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Factors affecting the performance of the acoustic ground discrimination system RoxAnn™

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The resolution, temporal variability and survey vessel speed dependence of the acoustic ground discrimination system RoxAnn™ was assessed over a 1 km^2 area in Loch Linnhe on the west coast of Scotland. The resolution of the system was relatively poor and of the sediment parameters quantified (stone cover and sediment texture), only stone cover was consistently and significantly related to the RoxAnn™ output. The output showed considerable variability over the same ground when sampled within the same day and between days and months. The effect of survey vessel speed on the output was also significant but highly variable during all surveys. The apparent magnitude and unpredictable nature of the variation in the RoxAnn™ output have implications for the use of such systems in habitat mapping, particularly when surveying biological communities where there are only small differences in the physical properties of the seabed and also where monitoring temporal change. These aspects are discussed.

Keywords: acoustic ground discrimination system, AGDS, benthic surveys, RoxAnn™, sediment mapping.

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Introduction

There are many instances during scientific or other survey work where there is a need to visualise the seabed. Survey methods range from stills photography and grab sampling used to sample a "representative" part of the area of interest, to more broad-scale acoustic ground discrimination systems (AGDS), which visualise strips of seabed under the survey vessel (Chivers *et al.*, 1990), or swathe systems such as side-scan sonar that allow "total coverage" of the seabed (Brown *et al.*, 2002). AGDS are relatively cheap and easily integrated with standard survey vessel hardware (echo sounder and geographical positioning system – GPS). As such, they represent a compromise between time-consuming photographic or grab surveys and technologically demanding (and costly) side-scan surveys (Kenny, 2000). Broad-scale surveys, such as a complete sea loch, can be undertaken relatively easily and this, combined with the relative ease of data handling and presentation, has led to the wide-spread use of AGDS in marine habitat and community mapping (Magorrian *et al.*, 1995; Davies *et al.*, 1997; Pinn *et al.*, 1998) and environmental monitoring (Service, 1998; Rukavina, 2001).

AGDS work on the principle that when an acoustic wave, such as emitted by an echo sounder, is reflected off the seabed, it is attenuated by the properties of the reflecting surfaces (Chivers *et al.*, 1990). AGDS such as RoxAnn™ (Stenmar Microsystems, Aberdeen, UK) interpret two distinct echoes from the seabed (Chivers *et al.*, 1990). The first echo (E1) is considered to relate to sediment "roughness" and is the partial integration of the first echo to return to the transducer. Further ground type information can be obtained by interpreting the second echo (E2) to return to the transducer. E2 is the complete integration of the echo resulting from a seabed–sea-surface–seabed reflection (the acoustic wave having reflected from the seabed twice) and is considered to relate to "hardness". The relative magnitudes of E1 and E2 are then used to characterise the seabed by comparison with ground-truthed data (Chivers *et al.*, 1990). Normally, a given seabed type is assigned to a range of E1/E2 paired values that are shown diagrammatically as user-defined RoxAnn™ "squares" (Cholwek *et al.*, 2000). In some applications, the user-defined categories can be quite specific such as "fine sand" or "rippled sand" and sometimes include biological parameters such as "weedy rock" or "bioturbated mud".

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Ground truthing of the seabed is commonly achieved by taking grab samples and/or cores to assess representative sediments (Greenstreet *et al.*, 1997) or through the use of towed underwater video (Pinn *et al.*, 1998) and/or still photographs (MacDougall and Black, 1999). Ground truthing should reflect the expected application of the survey data (Chivers *et al.*, 1990) and is frequently a major expense within the overall survey.

The data string produced by RoxAnn™ includes positional information from the integrated GPS, depth and one or more indices of bottom type. These data are usually interpreted using a geographical information system (GIS) to produce contour maps of the factor of interest (Davies *et al.*, 1997; Sotheran *et al.*, 1997).

In using this survey tool for scientific monitoring, the system's sensitivity to changes in bottom type has to be assessed. Also, the extent and, where possible, cause of variation over the same ground have to be identified, with a view to eliminating as much "noise" as possible. Such an approach improves the standardisation and repeatability of the technique. Our objectives were to assess the association between indices of sedimentary texture and the RoxAnn™ output, to quantify temporal variability over a range of scales (hours, days and months) and to quantify the effect of survey vessel speed.

Materials and methods

Survey location and dates

The survey work was carried out using the RV "Seol Mara" in an area of approximately 1 km^2 in Loch Linnhe (Figure 1), north-east of Eliean Dubh (56°32′N, 5°27′W) on the west coast of Scotland. The area was chosen because it exhibited a gradation in seabed type at a depth that allowed detailed ground truthing through diver-based surveys.

