NEAR SURFACE BACKSCATTER: ITS MODELLING AND USE AS A MIXING MARKER

A. Graham

University of Southampton, Department of Oceanography, Highfield, Southampton S09 5NH, UK

1. INTRODUCTION

Near surface acoustic scattering is a powerful tool for obtaining information on the environment at the sea surface, and also for revealing the surface signature of mixing processes. At low frequencies, of order a few hundred hertz or less, the scattering occurs specularly at the surface, and depends on the modulation of the surface by capillary waves, wind waves and swell [1, 2]. At higher frequencies, of up to a few kilohertz, it is thought that the scattering is caused primarily by variations in the concentration of bubbles (Section 4). Thereafter, for frequencies of up to a few megahertz, scattering results from the individual bubbles themselves, as the mass of water that rides on a bubble is driven into resonance (Section 3). The scattering field associated with the subsurface void fraction is then well resolved, and single bubbles may be identified [3].

Bubbles are injected into the water column in dense clouds by breaking wind waves. The bubbles then diffuse from these sources, in a manner dependent on both their intrinsic dynamical properties and on the diffusive processes occurring about them in the water. The intrinsic properties of a bubble, such as buoyancy and rise speed, are governed by its size and shape, the composition of its gases, and the organic coating it scavenges within a few tens of seconds of its inception [4]. With the exception of the horizontal dispersion induced by stably sheared flow, the diffusive processes in the water are three-dimensional. The circulation and turbulence induced by a breaking wave determines the initial development of a cloud, and may distort or even fragment a fully developed cloud nearby. Instabilities in the flow observed to affect the acoustic scattering field include unstably stratified shear flow [4] and, in shallow water, turbulence generated by tidal flow over the seabed [5]. Steadier acoustic signatures result from Langmuir circulation, internal waves and fronts [6]. The pronounced cross-wind shear in the downwind current associated with Langmuir circulation will distort clouds as they converge into its downwelling zones. Once a cloud has converged, its bubbles may undergo significant vertical diffusion in the downwelling current.

2. RECENT HIGH FREQUENCY EXPERIMENTS IN THE NORTH SEA

Two datasets were recently acquired using a system of two perpendicular, pulsed, side-scan sonars, deployed on the seabed in the southern North Sea. The sonars are of frequency 80 and 90 kHz. The system also employs a narrow beam, near vertical, sonar, of frequency 250 kHz. One dataset was obtained in 1991-92, fifty kilometres off the Suffolk coast, at 52°N, 2°E (Fig. 1), while the other was obtained in 1993, eight kilometres off the Dutch coast, at 52°N, 4°E. In both cases, the predominant environment is well mixed, the tide is strong, and the seabed is fairly flat and sandy. The system is orientated such that one of the side-scans is nearly parallel, and the other nearly normal, to the mean flow. The system is described further by Thorpe and Hall [7]. The experiment at 52°N, 2°E is at depth 45 m, and is described fully by Thorpe *et al* [8]. The experiment at 52°N, 4°E is at depth 17 m.

