

Dynamic Attenuation Extraction of Seafloor Sediments from Very High Resolution Acoustic Data

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Abstract

An approach to acquire geophysical information of seabed sediments as derived from acoustic attenuation is described. Using the frequencies corresponding to the signal power spectrum maximum and a point 3 dB below, signal loss in the sediment is calculated. These results are compared to reference data for attenuation in sediments published by several authors. Data collected on the Grand Banks of Newfoundland during a controlled trawling experiment was processed using this technique, with results illustrating close agreement with the underpinning theory. Calculations of fractal dimensions were performed to evaluate levels of roughness in the inner structure of the sediments. Since lower levels of the fractal dimensions represent less of a microfaunal presence [1] only the lower fractal valued data were used in the dynamic attenuation extractions. Hence, the correlations were found to be more reliable and reflective of homogeneous sediment structures.

1. Introduction

Quantitative and reliable measurements of acoustic attenuation enable correlations between the acoustic responses and the properties of sediment to be forged. Geotechnical information such as consolidation characteristics and bulk density in marine sediments can be estimated through the acoustic attenuation associated with sound waves propagating into the subseabed sediments [2]. It is recognized in the literature that attenuation is linked to the physical aspects of the sediment such as porosity, particle shape and grain size.

This paper exhibits an approach for rapid and objective computation of attenuation as perturbed by the properties of near surface sediments. The application of the technique was performed on very high resolution acoustic data using a new class of sonar called Benthic-DRUMS™ during a controlled set of trawling experiments conducted on the Grand Banks of Newfoundland [1]. Benthic-DRUMS™ is a very high resolution 40-element non-linear acoustic array developed by Guigné International Ltd. to measure the small scale chaotic changes in a benthic habitat caused by otter trawling.

2. Description of Model and Analysis Approach

2.1 Model

The approach is based on a dynamic (adaptive) model of attenuation first introduced by Guigné [2, 3]. This model assumes non-linear dependence of signal loss on frequency as

$$a = kf^N \tag{1}$$

where k is the attenuation coefficient in dB/m/kHz^N at an associated frequency f , and N is the exponent of frequency. Equation (1) expresses the composite effects of intergranular and viscous losses; N values reflecting the combined effects of both. In the literature, a very wide range of both measured N values and models for the prediction of N have been exhibited and debated, starting from Urlick, [4], Biot, [5,6], Shumway, [7, 8], Nolle, [9], Hampton, [10], McCann and McCann, [11, 12], Shirmer, [13], Stoll and Bryan, [14], Hamilton, [15], and Guigné, [2, 3].

Since the Benthic-DRUMS™ sonar is an application of non-linear acoustics, it relies on a matrix of terminated parametric arrays. A useful mode of operation of the parametric array is when the parametric source volume is terminated abruptly by, for example, the water/seabed interface, to give a truncated parametric array. Research performed by Guigné [16], Wingham [17], Pace and Ceen [18], and Muir [19] on this mode of operation of the array has given insight on its characteristics and performance. The equation below represents a base approximation which accounts for the received spectral character of the terminated parametric array in the presence of attenuation losses:

$$P(f) = B_1 f^2 \exp(-\beta f^n) \tag{2}$$

where: B_1 is a constant

f squared is by the parametric generation
 β is equal to $kR/8.6859$; whilst R is the penetration range

The frequency at maximum pressure can be found by:

$$f_{\max} = (2 / (N\beta))^{1/N} \tag{3}$$

Substituting:

$$x = \beta f^N \tag{4}$$

We can express a normalized spectrum by:

$$\frac{P(x)}{P_{\max}(x)} = \left[\frac{Nx}{2} \right]^{2/N} \exp(2 / N - x) \tag{5}$$

Setting the bandwidth of the received pressure at -3dB we receive:

$$\frac{P(x)}{P_{\max}(x)} = 1/\sqrt{2} \quad ; \text{ i.e. -3dB} \tag{6}$$

and

$$f_3 = \left[\frac{x_1}{\beta} \right]^{1/N} \quad \text{where } x_1 \text{ is left as a root} \tag{7}$$

Combining expressions for the frequencies, we realize:

$$\left[\frac{f_{\max}}{f^3} \right]^N = \frac{2}{N\lambda_1} \quad (8)$$

2.2 Time Window Selection

The signal processing logic as used to implement the dynamic loss model is introduced in Figure 1. This adaptive attenuation model can be reliably applied to signal portions that compare to an ideal impulse shape. A Butterworth filter of the order of 6 with a cut off frequency of 280 kHz is used to prevent possible interference from residual parametric array carrier frequencies. A Hilbert transform is also applied to acquire an envelope shape. Figure 2 illustrates a typical signal as collected by the sonar with Figure 3 exhibiting the envelope. Figure 4 presents the filtered signal with envelope.

