Geol. Bull. Univ. Peshawar, 1990, Vol. 23, pp. 161-173

UNDERWATER ACOUSTIC MEASUREMENT OF SUSPENDED SEDIMENTS: THE CALIBRATION OF A HIGH-FREQUENCY ACOUSTIC BACKSCATTER METER

SYED SHAFIQUR REHMAN[1] & C.E. VINCENT[2]

[1]Department of Geology, University of Peshawar, Peshawar, Pakistan

[2]School of Environmental Sciences, University of East Anglia, Norwich, England

ABSTRACT

A shortwave multi-frequency acoustic backscatter meter (ABM) has been developed for measuring profiles of near-bed suspended sediments in shallow marine and fluvial environments. The system comprises of a monostatic, active pulse sonar using three frequencies 5.65, 7.0 and 10.1 MHz, simultaneously and is capable of taking measurements over a range of 1.28 m.

Before its field deployment the ABM was calibrated in a tank, with 40 l of recirculating water, against a wide range of particle sizes including fine-sand and coarse- to medium-silt. The averaged profiles of backscattered pressure revealed that the rate of attenuation increases rapidly with increase in the frequency. Inspection of the raw data indicated that the size of suspended particles determines the amplitude of the backscattered signal more effectively than the quantity.

A model has been developed to convert the measured backscattered pressure into sediment concentration (mg/l). The model takes into account coefficients of attenuation due to water and sediments as well as beam strength and the acoustic cross-section of particles. Results indicate that the model is fairly reliable.

INTRODUCTION

Particulate matter suspended in water is called *seston*. It ranges in size from a fraction of a μm to a couple of mm, and in densities between values very close to that of seawater (for organic matter) to about 2.65 g/cm^3 (for quartz). Sediments are lifted into suspension when the vertical upward velocity of turbulent eddies exceeds the grain weight. These particles are transported as suspended load by horizontal currents untill they settle out when the currents stop flowing. Hence, current velocity and shear stress (caused by friction at the boundary layer) play a very important role in sediment transport. Accurate determination of the size and concentration of suspended sediment is, therefore, considered very important to understand the relationship between flow dynamics and sediment transport.

The application of acoustics for under-water measurement has markedly increased after its successfull military uses like ASDIC (Anti Submarine Detection Investigation Code) and SONAR (Sound Navigation and Ranging). Acoustics are preferred over other forms of underwater sensing for their better impedance (product of sound velocity and density of water), relatively longer range of transmissions and non-intrusive nature. Acoustical methods can provide very reliable and spontaneous measurements of suspended sediments with high spatial and temporal resolution.

A major difficulty involved in using acoustic devices for measuring suspended sediment flux is the translation of data from digitized output into a certain concentration (as mg/l). This requires a careful calibration of the instruments prior to their field deployment. In the last decade or so acoustic devices have been used by several workers to obtain profiles of suspended load from marine environments. These include Orr & Hess (1978); Young et al. (1982); Vincent et al. (1982, 1986); Hay (1983); Hess & Bedford (1985); Hanes & Vincent (1987); and Vincent & Green (1990). Despite the fact that so many workers have described and used the technique in recent years a standard calibration model has not yet been evolved. However, attempts made by Young et al. (1982); Tamura & Hanes (1986) and, Thorne et al. (1990) to calibrate the acoustic devices using semi-empirical techniques are noteworthy.

In this paper also, an attemp has been made to describe a Multi-Frequency ultrasonic system (Acoustic Backscatter Meter or ABM for short) and develop a calibration model for it. The system uses three short wavelength frequencies (5.65, 7.0 and 10.1 MHz) simultaneously. The components and working mechanism of a similar system, have been discussed by Rehman & Vincent (1988).

THEORY

Before describing the ABM's calibration procedure and model, it is important to explain some of the basic terms and principles involved in the use of underwater sound.

(i) The precision of acoustic data depend on the magnitude of signal to noise ratio. Part of the acoustic field at a receiver is the backscattered portion of an incident signal, however, the remainder is undesired and may be regarded as the *background*. This background may further be classified into *noise* or *reverberation*. Noise is produced by the electronic circuitry of the instrument (self noise) and also by other sources present in water (ambient noise). While reverberation is the slowly decaying portion of background representing the sound scattered towards the source by bottom or other small scatterers along the transmission path.