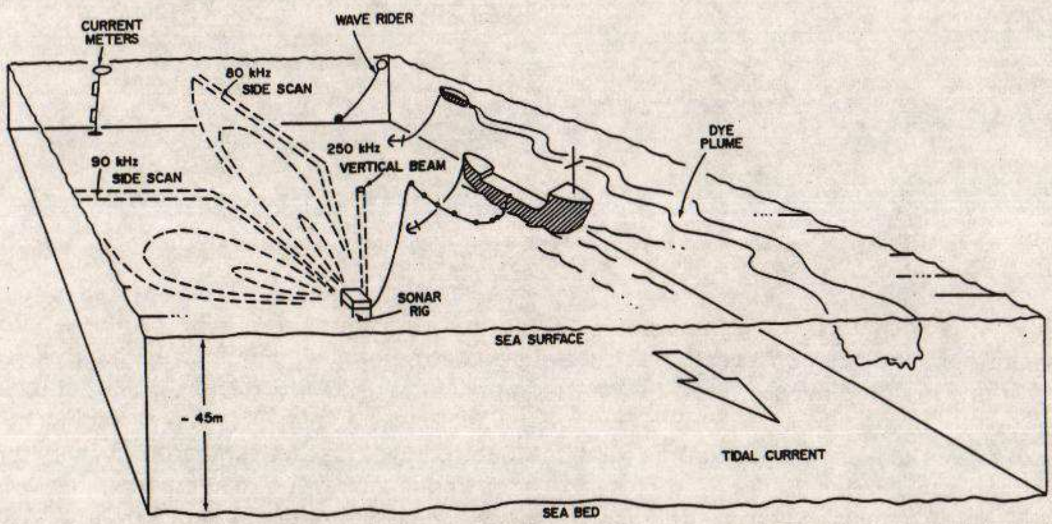


Fig. 1 Sketch showing the site and sonar beam orientations in the 45 m depth North Sea experiment. The dye release was part of another, related, experiment.