Within the surveyed area, eleven point stations (Figure 1b) were designated on the basis of depth: two shallow stations S1 and S2 (10 m), six mid-depth stations M1−M6 (14−20 m) and three deep stations D1−D3 (23−25 m). Stations M1, M2, M4 and M6 were connected to form a continuous transect across the surveyed area along the 20 m contour. Along the transect, 40 stone counting stations (SC stations) were assigned (one every 15 m) that included the extremes of sediment types present in the surveyed area. RoxAnn™ surveys were conducted in May and August 2000 and on two consecutive days in February (6/7) and March (15/16) 2001.

Physical characterisation of the seabed

Seabed sediment parameters measured included stone cover and granulometry. Stone cover was measured at the 40 SC stations (along the transect M1−M6) by SCUBA divers using a rigid mesh grid. This grid consisted of 100 (10 by 10) cells, each 5 × 5 cm, and was placed on the seabed within approximately 1 m of each SC station. A stone (>30 mm) was counted if any part of it lay under the 100 mesh intersections giving a direct measure of percentage cover. The total number of stone counts at each SC station over the period March to July 2000 varied between 4 and 31. Survey frequency was highest in areas where the variance was highest. An additional four stone count surveys were conducted along the transect in March 2001 to determine possible temporal changes in stone cover. Stone cover was also measured (8−27×) at the seven other stations not included in the transect between 22 July 1998 and

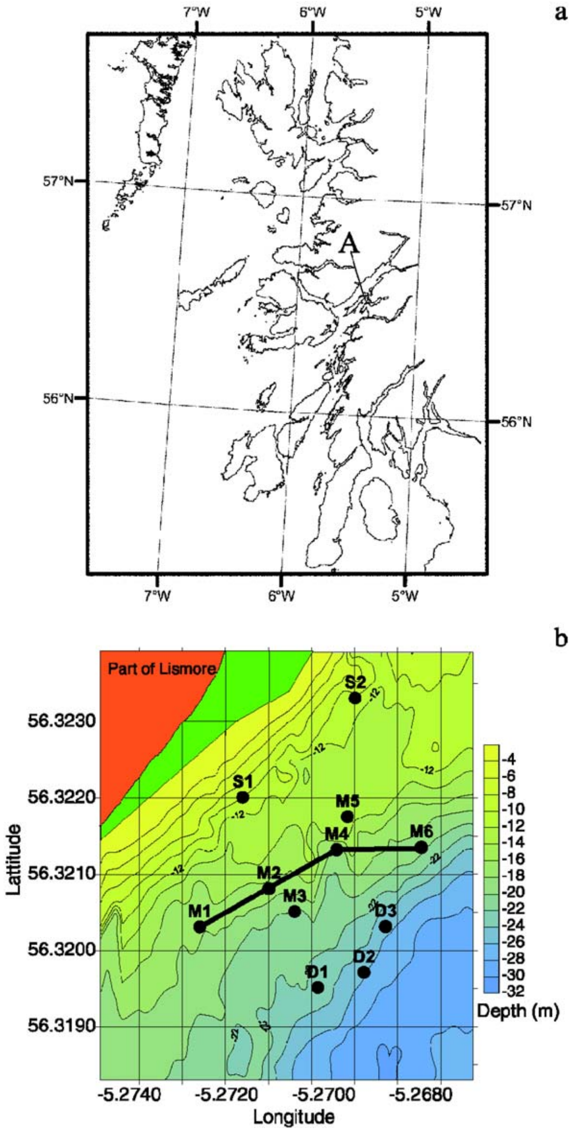

Figure 1. (a) Location of surveyed area in Loch Linnhe (A) on the west coast of Scotland and (b) bathymetric detail of the surveyed area (latitude and longitude in decimal minutes), location of sampling stations (S1, S2, M1−M6, D1−D3) and of the transect (M1−M2−M4−M6; total distance 585 m).

06 April 2000. Where appropriate, diver observations of the bottom type were also recorded.

Granulometric analysis was undertaken on hand-collected 58 mm (internal diameter) sediment cores taken at the 11 point stations between June and September 1998 (Table 1). Following collection, the top 6 cm of sediment was prepared as described by Buchanan (1984) and split into seven size fractions using a sieve stack (*Endecotts*, London) mounted on a sieve shaker (Omron "Impact" SV001, Stevenson, Ayrshire, Scotland). The size fractions were <63 µm ($\phi > 4$), 63−125 µm ($4 > \phi > 3$), 125−250 µm ($3 > \phi > 2\phi$), 250−500 µm ($2 > \phi > 1$), 500−1000 µm ($1 > \phi > 0$), 1000−2000 µm ($0 > \phi > -1$) and 2000−4000 µm ($-1 > \phi > -2$), where $\phi = -\log 2$ of the particle size (mm). The >4 mm fraction ($\phi < -2$) was discarded as the size of the cores was considered too small to get a representative sample of this fraction and the chance inclusion of such material could introduce bias.

