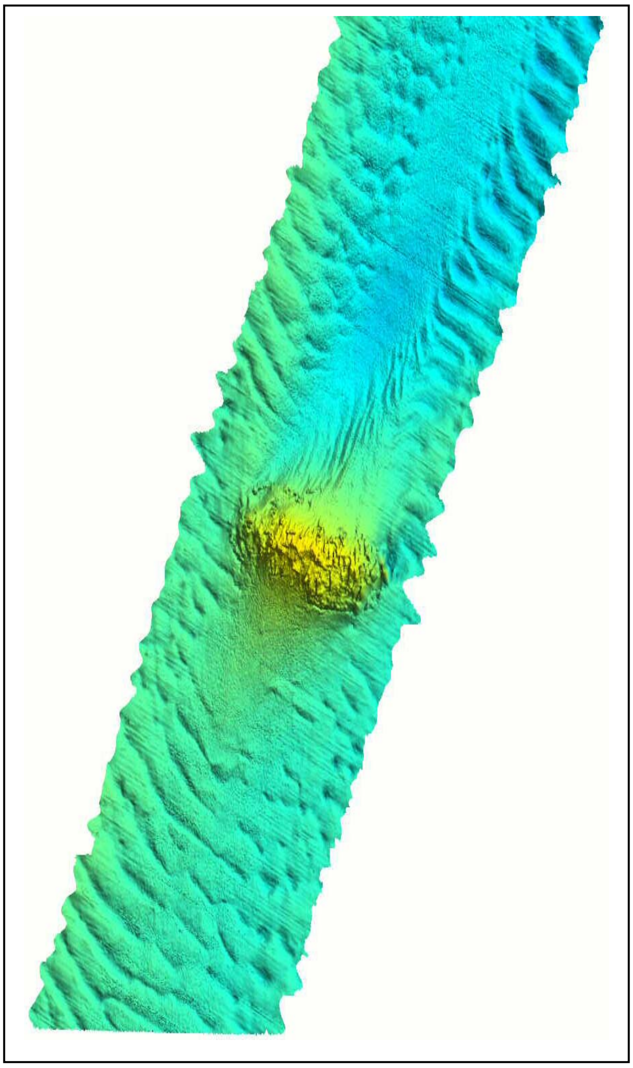
Innovative approaches to Rapid Archaeological Site Surveying and Evaluation (RASSE)

Final Report
For English Heritage
Project Number 3837



Multibeam image of the *Stirling Castle* site

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ENGLISH HERITAGE | University of St Andrews

17 January 2007

Executive summary

The RASSE project was undertaken by the University of St Andrews with partners as part of the three year research project funded by Round 2 of the Aggregates Levy Sustainability Fund (ALSF) administered by English Heritage (EH). The principal aim of the project was to test and develop rapid, quantitative, remote (geophysical) sensing techniques for the enhanced investigation of maritime archaeological sites in sensitive aggregate extraction areas. Furthermore, the project attempted to improve temporal and environmental assessment methods for sites and areas of key archaeological significance.

The project addressed issues of direct relevance to the aggregate industry such as the rapid and timely surveying of submerged archaeological sites. The project also addressed issues of relevance to archaeological curators and academia such as the long term monitoring of sites. The work complemented Round 1 ALSF funded projects administered by EH and Round 2 projects by Wessex Archaeology; and the University of Southampton.

The project involved analysis of historical data sets, and the construction of a test site in Plymouth Sound to enable development of protocols to maximise the potential of geophysical techniques in monitoring marine archaeological sites. Following this background work, methodologies for the enhanced use of multibeam sonar with a spar-buoy, deep-tow arrangement were tested. The resulting increased spatial resolution obtained for data over wreck sites, together with enhanced rendition of the geophysical data, provides both a new level of investigation and also a new forum for visualisation of submerged archaeology. Both of these achievements are of immediate relevance to the offshore aggregate industry and the archaeological community as they will not only allow better site investigation practice together with quantitative site monitoring but they will also allow far wider dissemination of site information to the general public.

1. Introduction

1.1. This document constitutes the final report of work carried out by the RASSE Project (hereafter called ‘the project’), at the University of St Andrews, during a three year research project funded by Round 2 of the Aggregates Levy Sustainability Fund (ALSF) administered by English Heritage (EH).

1.2. The work was conducted in accordance with an initial Project Design (Bates et al., 2004) together with additional Project Variations (Bates et al., 2005 & 2006) submitted by the University of St Andrews to EH.

1.3. Since the project’s commencement in 2004, periodic project updates and the following milestone interim reports have been presented to English Heritage:

- Plymouth Test report
- Year One Report

1.4. This final report is designed to act as a standalone report, bringing together all aspects of the Project, and synthesising results and discussions covered in previous reports.

2. Background

2.1. Aim

2.1.1. The main aim of the project is to further develop rapid quantitative assessment methods for submerged archaeological sites through the use of advanced geophysical technologies (Bates et al., 2004).

2.1.2. In defining aims and objectives relevant at regional, national as well as international levels, the project has paid attention to the following principles.

- The project has addressed issues of direct relevance to the aggregate industry, to archaeological curators, and to academia. For example the rapid assessment using geophysical methodologies, methods for monitoring change on sites and methods for visualisation of sites and changes (see sections 6.7, 8.0 for full discussions)
- The project had to complement work undertaken during Round 1 of ALSF funded work administered by EH, and to complement other major projects within Round 2, as well as non ALSF management related work. Examples of parallel projects include Wrecks on the Seabed, Assessment, Evaluation and Recording (Wessex Archaeology); Submerged Palaeo-Arun & Solent Rivers: Reconstruction of Prehistoric Landscapes Pt 1 (Imperial College, London);

Multi-Beam sonar on wrecks (Wessex Archaeology); Archaeological Services Contract for the Protection of Wrecks Act 1973 (Wessex Archaeology)

- The project had to exploit the expertise and research experience of the authors and their Project Partners, including teams from the University of Southampton and Wessex Archaeology.
- The project had to make use of past knowledge derived from observations and collections made in former marine geological and archaeological investigations and from previous aggregate extraction reports.
- In particular the project attempted to improve temporal and environmental assessment methods for sites and areas of key archaeological significance.

2.2. Objectives, tasks, and reporting of results

2.2.1. Appendix 1 lists 12 objectives relating to academic research, curatorial management, and dissemination. These objectives cover the following areas of work:

- Documentation and evaluation of historical records
- Appraisal of geophysical equipment
- Development of enhanced geophysical processing techniques
- Characterisation of environmental setting and environmental change
- Public dissemination/outreach

2.2.2. To tackle the 12 objectives, the project devised a programme of tasks involving laboratory research, fieldwork, and outreach.

2.2.3. Sections 3 to 7describe the methodology, results and conclusions of work towards the 12 objectives.

2.2.4. Section 8 identifies the most important lessons that should be drawn from the project.

2.2.5. Appendix 2 provides guidance notes for curators and archaeologists on the application of multibeam sonar for rapid archaeological site survey and evaluation

2.2.6. Appendix 3 provides technical notes on the sonar systems used by the project.

3. Project background research

3.1. Introduction

3.1.1. At its commencement, the project carried out background research in order to refine knowledge and understanding of appropriate techniques for the mapping of a wreck site's environmental context (Objective 1), and to determine some of the key environmental features relating to the stability of archaeological sites in aggregate dredging zones.

3.1.2. English Heritage is in the position of not only having to make decisions on the archaeological importance of wreck sites but following on from these decisions, evaluations must be made on the long term protection of sites. Academia is specifically concerned with extracting the maximum information from any heritage situation. The aggregate industry, while needing to develop a resource location, must do so under compliance restrictions that protect the heritage. Information is the key to addressing each of these partners needs. Information must be rapidly acquired and be of the highest quality. The driver for this project was therefore rooted in supporting these needs and thus meeting both the aggregate industry requirements and EH aspirations.

3.2. Work undertaken

3.2.1. In recent years, the successful application of investigation technologies currently used in other marine survey industries has aided better understanding of complex environmental parameters that influence submerged cultural material lying on or buried just beneath the seabed surface. Case studies on specific technologies include ultra high resolution, full coverage 3D bathymetry (Dean & Frazer, 2004), single beam acoustic classification using acoustic ground discrimination sonar (AGDS) (Lawrence and Bates, 2002), classified sidescan seafloor object recognition (Quinn et al, 2005) and acoustic based sediment identification (Bates and Moore, 2002).

3.2.2. When applied to the investigation of maritime archaeological sites and their surrounding context, the considerable potential of sidescan sonar in particular has been realised over the last two decades (Rao, 1988; Redknap, 1990; Quinn et al, 2005). 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; Fish and Carr, 2001; Quinn *et al*, forthcoming). Chirp sub-bottom systems have been tested for non-invasive, high-resolution investigations of sites of maritime archaeological interest (Quinn *et al.,* 1997) and in addition, it has been recognised that bathymetric data from phase-based and multibeam sonar has important an important contribution to make to archaeological investigation (Momber & Geen, 2000; Dean & Frazer 2004).

3.2.3. Considering previous in-house experience the project selected multibeam sonar (beam forming and interferometric), sidescan sonar and acoustic ground discrimination systems for testing work. Research also specified currently available systems which have a track record of providing high resolution results of a standard suitable for archaeological purposes.

3.2.4. To ensure that the project benefited from prior investigations on key sites, research into environmental factors relevant to the stability of archaeological sites in aggregate dredging zones was carried out on the wreck of the *Stirling Castle*, Goodwin Sands. This site provided an excellent working example because a considerable body of geophysical work and diver observations was available to inform research. The key environmental features identified and relevant to the stability of the *Stirling Castle* site are discussed in Elderfield (2001).

3.2.5. The project team's previous involvement in successful sidescan sonar test experiments in Belfast Lough informed decisions relating to the setting up of a test site for the RASSE project (Quinn et al., 2005) for the purpose of testing a wider range of geophysical techniques in controlled conditions. The sheltered waters around Plymouth Sound were identified for this purpose because of the availability of an accurate position fixing network and ongoing sonar testing facilities, combined with project members' experience of work in the area.

3.2.6. Existing datasets from Belfast Lough were selected and supplied to project partner Dr Louis Atallah (Imperial College) by Dr Rory Quinn (Centre for Maritime Archaeology, University of Ulster). This data was then used to test various algorithms that will automate object testing and matching.

3.2.7. During the preparatory phase, team members established GIS projects using Arcview 8.2 to facilitate accurate analysis reporting of results generated from each test site.

4. Enhanced geophysical tool evaluation

4.1. Introduction

4.1.1. Object detection and manual processing in sonar imaging can represent a considerable challenge because sidescan images vary in terms of intensity, scale and rotation, and are generally blurred with noise. Sonar images are often corrupted by noise during the process of their acquisition and transmission. Although several parameters are assumed to be fixed, they normally vary within a survey and between different surveys (e.g., the range and fish height). Image ‘de-noising’ is therefore necessary to remove the added noise while retaining as much as possible the important image features. However, differentiation of real data from noise is often problematic in practice.

4.1.2. This part of the project aimed at automating the process of object detection and matching to address the following issues:

- How can we identify ‘salient’ (or interesting) areas in images? What distinguishes an object from background clutter and seabed structure?
- What features can a computer pick up to tell us that two objects in different images are the same? And can we develop a method that is invariant to resolution variation?
- Having seen objects in a certain image, can we (or the computer) recognize these objects if they are seen from a totally different sonar direction? I.e. is there an object model we can deduce?
- Can the routines be used to identify changes between repeat surveys of the same objects?

4.2. Noise

4.2.1. There exists a substantial amount of research in this area with many noise reduction techniques developed for handling noisy (sonar) images (Cervenka and de Moustier, 1993). In particular, a spatially pixel-wise Wiener filter (Gonzalez, 1992; Pratt, 2001) is used in this work. The filter is suitable for intensity images that have been degraded by additive noise of a constant power (assumed to be white). It performs 2-D noise reduction without destroying essential details contained within the images. Experiment results have demonstrated that using this filter before image analysis; say applying an algorithm for object detection can improve the algorithm accuracy. When using such a filter, care has to be taken in selecting an appropriate size of the local filtering window. Based on a range of experimental simulations, the window size in this work is empirically set to be 5 × 5 in order to maximise the benefit of utilising this filter.

4.3. Historic data testing

Work carried out

4.3.1. A programme of algorithm testing was completed on historic datasets in order to maximise the archaeological and environmental detail obtained by high resolution sonar systems during the processing and analysis phase.

4.3.2. All work was carried out by Dr Louis Atallah, at the British University in Dubai and the University of Edinburgh, with some collaboration from MSc students.

Identifying salient areas and working with varying resolution

4.3.3. The initial part of this work used a dataset obtained from a control experiment in Smelt Mill Bay, Belfast Lough, during July and August 2001 (Quinn et al. 2005). Smelt Mill Bay is located in 10m of water in a sheltered cove with a uniform, fine-grained plane sand substrate. A test site of material types was set out on the seafloor and repeat surveys were conducted over the control site using three different side-scan systems (EdgeTech 272-TD: 100/500 kHz, Imagenex 885; 675 kHz, and Geoacoustics 159-A; 100/500 kHz).

4.3.4. Four sonar images were selected, and the sonar parameters (frequency, location, depth) were given for each image. Each image contains 8 objects which include a car tyre (objects 1 and 2 in Figure 1), an amphora shoulder and neck (object 3), a ceramic ball (object 4), baskets of different types (objects 5, 6 and 7) and a leather jacket (object 8). Figure 1 shows one of the images.

Scale saliency matching

4.3.5. The method of scale–saliency was first developed by Kadir and Brady (2001) and described in detail by Kadir (2002). Scale-saliency method was used for the purpose of identifying ‘salient’ areas in the images.

4.3.6. This method defines ‘saliency’ in terms of local signal unpredictability or complexity. Thus, the most interesting areas in an image are the most unpredictable ones. The method is implemented in the following way:

- Given a point x, the algorithm starts by calculating the local Shannon entropy over a range of scales. To calculate the entropy, a local feature descriptor is defined around point x (in this work, this is selected as the gray level amplitude $d \in D$, where D is the set of all descriptor values). The PDF (probability density function) of the local descriptor (amplitude) is calculated over a set of scales s (circular windows, where the radius corresponds to ‘scale’). Areas corresponding to high signal complexity tend to have higher entropy (Kadir and Brady, 2001).

- The next step is to select scales where the entropy is peaked. However, there could be several peaks in the entropy function corresponding to different features at different scales. To select the most ‘salient’ one, statistics of the local descriptor are used to ‘weigh’ the entropy function for each of these peaks. A measure that can be used is the magnitude change of the PDF as a function of the scale on the peak point.
- The final measure of ‘scale- saliency’ is obtained as the product of the local Shannon Entropy and the weighting function. This measure of ‘scale-saliency’ is a useful indicator for certain significant features in an image at a large range of scales.

4.3.7. For each pixel within a given (real sonar) image, its corresponding salient feature and scale can be obtained as described in Atallah et al (2005). To extend this salient feature measurement to identify regions of saliency corresponding to objects within the images, Kadir (2002) used a modified version of the K-nearest neighbour algorithm to find the most salient areas.

4.3.8. Results of applying the scale-saliency algorithm are given in Figure 2. The object parts selected as ‘salient’ are marked with a red circle (showing the scale of the object selected also). It should be noted that these images are considered challenging in terms of object detection and an expert user would find it hard to locate salient areas. The method is invariant to rotation and scale variation and achieved success rates of more than 90% in object detection (as compared to the objects marked by an expert).An algorithm was developed in order to use scale saliency features to match objects in images. The algorithm first runs the scale saliency method on each of the images and selects areas of high saliency or importance.

4.3.9. The scale-saliency method successfully located object parts of the 8 objects present in the control experiment sonar images. The next question was how to match these objects in different images.

Object Matching

4.3.10. An algorithm was developed in order to use scale saliency features to match objects in images. The algorithm first runs the scale saliency method on each of the images and selects areas of high saliency or importance.

4.3.11. Features from each of these areas (object part) are selected. These features are: location, scale of the object part, weighted saliency and normalised histogram. The object parts are matched between different images by using a nearest neighbour algorithm.

4.3.12. The method achieved an error rate of around 5% of incorrect object-part recognition which is considered to be reasonable.

4.3.13. However, the Project decided to investigate another method (SIFT) used in camera-image recognition. The method was developed by David Lowe, University of British Columbia (Lowe 2004).

Sale-Invariant Feature Transform (SIFT) and Object matching

4.3.14. Scale-Invariant Feature Transform (SIFT) is a computer vision algorithm for extracting distinctive features from images, to be used in algorithms for tasks like matching different views of an object or scene (e.g. for stereo vision) and object recognition. The features are invariant to image scale, rotation, and partially invariant (i.e. robust) to changing viewpoints, and change in illumination. The name Scale-Invariant Feature Transform was chosen, as the algorithm transforms image data into scale-invariant coordinates relative to local features. However, there also exist other scale invariant image descriptors in the computer vision literature. The algorithm was devised in 2004 by David Lowe (2004).

4.3.15. First, the original image is progressively Gaussian blurred with σ (the standard deviation of the Gaussian distribution) in a band from 1 to 2 resulting in a series of Gaussian blurred images (a scale-space produced by cascade filtering). Then, these images are subtracted from their direct neighbours (by σ) to produce a new series of images (with difference of Gaussians which approximate the Laplacian of the Gaussian).The major steps in the computation of the image features are:

- Scale-space extrema detection - a specific type of blob detection where each pixel in the images is compared to its neighbours.
- Keypoint localization - keypoints are chosen from the extrema in scale space.
- Orientation assignment - for each keypoint, in a 16x16 window, histograms of gradient directions are computed (using bilinear interpolation).
- Keypoint descriptor - representation in a 128-dimensional vector.

4.3.16. For the application of SIFT keypoints in matching and object recognition, Lowe applied a nearest neighbour algorithm, followed by a Hough transform for object recognition (as described in Lowe, 2004).

4.3.17. The feature representations found by SIFT are thought to be analogous to those of neurons in inferior temporal cortex, a region used for object recognition in primate vision. The invariance of SIFT towards different image transformations like image rotation, scale changes (zoom), and off-plane rotations made it one of the most used detection/description scheme.

4.3.18. The method is quite fast to run on images and includes the following steps:

- Find the interesting areas in terms of scale (how large are the objects) and location (where are the objects);
- Select key-points on the most interesting areas;
- Find out the orientation on each interesting area (how are the pixels oriented?);
- Describe each key point by the strength of the image gradient around it.

4.3.19. To match objects in different images, the method selects key points in both images, and then finds out which ones are most similar.

4.3.20. This method was tested by investigating 10 images from the Plymouth Test site surveyed by RASSE in 2005 (see section 5).

4.3.21. The resolution in the images provided is higher than the control experiment images from Belfast Lough, and the objects are clearer.

4.3.22. However, the object type is still difficult to identify. Ten images were provided with varying resolution and sonar direction. Results of matching between different images are given in Figures 3 and 4.

4.3.23. Figure 3 shows matching areas between two images. The matching areas are joined with a blue line. It should be noted that this method can find matching areas even if a part of the object was occluded.

4.3.24. Figure 4 shows matching areas between two images a further two images. Matching areas are joined with a blue line. The images are of different sizes, yet the method managed to find the matching areas.

Object Modelling

4.3.25. Although the two methods (scale saliency and SIFT) presented in previous sections appear very successful in matching objects in different camera images, there are several challenges when dealing with sonar images, which can be summarized as follows:

4.3.26. The change of sonar direction can lead to a change in the way a certain object appears in an image. In this case, we are not dealing with a problem of simple rotation or scale variation. When a person looks at a sonar image, he/she tries to form a mental image of what the object really looks like. Shadows around the object give an indication of the object’s shape and height. To match this object with another one, the mental images are compared, as well as some features that appear in both images.

4.3.27. Sonar images show several noisy areas that are selected as key points. These areas are not always object parts or salient areas from a pattern recognition perspective. In addition to that, the seafloor might contain several areas that appear as salient due to bathymetric variation. In any future research, it will be important in the future to differentiate between these areas and salient object parts.

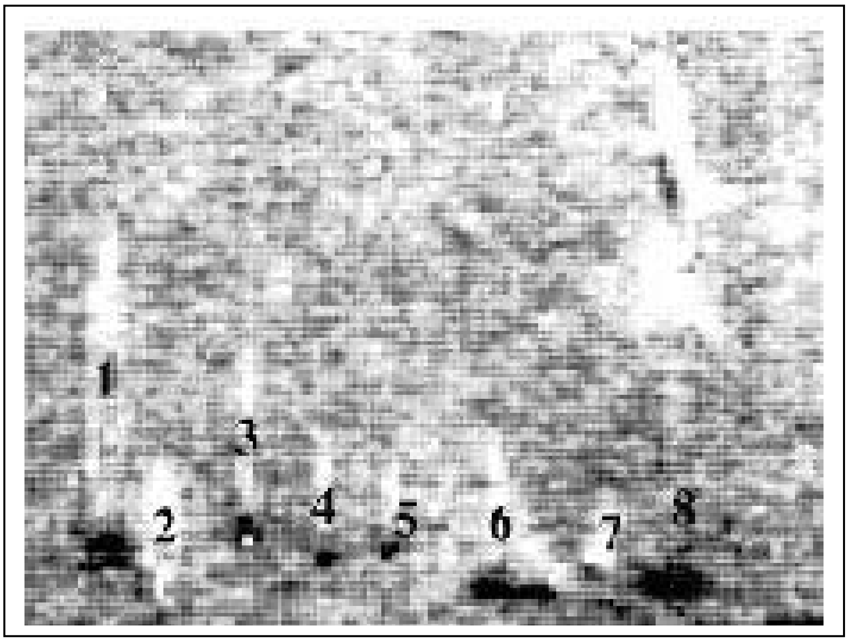


Figure 1: Eight objects can be seen in this image from the control experiment in Belfast Lough

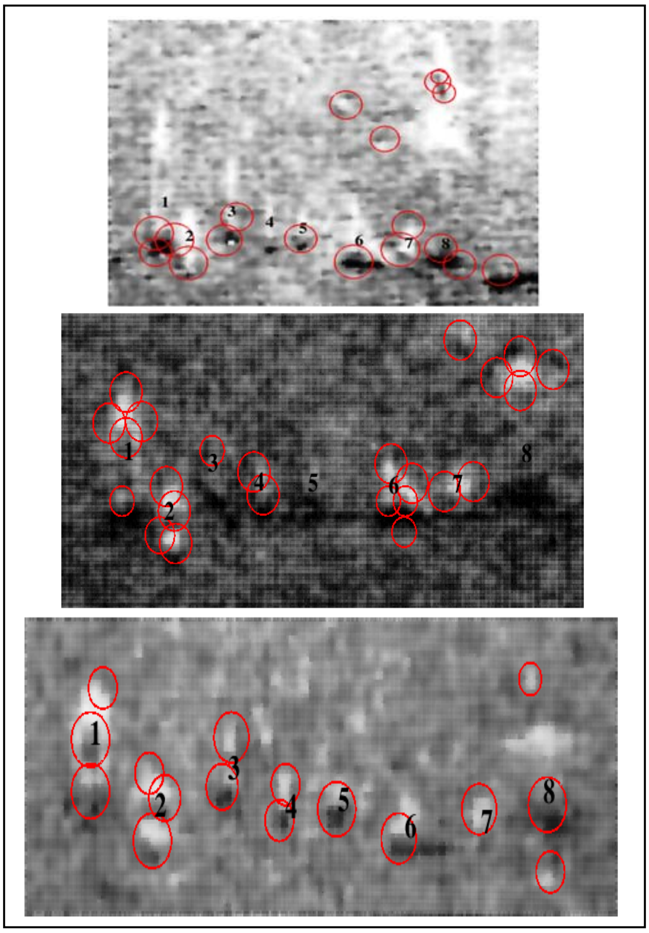


Figure 2: Results of the scale saliency algorithm on images from the Belfast Lough control experiment

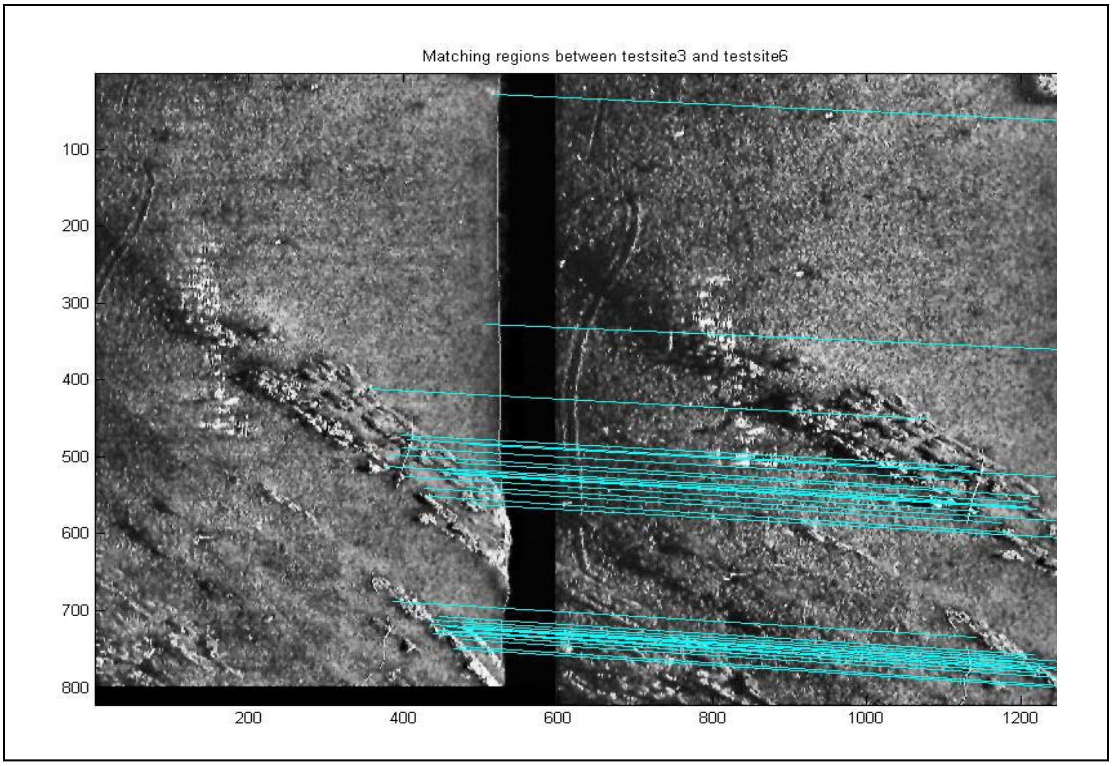


Figure 3: Matching areas between two images (testsite 3 and testsite 6) identified using the SIFT object matching method. A blue lien joins the matching areas

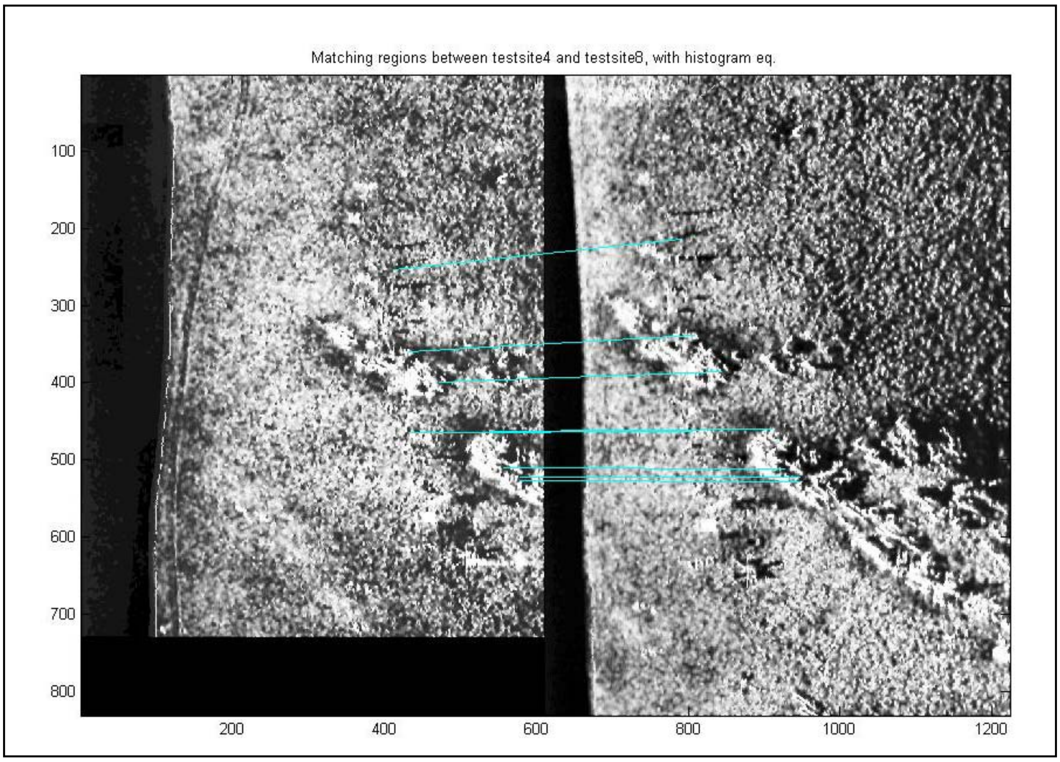


Figure 4: Matching areas between two images (testsite 4 and testsite 8) identified using the SIFT object matching method. The matching areas are joined with a blue line. The images are of different sizes, yet the method managed to find the matching areas

4.4. Testing enhanced geophysical tool evaluation on Hastings shingle bank.

Introduction

4.4.1. The Hastings shingle bank is located approximately 20km east of Beachy Head and 13km south of Hastings. The area is typical of aggregate extraction zones in the English Channel. Water depths range from 10m to 20m over the site. Sediments within the area consist of cobbles and coarse gravels on the shingle banks to various grades of sand and silt to the north of the site (Brown et al. 2004). Dredging at the site has been ongoing for a number of years with current dredging activity is focused on an area to the north part of the licence.

4.4.2. Hastings shingle bank is known to contain a number of identified and unidentified wrecks

4.4.3. Furthermore, the area is one where other ALSF funded projects are investigating issues of sediment movement and remote sensing of the sediment movement (see Wessex Archaeology MALSF Project MAIN 3877, Wrecks on the Seabed R2 and Southampton University MALSF Project MAIN 3365, Modelling exclusion zones for marine aggregate dredging).

4.4.4. Therefore, Hastings Shingle Bank was chosen as an area to test the enhanced image discrimination algorithms outlined in section 4.3.

Work undertaken

4.4.5. In 2005, two distinct objects were constructed and deployed on the site. The objects included a 1x1x1m open aluminium framework and a standard 55 gal empty oil drum. The objects were deployed by Wessex Archaeology prior to routine surveying with a Klein 3000 sidescan sonar. The objects were deployed using polypropylene rope and marker buoys for subsequent recovery.

4.4.6. Sidescan sonar data was acquired over the target horizons in north-south lines offset from the targets at a number of discrete line offset distances. Images taken from individual lines for both of the targets is shown as a mosaic in Figure 5.

4.4.7. The scale saliency method was applied to the Hastings Shingle bank sidescan sonar data after mosaicing parallel line tracks. The method was applied with different parameters on the image in order that the scale saliency could pick up areas in the image that 'stand-out' or are salient at different scales.

Results

4.4.8. The results of applying the algorithm on the images as a whole are shown in Figure 7.. In these images it can be seen that the objects are not detected above the general sea floor noise. This noise results from areas where dredging has already taken place and areas of natural sea floor changes. The method showed greater success when the area of interest was increased in magnification (Figure 8). In this figure there is clear clustering of the salient points around the objects.

4.5. Discussion

4.5.1. While the method does at a certain resolution show isolated features within a general area of "average" seafloor the results are not sufficiently convincing to suggest that the methods outlined in could be used for widescale prospecting for features of archaeological (anthropogenic) significance.

4.5.2. However following the trials at Plymouth and these at the Hastings Shingle Bank it is speculated that it might prove a useful method to pick out areas of change between different sonar surveys of wide areas or within small areas such as around wreck sites. The potential for the method to measure change was tested on the Stirling Castle site and is reported in section 6.4.

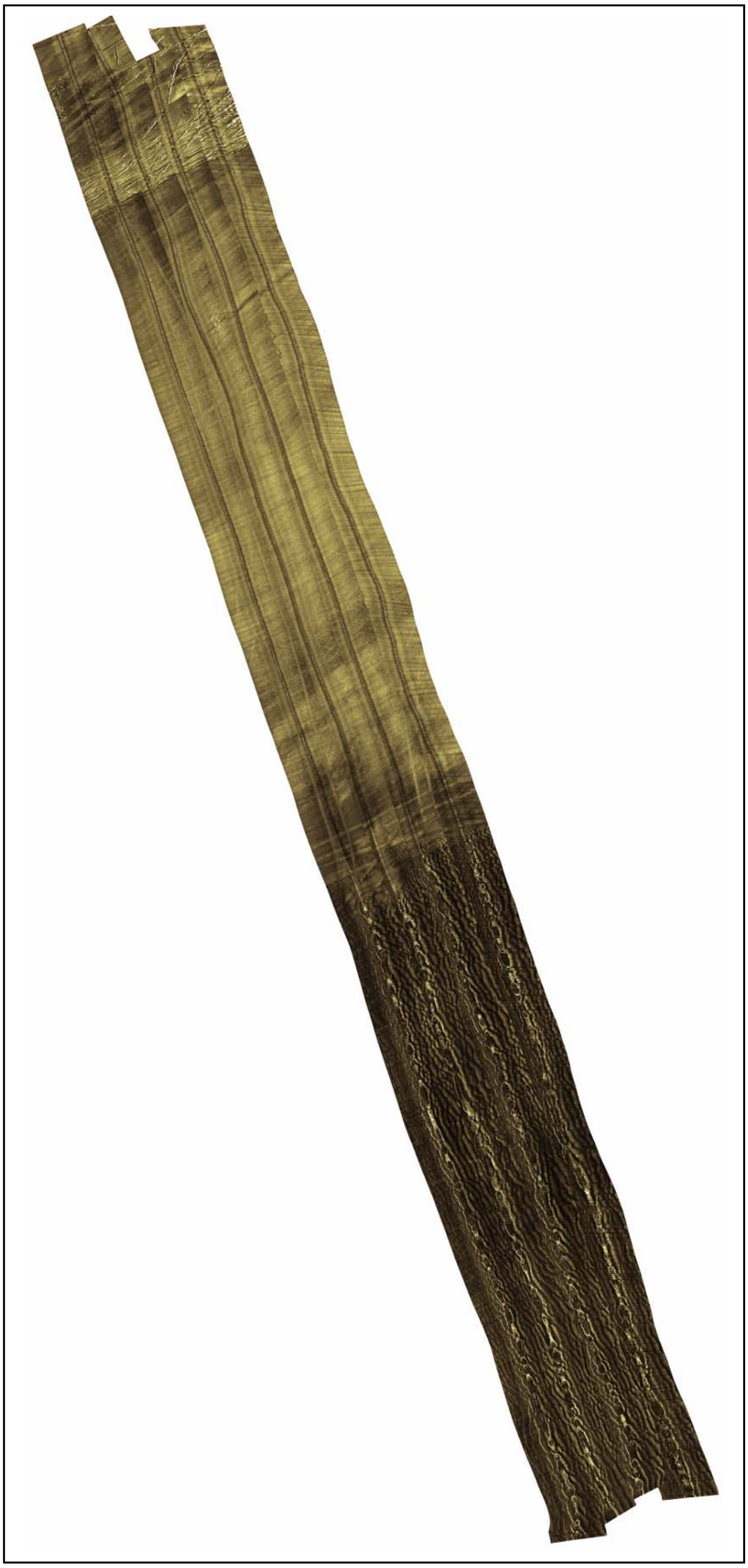


Figure 5: Sidescan sonar mosaic of Hastings Shingle Bank

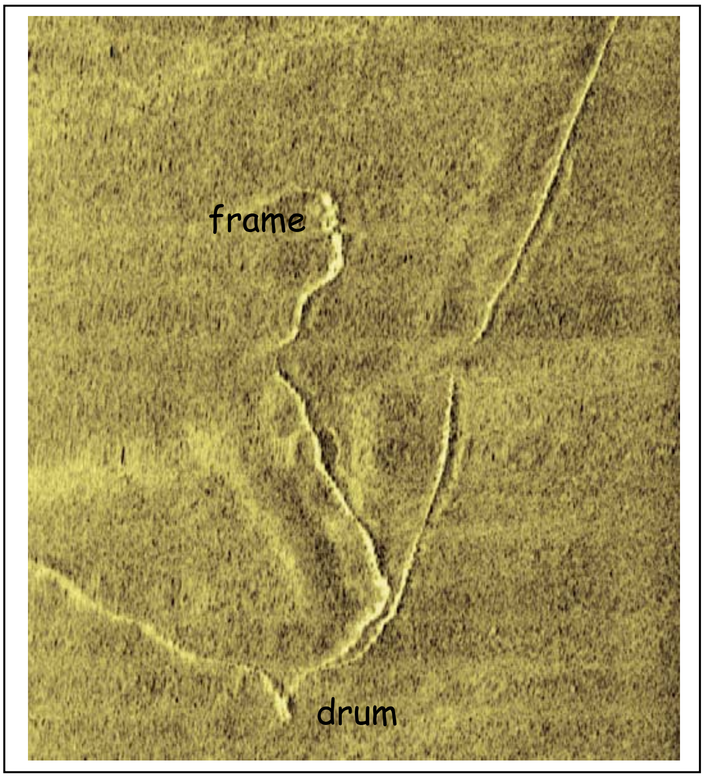


Figure 6: Hastings Shingle Bank targets – 55 gal. oil drum and open aluminium framework

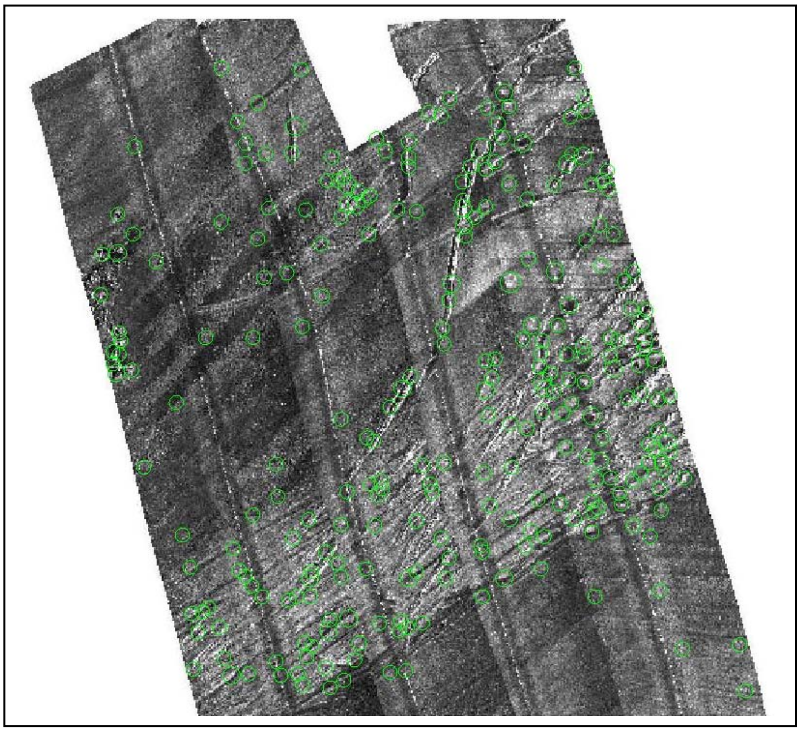


Figure 7: Object detection over aggregate extraction area

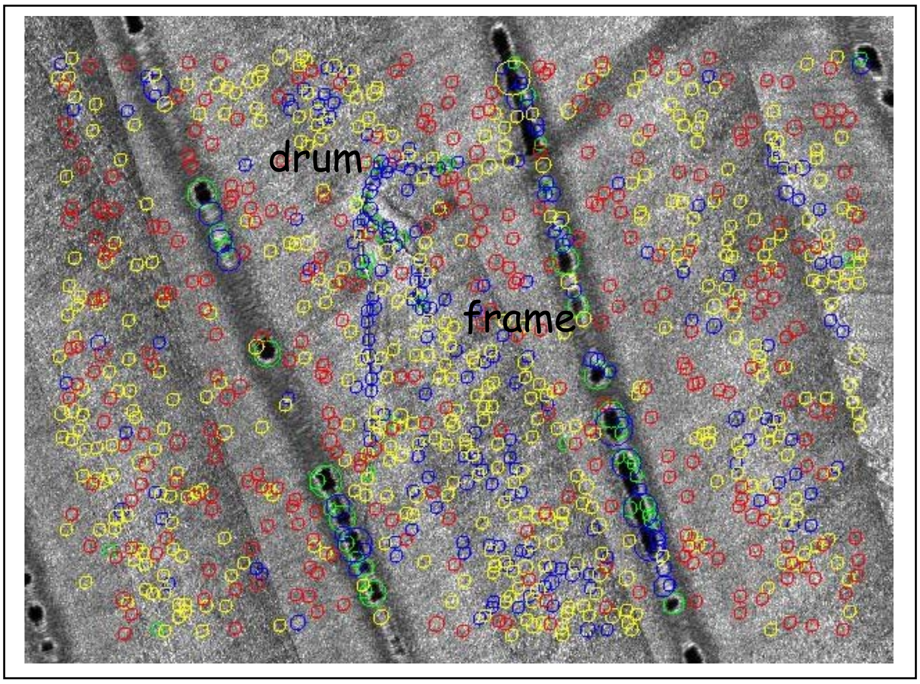


Figure 8: Object detection and discrimination over target zone

5. Plymouth Sound test site

5.1. Introduction

5.1.1. In 2005 the Project established a test site in Plymouth Sound where a number of artefacts and other objects were deployed on the seabed (see figure12). This test site provided controlled test conditions for the development of methodologies to maximise the archaeological and environmental detail obtained from high resolution sonar (Objective 4)

5.2. Artificial test site preparation

5.2.1. During project planning, a test site on apparently flat seabed at a depth of 5 - 6m was identified from UKHO charts in a sheltered location close to the Plymouth harbour breakwater, Plymouth Sound. On arrival, this location proved to be rockier and less flat than required. As a result, it was decided to utilise the flattest part of the seabed within the area allocated by Queens' Harbour Master at Plymouth.