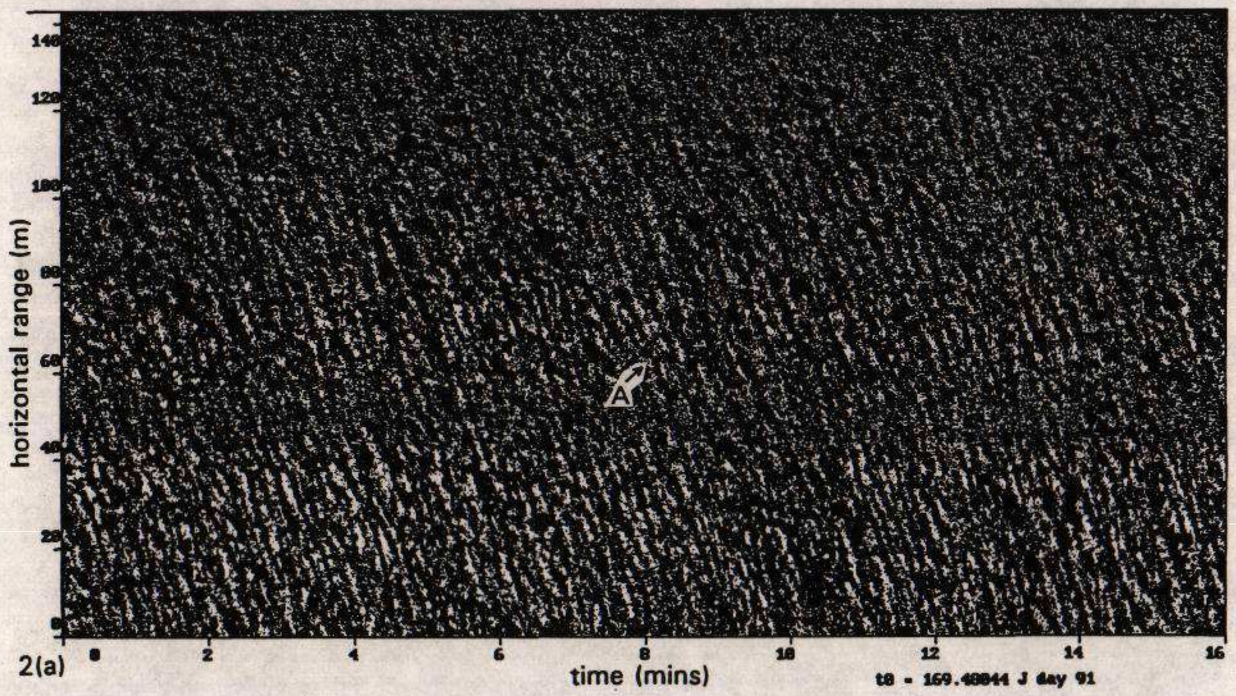
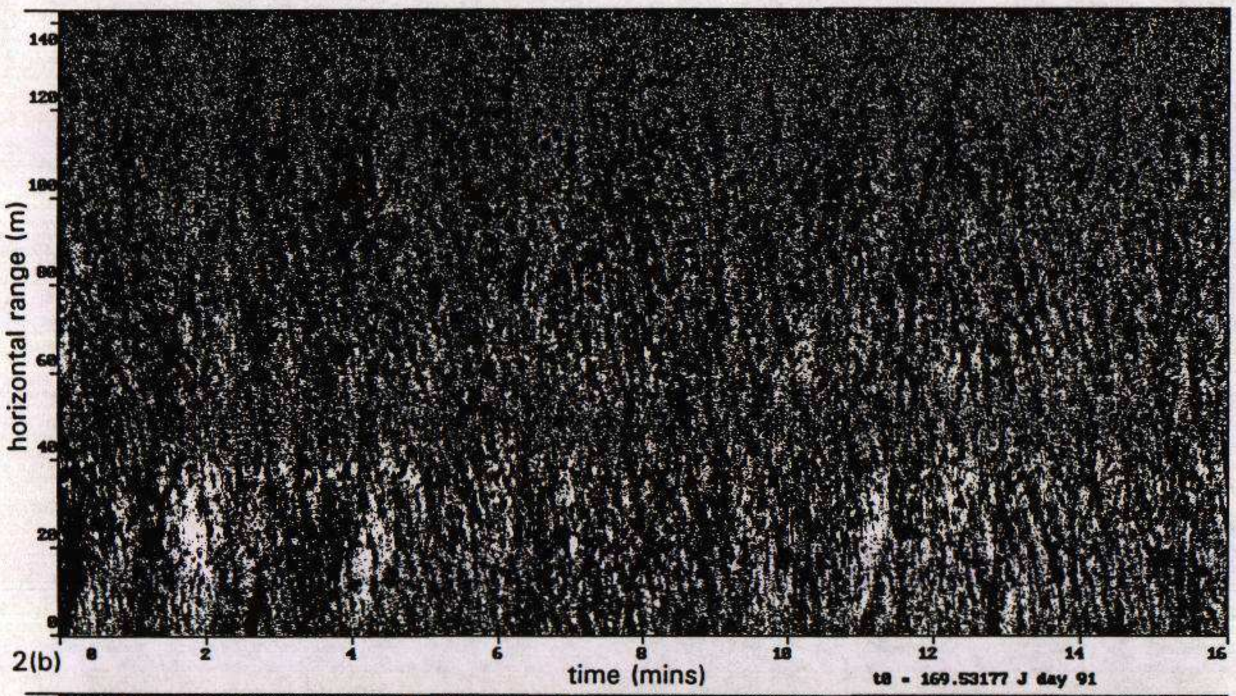
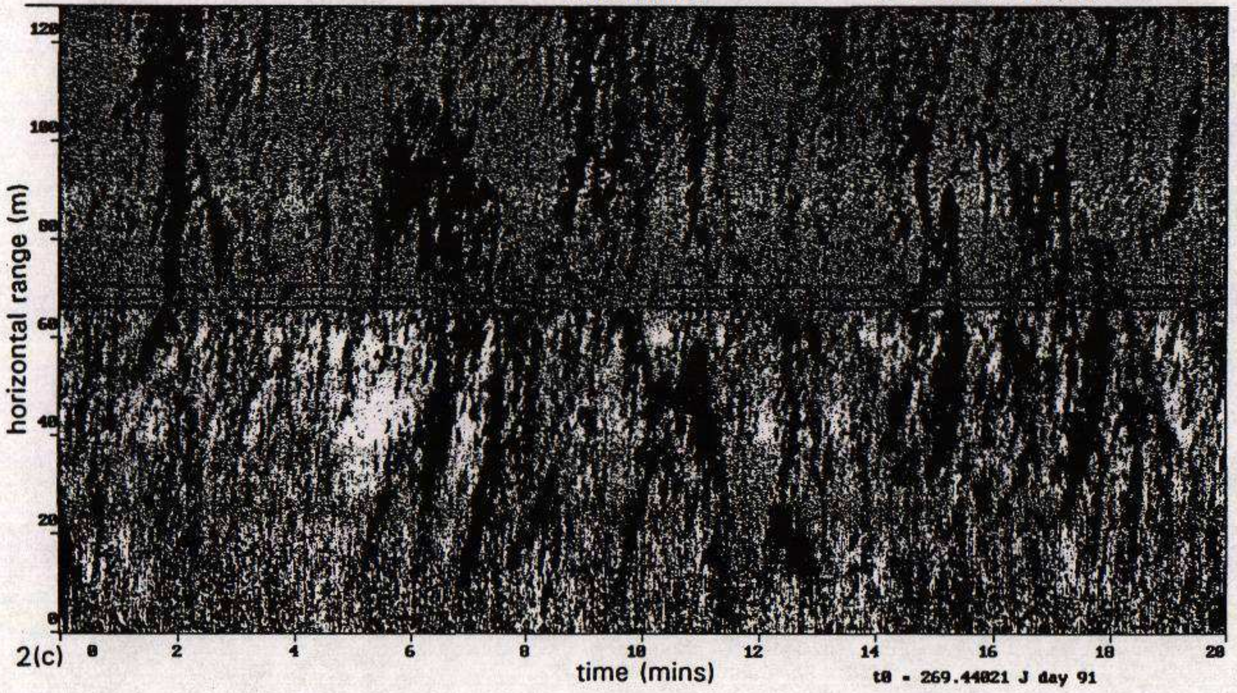