Reverberation levels generally increase linearly with the duration of pulse, range of sonar, and numbers of scatterers. In the present study reverberation was ignored because the pulse length was 10 μs long and range of the ABM was 128 cm. Noise was measured directly (ambient/self noise) and subtracted from the output before calculating the concentration of suspended sediment.

(ii) *Transmission loss* is the difference in the amplitude of the incident and backscattered acoustic signal. It is caused by a loss in the strength incurred during two-way travel of the signal between the source and the target. Two important phenomena namely, *spreading* and *attenuation* are responsible for this loss. *Spreading loss* is the geometrically regular weakening of signal as it spalys outward from the source whereby its intensity decreases and the spreading loss increases as a square of the range. Attenuation is however, independent of geometrical spreading and can be caused due to absorption of the signal by water and suspended particles.

Attenuation losses vary linearly with the range and are expressed as the number of decibels per unit area. They primarily depend on the measuring frequency but are also affected by the variations in temperature, salinity, density and depth of water. Coefficients of attenuation α_W (absorption due to water) can be calculated as follows and the results for frequencies used in this research are listed in Table 1 (Fisher & Simmons, 1977) :

$$\alpha_W = (55.9 - 2.37\ T + 4.77 \times 10^{-2}\ T^2 - 3.84 \times 10^{-4}\ T^3) \times 10^{-3}\ f^2 \quad .....(I)$$

Values presented in Table 1 suggest that the absorption of sound by water is directly proportional to the wavelength of the measuring frequency. This results in a rapid fall of the range of propagation for higher frequencies and confirms Hunter's (1970) observation that in underwater acoustics a frequency of 10 MHz is unusable because the absorption would be more than 30 dB/m. The relationship between wavelength of various frequencies and range (distance travelled by the beam) suggests that low frequencies are more useful for long range propagation compared to higher frequencies (Fig. 1).

(iii) Attenuation by suspended particles (α_s) is not significant at low concentrations found in normal marine environments (< 100 mg/l; Libicki et al., 1989). Nonetheless, at high current velocity the concentration may considerably increase beyond 100 mg/l, particularly in the boundary layer. Under such circumstances a significant part of the beam pressure may be attenuated by the suspended particles also.

TABLE 1. COEFFICIENTS OF ATTENUATION (ABSORPTION BY WATER) FOR THE THREE USED FREQUENCIES IN FRESH AND SEAWATER.

Frequency (MHz)	Coefficients of absorption (dB/m) Seawater T = 8 °C S = 34 ppt	Fresh water T = 14 °C S = 0 ppt
5.65	9.7	8.57
7.0	14.87	13.16
10.1	30.87	27.39