Selected parts of the signal are chosen (using MATLAB) for processing, based on three criteria: i) shape similar to ideal impulse, ii) length of about 50 points, which represents about 1 cm of depth, iii) belonging to one portion of the envelope signal.

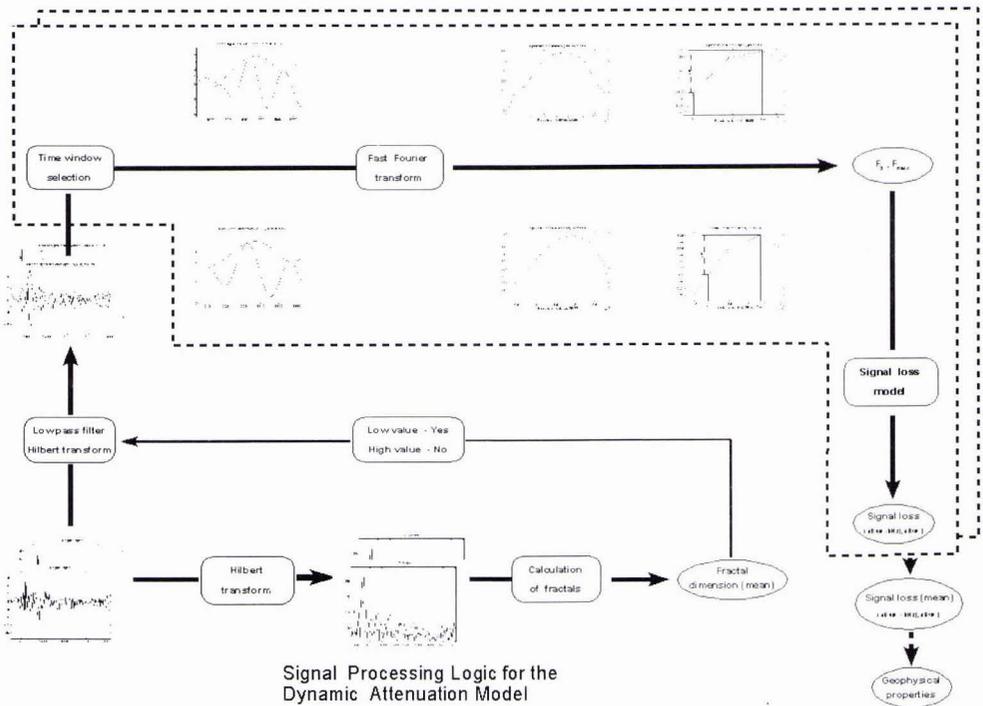


Figure 1: Signal processing flowchart leading to signal loss values

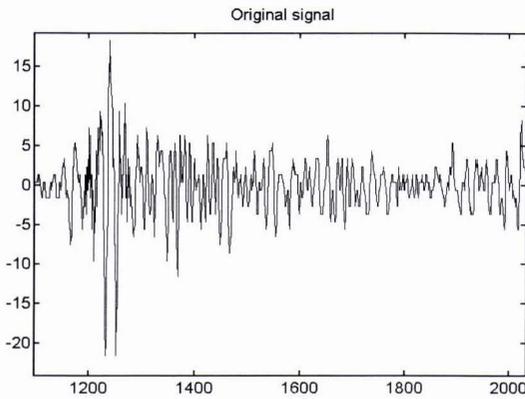


Figure 2: Signal as used in analysis
(Vertical axis in dB; horizontal axis represents collected data points)

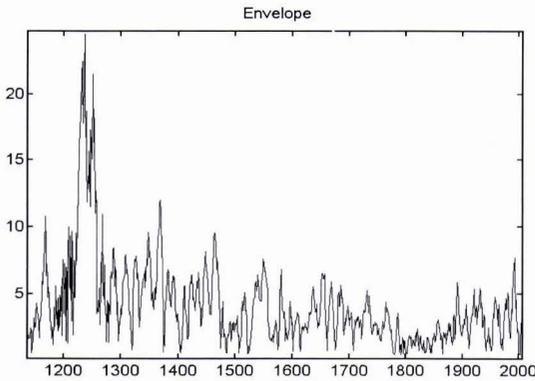


Figure 3: Hilbert Transform envelope of signal
(Vertical axis in dB; horizontal axis represents collected data points)

