Acoustic ground discrimination techniques for submerged archaeological site investigations

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Abstract

Single beam acoustic ground discrimination systems (AGDS) based on standard echo sounders are routinely used for commercial and research applications. Analysis of the return echo signals using these systems produces indexes of seabed “roughness” and “hardness” which have been used to classify seabed type and are here used to map submerged archaeological materials.

The aim of this paper is to assess the potential for this technology to characterise submerged archaeological sites. Benefits of characterising sites in this way include the potential for assessing future impacts on the archaeological material based on the assessment of sediment type and stability from the acoustic data. The technology could offer a means by which sites can regularly be monitored for changes over time, allowing for mitigation strategies to be employed to prevent loss of cultural material.

AGDS systems have already been shown to differentiate wide-ranging bottom types over large areas of seabed. Examples are given from two archaeological sites where trials of one particular AGDS indicate that it is possible for small areas of seabed containing exposed archaeological material to be readily distinguished from the surrounding seabed in terms of the character of the acoustic responses.

Further research is necessary to determine if, on a site-to-site basis, relationships can be established between acoustic signature, generic archaeological material, sediment type and the degree of preservation of archaeological material.

Introduction

Within the Territorial Waters of the UK numerous sites of maritime archaeological interest have been discovered over the last three decades. These waters are also experiencing an increasing use of natural resources and an expansion of leisure activities such as sport diving. The ever-increasing depth and range of diving being achieved by technical sports divers will mean that discoveries of outstanding archaeological significance will continue to be found. Full archaeological investigation of every site discovered is not economically viable and therefore strategies are urgently required for the rapid assessment and effective management of new sites. Identification, rapid appraisal and the ability to detect change over time in these sites is fundamental to ensuring the preservation of our submerged cultural heritage. In order to formulate management strategies research is necessary to understand fully the environmental parameters that influence submerged cultural material in-situ.

A definitive research agenda requires a multi-disciplinary approach that relies on the integration of geophysical (remote surveying), physical (sedimentological & engineering), biological, chemical, geographical and historical applications to fully understand the factors affecting submerged archaeological material, their level of preservation and relative stability. The multi-disciplinary approach is essential for the effective management of any form of submerged cultural heritage and if successful could provide the opportunity to establish a blueprint for the geophysical approach to marine archaeological survey methodology.

Character of the Seabed

There are many factors that influence the character of the seabed around a submerged archaeological site, each of which have their part to play in the overall site formation process. These factors include the location of the site itself and the physical, chemical and biological environment surrounding it. Advances have been made into understanding the deterioration characteristics of various types of submerged archaeological material on shipwreck sites due to these factors (Gregory, 1995 & 1998; Macleod, 1998 & 1989). More research is required to relate these factors to the degree of preservation of sites in different geographical locations and the degree of stability of sediments that contain such material. Before this can be effectively achieved we must address the means by which it is possible to rapidly and remotely characterise seabed sediments.

A range of acoustic methods have been used for the investigation of maritime archaeological sites, and the considerable potential of sidescan sonar in particular has been realised over the last two decades (Bass, 1968; Rao, 1988; Redknap, 1990). The distribution of sediment types determined from sidescan sonar images has been recognised as having important archaeological implications (Duck, 1995). The effect on the acoustic response of the seabed (altered backscatter levels) from buried archaeological material has also been recognised (Fish and Carr, 1990). Chirp sub-bottom systems have also been tested for non-invasive, high-resolution investigations of sites of maritime archaeological interest (Quinn et al*.,* 1997) and in addition, bathymetric data from multibeam sonar has important archaeological implications (Momber & Geen, 2000).

In attempting to understand the environment of any individual submerged archaeological site, the following factors must be considered: the maximum offshore fetch, storm winds, tidal currents, depth, underwater topography, the nature of the seabed sediments and the biological environment. The character of the seabed sediments has been shown to be a significant factor in the preservation of archaeological material underwater (Muckelroy, 1977).

In this context the authors consider the character of the seabed to reflect more than just its composition in terms of material and grain size, but also what other information it can provide that can be detected acoustically. Sands and fine gravels, for example, have been found in many archaeological sites to be more prone to be mobile in response to tidal flow than fine-grained cohesive muds or very coarse materials. The characterisation of areas of seabed that show evidence of sediment mobility – for example the ripples and dunes in the near shore zone such as the Goodwin Sands off the coast of Kent, England, is important when assessing site vulnerability to erosion or burial by sediments. Experience gained by the Archaeological Diving Unit (ADU) through visiting many submerged archaeological sites around the UK over the last 15 years has indicated that even in areas of high current dynamics some sites are at greater risk than others. An indicator of this higher current activity is often seen in the form of scour marks in the sediments around exposed wreck sites (Caston, 1979). Scour marks surrounding ship wreck sites are relatively easily seen using remote acoustic technologies and furthermore, evidence for sub bottom palaeo-scour marks appears in the literature (Quinn et al., 1997). Scour marks around exposed wreck sites in areas of dynamic tidal flow have been characterised differently to the surrounding seabed using acoustic ground discrimination sonar systems under discussion in this paper.