5.2.2. The final test site was located close to the east end of the breakwater fort and north of the breakwater on a flat sandy seabed, with a low rocky reef at a depth of 9-10m, somewhat deeper than was initially planned.

5.2.3. The project was able to undertake comparative surveys on a secondary test site located 200m to the west. This test area was developed by Fort Bovisand, South West branch of the Nautical Archaeology Society (NASSW) and Sonardyne Ltd. It consists of larger targets up to 4m high distributed around the base of the Breakwater Fort in depths of up to 13 m. The largest objects included a CSWIT lattice framework 8.5m x 2.6m x 3.7m high, two hollow concrete blocks 3m x 2m x 4m high, and a wooden wreck, the *Tavy*, 7.75m long.

5.2.4. The project team selected 42 targets and target groups, ranging in size from an 8-armed cross made up of 0.2m tubes each 1m in length, to a dining fork less than 10mm wide (figure 18a,b,c,d,e). The test artefacts were made of various materials, generating different acoustic signatures, and representing artefact types commonly present on archaeological sites underwater. These objects were photographed ashore prior to emplacement on the seabed.

5.2.5. The setting up of the site was undertaken over a three day period by Falmouth Divers Ltd. The dive team deployed a fibreglass-reinforced plastic surveying line for 70m east to west on the seabed. This line was pinned to the seafloor at intervals and test objects were then placed at set positions for 60m along it.

5.2.6. A list of the items deployed, their orientation with respect to the line, and their orientation with respect to the seafloor is given in Tables 2 and 3.

5.2.7. Absolute positions for the targets were calculated from the acoustic data. Four acoustic beacons were placed at 20m intervals from zero on the base line. These were positioned by Sonardyne Ltd., using a Scout ultra short base line (USBL) acoustic positioning system deployed from one of their survey vessels.

5.2.8. Under supervision from the Project members, all test site material was finally removed by the Falmouth Divers team on 09/04/05, and the seabed was left clear of all objects as required under the conditions imposed by the Queens' Harbour Master at Plymouth.

Figure 9: Survey vessel Xplorer

Figure 10: Reson 8125 Seabat multibeam system twin sonar head configuration and wheelhouse data acquisition hardware

XPLORER – RESON SeaBat 8125 Installation

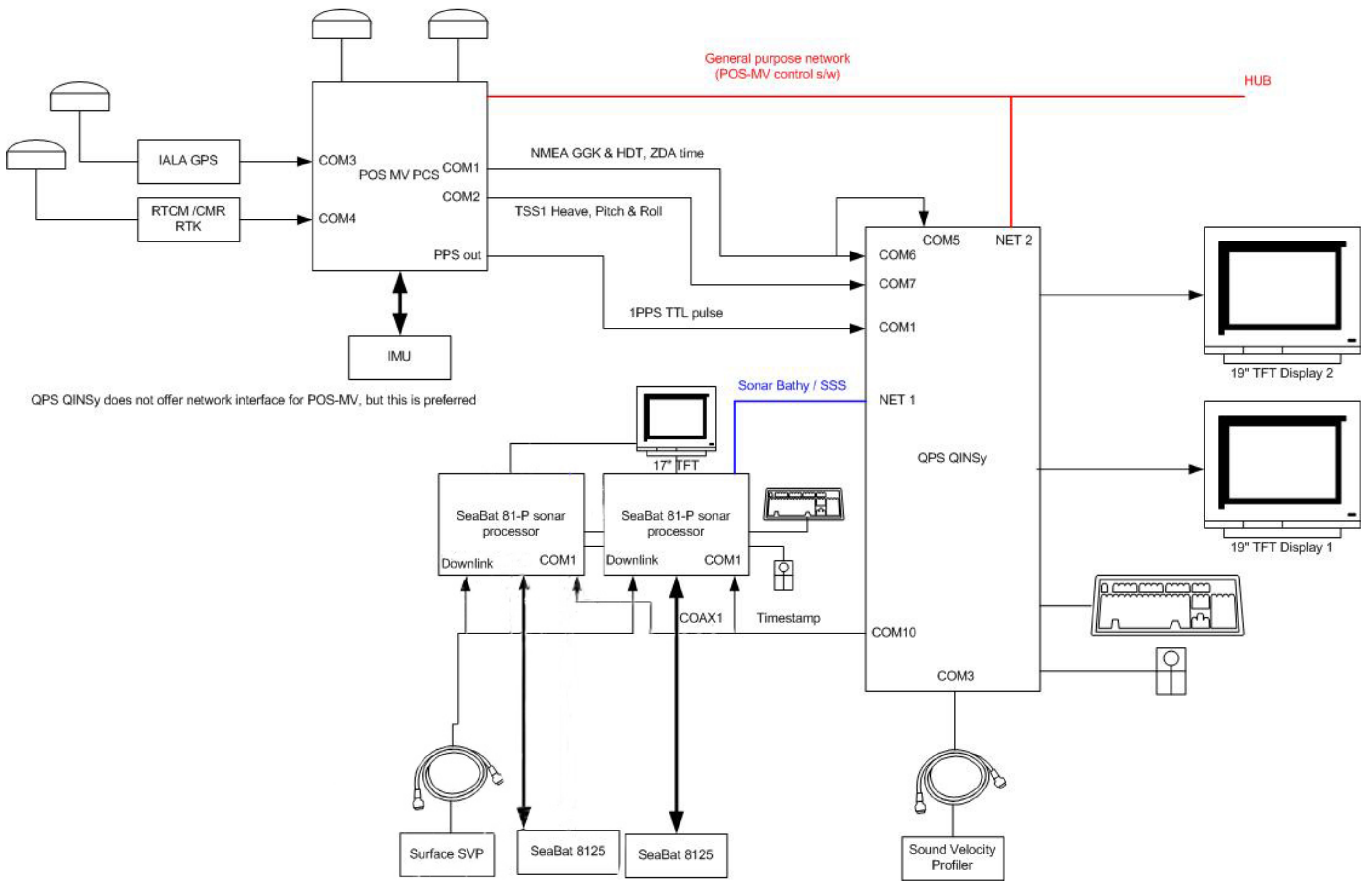


Figure 11: Dual head RESON installation on board Xplorer

Figure 12: a selection of test artefacts used at the Plymouth Sound test site

5.3. Test methodology

Position fixing and orientation

5.3.1. The survey and navigation system onboard *Xplorer* (figure 9) consisted of an Applanix POS-MV 320 (Position and Orientation System for Marine Vessels) that combined Real Time Kinematics (RTK) with the most accurate of the commercially available motion reference compensation systems.

5.3.2. Positional accuracy to centimetric levels in XY and Z was achieved using the RTK system. RTK works on a similar principle to conventional differential GPS, but phase-based corrections are applied using a dedicated base station instead of publicly available long-distance range-based corrections.

5.3.3. RTK CMR+ correction messages from Sonardyne's semi-permanent GPS base station were provided to the POS-MV via Trimtalk 450 radios. The POS-MV was then able to operate in 'tightly coupled' fixed RTK mode.

5.3.4. The base station is located in Sonardyne's offices in Turnchapel, approximately 3km from the test site on the breakwater at location:

Station	Easting (UTM 30)	Northing (UTM 30)	Elevation (above WGS84 ellipsoid)
Sonardyne Turnchapel	418984.503 [50 21.843999 N]	5579730.8 [004 08.344867 W]	93.033

Table 1: Positions of the Sonardyne base station at Turnchapel

5.3.5. Sonar Head movement was compensated for in all 2005 survey work using an Applanix POS MV to deliver heading and motion information, utilising two Novatel GPS antennas mounted either side at the bow of *Xplorer*, 3m apart and a motion reference unit to correct heave, pitch and roll. Great attention to detail was given to the measurement of the lever arms (offsets) between the sonar heads and the motion and positioning sensors.

5.3.6. The tidal variation was exploited to utilise the optimum range between the sonar head and the sites so that the best survey definition was achieved.

5.3.7. Data acquired onboard the survey vessel used the ETRS 89 Datum (UTM Grid) and heights were adjusted to Ordnance Datum Newlyn (ODN) during post-processing.

5.3.8. For the purposes of the Plymouth survey, the difference in height between the WGS84 ellipsoid and ODN was calculated using proprietary software.

Sonar systems deployed

Multibeam sonar (beam forming type)

5.3.9. Beam-forming multibeam systems form a set of virtual 'beams' mathematically and detect the range to the seabed in each beam. The best archaeological survey results using multibeam systems have involved beam-forming systems. In 2005, the RASSE team trialled a dual head Reson 8125 Ultra High Resolution Multibeam Echosounder (See Appendix 3 for technical specifications).

5.3.10. The 8125 multibeam sonar heads were attached over the port side of the survey vessel on a rigid mounting at the stern quarter designed by a student engineer at the University of Glasgow. The twin-pole arrangement prevented free movement of the head relative to the vessel, yet could be dismounted and remounted within minutes without the need for time consuming recalibration. This prototype system proved highly effective in the field and contributed significantly to improved data collection. Furthermore, the easy deployment without extensive re-calibration significantly reduced mobilisation time between successive surveys both on and between sites.

5.3.11. Components of the sonar system comprise the sonar heads themselves, two sonar processor units, Seabird CTD and Navitronic SVP-15 sound velocity probes, and a dual processor PC with increased hard disk capacity for sonar acquisition (see figures 10 and 11).

5.3.12. One sound velocity probe was attached near the sonar heads on the pole. The probe provided continuous measurements for the purposes of the beam forming process employed by the Reson system.

5.3.13. A second sound velocity probe was used for obtaining sound velocity profiles through the entire water column at regular intervals during the survey.

5.3.14. Sonar processors that control the acoustic parameters of the sonar heads were placed inside the wheelhouse alongside the system PC. Constant adjustment to these processor units was required during the surveys, aided by a visual display of the raw sonar data. Various settings for range, gain and ping rate limited the number of bad soundings acquired during the survey and facilitated post-processing.

5.3.15. Full calibration of the system was undertaken prior to commencing survey work.

Multibeam Sonar data acquisition

5.3.16. QINSy v7.5 survey and acquisition software running on the PC was used to control the survey with a navigational chart backdrop for the positioning of survey grids and the provision of detailed navigational information (which could be displayed on a separate helm screen) to aid *Xplorer*'s skipper during the running of survey lines.

5.3.17. The QINSy software co-ordinated a database of all aspects of the system setup which included the offset measurements necessary between the various components and also water column sound velocity profile data. The software also created appropriate file folders during data acquisition to aid file management.

5.3.18. The data collected by the system comprises QINSy database files for each individual survey line, and optional point files (as XYZ ASCII text). The point files could be imported immediately into other visualisation software (such as Terramodel Visualiser or Fledermaus Pro) to view the data just collected in three dimensions during or after the survey. This was very useful in determining whether any problems existed with the data during the survey.

5.3.19. The QINSy database files were in effect the end result of the field survey. These files can be subsequently replayed if necessary (generating new XYZ files) following adjustments to certain parameters (such as patch test settings, tidal data, or sound velocity files).

Multibeam Post-Processing

5.3.20. Post-processing was conducted by Netsurvey Ltd. using QINSy software initially and then Caris HIPS to clean the data and ignore erroneous soundings. This process required an experienced data processor to manually delete bad soundings, using automated processes that perform a statistical analysis of the soundings in each swath. Basic XYZ coordinate positions for each acoustic reflection were recorded in a number of formats, including ASCII text files.

5.3.21. The QINSy software stored all the soundings generated during the surveys.

5.3.22. QINSy database files were used to generate separate XTF files for each of the sonar heads - port and starboard - for use in Caris software.

5.3.23. Patch test values were applied in real-time, as was the single sound velocity value from the Seabird CTD (typically 1520m/sec) for refraction. Sound Velocity Profiles were regularly measured and showed the velocity to be the same throughout the water column. For the Plymouth work QINSy was able to use the GPS RTK height in real-time, so that fully corrected soundings were recorded to processing data files in real-time, and available for editing immediately at the end of each line.

5.3.24. The method employed for the RASSE surveys produced vast numbers of bathymetric points. To ensure that complete coverage was provided for the sites the survey lines often overlapped and therefore any one object was likely to be ensonified a number of times during different survey passes. Errors in the positioning system and/or motion reference unit will be carried through into positioning errors for the individual soundings. Even these small errors will lead to objects appearing 'blurred'. These errors were reduced by the use of a GPS RTK positioning system and further reduced by only viewing critical sites using a limited number of samples, see below.

5.3.25. Therefore single passes at slow speed, typically 1kt or less, were used to collect maximum detail of the Plymouth test site rather than combining the soundings from multiple passes to increase data density.

5.3.26. Ideally, positioning provided from RTK systems on this survey is essential for the longer-term comparison of subsequent datasets (i.e. for monitoring purposes).

Multibeam visualisation and analysis

5.3.27. The processed XYZ data was transferred to Trimble Terramodel software where it was examined with Trimble Terramodel 3-D Visualiser using point clouds, rather than rendered surfaces. The data was also examined as point clouds and surfaces in Fledermaus Pro (IVS). This allowed measurements to be taken and features to be identified for subsequent attention. Data was saved and exported using Geotiff format.

5.3.28. ArcGIS 8.1 software was used to perform further data analysis in relation to data sets.

Bathymetric sidescan (Interferometric multibeam system)

5.3.29. Interferometric (phase comparison) multibeam systems measure angle for each of a set of ranges (as opposed to measuring the range for each of a set of angles). In 2005, the RASSE project trialled a Submetrix 2000 (SEA Ltd.) bathymetric sidescan (For technical specifications see Appendix 2.

5.3.30. The sonar transducers were mounted on a side pole mount together with the motion reference unit (TSS DMS-05) onto the starboard side of *Xplorer* amidships. Both were connected to the control computer together with a DGPS and magnetic compass for positioning (accuracy less than 20cm). The motion reference unit was a TSS DMS-05 dynamic motion sensor which used solid state sensing elements to measure instantaneous linear accelerations and angular rates of motion change to 0.05º. The magnetic compass used was an Aximuth 1000 produced by KVH Industries, Inc. This fluxgate digital compass provides azimuth information to 0.5º accuracy after compensation and is predominantly used for stabilisation of the motion reference unit for long wavelength variations.

5.3.31. Sonar processors that control the acoustic parameters of the sonar heads were placed inside the wheelhouse alongside the system PC. The acquisition was accomplished using SEA Swathplus software. The data was constantly monitored during acquisition in order to achieve the best data quality control.

5.3.32.Prior to surveying, a calibration patch test was conducted for the swath-bathymetry system that included calibration for roll, pitch, heave, skew and time lags The patch test was conducted in an area of flat sea floor and an area where there were known objects.

5.3.33. The bathymetric sidescan was also used in a similar manner to the 8125 multibeam with offset lines tested at various survey speeds.

Bathymetric sidescan sonar data acquisition

5.3.34. Swathplus (SEA Products) survey and acquisition software running on the PC was used to control the survey together with navigation software Hypack Max from Coastal Oceanographics Inc., which could be displayed on a separate helm screen to aid *Xplorer*'s skipper during the running of survey lines.

5.3.35. The data collected by the system comprises Swathplus .RAW acquisition files for later processing using the same software.

Backscatter data

5.3.36. For each ping the SEA System 2000 also outputs two channels of backscatter data (swath bathymetry side scan). The Swathplus software stores the backscatter sidescan in the same database as the bathymetry data. Backscatter datasets from the Swathplus were acquired for the Plymouth Sound Test site.

Bathymetric sidescan post-Processing

5.3.37. Post-processing is being conducted by the University of St Andrews using Swathplus and Grid2000 software initially and then IVS Fledermaus Pro to clean the data and ignore erroneous soundings.

5.3.38. Results from the patch test values were applied in preliminary format in real-time but were fully applied in later processing. During this time, tidal corrections together with velocity corrections were applied.

5.3.39. The method employed for the RASSE surveys produced vast numbers of bathymetric points. To ensure that complete coverage was provided for the sites the survey lines often overlapped and therefore any one object was likely to be ensonified a number of times during different survey passes. Errors in the positioning system and/or motion reference unit will be carried through into positioning errors for the individual soundings. Even these small errors will lead to objects appearing ‘blurred’. These errors were reduced by the use of a GPS RTK positioning system and further reduced by only viewing critical sites using a limited number of samples.

5.3.40. Ideally, positioning provided from RTK systems on this survey is essential for the longer-term comparison of subsequent datasets (i.e. for monitoring purposes).

Bathymetric sidescan visualisation

5.3.41. The bathymetric sidescan data was first examined with IVS Fledermaus Pro using both point clouds and rendered surfaces, from which measurements were taken and features identified for subsequent attention.

Sidescan sonar

5.3.42. Sidescan sonars transmit a narrow acoustic beam to the side of the survey track line. As the acoustic beam travels outward, the seabed and other obstructions reflect some of the incident sound energy back to the sonar. The travel time of the acoustic pulses from the sonar are recorded together with the amplitude of the returned signal as a time series and sent to a topside console for interpretation and display.

5.3.43. The project used the Klein 3000 side scan sonar, one of the best in a new generation of digital sidescan survey instruments that is readily available to the archaeological community (for technical specifications see Appendix 3). The survey also tested an Edgetech sidescan sonar however this is not reported on here as the results did not give as clear discrimination compared to the Klein sonar of the target objects.

5.3.44. Antennae to fish ‘lay-back’ distances were calculated from the GPS antennae on board and keyed into the software, to enable estimation of the fish location. The fish was not tracked acoustically although this would greatly improve the quality and quantitative value of the results in future surveys.

Sidescan sonar post-processing

5.3.45. Post-processing was carried out using Klein Sonar Pro Software and Cheseapeake Sonarweb Pro software. All results were logged on DVD Rom. SonarWeb Pro processing uses amplitude corrections to the amplitude time series based on the work of the USGS. In addition to reviewing the raw sidescan records, the following processing methods were incorporated:

- Import raw data from the bathymetric sidescan together with the full navigation information. The lines are imported at the maximum resolution or at a resolution to match the bathymetric model – 1m for the whole site with 10cm for specific areas of detail;
- Geometrical correction and amplitudes adjustment for offset angles from the transducers. Nadir is removed using bottom tracking algorithms with manual adjustment in areas of rapidly changing bathymetry;
- Line projection onto the relevant datum and overlapping data is combined to give a mosaic of the whole site. Overlap data points are averaged to give the mean amplitude values from all crossing tracks;
- Final output in the form of geo-referenced TIFF and geo-referenced JPEG files together with high resolution single pass sonar lines.

The survey

5.3.46. The test sites were surveyed over a four day period. Multibeam surveying of the test sites took place on 07/04/05 at low water to reduce the distance between the sonar heads and the targets.

5.3.47. Each survey line represented one recorded database file. Each database file was given a unique Sequence Number.

5.3.48. Survey lines were established over the test site to ensure that successive surveys with different equipment could follow the same course over the seabed.

5.3.49. Unfortunately, it was not possible to record the site visually using either an ROV or a diver held stills camera because strong winds prevented anchoring.

5.3.50. Processed multibeam XYZ data was transferred to Trimble Terramodel software and the Visualiser option in the program was then used to interrogate every object in the main test site and also the neighbouring larger targets. Further analysis was conducted on the data sets using Fledermaus Pro, Sonarweb Pro and SonarPro.

5.4. Test results

5.4.1. An analysis of the signatures recorded by the different sonar techniques follows. First results for the multibeam sonar and sidescan sonar are discussed as these both showed greatest utility in the identification of each target. This is followed by a brief description of the signatures obtained by the other sonar techniques. Figures 18a,b,c,d,e list the various targets and the success of detection with the multibeam sonar and the sidescan sonar. Each target that was located or identified is shown in the table 3a,b. Two views of the site are shown in figures 13 and 14 from the multibeam and Klein 3000 sidescan survey respectively.

5.4.2. Using the Reson 8125 multibeam data, it is possible to identify the location for 16 of the 42 targets, far fewer than was anticipated due to the water being deeper than had been planned. Of these 14 objects at least 4 were recognisable from the point cloud data.

5.4.3. Using the Klein 3000 sonar it is possible to identify 17 of the 42 objects in location but only 4 with full recognition.

5.4.4. Using the Edgetech sonar is was only possible to identify the broad pattern of object scatter on the sea floor. Examples of the whole line signatures are shown in figure 15. Further analysis of the records has not been accomplished

5.4.5. Using the 117kHz SwathPlus bathymetric sidescan, no features were seen along the test site and therefore no further analysis was accomplished.

Signatures of Individual Targets

5.4.6. Reference should be made to figures 18a to 18e with respect to the signatures for the following objects:

100mm Star

Multibeam - at 10m along the line from the west end a star-shaped arrangement of 8 thin gauge aluminium tubes, each 1m long and 100m in diameter were laid flat on the seabed. The long axis of two of the star tubes ran parallel to the line. On the multibeam runs all that could be identified were the two opposing arms of the star parallel to the track of the vessel. The arms at right angles and at 45degree to the line were not visible
Sidescan – the star is visible on a number of the sidescan runs for the sonar to both port and starboard sides at offsets (range) up to 25 from the line. For all of the sidescan runs, the sonar was flown at the closest position to the seafloor to be safely practical. This was typically less than 5m from the seafloor.

200mm Star

Multibeam – at 20m along the line the star shape made up from 200mm alluminium tubing was identifiable in all passes. The separate arms of the star are visible with enough clarity to be able to measure length and height of the arms above the sea floor.

Sidescan – the 200mm start is visible in all passes with the sidescan both to port and starboard to offsets of 30m. All arms of the star are clearly visible and the shadow created when the sidescan was deployed at less than 5m from the sea floor allows a height estimate to be made of the tubes.

1m² Aluminium Plate

Multibeam – at 23m a 1m square aluminium plate was laid flat on the seabed. This did not show up on all passes but, where it did, it was as a nil return or void in the multibeam data. This type of response could have occurred as a result of total reflection of the multibeam wave signal.
Sidescan – the reflection signal from the aluminium plate was clear on near all passes with the sidescan sonar out to a range offset of greater than 30m.

Bicycle

Multibeam – at 25m a ladies bicycle was positioned upright and at 45° to the alignment of the survey corridor. This was readily detected and identifiable as a bicycle in all passes. A similar bicycle laid on the seabed at 27m was not identifiable but showed up as an irregularity on the seabed.
Sidescan – the signature of the bicycle was clear as an upstanding object and on some passes an indication of the shadow caused by the wheels was particularly clear. The bicycle that was laid flat on the seabed also showed a strong reflection signature however without any characteristic shape.

Stone Statue

Multibeam – at 31m a 0.75m high stone statue of a cherub was placed upright. This was detected as an upstanding feature 51cm above the surrounding seabed despite the fact that the statue was surrounded by a large amount of high reflectivity material, likely rough seabed.
Sidescan – the statue shows up as a small high reflectivity object with a large and easily measurable shadow.

Divers Helmet

Multibeam – at 35m a 0.5m high copper standard dress divers helmet was detected as a rounded feature 0.35m above the surrounding seabed.
Sidescan – the diver's helmet shows up as a high reflectivity object of the size and shape consistent with the helmet. The feature is clearly visible in the data to a range of over 30m.

Ceramic Urn

Multibeam – at 44m a ceramic garden urn 0.4m high showed as an upstanding feature 0.35m above the seabed. When viewed at a number of different angles there is the suggestion that the urn has fallen over and is on its side.

Sidescan – the urn is again seen as a high reflectivity object that casts a significant and measurable shadow that is consistent with the urn.

Wooden Chest

Multibeam - at 48m a wooden chest was detected as a rectangular object with acoustic reflection up to 0.83m above the seabed. The upper returns are from the wooden lid which floated open as there was no catch to retain it, below that is the edge of the chest and just above the seabed are returns from the lead weights that held the chest to the seabed. The tray with coins shown in the photograph of the chest was not deployed on the seabed.

Sidescan – the signature for the wooden box shows as reflections from the two panels that are upstanding with respect to the sonar signal, i.e. the faces that are perpendicular to the sonar beams. The edge of the open lid also shows as a small signature. What is more obvious however is the shadow cast by the box. This shadow clearly shows the bulk of the box and the open lid above it.

Leather Coat on Frame

Multibeam – at 50m a leather coat supported at 45^{O} on a simple wooden framework was detected as a indefinable feature standing 0.6m above the seabed.

Sidescan – the leather coat and frame was clearly seen when the sidescan illuminated the part of frame that was extending away from the sonar however when the sonar illuminated the frame from the reverse side the signature became confused.

Triangular Trellis

Multibeam – at 52m a triangular trellis from a garden centre, made of 8mm withies, and supported at an angle of 45^{O} was readily identifiable as a triangular object standing 0.45m above the seabed.

Sidescan – the trellis also is seen in the sidescan sonar record and its dimensions can be estimated from the size of the anomaly and the size of the shadow.

1m2 Aluminium frame with tubes

Multibeam – at 59m a 1m square frame in-filled with a course mesh and, attached to which, were aluminium tubes of different diameters and lengths, was suspended in the water column 1m above the seabed utilising 250mm diameter plastic buoys attached to each corner. The sonar return on every run shows the floating target below the seabed instead of above it. In Fig.18a it is shown as an inverted arc 1m below the surface. In others it is a double line of returns with one end touching the surface while, in one, it is just a jumble of returns with no discernable pattern in section. All the images show in plan view a losenge-shaped discontinuity of the seabed rather than a square and this is possibly due to the disposition of the floats at two opposing corners.

Sidescan – the metal framework is clearly seen in all of the sidescan records however its position varies depending on the position with respect to the sidescan fish. When the sidescan is nearly at nadir to the target its true position is best estimated with it clearly located above the seafloor.

5.5. Data analysis

Multibeam

5.5.1. The information gleaned from this test, supported by observations made during other multibeam surveys, indicate that numerous factors influence the quality of multibeam sonar surveys for archaeological purposes. These are listed below:

Human

- Experience and enthusiasm of the surveyor
- Working conditions of the surveyor
- Experience and enthusiasm of the processor of the survey data
- Skill and enthusiasm of the survey vessel helmsman
- Client's understanding of the survey requirements
- Surveyors understanding of the client's requirements

Environmental

- Sea state

Engineering

- Stability of the survey vessel
- Rigidity of the survey vessel
- Effectiveness of the motion reference system
- Rigidity of the mounting of the sonar heads
- Accuracy of the measurement of the offsets between the sonar head, positioning and motion reference sensors
- Hydrodynamics of the sonar heads
- Noise generated by the survey vessel and its equipment
- Accuracy of positional information
- Operating frequency
- Pulse update rate
- Pulse width
- Accuracy and frequency of sound velocity measurements

- Software used to interpret and display the results
- Range setting
- Speed over the ground
- Distance between sonar head and the targets

5.5.2. Although we strived to address many of the issues, some, such as sea state, were beyond our control. Many of the engineering aspects were difficult to control, particularly the measurement of lever arms between the various sensors and the rigidity of the survey vessel. It is for these reasons that an alternative independent sonar head mounting system has been proposed for the next stage of research.

5.5.3. At our slowest survey speed of c. 2 Knots in a depth of 10m there is insufficient information being returned from the seabed to resolve 100mm sized objects. The distance the acoustic signal has to pass through water to the seabed and back dictates the maximum number of pulses that can be transmitted in any second. During the test the ping rate was generally at 22/sec which combined with a boat survey speed of 1m/sec (c. 2 Knots) over the ground, equals an acoustic return every 50mm along track. In order to avoid spatial aliasing of the data it is necessary to record three or more hits on a target for identification with five or more desired for full definition. Thus for an object of 100mm, the curve of a tube perpendicular to the track would have not been conducive to a good acoustic return except along the centre. This may explain why the non-parallel 100mm tubes were not detected.

5.5.4. The imaging of the wire framed pannier on the bicycle and the withy trellis, both objects being of open construction with as much space as solid material, suggests that such mesh-like targets probably act as excellent acoustic reflectors regardless of the size of the material from which they are constructed. This is likely because the overall size of the object is large enough to meet the spatial aliasing requirements.

Sidescan Sonar

5.5.5. The Klein 3000 is a high resolution (500kHz) digital sonar that is easily deployed from a range of survey vessels. Like most sidescan sonar available today it does not typically come with an acoustic beacon and thus knowing exactly where the sonar is in the water relies on manual calculations based on the length of cable deployed, the speed of survey, the currents and the depressors added to the sonar. The errors that are cumulated through these aspects mean that any the position of any object recognised in the final data cannot be known with a high degree of accuracy. However, the fidelity or resolution of the system means that it is possible to image small objects and to know their relative position within a final data set with high precision.

5.5.6. The Klein 3000 has a potential acoustic footprint at 25m range (25usec pulse) of 10cm along track and 5cm across track. Within this at a survey speed of 2kts the potential object detection is similar to the 8125 multibeam. This was confirmed with the analysis of most of the targets that were identified from the site. However, the manner in which targets were imaged with the sidescan is very different to that of the multibeam. This is shown by the signatures of certain targets. For example, the upstanding bike showed up in the shadow profile with more understandable signature than its reflected surface image. The wooden trunk showed reflections from the two faces that were perpendicular to the sonar with again the shadow showing most diagnostic signature of the open lid. The small upstanding objects such as the statue and urn were most readily identified by the length of their shadows rather than the acoustic footprint of the objects themselves. It is therefore imperative that the highest shadow definition is obtained with a sidescan sonar, that is that a low grazing angle is achieved with the fish with respect to the seafloor.

5.5.7. For future surveying, it is likely that higher frequency sonar could be of additional use on archaeological sites. It is imperative that the sonar is deployed to be flown at minimum height from the seafloor so that the shadows are maximised as these form a very important part of the signal for object identification. It is recommended that the sonar fish is deployed with acoustic beacon so that its position in the water is better known and thus the overall final accuracy of positioning targets is increased. As the spatial resolution is defined by the number of pings or hits on a target, this may also be improved by using a sidescan system that has the capability of multiple channel operation. The current commercial available systems include the Klein 5000 and the Edgetech 4200-FS. A new generation of sidescan that operate a synthetic aperture mode have recently become available and likely will also increase the potential resolution over targets.

5.5.8. Specific lessons learned through surveying with sidescan sonar in this project and associated site surveys include the following:

Human

- Experience and enthusiasm of the surveyor
- Working conditions of the surveyor
- Experience and enthusiasm of the processor of the survey data
- Skill and enthusiasm of the survey vessel helmsman
- Client’s understanding of the survey requirements
- Surveyors understanding of the client’s requirements

Environmental

- Sea state
- Current direction

Engineering

- Stability of the survey vessel
- Survey directions with respect to current directions
- Seafloor topography
- Accuracy of the measurement of the offsets between the sonar head and positioning system
- Electrical Noise generated by the survey vessel and its equipment
- Acoustic noise generated by the survey vessel
- Accuracy of positional information
- Operating frequency
- Pulse update rate
- Pulse width
- Software used to interpret and display the results
- Range setting
- Speed over the ground
- Distance between sonar head and the targets
- Flight height of the sonar above the seafloor

Bathymetric sidescan sonar

5.5.9. The results of surveying with the bathymetric sidescan sonar showed the general topography of the survey site outlining the rock skerries. The backscatter component also identified the differences in general seabed type (sediment vs. rock). However, the frequency of the bathymetric sidescan was not high enough to discriminate any of the target features on the site. The choice of frequency, 117kHz in this case, is critical to the detection of small objects. Since the trials in Plymouth two different manufacturers have developed higher frequency systems and these might hold more hope for the potential of this technique for mapping artifacts on archaeological sites.

5.6. Discussion

5.6.1. The lessons learned from application of multibeam on the Plymouth Test project have been synthesised into a set of draft guidance notes which are provided in Appendix 2.

5.6.2. Many of the targets used for this test proved to be too small for detection at the depth range we were restricted to, however many of them were located. Of the located objects some were easily identified but most would not have been correctly identified without prior knowledge of what the object looked like. This lack of resolvability was due to the physical limits of acoustic sampling of the instruments used and the acoustic range from transducers to the targets, i.e. the depth of water. Adjacent to the test site a number of larger objects have been placed to assist commercial diver training and NAS tape survey training. Figure 16 and 17 shows both a multibeam image and also a sidescan sonar image of this site. In these images the various objects (frameworks, cannon and a boat) can be readily identified. It is interesting to note that many of the features on this test site, for example 30mm diameter hand rails were imaged with the multibeam sonar. These features were considerably closer to the sonar head being at the top of the upstanding structures.

5.6.3. The project has pinpointed a major lesson that does not seem to appear in related literature but is of common knowledge to archaeological surveyors: the higher the density of good quality data, the better the definition. In other words, passes at slow speed with the sonar head as close as possible to the targets to allow the maximum possible ping rate, will give the best results for archaeological purposes.

5.6.4. There are still issues which we do not fully understand such as the particular response of different materials to acoustic pulses. The response of different materials to an acoustic pulse is a function of the wave length of the acoustics (determined by the frequency of the sonar), the pulse length, the number of hits or pings on a surface and the angle of the main acoustic lobe with respect to the target. Further response differences are a function of the target material: that is the acoustic impedance contrast with the surrounding water and the surface texture of the target, which is determined by the target surface roughness in relation to the wavelength of the acoustic energy. The acoustic response of a target is therefore complex and dependant on the reaction of the wave in terms of reflection vs. scattering. These issues are seen in the different response of the flat metal plate – at times this acts as a reflector and is readily imaged. At other times the signal merges with that of the seafloor. Other “unusual” responses are seen with other targets such as the floating metal array at 59m. In the multibeam surveys this is always seen as a below-surface response. This is a function of the way that multibeam sonar calculates where reflection signals are derived from, and is inherent in such systems that have very good angular resolution but poorer time resolution for signals.

5.6.5. The highest standard of bathymetric marine surveying, IHO Special Order, has a minimum size of object detection set at 1m3. Archaeological surveys regularly exceed that requirement. Although a range of cube sizes was not included in the test site assemblage, a near-spherical object (a more difficult object to detect) of 0.6m diameter (diver’s helmet) was detected in all five passes, as was the star shape made from eight 0.2m diameter tubes each a 1m long.

5.6.6. In the surveys at Plymouth a twin head Reson 8125 system was deployed to test if this would give a higher sampling rate and better spatial coverage over objects. As indicated in the Year One report (Bates et al., 2005), this does not appear to be the case. Therefore, deployment of a twin head system does not warrant the additional cost and effort of installation in standard configuration. Two heads gives two slightly differing viewpoints of the sonar record but this is only of advantage when viewed as stereo images, something which can now be done by an alternative approach as software like Fledermaus Pro allows virtual stereo images to be produced by calculating the necessary sight lines through the cloud of point data. The distinct disadvantage of two heads is that each sonar head has to wait for the return echoes from the other's transmitted pulse before it can transmit a pulse. This effectively reduces the number of pings from each head and so the overall number of pings per second is not significantly different to a single head system. It might be however that the use of two heads would give significant advantage on a very detailed wreck survey if the heads were both separated by a distance of 1-2m and deployed nearer the targets on a work-class ROV. In this case the two heads would potentially give a greater chance of resolving the full 3 dimensionality of objects. We confirmed that objects of well delineated shape are more easy to identify visually in Terramodel than amorphous shapes but, although that was always likely to be obvious, we learnt that the use of 3-D software which allows objects to be rotated in front of the viewer, e.g. Terramodel or Fledermaus Pro, allows a better understanding of not only how the features are ensonified, but also what form the ensonification takes, and this greatly helps interpretation It is likely that the lack of object definition evident on the Reson 8125 dataset is a result of surveying in water depth deeper than was originally planned. At a depth of 9-11 metres, the system provides on average slightly fewer than 600 pings within every metre square of the seabed whereas we had hoped to reach the 1800 pings obtainable with range settings of less than 7m. This reduction in potential resolution by more than 1/3 meant that fewer objects at the smaller end of the size scale were detected than anticipated, and far fewer were identifiable.

5.6.7. Range settings of the Reson 8125 is related to depth of water and controls the number of pulses of acoustic energy (pings) that can be placed in the water at any one time because the returning echoes from the first ping have to be received before the next ping is transmitted, otherwise there would be too much noise in the water at any one time. This would result in so much noise in the data that it would be impossible to separate good information from bad. For that reason range setting controls the number of pings from 40Hz at 5m, 31Hz at 10m and 17Hz at 20m. Even with the very narrow beam forms of the Reson 8125 of 0.5º across track and 1º along track, range has a measurable effect on the footprint of each beam and the number of beams formed within every square meter of seabed. Differences in a survey vessel's speed over the ground have an even more pronounced effect on the along-track gap between the footprint of each beam, with more data being collected at very slow speeds when the gap between each set of pings is reduced.