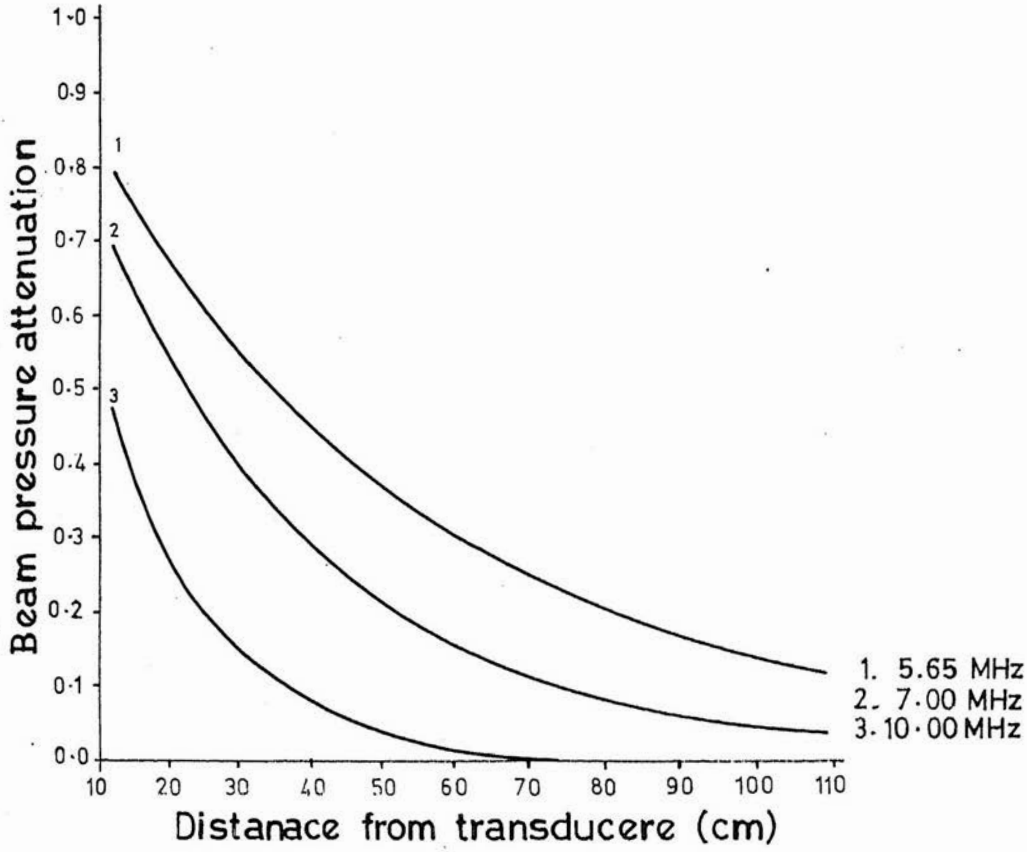

Fig. 1. The effect of beam pressure attenuation (due to water) in a two-way transmission on different frequencies.

The calculation of α_s is slightly more complex than α_w. It takes into account mass concentration and physical properties of the particles including their bulk compressibilities, number, radii, densities and shape. It has been suggested that losses due to absorption are minor and should be ignored, whereas, scattering is the predominant cause of attenuation [Hay, 1983; Libicki et al., 1989; Thorne, 1989 (Pers.Comm)].

(iv) The ensonified field of any transceiver can be divided into two distinct zones on the basis of beam spreading behaviour. The inner circle of high pressure amplitude is termed as *nearfield* separated by a transition zone (r_{nf}) from the perepheral somewhat lesser pressure amplitude circle *farfield*. In the farfield ($r > r_{nf}$) the acoustic pressure of the signal is inversely proportional to the distance (r) from the source (Urick, 1983). Whereas, in the nearfield ($r < r_{nf}$) the spreading is complex and irregular and, therefore, does not fall off smoothly with distance.

In the present work the near-far field transition was determined from the expression:

$$r_{nf} = kr_t2$$

where k is the acoustic wavenumber, and r_t is the radius of the transducer. k can be determined by:

$$k = 2\pi/\lambda$$

where λ represents the wavelength of the beam and its value can be obtained from λ = C/f (the speed of sound in m/s divided by the frequency in Hz).

The values of r_{nf} thus obtained were 0.87, 1.08 and 1.28 m for 5.65, 7.0 and 10.1 MHz, respectively. If the point (from where the acoustic reflection was to be measured) fell outside the transition zone, for a particular transducer, the actual distance r (cm) was used in the calculations. However, inside the circle it had to be replaced by a new value (r_1) which worked as a first order correction to the nearfield (Thorne et al., 1990):

$$r_1 = (2\,(r_{nf}/r))/3 \text{ .... (II)}$$

(v) A high attenuation rate of the beam was anticipated at the time of designing the ABM and to compensate for that loss, *Time Variable Gain* (TVG) was included in the receiver. The TVG amplifies the signal linrely with time whereby an output of 3 and 4 volts is produced from an input of 14 and 22 μV, respectively, in a matter of 2.2 milli-seconds (Fig. 2). In order to calculate the correction factor for various distances (r) from the transceiver, the gain level at 2.2 milli-seconds was taken as unity (1) and rest of the distances were accordingly scaled down.