Any process that alters or controls the physical properties of sediment will also change the acoustic properties of that sediment (Richardson and Briggs, 1993). The presence of archaeological material will therefore affect the acoustic properties of sediment both while the archaeology is upstanding from the bottom and while it decays within the sediment. The scattering and reflection of high-frequency sound at and within the seabed is controlled by the physical and geo-acoustic properties of the sediments (Richardson et al., 1983), surface layer roughness (Jackson and Briggs, 1992) and, it is postulated, archaeological material.

A reliable means, therefore, of determining the site characteristics that exist in different areas with seabed classification techniques will provide a good basis for a rapid assessment of the level of preservation potential of material on these sites and perhaps also provide an indication of their stability. The degree of likely levels of preservation and relative stability are the two key issues on which future management strategies should be based.

There is a need to establish a set of integrated, multi-disciplinary methodologies for assessing the current state and future condition and stability of underwater archaeological sites. It is felt that the use of acoustic ground discriminating sonar will have an important role to play in these methodologies.

Background to acoustic ground discriminating systems

The echo-sounder or single beam sonar has been used for a number of decades to measure bathymetry and also to record reflecting objects such as fish within the water column (Urick, 1983; Jones, 1999). More recently, the acoustic amplitude variations have also been processed using acoustic ground discrimination systems for seabed classification (Chivers et al., 1990; Sotheran et al., 1997).

Seabed classification with single beam sonar

The strength of acoustic energy reflected from the seabed with single beam sonar has also been used to classify the bottom type in acoustic ground discriminating systems. The basis of this technique is that different amounts of energy will be reflected or scattered from the sea floor based on the contrast in acoustic impedance between the bottom type and the water column. For example, a soft bottom such as mud will have a different reflection signature than a hard bottom such as rock and exposed archaeological material will have a different response to undisturbed seabed. A number of methods have been proposed for analysing the acoustic signal property in terms of seabed classification and include the work of Jackson and Briggs (1992), Orlowski (1984), Burns et al. (1985), and Chivers et al. (1990).

Two commercial systems, Roxann and Echoplus, have been developed from this work through the analysis of the first echo and second echo or first multiple echo. Both these systems generate two indexes, E1 and E2, in order to provide a seabed character in terms of roughness and hardness.

The first echo (E1) has been related to the roughness of the seabed. The first echo contains contributions from both sub-bottom reverberation and oblique surface backscatter from the seabed. It has been shown that there is dependence of oblique backscattering strength on the angle of incidence for different seabed materials. At 30 degrees there is almost a 10 dB difference in scattering level between mud, sand, gravel and rock (Chivers et al., 1990). The first part of the first echo contains ambiguous sub-bottom reverberations and is therefore removed. Most or the entire remaining portion of the first echo is then integrated to provide E1, the measure of roughness.

Considering the E1 value, on a perfectly flat sea floor, non-normal rays would be expected to reflect entirely away from the transducer. As the sea floor is not perfectly flat, the returning energy from non-normal rays coincides and interferes with the perpendicular rays and indicates the roughness of the sea floor (Chivers et al., 1990). When used over archaeological sites with objects that are upstanding from the sea floor, as at both sites presented in this study, it is anticipated that the reflection signature strength will vary as a function of the angle between the incident energy to the object surfaces and the nature of object material itself which controls the microscopic scattering related to the acoustic wavelength.

The second echo (E2) has been interpreted by Chivers et al. (1990) to represent two reflections at the seabed and a single scattering at the sea surface. The specular reflection of the sea floor is a direct measurement of acoustic impedance relative to the sea water above it. Measuring hardness through E2 is possible since the acoustic impedance is a product of the density and speed of longitudinal sound in the seabed (Chivers et al., 1990). Thus for many archaeological sites that are more integrated with the seabed, the acoustic density contrast is achieved between the archaeological material itself and the sea water, however for some more exposed sites with large objects upstanding from the seabed, greatly reduced E2 values are anticipated when much of the primary energy will be reflected away from the transducer. The two examples given for this study were chosen as they both show well defined upstanding objects of different material type. It is suggested therefore that interpretation of E1 and E2 values computed for some archaeological sites will not be possible in strict geo-acoustic physical terminology as is the case for simple sediment configurations but that the values will nonetheless still hold significant information about the sites when properly calibrated.

QTC View is an alternate system based on single beam echo sounders that uses only the first echo (Collins et al., 1996). The technique records both transmit and receive waves in order to perform compensations for beam spreading before principal component analysis is used on the statistics computed from the acoustic return energy to identify key parameters of the echo shape (Collins et al., 1996).

In order to ensure high quality results using each acoustic ground discrimination system, procedures are recommended where repeat surveys are made over two or more areas of known sea floor in order to calibrate the amplitude response. Furthermore, it is recommended that when surveys are made of large areas using more than one sonar, or surveys are made over a number of years using different sonars and different survey vessels, further calibration procedures are conducted over known, non-changeable sea floor (Foster-Smith et al., 2000).

The final output of the acoustic ground discriminating system based on single beam echo sounders is a depth chart and line plot of backscatter or reflection characteristics in the form of roughness (E1) and hardness (E2) of the seabed. It is also possible to interpolate the data between individual lines and produce maps of bottom roughness and hardness. Once an interpolation of data between lines has been made, it is possible to apply image-processing procedures, and modelling with geographic information systems, based on correlation of acoustic signature and bottom type. The final step in image classification is the prediction of likelihood of finding similar or dissimilar bottom types across the survey area.