AGDS and echosounder specifications

The echo sounder (Furuno, 200 kHz, 10° beam angle, depth range set at 80 m, gain = 4) was attached to the survey vessel using a purpose-built rigid support ensuring that transducer location and orientation were kept constant during and among surveys. The RoxAnn™ system (GroundMaster, Dual Frequency, purchased in 2000) was set-up and calibrated according to the manufacturer's recommendations. The configuration was standardised between surveys and the system was allowed to stabilise for approximately 40 min prior to use. Surveys lasted up to 4.75 h. The data string produced by the system was logged using RoxMap 32™ software (version 3.2.1.1S, set at 30 Hz) and consisted of longitude, latitude, depth, E1, E2, date and time.

RoxAnn™ survey methodology

During each survey, the vessel moved above each of the point stations (Figure 1) at approximately 6 knots and along the transect M1−M6 (at different speeds, see below). Vessel speed was determined using the on-board dGPS system and relates to speed over the ground. Survey progression was monitored using the on-board differential GPS (Furuno GP36; WGS84 datum) shown in real time using SeaPro 2000™ software (Euronav, Portsmouth) on which the station and transect locations had been superimposed. The on-board navigation system was used to determine speed and heading during surveys. Each point station was surveyed at least twice, ensuring that the vessel tracks were perpendicular to each other. The surveyed site area is relatively unexposed and surveys were only conducted in calm to slight sea-surface conditions.

The effect of vessel speed and stone cover (as a single factor, see below) on E1 and E2 was determined along the transect by traversing M1−M6 at different speeds (2, 4 and 6 knots and, during February and March, 8 knots). Different speeds and starting points (either M1 or M6) were randomly assigned and the appropriate speed and heading were obtained at least 50 m ahead of the first station. At each speed, the transect was tracked four times and the start and finish times were recorded.

Data analysis

Mean stone cover was calculated from the combined data set (March to July 2000 and March 2001 surveys) for each SC station. The median particle size (MDϕ) was calculated by pooling data from each core (where more than one core was analysed) and reading off the median value from a cumulative plot (linear interpolation). The proportion of sediment passing the 63 µm (4ϕ) sieve represented the % silt and clay. The pooled granulometric data for each station, consisting of the relative proportion made up by each sediment size fraction, were then subject to principle component analysis (PCA; Primer, Primer-E Ltd, Plymouth, UK). The degree to which PCA could explain the variation in the sediment was assessed with a view to using

Table 1. Summary of mean sediment characteristics for the 11 sampling stations (n: number of cores analysed; depth: chart datum in m; %<63 µm: percentage silt and clay; MDϕ: median particle size; QDϕ: quartile deviation (measure of sorting); skew: ϕ quartile skewness − Buchanan, 1984; PC1 and PC2: principle component axis scores).

Station	n	Depth	%<63 µm	MDϕ	QDϕ	Skew	PC1	PC2
S1	2	10	45	3.53	1.50	−1.76	−16.85	17.17
S2	2	10	28	2.45	1.50	0.25	−2.33	−1.70
M1	2	18	33	3.00	1.05	0.15	−13.22	−12.42
M2	2	17	35	2.86	1.40	−0.46	−9.61	−0.55
M3	1	20	26	2.28	1.50	0.32	0.77	−3.02
M4	2	18	32	2.18	1.55	0.47	1.03	2.25
M5	3	14	27	2.58	1.29	0.21	−2.57	−8.57
M6	2	19	12	1.16	0.90	0.04	17.87	3.14
D1	3	23	27	1.97	1.50	0.56	5.69	−0.71
D2	2	25	23	1.66	1.35	0.49	10.56	1.83
D3	2	25	24	1.68	1.45	0.67	8.66	2.59

the first two principle components (PC1 and PC2) in further analyses (path analysis) as predictor variables. Prior to path and regression analysis, data normality was checked using the Shapiro−Wilk's statistic (SAS, 1985) and homoscedasticity by the examination of residuals (Littel *et al.*, 1991). PC1 and PC2 have the advantage over MDϕ and % silt and clay as factors in path analysis as they are, by definition, uncorrelated and have the potential to more completely describe the sediment. The relative importance and significance of the factors in predicting E1 and E2 were evaluated by comparing standardised regression coefficients (Sokal and Rohlf, 1995).

Before comparing E1 and E2 at different times and speeds, their values, from the same location (±5 m for the 40 SC transect stations and ±10 m for the point stations), were extracted from the data set for any one survey day as appropriate. Changes in the correlation between E1 and E2, from the same location occurring over time, at different speeds and against stone cover, without granulometric indices PC1 and PC2, were tested using Fisher's Z transformation (Snedecor and Cochran, 1980). The extent of the relationship between stone cover, PC1 and PC2 and E1 and E2 at the 11 point stations was determined using path analysis (Sokal and Rohlf, 1995). The path model assumed that the predictor variable stone cover was correlated with PC1 and PC2 but that PC1 and PC2 were not correlated and that all directly predicted both E1 and E2. When examining the E1 and E2 relationship with the physical parameters over time, it was assumed that their actual values did not change over time. For stone cover, this assumption was tested by comparing the 95% confidence limits of the means from the June/July 2000 and March 2001 surveys.

