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STATISTICAL PROPERTIES OF SIDESCAN SONAR SIGNALS AND THE COMPUTER CLASSIFICATION OF SEA-BEDS

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INTRODUCTION

Sidescan sonars are nowadays routinely and widely used in underwater surveying. They employ only the sound field backscattered from the superficial sea-bed and at the usual frequencies there is hardly any penetration of the sea-bed. The usual paper display contains less information than the signal creating it, and moreover the interpretation of the usual display is often difficult especially regarding sediment types. In order to overcome these two shortcomings computer analysis drawing upon suitable statistical properties of signals is indicated *[1]*. In the case of homogeneous regions (containing only small scale features that cannot be resolved) the usual methods of pattern recognition are not so useful *[2]*. The backscattering strength is a useful quantity, but meaningful numerical values can be obtained only with a calibrated system *[3]*. We here demonstrate that certain integral features of the cepstrum and the normalized central moments of the probability distribution function are suitable for sea-bed classification procedures.

BASIC CONCEPTS

It can be demonstrated theoretically that the scattered sound field depends both upon roughness and hardness of the sediment-water interface *[4]*, but analytical expressions are unsuitable for most practical applications not so much on the account of their complexity but due to the difficulty in quantifying roughness (statistically random corrugations) and hardness (mixed boundary conditions) of real sea-beds. Statistical properties of scattered sound fields corresponding to an ensemble of sea-bed patches manifest only indirectly the combined effect of roughness and hardness on the incident sound field, but they are more suitable for our present semi-empirical approach. The probability distribution (of the scattered field intensity) shape does relate to the sea-bed roughness *[5]*, but is not so sensitive to its hardness.

Let us now consider a sidescan sonar transmitting a rectangular pulse of length T ($\gg T_O$) at carrier angular frequency ω_0 ($=2\pi/T_O$). Received signal amplitude is proportional to the pressure of the sound field at transducer. The received signal is a quasi-harmonic stochastic function of time ("reverberation") given by

$$a(t)\cos\left[\omega_0 t + \psi(t)\right],$$

where $a(t)$ and $\psi(t)$ are the amplitude and the phase of the signal respectively. Both $a(t)$ and $\psi(t)$ are assumed to be slowly varying functions of time in comparison with $\cos\omega_0 t$. The present method makes use of $a(t)$ only and yields numerical features that are invariant under the linear transformation of it and hence independent of the signal d.c. level and gain.

Let us denote by $a_i(t)$ the signal amplitude within the i^{th} rectangular window of a fixed time duration T_W ($\gg T$). The minimum value of the signal amplitude is set equal to zero so that $a_i(t) \geqslant 0$ ($i = 1, 2, \ldots, n$). The windows should have no temporal overlaps and can be taken from any number of pings. Let us further denote by $w(t)$ the time window function (other than rectangular) such that

$w(t) = 0$ for $t < T_D$ and $t > T_D + T_W$, where T_D is the initial delay (measured from the instant of transmission). The resulting windowed signal can be written as

$$g_i(t) = w(t)a_i(t) \qquad (i = 1, 2, \ldots, n).$$

If the signal is digitised so that N samples are taken in each window with sampling interval Δt, we have $T_W = N\,\Delta t$. The Nyquist frequency is equal to $\pi/\Delta t$; if ω_B is the highest angular frequency of interest, the Nyquist sampling theorem implies $\Delta t \lesssim \pi/\omega_B$.

CEPSTRUM

For a given sample area the N-point Fourier transform is performed on each of n windows.

The power cepstrum (or simply "cepstrum") is by definition *[6,7]*

$$C(\tau) = |\mathfrak{F}\{\log\langle P(f)\rangle\}|^2 ,$$

where $\langle P(f)\rangle$ is the power spectrum averaged over n windows, $\mathfrak{F}$ denotes the Fourier transform, and τ is the time-lag variable called quefrency. The power cepstrum integral (cumulative power cepstrum) is given by

$$I(\tau') = \int_0^{\tau'} C(\tau)\,d\tau \Big/ \int_0^{T_W} C(\tau)\,d\tau ,$$

with the variable τ' in the range $\tau_0 \lesssim \tau' \lesssim T_W$, where τ_0 ($\lesssim T$) is a fixed interval.