Survey Equipment and Methodology

The seabed classification data for the purposes of this initial trial was collected with a digital Echoplus (SEA Advanced Products Ltd.) unit using a Koden CVS 822 echosounder with 200kHz, 8° beam width transducer. Navigation was provided by a Trimble DSM Pro and latterly a Trimble 212L DGPS system and surveys were undertaken using Norcom's SeaNav software and latterly Coastal Oceanographics Inc.'s Hypack software.

When using the Norcom software, data from the Echoplus unit was routed via a multiplexer in order that the DGPS position, time and ship bearing data could be simultaneously collected via one communications port. Since the Echoplus samples approximately four to eight times a second depending on water depth, the position between DGPS fixes (at one second intervals) was then interpolated to give a position for each Echoplus measurement. With Hypack software the Echoplus data was collected using a purpose written software driver to provide a structured raw data file without the need to interpolate positions.

The data for roughness (E1), hardness (E2) and position was then reviewed in database format to determine bad data from system noise usually manifested as sudden increases or decreases in Echoplus values and bad data from navigation jumps. The 95th percentiles for E1 and E2 were individually calculated and the data normalised by these in order to be able to make comparisons between sites possible.

The data was then imported to ESRI's Arcview geographic information system for further analysis and display. Continuous density surfaces were created within the software for the E1 E2 plots (shown in figures 3 and 6). Conceptually, a circle was drawn around each grid cell centre using a defined radius, and the number of points that fell within the circle was totalled and divided by the circle's area. The density was then calculated as the value of points per unit of area.

Georeferenced sidescan images were also imported into Arcview and used as a backdrop for those figures relating to the *Stirling Castle* site so that the Echoplus data could be visually compared against the features on the seabed. The sidescan images were georeferenced to known points on the sites that were surveyed by divers using ORE's LXT ultra short baseline acoustic tracking equipment. The sidescan images were produced with the ADU's Imagenex 858 sidecan sonar system. The bathymetric surfaces for both sites were produced entirely from the Echoplus data using the *Surfer* processing package with the Kriging method for gridding. The lane spacing for the latter is therefore the same as that indicated in figures 2 and 5. In the case of the *Markgraf* site a recently acquired georeferenced image produced from a Reson 8125 multibeam system was used as a backdrop. The image was created as a shaded relief map in *Surfer* using a grid file created from original xyz data.

Ground truth observations were collected at the various sites during routine diving inspections that form part of the work of the ADU and also with ROVs for extended inspections in deeper water. All dives were routinely videotaped using a helmet mounted camera on the ADU diver and with cameras attached to the ROV. The position of the diver and ROV was recorded on the seabed using the ORE LXT acoustic tracking system. Seabed samples were also collected using the diver and a grab sampler for future analysis.

Archaeological background to Sites

The results of AGDS surveys at two sites collected during the 2000 season are presented here. The *Stirling Castle* is a wooden warship which sank on the Goodwin Sands off Kent in the Great Gale of 1703 and the *Markgraf* is one of the German steel battleships scuttled in Scapa Flow, Orkney.

The *Stirling Castle*

The *Stirling Castle* was a 70-gun 3rd rate ship of the line. She was built in 1678 at Deptford as part of Samuel Pepy's regeneration of the Navy and was lost with her crew on the Goodwin Sands in the Great Gale of 1703 (Defoe, 1704). Local sport divers investigating fishermen's net fastenings found the site in 1979 when it was dramatically exposed, probably for the first time since it sank, due to a lowering of sand levels at this location on the Goodwins (Lyon, 1980). When originally discovered the hull and its contents were in an exceptional state of preservation (Cates et al., 1998). Sports divers originally spent more time recovering objects from the site than surveying the area, and at the time of designation under the Protection of Wrecks Act 1973 (UK), the sands covered the site again, keeping the wreck largely covered until changing seabed conditions during 1997.

The site is on the Goodwin Sands, a series of banks off the East Kent coast that dry at low water and change shape on a seasonal and apparently rotational basis (Cloet,1954). The site consists of fine sand with no binding or cohesive component (clay or vegetation). The exposed structure shows no evidence of weed growth and a lack of mussels or other colonising organisms indicate that the wreck has been almost totally covered by sand until recently. With the strong currents in the area the sand grains move easily into suspension in the water column resulting in reduced visibility and poor light penetration except after extended periods of calm weather.

The level of wreck exposure today is similar to that when first discovered in 1979. The sandbank on the starboard side of the wreck appears to have migrated to the northwest causing a significant reduction in seabed levels over the whole site by approximately 5m. This is particularly evident at the stern along the port side where scouring can be seen on the sidescan images. This is the area that is most disturbed by fishing nets that get caught on the site.

The Markgraf

The German High Seas Fleet was scuttled in Scapa Flow in 1919 under the orders of its commander Rear Admiral Ludwig von Reuter. The site contained five battle cruisers, eleven battle ships, eight cruisers and fifty torpedo boat destroyers. Between 1920 and 1946 most of the warships were salvaged but seven large wrecks still survive on the seabed including the *Markgraf*.