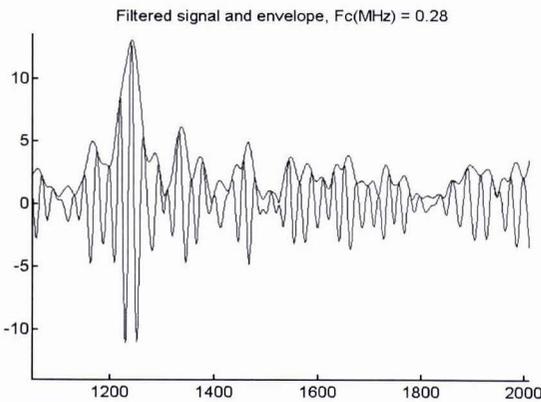


Figure 4: Filtered signal (cut off frequency 280 kHz) and its envelope
(Vertical axis in dB; horizontal axis represents collected data points)

Figures 5 and 6 present portions of the signal selected to conform to these criteria which meet the theoretical requirements for inputting into our dynamic signal loss model.

The data collected was held to the first 15 cm of the seabed, with fractal analysis conducted on the initial near surface zones (approx. 4 – 5 cm) conforming to the active zones of a benthic habitat.

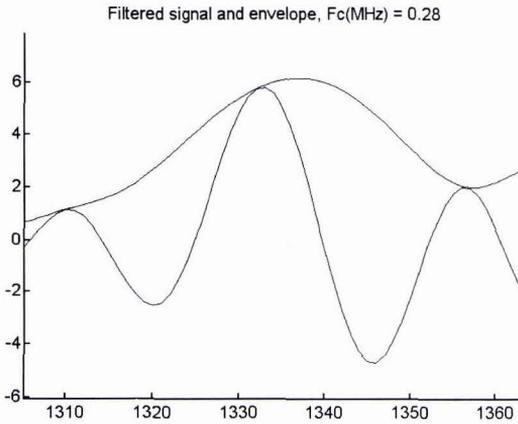


Figure 5: Upper Curve represents chosen time window of envelope superimposed on lower curve, which represents signal, real part.
Shape of envelope suitable for inputting into the Signal Loss Model
(Vertical axis in dB; horizontal axis represents collected data points)

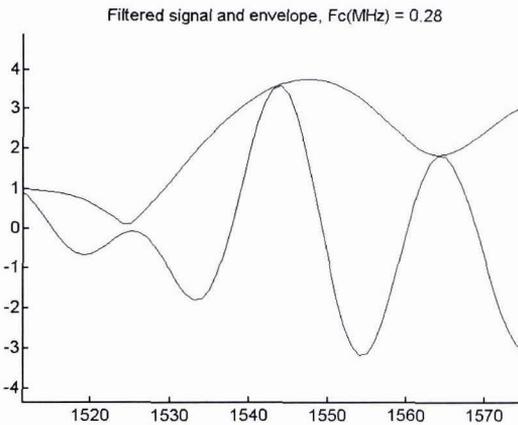


Figure 6: Upper curve represents chosen time window of envelope superimposed on lower curve which represents signal, real part.
Shape of envelope suitable for inputting into the Signal Loss Model
(Vertical axis in dB; horizontal axis represents collected data points)

2.3 Fractal Analysis

The Benthic-DRUMSTM data can be analysed in terms of fractal dimensions associated with the signal's "roughness" [1]. From the past research by Schwinghamer and Guigné [1], the Hilbert-transformed acoustic signals occupy 1-dimensional topological space; however, they are more complex than a simple straight line, and they fill 2-dimensional space to a

degree that depends on the frequencies and amplitudes of peaks and undulations which make them complex. The extent to which they fill 2-dimensional space is measured by a non-integer dimension between 1 and 2, called a fractal. By analysing the time series data as fractal curves, the complexity of the acoustic signals in response to structural complexity in the sediment can be quantified.

A modified box counting method by Malinverno [20] was used to determine the fractal dimension for the Hilbert time series from each depth stratum k of each acoustic element M_{ij} of the acoustic array. In this method, the data M_{ijk} were first fully enclosed in a square; thus 1 box contained the whole line. Then the box was divided into quarters and the number of these smaller boxes that contained parts of the line was counted. Each of these smaller boxes was then similarly divided and the number containing parts of the line counted and so on until an arbitrarily small box size was reached.