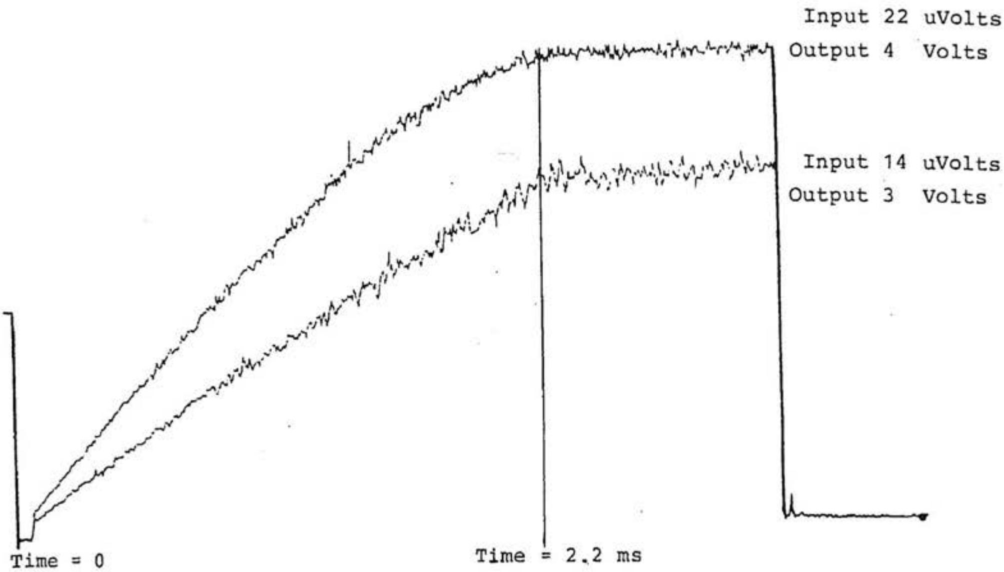

Fig. 2. Time Variable Gain (TVG). The amplitude of backscattered signal increases with time from 14 and 22 micro-volts to 3 and 4 Volts, respectively in a matter of 2.2 millisecond.

INSTRUMENTATION

The ABM belongs to *monostatic active pulse* SONAR system having three disc-shaped transducers of 12 mm diameter for 5.65, 7.0 and 10.1 MHz frequencies, respectively. It emits a burst of individual sound signals (pings of 10 μs duration each) at a rate of 4 Hz and then remains quiet untill the next burst. The signal is emitted in a narrow beam which ensonifies the particles lying in the path of the beam. The particles backscatter the signal towards the tranceiver where it is received, as backscattered-pressure (P_b), digitized, amplified and recorded as a complete profile.

Between amplification and recording an important phenomenon of range-gating of the return signal also took place. At the end of each ping the transceiver starts receiving echos continuously. These echos are grouped into independent cells after every 12.5 μs in order to produce a single average digitized P_b value from successive range-cells of about 1 cm height. Thus a complete profile contains 128 P_b values for the 128 cm working range of the ABM.

Due to the shortage of recording space and to get reliable data, significant temporal and spatial averaging of the signal was performed before recording. The profile of 128 P_b values was reduced to 31 by vertical averaging of adjacent cells. The top most 64 cm are represented with a resolution of 8 cm, the next 32 cm with a rseolution of 4 cm, and the near-bottom 32 cm with a 2 cm vertical resolution. The first 8 cm distance (nearest to the transceiver) was discarded and the space was used to record the date and time of the burst. Similarly, data from all the pings of a burst was temporally averaged to give a single P_b value per segment per burst.

CALIBRATION

Preparation

Calibration exercises of the ABM were performed in 1m long cylindrical plastic tank with a capacity of about 42 litres of water (Fig. 3). At the open base of the tank a funnel and a small pump were fixed to recirculate water through an external hose and a diffuser at the top of the tank. This was necessary to keep the particles uniformly suspended in the tank throughout the exercise. The tank was vertically mounted on a frame with one transceiver (at a time) positioned at the top, looking straight down along its central axis. The data were recorded in a logger connected through a cable to the transceivers, whereas an oscillo-scope was used to dispaly the signal simultaneously.

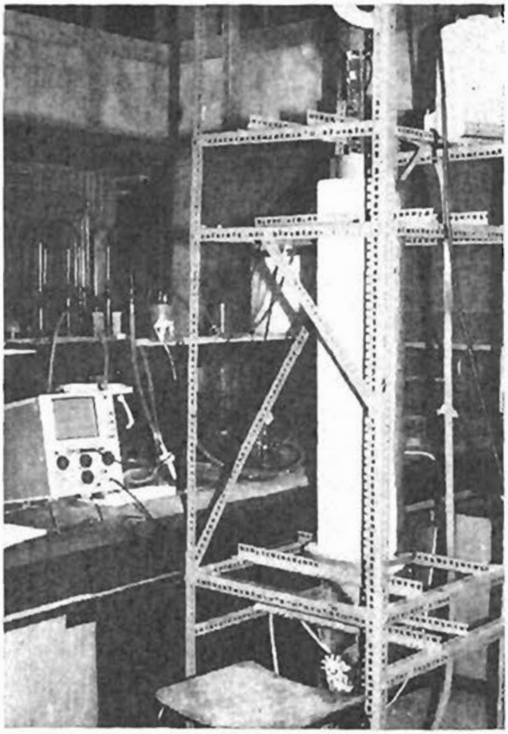

Fig. 3. Photograph showing the cylindrical tank, the pump, the external hose and ABM for laboratory calibration.