The *Markgraf* was a König-class battleship built in Germany by AG Weser at Bremen. She was launched on the 4th June 1913 and became part of the third Battleship Squadron that took place in the conquest of the Baltic Islands in 1917. She was 575ft long with a beam of 97ft and a draught of 30ft. Today the *Markgraf* lies upturned resting on her port side main deck (Macdonald, 1990). The hull of the *Markgraf* is generally whole apart from holes at the bow and near the engine room that were blasted during salvage operations that began in the 1920s and continued until the start of WW2.

Results

The data presented here is the result of initial trials of the Echoplus system from the 2000 season of fieldwork.

Stirling Castle

Figure 1 is a bathymetric contour plot of the *Stirling Castle* site using the depth data collected from the Echoplus system. The degree of exposure of the wreck and its position relative to the receding sandbank to the northwest is shown by 2-5m variations in topography across the site. The small (1-2m) mound to the southeast of the *Stirling Castle* represents the later wreck of an unknown (circa 18th century) wooden merchantman.

Figure 2 show the plots produced in ESRI's Arcview of the line track data gathered with the Echoplus system colour graduated for the roughness (E1) and hardness (E2) indexes respectively. A georeferenced sidescan image of the site is presented as an underlay in each case.

The roughness values (normalised by their 95th percentile) show a clear relationship to the exposed material of the wreck as might be expected. The values increase over the wreck site indicating a "more rough" seabed because of the increased backscattering effect that takes place as the sonar path crosses the exposed archaeological material.

The hardness index in figure 2 also shows a clear association with the wreck site. The values (normalised by their 95th percentile) show a marked decrease over the area of the wreck indicating a "less hard" seabed over the site. It is postulated that the level of exposed waterlogged wood on the site might be having an effect on the second echo return and/or the site is likely to have different physical properties associated with the sediments within the wreck compared with the sediments surrounding the site. The nature of the sediment at the site is the focus of ongoing research.

Figure 3 shows a density plot of the roughness (E1) values plotted against the hardness (E2) values for all the data collected over the *Stirling Castle* site. Two statistically distinct clusters of E1-E2 are apparent within the area of survey indicated by the darker areas. The smaller cluster in Figure 3 represents those E1-E2 values that are associated with the area of the wreck and this is illustrated where the E1-E2 values that make up this cluster are re-plotted on the georeferenced sidescan image (lower part of Figure 3). The association with the general area of the wreck is clear. However, the acoustic data also indicates an anomalous signature to the north of the wreck site that will require further investigation. The larger cluster represents the E1-E2 values for the survey area surrounding the wreck site that comprises largely sand.

The wreck represents a small area with respect to the total area covered in the survey nonetheless the density of site specific E1-E2 values is sufficient to be apparent in the data collected. In addition a small number of these anomalous E1-E2 values contained within the cluster also plot out in the area to the southeast where the wreck of the merchantman is know to lie.

In summary a discrete cluster of E1-E2 values, quite separate from the majority of E1-E2 values that represent the surrounding sediments, appears to define the *Stirling Castle* wreck site.

The *Markgraf*

Figure 4 is a bathymetric plot of the *Markgraf* site using the depth data from the Echoplus system. The degree of exposure of this wreck is much greater than that of the *Stirling Castle* as indicated by the 15-20m variation in depth over the site. Figure 5 shows the plots produced in ESRI's Arcview of the line track data colour graduated for the roughness (E1) and hardness (E2) indexes respectively. A georeferenced multibeam sonar image of the site is present as an underlay in each case.

As with the *Stirling Castle* data the roughness and hardness indexes (normalised by their 95th percentiles) are different over the wreck site. Higher roughness values were recorded as the sonar crossed the wreck however the hardness showed a range of both high and low values over the steel hull compared with the hardness values of the surrounding sediments. It is postulated the lower hardness values were a result of the relatively smooth and curved sections of hull of the battleship deflecting energy away from the echosounder transducer therefore giving lower hardness values than might be expected. The high hardness values occur either because energy is being strongly backscattered through damaged areas or because they coincide with those areas of the hull that present at right angles to the sonar giving a strong reflection.

As with the *Stirling Castle* the density plot of roughness (E1) indexes plotted against hardness (E2) indexes for all of the data collected on the site, shown in Figure 6, shows two obvious clusters of E1-E2 values. The smaller cluster effectively represents the wreck as opposed to the other larger cluster which represents the surrounding sediments. This is clearly illustrated by plotting the positions at which the E1-E2 values in the smaller cluster were derived onto the georeferenced multibeam image in the lower part of Figure 6.

Discussion

The results from initial trials of the AGDS presented here do not by any means provide a definitive classification for the archaeological sites surveyed. However, the *Stirling Castle* is identified by anomalous roughness-hardness values produced by the Echoplus system. Similarly the *Markgraf* site produces distinct and anomalous roughness-hardness values. The E1-E2 density plots for both sites also indicate two statistically distinct clusters of data that are clearly associated with the wreck site and wreck characteristics and are quite apart from those characterising the surrounding seabed.

In order to fully understand these results it is necessary to be able to separate the contributions to reflection strength by the wavelength dominated scattering function related to material type from that of the reflected energy due to the relative angle between the object and the incident acoustic wave. In order to accomplish this further work involving the multibeam sonar will be required. This is the focus of continuing work at St. Andrews together with an assessment of the wider application of the technique for exploration of new sites and characterisation of known sites.