The number of boxes, M , containing the line is a function, I , of the size, t , of the boxes:

$$M = t^I \quad (9)$$

The function, $I_{i,j,k}$ is the fractal dimension for each depth stratum of each element. It can be calculated as:

$$I_{i,j,k} = - \frac{\log_{10}(M)}{\log_{10}(t)} \quad (10)$$

3. Experimental Setting and Application of the Dynamic Loss Model

3.1 Data Collection

An in situ experiment to determine the impacts of otter trawls on the sandy seabed, which covers large areas of the Grand Banks and Scotia Shelf, has been underway since 1993. It was initiated as part of the Northern Cod Science and Atlantic Fisheries Adjustment Programs in response to debate regarding the role of fishing technology in the collapse of the northern cod stock [1]. The experiment allowed for Benthic-DRUMS™ data to be collected in 1994 and 1995. The 40-element array (10 x 4) was reduced to 28 elements (7 x 4) due to structural blockage of the acoustics by the sampling frame. The average water depth in the area was reported to be approximately 135 metres. The bottom sediment was mostly sand with typical grain sizes of approximately 200Φm and registering a water content of 20 ∓ 3%. The overall experimental equipment and field operation / setting are described in detail along with sampling procedures in Schwinghamer and Guigné's work [1].

The data collected was held to the first 15 cm of the seabed, with fractal analysis conducted on the initial near surface zones (approximately 4 – 5 cm) conforming to the active zones of a benthic habitat.

3.2 Calculations

Power spectra of chosen intervals were calculated using a zero-padded Fast Fourier Transform (FFT). Figures 7 and 8 illustrate shapes of the power spectra used, while Figures 9 and 10 depict values for the frequencies associated with peak pressure levels (f_{max}) and with the lower frequencies (3 dB less (f_3)).

Altogether, more than 2500 calculations were performed using the collected data. Distribution of f_{max} is shown in Figure 11.

The calculations of fractal dimensions were used to establish an acceptance level for the data to be considered valid before making the attenuation loss calculations (refer to Figure 1). Signals of low values (below 1.5) were allowed to be analysed for their attenuation; higher values were removed as these indicate strong benthic fauna activity in the sediment.

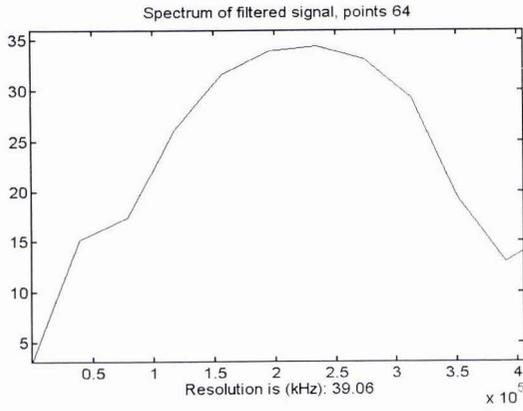


Figure 7: Response in the Frequency Domain
(Vertical axis in dB)

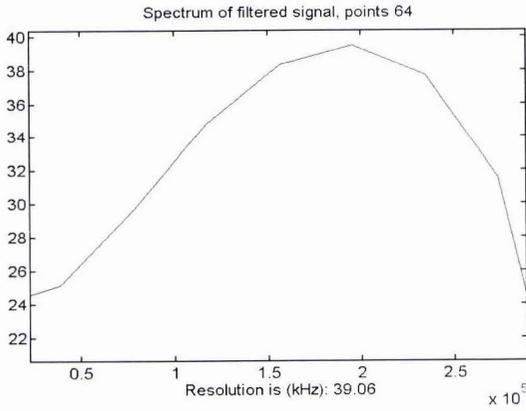


Figure 8: Spectrum of the Second Impulse
(Vertical axis in dB)

