seabed (due to side lobe effects).

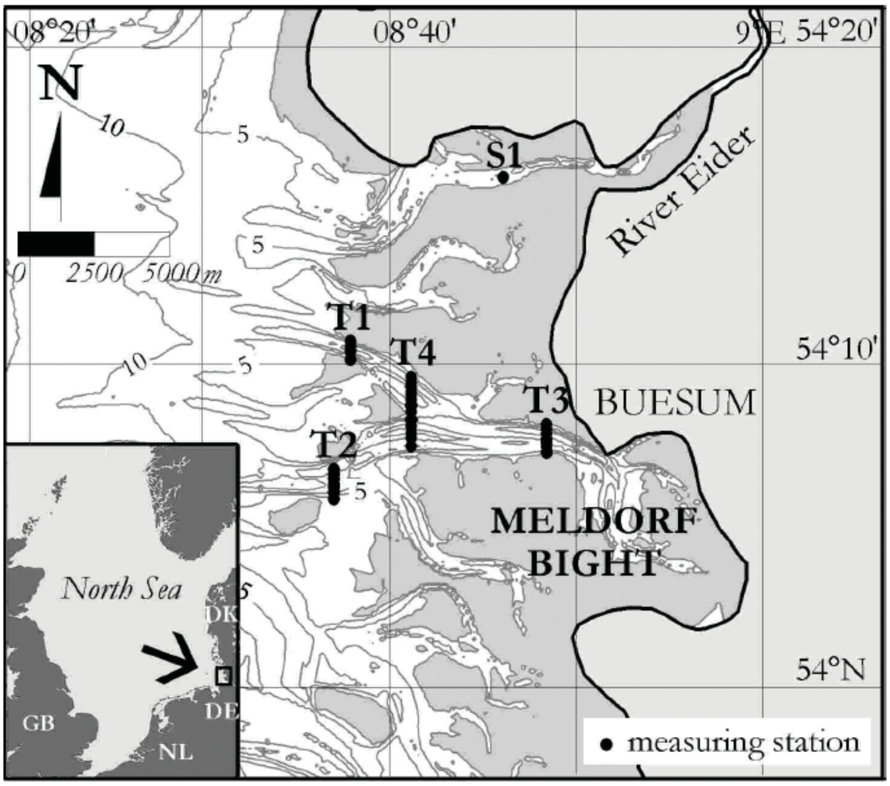


Fig. 3: Measurement locations in the study area

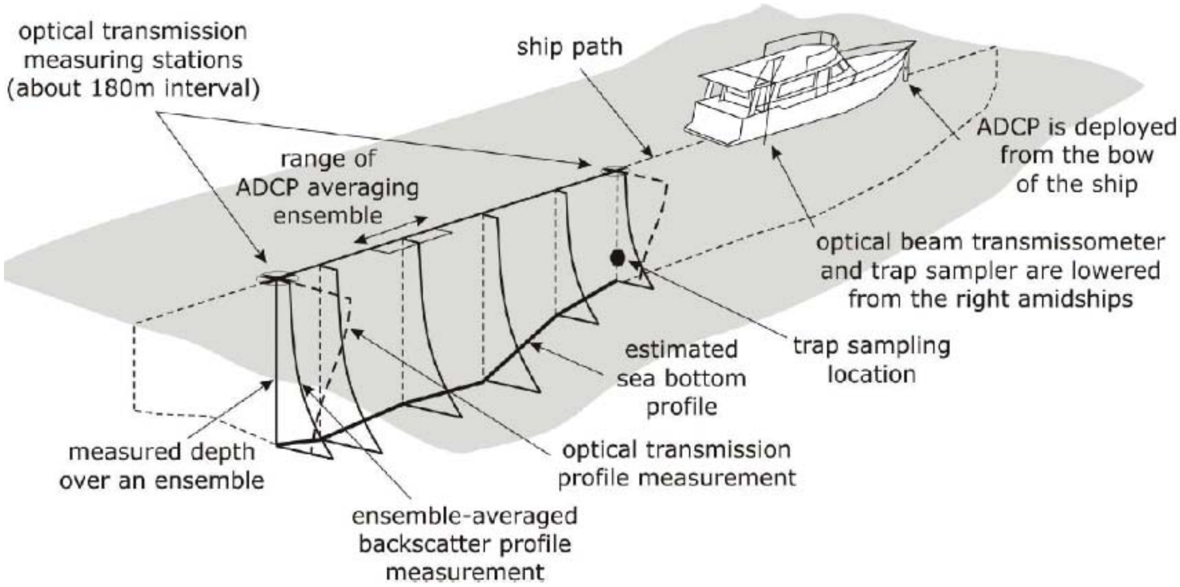


Fig. 4: Measurement procedure

Vertical optical transmission profiles at specified locations (measuring stations) at distances of about 180 m within the cross-section were measured simultaneously by lowering the optical beam transmissometer from starboard midships. The vertical resolution of the optical beam transmissometer was set to 0.2 m. The water depth and physical properties of the water column were also measured using CTD probe. Optical measurements over the water column were performed from close to the free surface down to about 0.25 m above the seabed. This restriction is due to the physical distance between the optical transmissometer and the protective frame mounted below the device. In addition, direct sampling of suspended material concentrations was also carried out deploying the Niskin bottle at a depth of approximately 1 m above the bottom. Suspended material concentrations determined from these samples varied between 0.02 to 1.15 kg/m^3.

3. Empirical Methods

A verification of the effectiveness of the two empirical methods for converting acoustic backscatter into suspended material concentration was carried out. Empirical methods are based on the assumption that the rate of acoustic attenuation is constant over the entire water column and that the grain size distribution of the sediments is uniform. In this study, two main categories were considered: a) methods based on the proportionality of the echo intensity increment between two depths in the water column and b) methods which directly relate the suspended material concentration to the echo intensity.

3.1 Methods based on the Proportionality between Echo Intensity Increments

The methods proposed by DEINES (1999) and SONTEK (2002) are based on the proportionality of the echo intensity increment ($\Delta EI = EI_z - EI_r$) between two depths in the water column. EI_z is the echo intensity value at a depth where the concentration is estimated from backscatter measurements (c_z) and EI_r is the echo intensity value at a depth where the sediment concentration is known. This level is also defined as the reference level. The suspended material concentration at the reference level (c_r) may be measured using any reliable device. The conversion equation is as follows:

$$10 \log_{10} (c_z/c_r) = K.\Delta EI \tag{2}$$

with K = proportionality constant

This method was simplified, assuming a constant acoustic attenuation coefficient, transmission power and pulse length. The best proportionality constant K was found to be 0.45 (POERBANDONO and MAYERLE, 2002). The concentration ratio between two measurement layers was thus assumed to be proportional to the echo intensity increment. The reference concentration c_r in Eq. 1 is obtained from the optically measured concentration. The reference echo intensity EI_r is the average of the backscatter values in the layer in which optical measurements are made. The choice of the reference level was found to influence the accuracy of suspended material concentrations. The effectiveness of the method improves with the number of reference levels over the vertical and proximity to the location of interest. At least one reference level is usually adopted for each vertical profile. The best agreement is achieved by setting the reference layer at mid-depth (POERBANDONO and MAYERLE, 2003).

3.2 Methods which relate Suspended Material Concentration to Echo Intensity

More simplified alternative methods relate suspended material concentration directly to echo intensity. An example of this is as follows:

$$10 \log_{10} (c_z) = a.EI_z + b \tag{3}$$

The coefficients of Eq. 3 are determined by a calibration based on simultaneous measurements of suspended material concentration using an acoustic and an alternative device. Optical devices or mechanical samplers may be used. The methods proposed by PATINO and BYRNE (2002) and GARTNER (2002) belong to this category. The advantage of this method is that the conversion does not require measurements at the reference level. The method proposed by GARTNER (2002) is evaluated. Fig. 5 shows the regression line relating backscatter data to the logarithm of concentration. 105 data sets were used in the calibration. The concentrations of physical samples collected from the Piep channel and the outer Eider Estuary were included in the analysis. These were found to vary between 0.03 and 0.7 kg/m^3. The resulting regression constants a and b in Eq. 2 obtained by calibration are 0.38 and 43.57, respectively. The conversion equation, with a corresponding correlation coefficient (r^2) of 0.81, was determined to be as follows:

$$c = 10^{(0.038EI - 4.357)} \tag{4}$$

with c = the suspended material concentration [kg/m^3]
EI = the acoustic backscatter [dB]