Both sites were surveyed over a short time period (a few hours) with equipment that could be mobilised onto a number of survey vessel platforms. The field logistics are therefore minimal. The technique described here therefore has the potential to offer a rapid form of site survey providing important additional information on the site and identification of the site limits. Further work is currently being undertaken on characterisation of the surrounding seabed at both sites and other sites in order to produce quantitative information on site characterisation at these sites and more generally at other archaeological sites. All the sites currently under investigation are less than 50m and it is uncertain how the techniques would perform in greater water depths.

The surveys detailed above have been repeated in the 2001 season using multiple frequencies so that the differences in acoustic response can be observed for the lower frequencies. This can perhaps be related to material that lies just under the seabed rather than on the surface. In addition data has been collected for single passes over sites attempting to cover the same ground but in different directions and at different speeds in order that these factors can be assessed for their effect on the interpretation of AGDS data. The present compensations that are applied to the acoustic signatures do not account for the topography or slope of the seabed and this could have a large impact on acoustic reflection. This is the focus of complementary research at the University of St. Andrews on multi-beam and bathymetric sidescan sonar. In addition controlled trials with the Echoplus system have recently been undertaken with waterlogged wood and other materials in more controlled environments within test tanks.

The ongoing archaeological research into this area will hope to establish a *stability* index for marine archaeological sites based on measurable seabed parameters that will include seabed type derived using acoustic techniques. Furthermore, it is suggested that this data could be used in the regular monitoring of submerged archaeological sites to make assessments of change over time and to quantify the threat this poses to site stability. The process and multidisciplinary nature of site characterisation has not changed since Muckelroy's assessment (Muckelroy, 1977), however the acoustic ground discrimination system could offer a valuable additional tool for the archaeologist.

Figures

Figure 1. Bathymetry for the *Stirling Castle* site using data collected with the Echoplus system.

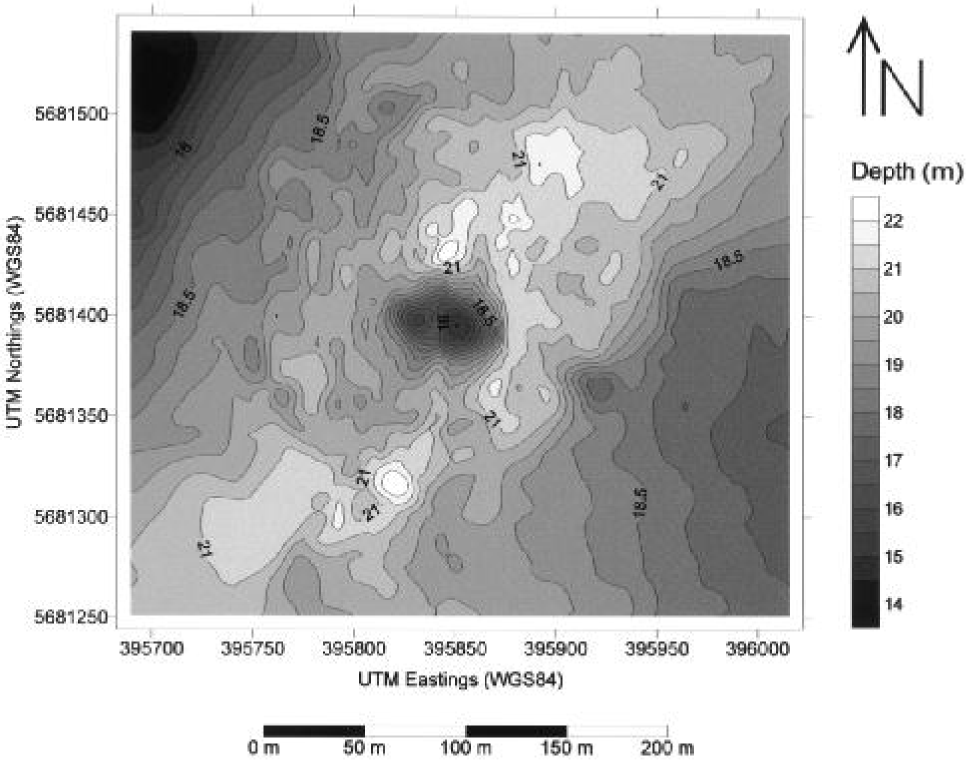


Figure 2. Line track data for the *Stirling Castle* colour graduated for Roughness (E1) and Hardness (E2) indexes.