5.6.8. The sidescan sonar was able to locate many of the locations of objects seen with the multibeam sonar. Some of these objects were also readily identifiable on the sidescan records however the majority would not be recognised without previous knowledge of what the objects looked like. The Klein 3000 was deployed at its highest definition mode using the 500kHz transducers. Other sidescan systems offer higher frequency transducers although they have not proved to give necessarily higher resolution images. Moving the sidescan transducers closer to the target does not significantly improve resolution with the sidescan as long as it is within the pre-defined range for digital sampling limit. This is set by the manufacturer and is based on the beam angle and pulse length. Improvements in the definition can be gained by reducing the towing speed but it is important that the fish is towed in as straight a line as possible without wandering. This is especially a problem if an acoustic beacon is not deployed on the fish as the final image is dependant on an assumption of the location of the fish in the water in order to correctly position the final mosaic.

5.6.9. The instrument of choice for archaeological surveys has been sidescan sonar (Quinn *et al* 2005) but, when making comparisons with multibeam sonar, it is important to consider what task each type of instrument is best suited for. Sidescan sonar systems are cheaper, easier to deploy and generally cover more area at a faster speed than high definition multibeam sonar systems. This makes sidescan sonar an effective tool for searching for sites and widely scattered archaeological material on the seabed.

5.6.10. High definition multibeam sonar is better suited to individual site rather than area surveys. Such systems are capable of producing accurate base-line surveys at a speed considerably faster than can be achieved by diver-based methods and considerably more accurately than sidescan sonar surveys. There are also a number of additional advantages of applying multibeam to archaeological investigations (Dean and Frazer 2005), including the production of meaningful images of submerged archaeological sites, quantification of changes over time and the ability to help place sites in their environmental context.

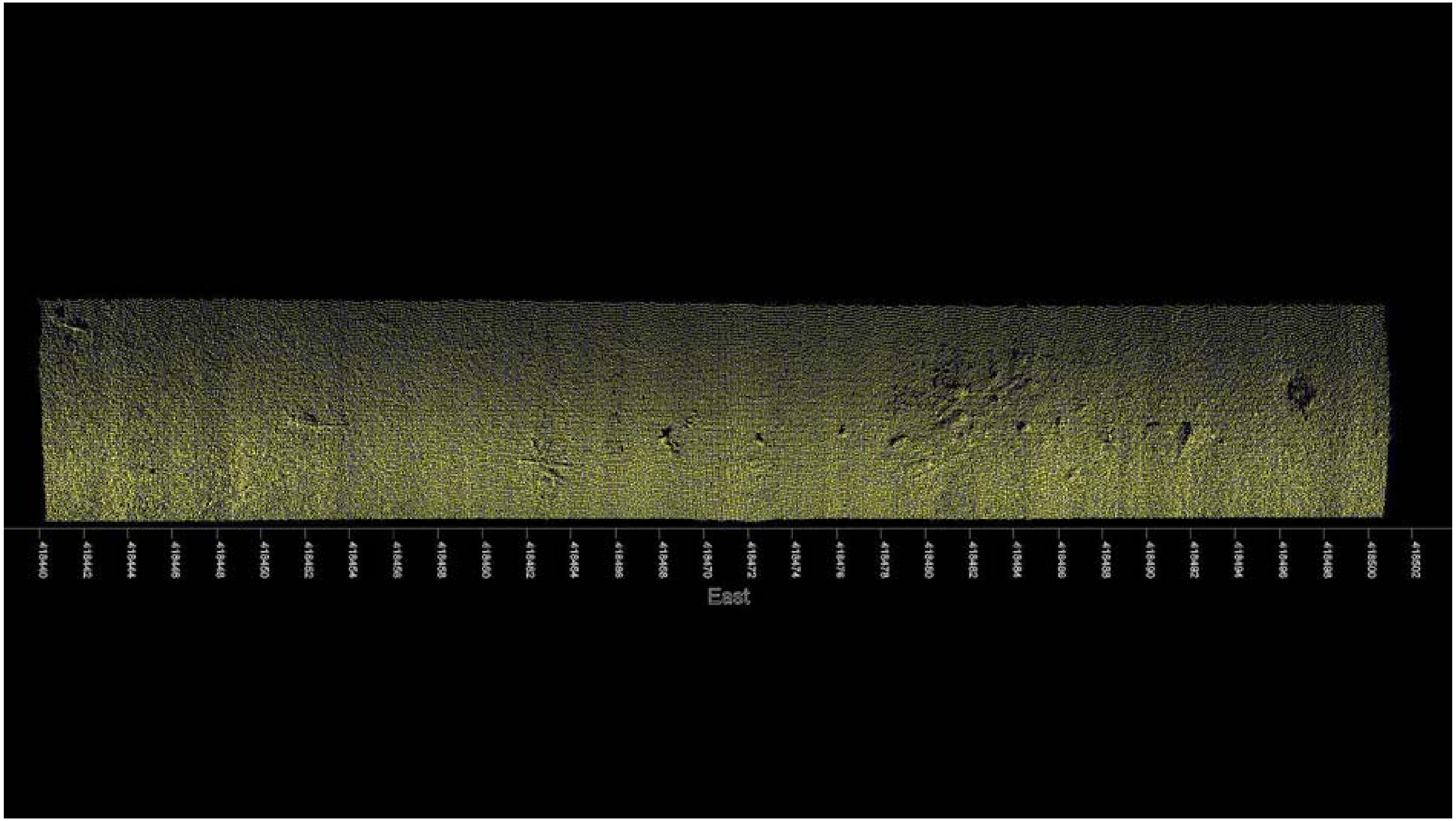


Figure 13: Image of test site acquired with Reson 8125 multibeam sonar

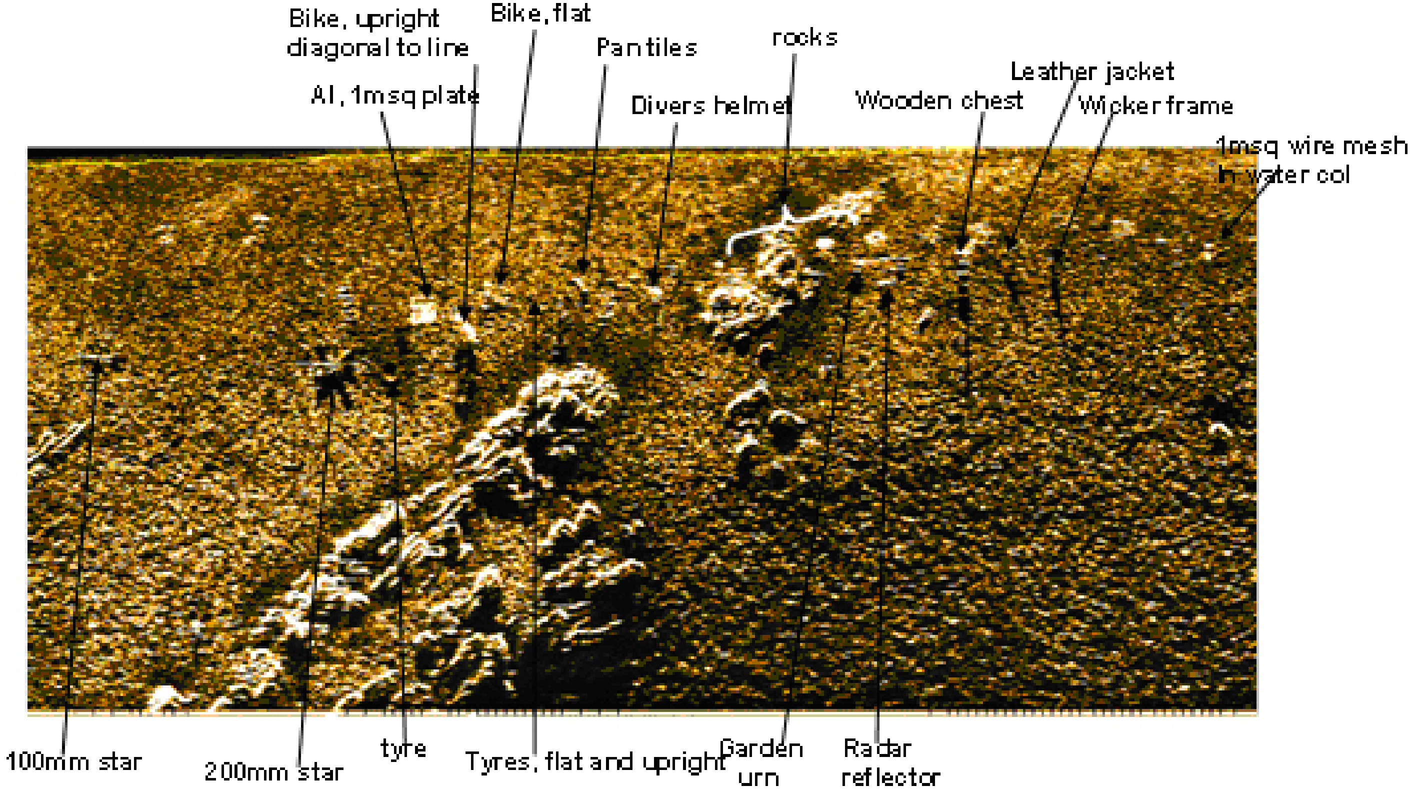


Figure 14: Image of test site acquired with Klein 3000 sidescan sonar

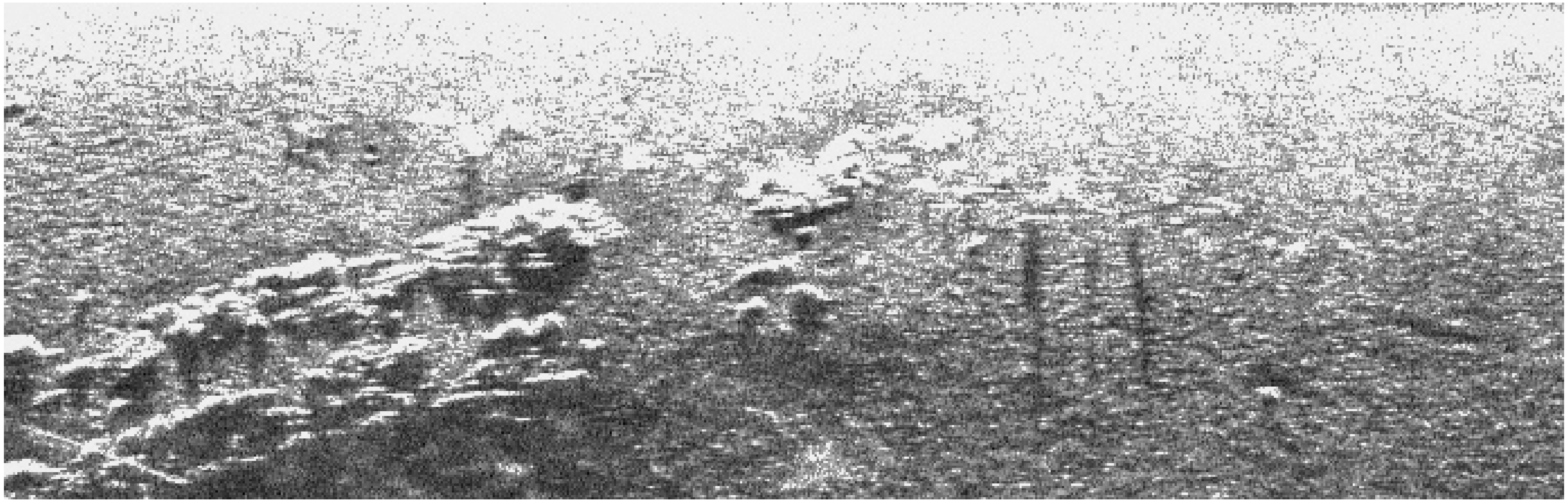


Figure 15: Image of test site acquired with Edgetech sidescan sonar

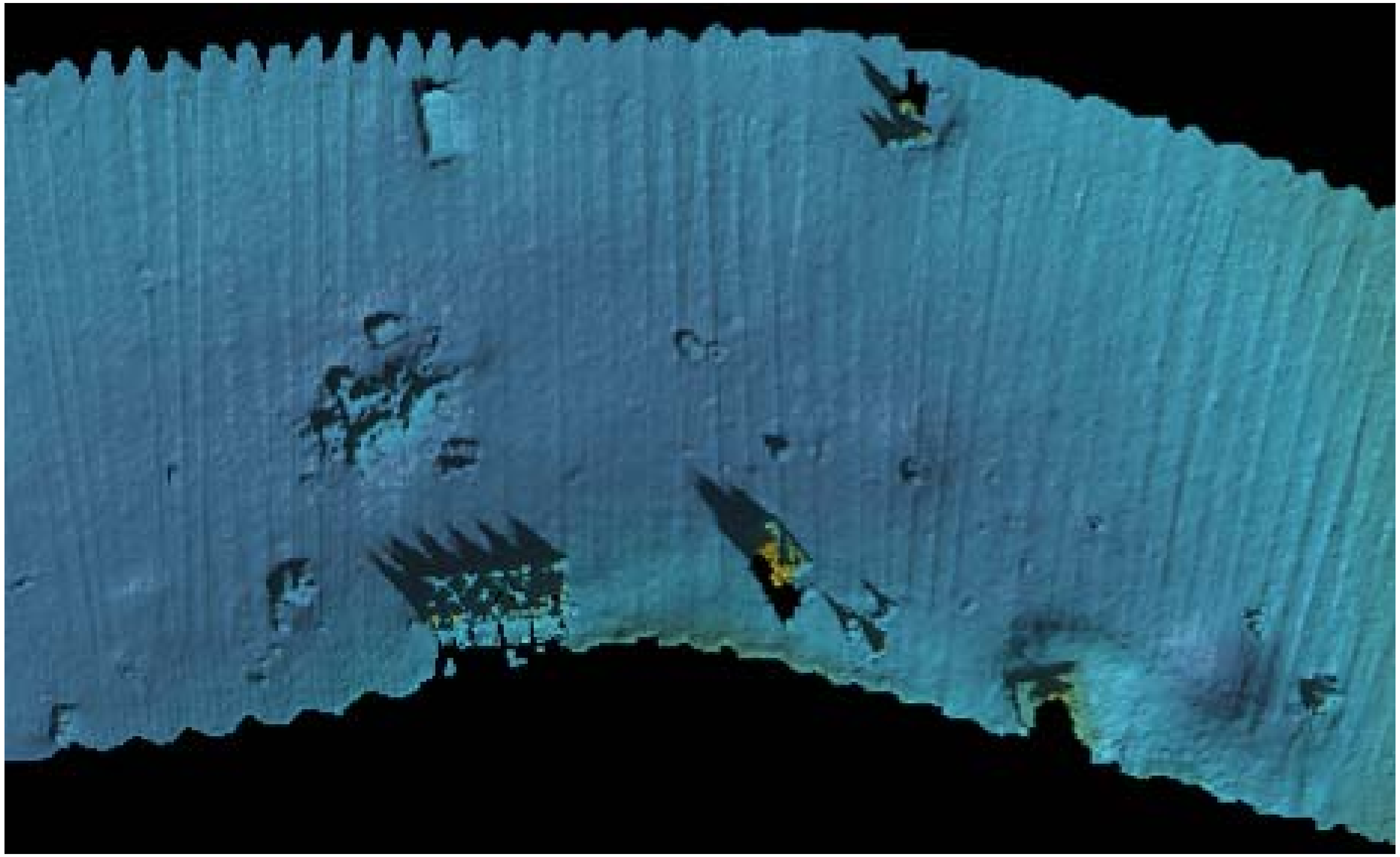


Figure 16: Multibeam image of Sonardyne test site

Figure 17: Sidescan sonar image of Sonardyne Test site

Target description	Target material	Target Dimensions	Offset from Line	Target Orientation
tube	100mm al. tube	1m long	north	horizontal Y-Y
star	12mm coated steel rod	1.6m dia.	south	horizontal
Sonardyne acoustic beacon	plastic	0.3m x 75mm dia.	on the line	horizontal
star	25mm al. tube	2m dia.	north	horizontal
star	50mm al. tube	2.1m dia.	south	horizontal
star	100mm al. tube	2.3m dia.	north	horizontal
Shopping bag	woven esparto grass	0.35m x 0.2m x 0.15m	north	
star	200mm al. tube	2.6m dia.	south	
tube	100mm al. tube	1m long	north	horizontal Y-Y
Sonardyne acoustic beacon	plastic	0.3m x 75mm dia.	on the line	horizontal
step ladder	al.	2m	north	horizontal
flat plate	al. sheet	1m x 1m	south	horzontal
target	al. tubes	1m x 1m	north	horizontal
ladies bicycle	mostly steel	1.7m x 0.6m	south	upright
ladies bicycle	mostly steel	1.7m x 1m	north	horizontal
2 car tyres	rubber	0.6 dia.	south	1 vertical and 1 horizontal
statue	stone	0.75m high	north	horizontal
pantiles	ceramic	1m x 1m	south	Horizontal
3-bladed propellor	bronze	0.6m dia.	north	horizontal
diver's helmet	copper	0.5m high	south	upright
ship's wheel	wood	0.9m dia.	north	horizontal
ship's bell	bronze	0.3m dia. X 0.4m long	south	on its side
lion's head fountain spout	lead	c.0.4m x 0.15	north	horizontal
wine bottles	glass	1m x 1m	south	horizontal
Sonardyne acoustic beacon	plastic	0.3m x 75mm dia.	on the line	horizontal
gravel	10mm	1m x 1m	north	
garden urn	ceramic	0.4m dia. x 0.5m	south	uptight
sand	course	1m x 1m	north	
2 radar reflectors	Al.	0.3m octahedron	south	
Assorted flower pots	ceramic	1m x 1m	north	upright
chest	wood	0.9m x 0.4m x 0.5m	south	Upright with lid floating up
assorted jars	stoneware	1m x 1m	north	upright
coat	leather	size 12 long	south	45° with arms out
2 boat timbers	waterlogged wood	c.0.8m x 0.15m x 0.15m	north	horizontal
wicker triangle	8mm dia. willow twigs	0.9m x 1.8m	south	45°
skeleton	bone	1m x 1m	north	laying flat
2 mini amphoras	ceramic	0.5m long	south	horizontal
assorted small finds	various	1m x 1m	north	laying flat
target	al. tubes	1m x 1m		floating flat 2m above seabed
Sonardyne acoustic beacon	plastic	0.3m x 75mm dia.	on the line	horizontal

Table 2: Objects placed on the seabed for the Plymouth Sound Test.

Target	Line	100mm Star		200mm Star		Large tyre		1x1m Flat Plate		Bicycle upright		Bicycle flat		Car tyres		Ceramic Statue		Pantiles	
Sonar Run	offset	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S
Line 0 over targets	0m	yes		yes		yes		yes		yes		yes		yes		yes		no	
Ln3 - 25 m range	10m north		yes		yes		yes		yes		yes		yes		yes		yes		yes
Ln2 - 25 m range	20m north		yes		yes		yes		yes		yes		yes		no		yes		
Ln4 - 25 m range	0m		no		no		no		no		no		no		no		no		no
Ln5 - 25 m range	15m south		yes		yes		yes		yes		yes		yes				yes		
Ln 3.5 - 25 m range	5-8m north		yes		yes		yes		yes		yes		yes		no		yes		no

M - Reson 8125 multibeam, S - Klein 3000 sidescan

Table 3 (a,b) : Identification of test objects on separate sonar runs.

Target		Divers hat		Garden Urn		Radar reflectors		Flowerpots		Wooden Chest		Leather Coat		Timber		Wicker Triangle		Aluminium mesh and tubes	
Sonar run	Line Offset	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S
Line 0 over targets	0m	yes		yes		yes		yes		yes		yes		yes		yes		yes	
Ln3 -25m range	10m north		yes		yes		yes		yes		yes		yes		no		yes		yes
Ln2 -25 m range	20m north		yes		yes		yes		no		yes		yes		no		yes		yes
Ln4 -25 m range	0m		no		no		no		no		no		no		no		no		yes
Ln5 -25m range	15m south		yes		yes		yes		yes		yes		yes		yes		yes		yes
Ln 3.5 - 25 m range	5-8m north		yes		yes		yes		no		yes		yes		no		yes		yes

M - Reson 8125 multibeam, S - Klein 3000 sidescan

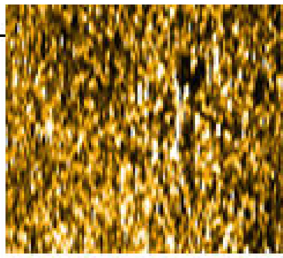
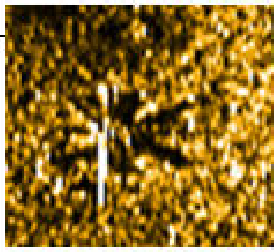
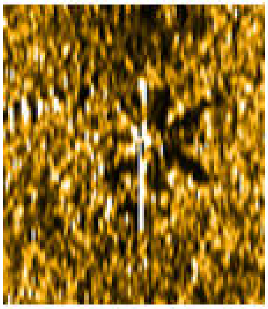
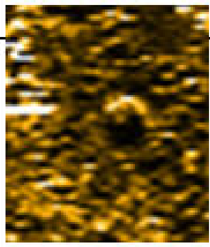
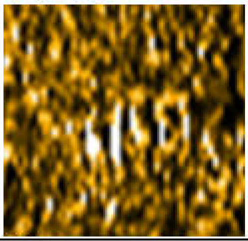
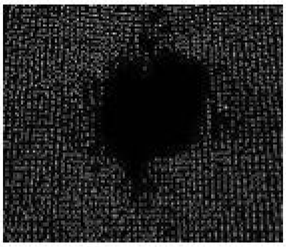
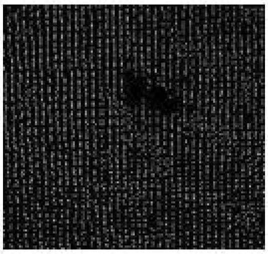
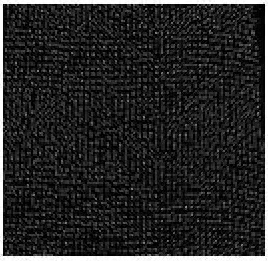
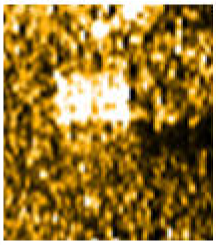
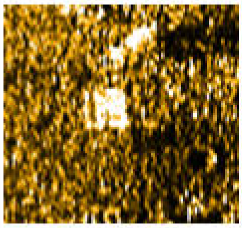
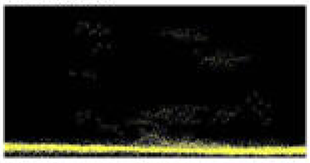
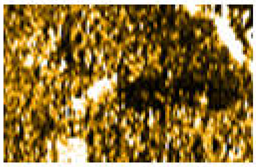
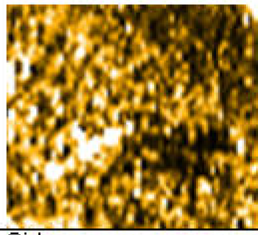
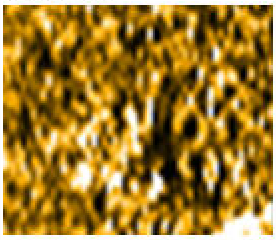
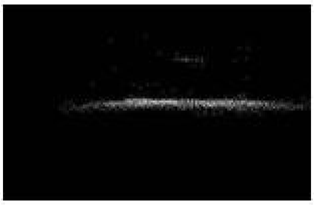
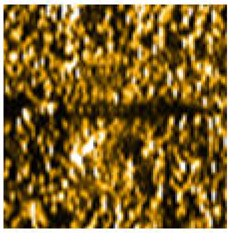
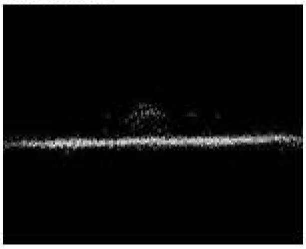
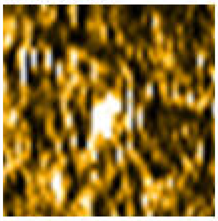
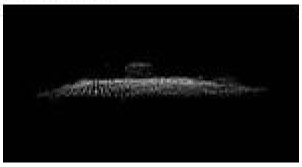
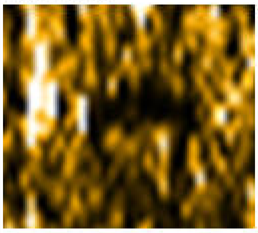
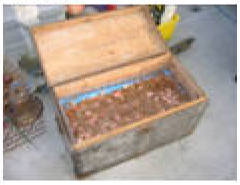
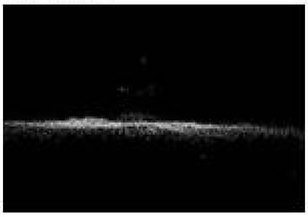
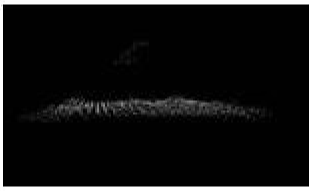
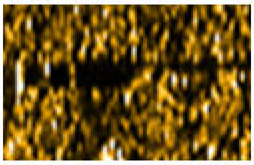
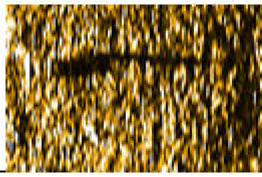
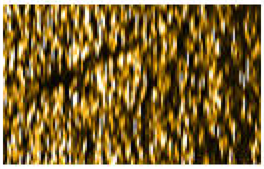
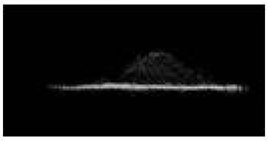
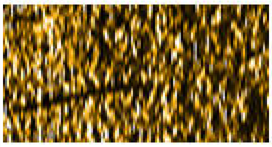
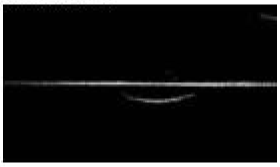
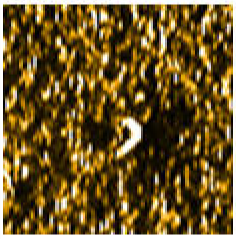
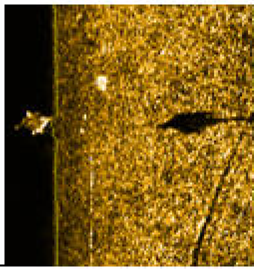
<table>
<tr><td colspan="3">Target objects for Plymouth Test site
Reson 8125 Multibeam images from Terramodel of single passes over the test site
All Klein 3000 images rotated to show sidescan fish to the left of the image</td></tr>
<tr><td>100mm Star
</td><td>Multibeam
</td><td></td></tr>
<tr><td>200mm Star
</td><td>Multibeam
</td><td>
</td></tr>
<tr><td>Large Tyre
</td><td>Multibeam</td><td></td></tr>
</table>

Figure 18 (a,b,c,d,e) :Test objects deposited on the seabed at Plymouth Sound, with corresponding multibeam and sidescan sonar signatures.

Al. Step ladder		Sidescan 
1mx1m Al. plate	Multibeam   	Sidescan  

Bike upright 	Multibeam 	Sidescan  
Bike flat		Sidescan 
Statue 	Multibeam 	Sidescan 

Divers Helmet 	Multibeam 	Sidescan 
Urn 	Multibeam 	Sidescan 
Chest 	Multibeam  	Sidescan  

Leather Jacket on frame		Sidescan 
Triangular Trellis 	Multibeam 	Sidescan 
Al tube frame – suspended in water col. 	Multibeam 	Sidescan  

6. Stirling Castle, Goodwin Sands

6.1. Introduction

6.1.1. The *Stirling Castle,* lost in the Great Storm of 1703, is located 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 is designated under the Protection of Wrecks Act 1973.

6.1.2. The *Stirling Castle* was one of 30 vessels built following orders by Samuel Pepys after 1675, to counter French and Dutch naval power in north-west Europe. The wreck is located within a dynamic burial environment and remote sensing systems offer a safe and accurate method of recording this important site within a mobile and complex seafloor.

6.1.3. The *Stirling Castle* site has an immediate relevance not only to EH as the regulatory body for the Protected Wrecks in UK Waters but also for the UK aggregate industry. While the *Stirling Castle* site is not within a currently active aggregate dredging area the site is in a location where the historical records show that the seafloor, and in particular the sand component, has high mobility. The mobility of sand and gravel in the vicinity of wreck sites is of great concern to the aggregate industry as it has been proved that aggregate extraction can cause changes to seafloor morphology for some distance around aggregate sites. Furthermore, since a number of previous surveys had been accomplished on the site using techniques commonly employed by the aggregate industry the project would be in a position to directly assess the new techniques in terms of rapid deployment and mapping effectiveness (resolution) and thus provide the industry with potential tools for future surveys elsewhere.

6.2. Review of historic datasets

6.2.1. In order to obtain a more coherent view of the changes in environmental factors over time that can impact a key maritime archaeological site, the project undertook a review of available data for the *Stirling Castle* and the Goodwin Sands.

6.2.2. Assessment of these datasets quickly illustrated that the movement of sediment in the vicinity of the wreck's complex archaeological deposits is a particularly important factor in relation to the stability of the *Stirling Castle* wreck, and thus the long term management of this important site.

Academic studies

6.2.3. Earlier work (Welsby 1987 and Cloet 1952) concerning the stability of the Goodwin Sands gives the overall impression that the banks are relatively stable features, albeit with seasonal rotational (clockwise) changes.

6.2.4. However, more recently Elderfield (2001) observed changes in the bathymetry for the whole of the Goodwin Sands, and suggested that there had been a more significant movement of between 0.5km and 1km between 1887 and 2000 datasets. This change was predominantly in a shoreward direction, equating to approx 120 million m3 of sediment movement.

6.2.5. More importantly perhaps, Elderfield (2001) observes that recent changes in the Goodwin Sands have occurred over relatively short periods (i.e. 5 years as opposed to 50).

6.2.6. Elderfield recognised a relatively quiet period in terms of bathymetric changes between 1986 and 1995. However looking at the bathymetric datasets for the year 2000, the Goodwin Sands appear to have undergone quite marked changes in some areas – including the area of the wreck – during the period 1995 - 2000.

Licensee work

6.2.7. Tape based surveys were begun on the site of the *Stirling Castle* in 1979, mostly by avocational archaeological divers but, occasionally, supplemented with input from professional diving archaeologists. However, the hostile diving environment at the *Stirling Castle* has meant that it has proved impossible to sustain long periods of survey work by divers. In 1987 the Archaeological Diving Unit, based at the University of St Andrews, set out to complete a basic offset survey of the site. After setting out a 50m tape as a mid-line datum, strong winds prevented access the following day and when diving resumed, the datum tape was found to be displaced and buried under 0.75m of sand in some places. It proved impossible to realign or recover without mechanical excavation assistance, which was not to hand, and so the remnants of the tape are still on site and appear occasionally.

6.2.8. Much of the licensee generated survey work has been carried out by the existing licensee Bob Peacock and his colleagues from Seadive, Kent. In August 1998, Mr Peacock contacted the Archaeological Diving Unit (University of St Andrews) to say that the wreck had 'come out of the sands'. Project "Man O War" followed and involved a major recording effort of the exposed structure. Subsequent discussions with Mr Peacock have confirmed that sediment movement remains an issue.

Archaeological Diving Unit (University of St. Andrews) and Wessex Archaeology, in support of the Protection of Wrecks Act 1973.

6.2.9. In 1995 the divers from the Archaeological Diving Unit (University of St Andrews), known as ADU, described the *Stirling Castle* site as 'stable' and although a degree of wreck structure is exposed on the top & sides of the wreck, silting up of the wreck, aided by snagged fishing nets, is apparent. In 1997 ADU divers reported the wreck in much the same condition as they had described in 1995.

6.2.10. Following Mr Peacock's report in 1998, the ADU visited the site, to be greeted to find that the *Stirling Castle* had become dramatically exposed – to a similar level to that described in 1979. The entire port side of the hull was visible at the stern from the upper parts of the keel and the turn of the bilge - up to the level of the gundeck. In fact the muzzle of a cannon was visible, emerging from a gunport.

6.2.11. The Archaeological Diving Unit at the University of St Andrews (1986, 2002) and Wessex Archaeology (2003) have undertaken archaeological and geophysical assessments while British Geological Survey and English Nature have collated environmental datasets. Information relating to these datasets is provided in Table 4

Sonar system	1979	1997	1998	1999	2000	2001	2002	2003	2004
Bathymetry (single beam)		ADU	ADU	ADU	Peacock				
Bathymetry (multibeam)							ADU RESON 8125		
Backscatter (multibeam)							?ADU RESON 8125		
Sidescan Sonar			ADU Imaginex 858 Imaginex 858		GSE Rentals (Wreck Detectives) Klein 2000. ADU Imaginex 858	ADU Imaginex 858	ADU Imaginex 858		
Acoustic Ground Discrimination						SEA's Echoplus- Dual Frequency 192KHz;50KHz			
Magnetometer			ADU - proton		ADU/ Licensee	Geometrics Flux	Geometrics Caesium		
Video	Licensee	ADU/ Licensee	ADU/ Licensee	ADU/ Licensee	ADU	ADU/ Licensee	ADU/ Licensee	Licensee	Licensee
Still	Licensee	ADU	ADU	ADU	ADU 00:17	ADU	ADU		
Ancillary Reports		ADU 97:26:00 95:08:00 93:23:00 92:23:00 1991 Licensee reports to ACHWS from designation in 1980	ADU 98:23 Licensee report to ACHWS	ADU 99:15 Licensee report to ACHWS	ADU 00:17 Licensee report to ACHWS	ADU 01:12 Licensee report to ACHWS	Licensee report to ACHWS Lawrence and Bates Acoustic ground discrimination techniques for submerged archaeological site investigations ADU 02:15; ADU 02:21	EH/ Wessex Archaeology DBA Licensee report to ACHWS	Licensee report to ACHWS

Table 4: Historic datasets for the *Stirling Castle site*

6.2.12. This corpus of work required more detailed analysis. For the purposes of monitoring and academic research, the most useful datasets were acquired in 2001 and 2002 by the Archaeological Diving Unit (University of St Andrews).

6.2.13. The 2001 dataset included data gathered using an SEA 'Echoplus' Acoustic Ground Discrimination System (AGDS).

6.2.14. The 2002 dataset for the *Stirling Castle* was undertaken using a Reson 8125 multibeam by the ADU (University of St Andrews) and Reson Offshore Ltd. during work in support of the Protection of Wrecks Act 1973. Analysis suggested that this data was accurately enough positioned and of sufficient resolution for use as a baseline for comparisons. As such, the 2002 dataset provides the best historical dataset in terms of monitoring the long term evolution of the *Stirling Castle* wreck in its environment.

6.3. Field work

Summary of work undertaken

6.3.1. A survey programme was compiled to carry out two surveys of the *Stirling Castle* site within the RASSE timescale using remote sensing equipment of a similar specification (if not better) to that used in 2002, combined with sampling of sediments and scientific analysis. The project methodology for this work was designed to quantify any sediment movement process, and to allow the beginnings of discussion on cause and effect.

6.3.2. Grain size, wave data and sediment volumetric analysis was undertaken by Sarah Laird, at the University of St Andrews during August 2006 fieldwork.

6.3.3. 3D visualisation of the multibeam sonar data was undertaken by Chris Rowland (University of Dundee, and ADUS).

6.3.4. The University of St Andrews undertook four surveys of the *Stirling Castle* in all during the course of the project. Of these, three were carried out for the project; a fourth was carried out by ADUS on an opportunistic basis.

6.4.Methodology

Vessels

6.4.1. The survey vessel for the Year One (2005) RASSE fieldwork was the 12m survey catamaran *Xplorer*, an MCA category 2 work boat operated by SeaTrax, a small survey charter boat company based in Portsmouth.

6.4.2. The survey vessel for the 2006 fieldwork was, in the first instance (March 2006) *Xplorer* (figure 9) but latterly *Wessex Explorer* (August 2006), a 15m MCA category 2 workboat operated by a small charter boat subsidiary of EGS Survey International Ltd.

6.4.3. The vessels were chosen because:

- They could both effectively house all survey equipment within the wheelhouse;
- Their size enabled them to manoeuvre effectively over the test site and the *Stirling Castle*;
- The RASSE mounting framework for deploying the Reson 8125 sonar head bolted directly on to existing mounting points on the hull of *Xplorer*, thereby considerably reducing mobilisation time on the sites during Year One fieldwork;
- The ISHAP system for deploying the Reson 8125 sonar head could be readily deployed utilising the A-frame on the stern of *Wessex Explorer* during Year Two fieldwork;

- A mounting framework existed on the starboard side of *Xplorer* suitable for use with the Submetrix bathymetric sidescan during Year One fieldwork;
- Both vessel came with a skippers used to the requirements for careful, high definition survey work;
- *Xplorer's* high-speed transit capability enabled mobilisation and deployment of the sonar in Plymouth and then subsequent use at the *Stirling Castle* within a reasonable timeframe during Year One fieldwork.

Position fixing and orientation

Motion reference

6.4.4. The survey and navigation system onboard consisted of an Applanix POS-MV 320 (Position and Orientation System for Marine Vessels) that combined Real Time Kinematics (RTK) with the most accurate of the commercially available motion reference compensation systems.

6.4.5. In 2005, the Applanix POS MV utilised two Novatel GPS antennas mounted on the top of the wheelhouse of *Xplorer,* 3m apart to deliver heading and motion information, and a motion reference unit to correct heave, pitch and roll. Great attention to detail was given to the measurement of the lever arms (offsets) between the sonar heads and the motion and positioning sensors. The tidal variation was exploited to utilise the optimum range between the sonar and the site so that the best survey definition was achieved.

6.4.6. In 2006 the POS MV was fed full RTK CMR+ corrections from a Trimble 5700 base station setup on the roof of Licensee Bob Peacock's house in Walmer, south along the coast from Ramsgate, approximately five miles from the site of the *Stirling Castle*.

Use of Differential GPS and Real Time Kinematic (RTK) Positioning

6.4.7. In 2005, survey work was restricted to Differential GPS. The distance of the site from the shore prevented the use of the radio link required for transmission of RTK CMR+ corrections. Higher powered radio links were ruled out due to the need for special broadcasting licenses.

6.4.8. Whilst the relative accuracy of the surveys completed in 2005 using Differential GPS (accuracy limited to sub 2m in absolute terms) was within acceptable limits to produce good results from the multibeam system, absolute accuracy, especially in the vertical, was lacking. This meant that for 2005, the *Stirling Castle* the datasets relied on tidal prediction software during the surveys to achieve vertical control.

6.4.9. In 2006, in order to further exploit the maximum potential of the multibeam system during the work on the *Stirling Castle*, positional accuracy to centimetric levels in XY *and Z* was achieved using an RTK system. Surveys undertaken with RTK negate the need to make use of any tidal predictions or separate tidal information; the Z values derived in real time are accurate enough alone to compensate for tidal effect.

6.4.10. RTK works on a similar principle to conventional differential GPS, but phase-based corrections are applied using a dedicated base station instead of publicly available long-distance range-based corrections.

6.4.11. The issue of the RTK CMR+ transmission to the survey vessel from the base station, a Trimble 5700 receiver located on the roof of Licensee Bob Peacock's house in Walmer, was overcome by the use of mobile phone (GSM) links. This type of datalink for use in these circumstances (i.e. multibeam surveys within 12 miles of the coast) was (surprisingly) not commonplace and significant effort was required to acquire the appropriate SIM cards and CSD data links necessary from Vodafone and the appropriate modems for the basestation and survey vessel.

6.4.12. Once setup, the Linkwave GSM modems working across the Vodafone network enabled the successful transmission of RTK CMR+ corrections necessary from the base station to allow the Applanix POS MV to operate in 'tightly coupled fixed RTK' mode for the August 2006 surveys on the *Stirling Castle*.