We further introduce two parameters to characterize the power cepstrum integral: the intercept and the slope at τ_0 given by

$$D_1 = 1 - I(\tau_0) ,$$

$$D_2 = \frac{d}{d\tau'} I(\tau')\Big|_{\tau' = \tau_0} ,$$

respectively, and refer to them as the cepstrum integral features.

PROBABILITY DISTRIBUTION FUNCTION (PDF)

For a given sample area the total of nN amplitudes is reduced to nN/n_s by simple averaging over n_s adjacent amplitudes in order to obtain practically uncorrelated mean amplitudes.

The probability density function p(a) is obtained simply by counting the number of points at each amplitude level and normalized so that

$$\sum_{i=1}^{256} p(a_i)\,\Delta a_i = 1 ,$$

since the total number of levels is 256 (8 bits).

The amplitude variance (standard deviation squared) is given by

$$\sigma_a^2 = \langle a^2\rangle - \langle a\rangle^2 ,$$

where $\langle\ldots\rangle$ denotes the mean value over all 256 levels.

The k^{th} order normalized central moment is by definition

$$M_k = \sigma_a^{-k} \sum_{i=1}^{256} (a_i - \langle a\rangle)^k p(a_i)\,\Delta a_i ,$$

where k = 3, 4, 5, . . . Since a_i's are represented by integers in the range 0 - 255, $\Delta a_i = 1$ (i = 1, 2, . . ., 256). The moments M_3 and M_4 are equal to the so-called coefficients of skewness and kurtosis, respectively.

DATA PROCESSING AND NUMERICAL RESULTS

The sidescan sonar which has been used for data acquisition is a standard medium range system operating at 48 kHz carrier frequency, 1 msec pulse length, 2 kHz nominal receiver bandwidth, and the usual time-varied gain. The amplitude envelope is recorded on magnetic tape in analogue form with 48 dB dynamic range. Hardware for data processing consists of an 8-bit A/D converter and a standard 32 K microcomputer with a dual disk drive. The amplitude envelope is digitized at a sufficiently high rate and integer values in the range 0 - 255 saved on disk for further processing.

The time window w(t) is chosen to be of the Hanning (cosine squared) type. All Fourier transforms are performed according to the FFT algorithm. The cepstrum is integrated numerically with a step equal to τ_0 and a parabola is interpolated through the first 8 points by the least squares method in evaluating D_1 and D_2.

The gain independence of D_1 and D_2 as evaluated by our software has been tested numerically. Change in gain by a factor of up to 4 causes deviations in D_1 and/or D_2 that are at most 5%.

The numerical values of D_1 and D_2 for a given sea-bed type do depend on the number of windows n especially when n is small. Both sequences (for D_1 and D_2) that correspond to n = 1, 2, 4, 8, 16, 32 converge relatively fast so that little can be gained by going to the values of n greater than 32.

The numerical values of M_3 and M_4 depend on the choice of n_s; its optimum value is related to the size of sea-bed scattering area and is presently set equal to 4.

All 120 sample areas dealt with here are homogeneous as far as could possibly be found in real sea-beds. They are all from regions familiar from previous surveys and free from noise and interference. On the basis of our records as well as other knowledge of the regions any one of the sample areas is assigned to one and only one of the six classes: mud, sand, clay, gravel, stones, and boulders. The sample areas are geographically distributed as follows: mud (25 from South Baltic Sea), sand (5 from Land's End, 10 from Outer Hebrides, and 10 from Western English Channel), clay (10 from Southern North Sea), gravel (10 from Southern North Sea, and 15 from Western English Channel), stones (10 from South Baltic Sea, and 15 from Outer Hebrides), and boulders (10 from South Baltic Sea).

Numerical values of the cepstrum integral features (scaled by a factor of ten) and the normalized central moments for all 120 sample areas are presented graphically in Figures 1 and 2, respectively. The scale is log-log for the former and linear for the latter. Each sample area corresponds to a single point and each sea-bed type to a geometrical region in (D_1,D_2) and (M_3,M_4) parametric planes. The boundaries to each sea-bed type in both Figures are drawn by hand for the clarity of display only.