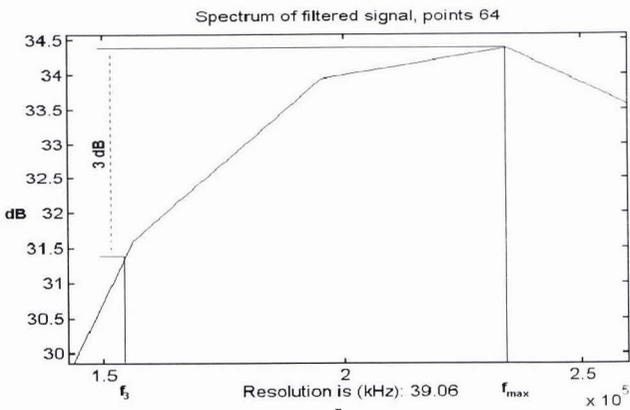


Figure 9: Frequencies at Maximum and -3 dB Pressure

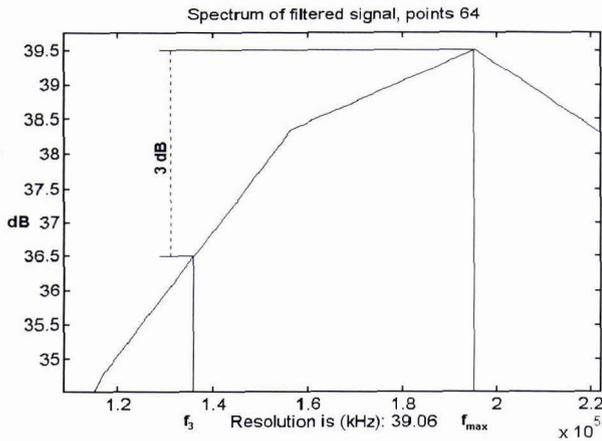


Figure 10: Frequencies at Maximum and - 3dB Pressure

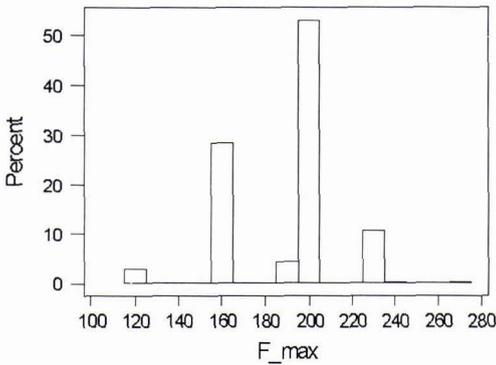


Figure 11: Distribution of Maximum Response Frequency (percentage)

4. Results

The results of the adaptive model's signal loss calculations were assessed by comparing them with published attenuation data. As it is clear from Figure 12, mean values of signal loss for associated frequencies in this research are in agreement with published attenuation data.

Water content data from samples collected on the Grand Banks in 1993 were used and found to be representative of seabed conditions for the Grand Banks (provided by Schwinghamer). Mean values for water content were 21.6% with a standard deviation of 1.8%. Assuming a density of dry soil (mostly sand) as 2.65 g/cm³, this translates into a porosity of around 43%. Figure 13 represents a relative position of mean value of a calculated signal loss against published data. The results of the dynamic attenuation model losses seem to concur with porosity values.

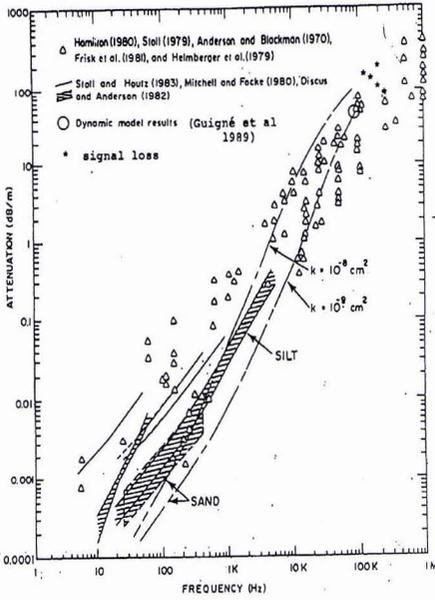


Figure 12: Signal loss values against frequency using the Dynamic Attenuation Model for the Grand Banks data (signal loss*) and against published data

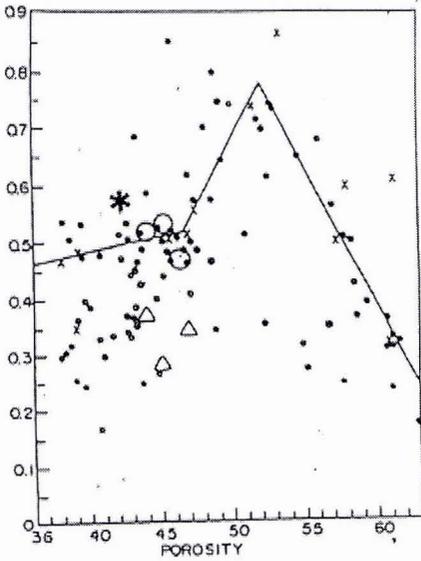


Figure 13: Signal loss values against porosity using the Dynamic Attenuation Model for the Grand Banks data (signal loss*) and against published data