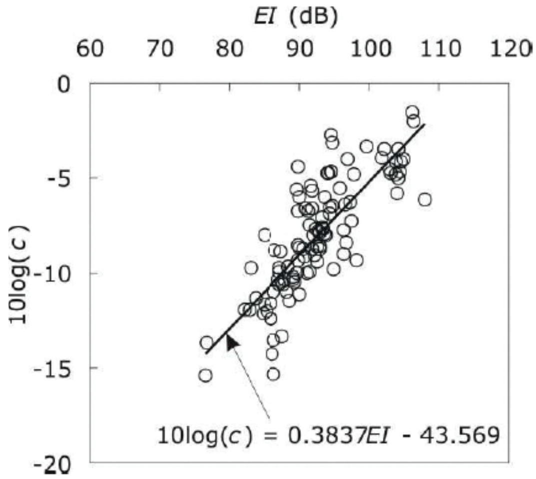


Fig. 5: Independent backscatter calibration based on direct sampling concentrations

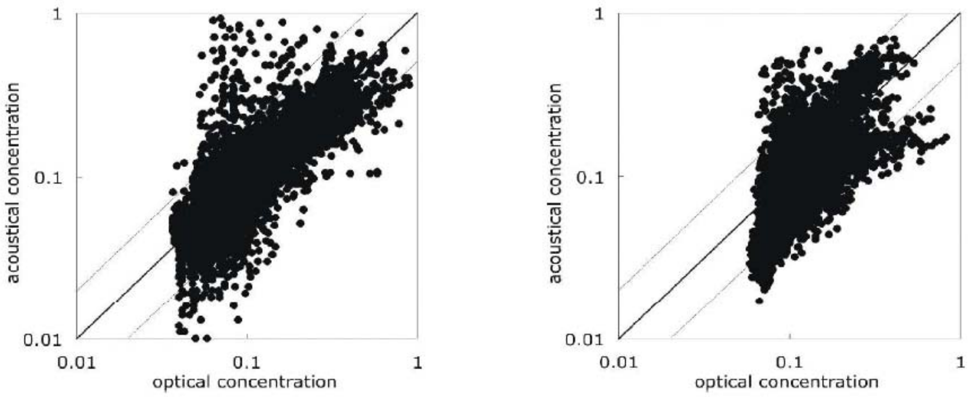
4. Effectiveness of Empirical Methods

The effectiveness of the methods of DEINES (1999) and GARTNER (2002) for estimating suspended material concentrations is quantified on the basis of agreement with measurements obtained from the optical beam transmissometer. Table 1 shows the results of comparisons of the performance of the two methods, including a summary of the range of data used. Agreement between suspended material concentrations obtained from the conversion of acoustic backscatter and optical transmissibility is quantified on the basis of the average relative error (given in %), the average absolute error (given in kg/m^3) and the discrepancy factor (% of data with a scatter of less than a factor of 2 about the regression line). The performance of the two methods investigated here is comparable. The relative errors were found to be between 21 % and 29 %, and 28 % and 31 %, according to the methods of DEINES (1999) and GARTNER (2002), respectively. An average absolute error of $\leq$ 0.08 kg/m^3 is observed. Both methods show that the majority of the data is within a discrepancy factor of 2.