CONCLUDING REMARKS

The cepstrum method suffices to distinguish six homogeneous sea-bed types (mud, sand, clay, gravel, stones, and boulders). The dependence of the discriminatory ability of the method on pulse length and carrier frequency is being investigated especially regarding the classification of non-homogeneous sea-bed types (e.g. sand with gravel). The PDF method is inferior to the cepstrum method for the purposes of the sea-bed classification, but it can be of some use as a back-up or special indicator method. It seems that the cepstrum relates to an average acoustic hardness, while the PDF is more sensitive to the roughness of sea-beds.

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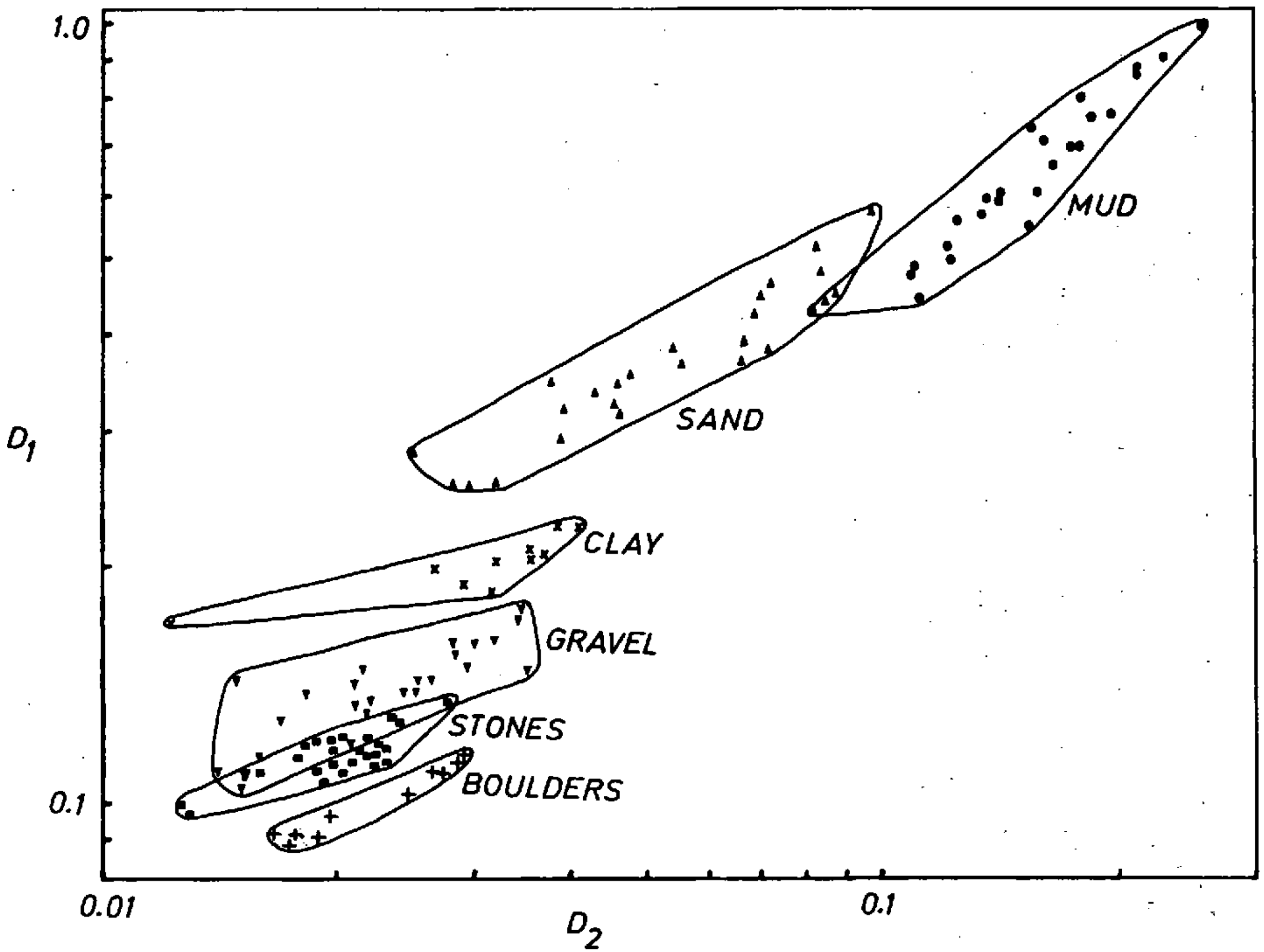

Figure 1.