It was essential to ensure the cleanliness of the system before starting exercises. Therefore, all components of the system including tank, funnel, pump and hose were thoroughly washed with a brush and rinsed repeatedly with clean water. The tank was then filled with about 40 l of filtered tap water and the pump was turned on to start circulation of water in the system (for 10-15 minutes) to enable the air bubbles to surface up and die out.

To calibrate the ABM against a wide range of particles, sediments of four different sizes were used in calibration. These included particles with a mean diameter of 125, 50, 40, and 30 μm. Between each sediment size, however, the tank was emptied, washed thoroughly and refilled with clean water. The concentration of all samples was gradually increased from 1 through 2, 3, 4, 5, and 10 g per 40 l of water in the tank. Acoustic measurements were recorded at each step with the 3 transceivers of the ABM, independently.

Methodology

The first set of measurements recorded by 3 transceivers of the ABM were with clean water in the tank to measure the noise. This was followed by injecting one gram of sediment into the tank which was allowed to circulate in the system for about 10 minutes to obtain a uniform distribution of the particles. At this stage the ABM was triggered externally to measure the concentration as P_b value for the transceiver using 5.65 MHz frequency. The next 2 measurements were recorded by using the transceivers for 7.0 and 10.1 MHz, respectively. The concentrations were likewise raised incrementally and data were recorded for all the 3 frequencies.

In order to obtain reliable acoustic data every sediment sample was run three times. On each occasion about half a litre of water was siphoned out from the middle of the tank to measure the suspended sediment concentration directly. The water sample was immediately filtered through a pre-weighed filter paper of high retention. After drying the paper, weight of the sediment per sample was determined and converted into mg/l. Average values of suspended sediment concentration in the tank, obtained by direct sampling are presented in Table 2.

After extensive temporal and spatial averaging of the data, a single profile consisting of 31 P_b values was produced per burst for each frequency. Background noise, measured during respective empty runs, was subtracted from the raw data and corrected P_b profiles were graphically plotted to see their general shape (Fig. 4). It is clearly evident from the figure that, size of the scatterers is more important than their number in producing high P_b values. The gradual drop in P_b values (from 20 cm downwards) reflect upon attenuation of the beam due to water and sediment. Abrupt termination of various curves along the X-axis for 7.0 and 10.1 MHz, clearly indicates that attenuation of the beam increases linearly with increase in the frequencies. Thus it was decided to abaondon the use of 10.1 MHz frequency for determining concentrations, on the basis of its extremely high attenuation rate.

TABLE 2. CONCENTRATIONS (mg/l) MEASURED BY SAMPLING FROM THE TANK DURING CALIBRATION EXERCISE (AVERAGE OF 3 RUNS).

Sediment szie	Amount of sediment/40 l water in the tank					
μm	1 g	2 g	3 g	4 g	5 g	10 g
125	15	25	34	46	56	
50	21	27	36	48	63	152
40	24	44	60	76	94	188
30	25	48	68	85	106	217

CONVERSION OF BACKSCATTER DATA INTO CONCENTRATIONS

According to acoustic backscatter theory, the amplitude of backscattered signal (P_b) from a suspension of an aggregate of particles at range r in the far field, is given by:

$$P_b = B \times (C_{(r)}/r) \times \exp^{-(2r \alpha w + 2 \alpha s \ C(r') \, dr')} \qquad \text{(III)}$$

where B represents acoustic cross-section of the sediment and the beam strength, $C_{(r)}$ is the concentration of suspended particles at a distance r from the device, α_w and α_s are the coefficients of beam pressure attenuation due to water and sediment, respectively. The factor of 2 in the exponential represents 2-way travel of the sound.

However, to convert the measured P_b value into suspended sediment concentration, equation III can be re-written as:

$$C = [(P_b \times r)/B \times TVG \times \exp^{-(2r \alpha w + \alpha s \ C(r) \, dr)}]^2 \qquad \text{(IV)}$$

where r represents the farfield ($r > r_{nf}$) of the transceiver and TVG is the correction factor for time variable gain as a function of range. If, however, P_b values from the nearfield ($r < r_{nf}$) are to be converted, r is substituted by r_1 (see equation II).

The values of B, including acoustic cross-section of the sediment and the beam strength, were calculated for all the three frequencies as follows:

$$B = P_b \, (r)/C \times \exp^{(2r \alpha w)} \qquad \text{(V)}$$

where C represents the concentration measured by direct sampling from the tank. Attenuation due to sediment was omitted because concentrations in the tank were not considered high enough to be causing attenuation (Libicki, 1989). Mean values of B, thus obtained are listed in Table 3.