Fig. 6 shows plots of the suspended material concentrations obtained by conversion of the measured acoustic backscatter using the two methods described versus those obtained by conversion of optical beam transmissometer measurements. Lines indicating discrepancy factors of 2 are shown in the figure. It can be seen that the optical concentration is limited to a value of approximately 0.03 kg/m^3. In the case of DEINES' approach the discrepancies are fairly uniformly distributed over the entire range of concentration values. In the case of GARTNER's approach a steeper trend of increasing concentration is observed, leading to a wider range of estimated concentrations. GARTNER's approach, on the other hand, appears to be simpler as it may be applied on the basis of an independent calibration using direct sampling concentrations.

Table 1: Summary of test results

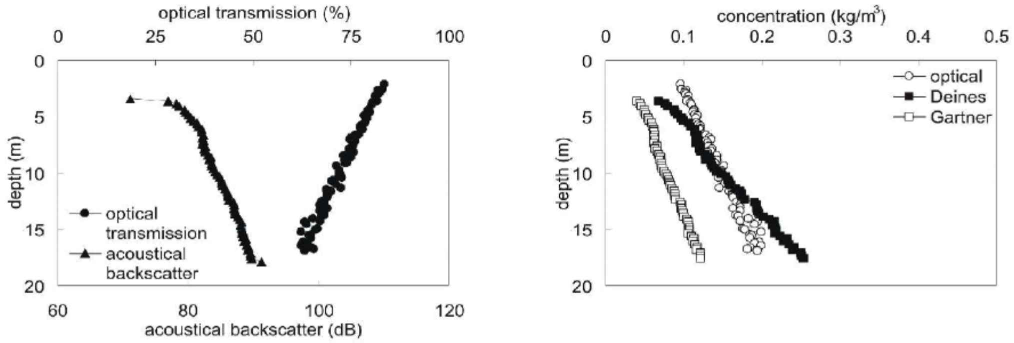
Test number	1	2	3	Average
Measurement locations	T1, T2 and T3	T3 and S1	T3 and T4	
Number of stations	201	205	345	
Number of data pairs	5174	2474	5325	
DEINES (1999):				
Relative error (%)	29	21	–	25
Absolute error (kg/m³)	0.06	0.07	–	0.07
Discrepancy factor of 2 (%)	97	97	–	97
GARTNER (2000):				
Relative error (%)	–	28	31	30
Absolute error (kg/m³)	–	0.08	0.03	0.06
Discrepancy factor of 2 (%)	–	94	93	94



(a) DEINES (1999) approach (b) GARTNER (2002) approach

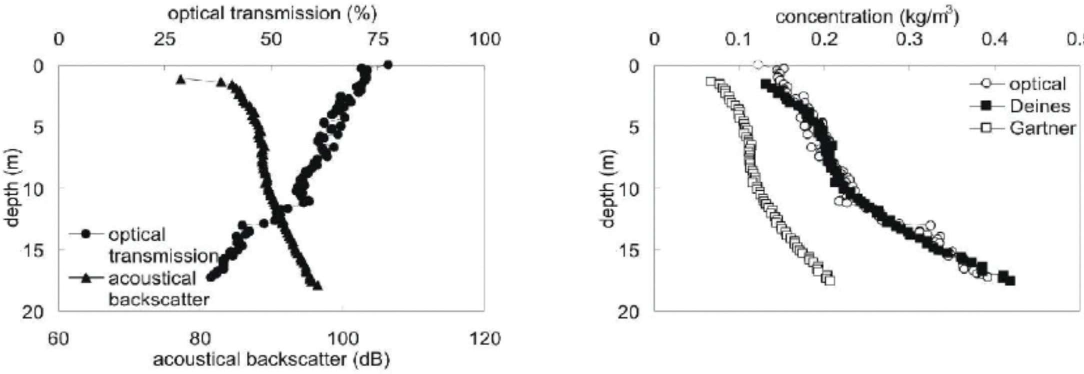
Fig. 6: Comparison of optical and acoustic concentration measurements in kg/m³

Typical profiles of measured and converted sediment concentrations at two locations over cross-section T3 are shown in Figs. 7 and 8. An example of a non-uniform concentration profile is shown in Fig. 9.