Fig. 2 Cross-current, side-scan sonographs from the 45 m depth experiment, showing the relative rms backscatter pressure over horizontal range and time. Shading darkens with increasing backscatter. The pulse repetition rate is 4 Hz. Figs. 2a and 2b have a range origin 34 m away from the sonar, and are generated by averages of 4 pulses. Fig. 2c has a range origin 17 m away from the sonar, and is generated by averages of 5 pulses. The backscatter has been normalised to compensate for attenuation. The event at A in Fig. 2a is referred to in the main text.



2(b)



2(c)

Fig. 2a. The (1 m) current is 69 ± 5 cm s^{-1}, heading 84 ± 3° to the left of the beam. The (10 m) wind is 6.4 ± 0.8 m s^{-1}, from 71 ± 8° left of the beam.
Fig. 2b. The (1 m) current is 103 ± 3 cm s^{-1}, heading 75 ± 2° to the left of the beam. The (10 m) wind is 5.7 ± 0.6 m s^{-1}, from 63 ± 15° left of the beam.
Fig. 2c. The (17 m) current is 97 ± 3 cm s^{-1}, heading 73 ± 1° to the left of the beam. The (10 m) wind is 6.0 ± 0.3 m s^{-1}, from 100 ± 15° right of the beam.

3. MEASUREMENTS OF THE BUBBLE CLOUD DISTRIBUTION

3.1 Observations

The side-scans achieve ranges of up to 200 m with a resolution of about 15 cm, revealing the horizontal distribution of bubble clouds. Most of the clouds are observed due to advection through, rather than the breaking of waves in, the beam.

Much can be learnt about the cloud distribution from the side-scan records prior to calibration. Sonographs are produced of the relative rms backscatter pressure over surface range and time, corrected for attenuation. The variation with surface range follows from ignoring the subsurface backscatter, as this decays rapidly with depth (the decay, as revealed by the narrow beam sonar, also allows the dispersion by bubbles to be ignored in the calculation of range from travel time). Correction for attenuation is achieved by normalising the backscatter at given range by its temporal average.