TABLE 3. MEAN VALUES OF B, CALCULATED FOR VARIOUS SEDIMENT SIZES FROM THE TWO FREQUENCIES 5.65 AND 7.0 MHz.

Sediment size μm	Mean values of B for frequencies 5.65 MHz	7.0 MHz
125	69.70	71.06
50	49.68	59.30
40	21.91	34.48
30	19.84	31.39

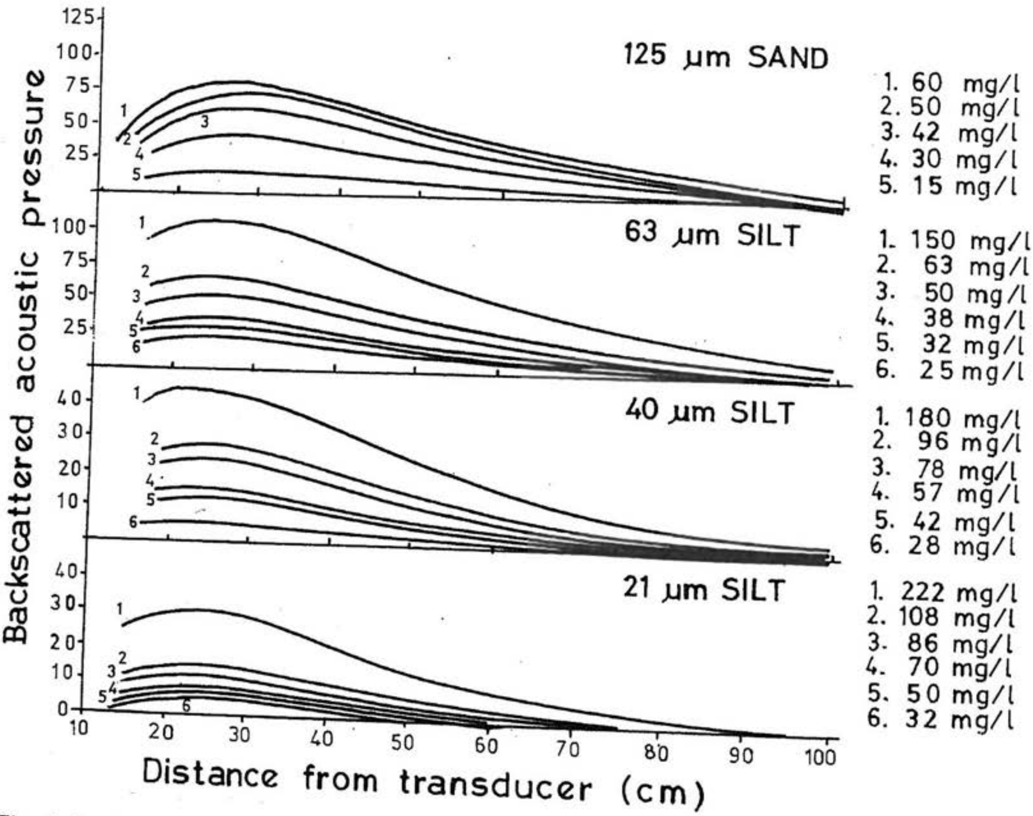

Fig. 4. Profiles of suspended sediment in the tank during calibration exercises. (a) values of backscattered pressure (P_b) from 5.65 MHz frequency.