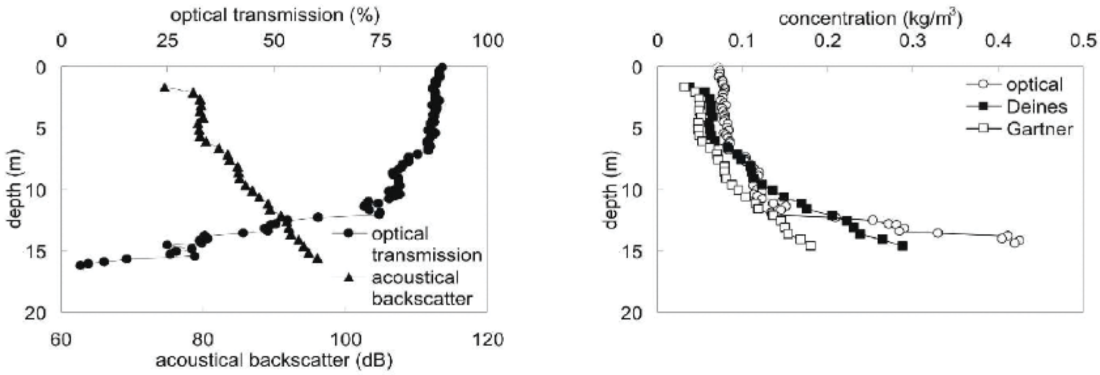
(a) Measured parameters (b) Estimated concentrations

Fig. 7: Profile measurement in cross-section T3 during slack water on 23 March 2000



(a) Measured parameters (b) Estimated concentrations

Fig. 8: Profile measurement in cross-section T3 during maximum flood flow on 23 March 2000



(a) Measured parameters (b) Estimated concentrations

Fig. 9: Profile measurement of high near-bed concentrations in cross-section T3 on 22 June 2001

The figures show the measured acoustic backscatter and optical transmissibility values as well as the suspended material concentrations obtained by conversion of the acoustic backscatter data using the two methods described as well as from optical transmissibility. The concentrations estimated from optical and acoustic measurements generally show a similar increase over the entire depth. The concentration profile obtained by DEINES' method exhibits gradient magnification due to the fact that this profile depends on the local reference concentration and the increment of backscatter values relative to the value at the reference level. The concentration profile obtained by Gartner's method tends to be underestimated.

Backscatter data recorded by the ADCP represent the scattering layer density of a water column. In the last bin (bin closest to the seabed) side lobe interference leads to a very high echo intensity value. In the bin closest to the transducers it is found that the backscatter data tend to be weaker. It is possible to identify such a tendency since the vertical profile of backscatter data usually exhibits extreme gradients in the second bin. This is due to the ADCP transient time required for transmitting and receiving a signal. A similar finding has also been reported by BIRCH et al. (1999) and LANE et al. (1999). For these reasons it is recommended to ignore the backscatter data from the first and last bins.

Figs. 10 and 11 show various measured quantities and suspended material concentrations obtained from conversions of optical and acoustic measurements over cross-section T3. Values are shown for slack water and maximum flood flow conditions for a spring tide on 23 March 2000. Acoustic backscatter measurements were performed over the entire cross-section whereas optical measurements were made at the point locations indicated in red in the figures.

According to the example shown in Fig. 10, the measured optical transmission during slack water is fairly evenly distributed over the cross-section, ranging between 70 % and 80 % (Fig. 10a). As may be seen in Fig. 10c, a similar tendency of uniform distribution in the measured acoustic backscatter was also obtained over the cross-section with values ranging between 80dB and 90dB. Higher turbidity was given by both optical and acoustic estimations in the deeper part of the channel. This is indicated by lower optical transmission and higher acoustic backscatter. The suspended material concentrations obtained from optical transmission and acoustic backscatter conversions are in very close agreement. The absolute suspended material concentrations given by DEINES' and GARTNER's methods differ from those obtained by optical transmission conversion by less than a factor of 2.