Unless the wind and current are close to perpendicular, the cross-current sonographs reveal linear or gently curvilinear features, of spacing 5-30 m, that persist for many minutes (Fig. 2a). The advective length scale normal to the beam that is associated with a feature, calculated from the locally measured current, may exceed 100 m. This is much larger than the dimensions of a bubble cloud, and so must correspond to a band of clouds. Some bands end by merging with another (Fig. 2a, point A). An angle to the beam, α, may be inferred from the feature's speed along the beam, v_y, corresponding to that of a straight band advected passively by the current, of speed, v, and angle to the beam, β:

$$\alpha = \cot^{-1}\left(\cot\beta - \frac{v_y}{v}\operatorname{cosec}\beta\right). \tag{1}$$

A set of sonographs, each of about an hour, with (10 m) wind speeds ranging from 5-10 m s^{-1}, has been analysed from the 45 m depth experiment, yielding values for α that are 24 ± 20° to the right of the wind, on average. As the bands lie close to the wind direction, they are taken to delineate the downwelling zones of Langmuir circulation (see Section 1): the bias to the right is seen elsewhere [9].

Other band statistics have been computed from this dataset: details are given by Thorpe *et al* [5]. The mean spacing of the bands, lateral to their mean axis, is 24 ± 4 m. Their mean length, allowing for the decay that occurs as a band is advected through the beam, exceeds 300 m. The mean speed of convergence into the bands may be estimated from the merging events, taking the converging band to be a passive tracer at convergence (although recent studies indicate that band junctions may be steady state phenomena [9]). A value of 16 ± 8 cm s^{-1} is derived from datasets where the mean current is small enough for the convergence speed to be resolved.

At currents exceeding 50 cm s^{-1} in the 45 m depth experiment, nonlinear, discontinuous, traces, of low along-beam speed and durations exceeding 15 mins, are often evident in the cross-current sonographs [5]. These traces are taken to delimit turbulent wakes from flow over rough features on the seabed. It is hypothesised that the turbulence decorrelates Langmuir cells from the wind-wave forcing, and makes the remaining bands less observable, as they pass more obliquely through the beam. The turbulence is marked at high, near peak, current, breaking up the circulation extensively (Fig. 2b, an hour after Fig. 2a), or completely (Fig. 2c). In the latter example, eddies reach the surface, where they induce intensely scattering patches of upper length scale comparable to the water depth. The 17 m depth experiment lends support to the hypothesis, as the nonlinearities there appear at lower currents. Further support comes from aerial photographs of the 45 m depth site, which reveal sediment clouds of scale of up to the water depth.

3.2 Discussion

Bands meander with respect to one another, as evidenced by their occasional merging. The meandering, merging and discontinuities in the array of bands will cause bubble clouds, along with other buoyant substances, to undergo sustained horizontal dispersion [5]. (Langmuir circulation may exist over a hierarchy of scales, in which case cells of scale smaller than the clouds will contribute to the sustained, background level of diffusion of microbubbles from the clouds, although these cells are not acoustically resolved.) The spatial coherence of the clouds may be important in low frequency scattering (see Section 4).

The nature of the intensely scattering patches observed at peak current is not yet clear. The signature may partly result from local, transient, convergence regions set up by the eddy field, resulting in the clustering of clouds in a manner analogous to that of Langmuir circulation. Alternatively, a patch may delimit a zone of enhanced wave breaking, the rising eddies destabilising the waves as they propagate above (enhanced breaking has been spatially correlated with submarine dunes in the southern North Sea [10]). A third possibility is that the scattering results from sand brought up with the eddy, although the sonar frequency is probably too low for this. These possibilities are to be investigated.

4. APPLICATION TO LOW FREQUENCY SCATTERING

4.1 Rationale

Models of low frequency scattering by bubbles are presently hindered by the following two, important, uncertainties, which high frequency measurements may help resolve.

(a) The distribution of bubble clouds is imprecisely known. Langmuir circulation may play an important role in sustaining and ordering the clouds, except perhaps at high current speeds in shallow water (see Section 3), by clustering them into bands in the downwelling zones, and therein working against their buoyancy. Although this mechanism is often cited in the models of low frequency scattering as that responsible for the existence of the clouds [11, 12], such models simultaneously take the scatterers to be spatially uncorrelated, at odds with the clustering of clouds in bands.