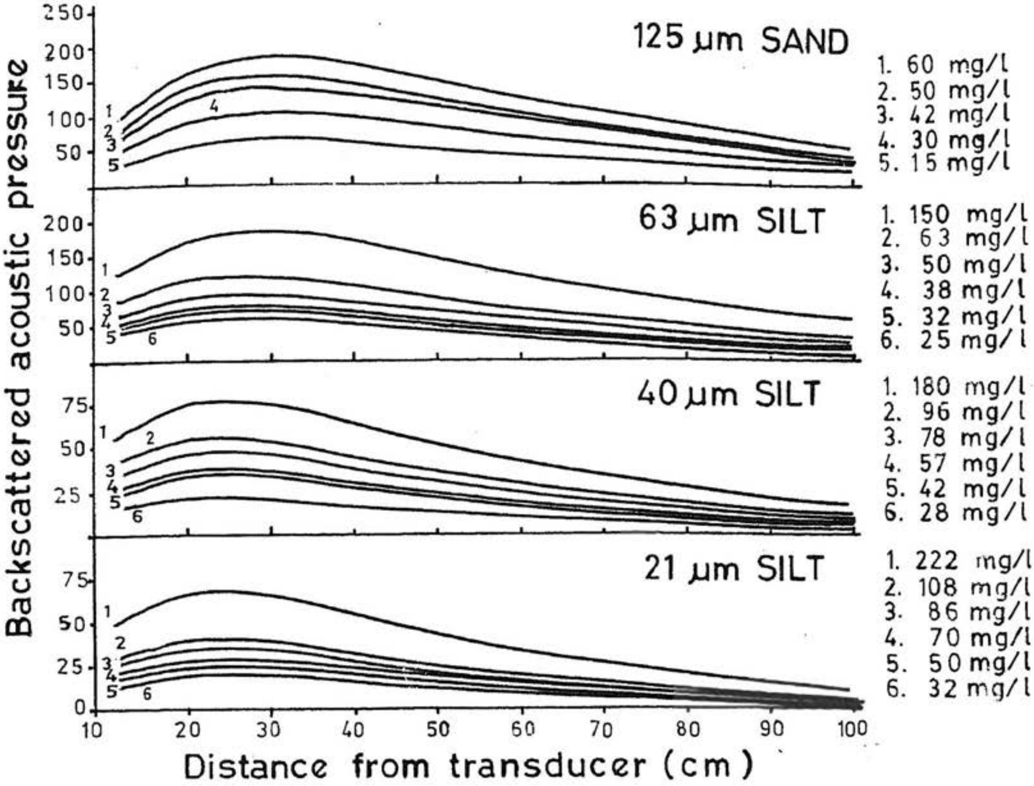

Fig. 4. (Continued) (b) P_b from 7.0 MHz frequency.

DISCUSSION AND CONCLUSIONS

The calibration model (equation IV) was used to convert the field data, comprising of raw P_b profiles, into concentration. The results seemed fairly reliable and clearly demonstrated that, of the three frequencies used by the ABM, 5.65 MHz was most useful while, 10.1 MHz was practically unusable due to their respective attenuation rates. The key factor, besides α_w and α_s, in the model seems to be the value of B. Inaccurate values of any of the three parameters, mentioned above, may lead to uncertainties in the final concentration.

Data in Table 3 shows a definite variation in the values of B with changes in the sediment diameter. Hence, priority should be given to sampling water from the sea from heights corresponding to the ABM measurements to know the size of material in suspension. During our exercise sieved sediments with short range of diameters, were used for calibration and values of B were determined for each size sparately. However, naturally occuring sediments have mixed sizes and in order for the B values to be precise, the ABM should be calibrated against mixed muds.