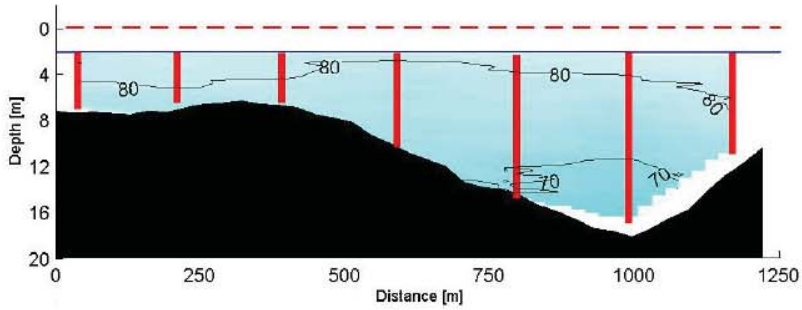
During maximum flow conditions, increased turbidity was observed with an increase in the magnitude and gradient of the measured optical transmission and acoustic backscatter profiles (Fig. 11). Optical transmission in the near-surface layer remains fairly constant at a value of about 80 % whereas close to seabed it decreases down to about 50 %. A similar tendency is also observed in the acoustic backscatter measurements. A slight increase in echo intensity is also observed in the upper layer. The measured acoustic backscatter is found to exceed 95 dB close to the seabed. Very close agreement is also obtained between the suspended material concentrations determined from optical transmission and acoustic backscatter conversions. Optical and acoustic measurements both indicate higher concentrations in the lower layer. In this case the acoustic concentration estimate based on Gartner's approach yields a very close value of approximately 0.3 kg/m^3, whereas acoustic estimation based on Deines' approach shows a slight deviation in the order of a factor of 1.5.

Investigations were also carried out to examine the possible dependency of discrepancies on various influencing factors such as spatial position, measurement location (different cross-sections and stations), water depth, velocity and levels of concentration (determined from optical measurements). A clear dependency of the discrepancies on location, water depth and magnitude of the current velocity was not identified.

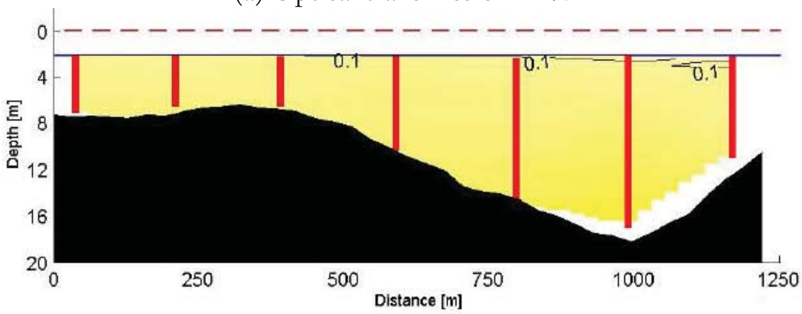
5. Conclusions

The effectiveness of empirical methods for converting acoustic backscatter strength measured by an ADCP into suspended material concentration has been demonstrated. The performance of the methods was found to be comparable to estimations obtained from an optical beam transmissometer. The method of GARTNER (2002) appears to be advantageous for practical applications as it is simpler and offers comparable performance. In this case the conversion may be carried out directly without the need for measurements of suspended sediment concentrations using other devices. It is recommended, however, to apply this method only within the range of applicability of the equation derived for conversion. The application of DEINES' method (1999), on the other hand, requires measurements of suspended sediment concentrations.