6.4.13. Data acquired onboard the survey vessel used the ETRS 89 Datum (UTM Grid) and heights were adjusted relative to Ordnance Datum Newlyn (ODN) during post-processing. The August 2006 dataset for the *Stirling Castle* thus became the most accurate in both relative and absolute terms and the one to which all earlier dataset's elevations were subsequently adjusted according to the methodology described below.

6.4.14. The difference in height between the WGS 84 ellipsoid and ODN for the purposes of the *Stirling Castle* survey was calculated using proprietary software to be 44.26m.

Datum name	OS Easting	OS Northing	Elevation
Roof of Bob Peacock's house	637190.41	150096.13	29.87

Table 5: Position of the basestation (accurate to about 1-2cm: absolute accuracy to OS)

6.4.15. The base station position was derived by Survey Solutions Scotland using raw observations collected by the base station prior to the survey (see table 5).

6.4.16. The procedure involved included the use of GPS Post processing software possessed by the company. RINEX data from the Ordnance Survey (OS) active network was imported was imported alongside the raw observation data collected by the base station.

6.4.17. Precise ephemerides (actual rather than predicted satellite Keplarian elements) were downloaded from NASA for best accuracy and also an Ionospheric model from University of Bern.

6.4.18. The project was then processed using L1 and L2 to appropriate OS stations, leaving all baselines activated so loop closures could be calculated. After the removal of noisy data and the application of a number of QC checks, the project was then adjusted using all the data (least squares adjustment) whilst holding OS stations fixed in ETRF-89.

6.4.19. After adjustment OSTN'02 and OSGM'02 were used to provide co-ordinates in OSGB'36 National Grid and OS datum.

6.4.20. As a check the whole project was repeated using only the nearest OS station – and very similar results were achieved.

6.4.21. The elevation was also checked manually using a total station situated over an OS spot height on the ground near to Bob Peacock's house. The results obtained for the elevation of the base station were within 2 cm.

Sonar systems used

Bathymetric multibeam sonar

6.4.22. Beam-forming multibeam systems form a set of virtual 'beams' mathematically and detect the range to the seabed in each beam. The best archaeological survey results using multibeam systems have involved beam-forming systems. In 2005, the RASSE team trialled a dual head Reson 8125 Ultra High Resolution Multibeam Echosounder (See Appendix 3 for technical specifications). In 2006, a single hear Reson 8125 was deployed using the ISHAP method (see section)

6.4.23. Components of the multibeam sonar system comprise the sonar head itself, a sonar processor unit, Seabird CTD and Navitronic SVP-15 sound velocity probes, and a dual processor PC with increased hard disk capacity for sonar acquisition.

6.4.24. One sound velocity probe was attached near the sonar head(s) on the pole/ISHAPS. The probe provided continuous measurements for the purposes of the beam forming process employed by the Reson system.

6.4.25. A second sound velocity probe was used for obtaining sound velocity profiles through the entire water column at regular intervals during all surveys.

6.4.26. The sonar processor that controls the acoustic parameters of the sonar head(s) were placed inside the wheelhouse alongside the system PC. Constant adjustment to these processor units was required during the surveys, aided by a visual display of the raw sonar data. Various settings for range, gain and ping rate limited the number of bad soundings acquired during the survey and facilitated post-processing.

6.4.27. Full calibration of the system was undertaken by carrying out patch tests prior to commencing all fieldwork. Patch test values were applied in real-time, as was the single sound velocity value from the sound velocity sensor at the head (typically 1520m/sec) for refraction. Sound Velocity Profiles were regularly measured and showed the velocity to be the same throughout the water column. QINSy is able to use the GPS RTK height in real-time, so that fully corrected soundings were recorded to processing data files in real-time, and available for editing immediately at the end of each line.

6.4.28. QINSy v7.5 survey and acquisition software running on the PC was used to control surveys with a navigational chart backdrop for the positioning of survey grids and the provision of detailed navigational information (which could be displayed on a separate helm screen) to aid the skippers during the running of survey lines during fieldwork.

6.4.29. The QINSy software co-ordinated a database of all aspects of the system setup which included the offset measurements necessary between the various components (with the ISHAP system these values had been predetermined, but still had to be entered into QINsy) and also water column sound velocity profile data. The software also created appropriate file folders during data acquisition to aid file management.

6.4.30. The data collected by the system comprises QINSy database files for each individual survey line, and optional point files (as XYZ ASCII text). The point files could be imported immediately into other visualisation software (such as Terramodel Visualiser or Fledermaus) to view the data just collected in three dimensions during or after the survey. This was very useful in determining whether any problems existed with the data during the survey.

6.4.31. The QINSy database files were in effect the end result of the field survey. These files can be subsequently replayed if necessary (generating new XYZ files) following adjustments to certain parameters (such as patch test settings, tidal data, or sound velocity files).

6.4.32. For each ping the Reson 8125 also outputs two channels of backscatter data (multi-beam side scan). One channel represents the sum of the port beams, the other the sum of the starboard beams. The QINSy software stores the backscatter in the same database as the bathymetry data.

6.4.33. Backscatter datasets from the 8125 were acquired for the Plymouth and *Stirling Castle* sites, although these datasets haven’t been processed as part of this project.

6.4.34. QINSy includes the Time Varied Gain (TVG) normalisation technique to dampen the amplitude of the strong nadir values and enhance the weaker outer beam values.

Bathymetric sidescan (Interferometric multibeam system)

6.4.35. Interferometric (phase comparison) multibeam systems measure angle for each of a set of ranges (as opposed to measuring the range for each of a set of angles). In 2005, the RASSE project trialled a Submetrix 2000 (SEA Ltd.) bathymetric sidescan (For technical specifications see Appendix 3).

6.4.36. For the wide area *Stirling Castle* survey the sonar transducers were mounted on a side pole mount together with the motion reference unit (TSS DMS-05) onto the starboard side of *Xplorer* amidships. Both were connected to the control computer together with a DGPS and magnetic compass for positioning (accuracy less than 20cm). The motion reference unit was a TSS DMS-05 dynamic motion sensor which used solid state sensing elements to measure instantaneous linear accelerations and angular rates of motion change to 0.05º. The magnetic compass used was an Aximuth 1000 produced by KVH Industries, Inc. This fluxgate digital compass provides azimuth information to 0.5º accuracy after compensation and is predominantly used for stabilisation of the motion reference unit for long wavelength variations.

6.4.37. Sonar processors that control the acoustic parameters of the sonar heads were placed inside the wheelhouse alongside the system PC. The acquisition was accomplished using SEA Swathplus software. The data was constantly monitored during acquisition in order to achieve the best data quality control.

6.4.38. Prior to surveying, a calibration patch test was conducted for the swath-bathymetry system that included calibration for roll, pitch, heave, skew and time lags The patch test was conducted in an area of flat sea floor.

6.4.39. The bathymetric sidescan was also used in a similar manner to the 8125 multibeam with northeast-southwest lines surveyed along the main channel between sand banks where the Stirling Castle is located.

6.4.40. Swathplus (SEA Products) survey and acquisition software running on the PC was used to control the survey together with navigation software Hypack Max from Coastal Oceanographics Inc., which was displayed on a separate helm screen to aid *Xplorer*'s skipper during the running of survey lines.

6.4.41. The data collected by the system comprises Swathplus RAW acquisition files for later processing using the same software.

6.4.42. For each ping the SEA System 2000 also outputs two channels of backscatter data (swath bathymetry side scan). The Swathplus software stores the backscatter sidescan in the same database as the bathymetry data. Backscatter datasets from the Swathplus were acquired for the *Stirling Castle* site.

Bathymetric sidescan post-Processing

6.4.43. Post-processing is being conducted by the University of St Andrews using Swathplus and Grid2000 software initially and then IVS Fledermaus Pro to clean the data and ignore erroneous soundings.

6.4.44. Results from the patch test values were applied in preliminary format in real-time but were fully applied in later processing. During this time, tidal corrections together with velocity corrections were applied.

6.4.45. The method employed for the RASSE surveys produced vast numbers of bathymetric points. To ensure that complete coverage was provided for the sites the survey lines often overlapped and therefore any one object was likely to be ensonified a number of times during different survey passes. Errors in the positioning system and/or motion reference unit will be carried through into positioning errors for the individual soundings. Even these small errors will lead to objects appearing 'blurred'.

6.4.46. Ideally, positioning provided from RTK systems on this survey is essential for the longer-term comparison of subsequent datasets (i.e. for monitoring purposes).

Bathymetric sidescan visualisation

6.4.47. The bathymetric sidescan data was first examined with IVS Fledermaus Pro using both point clouds and rendered surfaces, from which measurements were taken and features identified for subsequent attention.

Sidescan sonar

6.4.48. Sidescan sonars transmit a narrow acoustic beam to the side of the survey track line. As the acoustic beam travels outward, the seabed and other obstructions reflect some of the incident sound energy back to the sonar. The travel time of the acoustic pulses from the sonar are recorded together with the amplitude of the returned signal as a time series and sent to a topside console for interpretation and display.

6.4.49. The project used the Klein 3000 side scan sonar, one of the best in a new generation of digital sidescan survey instruments that is readily available to the archaeological community (for technical specifications see Appendix ???). The survey also tested an Edgetech sidescan sonar however this is not reported on here as the results did not give as clear discrimination compared to the Klein sonar of the target objects.

6.4.50. Antennae to fish 'lay-back' distances were calculated from the GPS antennae on board and keyed into the software, to enable estimation of the fish location. The fish was not tracked acoustically although this would greatly improve the quality and quantitative value of the results in future surveys.

Sidescan sonar post-processing

6.4.51. Post-processing was carried out using Klein Sonar Pro Software and Cheseapeake Sonarweb Pro software. All results were logged on DVD

Rom. SonarWeb Pro processing uses amplitude corrections to the amplitude time series based on the work of the USGS. In addition to reviewing the raw sidescan records, the following processing methods were incorporated:

- Import raw data from the bathymetric sidescan together with the full navigation information. The lines are imported at the maximum resolution or at a resolution to match the bathymetric model – 1m for the whole site with 10cm for specific areas of detail;
- Geometrical correction and amplitudes adjustment for offset angles from the transducers. Nadir is removed using bottom tracking algorithms with manual adjustment in areas of rapidly changing bathymetry;
- Line projection onto the relevant datum and overlapping data is combined to give a mosaic of the whole site. Overlap data points are averaged to give the mean amplitude values from all crossing tracks;
- Final output in the form of geo-referenced TIFF and geo-referenced JPEG files together with high resolution single pass sonar lines.

Sonar deployment methodology

Dual Head Reson multibeam sonar

6.4.52. In 2005, deployment consisted of two Reson Seabat 8125 sonar heads operating in a dual head configuration and mounted just beneath the hull of the survey vessel on a rigid pole attached to its side (Configuration appears as Figure 7 in the year one report.). Ancillary systems (GPS & Motion Reference) were located inboard (separate to the pole) - in the way traditionally considered appropriate by surveyors undertaking multibeam surveys using smaller vessels.

6.4.53. The 8125 multibeam sonar heads were attached over the port side of the survey vessel on a rigid mounting at the stern quarter designed by an engineer at the University of Glasgow. The twin-pole arrangement prevented free movement of the head relative to the vessel, yet could be dismounted and remounted within minutes without the need for time consuming recalibration. This prototype system proved highly effective in the field and contributed significantly to improved data collection. Furthermore, the easy deployment without extensive re-calibration significantly reduced mobilisation time between successive surveys both on and between sites.

Independent Sonar Head Attitude and Positioning System (ISHAP)

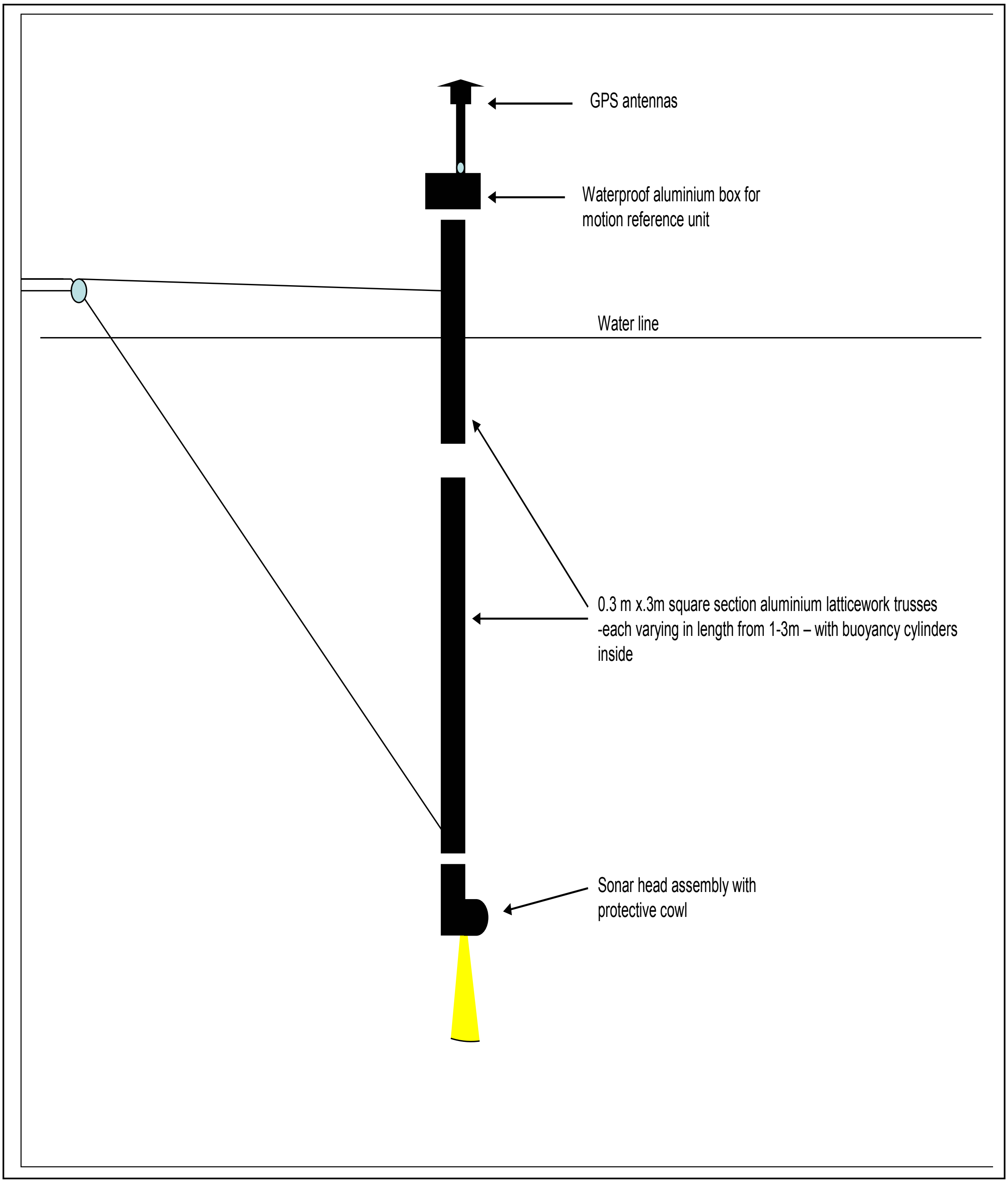
6.4.54. The dual head sonar configuration deployed during 2004/2005 did not significantly improve the resolution of the data collected when compared with a single head configuration. On analysis of the results, it became clear that the key to improving the resolution of the sonar footprint lay in reducing the distance between the sonar head and target.

6.4.55. To tackle this challenge, the project built and trialled in August 2006 a single Reson SeaBat 8125 was deployed using an Independant Sonar Head Attitude and Positioning System, known as ISHAP (See EH ref).

6.4.56. The ISHAP system consists of a vertical framework of modular aluminium space-frame trusses connected together to form a spar between 4.5m and 8.5m long (figure 19). A single Reson 8125 sonar head is located at the lower end; at the upper end is a waterproof compartment for the POS-MV motion reference unit (the IMU). On top of that is mounted a 2m long horizontal beam supporting the twin RTK antennas (Fig. 19). The integral design of this system reduces offset errors between components

6.4.57. Although the ISHAP system has the capability of being towed, manoeuvrability considerations in the sea conditions experienced over the site of the *Stirling Castle* dictated that it should be attached to the "A" frame of the vessel for the Year Two fieldwork. This arrangement allowed the whole array to be lowered as required in order to place the sonar head close to the wreck for better definition, or raised to cover more area of seabed and to avoid shallow obstructions.

Figure 19: ISHAP sonar platform.



Data post-processing and analysis

Sidescan data

6.4.58. Post Processing was carried out using Klein Sonar Pro Software and Cheseapeake Sonarweb Pro software. All results were logged on DVD Rom. SonarWeb Pro processing uses amplitude corrections to the amplitude time series based on the work of the USGS. In addition to reviewing the raw sidescan records, the following processing methods were incorporated:

- Import raw data from the bathymetric sidescan together with the full navigation information. The lines are imported at the maximum resolution or at a resolution to match the bathymetric model – 1m for the whole site with 10cm for specific areas of detail;
- Geometrical correction and amplitudes adjustment for offset angles from the transducers. Nadir is removed using bottom tracking algorithms with manual adjustment in areas of rapidly changing bathymetry;
- Line projection onto the relevant datum and overlapping data is combined to give a mosaic of the whole site. Overlap data points are averaged to give the mean amplitude values from all crossing tracks;
- Final output in the form of geo-referenced TIFF and geo-referenced JPEG files together with high resolution single pass sonar lines.

Bathymetric (interferometric) multibeam sonar

6.4.59. Post-processing was conducted by the University of St Andrews using Swathplus and Grid2000 software initially and then IVS Fledermaus Pro to clean the data and ignore erroneous soundings.

6.4.60. Results from the patch test values were applied in preliminary format in real-time but were fully applied in later processing. During this time, tidal corrections together with velocity corrections were applied.

6.4.61. The bathymetric sidescan data was first examined with IVS Fledermaus Pro using both point clouds and rendered surfaces, from which measurements were taken and features identified for subsequent attention.

Reson Multibeam sonar

6.4.62. By the end of 2006 fieldwork twelve processed multibeam datasets had been collated to inform comparative studies. These data sets included multibeam surveys carried out in July 2002 by the ADU, RASSE project fieldwork conducted in April 2005, April and August 2006, as well as opportunistic fieldwork conducted by ADUS in September 2005.

6.4.63. The datasets have been processed according to methodology outlined in section 6.4 so that they can be compared directly, both to enhance understanding of methodological approaches, and to inform knowledge of sediment moving in the vicinity of the *Stirling Castle*.

Dataset name	Covering	Date collected	Notes
Stirling Castle Wreck April 2005_adjusted_Aug06	Stirling Castle Wreck only	Apr-05	RASSE Year One dataset (dual head sonar)
Stirling Castle Wreck Sept 2005_adjusted_Aug06	Stirling Castle Wreck only	Sep-05	Data collected by ADUS
Stirling Castle Wreck March 2006_adjusted_Aug06	Stirling Castle Wreck only	Mar-06	
Stirling Castle Wreck July 2002_adjusted_Aug06	Stirling Castle Wreck only	Jul-02	Data gathered by ADU
Stirling Castle Wreck August 2006_ODN	Stirling Castle Wreck only	Aug-06	
Stirling Castle Area August 2006_ODN	Stirling Castle & full surrounding area	Aug-06	Elevations in ODN – data collected using RTK – elevations in other datasets adjusted to match for comparisions
Stirling Castle Area July 2002_adjusted_Aug06	Stirling Castle & full surrounding area	Jul-02	Data gathered by ADU
Stirling Castle Area April 2005 adjusted_Aug06	Stirling Castle & full surrounding area	Apr-05	
Bowsprit Wreck March 2006_adjusted_Aug06	Bowsprit wreck only	Mar-06	
Bowsprit Wreck Sept 2005_adjusted_Aug06	Bowsprit wreck only	Sep-05	
Bowsprit Wreck August 2006_ODN	Bowsprit wreck only	Aug-06	
Bowsprit Wreck April 2005_adjusted_Aug06	Bowsprit wreck only	Apr-05	

Table 6: Data sets processed by the project

6.4.64. The ADU 2002 dataset required complete re-processing, including the incorporation of calibration values and tidal data and the removal of erroneous soundings. Although images of the final product of original post processing for the 2002 data were available in the ADU archive, the processed datasets were not – only the original raw data files from the survey. In 2002 Reson Offshore Ltd. had processed the data, but they had only returned images of the final product.

6.4.65. Post processing of the results of the multibeam data from 2005 consisted of initial tidal corrections and cleaning being undertaken by Netsurvey Ltd., with analysis of the resulting data conducted in house using ArcGIS software. A full description of the methods used to analyse Year One data appears in the Year One report previously submitted to EH, but has been paraphrased here under the GIS heading below.

6.4.66. The post processing of Year Two results, data acquired opportunistically in September 2005, and the reprocessing of 2002 ADU multibeam data for the *Stirling Castle* and surrounding area was undertaken entirely in house.

6.4.67. The method employed for the RASSE surveys produced vast numbers of bathymetric points. To ensure that complete coverage was provided for the sites the survey lines often overlapped and therefore any one object was likely to be ensonified a number of times during different survey passes. Errors in the positioning system and/or motion reference unit will be carried through into positioning errors for the individual soundings. Even these small errors will lead to objects appearing ‘blurred’.

6.4.68. The methodology employed for the analysis was also improved significantly from Year One, making full use of Fledermaus software in preference to GIS. During 2006 project staff undertook training in the use of Fledermaus software in order that its superior functionality in terms of the handling and visualisation of 3D point data could be brought fully to bear on the results of the RASSE project.

6.4.69. The methodology employed for the analysis of the data during Year Two of the project appears under the heading Fledermaus below.

GIS (Year One data analysis methodology)

6.4.70. In the first instance tidally corrected and cleaned XYZ data processed from the April 2005 fieldwork on the *Stirling Castle* by Netsurvey Ltd., was imported into Terramodel (version 10.3) software onto different layers. Each XYZ file imported represented a survey line and each was placed on a different layer within Terramodel. Four line files from the April 2005 fieldwork survey were imported representing the port and starboard sonar head output from lines 151 and 152 (Unique Sequence Numbers).

6.4.71. Importing the XYZ files generated from the multibeam into Terramodel at this stage had the following advantage: It provided a means by which the vast numbers of bathymetric points within each file could be seen to cover the area of interest for specific analysis and seen to be of appropriate quality. Undertaking the same process using ArcGIS would have presented problems purely due to the large numbers of points involved.

6.4.72. Within Terramodel, an area (approximately 50m^2) immediately surrounding the *Stirling Castle* was chosen and this area then used to select all bathymetric points within it from the four imported files existing on each layer.

6.4.73. All selected April 2005 bathymetric points were then output as a single XYZ file in comma separated form (*.csv).

6.4.74. Moving to ArcMap 8.1 the single *.csv file was imported via the ‘Add Data’ dialogue and selecting the *.csv file. The point data was then displayed in a new workspace within the GIS using the ‘ADD XY Data’ tool.

6.4.75. Making use of the 3D Analyst within ArcMap a TIN (triangular irregular network) surface was then created using the events derived from the imported XYZ points, making sure that the height source was correctly set to the ‘elevation’ field of the *.csv file. The points were triangulated as mass points.

6.4.76. Within ArcMap a series of five points were chosen across the highest points of the *Stirling Castle* as represented by the TIN running from the bow to the stern along the centre line. The elevations of these five points were noted to three decimal places for the purposes of adjusting and matching the elevations of subsequent (un-tidally corrected) datasets for comparative purposes. It was assumed that these five points were of objects on the wreck site that were least likely to have moved over the last three years.

6.4.77. Returning to the Terramodel software, multibeam data from 2002 was imported in the same way as that for the April 2005 data described above. In this instance un-tidally corrected and raw XYZ data from 2002 survey lines 26, 27 and 28 (east-west passes) were imported, necessitating adjustment of the elevations.

6.4.78. The 50m2 area surrounding the *Stirling Castle* referred to above was then used to select all 2002 bathymetric points falling within it.

6.4.79. All selected July 2002 bathymetric points were then output as a single XYZ file in comma separated form (*.csv).

6.4.80. Using ArcMap the *.csv file was imported and, in the same way described above, used to create a TIN surface.

6.4.81. Still within GIS the same five locations across the highest part of the *Stirling Castle* referred to above were revisited utilising the July 2002 TIN and the elevations noted. The average difference in heights observed on the wreck at the points listed in the table below was used to adjust all elevations in the July 2002 *.csv file. The adjusted file was then exported to a new *.csv file in order that it could be directly compared to the April 2005 data.

6.4.82. Comparisons of elevations gathered for the five fixed locations given above are provided in table 4. In summary, the calculated average difference in elevation for the five fixed points was -0.129 m.

Dataset	Point	Easting	Northing	Elevation	Difference
2005	1	395831.16	5681399.51	-12.14	
2002	1	395831.15	5681399.5	-12.197	-0.057
2005	2	395834.22	5681399.63	-12.004	
2002	2	395834.24	5681399.62	-12.059	-0.055
2005	3	395837.17	5681399.36	-11.733	
2002	3	395837.17	5681399.35	-11.946	-0.213
2005	4	395840.39	5681398.5	-11.89	
2002	4	395840.38	5681398.5	-12.101	-0.211
2005	5	395843.26	5681397.38	-11.857	
2002	5	395843.26	5681397.38	-11.967	-0.11

Table 7: Differences in elevation for five fixed points from 2002-2005

6.4.83. Returning to ArcGIS the adjusted *csv file for the July 2002 dataset was used to create a revised TIN directly comparable with the 2005 data.

6.4.84. In order to facilitate further processing both the revised 2002 TIN and the 2005 TIN were converted within ArcGIS to raster surfaces using the “Tin to raster’ tool within ArcGIS’ 3D analyst.

6.4.85. Rasters of both July 2002 (adjusted) and April 2005 datasets were imported to ArcGIS Arcscene in order to begin visualising differences apparent between the two.

6.4.86. The raster datasets were also used with the raster calculator tool in ArcMap to produce maps that represented the difference between the two.

Fledermaus (Year Two data analysis methodology)

6.4.87. In Year Two the methodology for post processing multibeam data was brought in house and the methodology for the comparisons of all datasets (including earlier 2002 ADU data, RASSE project 2006 data and opportunistic data collected by ADUS) was improved to allow a better appreciation of the differences apparent.

6.4.88. Due to the continued need to compare datasets that are at variation with respect to the absolute vertical control (i.e. earlier datasets collected with DGPS and predicted tidal information as opposed to full RTK) the same basic premise was adopted as described in the Year One report.

6.4.89. This premise is that in order to directly compare each dataset collected without absolute vertical control, the assumption has been made that the central part of the wreck of the *Stirling Castle* has been constant in terms of elevation since July 2002. This assumption is supported by diver based observations, primarily by the Licensee Bob Peacock, but also by the Archaeological Diving Unit, over the period 2002 to 2006.

6.4.90. The assumption is necessary since all datasets earlier than August 2006 have been manually adjusted in the Z (elevation) so that the central part of the wreck matches in each. It is stipulated that since the central part of the wreck is constant and matched between each dataset, it becomes possible to compare the surrounding sediment regime for each dataset and comment on real changes over time in terms of elevation.

6.4.91. In any event, the changes apparent in the wider area surrounding the *Stirling Castle* are large enough to be clearly seen, even without the assumption made above and certainly larger than any real differences apparent in elevation on the central area of the wreck.

6.4.92. Clearly though, and as discussed further later, the level or scale to which these changes can be considered real is limited.

6.4.93. Significant changes in the sediment regime in terms of X and Y dimensions also apparent and these have obviously not required adjustments in elevation to see.

6.4.94. The methodology will be redundant when at some point in the future all datasets being compared for this purpose have full RTK positioning and the same absolute vertical control.

6.4.95. Initial stage post processing for the April 2005 RASSE multibeam datasets (i.e. incorporation of tidal information and removal of obvious fliers) had already been carried out during Year One. Opportunistic data for September 2005 was processed by ADUS and March and August 2006 RASSE data, being collected using RTK, did not require tidal corrections but did require editing to remove erroneous soundings and fliers etc.

6.4.96. The ADU 2002 data required complete reprocessing including the incorporation of recalculated patch test calibration values as well as recalculated tidal data. This was undertaken using Qynsy software on hire from Seatronics during the RASSE fieldwork in August 2006.

6.4.97. All datasets available were then brought into Feldermaus via the PFM (Pure File Magic) module and edited as point data. The August and March 2006 datasets required the building of a PFM file that consisted of all appropriate individual line files from the surveys.

6.4.98. The end result of the first round of processing in Fledermaus therefore, was a single points file (XYZ file) for each dataset. Details of all the datasets collated by the end of Year Two are supplied in table 6.

Dataset matching

6.4.99. Using the main Fledermaus module within the Fledermaus software suite, two datasets at a time were imported directly as xyz point files. Using the August 2006 (RTK) dataset as the primary (elevations for which were relative to ODN), offsets were then applied in the Z to all points in the secondary dataset in order that the central area of the wreck matched the elevations of the August 2006 data. This process was straightforward and made easier by being able to view two point clouds (one from each dataset) in 3D, and making use of the transparency features in the software; the secondary dataset could be made slightly transparent, aiding the process of matching the elevations in both datasets at the central area of the wreck.

6.4.100. Once figures were obtained for the adjustments necessary in all the datasets to match them with the August 2006 data, the raw points files for each were permanently adjusted using *Surfer* software. This was necessary, as the adjustments made in Fledermaus, as described above, did not physically alter the raw points files.

6.4.101. The adjustments necessary for each dataset were as follows:

Dataset	Adjustment in elevation to achieve best fit with Aug 2006 data at central part of wreck (metres)	Comments
Sep-05	-42.89	Large offset due to positive elevations in original data
Mar-06	-4.43	This data was actually collected with RTK, but an error in the basestation set up mean that the elevations collected were not correct to ODN. The basestation position was estimated & not derived accurately using raw obs etc., as it was in Aug 2006
Jul-02	-1.6	
Apr-05	-2	
Aug-06	No adjustment	Fixed RTK & elevations correct to ODN. Basestation properly setup & its position fixed in x,y &z to 2cm.

Table 8: Elevation adjustments made to datasets

6.4.102.The collection of adjusted points files for each dataset were then imported back into Fledermaus via the PFM module. The resulting PFM files were then taken into the DMagic module having first been gridded by the AvGrid module.

6.4.103.Within the Dmagic module the gridded datasets were used to create surfaces, and colour mapping was achieved at this stage also. Finally the datasets were exported from DMagic as .sd (data object) files ready to load straight back into the main Fledermaus module. Being in data object (.sd) form meant that the surface querying functionality became available.

Environmental comparisons

6.4.104.Using the surface difference function in Fledermaus, each dataset (or surface) could be subtracted from another to arrive at the 'difference maps' shown in figures 35-38.

6.4.105.For example the surface relating to July 2002 was subtracted from the August 2006 surface. By way of explanation, if there had been no change in the elevations for each surface in the intervening time period, the subtraction of one surface from another would produce zero elevations. If however there had been a net deposition of sediment in a certain area on the surface in the time between July 2002 and August 2006, the subtraction of the 2002 data from 2006 would result in positive elevations in that area on the difference map. Conversely any loss of sediment in an area in the period since 2002 would result in a negative elevation on the difference map.

6.4.106.For ease of interpretation, the colour scales accompanying each difference map have a obvious change in colours as they pass the zero mark; positive elevations (ie net depositions of sediment) appear as ranges of green, yellow and red, and negative elevations (net losses in sediment) appear as ranges of blue and purple.

6.4.107.Each surface query also produced figures in terms of the values of positive volume, negative volume and the net difference. The figures for each surface query are presented in table 12. The volume figures for the wider area datasets are however based on calculations made over different areas and are therefore not directly comparable. The volume figures for the wreck comparison are directly comparable since they were calculated over the same area.

6.4.108. Using this methodology the following comparisons have been made:

Area comparisons	Reason for comparing
Aug 2006 subtract July 2002	Longest time span available to see extent of changes apparent both in wider area and over the wreck
Aug 2006 subtract April 2005	Allows differences in wider area to be compared over shorter period of 9 months
April 2005 subtract July 2002	Allows some idea whether changes are linear through time (actually more change appears to occurs latterly – see Results)

Table 9: Area data set comparisons

Wreck comparisons	Reason for comparing
Mar 2006 subtract Apr 2005	Differences apparent in one year: Spring to Spring
Aug 2006 subtract Sep 2005	Differences apparent in one year: Autumn to Autumn
Aug 2006 subtract Mar 2006	Differences apparent over Summer 2006 (calmer weather)
Sep 2005 subtract Apr 2005	Differences apparent over Summer 2005 (calmer weather)
Mar 2006 subtract Sept 2005	Differences apparent over Winter 2005 -2006 (stormier weather)

Table 10: Wreck data set comparisons

Seafloor classification

6.4.109. A number of different seafloor classification algorithms currently exist for automatically classifying different seafloor conditions. These algorithms have been developed over the last 5 years in response to the routine use of sidescan sonar and multibeam sonar in wide area survey. The development has been largely stimulated by the deep ocean community (see for example Blondel, 1996) and the biological community in a drive to construct benthic habitat maps of the seafloor (see for example Cochrane and Lafferty, 2002; Brown et al. 2004).

6.4.110. The use of such automatic classification routines as not been actively applied to wide area archaeological prospecting or to site characterisation. One of the current leaders in the field of automated classification methodologies is Questar Tangent Corp., Canada. Using research work of Dr John Preston, this company has developed products for both the classification of single beam sonar, multibeam sonar and sidescan sonar. These different applications have been tested in a number of studies (see for example Preston et al. 2004). For this project the software was tested using data from the Klein 3000 sidescan sonar survey over the Stirling Castle site.

6.4.111. Sideview is an integrated software package that uses a statistical approach to classify the seafloor based on the backscatter (sidescan greyscale) images. The software attempts to first compensate an image from the sidescan sonar to exclude regions of poor data quality and where the sidescan acquisition parameters changed pulse length or frequency. The image is then divided into rectangular patches dependant on the overall image dimensions and the resolution of the survey. A set of features is then extracted from the backscatter intensities for each rectangle and multivariate statistics is applied in order to determine the principal components of the features over the entire data set. In principal component analysis the features represent linear combinations of raw features ordered by the degree of variance. The first three combinations of variance represent the most significant amount of variance from all the combinations and this information is stored along with the position and time identifiers to an individual patch. Following this the three components are analysed for clustering in a three dimensional space. A catalogue of where these plot in space and the boundaries to the clustering is analysed, stored and applied to the data set as a whole to produce a classed image. The technique has found considerable success in classification of seafloor with highly contrasting conditions such as between rock areas, sand and mud. This method was applied to the *Stirling Castle* site using various Klein 3000 sidescan sonar images.

Sedimentary studies

Grain size analysis:

6.4.112. In order to gain an understanding of the sediment grain size distribution around the *Stirling Castle* it was necessary to carry out a series of sediment grabs in a grid across the wreck site. 32 sediment grab sites were pre-selected to meet this objective and 31 sediment grabs were accomplished with good proximity to their targets. The sediments collected as a result of these sediment grabs were brought back to the laboratory at the University of St. Andrews for analysis using the Sedigraph Laser Particle Analyser. The samples were sieved in preparation for this procedure before each sample was run through the Sedigraph with three separate repeat runs performed per sample. The results of this analysis were provided and processed in Microsoft Excel with a graph of sediment grain size output for each sample together with a summary table of the sediment grain size results.

6.4.113. The summary table of sediment grain size information was then entered into the attribute table of each of the sediment grab sites within Arc GIS. The symbology of the grab locations was selected to highlight the various properties of sediment grain size, primarily the mean, the median and the mode. The result of the distribution of these attributes is discussed in the results section.

Sediment volume

6.4.114. In order to determine the overall sediment distribution across the wreck site it was necessary to take the sonar data collected by the RASSE team over the 2002-2006 period and import it into the GIS, allowing the creation of rasters showing the sediment distribution across the shipwreck site – this is reported and discussed in full detail in 6.4.1. The results of these calculations have also been compared to the sediment grain size information, and this comparison is discussed in the results section.

Wave data

6.4.115. Of significance to any study of marine sediment distribution are the weather patterns generated at a surface level, particularly storm activity. In order to incorporate this phenomenon into the study of sediment distribution data was taken from the CEFAS Wavenet program (Centre for Environment, Fisheries and Aquacultural Science), which provides wave data from the area around the *Stirling Castle*. Of particular interest to this study were changes in significant wave height across the period from 2002-2006, and any changes in the predominant wave direction.

6.4.116. The raw data procured from Wavenet was processed and graphed to show significant wave height on both a monthly and yearly scale, and by the winter and summer months to show seasonal variations. This allowed a direct comparison of wave height in 2002 relative to wave height in 2006, and showed the variation in wave height over a four-year period, the results of which are also discussed in the results section.

6.4.117. Furthermore the wave direction was plotted relative to the wave height using "Rose Diagrams" to best display the data. This data was plotted by month, and again allowed the comparison of winter and summer months between 2002 and 2006 to show changes in the wave direction.

3D Visualisation

Point Cloud Processing

6.4.118. The multibeam sonar data was edited in the form of point clouds. Point clouds are simply xyz co-ordinates that locate a sonar reflection in 3D space. It is possible to convert the point cloud data into surface data but this process adds new data to the scene as the surface fills in the spaces between the individual points producing an image that compromises the integrity of the original data set. Our method retains the integrity of the sonar scan data throughout the process.

6.4.119. The 3D Visualisation of the *Stirling Castle* site presents particular problems when compared to wrecks which are more upright from the sea bed. Many of the artefacts are partially buried in sand and can be difficult to visually identify for the viewer. The data sets showing details of the wreck are carefully combined in the editing process. Data that distracts from the main points of interest is rejected and removed from the final scene.

Depth Cueing

6.4.120. Point clouds have a number of characteristics that have to be considered when the wreck images are rendered. Each point is equal in size to every other point in the data set irrespective of its distance from the viewer. i.e.

Point A lying 5 metres from the viewer is perceived to be the same size as Point B which lies 25 metres from the viewer. This can cause perception difficulties when a large number of points (up to 2 million) are viewed in the same scene. ADUS use several proprietary software based depth cueing devices to alleviate this problem. These include the use of colour ramps oriented along the primary axes of the scene, opacity maps, occlusion objects and digital cinematography.

Digital Cinematography and High Definition (HD1080)

6.4.121. A key feature of displaying point cloud data is the fact that perception of the 3D form is enhanced by the use of digital cinematography. In particular, camera movement over the scene significantly improves the perception of depth and detail in the data. Therefore ADUS has exploited the use of 3D camera moves across the wreck data to help the viewer to visualise the scene more effectively. The relative movement of points over distance helps the viewer to discern which points are closer to the camera than others through the apparent speed of their movement ie. points further away move more slowly than those that are closer.

6.4.122. The final scenes are rendered as digital movies in High Definition format (HD 1080). This format shows much higher levels of detail than the standard PAL (normal TV) resolution of 720 x 576. The resulting moving images have less tendency to flicker during playback. At present, the UK has not adopted a standard for HD video. This has led to a delay in the mass production of HD playback devices. eg DVD players. The final movies are available on the project website.

6.4.123. However, a number of Apple computers can play back HD resolution video successfully and domestic DVD players will be available in the near future. Therefore ADUS has mastered the wreck video sequences in this new format whilst also producing a standard PAL version for use on standard DVD players and computers.

6.5. Survey results

Year One Survey (2005)

Multibeam

6.5.1. A bathymetric map generated from the 2002 Reson multibeam dataset of the site may be seen in figure 39. This has been produced using the methodology outlined in section 6.6 and following.