(b) The models may be split into two groups: those that consider the scatter to originate from clouds with a well defined surface [11, 13], and those that consider it to result from the ambient near surface bubble layer, due to waveguide effects [14] or Kolmogorov scatter from inhomogeneities in the bubble distribution [15]. The diffuseness of the clouds will determine the relative importance of these two, probably co-existing, processes.

Point (b) is not considered further here, save to note in passing that it is probably best addressed by estimating the void fraction or phase speed from the calibrated, narrow beam sonographs. The limiting uncertainty then lies in the transient bubble density and two phase flow of wave breaking.

Point (a) may be addressed simply with the uncalibrated side-scans. The hypothesis considered here is that Langmuir circulation, which is more ordered than most upper ocean processes occurring over similar length and time scales, may give rise to an array of bands sufficiently regular for a Bragg interference, analogous to that seen for surface waves, to occur, in a low frequency, CW, side-scan sonar. The resonance would be seen by rotating the beam, once its frequency was tuned to the domain of resonance, or by sweeping the frequency, if it were known *a priori* that the beam was normal to the bands. Simulation studies, to be described elsewhere, confirm that this resonance is possible, provided that the array of bands meets the predicted regularity criterion.

Bragg resonance, if proven, might well be more important than resonance associated with a single cloud. The latter is determined by the bubble density, the size, and, to a lesser extent, the shape of the cloud [16], and will consequently be smoothed out in an oceanic ensemble of different clouds. Bragg resonance, in contrast, is more sensitive to the distribution of clouds than to the variability in their scattering cross-sections. The resonance would also indicate that the bands will act as line sources of backscatter under ensonification by a spherical beam.

4.2 Analysis

The sonographs are analysed to see if the array of bands instantaneously in the cross-current, side-scan beam (Fig. 2a) is more regular than the ensemble of scatterers instantaneously in the beam when Langmuir circulation is absent (Figs. 2b, c), and if so, to assess whether the regularity meets the criterion from the simulations for Bragg resonance to occur. Discrete scatterers are identified following the specification of a relative intensity threshold. A pertinent statistic that is then calculated is the coefficient of variation, c_l, of the spacing, L, between neighbouring scatterers, defined as follows:

$$c_l(t) \doteq \langle (L - \langle L\rangle_l)^2 \rangle_l^{1/2} / \langle\langle L\rangle_l\rangle_t \, , \tag{2}$$

where $\langle\,\rangle_i$ denotes the average over all scatterers instantaneously in the beam, and $\langle\,\rangle_t$ denotes the temporal average. The coefficient is generated at each digitised sonograph time (subject to there being a minimum of six scatterers in the beam), and its histogram is built up.

The result for Fig. 2a, shown in Fig. 3a, reveals that c_l is roughly Gaussian about a mean of 0.8. The histograms for Figs. 2b and 2c (not shown) are also Gaussian, about a larger mean of 1.1. The array of bands is therefore on average more regular than the ensemble of scatterers in the absence of Langmuir circulation. The regularity is, however, at all times insufficient to yield values of $c_l < 0.1$, the criterion from the simulations for Bragg resonance to be possible.

Bragg resonance cannot yet be dismissed on the strength of this dataset, however, as the spacings in the simulations are generated independently of one another. This is invalid if Langmuir circulation, as an ordered process, tends to oppose random perturbations in the spacing, through the dynamic coupling of the cells. Perturbation of a spacing in one sense from the mean would then render a perturbation in the opposite sense in a neighbouring spacing more likely. The regularity criterion for Bragg resonance should then be made less stringent than that predicted from the simulations.