5. Conclusions

A dynamic approach to acquire attenuation in sediment was demonstrated with good agreement between the results of the model as used on Grand Banks data with that seen for published data (related to sands). This analysis approach introduces a potentially rapid and reliable technique to extract attenuation from the wave shape of parametric arrays used as subbottom profilers. The introduction of fractal dimensions as a filter cut off, allowed for the chaotic effects of a benthic habitat to be excluded from the computations, thereby removing a potential source of error in the resultant signal loss values.

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REFERENCES

- 1 Schwinghamer, P., Guigné, J. Y., and W. C. Siu, Quantifying the impact of trawling on the benthic habitat structure using high resolution acoustics and chaos theory, *Can. J. Fish. Aquatic Sci.*, 53, 288 – 296, 1996.
- 2 Guigné, J. Y., Chin, V. H., and S. M. Solomon, Acoustic attenuation measurements using parametric arrays, *Ultrasonics*, Vol. 27, 1989.
- 3 Guigné, J. Y., Pace, N. G., and V. H. Chin, Dynamic extraction of attenuation from sub-bottom acoustic data, *J. Geophys. Res.* 94, 5745 – 5755, 1989.
- 4 Urlick, R. J., Absorption of sound in suspension of irregular particles, *J. Acoust. Soc. Am.*, 20, 283 – 289, 1948.
- 5 Biot, M.A., Theory of elastic waves in a fluid saturated porous solid, I. Low frequency range, *Acoust. Soc Am.*, 28, 168 – 178, 1956a.
- 6 Biot, M.A., Theory of elastic waves in a fluid saturated porous solid, II. Higher frequency range *J. Acoust. Soc Am.*, 28, 179 – 191, 1956a. Shumway, G., Sound speed and absorption studies of marine sediments by a resonance method, I, *Geophysics*, 25, 451 – 467, 1960a.
- 7 Shumway, G., Sound speed and absorption studies of marine sediments by a resonance method, II, *Geophysics*, 25, 659 – 682, 1960b.
- 8 Nolle, A. W., W. A. Hoyer, J. F. Misfud, W. R. Runyan, and M. B. Ward. Acoustical properties of water-filled sands, *J. Acoust. Soc Am.*, 35, 1394 – 1408, 1963.
- 9 Hampton, L. D., Acoustic properties of sediments, , *J. Acoust. Soc Am.*, 42, 882 – 890, 1967.
- 10 McCann, C., and D. M. McCann. The attenuation of compressional waves in marine sediments, *Geophysics*, 34, 882 – 892, 1969.
- 11 McCann, C., and D. M. McCann. Compressional wave attenuation in concentrated clay suspensions, *Acoustica*, 22, 352 – 256, 1970.
- 12 Shirmer, F., Schallausbreitung im Schlick, *Deut. Hydrog. Z.*, 23, 24 – 30, 1970.
- 13 Stoll, R. D., and G. M. Bryan, Wave attenuation in saturated sediments, *J. Acoust. Soc Am.*, 47, 1440 – 1447, 1970.
- 14 Hamilton, E.L., Compressional wave attenuation in marine sediments, *Geophysics*, 37, 620 – 646, 1972.
- 15 Guigné, J. Y., The concept, design and experimental evaluation of an acoustic sub-seabed interrogator, *Ph.D. Thesis*, University of Bath, Bath, UK (1986).
- 16 Wingham, D. J., The penetration of a water–sediment interface by a parametric array, *Ph.D. Thesis*, University of Bath, School of Physics, UK (1984).
- 17 Pace, N. G. and R. V. Ceen, Time domain study of the terminated parametric array, *J. Acoust. Soc Am.*, 73 (6), 1972, 1983.
- 18 Muir, T. G., A survey of several nonlinear acoustic experiments on travelling wave fields, finite-amplitude wave effects in fluids, Proceedings of the 1973 Symposium, Copenhagen. 1973.
- 19 Malinverno, A., A simple method to estimate the fractal dimension of a self-affine series, *Geophysical Research Letters*, Vol. 17, No. 11, 1953 – 1956.