6.5.2. A bathymetric map generated from the 2005 Reson multibeam dataset may be seen in figure 40. This has been produced using the methodology outlined in 6.6 and following.

6.5.3. The results of the grain size analysis are given in table 11.

Sample Name	N	E	Mean	Median
Enh9	5682428	396216	534	372
Enh11	5681400	396134	527	315
Enh8	5681591	395773	335	303
Enh21	5681336	395859	1835	263
Enh20	5681358	395900	345	276
Enh19	5681423	395920	2421	353
Enh18	5681461	395890	3868	1794
Enh17	5681475	395811	780	494
Enh16	5681362	395781	742	477

Table 11 grainsize analysis from the *Stirling Castle* 2005

Sidescan

6.5.4. The sidescan sonar data was processed using both a standard visual inspection method and also using advanced computer pattern matching. The images from a number of passes with the sidescan sonar are shown in Figure 20. The Stirling Castle is clearly identified as an upstanding wreck site with strong reflectors from the surrounding sediment showing large scale sand waves with deep shadow relief. Within the wreck site various objects are readily identified such as the canons, stern post and anchor. Of particular note is also the accumulation of sediment behind some of the upstanding objects which act as mini-groynes. These groynes serve to slow the velocity of currents across the wreck thereby causing sediment to come out of suspension and be deposited. This feature is highlighted in figure 27.

Bathymetric sidescan results

6.5.5. The Results of the bathymetric sidescan are shown for the wide area survey in figure 24. The resolution of this instrument is such that it was only possible to record the basic information within the Stirling Castle site itself together with only the largest of the sand dunes and sand waves. A profile through these features is given in Figure 25. In this figure the location of the profile is shown in map view and the profile shown as a cross section. The cross section shows large sand dunes with amplitudes greater than 3m on piggy-backed by smaller (amplitude less than 1m) sand waves. Both the sand waves and sand dunes are predominantly asymmetric with stoss slopes oriented to the north east. This orientation indicates a dominant current flow to the north east.

Year Two surveys (2006)

Sediment studies- grain size and volume

6.5.6. The results of the sediment grain size distribution can be seen in Figure 30. The sediment grain size distribution is predominantly bi-modal for the mean, the median and the mode of the sedigraph analysis. In order to understand the bi-modal distribution of sediment grain size it is necessary to compare this data with the sediment volume data calculated from the sonar data between 2002 and 2006.

6.5.7. A raster calculation comparing the sediment volume across the site in 2006 relative to the sediment volume across the site in 2002 show a pattern of erosion to the west of and around the wreck site and deposition to the east of the wreck. This correlates with the sediment grain size results obtained where the bi-modal distribution is due to a division between areas of erosion and deposition. The coarser grained sediments are located in areas of erosion where the fines have been removed while the finer grained sediments are to be found in the areas of more gentle erosion and deposition to the east of the wreck (Figure 31).

6.5.8. More detailed results concerning the deposition and loss of sediments in and around the wreck – both on wider area and more local scales – can be found later.

Wave data:

6.5.9. A comparison of the years of 2002 and 2006 in terms of both significant wave height and wave direction for the area yielded significant results. The results for the winter months of 2002-2003 shows peak wave heights of under 3m (Figure 32). The results for the same period in 2005-2006 (Figure 33) show peak wave heights of ~4m. The results for the summer months of 2003 shows peak wave heights with an outlier peak of 3.5m and average maximum heights of 2.5m (Figure 34). The summer months of 2006 show peak wave height of under 4m (Figure 35). These data indicate an increase in average wave height of over 1m during both the winter and summer months between 2002 and 2006.

6.5.10. Interestingly if the wave roses showing wave direction plotted against wave height are compared for the winter and summer months of 2002-2003 and 2005-2006 they show that there has not been a change in wave height relative to the predominant wave direction. Predominant wave direction for both time periods was from the ENE and the SSW, indicating that it is not a change in wave direction that is contributing to the increased wave height.

Object pattern recognition

6.5.11. Several images of the Stirling castle were obtained, over a number of days survey in 2005. The conditions of acquisition of these sonar images varied between surveys. These conditions include the direction of the sonar and the sea floor conditions which lead to the covering of some parts of the ship with sediment or the un-covering of others. These conditions lead to variations between the images acquired, as can be seen in Figure 20.

6.5.12. Figure 21 shows the SIFT method applied to Images 6, 8 and 9 from Figure 20. The keypoints selected are plotted and their orientation shown. Figure 22 shows the results of matching between different images. After the keypoints are selected in each, the areas that show the largest similarities in terms of their keypoint properties are matched together.

6.5.13. To find out areas in the images that are most common with other images of the survey, common keypoints can be found between the image, for example, image 1 and all other images 2 to 9. The keypoints are then ranked in order of importance with additional weighting given to those keypoints with greater frequency of occurrence. Figure 23 shows the result of applying this method to all 9 images from Figure 21. On each image, the circles show the centres of the areas that showed the most similarity with other images of the survey (the location of keypoints with most occurrence).

Seafloor classification

6.5.14. An example image is shown in figure 28. Analysis of this image produced five distinct clusters of data. The corresponding classified cluster analysis for these 5 types is shown in Figure 28 and is plotted as an overlay to the original sidescan image in Figure 29. The cluster analysis was clearly capable of identifying the wreck site however the method also picked out abrupt changes in bathymetry that caused large shadows in the image due to the sandwaves and sand dunes to the east quarter of the image. A large problem with the classification of sidescan sonar images can result from the angle of observation of the seafloor and the presence of shadows behind significant changes in bathymetry.

Multibeam Sonar

6.5.15. A bathymetric map generated from the March 2006 Reson multibeam dataset of the site may be seen in figure 44.

6.5.16. A bathymetric map generated from the August 2006 Reson multibeam dataset of the wider area may be seen in figure 46.

Figure 20: Several images of the *Stirling Castle* site obtained at different orientations and depths

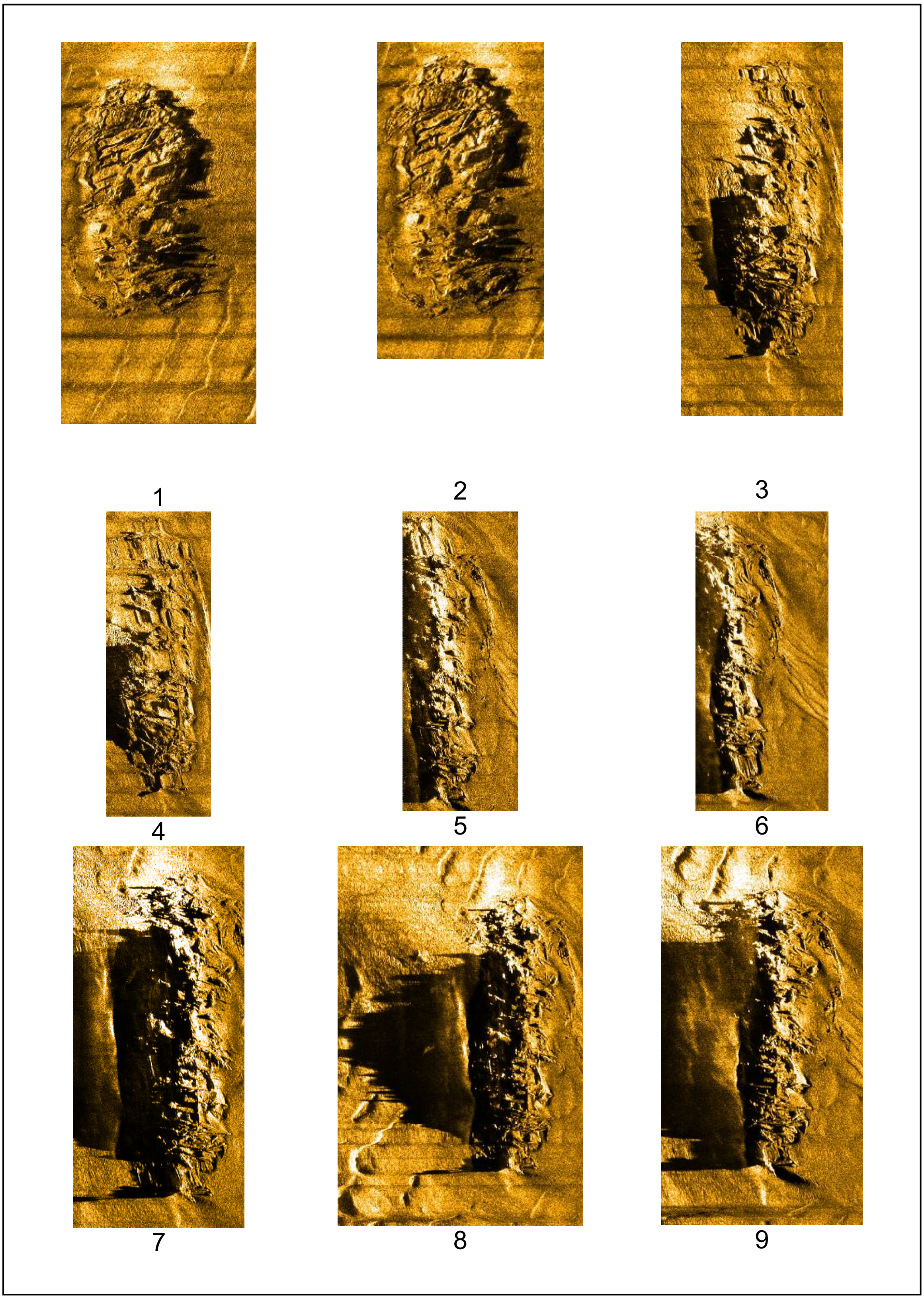
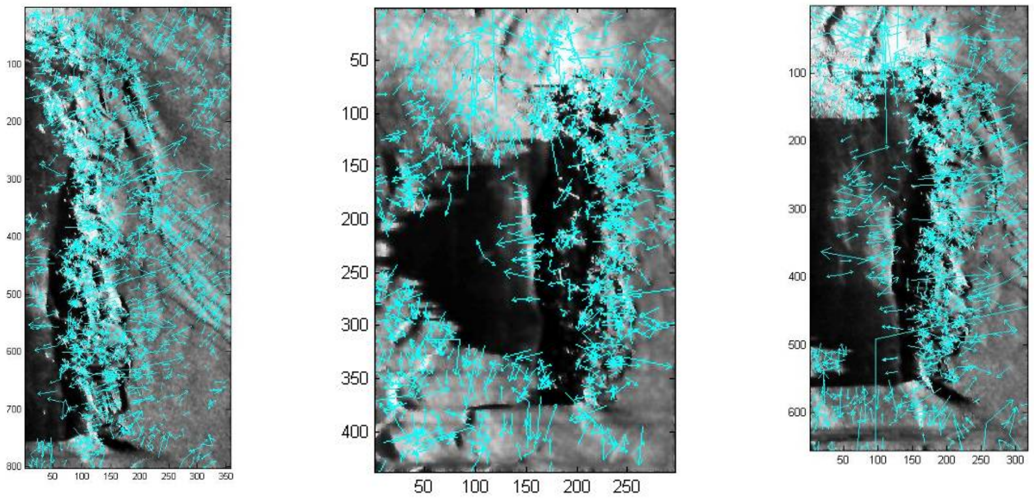
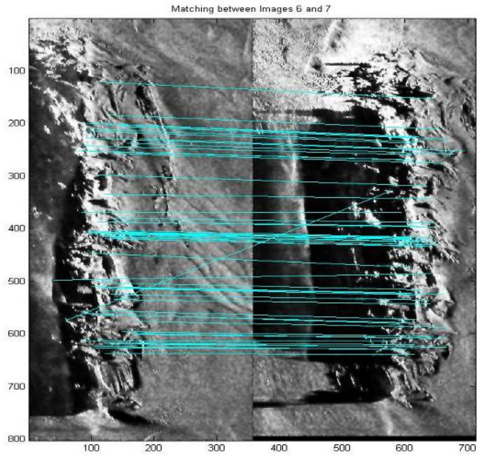
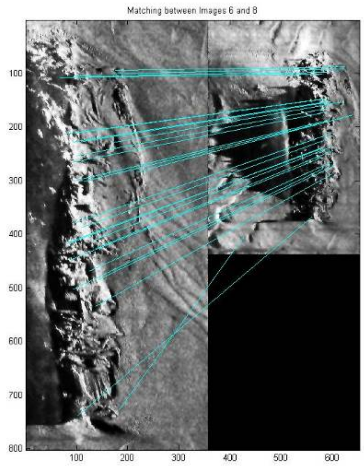


Figure 21: The SIFT keypoints shown on images 6,8, and 9 respectively

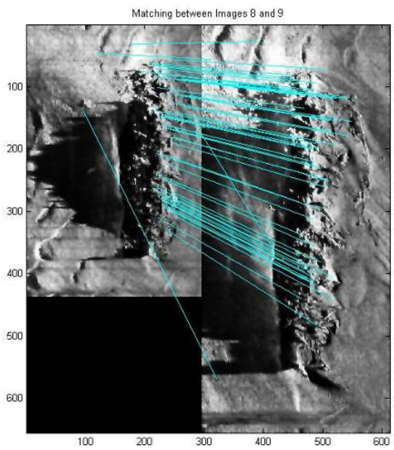




a



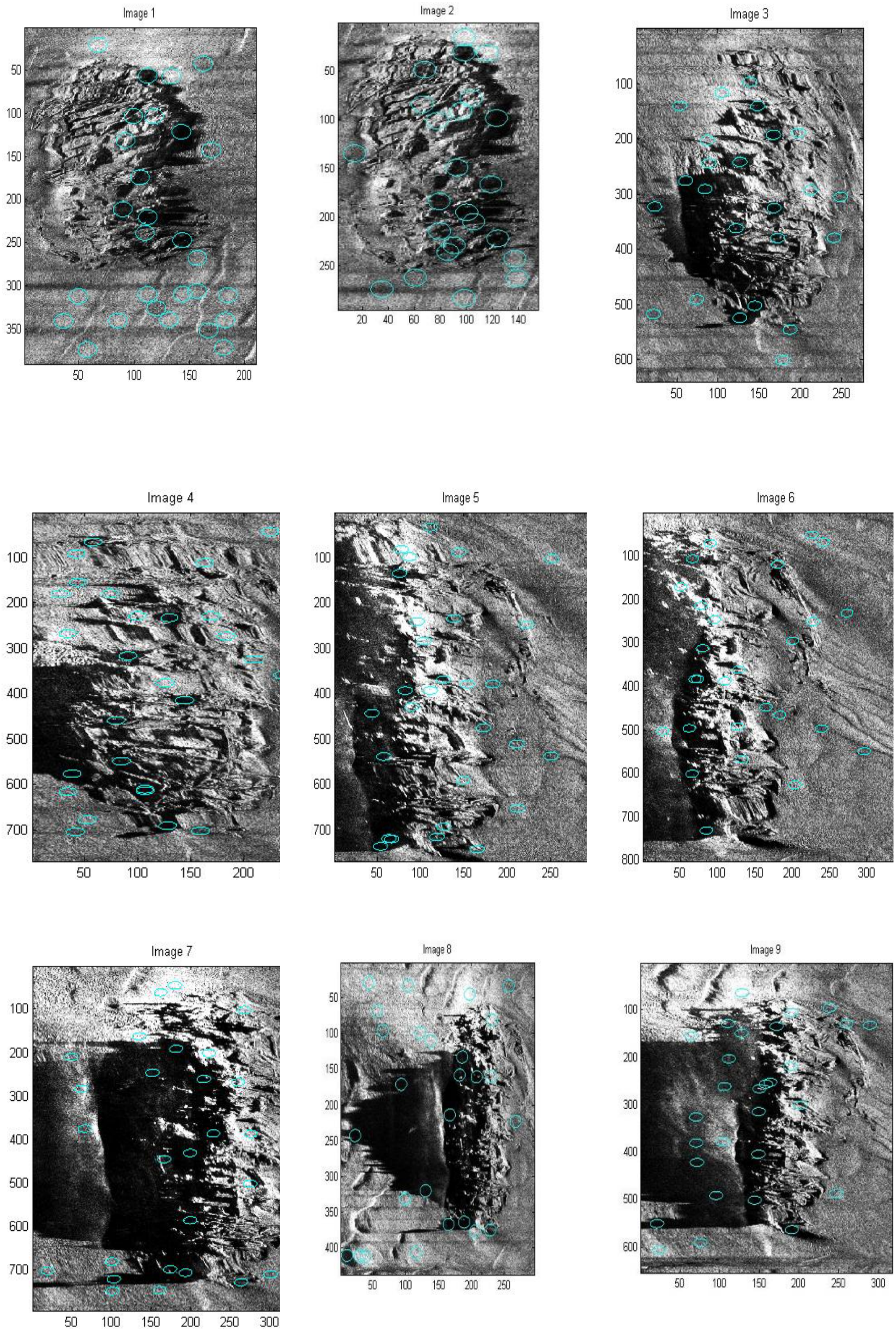
b



c

Figure 22: SIFT feature matching between (a) images 6 and 7, (b) images 6 and 9 and (c) images 8 and 9.

Figure 23: Areas in each image that have a high percentage of matching the other images in the database



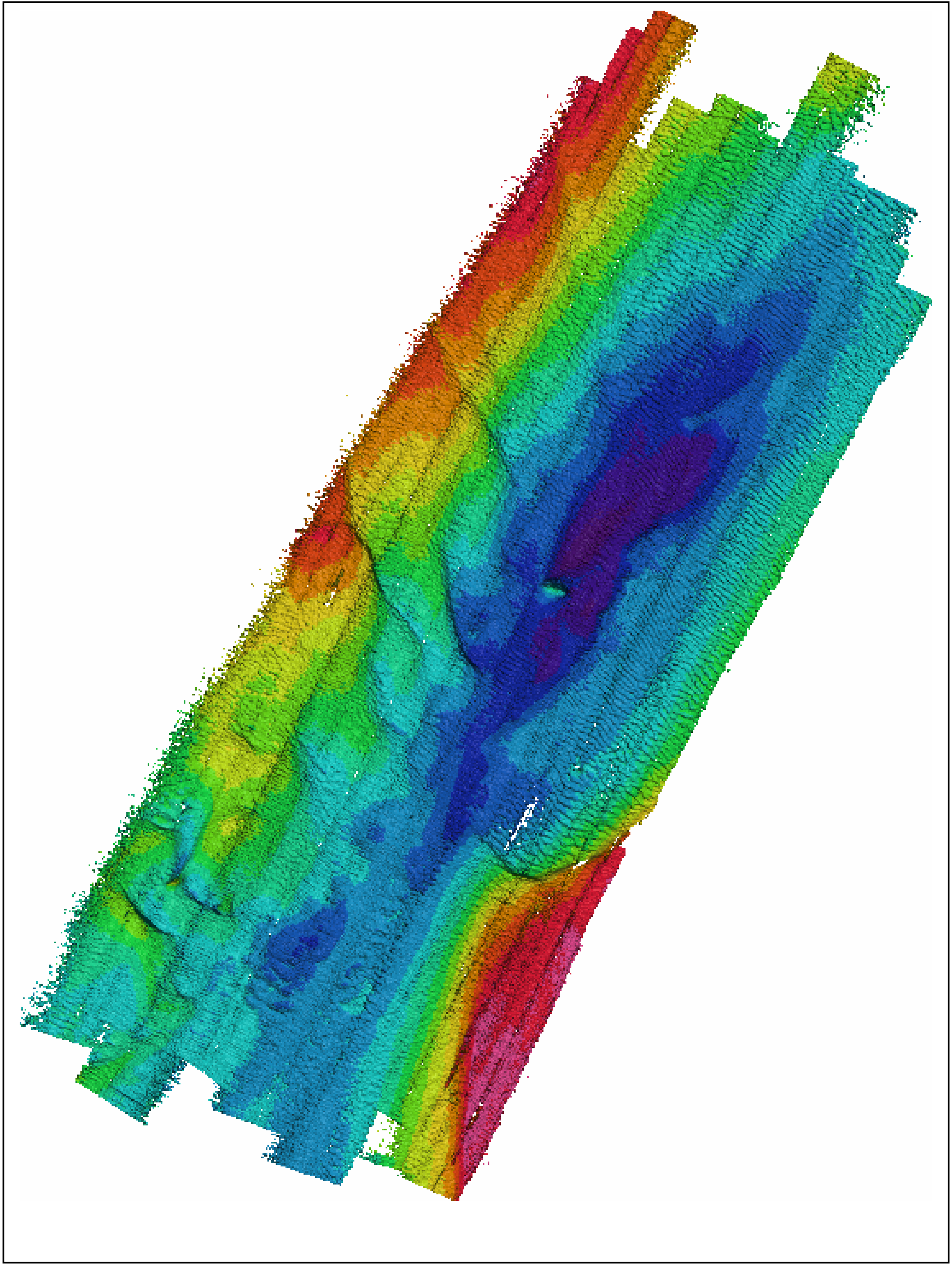


Figure 24: Bathymetric sidescan sonar image of *Stirling Castle wide area survey*

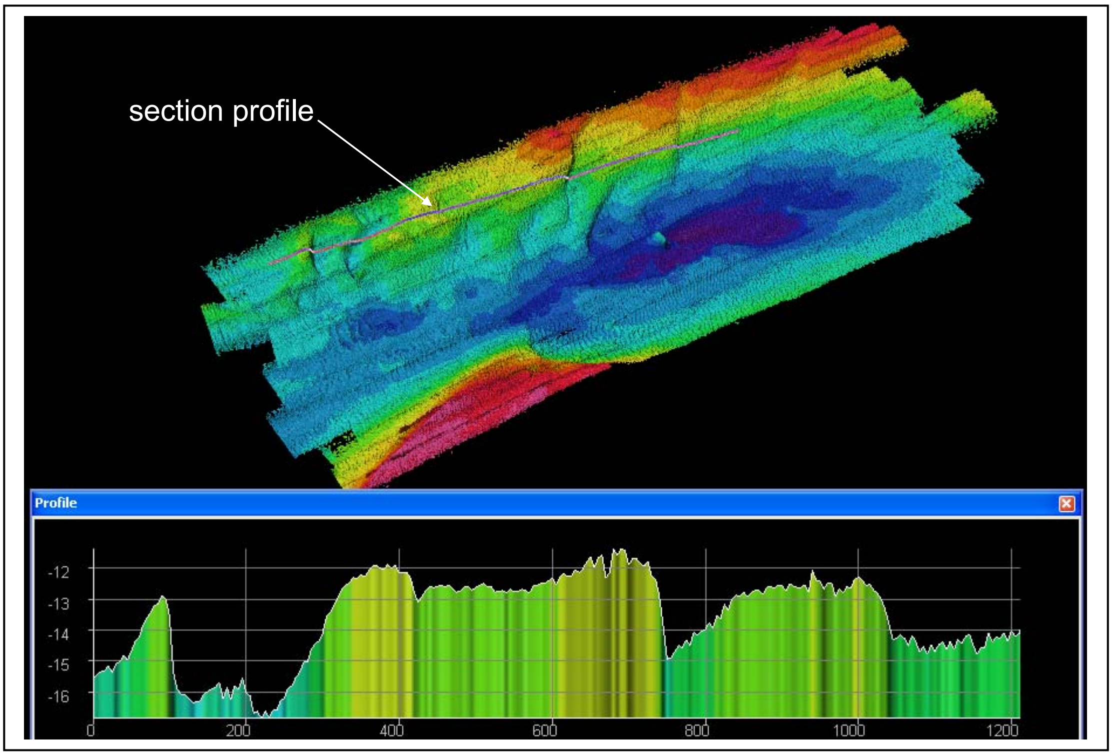


Figure 25: Bathymetric sidescan profile through sand waves and sand dunes to the northwest of the Stirling Castle site. Distances and depths are shown in metres.

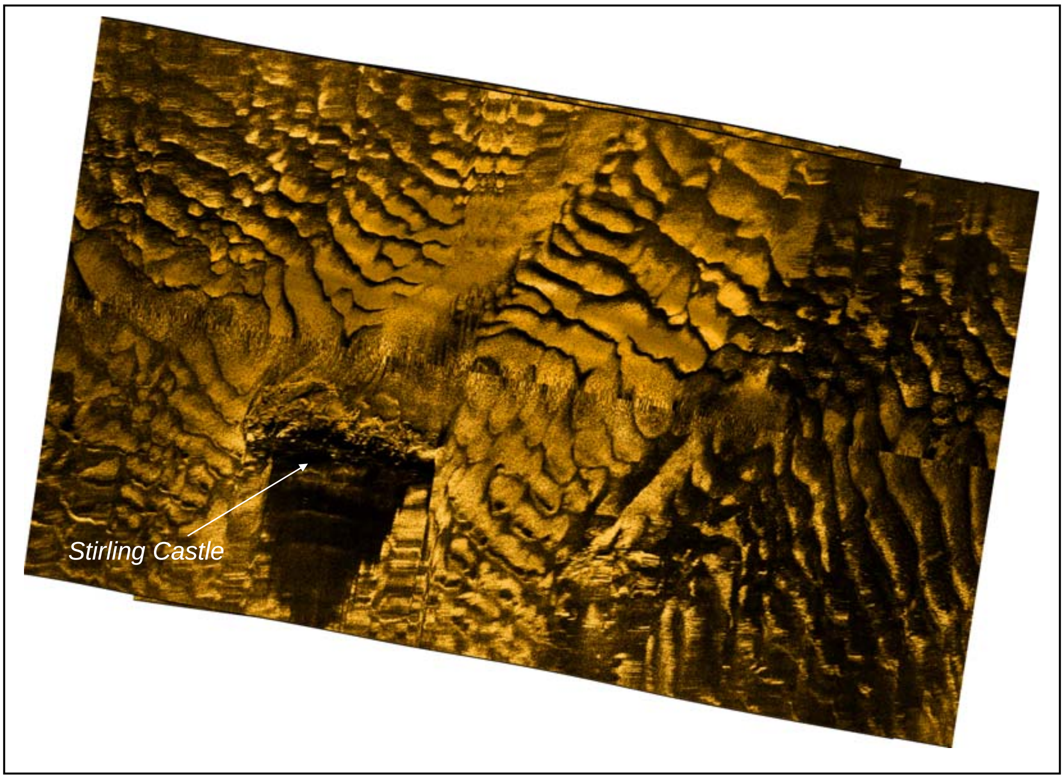


Figure 26: Sidescan sonar image with Klein 3000 of *Stirling Castle* site

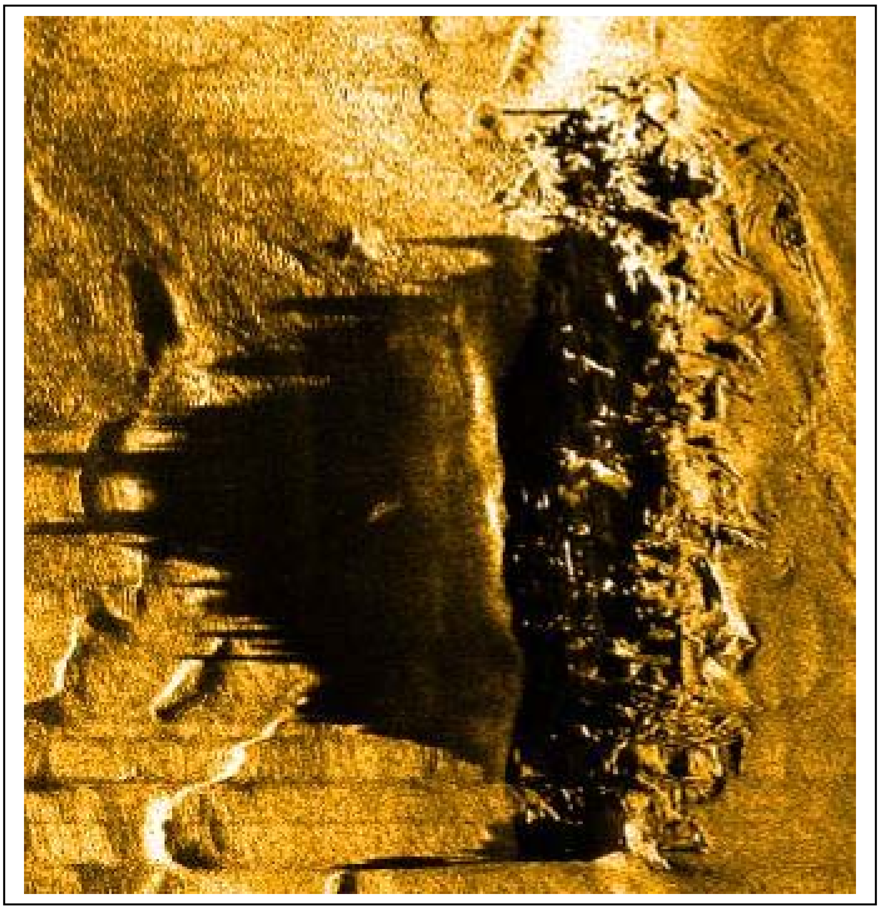


Figure 27: Sidescan sonar image with Klein 3000 of *Stirling Castle* site showing sediment accumulation between wreck debris

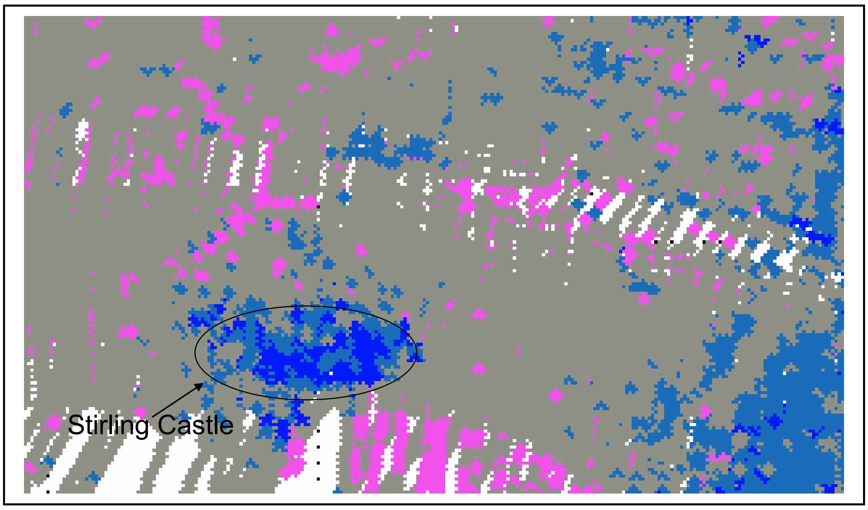


Figure 28: Classified image of *Stirling Castle* site. Note 5 classes of seafloor have been recognised

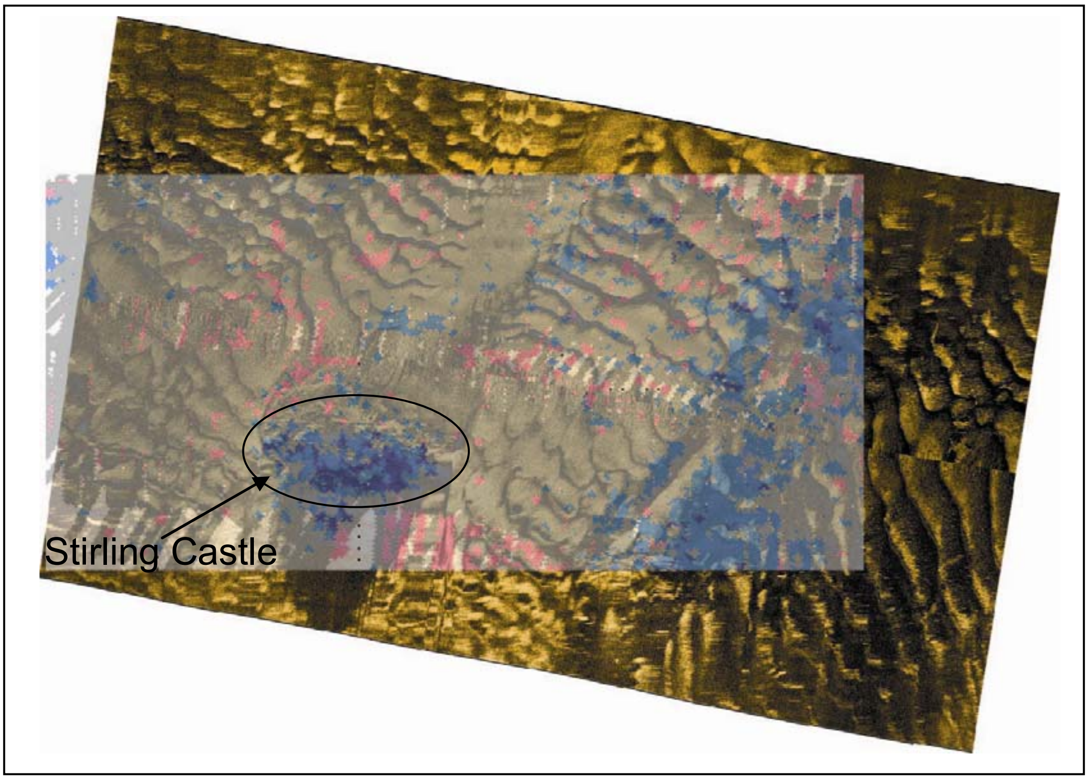


Figure 29: Classified image of *Stirling Castle* site, with overlay of the original Klein 3000 sidescan sonar image.

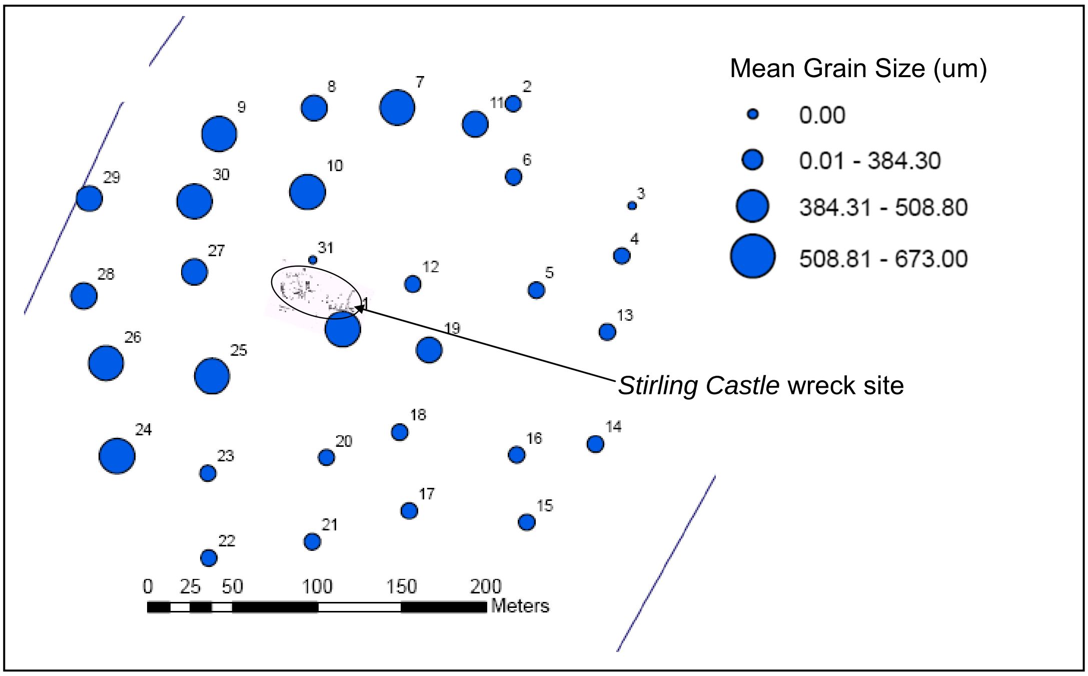


Figure 30: Mean sediment grain size distribution at *Stirling Castle site*

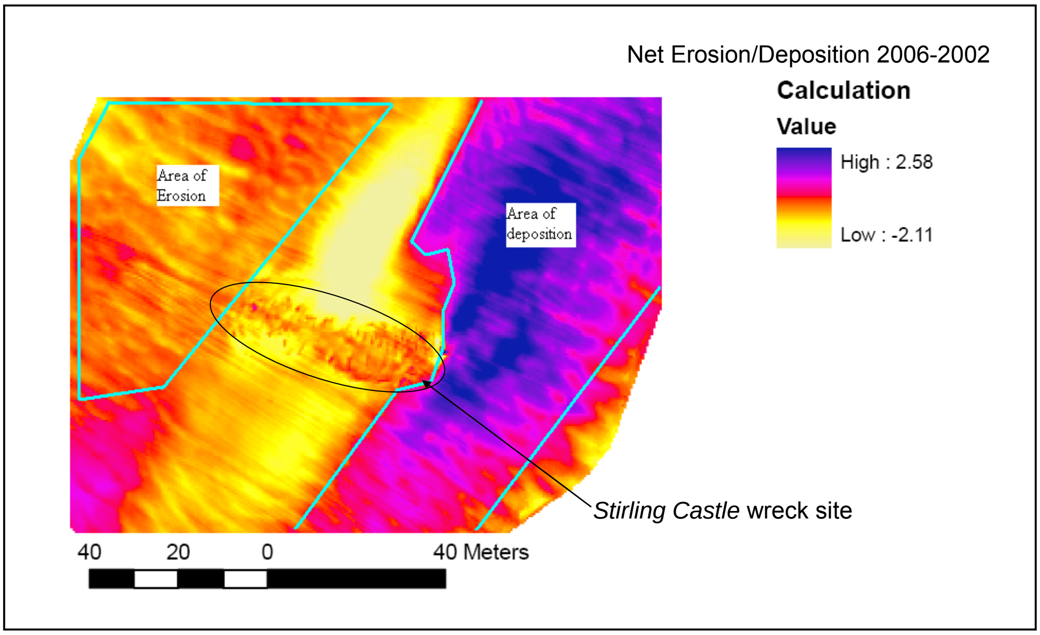


Figure 31: Net deposition and erosion around the *Stirling Castle site, 2006-2002*

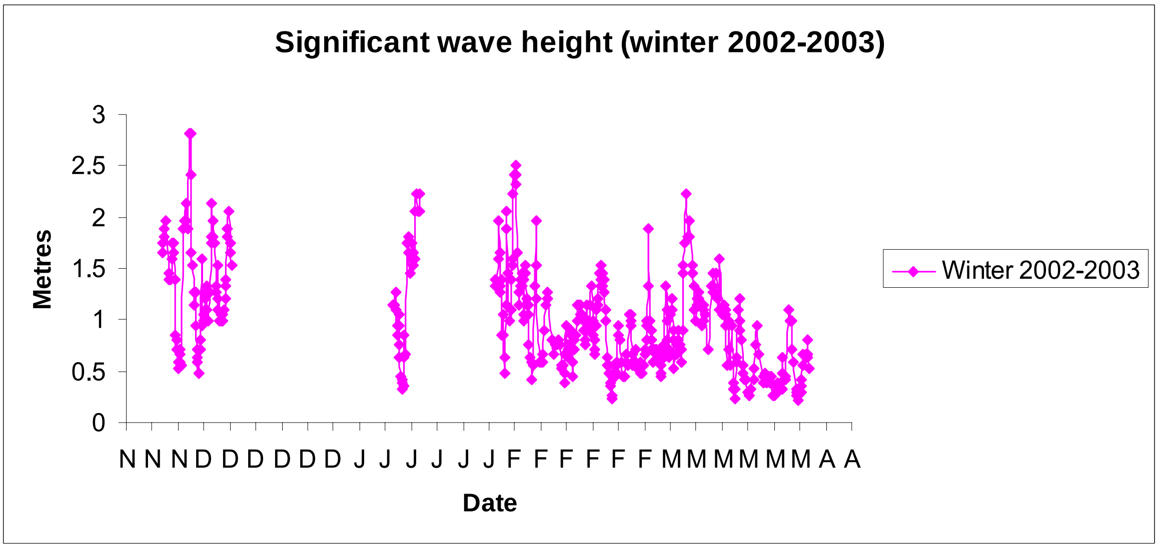


Figure 32: Significant wave height around *Stirling Castle site during the winter 2002-2003*