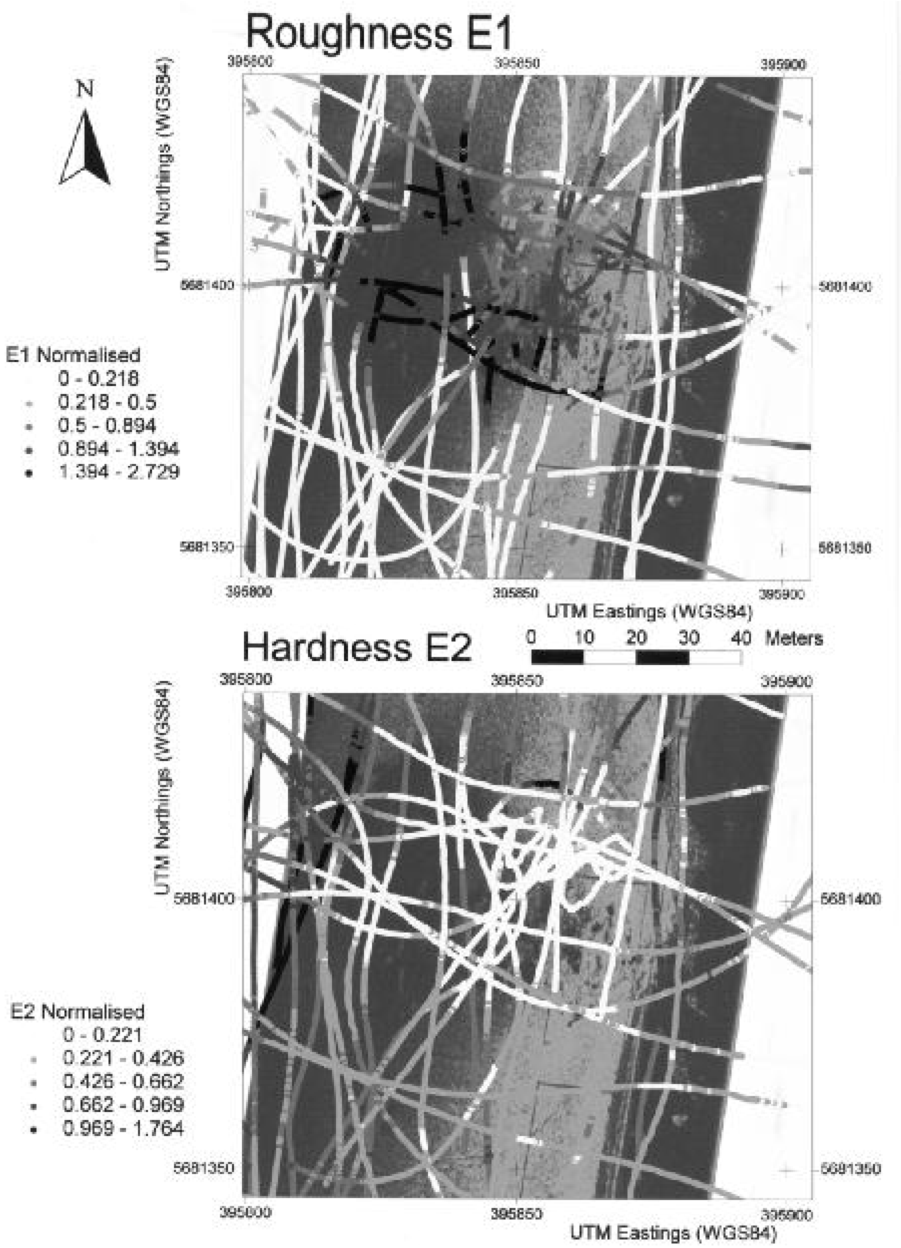


Figure 3. Density plot of E1-E2 indexes for the *Stirling Castle* showing two distinct clusters.