For comparisons of temporal changes in E1/E2 against stone cover and PC1 and PC2, values from the surveys with different speeds were pooled. Temporal variation within surveys was determined by comparing repeated E1/E2 measurements from the same location (±5 m) against the time difference between the repeated measurements, using regression analysis. The within-survey drift in these parameters was also expressed as the mean of the average change, as a proportion of the total range, from measurements taken at different times over the same ground. For the analysis of daily and seasonal variation, the E1/E2 correlation from surveys carried out during consecutive days and during August, February and March surveys (pooling information from consecutive daily surveys), respectively, were compared using Fisher's Z transformation.

For the analysis of the speed effect, the data string produced by the RoxAnn™ system was split according to the start and finish times of each survey as appropriate. E1 and E2 were regressed on speed individually and also changes in the correlation (using Fisher's Z transformation) between the two parameters obtained at different speeds were investigated.

Path models and regression analyses were developed and tested using AMOS 4™ (SmallWaters Corp., Chicago), other data analysis and management was done using SAS™ (SAS Institute Inc., Carry, NC, USA).

Results

Physical characterisation

Visually, the sediment in the surveyed area consisted of muds and sandy muds with the south-west part (M1) being characterised by a uniform and flat mud that gradated, towards station M6, to a cobble-strewn sandy mud. Station M4 consisted of gravel and shell gravel mixed with sandy mud. No larger-scale physical features, such as ripples or underwater dunes were observed. Benthic macrophytes were absent at all times of year except at the shallow stations where a slight algal turf was present during the summer months.

Visual observations were corroborated by granulometric and stone cover measurements. With the exception of station S1, the finest and coarsest sediments were located in the south-west (M1: 33% silt and clay) and north-east (M6: 12%) of the surveyed area, respectively (Table 1). Between these extremes, a uniform gradient existed as indicated by the relative positions of the transect stations M1, M2, M4 and M6 on the PCA ordination (Figure 2). PC1 is closely associated with sediment coarseness with low values representing finer sediments (M1) and high values coarser sediments (M6). The granulometric data were essentially two-dimensional with 62.4 and 30.2% of the variance being explained by the first two principle components, respectively (total 92.6%). PC1 and PC2 are, therefore, ideal indices for inclusion in path analysis as predictor variables as they almost completely describe the granulometric make-up (texture) of the sediment. S1 was an anomalous station in the area that did not cluster closely with any of

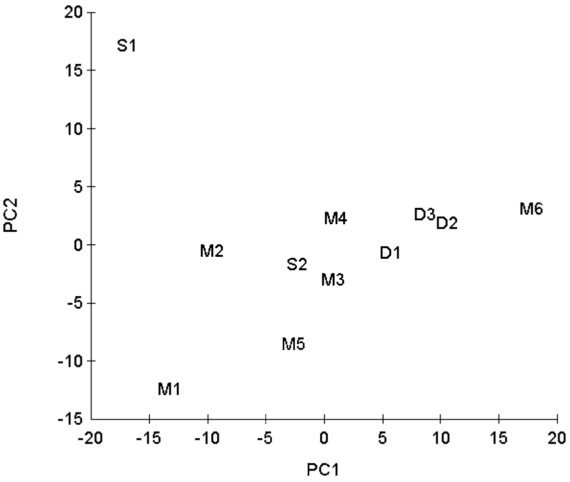

Figure 2. Principle component ordination (PCA; two dimensions; 92.6% of the variance explained) of the sediments from the 11 point stations (see Figure 1).

the other stations on the PCA ordination (Figure 2), including those with similarly high MDϕ values, because it was dominated by silt and clay (45%) and highly negatively skewed as a consequence (Table 1). Under the classification system suggested by Buchanan (1984), the sediment could be considered a poorly sorted and fine skewed silty sand.

Along the transect stone cover increased gradually from 5 to 53%, apart from a steep drop to a minimum of 20% between 375 and 500 m from M1 (Figure 3a), which consisted of a patch of gravel. The general trend in stone cover along the transect was consistent between surveys (March–July 2000 vs March 2001) but the non-overlap of the 95% confidence limits at four of the 40 stations indicate that changes did occur (Figure 3a). Stone cover was significantly and positively associated with PC1 ($r = 0.82$, $p < 0.01$, $n = 11$) but not with PC2 ($r = 0.43$, $n = 11$).

Factors affecting E1 and E2

E1 and E2 were closely associated (rough areas tended to be hard, $p < 0.0001$, $n = 3191–13485$) during all surveys. However, the correlation varied between 0.26 (May, $n = 4456$) and 0.68 (February, $n = 4204$).

Along the transect, stone cover was significantly correlated with both E1 and E2 during all surveys ($r = 0.46–0.81$, all $p < 0.005$, $n = 40$), with the relationship with E1 exhibiting higher variability compared with E2 (range in r: 0.35 and 0.20, respectively). During February and August, E1 showed a higher correlation with stone cover (both $r = 0.81$) compared with E2 ($r = 0.58$ and 0.55, respectively). However, during March the relationship was reversed (E1: $r = 0.46$; E2: $r = 0.72$). Although there was a significant association between both E1 and E2 and stone cover, neither E1 nor E2 showed any change concomitant with the drop in stone cover between M4 and M6 during any survey (Figure 3).