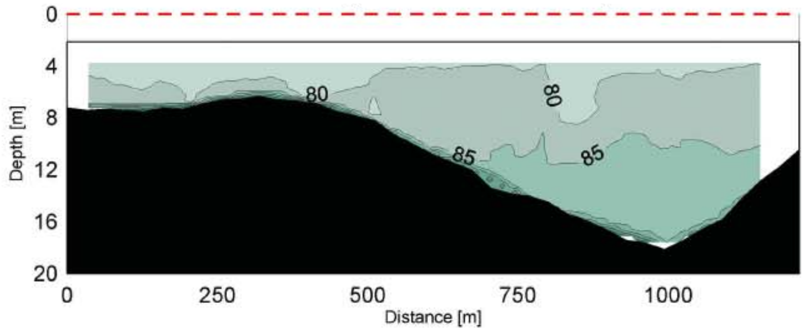
The performance of the two methods was found to be comparable for conditions in



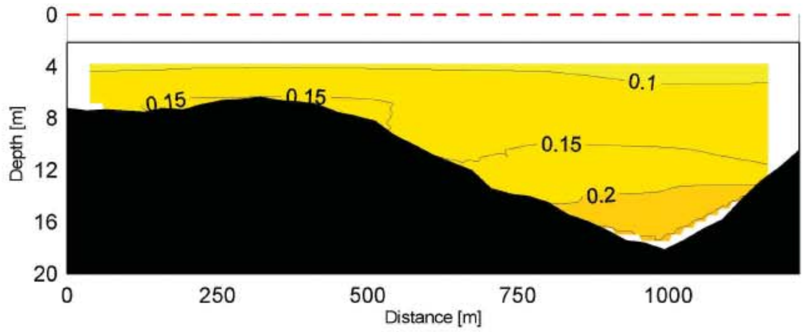
(a) Optical transmission in %



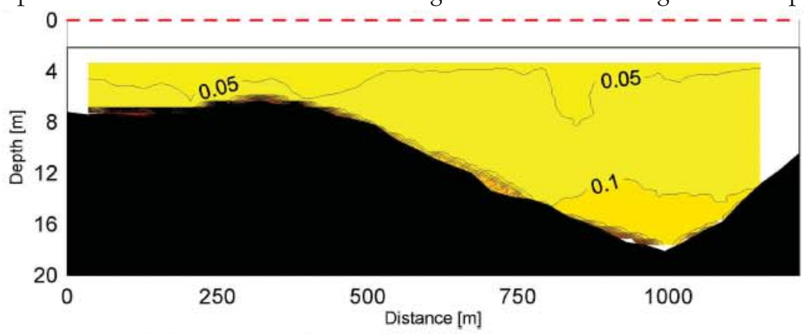
(b) Suspended material concentrations in kg/m^3 obtained from optical transmission conversion



(c) Acoustic backscatter in dB

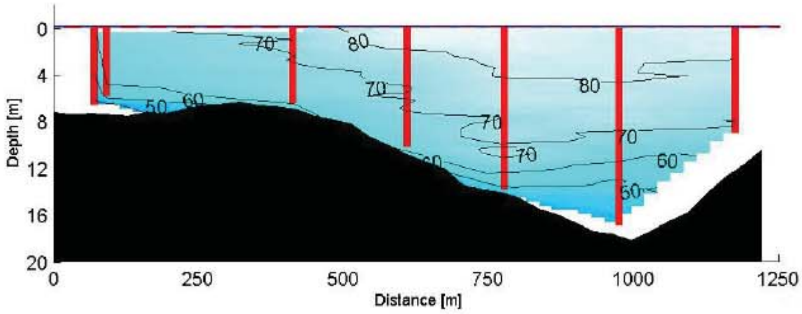


(d) Suspended material concentrations in kg/m^3 estimated using DEINES' approach

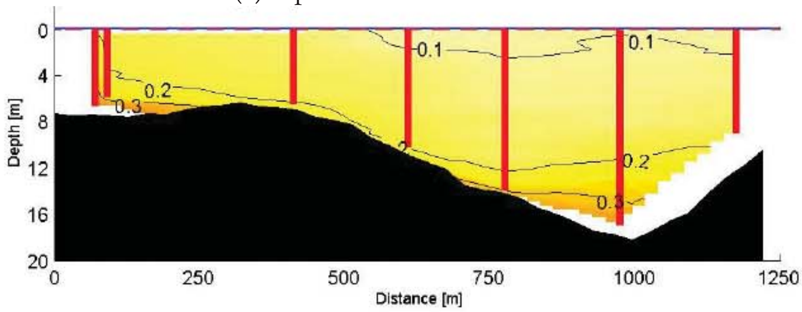


(e) Suspended material concentrations in kg/m^3 estimated using GARTNER's approach