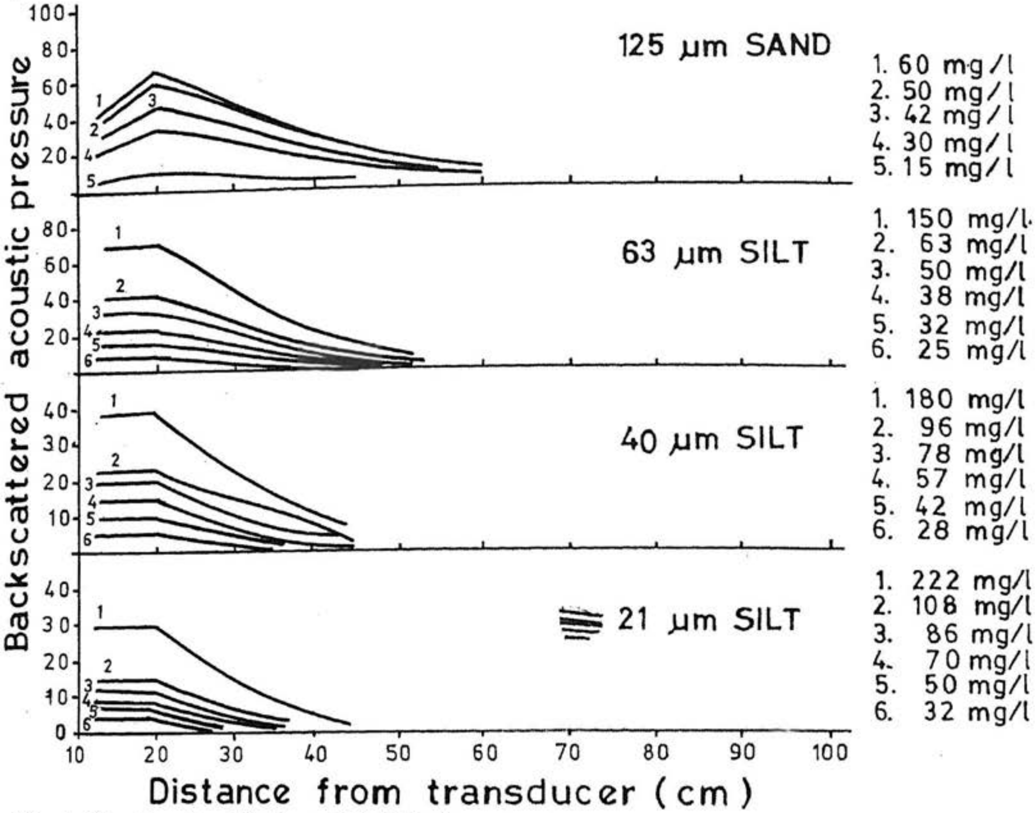

Fig. 4. (Continued) (c) P_b from 10.1 MHz frequency.

The rationale behind using a short wavelength multi-frequency system was to be able to distinguish various sizes in suspension (finer sediments). However, the present model can only calculate concentrations for a homogeneous suspension of uniform size particles. The choice of frequencies used for measurement has to be appropriate (preferably between 2 and 5 MHz) because higher frequencies can not be effectively propagated over a range of 1 m.

REFERENCES

Clay, C.S. & Medwin, H., 1977. Acoustical Oceanography: Principles and Applications. John Wiley Sons, New York.

Fisher, F.H. & Simmons, V.P., 1977. Sound Adsorption in sea water. J. Acous. Soc. Amer. 62, 558-564.

Hanes, D.M. & Vincent, C.E., 1987. Detailed dynamics of nearshore suspended sediment. Coastal Sediments '87, Amer. Soc. Civil Engineers 2, 285-299.

Hay, A., 1983. On the remote acoustic detection of suspended sediment at long wavelengths. J. Geophys. Res. 88, 7525-7542.

Hess, F.R. & Bedford, K.W., 1985. Acoustic backscatter system (ABSS): The instrument and some preliminary results. Marine Geology 66, 357-379.

Hunter, W.F., 1970. An introduction to acoustic exploration. In: Underwater acoustics (R.W.B. Stephens, ed.). John Wiley & Sons Ltd., London, 91-127.

Libicki, C., Bedford, K.W. & Lynch, J.F., 1989. The interpretation and evaluation of a 3MHz acoustic backscatter device for measuring benthic boundary layer sediment dynamics. J. Acous. Soc. Amer. 85, 1501-1511.

Lynch, J.F., 1985. Theoretical analysis of ABSS data for HEBBLE. Marine Geology 66, 277-290.

Orr, M.H. & Hess, F.R., 1978. Remote acoustic monitoring of natural suspensate distributions, Active suspensate resuspension and Slope/Shelf water intrusions. J. Geophys. Res. 83, 4062-4068.

Rehman, S.S. & Vincent, C.E., 1988. Acoustic measurement of suspended sediments in the Eastern Irish Sea. Geol Bull. univ. Peshawar 21, 105-116.

Sheng, J. & Hay, A.E., 1988. An examination of the spherical scatterer approximation in aqueous suspensions of sand. J. Acous. Soc. Amer. 83, 598-610.

Urick, R.J., 1983. Principles of Underwater Sound (3rd ed). McGraw-Hill Book Company.

Vincent, C.E. & Green, M.O., 1990. Field measurement of the suspended sand concentration profiles, and of the resuspension coefficient g over a rippled bed. J. Geophys. Res. (in press).

Vincent, C.E. Hanes, D., Tamura, T. & Clarke, T.L., 1986. The acoustic measurement of suspended sand in the surfzone. Proc. International Conference on MEASURING TECHNIQUES of hydraulic phenomena in offshore coastal and inland waters, London, Paper K3, 443-451.

Vincent, C.E., Young, R.A. & Swift, D.J.P., 1982. On the relationship between bedload and suspended sand transport on the inner shelf, Long Island, New York. J. Geophys. Res. 87, 4163-4170.

Young, R.A., Merril, J.T., Clarke, T.L. & Proni, J.R., 1982. Acoustic profiling of suspended sediments in the marine bottom boundary layer. Geophys. Res. Letters 9, 175-178.