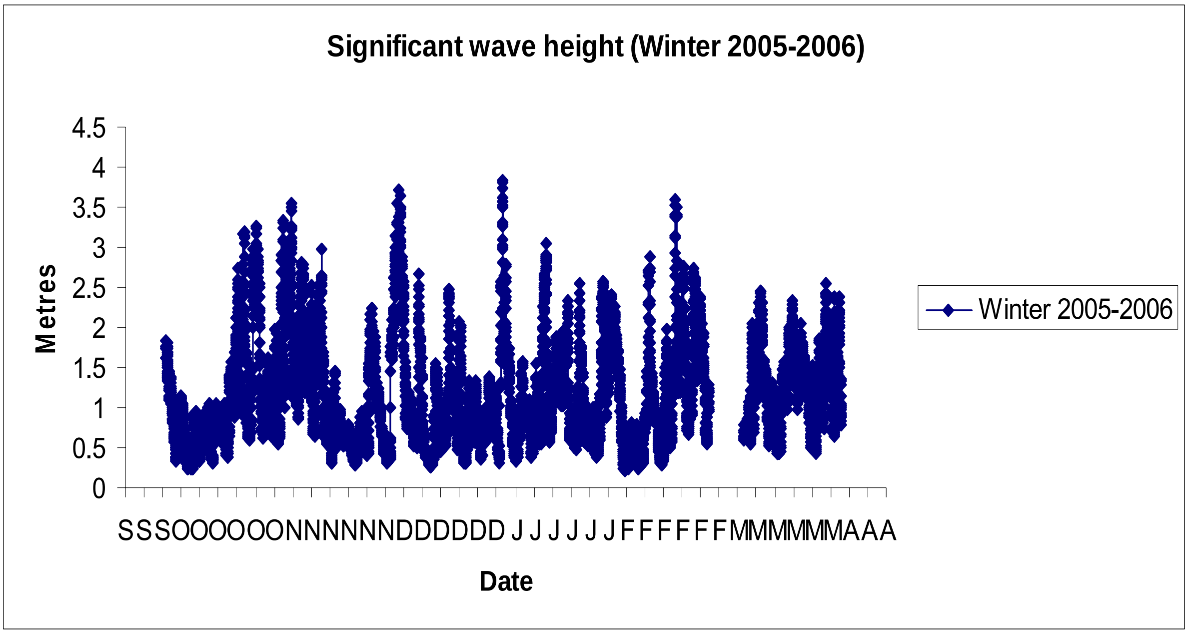


Figure 33: Significant wave height around *Stirling Castle* site, winter 2005-2006

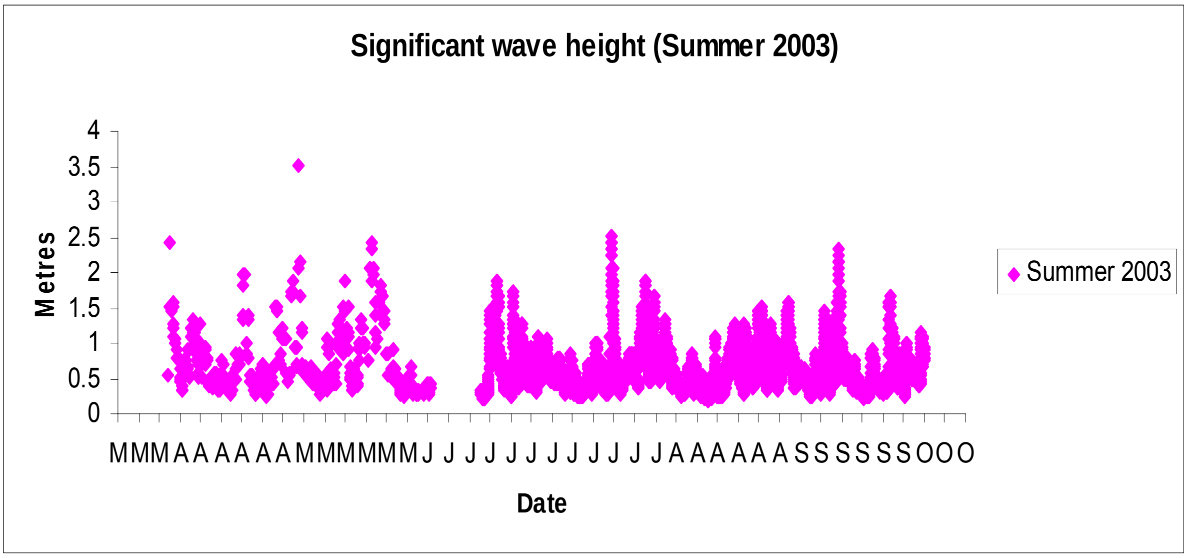


Figure 34: Significant wave height around *Stirling Castle* site, summer 2003

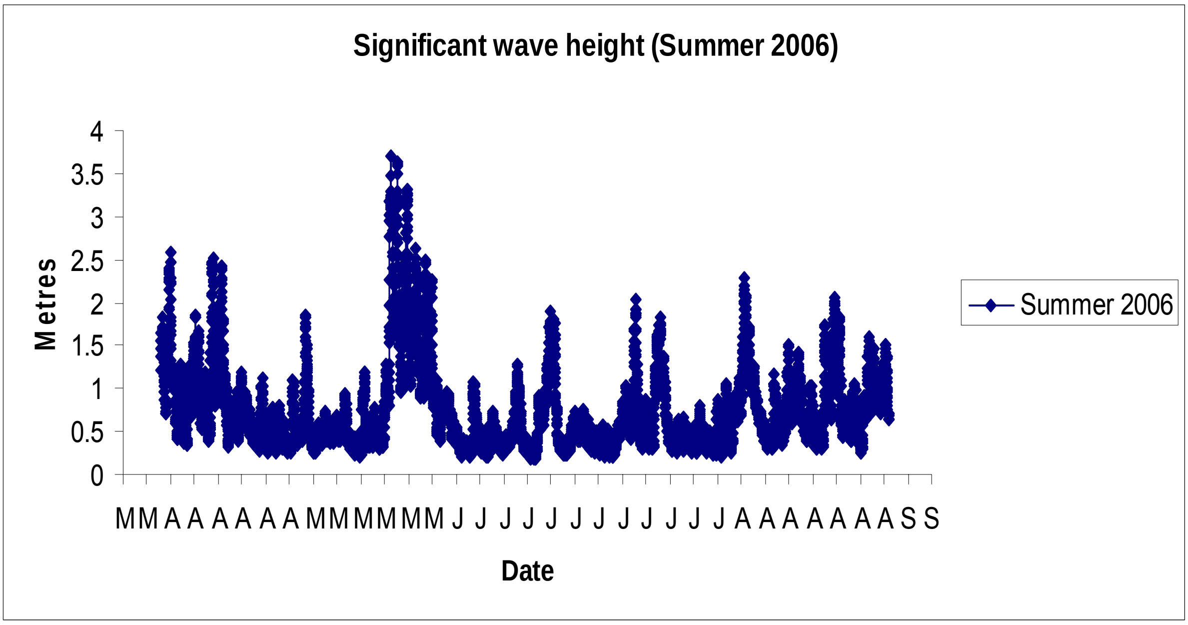


Figure 35: Significant wave height around *Stirling Castle* site, summer 2006

6.6. Results of comparative studies

6.6.1. Based on the assumption that the elevation of the points on the wreck remained constant between 2002-2006, it is possible to attribute changes in elevation of the surrounding seabed level to real effects, i.e. the movement of sediment.

Comparisons within the Stirling Castle site matrix

6.6.2. The datasets for the area immediately around the wreck are more easily compared with each other since the area being considered is the same for each comparison. Table 12 demonstrates the changes in sediment that have occurred within the same 12,000 m^2 sector of the Stirling Castle site matrix.

Wreck Datasets	Positive Volume (m^3)	Negative Volume (m^3)	Net Difference (m^3)	Net Area (m^2)	Diff/m^2	Comment	See Fig.
Aug2006 subtract Jul2002	9481	-803	8677	12768	0.68	Longest time span	
Sep2005 subtract Jul2002	7072	-1165	5907	12119	0.487		
Apr2005 subtract Jul2002	6677	-1531	5145	12867	0.34		
Aug2006 subtract Apr2005	4130	-564	3566				
Mar2006 subtract Apr2005	2018	-877	2018			One year: spring to spring	
Aug2006 subtract Mar2006	2561	-975	1585	12869	0.123	Summer 2006	
Sep2005 subtract Apr2005	1504	-1048	456	12179	0.037	Summer 2005	
Aug2006 subtract Sep2005	3326	-626	2699			One year: late summer to late summer	
Mar2006 subtract Sept2005	2325	-848	1476	12105	0.122	Winter 2005 – 2006	

Table 12: Sediment volume changes between different data sets

Wreck comparison: Aug2006 subtract Jul2002 datasets

6.6.3. Figure 46 represents the changes apparent in the sediment regime around the wreck between July 2002 and August 2006.

6.6.4. Over this four year period,.there is a net deposition of sediment over 12,768m^2 of seabed (with the wreck lying in the centre) of 8677m^3. It appears that most of the deposition has occurred immediately to the east (stern) of the wreck (indicated by the band of red colour running southwest to northeast on figure 48)

6.6.5. It is possible that sediment levels may have fluctuated up and down during the intervening period between surveys, although the net movement is corroborated by other comparisons the project has made.

6.6.6. Within this picture of net sediment deposition, notable areas of sediment loss are apparent in this comparison. For instance, a bank of sediment that formed a large spit in July 2002 running to the northeast directly from the north side of the wreck just forward of the midship area does not appear in the latter data set.

Wreck comparison: Aug2006 subtract Mar2006

6.6.7. Figure 49 represents the changes apparent in the sediment regime around the wreck during the summer of 2006.

6.6.8. The range of elevation changes within the area is 1.6m of sediment deposition to 1.2m of loss. The net deposition over the area is 1585m^3, with the majority of this deposition occurring in the area to the east of the wreck (as indicated by the yellows and reds in figure 49).

6.6.9. Loss of sediment has occurred (represented in blues in figure 49) from the stern of the wreck. It appears that this is due to scouring of sediments caused by upstanding wreck structure (i.e. the stern post). This pattern of sediment loss has also been observed over the summer of 2005 (see 6.6.11).

6.6.10. A net loss of sediment has occurred west of the bow of the wreck over the summer of 2006 (an area of blue colours and patches of purple on figure 49). It is likely that this represents the development of a trough between two of the sand dunes as they migrate north-eastwards.

Wreck comparison: Sep2005 subtract Apr2005

6.6.11. Figure 51 represents changes occurring in the sediment regime over the summer of 2005. In general, the degree of overall deposition during is much lower that the summer of 2006.

6.6.12. The range of elevation change within the area during this period is +1.2m to -1.3m and net deposition of sediment is 456m^3; a much lower figure than the summer of 2006 and with little or no deposition occurring to the east of the wreck. Most of deposition over the summer of 2005 occurs to the north east of the wreck – indicated by the yellows and reds in the figure.

6.6.13. The same pattern of sediment loss occurring immediately north-eastward from the stern over the summer of 2006 (See section 6.6.7). is also apparent over the summer of 2005.

6.6.14. A similar but larger area of sediment loss has emanated north-eastwards directly from the bow of the wreck in 2005 but this is not evident by the summer of 2006. This change may have been caused by close proximity of either a sand dune peak or trough and the effect this has on the tidal flow around the wreck.

6.6.15. For instance, it appears that the presence of a sand dune peak to the west of the bow coincides with the presence of the scour pattern seen emanating from the bow (as in Fig 51 comparison over summer 2005). Conversely the presence of a trough of a migrating sand dune to the west of the bow of the wreck coincides with the lack of any such scour running north from the bow.

Wider area comparisons

General comments

6.6.16. The datasets for the wider area around the wreck in July 2002, April 2005 and August 2006 reveal the movement of large (submerged) sand dunes to the west of the wreck, migrating northeast. The direction of movement is confirmed by the obvious lee and stoss sides of the dunes that can be seen in the cross section (Figure 39) .

6.6.17. The progression of the sand dunes can clearly be seen in Figures 38-41; in 2002 the nearest leading sand dune is at approximately 240m from the centre of the wreck to the southwest. By 2005 the distance to the nearest sand dune is approximately 165m and by 2006 only about 65m away.

6.6.18. The wider area volume figures cannot be compared directly with each other since they are calculated from different sized areas. However, by expressing net change as a difference per m2, a general trend of net positive deposition between July 2002 and August 2006 can be observed (see table 13).

Area Datasets compared	Positive Volume(m3)	Negative Volume (m3)	Net Difference (m3)	Net Area (m2)	Diff per m2	See Fig.
Aug2006 - Jul2002	307376	-52546	254830	329766	0.773	
Aug2006 - Apr2005	296216	-180854	115359	644645	0.179	
Apr2005 - Jul2002	383219	-120488	262731	467980	0.561	

Table 13: volume changes for wider area surveys (the areas covered by each dataset are different)

6.6.19. Although net deposition is apparent over the entire area, localized erosion of sediments is apparent around the eastern end of the wreck on the 2002 area dataset (showing up as a distinct purple zone on figure 40); net deposition of sediment is apparent by 2005 and is increasing by 2006.

Area comparison: August 2006 subtract July 2002 datasets

6.6.20. Figure 38 shows the differences in sediment height between July 2002 and August 2006,; the longest period of time available for comparison for this report. This long interval between sampling occasions requires a degree of care when postulating about events in between, since a far more complex sediment regime may have occurred in the intervening period.

6.6.21. The main features apparent are the differences highlighted by the movements of the large sand dunes to the west of the wreck, and the encroachment of what appears to be an even larger sand bank into the south-eastern corner of the surveyed area, which was not present in 2002.

6.6.22. Immediately to the west of the bow of the wreck is an area coloured blue that indicates a significant loss of sediment since 2002, a result of the migration of sand dunes to the northeast.

Area comparison: August 2006 subtract April 2005 datasets

6.6.23. Figure 41 shows the differences in sediment height between April 2005 and August2006 (16 months).

6.6.24. The range of elevation changes is in the order of 6.5m in sediment deposition to 4.5m loss, attributable to the movement of the large sand dunes. However, an overall net positive deposition of 11,5359m3 of is apparent.

6.6.25.There is a clear progression of large sand dunes to the west of the wreck, which run from the southwest to northeast in line with what appears to be the dominant tidal flow.

6.6.26. The distance between each peak and trough is approximately 120m, which indicates the least distance moved by the dune in this time frame.

6.7. Discussion

Methodology

RTK & standalone GPS – height control

6.7.1. The surveys before 2006 did not have the benefit of Real Time Kinematic (RTK) positioning and relied on publicly available differential correction of GPS positions which gave accuracies in excess of 1m. With RTK the positional errors were reduced to centimetric levels. Although RTK was used for the RASSE Project test site survey in Plymouth in 2005, The *Stirling Castle* site was too far offshore to use standard RTK radio links. The alternative of using mobile phone links was, at the time, problematic, and had been found to be unreliable. This was resolved for 2006 surveys when high quality data transmission eventually became viable with a cell phone system. This brought the *Stirling Castle* site into the range of RTK.

6.7.2. Possibility exists that datasets collected using DGPS & tidal predictions will produce elevations that are consistently different to the RTK dataset used for comparisons – ie tidal prediction doesn't match real height (RTK height) at certain times during tidal cycle.

Comparison ISHAPS vs earlier methodology

6.7.3. The ISHAPS deployment for the Reson 8125 multibeam survey head was only achieved on the last survey over the Stirling Castle during September, 2007. A number of passes were achieved over the target site and also across that of the Bow Sprit Wreck. The increased resolution of the ISHAPS arrangement when the sonar head is significantly closer to the target is illustrated in figure XX where a comparison is made between the ISHAPS data and that with the Reson 8125 acquire in 2005.

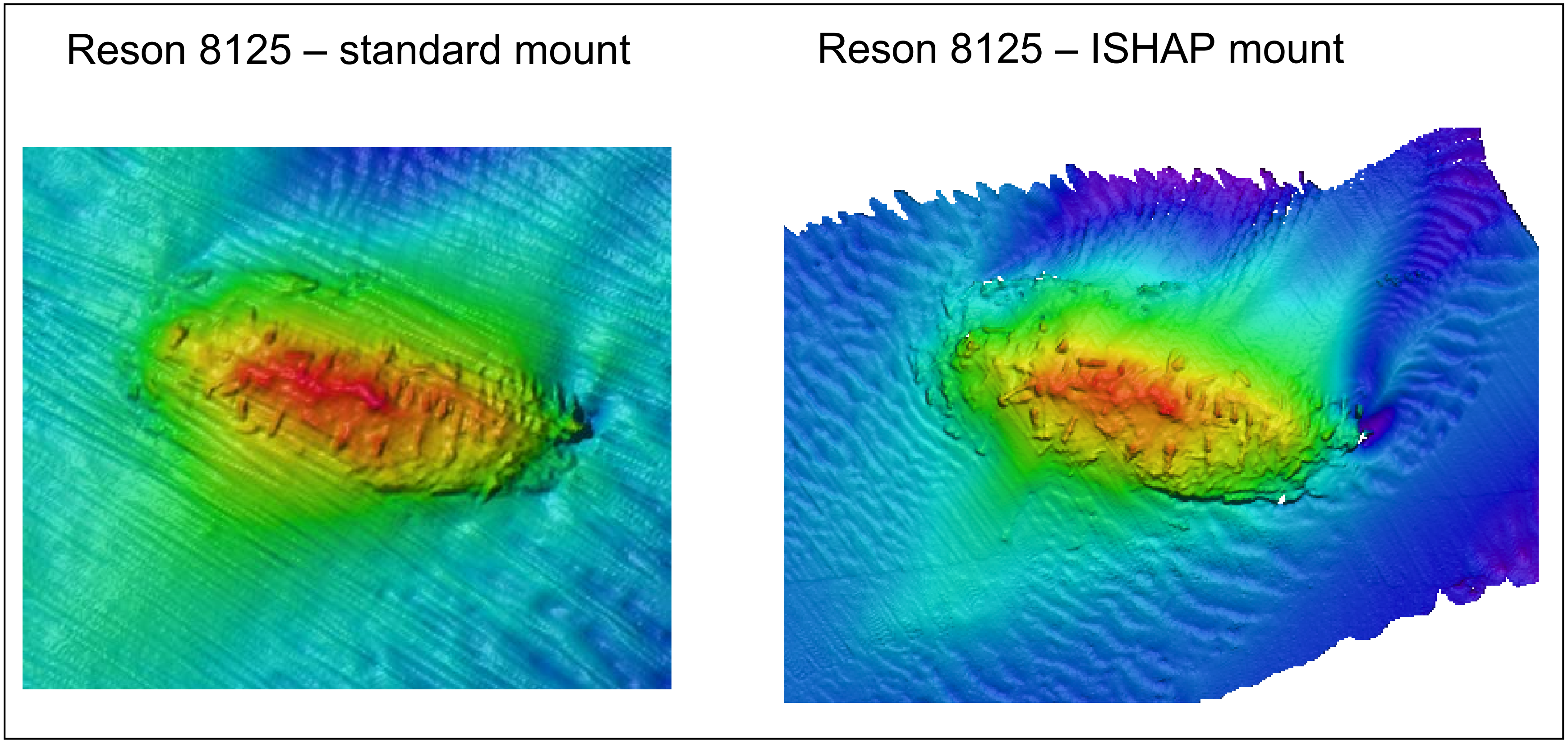


Figure 36: comparison of data between ISHAP survey platform for the Reson 8125 sonar and the standard over-the side mount.

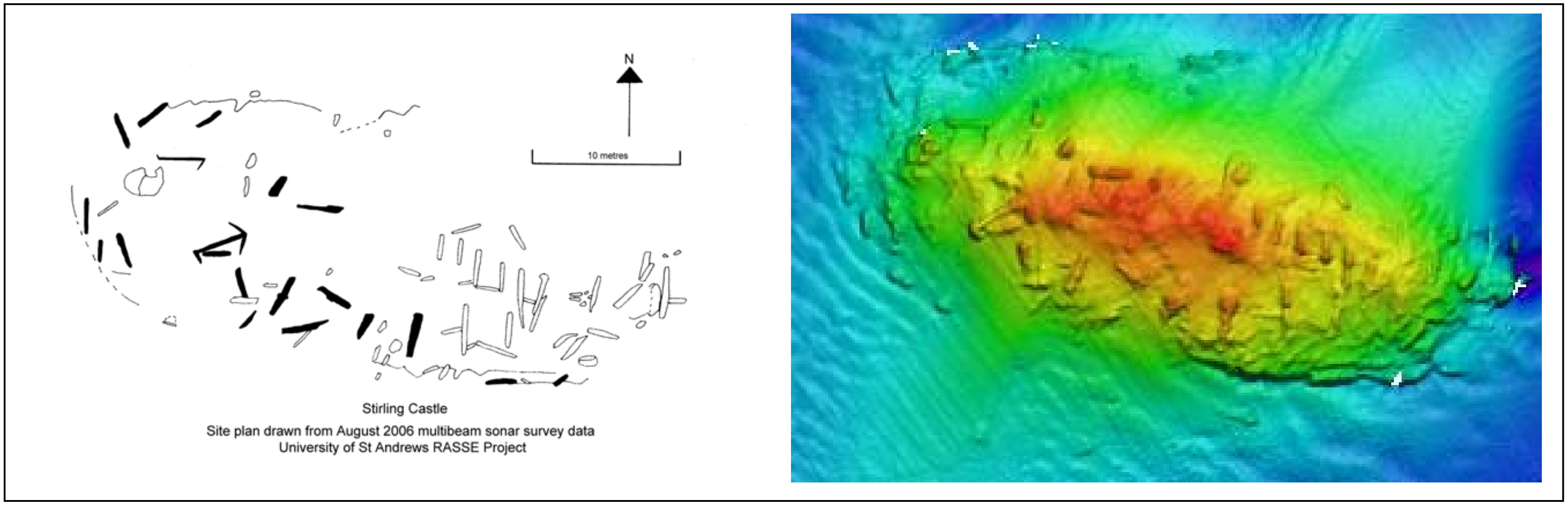


Figure 37: Site plan derived from Reson 8125 sonar survey using ISHAP platform.

Careful survey design

6.7.4. To ensure that complete coverage was provided for the sites the survey lines often overlapped and therefore any one object was likely to be ensonified a number of times during different survey passes. Errors in the positioning system and/or motion reference unit will be carried through into positioning errors for the individual soundings. Even these small errors will lead to objects appearing 'blurred'. Therefore single passes at slow speed were used to collect maximum detail rather than combining the soundings from multiple passes to increase data density.

New Automated Classification Algorithms

6.7.5. Given that automated classification has identified the *Stirling Castle* site, but that it is interpreting clustering of the sand waves in the same way, it is felt that the systems used are not yet effective at routinely identifying clusters of artefacts on the seabed.

6.7.6. This type of automatic classification may still prove useful in the future for mapping areas of the seafloor where unknown archaeological sites exist and for monitoring areas where known archaeological sites are of significance .It is likely that the best results will be obtained when these techniques are applied to backscatter data gathered from the new generation of high resolution multibeam, most of which (e.g.,Reson and Simrad) are currently capable of recording and exporting the necessary information.

Multibeam sonar as a tool for wreck site management

6.7.7. When properly configured, multibeam sonar survey can quickly map a site at a relatively rapid rate, producing site plans, and profiles, and providing bathymetric data suitable for setting a site in its environmental context. When very-high definition surveys are repeated in 'timelapse' fashion, this technique has proven to be effective for monitoring and quantifying sediment level changes on and around sites.

6.7.8. In addition, multibeam sonar can be effective at rapidly detecting structural changes within a site. This capability is best illustrated by the mapping of changes to a more recent wreck site, located 580m to the southwest of the *Stirling Castle*. This site has become known as the "Bow Sprit Wreck" was first discovered during the RASSE sonar survey around the *Stirling Castle* in April 2005. The resolution of the data was appropriate for investigation of a survey of an area of seabed but it is not to the standard appropriate for a specific wreck survey. Nevertheless, the quality was sufficient to identify what appears to be the wreck of a mid 19th century wooden merchantman with its stern mostly buried (Figure 56). The bow was well above the seabed level with a bow sprit projecting 7m from the stem. It was also possible to identify the dolphin striker under the bowsprit, a horizontal anchor winch, hatch comings and other numerous other items that had collapsed onto the fore deck.

6.7.9. In the following September, ADUS (University of St Andrews) were surveying a more modern wreck in the area for the Maritime and Coastguard Agency. They took time to do two quick passes over the wreck, totalling less than 300 seconds. This revealed that significant changes to the wreck had taken place (Figure 56). The distal end of the bowsprit was found to be resting on the seabed with the inboard end higher than the pivoting point adjacent to the top of the stem post. There was also a significant change to the sedimentation around the wreck causing the whole length of the wreck to be exposed. The two visits 12 weeks apart, which had a total survey time of less than 15 minutes, captured dramatic changes to the remains of a near complete wooden shipwreck.

Exploiting multibeam sonar to produce baseline data for a site plan

6.7.10. As stated in Appendix 2 there a numerous factors that influence the quality of the multibeam sonar survey data. Many lessons have been learnt as is evident from the quality of survey results: the September 2006 data has considerably improved resolution than the first (2002) data set with the data from each year showing noticeably better quality than the preceding data. The exception to this was in April 2006 which was well below expectations because of poor weather conditions.

6.7.11. The project has also investigated how to turn multi beam sonar data into an archaeological site plan (i.e., one which seeks to identify, record and interpret features on the seabed). Sonar XYZ data produced from one multibeam pass (number 009 on 9th August 2006 which took <180 seconds to complete) was imported into Trimble Terramodel Visualiser software and a high-contrast monochrome plan view was then printed out. The edges of obvious features and shadows were then inked in, with additional detail being identified by moving the three dimensional point cloud image of the site in Terramodel to allow different perspectives and views of individual problematic features. This was supplemented by using the same technique on point clouds produced from some of the other 20 data sets from other passes over the wreck on that day. The resultant site plan together with the original multibeam image is shown in Figure 37.

6.7.12. Comparisons have been made between the RASSE site plan (fig ??) and a plan compiled by Wessex Archaeology and provided to the RASSE project in November 2006. It is assumed that the WA site plan involved some sketches and controlled surveys of defined areas by diving archaeologists. The RASSE site plan (figure 37) denotes artefacts in association over a wider area; the WA site plan covers less area but shows detail not detectable in the sonar data. It is possible that these items were covered at the time of the sonar survey but it is more likely that they have simply not been identified by the sonar record.

6.7.13. Therefore, diving and geophysical methodologies have succeeded in producing detailed plans but neither approach can claim to have achieved a total record and it is unlikely that this would change given a longer time spent on site. Therefore, it is reasonable to conclude that the diver and geophysical survey techniques should be seen as being complimentary and not competing.

6.7.14. Both diving and sonar surveying operations on the site are limited generally to operation in winds of Force 4 or less. However, diving operations are restricted to two short tidal windows (c. 3 hours in every 24 hours) And by a lack of underwater visibility. Based on experience by staff from the University of St Andrews, and by discussion with local divers suggests, it is reasonable to suggest that there would be sufficient visibility to undertake archaeological work on a maximum of 28 days per annum. In an average year, this figure might be just 14 days.

6.7.15. Fortunately the licensee and his colleagues from Seadive are able to visit at short notice to take advantage of good diving conditions. This is an advantage in the long term monitoring of this site. However, it is apparent that even with help from professional teams, diving fieldwork on a site such as the *Stirling Castle* cannot keep up with the pace of environmental change. Simply put, the site has often altered beyond recognition before a site plan has been completed.

6.7.16. The hostile environment of the Goodwin Sands also impacts sonar surveys, and it is not always easy to undertake such work to the required standard, as demonstrated by the aborted survey in March 2006. By comparison sonar operations are not normally restricted by the diurnal tidal cycle, and never by underwater visibility, and so can, theoretically, be undertaken for 24 hours in a day.

6.7.17. Nevertheless, on balance sonar surveys can take place on the Goodwin Sands more frequently than diving operations. These factors, together with the relative speed of the sonar survey process and the patent slowness of diver surveys, leads us to suggest that sonar survey is a more effective technique for initiating a basic site plan on a site such as the *Stirling Castle.*

Use of Bathymetric Sidescan

6.7.18. Bathymetric sidescan sonar has not proved to be as effective a tool for detailed site investigation as multibeam sonar. This is mainly because the fidelity of the bathymetric sidescan is not of the same resolution as that for the multibeam sonar. However, since completing the project surveys, SEA Ltd. have designed and produced a new generation of bathymetric sidescan sonar instruments with increased resolution. These sonars are capable of producing 15-20 pings per second with a swath width of 75m in 10m or less of water and up to 40 pints per second in water of 5-10m. With appropriate positioning systems it is therefore recommended that for rapid wide area survey these are tested in future investigations.

Use of Klein 3000 Sidescan Sonar

6.7.19. The information gathered during this project has indicated a number of lessons to be learned from the use of the sidescan sonar. The Klein 3000 is a high resolution (500kHz) digital sonar that is easily deployed from a range of survey vessels. Like most sidescan sonar available today it does not typically come with an acoustic beacon and thus knowing exactly where the sonar is in the water relies on manual calculations based on the length of cable deployed, the speed of survey, the currents and the depressors added to the sonar. The errors that are cumulated through these aspects mean that any the position of any object recognised in the final data cannot be known with a high degree of spatial accuracy. However, the fidelity or resolution of the system means that it is possible to image small objects and to know their relative position within a final data set with high precision.

6.7.20. The Klein 3000 has a potential acoustic footprint at 25m range (25usec pulse) of 10cm along track and 5cm across track. Within this at a survey speed of 2kts the potential object detection is similar to the 8125 multibeam. This was confirmed with the analysis of most of the targets that were identified from both the Plymouth Test Site and also on the *Stirling Castle* site. However, the manner in which targets were imaged with the sidescan is very different to that of the multibeam. This is shown by the signatures of certain targets at the Plymouth Test Site. For example, the upstanding bike showed up in the shadow profile with more understandable signature than its reflected surface image. The wooden trunk showed reflections from the two faces that were perpendicular to the sonar with again the shadow showing most diagnostic signature of the open lid. The small upstanding objects such as the statue and urn were most readily identified by the length of their shadows rather than the acoustic footprint of the objects themselves. On the *Stirling Castle*, a number of the upstanding guns are illuminated by their significant shadows as is the sediment accumulation behind some of the upstanding ribs. It is therefore imperative that the highest shadow definition is obtained with a sidescan sonar, that is that a low grazing angle is achieved with the fish with respect to the seafloor.

6.7.21. For future surveying, it is likely that higher frequency sonar could be of additional use on archaeological sites. It is imperative that the sonar is deployed to be flown at minimum height from the seafloor so that the shadows are maximised as these form a very important part of the signal for object identification. It is recommended that the sonar fish is deployed with acoustic beacon so that its position in the water is better known and thus the overall final accuracy of positioning targets is increased. As the spatial resolution is defined by the number of pings or hits on a target, this may also be improved by using a sidescan system that has the capability of multiple channel operation. The current commercial available systems include the Klein 5000 and the Edgetech 4200-FS. A new generation of sidescan that operate a synthetic aperture mode have recently become available and likely will also increase the potential resolution over targets. It is recommended that these be tested as they become commercially available.

Environmental discussion

6.7.22 Understanding the environmental context of a wreck site is an important step in assessing the likely *quality* of surviving remains. When coupled with the ability to assess change in the environment over time, a greater understanding of likely current and future *preservation* becomes possible.

6.7.22. In respect of the *Stirling Castle,* the ability to assess change, and even to predict likely exposure or burial in the future is an important consideration in the development of a coherent wreck management strategy.

Changes to the *Stirling Castle* site over 20 years

6.7.23. Between 2002-2006, there is a general trend of net positive deposition, with the deposition mostly occurring in the area to the east (stern) of the wreck. The smallest net deposition is seen in the six months between April 2005 and September 2005 ($456m^3$)

6.7.24. Although the overall trend has been for a net deposition when comparing the datasets, there are areas of sediment loss apparent (indicated as areas of blues and purples). Nevertheless, at no time between 2002-6 has a net loss of sediment been observed.

6.7.25. Analysis of sediment grain size and historic weather pattern data corroborates this process of sediment movement, and also suggests that different portions of the sediment distribution have moved in a preferential manner. The high resolution multibeam survey was not capable of resolving these differences however full use of backscatter information may, in the future, facilitate analysis of this sort.

6.7.26. When considering cause and effect, it is necessary to look at global factors (controlled by environmental drivers of change, irrespective of the wreck), local factors (related to the presence of the wreck itself), and a combination of both.

6.7.27. The deposition is considered to be primarily a result of the global changes apparent in the wider area. See for instance the area comparison of August 2006 subtract July2002 (Figure 40) where the net deposition of sediment can be seen as green & yellow colours running in a band from southwest to northeast past the stern of the wreck and beyond.

6.7.28. The *Stirling Castle* is situated in a channel between two large sand banks. On the seabed there are a series of submerged sand dunes which are smaller in scale than the banks, but still many times the size of the wreck, and, smaller in scale still, sand waves and ripples.

6.7.29. These large sand dunes appear to be mobile, approaching the *Stirling Castle* from the southwest and the eastern end of the dune system appears to be impacting on the wreck site.

6.7.30. The proximity of this mobile dune system to the wreck undoubtedly affects the tidal flow locally around the wreck and therefore the sediment regime. It is unlikely however that the movement of these dunes alone is enough to explain the changes in sediment levels that have been witnessed since 1998 on the *Stirling Castle* – i.e. the progression of burial and exposure. The exposure of the wreck since 1998 appears to be happening over a much longer timescale compared with the frequency at which the sand dunes pass by.

6.7.31. The second effect is local and results from the presence of a wreck structure within the seabed matrix. For example, where upstanding structure has been recorded, it appears that this can create interruptions in tidal flow, which in turn causes sediment scour. In this respect, the RASSE data tends to corroborate research by Dr Justin Dix in the University of Southampton, Round 2 ALSF project who has observed that the local effect of the wreck on the surrounding sediment regime can extend a distance from the wreck equal to many times the size of the wreck itself.

Changes within the Goodwin Sands

6.7.32. Analysis of historic data sources suggests a period of stability and then erosion of deposits on the Goodwin Sands over the last 20yrs (see section 6.2)

6.7.33. However, the project's wider area bathymetry datasets indicate obvious and large changes in sediment patterns focused between 2002-6.

6.7.34. Although the *Stirling Castle* may have an effect on these changes, the sedimentary regime of the entire Goodwin Sands is complex, and movement is occurring over a wide area. Therefore, it is difficult to draw firm conclusions on patterns of change for the Goodwin Sands because the project has only provided a limited snapshot of a defined area over a four year time frame.

6.7.35. That said, it seems likely that global changes in sediment regimes have resulted from environmental factors such as wave, climate, weather and tide. These are ongoing and would be apparent with or without the presence of *Stirling Castle*.

Recommendations for future monitoring of the Stirling Castle

6.7.36. Multibeam sonar surveys should be repeated at periodic intervals. In addition monitoring instruments should be deployed on the seabed to monitor sediment movement and other environmental factors. Data-loggers will allow evaluation of sediment movement around the site at a micro-scale for integration with the macro movements that have been recorded using the geophysical methodologies.

6.7.37. Continued monitoring of this sort may eventually provide a corpus of data sufficient to allow a full assessment of the changes and patterns that exist in the sediment regime to the extent that predictions about the likely burial or exposure of the *Stirling Castle* and other wrecks in the Goodwins are possible.

6.7.38. Once that point has been reached, the next step may be to define methods which could (if required) mitigate the effects of sediment instability on the *Stirling Castle.*

6.7.39. The procedures identified at the Sitrling Castle site for use of mutlbeam sonar in monitoring wreck site stability are applicable in nearly ever other marine archaeological site where there is a highly mobile seafloor. Such conditions, commonly occur at or around aggregate extraction sites.