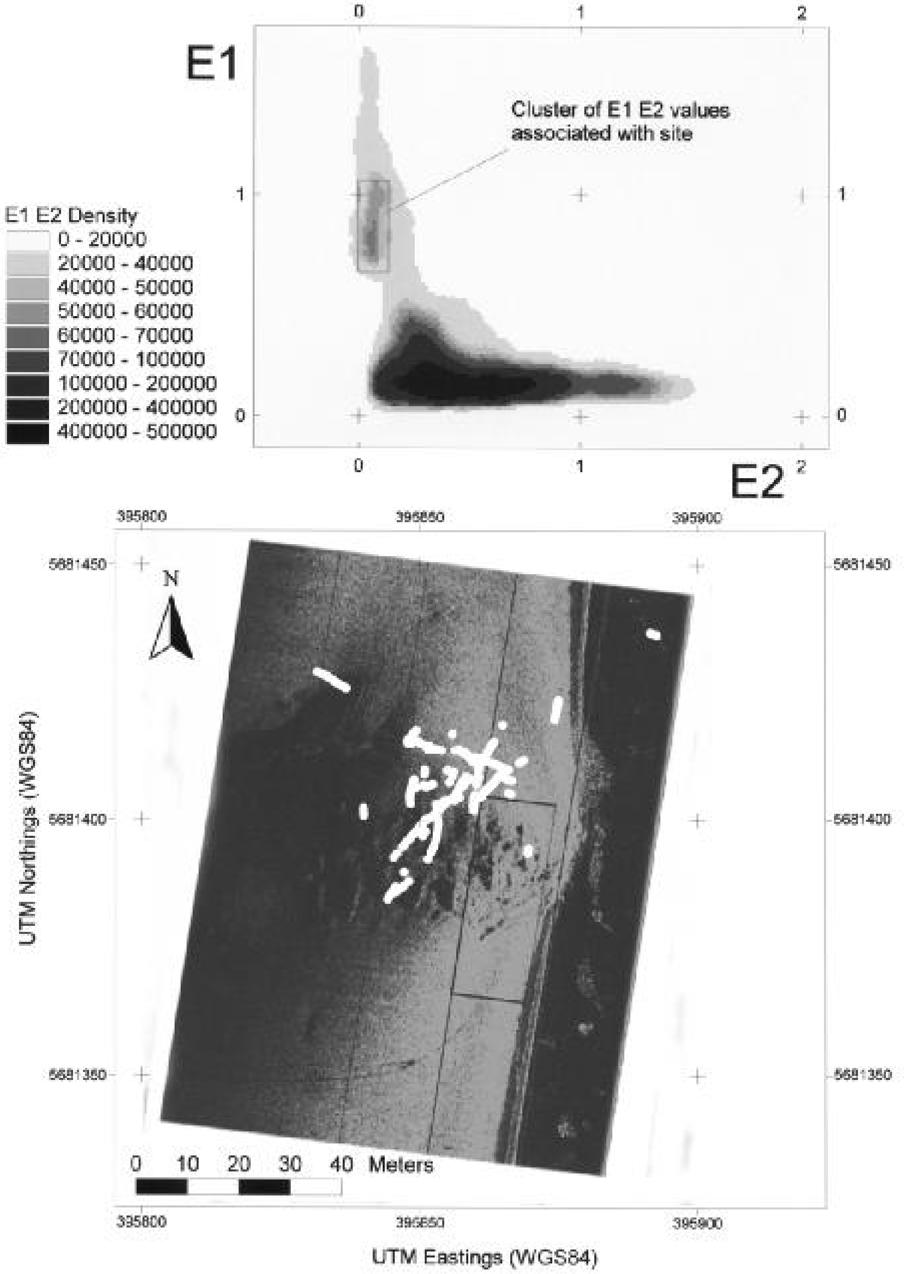


Figure 4. Bathymetry for the *Markgraf* site using data collected with the Echoplus system.

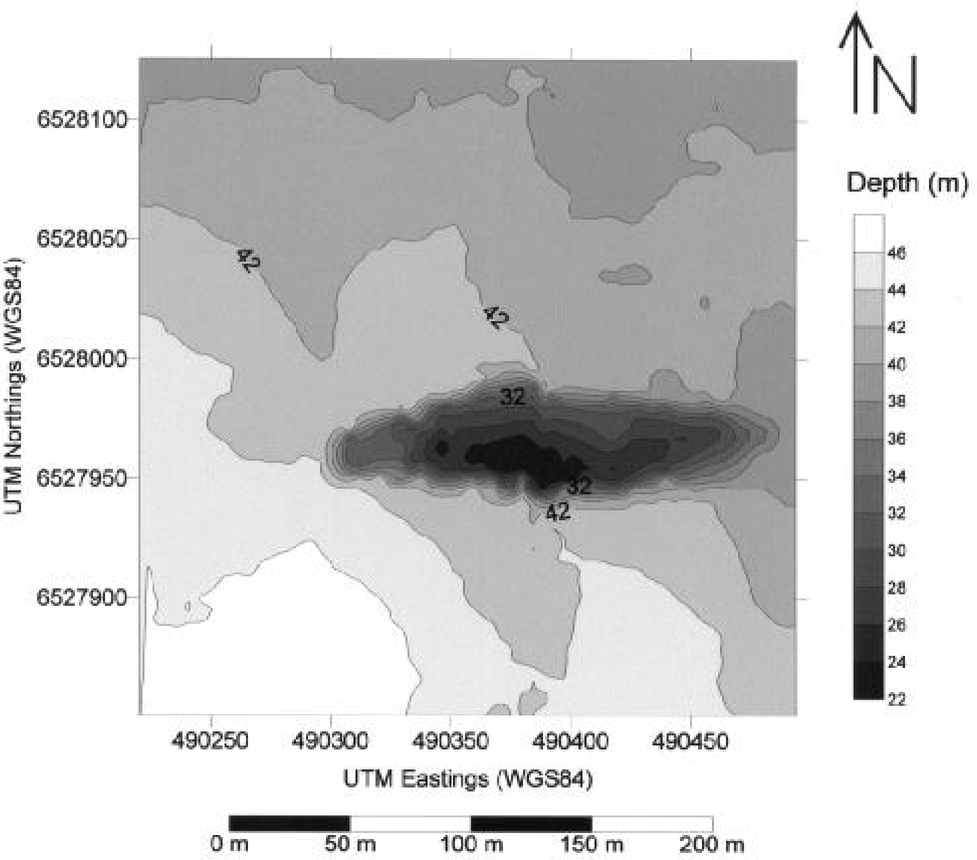


Figure 5. Line track data for the *Markgraf* site colour graduated for roughness (E1) and hardness (E2) indexes.