The relationships between stone cover, PC1 and PC2 and both E1 and E2 varied and changed over time. Stone cover was the only significant predictor of E1 and E2 in February and of E1 in March (Table 2). The total variance explained by the path model ranged between 9% (March, E2) and 84% (March, E1).

Temporal variation in E1 and E2

The drift in RoxAnn™ output was tested over three temporal scales: within survey (up to 4.5 h), between consecutive days (over ~24 h) and between months (from 1 to 7 months).

The within-survey time effect was significant in seven of the 10 series (consisting of E1/E2 pairs on five different dates; Table 3) with the proportion of the variance explained by drift over time varying between <0.1% (07 February, E1) and 22% (August, E2). The average drift in E1/E2 over all surveys was 7.6% (range during any one survey: 6–11%) but the nature (positive or negative) of the relationship varied.

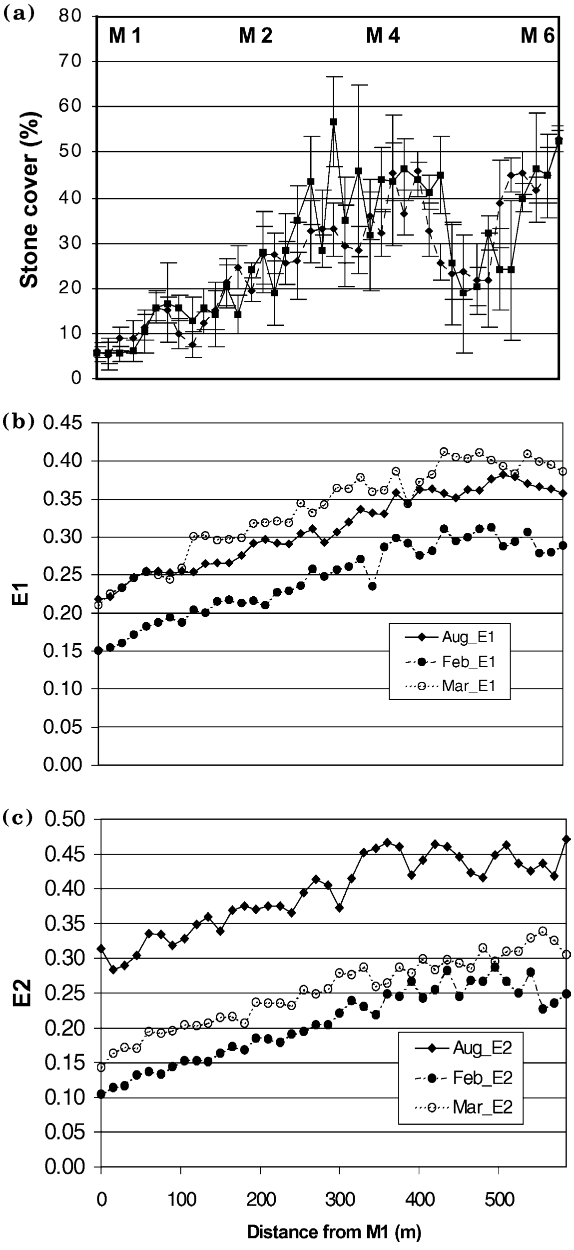

Figure 3. Variation in (a) mean stone cover at the 40 stations with 95% confidence limits ($n = 4–31$) during 2000 and 2001 surveys, (b) E1 and (c) E2 during different surveys along the transect M1–M6.

The relationship between E1 and E2 also changed between consecutive survey dates on both occasions (6/7 February and 15/16 March, $p = 0.002$ and 0.0001, $n = 426$ and 3405, respectively). Between months, systematic differences were observed in the values of both E1 and E2 measured along the transect, although the generally increasing trend from M1 to M6 appeared similar during

Table 2. Standardised partial regression coefficients (b′) obtained from path analysis with E1 and E2 as predicted variables and stone cover (SC) and principle components (PC1 and PC2) as predictor variables ($*p < 0.05$; $**p < 0.01$; R^2: total proportion of the variance of E1 or E2 accounted for by the predictor variables).

		b′			
Date	Echo	SC	PC1	PC2	R^2 (%)
February 2001	E1	0.68*	0.17	0.19	83
	E2	1.09*	−0.12	−0.45	69
March 2001	E1	0.75*	0.16	0.08	84
	E2	0.30	−0.01	0.00	9

all surveys (Figure 3b and c). Values were lowest during the February survey, while the relationship between E1 and E2 changed between March (higher E1) and August (higher E2). These observations are corroborated statistically as differences in the relationship between E1 and E2 were observed for each of the three pairs of monthly data ($p = 0.0001-0.001$, $n = 1148-4571$).