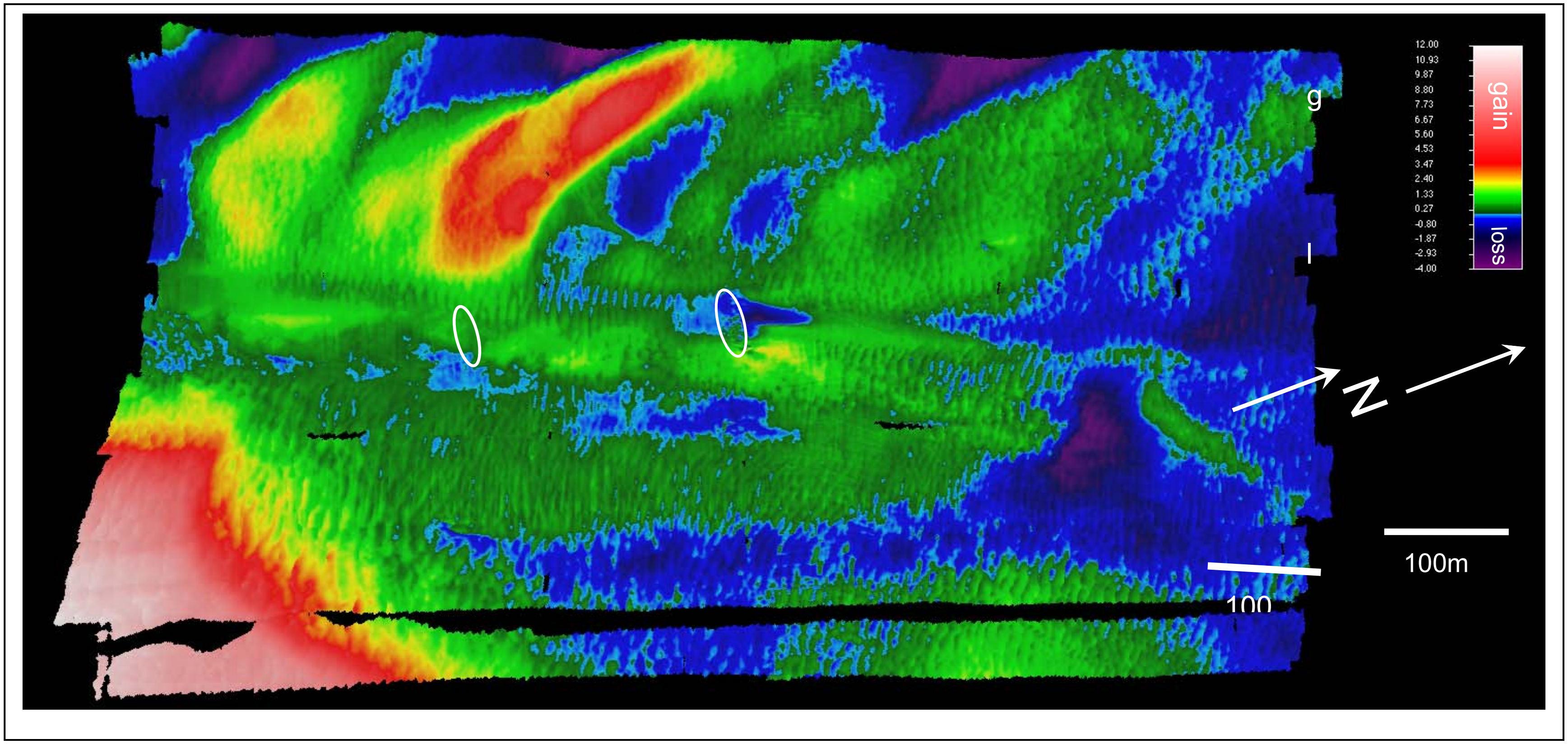


Figure 38: ***Stirling Castle*** **area difference map – April 2005 Subtract July 2002**

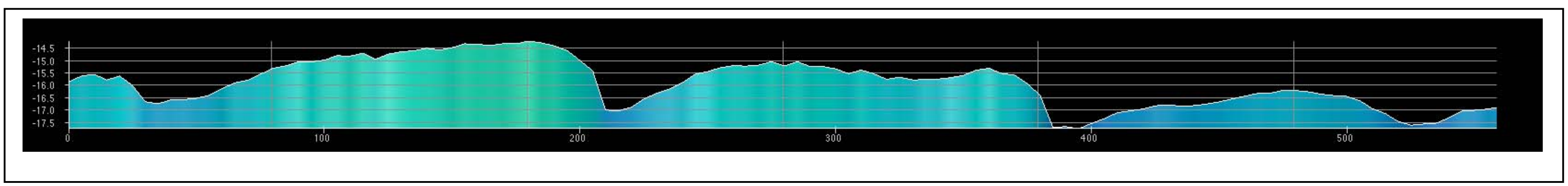


Figure 39: ***Stirling Castle*** **cross section of migrating sand dunes – August 2006, illustrating direction of travel northeast**

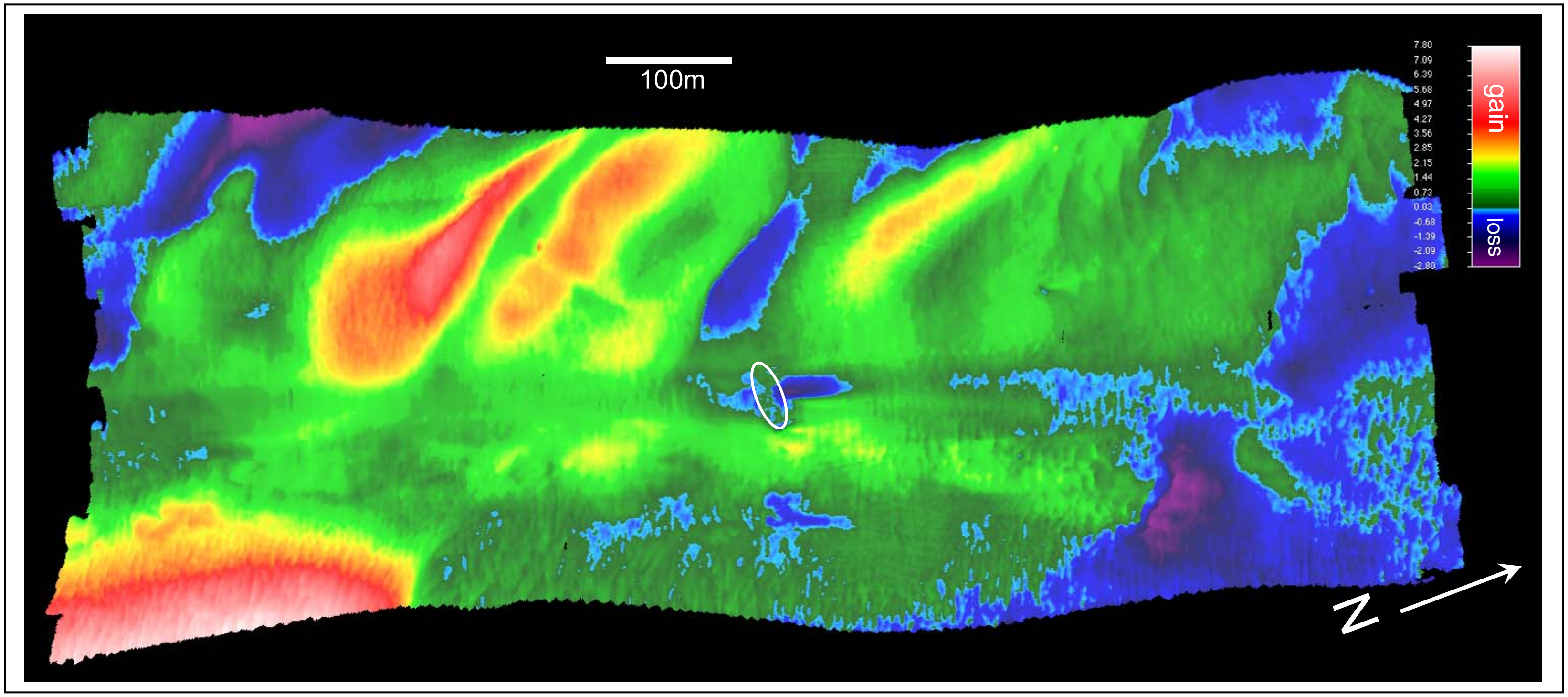


Figure 40: *Stirling Castle* – Area Difference Map August 2006 Subtract July 2002

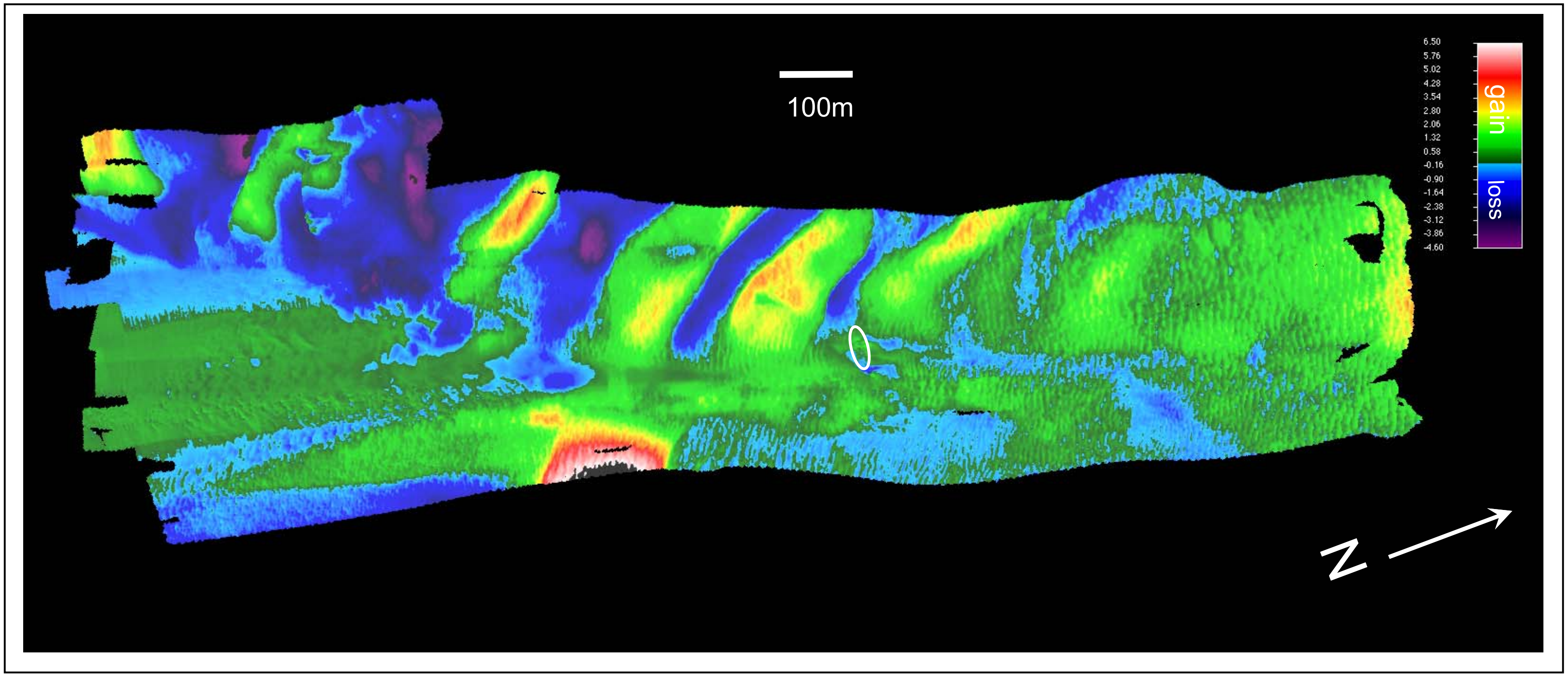


Figure 41: *Stirling Castle* – Area difference map August 2006 subtract April 2005

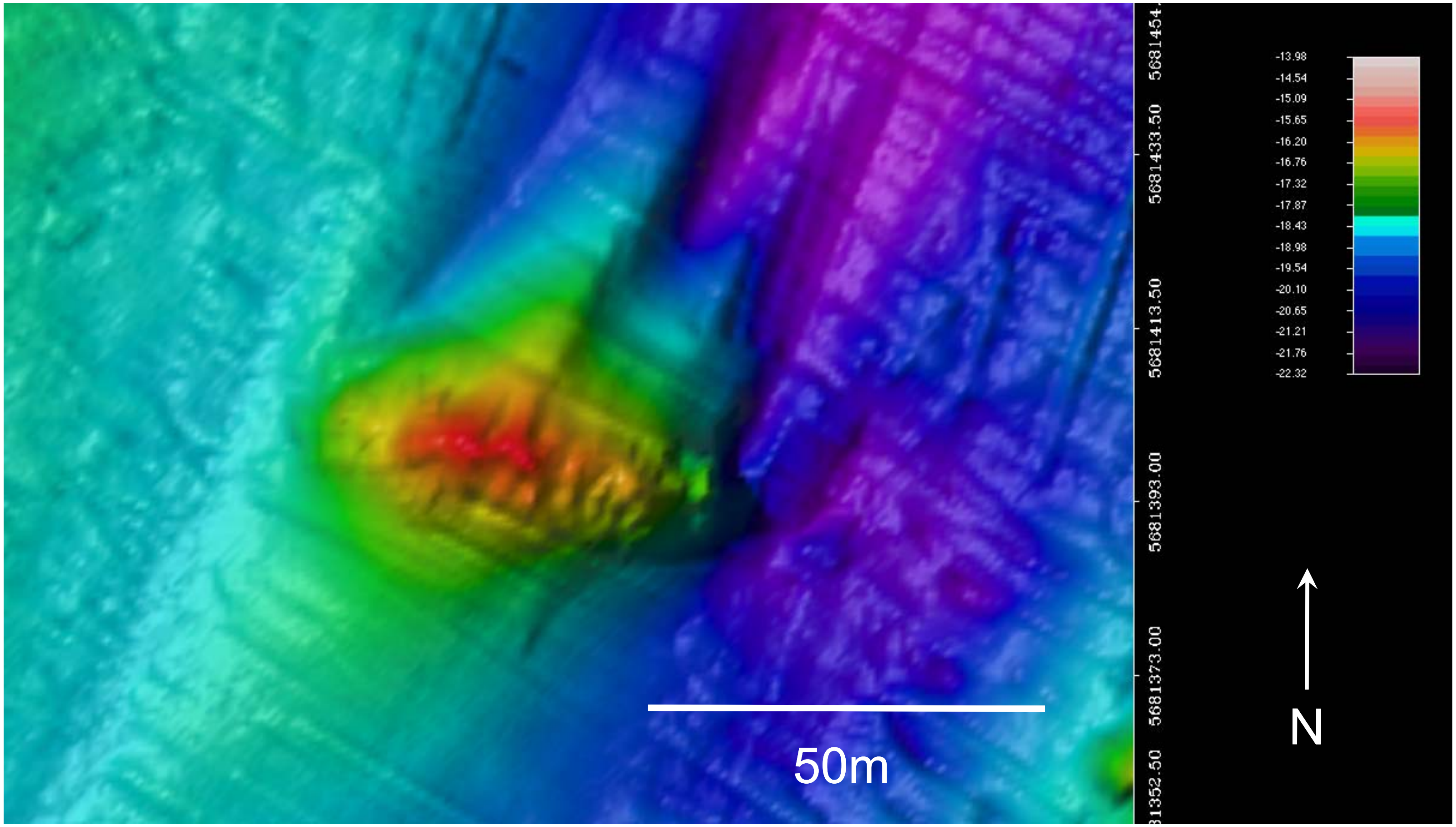


Figure 42: *Stirling Castle* - wreck bathymetry (ODN) July 2002

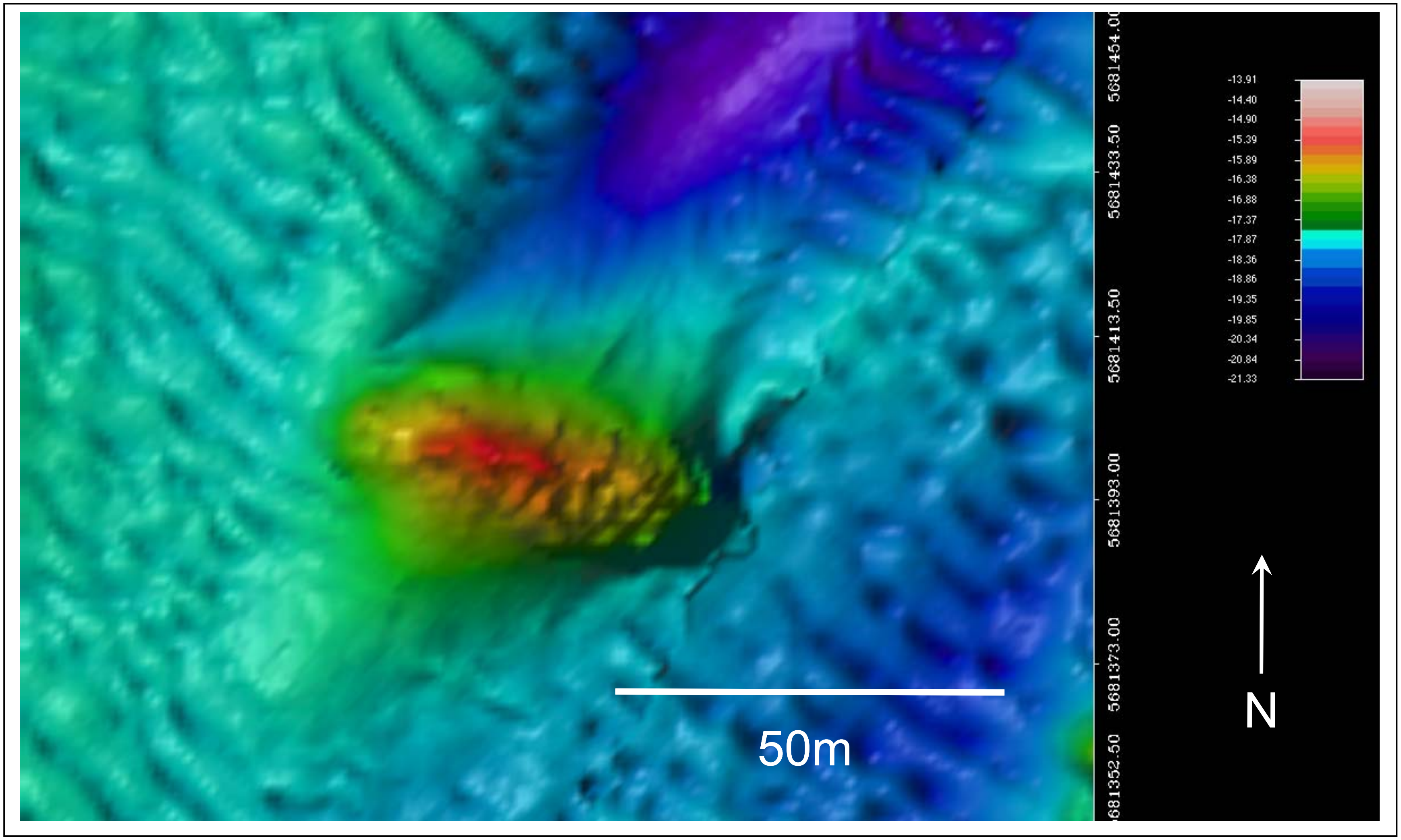


Figure 43: *Stirling Castle* - wreck bathymetry (ODN) April 2005

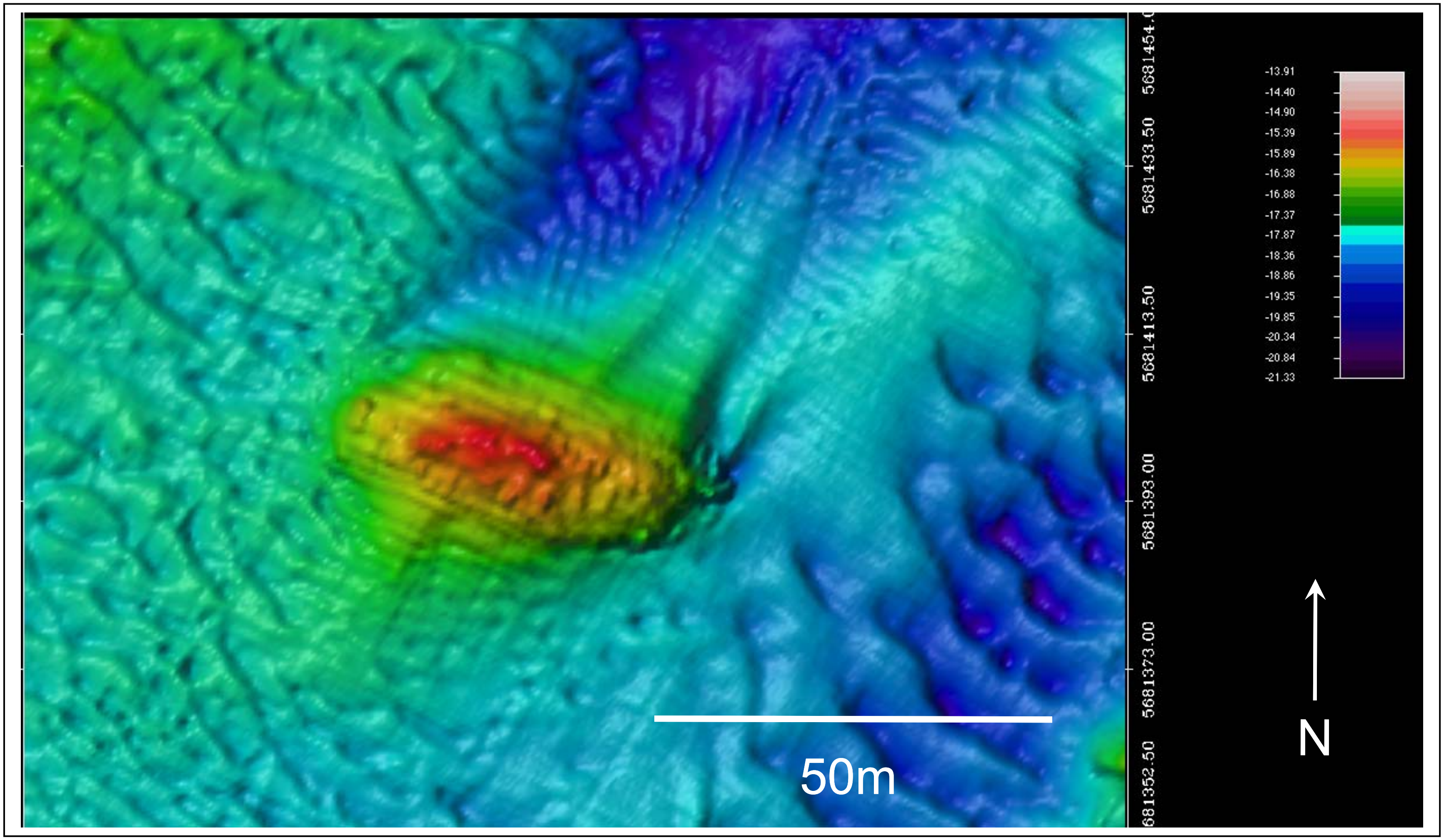


Figure 44: *Stirling Castle* - wreck bathymetry (ODN) March 2006

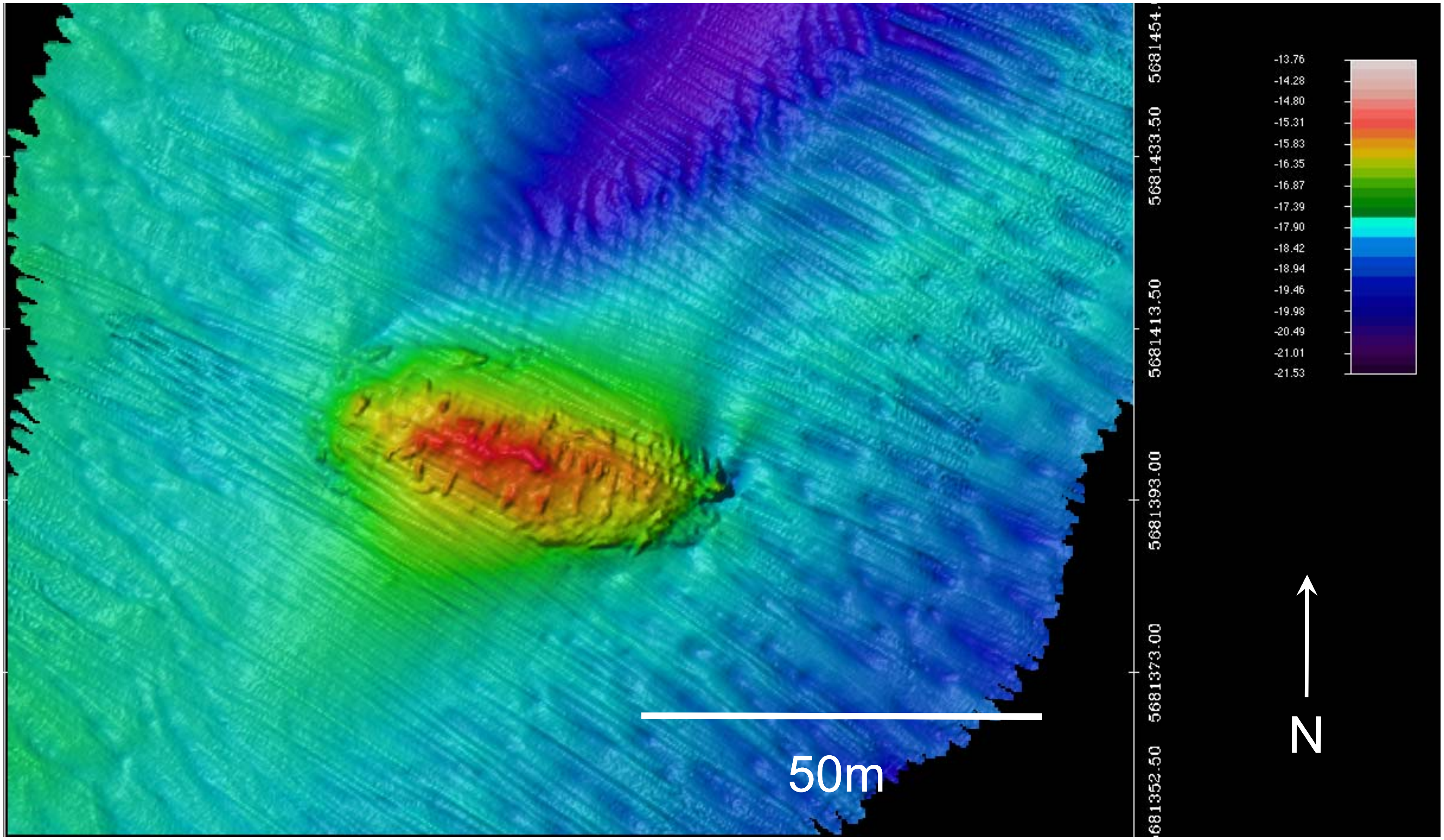


Figure 45: ***Stirling Castle*** **wreck bathymetry (ODN) September 2005**

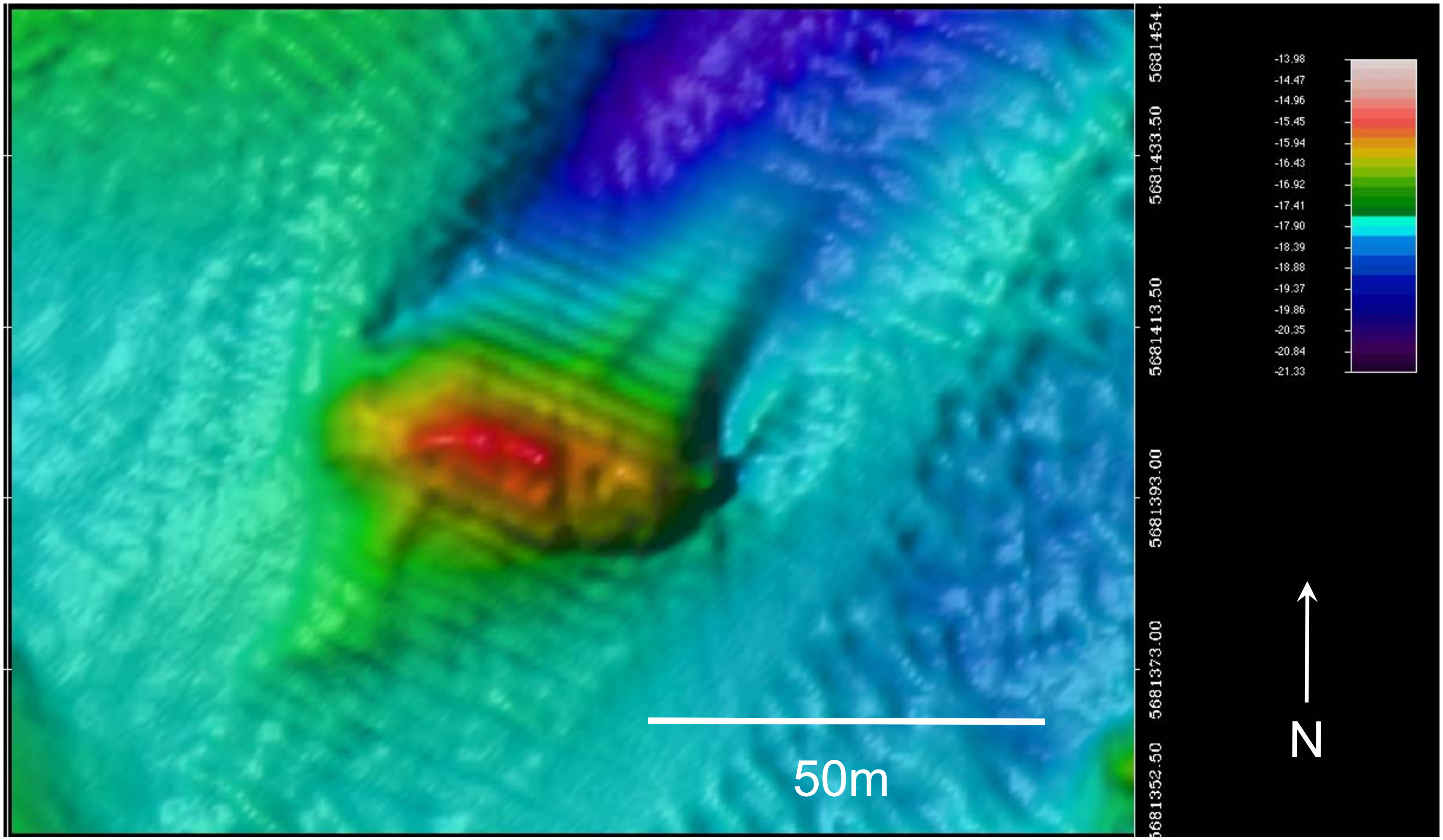


Figure 46: ***Stirling Castle*** **- wreck bathymetry (ODN) August 2006**

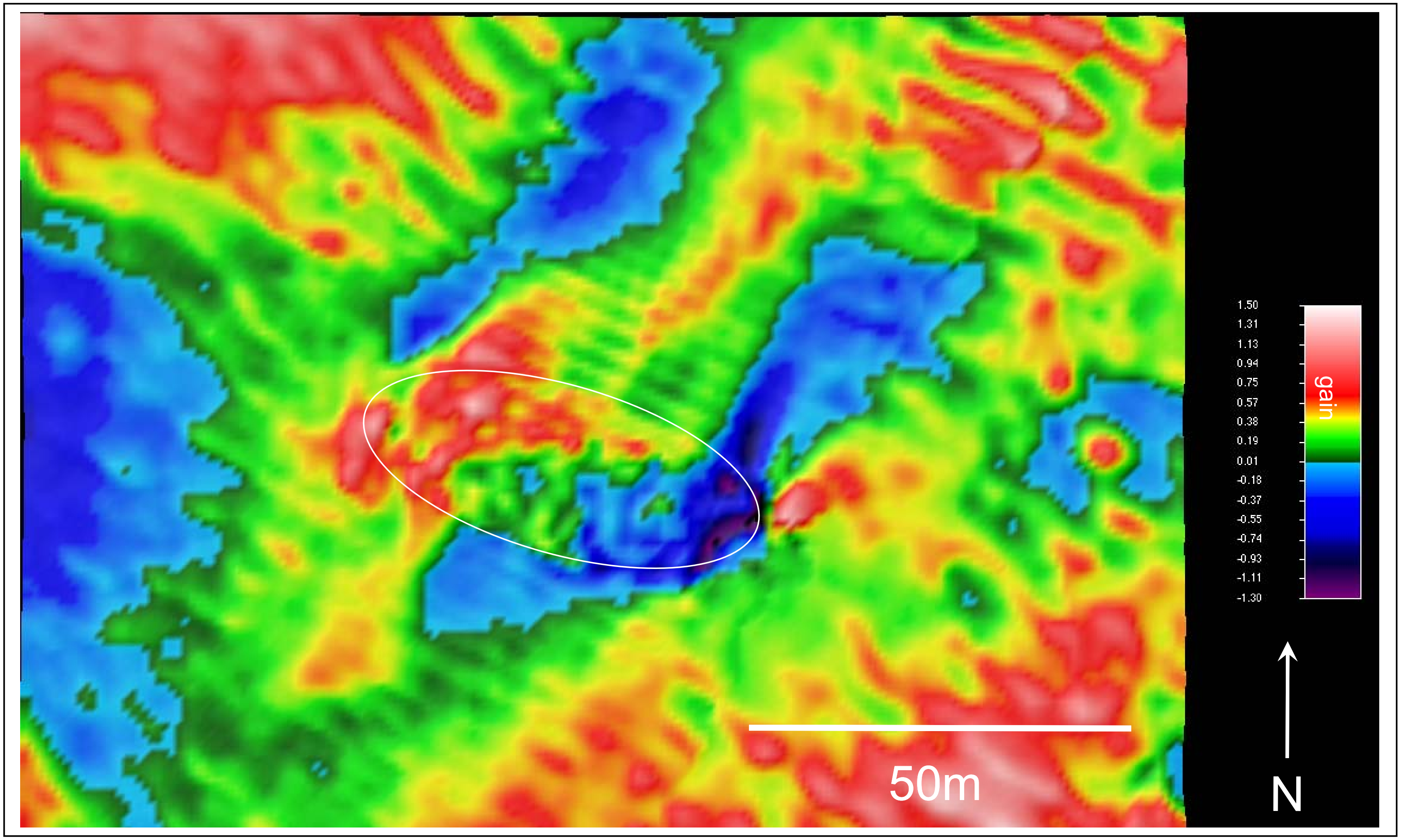


Figure 47: ***Stirling Castle*** **- Wreck Difference Map , August 2006 Subtract April 2005**

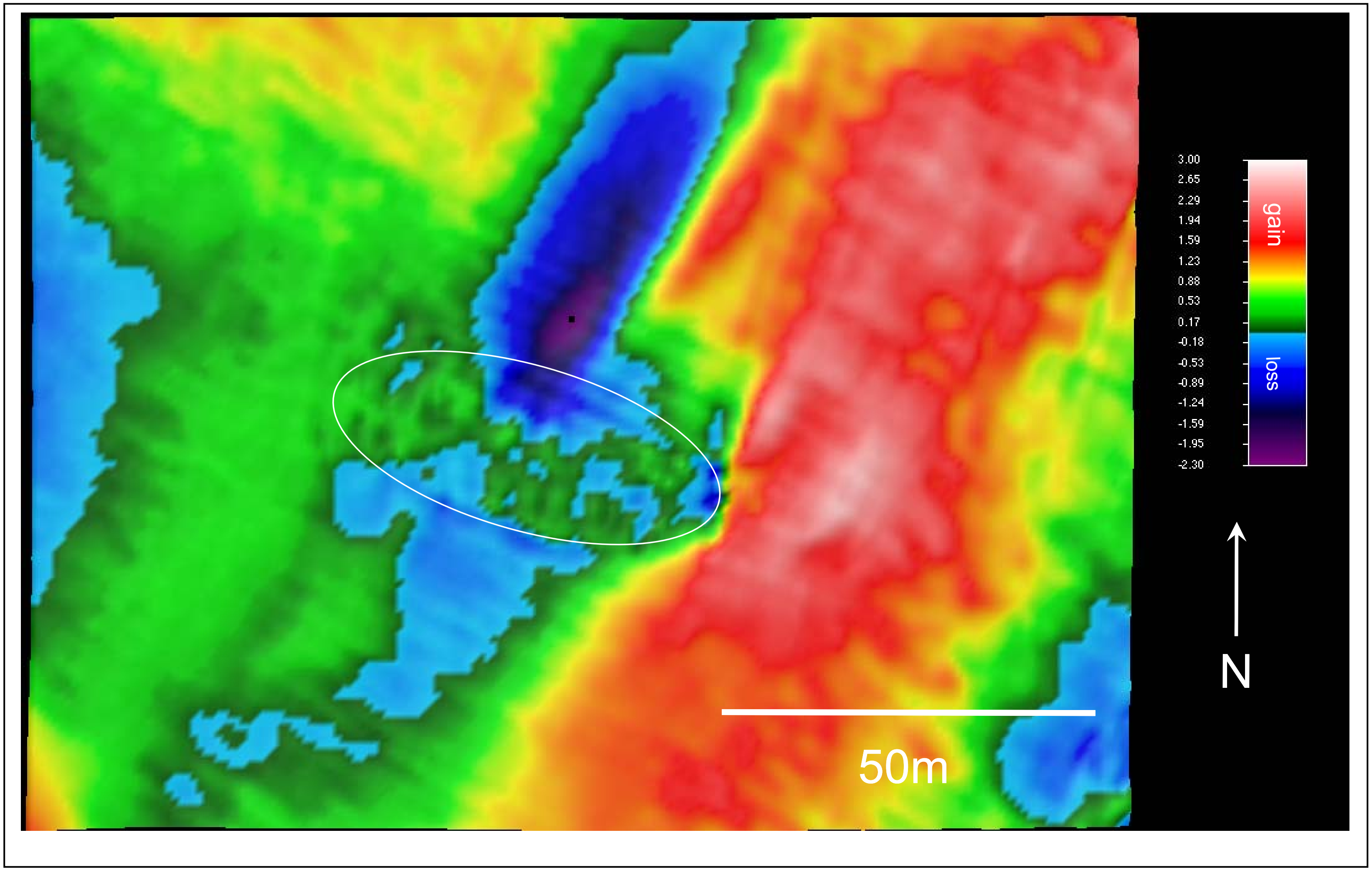


Figure 48: ***Stirling Castle*** **- Wreck Difference Map , August 2006 subtract July 2002 (longest time period)**

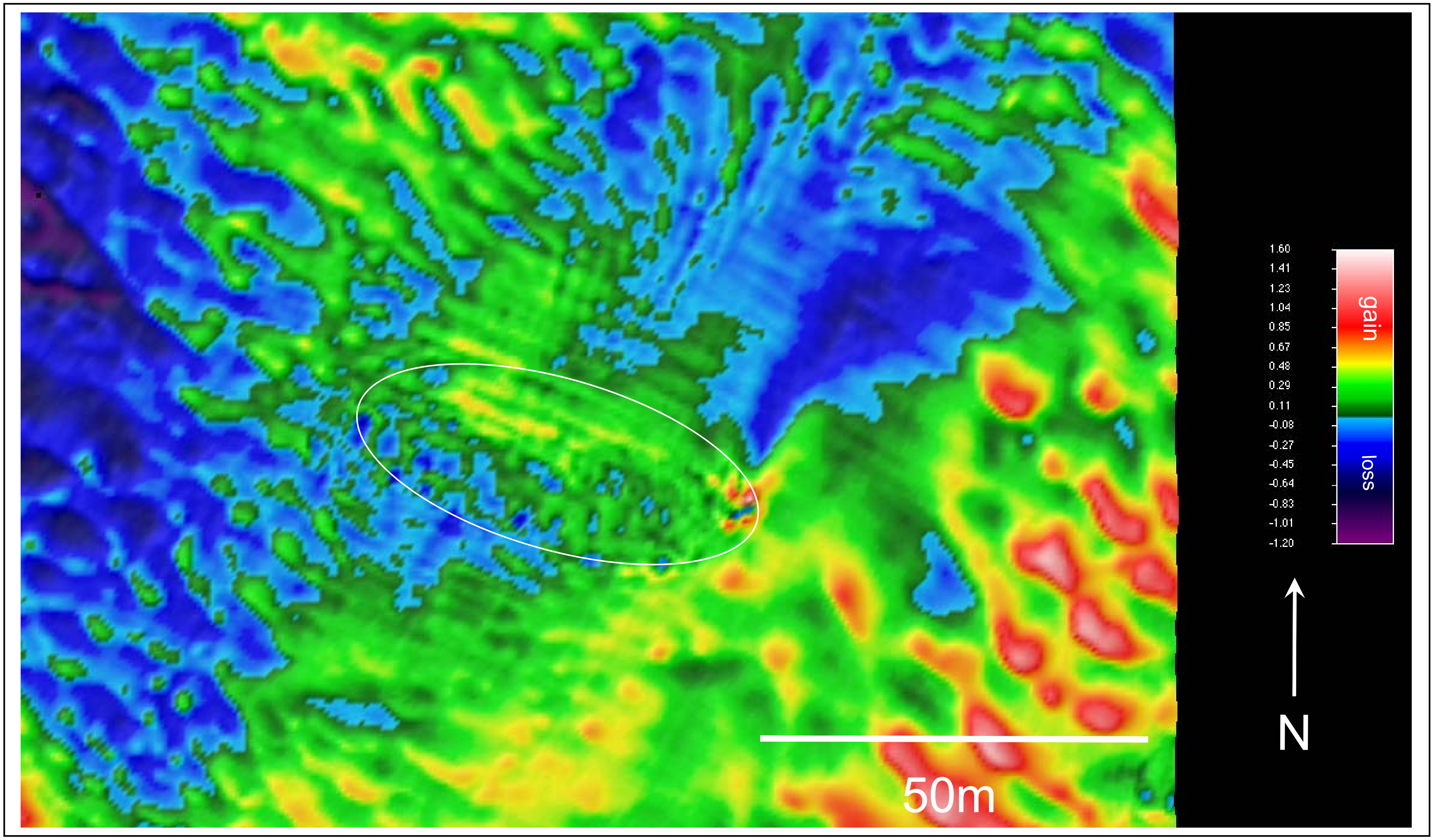


Figure 49: *Stirling Castle* - Wreck Difference Map, August 2006 subtract March 2006 (summer season 2006)