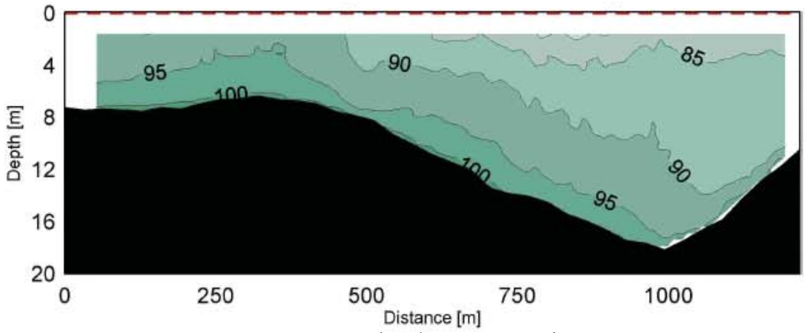
Fig. 10: Measurements over cross-section T3 during slack water on 23 March 2000



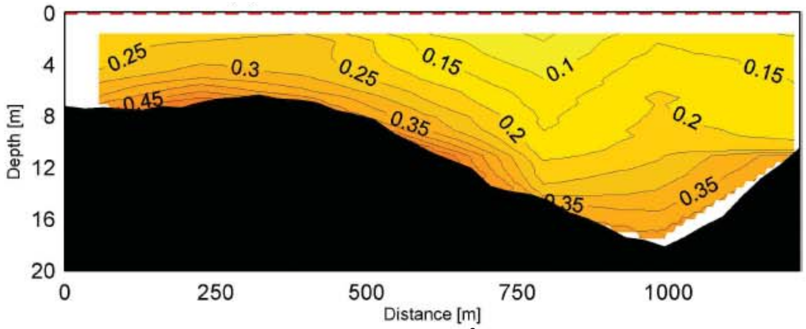
(a) Optical transmission in %



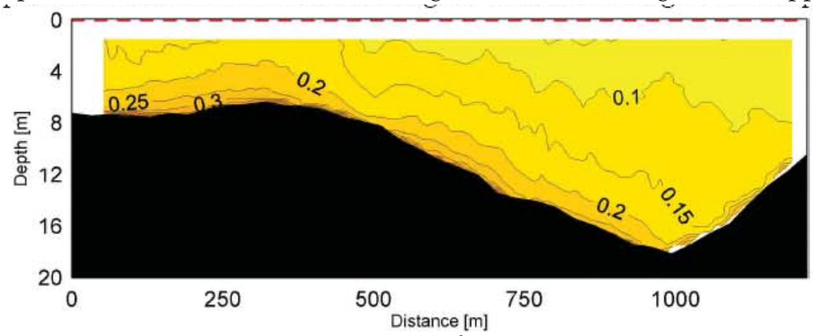
(b) Suspended material concentrations in kg/m³ obtained from optical transmission conversion



(c) Acoustic backscatter in dB



(d) Suspended material concentrations in kg/m³ estimated using DEINES' approach



(e) Suspended material concentrations in kg/m³ estimated using GARTNER's approach

Fig. 11: Measurements over cross-section T3 during maximum flood flow conditions on 23 March 2000

the study area, with suspended sediment concentrations ranging between about 0.02 and 1.2 kg/m^3 . Estimates of suspended material concentration were found to be within a factor of 2 compared with measurements obtained using an optical beam transmissometer. The average relative error was found to be about 30 % whereas values the absolute error were found to be approximately equal to or better than 0.08 kg/m^3 on average. It was not possible to detect any effects of water depth, current velocity or location on the performance of the methods of conversion within the considered limit of a discrepancy factor of 2.

6. Acknowledgements

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