Effect of vessel speed

Effects of vessel speed on both E1 and E2 were significant during all surveys and both decreased as speed increased, with the effect on E2 being greater (Table 4). Speed had the lowest effect during the August survey accounting for $< 1\%$ of the total variance in both E1 and E2. However, in March 10% of the variance in E2 was explained by speed.

The effect of speed on the correlation between E1 and E2 differed between surveys and showed no consistent trend. The magnitude of the speed effect varied and did not depend on the absolute speed difference. For example, there was no statistical difference in the correlation between E1 and E2 between the 2-knot and 8-knot surveys undertaken in February and March.

Table 3. Mean within-survey drift in E1 and E2 as a % of the total range during each survey (duration: maximum difference in hours between any two stations crossed; n: number of observations; b: slope of regression line; p: probability of no survey drift; R^2: percentage variance explained by time).

Date	Duration	n	Echo	Mean (%)	b ($\times 10^{-3}$)	p	R^2 (%)
August	2.84	3724	E1	8	−0.10	<0.001	0.4
			E2	11	−0.81	<0.0001	21.6
06 February	4.46	796	E1	7	−0.16	<0.0001	3.6
			E2	7	−0.18	<0.0001	4.3
07 February	3.00	326	E1	7	0.00	0.95	<0.1
			E2	11	−0.13	0.08	0.9
15 March	4.21	4600	E1	6	0.04	<0.05	0.1
			E2	10	0.05	<0.05	0.1
16 March	1.97	3456	E1	6	−0.03	0.32	<0.1
			E2	10	0.18	<0.0001	0.6
Mean				7.6			

Table 4. Results of regression analysis of speed on E1 and E2 by survey (n: number of observations; b: slope; p: significance; R^2: percentage of observed variance explained by speed).

Month	n	Echo	b	p	R^2 (%)
August	2115	E1	−0.0020	<0.05	0.3
		E2	−0.0031	<0.01	0.5
February	1459	E1	−0.0029	<0.0001	1.4
		E2	−0.0076	<0.0001	7.7
March	4589	E1	−0.0055	<0.0001	3.1
		E2	−0.0124	<0.0001	9.9

Discussion

Under the conditions described here, the RoxAnn™ system used recorded large and inexplicable variation over the same ground when sampled at different times and was significantly influenced by the speed of the survey vessel. In addition, the factors influencing the output (E1 and E2) were complex and not consistently related to sediment parameters such as stone cover or sediment texture (PC1 and PC2).

In any assessment of a remote mapping system, where logistics limit the number of samples that can be analysed and absolute positional accuracy cannot be guaranteed, several assumptions have to be made. First of all, we have assumed that the sediment was not changing over the temporal scales investigated. This assumption is difficult to verify, but the lack of large-scale interannual change in stone cover and the high correlation between stone cover and MDϕ suggest a high degree of sediment stability.

A second assumption has been that the granulometric measurements (stone cover, PC1 and PC2) were representative of the area esonified by the RoxAnn™ integrated echo sounder. At the specified beam angle of the sounder (10°), the area esonified at 10 and 20 m depth is approximately 10 and 39 m^2, respectively. Therefore, measurements of E1 and E2 represent relatively discrete approximations of seabed acoustic reflectivity (under the RoxMap data logging system only values from the echo pulse immediately preceding the save are recorded). However, some analyses were based on the mean of all data from a given area (10 m radius for the point stations, 5 m radius for the SC stations). This introduces additional "blurring" of the E1/E2 response to the seabed such that, at 20 m depth, values could effectively come from an area ("footprint") of 182 m^2 (point stations) or 72 m^2 (SC stations). It is unrealistic to expect an acoustic system to be able to distinguish sediment patches that are smaller than the footprint. However, the clear trend in sediment type shown, for example along the transect, occurs on a scale much larger than the system's footprint (under the conditions described), validating the comparison of discrete measurements of seabed parameters and E1 and E2.

The third assumption is that the combination of data from surveys conducted at different speeds into single data sets is valid. This procedure can be justified on the basis that the random assignment of the starting location and speed would prevent the introduction of any systematic speed effect that could lead to erroneous conclusions regarding temporal stability. This would only increase the "noise" and reduce the power of the comparisons between, for example, different days. This is not an issue in the results presented as the null hypothesis of no change was rejected.

The fourth assumption was that inevitable variations in sea conditions did not introduce systematic changes in the values of E1 and E2. Although this has been identified as a potential source of variation (Hamilton *et al.*, 1999), the area was partly selected because it offered considerable shelter from all directions. Essentially, all surveys were conducted in similarly calm to slight sea conditions. Finally, we measured speed over the ground, which may be different from speed through the water as a consequence of variable currents. However, systematic error occurring as a consequence of water currents would have been minimised as surveys were conducted in opposite directions along the transect and perpendicularly over the point stations.