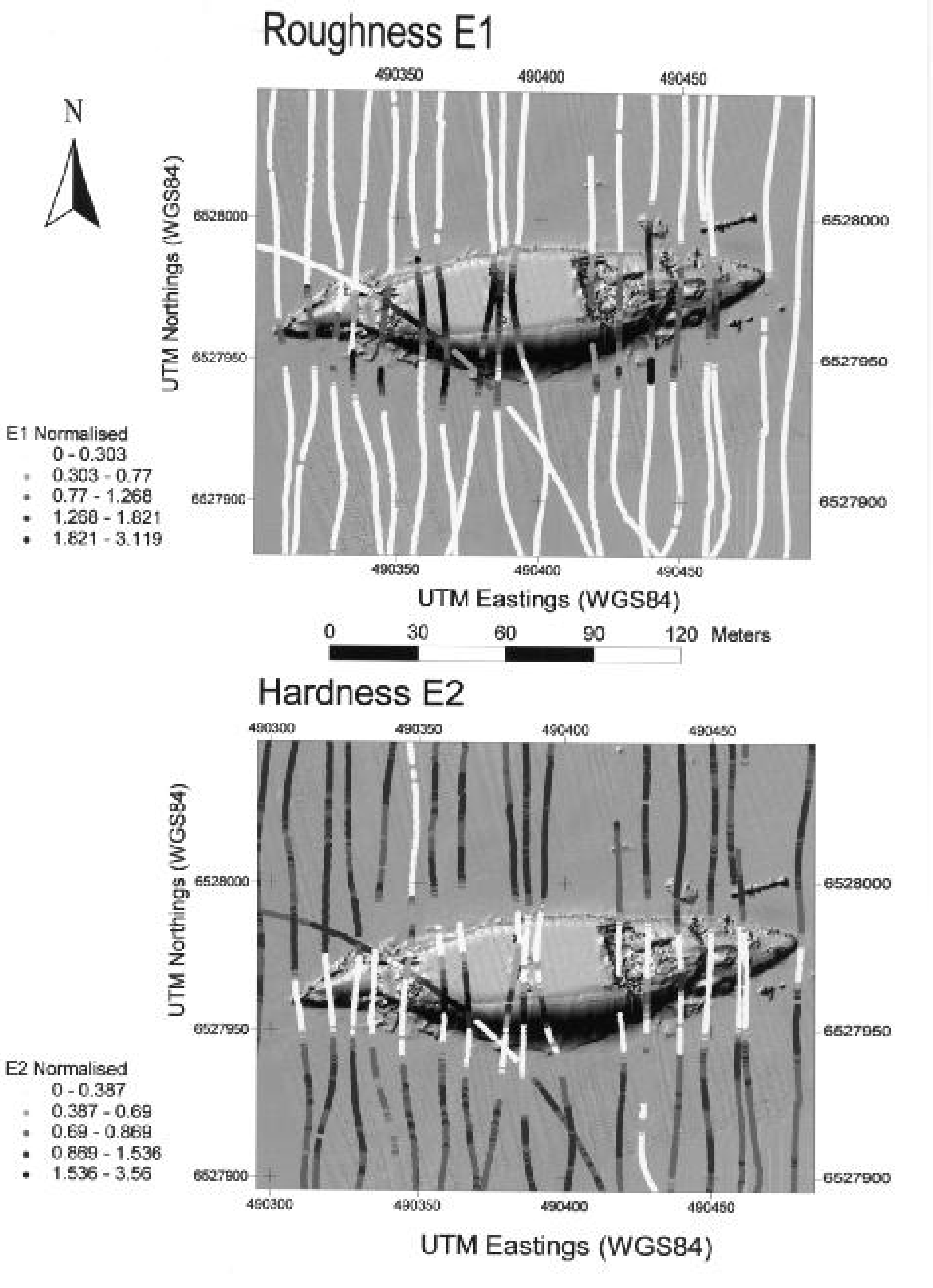
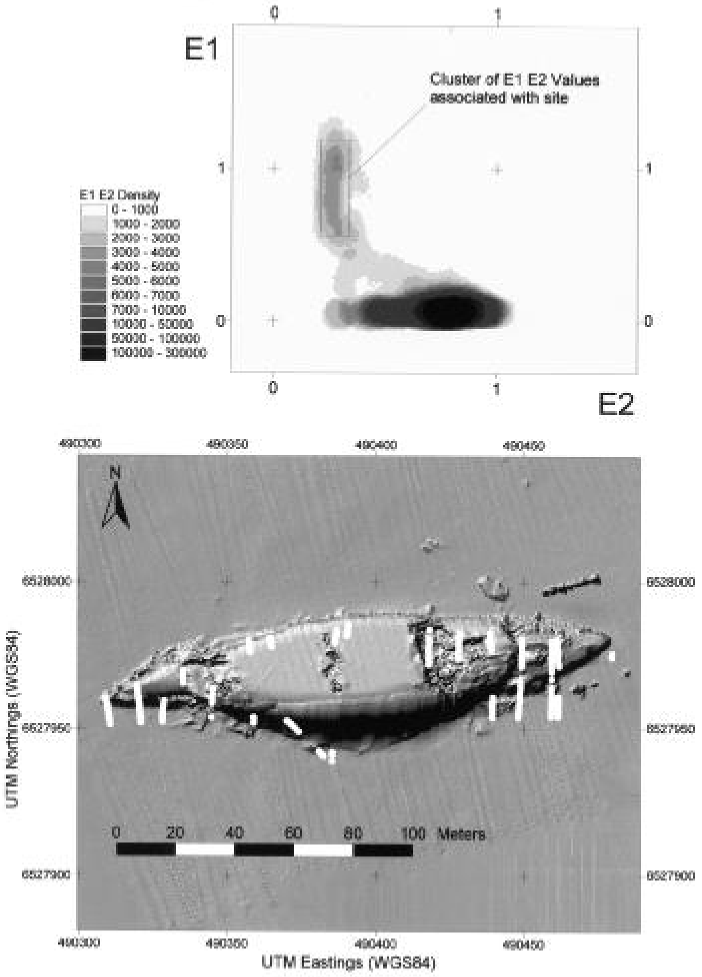


Figure 6. Density plot of E1-E2 values for the *Markgraf* site showing two distinct clusters.



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