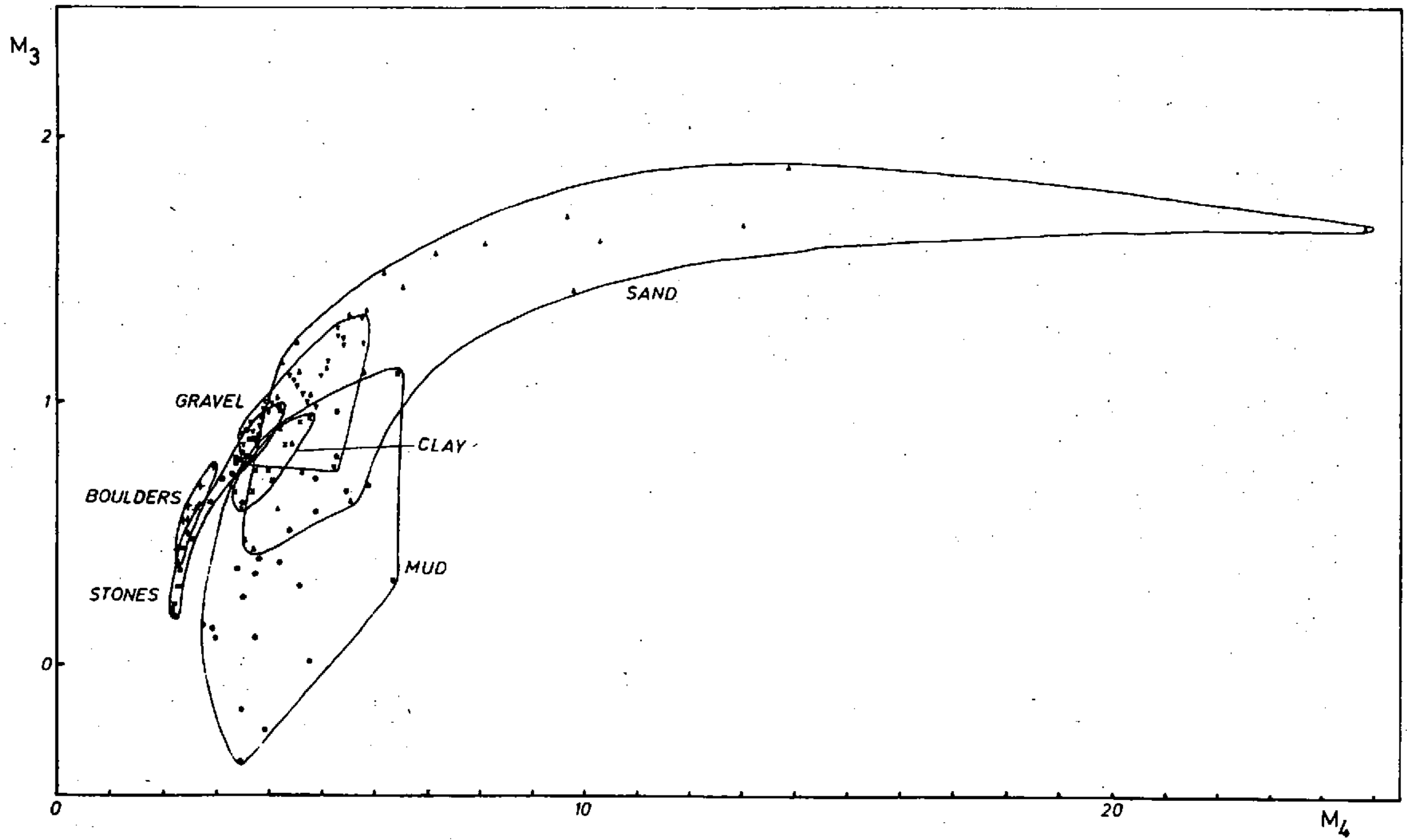

Figure 2.