When used for scientific purposes, any AGDS should have a known reliability and resolution in order to evaluate its ability to distinguish different bottom types. Stone cover showed the highest degree of predictability in respect of RoxAnn™ output. The overall trend in stone cover was consistently associated with E1 during all surveys and the system may be considered to have some use, within the surveyed area, for tracking this parameter. However, the lack of a response in E1 (or E2) to the marked drop in stone cover along the transect suggests that the relationship is not a simple one. Rather, stone cover may correlate with one or more factors that determine E1 and E2. The other granulometric parameters examined (PC1 and PC2 as measures of sediment texture) did not significantly contribute to the predictive capability of the models investigated. Thus, under the conditions described, RoxAnn™ cannot be considered a useful tool in predicting sediment texture and could not distinguish between the muddiest (M1 and S1) and the coarsest stations (M6) on the basis of particle size alone.

This lack of "resolution" has implications for its use for community mapping as the biological communities at M1 and M6 are very different (Wilding and Sayer, 2002). The apparent complexity of the factor(s) determining E1 and E2 concurs with the findings of Pinn and Robertson (2001). Greenstreet *et al.* (1997) could only reliably distinguish three sediment types (over the range muddy sand to gravel) in the Moray Firth (Scotland) using the same system. The authors commend RoxAnn™ for achieving this level of resolution but the results presented here suggest that some other factor correlating with particle size was determining E1 and E2 rather than particle size itself.

Previous research has indicated that systematic as well as complex changes in RoxAnn™ output occur over time. Greenstreet *et al.* (1997) observed a change in E1/E2 between October/November and the following January over the same ground. Our results indicate that such differences might occur at much shorter time scales, even between consecutive days and within surveys. This short-term variation in the output must obviously be evaluated before the conclusion can be drawn that seasonally changing bottom conditions are responsible for the variation. The temporal changes reported here reaffirm the importance of revisiting the same ground within any one survey to assess short-term temporal drift, and the need for repeated and frequent ground truthing between surveys. The effect of within-survey drift is to increase noise and reduce system resolution. This loss of resolution appears to be in the order of 7.6% of the total signal range (mean over both E1 and E2), but up to 22% of the variance in E2 may be attributable to within-survey drift.

The scientific usefulness of AGDS depends on a consistent response to the same bottom type until such a time when ground truthing can be repeated. For a given resolution, a more stable system will require ground truthing less often making it more cost-effective. The within-survey temporal variation observed has several important practical implications. For instance, survey results should be interpreted carefully, especially if an area is surveyed systematically where a trend in sediment type may simply reflect a progressive drift in the output. Also, ground truthing should be conducted on each day the system is used, even when over the same ground.

Vessel speed showed an inverse relationship with RoxAnn™ output with the greatest effect on E2, concurring with the findings of Hamilton *et al.* (1999). Users may therefore expect that if an area is surveyed at a speed faster than used to calibrate the system, the bottom will appear to be both smoother and softer than it actually is. Speed effects may be more problematic where survey vessel speed changes systematically during a survey. For example, slowing down in shallow water for safety reasons may result in erroneous increases in the apparent hardness of the substratum. Whilst further research is required to distinguish between variance in E1/E2 caused by current speed and vessel speed, as their separate effects could not be determined here, the considerable effect observed during some surveys (up to 10%) means that speed must be standardised within and between surveys.

Several factors, ranging from hardware issues to (a)biotic conditions, may be responsible for temporal variation in E1 and E2 over the same ground. Within-survey sources of variation include RoxAnn™ processor and transducer stability. Quantifying the separate effects of such factors is difficult in the field but until stability has been proven, consideration should be given to standardising such factors as far as is possible. This could include housing the processor in a stable environment (with regard to temperature and humidity) and standardising transducer soak-time prior to use. Changes in the physical environment may also affect the output. For example, Loch Linnhe is subject to strong tidal currents and, although surveys were conducted during neap tides, changes in tidal current patterns would be inevitable during any given survey. In addition low-salinity water enters the area during ebb, which might affect the passage of sound through water. Changing temperature and biotic conditions might cause longer-term variations. For example, benthic infauna and bioturbation may vary considerably over the year. Rowden *et al.* (1998) recorded a 45% reduction in sediment shear strength (which may affect acoustic reflectivity) in the top 5 cm of sediment as a result of bioturbation. The sediment at the survey site hosts several bioturbating species, particularly belonging to the genus *Amphiura* (Wilding and Sayer, 2002) that might be responsible for seasonal changes in acoustic reflective properties of the sediment. However, such biota-mediated changes cannot explain daily variations in E1/E2 or even those between February and March. Other sources of potential variance including large-scale macroalgae growth and presence of ripples and extensive megafaunal burrows/mounds (Pinn and Robertson, 1998, 2001) were absent during all surveys. Whatever the cause of temporal variation, it will reduce the resolution of the system until it can be identified and taken into account.