A statistic that reveals whether the spacings between bands are, indeed, correlated in this manner is the autocorrelation covariance coefficient, c_a, of the i^{th} and j^{th} spacings, defined by

$$c_a(i,j) \doteq \langle (L - \langle L\rangle_t)_i (L - \langle L\rangle_t)_j \rangle_t / \langle\langle L\rangle_l\rangle_t^2 \, , \tag{3}$$

where $()_n$ denotes that the inner term is evaluated for the n^{th} spacing. Values for c_a are therefore computed, by identifying discrete scatterers, as for c_l, and by assuming that the temporally averaged statistics are invariant over the beam, that is,

$$c_a(i,j) = c_a(n) = \langle\langle (L - \langle L\rangle_t)_i (L - \langle L\rangle_t)_{i+n} \rangle_l \rangle_t / \langle\langle L\rangle_l\rangle_t^2 \, . \tag{4}$$

If c_a is significantly negative for small nonzero n then the spacings are correlated in the manner described. If c_a is zero for all nonzero n then the spacings are independent.

The coefficient is shown against spacing number, n, for Fig. 2a, in Fig. 3b. It is clear that the spacings are independent.

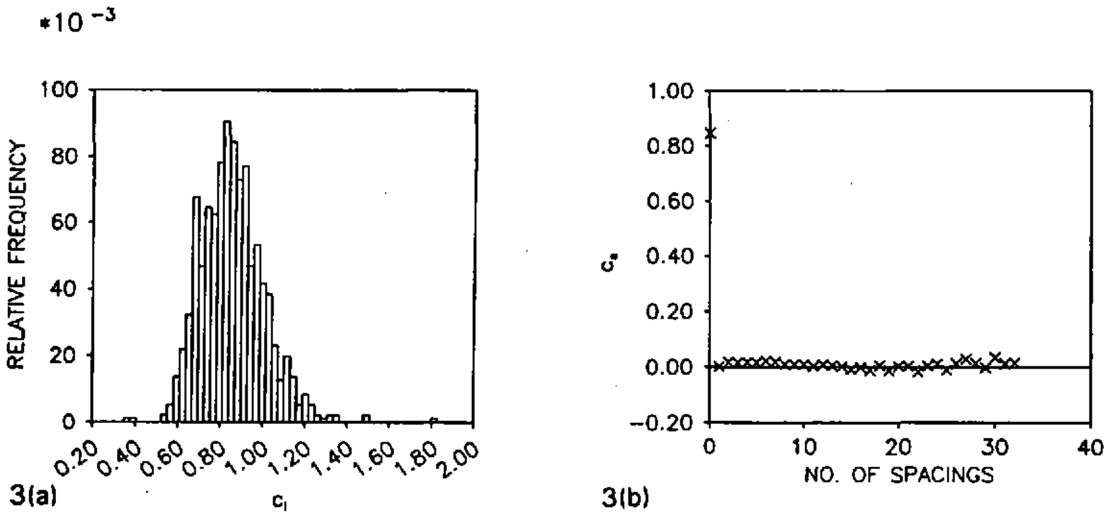


Fig. 3. Statistics of the spacing, L, between neighbouring scatterers identified in Fig. 2a. The threshold identification intensity is the top 10% of the sonograph by area.
Fig. 3a. Histogram of the coefficient of variation, c_l, of L.
Fig. 3b. Sequence of the autocorrelation covariance coefficient, c_a, of L.

4.3 Discussion

A leading hypothesis is that it is the meandering of the bubble bands that causes their observed independence. Meandering may partly result from bottom generated turbulence, but occurs even in deep water [17]. Faller and Auer [18] propose that bands meander, and consequently merge, due to random spatial fluctuation of the momentum flux from the wind and wave fields to the Langmuir cells.

5. CONCLUSIONS

High frequency scattering from the near surface layer in the southern North Sea reveals the presence of Langmuir circulation, and, at high currents, turbulence generated from flow over the seabed. Langmuir circulation orders bubble clouds into bands, aligned close to the wind, which the bottom generated turbulence, when present in the mixed layer, tends to break up.

The variability in the spacing of the bands is too great to permit a Bragg, directional, resonance, in a low frequency, CW, side-scan sonar. Models of low frequency scattering that take the cloud distribution to be uniformly random, are, on the basis of this dataset, probably good to first order.

6. REFERENCES

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