Despite the apparent limitations of the system, RoxAnn™ was able to distinguish muds from cobble-strewn sandy muds and, as such, remains a useful broad-scale indication of bottom type that could be useful, for example, in finding fishing grounds. However, RoxAnn™ could not distinguish sediments that differed quite markedly in sediment texture alone limiting its potential use in biotope mapping. In addition, the magnitude of the temporal instability and speed dependence of the system means that monitoring changes in bottom type using this type of system may be easily compromised.

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References

Brown, C. J., Cooper, K. M., Meadows, W. J., Limpenny, D. S., and Rees, H. L. 2002. Small-scale mapping of sea-bed assemblages in the eastern English Channel using sidescan sonar and remote sampling techniques. Estuarine, Coastal and Shelf Science, 54(2): 263−278.

Buchanan, J. B. 1984. Sediment analysis. *In* Methods for the Study of Marine Benthos, pp. 41−65. Ed. by N. A. Holme, and A. D. McIntyre. Blackwell Scientific Publications, Oxford, London, Edinburgh.

Chivers, R. C., Emerson, N., and Burns, D. R. 1990. New acoustic processing for underway surveying. The Hydrographic Journal, 56: 9−17.

Cholwek, G., Bonde, J., Li, X., Richards, C., and Yin, K. 2000. Processing RoxAnn sonar data to improve its categorization of lake bed surficial substrates dagger. Marine Geophysical Researches, 21(5): 409−421.

Davies, J., Foster-Smith, R., and Sotheran, I. S. 1997. Marine biological mapping for environment management using acoustic ground discrimination systems and geographic information systems. Underwater Technology, 22(4): 167−172.

Greenstreet, S. P. R., Tuck, I. D., Grewar, G. N., Armstrong, E., Reid, D. G., and Wright, P. J. 1997. An assessment of the acoustic survey technique, RoxAnn, as a means of mapping seabed habitat. ICES Journal of Marine Science, 54(5): 939−959.

Hamilton, L. J., Mulhearn, P. J., and Poeckert, R. 1999. Comparison of RoxAnn and QTC-View acoustic bottom classification system performance for the Cairns area, Great Barrier Reef, Australia. Continental Shelf Research, 19(12): 1577−1597.

Kenny, A. J. 2000. Acoustic seabed survey techniques for monitoring marine SACs: a trial of three systems. English Nature Research Reports No. 411, Peterborough. 38 pp.

Littel, R. C., Freund, R. J., and Spector, P. C. 1991. SAS Systems for Linear Models, 3rd edition. SAS Institute Inc., Cary.

MacDougall, N., and Black, K. D. 1999. Determining sediment properties around a marine cage farm using acoustic ground discrimination: RoxAnn™. Aquaculture Research, 30(6): 451−458.

Magorrian, B. H., Service, M., and Clarke, W. 1995. An acoustic bottom classification survey of Strangford Lough, Northern Island. Journal of the Marine Biological Association of the United Kingdom, 75(4): 987−992.

Pinn, E. H., and Robertson, M. R. 1998. The effect of bioturbation on Roxann® a remote acoustic seabed discrimination system. Journal of the Marine Biological Association of the United Kingdom, 78(3): 707−715.

Pinn, E. H., and Robertson, M. R. 2001. Further analysis of the effect of bioturbation by *Nephrops norvegicus* (L.) on the acoustic return of the RoxAnn™ seabed discrimination system. ICES Journal of Marine Science, 58(1): 216−219.

Pinn, E. H., Robertson, M. R., Shand, C. W., and Armstrong, F. 1998. Broad-scale benthic community analysis in the Greater Minch Area (Scottish west coast) using remote and non-destructive techniques. International Journal of Remote Sensing, 19(16): 3039−3054.

Rowden, A. A., Jago, C. F., and Jones, S. E. 1998. Influence of benthic macrofauna on the geotechnical and geophysical properties of surficial sediment, North Sea. Continental Shelf Research, 18(11): 1347−1363.

Rukavina, N. 2001. Mapping and monitoring contaminated-sediment geometry and stability. Science of the Total Environment, 266(1−3): 33−39.

SAS 1985. SAS User’s Guide: Basics, Version 5. SAS Institute Inc., Cary.

Service, M. 1998. Monitoring benthic habitats in a Marine Nature Reserve. Journal of Shellfish Research, 17(5): 1487−1489.

Snedecor, G. W., and Cochran, W. G. 1980. Statistical Methods. Iowa State University Press, Iowa.

Sokal, R. R., and Rohlf, F. J. 1995. Biometry: The Principles and Practice of Statistics in Biological Research, 3rd edition. W.H. Freeman and Company, New York.

Sotheran, I. S., FosterSmith, R. L., and Davies, J. 1997. Mapping of marine benthic habitats using image processing techniques within a raster-based geographic information system. Estuarine, Coastal and Shelf Science, 44(SA): 25−31.

Wilding, T. A., and Sayer, M. D. J. 2002. Evaluating artificial reef performance: approaches to pre-deployment research. ICES Journal of Marine Science, 59: S222−S230.