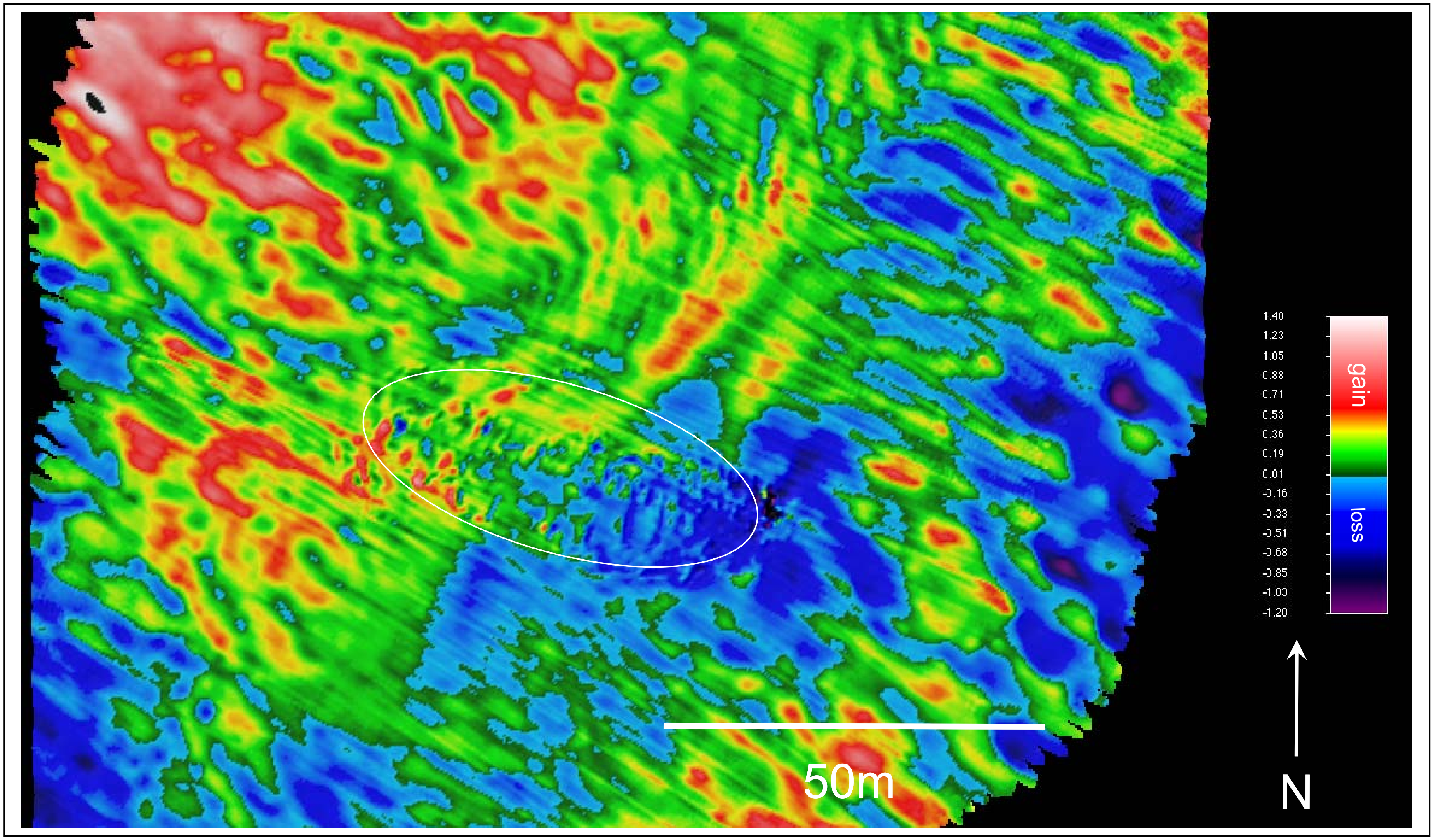


Figure 50: *Stirling Castle* - Wreck Difference Map, March 2006 subtract September 2005 (winter 05-06)

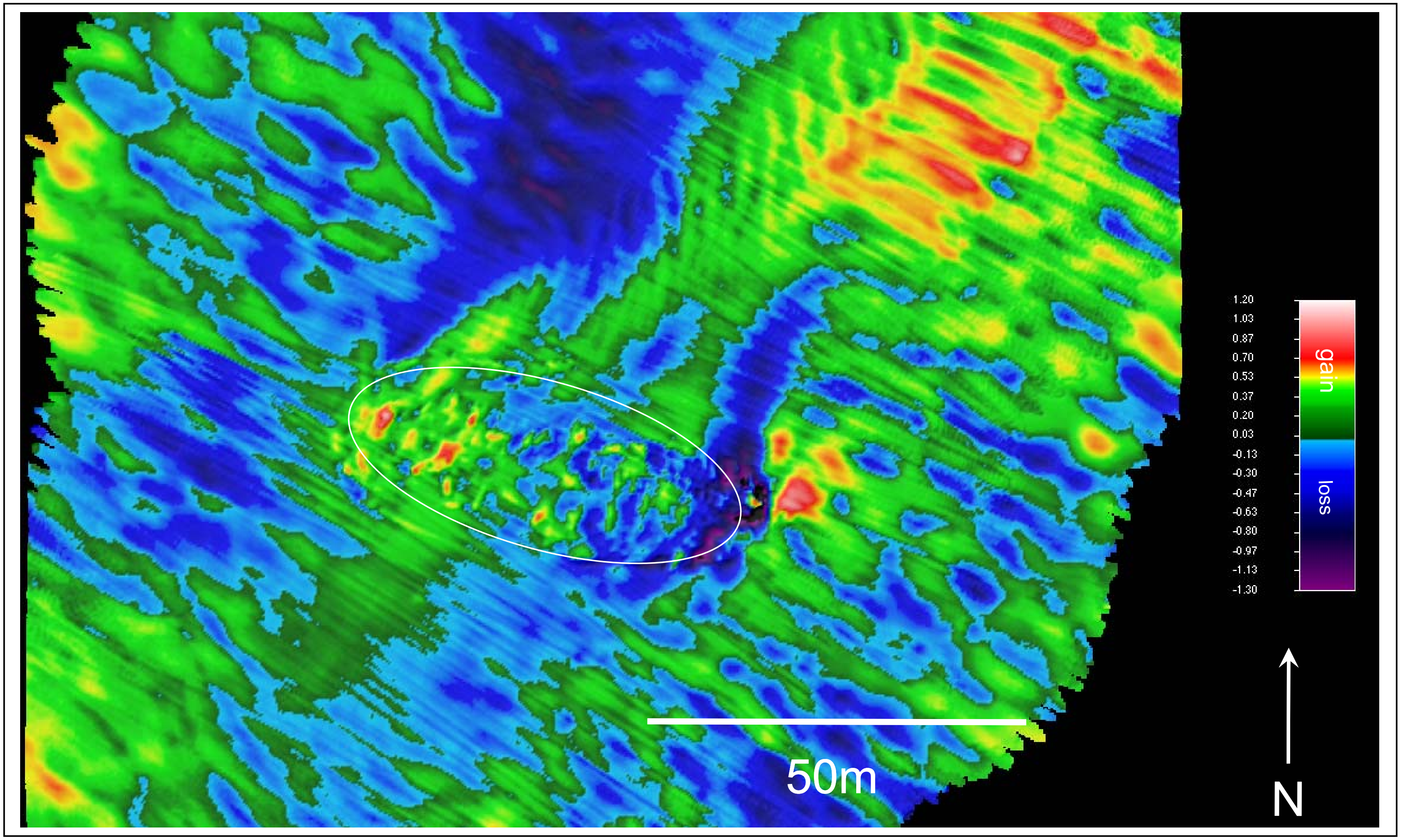


Figure 51: *Stirling Castle* - Wreck Difference Map, September 2005 subtract April 2005 (summer season 2005)

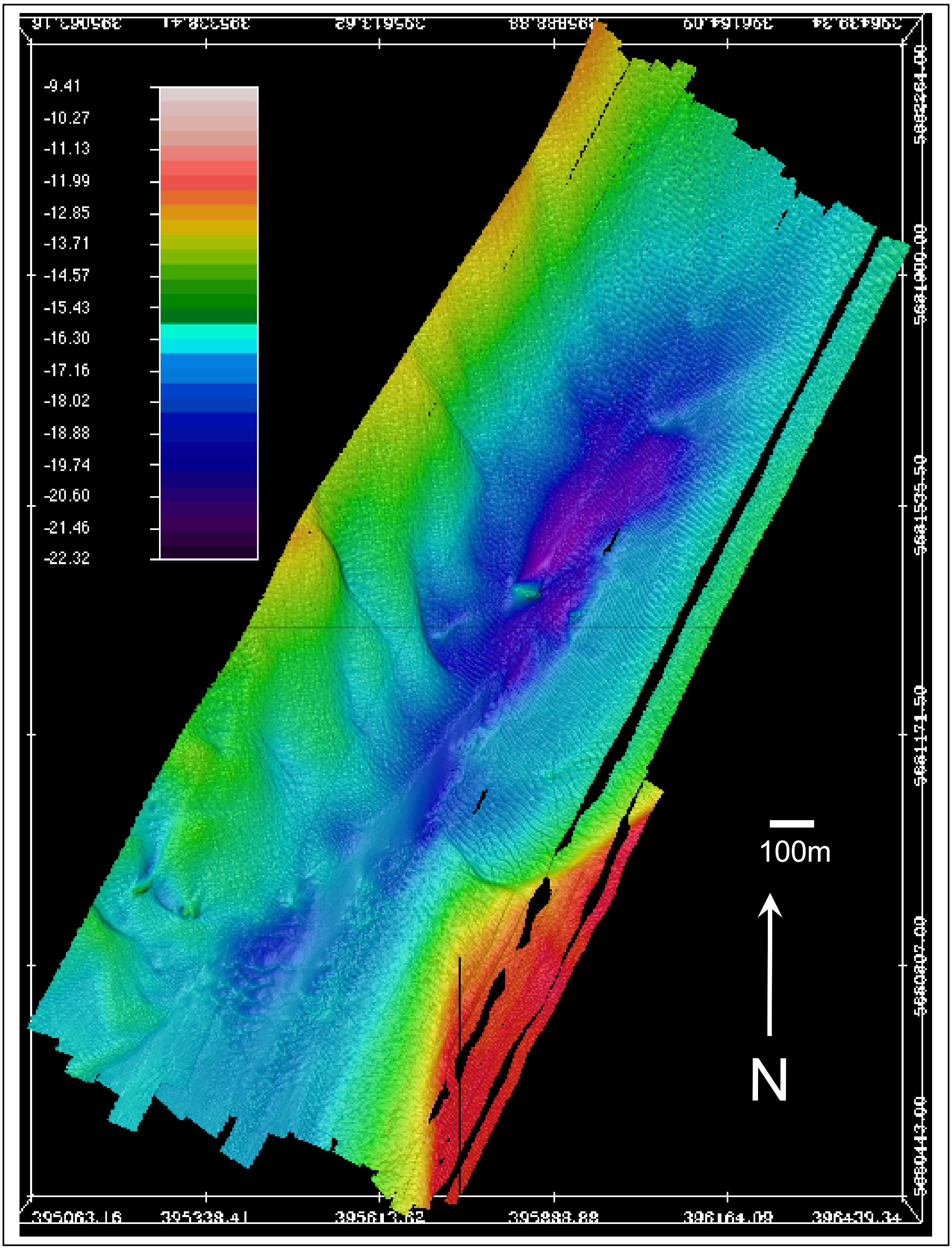


Figure 52: ***Stirling Castle*** **area bathymetry (ODN) April 2005**

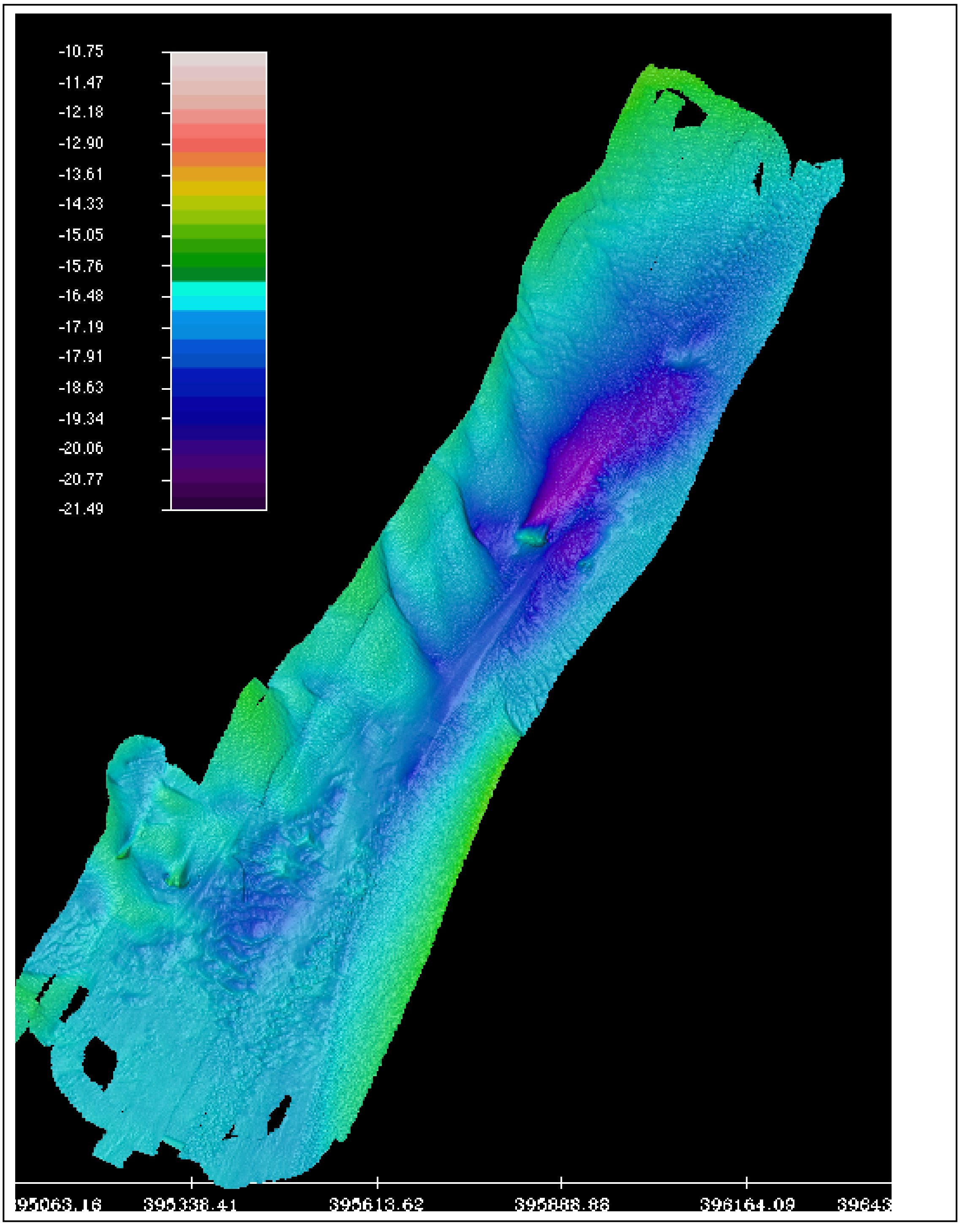


Figure 53: *Stirling Castle* area bathymetry (ODN) August 2006

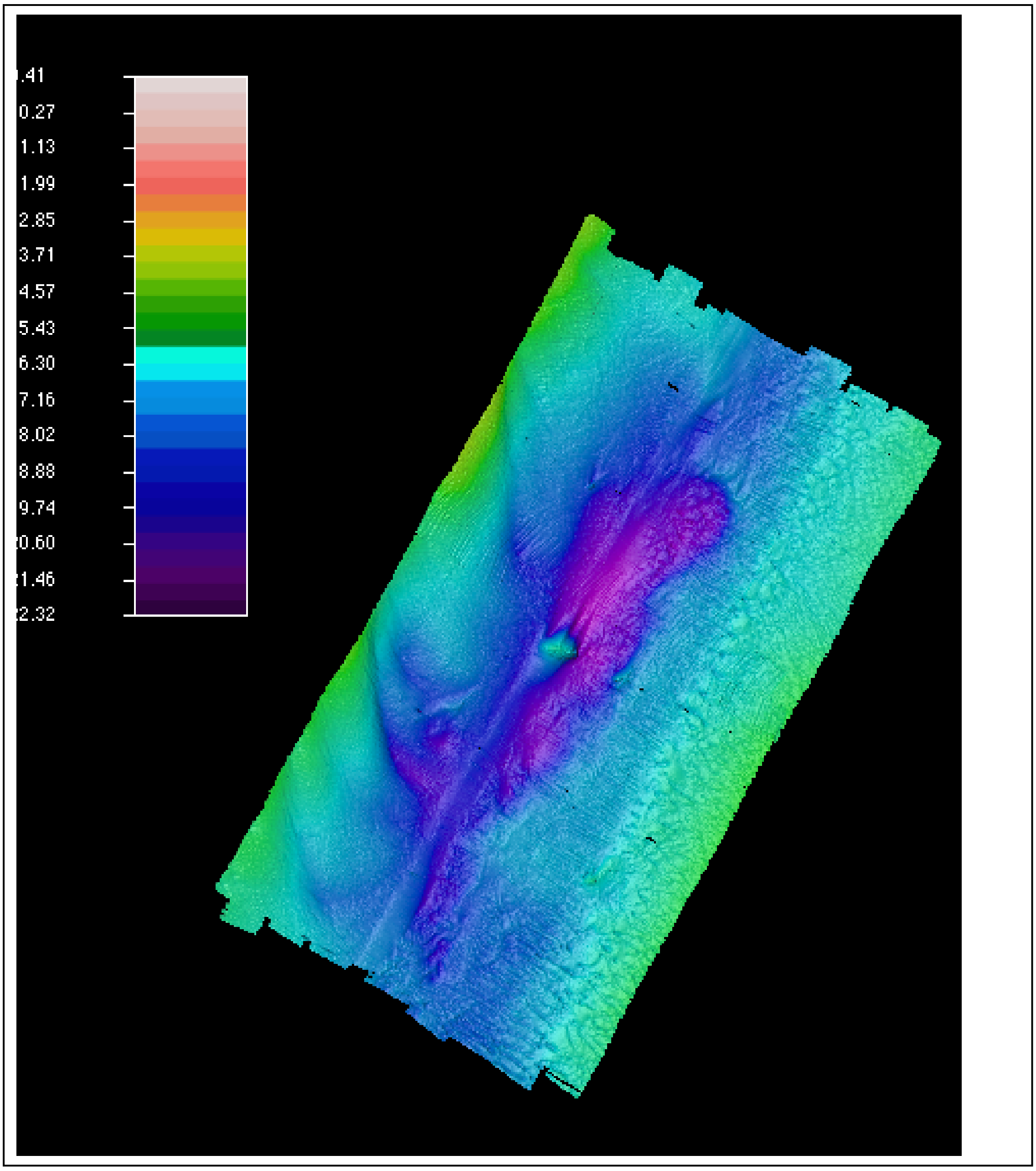


Figure 54: *Stirling Castle* area bathymetry (ODN) July 2002

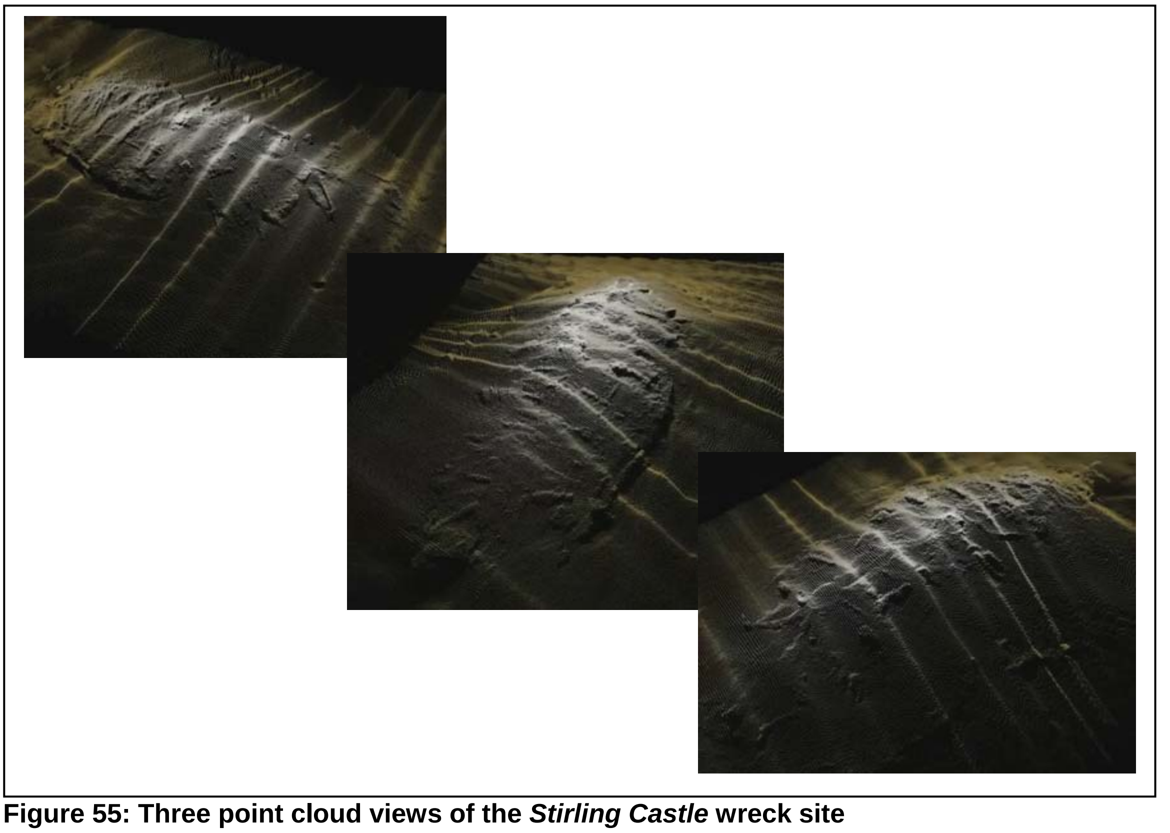


Figure 55: Three point cloud views of the *Stirling Castle* wreck site

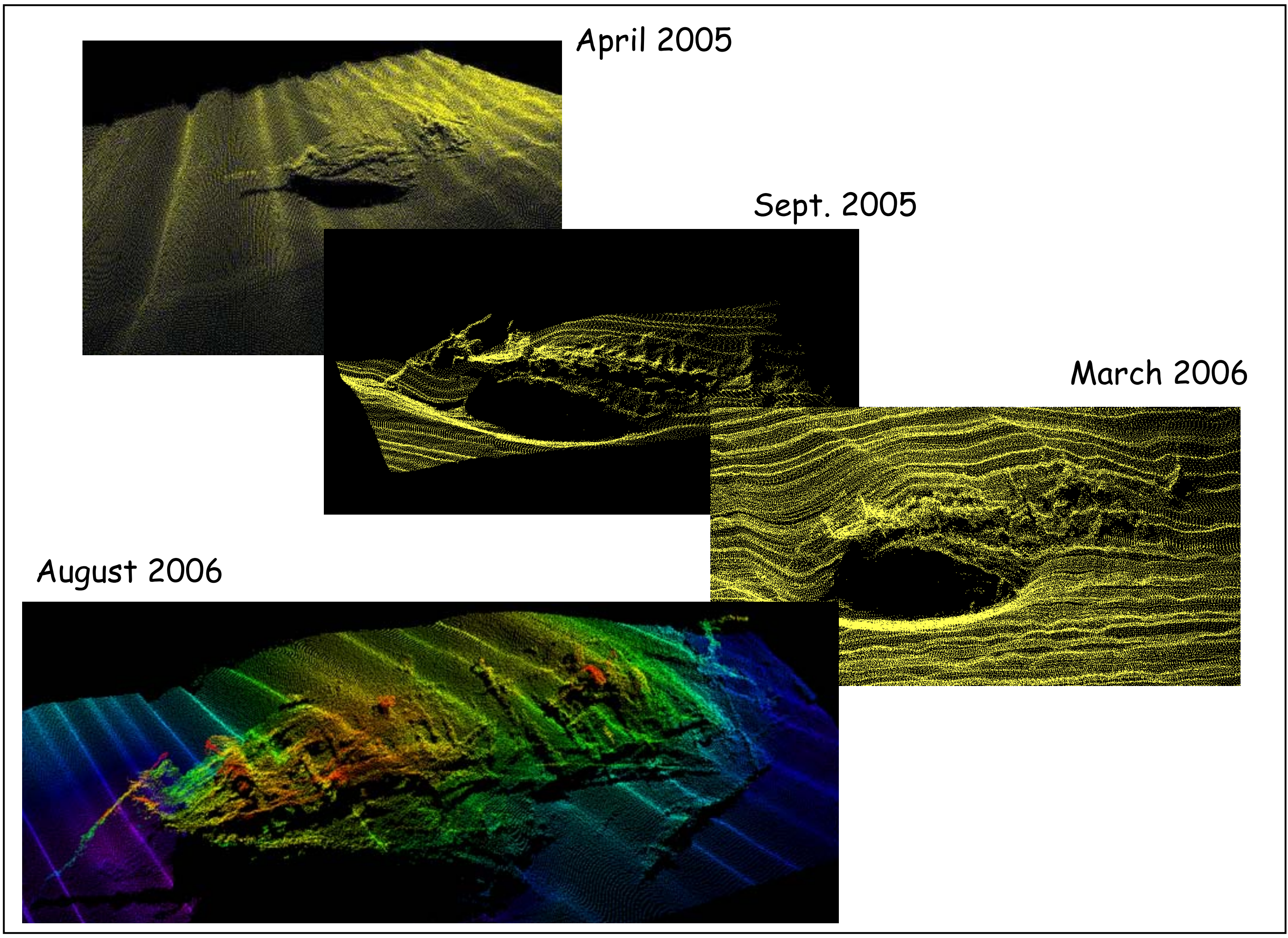


Figure 56: Four point cloud views of the Bow Sprit wreck site: note the fallen bow sprit which occurred sometime between April and September 2005

7. Outreach

7.1.1. A project web site (www.st-andrews.ac.uk/~wrecks) was designed and created using information already gathered for the project.

7.1.2. The website was made live in June 2005 and the results of surveys frequently update. Currently all reports and 3D visualisations have been uploaded to the website. This will remain active for the entirety of this project and will continue to be updated in the future.

7.1.3. Project review meetings were held throughout the course of the project together with annual meetings between ALSF partners. In addition, open ALSF meetings were attended at SOAS, London, and Southampton. Copies of Powerpoint presentations made at these events is posted on the project website.

7.1.4. Data dissemination of this project will also take place via the Archaeological Data Service (ADS) website, similar to all other ALSF projects. The full report will be available via: http://ads.ahds.ac.uk/project/alsf/

7.1.5. Table 14 details the public presentations given of the Project's work:

Date	Event	Presenter	References	Audience
2005	Shallow Water 2005 Conference	Martin Dean	Dean et al., 2005	Industry/academia
2005	Ocean 05 Conference, Brest	Dr Louis Attalah	Atallah et al., 2005	Industry/academia
2005	Institute of Field Archaeologists Annual Conference – poster session	N/A	N/A	Industry/academia
2006	Society of Historical Archaeology Annual Conference	Martin Dean	N/A	Industry/academia
2006	Reson Multibeam users group St Petersburg	Martin Dean	N/A	Industry
2006	Project Open Day Ramsgate (30 March 2006) – talk, open day on survey vessel, and poster session in museum	All	N/A	Industry, academia and general public

8. Conclusions

8.1. Progress against aims

8.1.1. Repeat surveys by high resolution multibeam sonar have achieved the project's aim of allowing rapid detailed investigation of submerged archaeological sites and their immediate surroundings for enhanced understanding of the environmental settings in which the sites are located.

8.1.2. Quantifiable environmental changes over time can be cost-effectively monitored on an important maritime archaeological site in order that the potential impact of anthropogenic activity such as aggregate extraction and natural cycles of change can be assessed more accurately.

8.1.3. The Plymouth Sound and Stirling Castle research has also enabled the Project to identify optimum configurations and deployment methods for acoustic instrument (i.e. the beam forming multibeam system here) to provide the best data for informed management decision making.

8.1.4. The following specific conclusions are relevant.

8.2. Long term site monitoring

8.2.1. The use of multibeam instruments for monitoring changes resulting from natural or anthropogenic factors, both around and within wreck sites has been clearly demonstrated by 'timelapse' application of the technique. On the *Stirling Castle* site, the interval between surveys varied from a few months to over a year. Within these timescales significant changes in wind, wave, and current activity have occurred on the site and it has not proven possible to isolate any one as the most significant driver of change. For sites of critical concern, multibeam surveys should be carried out at discrete intervals. In addition, continuous environmental monitoring instruments should be deployed at strategic positions on the seabed to enable closer scrutiny of cause and effect.

8.3. Rapid archaeological site survey and evaluation

8.3.1. Initial mapping of complex archaeological sites on the seabed surface and located in challenging burial environments (like the *Stirling Castle*) is best undertaken with multibeam sonar. The one critical proviso is that the system must be deployed in such a way that the collected data will be of sufficient quality to provide essential basic archaeological information. Once a multibeam survey has been completed, it is very important that diving archaeologists undertake ground truth investigation because this provides a means of recording at a level of detail that is not yet possible acoustically. Follow up surveys should include identification of specific features within the multibeam data set and, where necessary, surveying of critical areas in detail using conventional archaeological methods.

8.3.2. This combination of survey by geophysics and then by divers would undoubtedly be the most cost effective way to produce pre-disturbance site plans of wrecks in difficult environmental conditions. It is arguable also that this is the most effective way to produce plans of sites in more benign conditions.

8.3.3. Despite the mobilisation costs, when correctly used, multibeam sonar offers curators and archaeologists a cost effective and rapid technique for undertaking wide area surveys at a resolution that is also effective for recording distinct sites in detail. Therefore, high resolution multibeam arguably provides the best possible chance of recording archaeological information before it is lost through change.

8.4. Use of multibeam

8.4.1. When multibeam sonar is used in the most appropriate manner, it is capable of highly accurate and detailed surveys of a wreck site. From the various methods tested in this project the ISHAP deployment proved to yield the highest resolution. The ISHAP method was successful because it brought the sonar head as close to the target as possible while still mounted on a stable and calibrated platform. However, it does have a limitation in its physical size and the sea state under which it can operate. For these reasons the ISHAP method would not be an appropriate method in deeper water. It is suggested that future work is initiated to test the methodologies proved in this project but on a deeper-water platform such as a Remotely Operated Vehicle (ROV).

8.4.2. All of the data collected with the geophysical survey instruments provides quantitative information on the seafloor and archaeological material. It is imperative that this information is correctly spatially referenced to the highest accuracy possible. Only through systems such as full RTK positioning will it be possible to make repeat measurements of seafloor changes.

8.5. Automated classification

8.5.1. The automated classification methods trialled by the Project were not particularly successful at differentiating between areas of seafloor that contained features of archaeological significance and areas that were barren. However, some progress was made on methods for identifying change on and around wreck sites and this may prove to be a fruitful area of future work as the sonar industry develops further capability to provide full backscatter amplitude maps together with the high resolution bathymetry.

8.5.2. In this respect, the project suggests that further trials take place on application of automated classification to backscatter data gathered from the new generation of high resolution multibeam, most of which (e.g.,Reson and Simrad) are currently now capable of recording and exporting the necessary information. In particular, it is recommended that commercially available techniques be tested on wide-area survey for the rapid classification over whole potential aggregate extraction areas.

8.6. Dissemination of information

8.6.1. In the future, it is likely that aggregate extraction will uncover many more archaeological sites which have the potential to contribute significantly to knowledge of the history of the British Isles. However, the seabed is out of sight, out of mind for most people and the challenge is to identify ways of raising awareness of this relatively inaccessible facet of the maritime heritage.

8.6.2. The visualisation in three dimensions of sonar data provides one exciting means of achieving this. However, until recently this involved specialist processing using expensive, proprietary programmes. A new generation of software is now allowing both scientific evaluation and public access and the World Wide Web provides an ideal medium for presentation. Visualisation by animation and stills view has the potential to transform public perception of the shelf areas around the British Isles. This would be of great benefit to the positive promotion of the work of the aggregate industry.

9. Acknowledgements

Dave Burden, Skipper Xplorer
Virginia Dellino Musgrave (English Heritage)
Anthony Firth (Wessex Archaeology)
Helen Keeley (English Heritage)
Ian Oxley (English Heritage)
Bob Peacock, Licensee and his colleagues from Seadive
Staff and volunteers of Ramsgate Museum

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Appendix 1 – Summary of project objectives

Academic objectives

Environmental Setting Mapping Techniques (Objective 1) To refine knowledge and understanding of the techniques for mapping the environmental context (the sedimentological and broader environmental including biological setting) of a wreck site, in particular in sites of medium to coarse sediment material at or near the sea bed surface.

Environmental and Palaeo-environmental Setting (Objective 2) -To determine the key environmental features and environmental stability surrounding sites of submerged archaeology.

Environmental Change (Objective 3) - To investigate the rate of environmental change and indicate potential causes (natural and anthropogenic) of change around maritime archaeological sites.

Development of methodologies (Objective 4) - to maximise the archaeological and environmental detail obtained by high resolution sonar.

Enhanced methods for Processing Remote Sensing Data (Objective 5) - To refine remote classification methods for mapping the environmental setting, and identifying the material within, submerged archaeological sites.

Curatorial objectives

Environmental Distribution (Objective 6) - To map the distribution of environmental factors surrounding key maritime archaeological sites of significance. Providing critical information on environmental factors to county planners, members of the aggregate industry, heritage managers and academics will enable informed decision to be made on the condition on the sites.

Environmental Change(Objective 7) -To assess the previous and current change in environmental conditions surrounding key maritime sites in order to provide vital information on the long term stability of sites.

Environmental Future Scenario (Objective 8) - To provide appropriate information for the modelling of future changes to wreck sites for the long term management of the sites and the potential impact that future aggregate extraction might have on them. The results of these aspects of the project will be passed to the relevant curatorial and management authorities in the study region for cross-referencing with mineral extraction plans and for the Stirling Castle will be provided to Dr Justin Dix for modelling within the SOC ALSF project.

Development (Objective 9) - To provide enhanced tools for the rapid mapping and quantitative, automated monitoring of maritime archaeological sites and their surrounding environment.

Dissemination Objectives

Dissemination of Data to EH and ALSF Partners (Objective 10) -To share data, results, conclusions and recommendations within English Heritage and the ALSF Partner projects through meetings, reports and digital information.

Dissemination of Results and Recommendations to Curators (Objective 11) - To communicate the results, findings and recommendations to local curators and prepare guidelines on the use of the enhanced geophysical techniques for contract surveyors and wider curatorial staff.

Dissemination of Results to Public Audience (Objective 12) - A Web site will be created for the dissemination of results from the project. The web site will contain information on the sites, the techniques used and the results of monitoring over the course of the project.

Dissemination of Results to Academic Audience (Objective 13) - Publication of the results in academic, peer reviewed journals and at national and international conferences on maritime archaeology.

Appendix 2 – Draft guidance notes on the application of bathymetric multibeam for rapid site survey and evaluation of archaeological sites in aggregate dredging zones

Purpose
This draft guidance note is intended to assist curators, archaeologists, managers, and surveyors in the application of bathymetric multibeam sonar for archaeological site survey of the seabed in aggregate dredging zones.

Issues
There are numerous factors that influence the quality of high definition multibeam. Generally speaking these can be grouped into:

- Human factors
- Engineering considerations
- The influence of the environment.

Unfortunately, many of the factors are often ignored, or never even considered when specialised equipment is used for archaeological research. Furthermore, it is often the case that the factors are not appreciated for their relevance by a survey industry that often uses the equipment for different purposes.

Recommendations
Based on the experience gained during this project, curators and archaeologists managing multibeam surveys for rapid archaeological site survey and evaluation, should take note of the following recommendations during the planning and execution of a project:

Human Factors
Client's understanding of the survey requirements.
It is important for the person or organisation commissioning the survey to understand the capabilities of the specified equipment and whether it is the correct choice for the survey.

Client's ability to communicate their wishes to the survey team.
It is important for surveyors to discuss with clients the aim and objectives of the proposed survey so that they can advise on choice of appropriate personnel and equipment. The client needs to be advised of advice such as: using twin head systems will not normally give better definition except if viewing the data as stereo images; and most multibeam systems are not useful for searching for small targets in large areas.

Experience of the surveyor
Best results are generally produced by the most experienced surveyors. But a very experienced multibeam surveyor who has no experience of archaeological work may

not produce results as good as a relatively inexperienced surveyor who has gained some experience on archaeological surveys.

Skill of the surveyor
Although there is obviously a strong correlation, experienced surveyors are not always the most skilful. One test of a surveyor's skill is whether he or she instinctively handles new software or whether they have to keep referring to manuals.

Enthusiasm of the surveyor
Generally marine surveyors enjoy archaeological surveys because it is different to their normal work and provides them with new challenges. However everyone, including surveyors, can suffer with domestic, financial and other pressures. The best surveyors will demonstrate their professionalism by not letting such external factors influence the quality of their work.

Working conditions of the surveyor.
Good surveyors can put up with having their computers and screens set up in cramped cubby holes, or in the lively forepeak of a small survey launch. While they may not complain too much with such conditions, the situation will not be conducive to the best results.

Survey lines along multiple orientations.
Small cross section linear features may not be visible unless the track of the survey is close to parallel to it. For this reason it is good practice to do three sets of survey lines over a site where small targets need to be detected, with an angle of 120º between each.

Experience of the processor of the survey data
It is best to have the same person acquire and process the data. As above, experience of processing data from similar archaeological surveys is more important than extensive experience of processing data where none has come from archaeological sites.

Skill of the survey processor
It is crucial that archaeological features in the data are not confused with noise (unwanted echoes) that occurs in all sonar data sets, and which is normally edited out at during the initial post processing. (See also above)

Enthusiasm of the processor of the survey data
See above)

Skill of the data interpreter
This analysis of post processed data is best done by a suitably skilled archaeologist rather than a surveyor who is not likely to understand or recognise features of archaeological significance.

Experience of the survey vessel helmsman
The helmsman is a crucial factor in quality of survey and the experience to anticipate what is going to happen ahead is important. A good helmsman should be an integral

part of the survey team and be involved in decisions such as which direction survey lines should be run, as the helmsman will have a better understanding of how the vessel behaves in a variety of wind and current situations.

Skill of the survey vessel helmsman
The best will be able to either follow lines precisely when guided by navigation information displayed on the helm monitor, and be able, after one such guided track, to adjust the boat position relative to changes in depth so that the most efficient coverage of the seabed is achieved, and the fewest gaps left to be filled in later.

Enthusiasm of the survey vessel helmsman.
See above

Sufficient funding for the survey
This is a significant factor in the quality of the survey data because, if insufficient resources are available for the most appropriate equipment,etc., then second best equipment will provide second best results. Similarly if there is insufficient time available to collect good data then the survey standard will suffer.

Engineering Factors
The choice of multibeam system
Although this is related to 7.2.15 above, even the best and most expensive survey equipment can be acquired at odd times for less than the commercial rate. For multibeam sonar, at present the Reson 8125 SeaBat seems to provide the best results for small scale archaeological site survey, and experience has shown that there are no appreciable gains in resolution using a twin head system, but there are additional costs and installation problems. A later version, the 7125 SeaBat, has yet to be tried for archaeological surveying.

The choice of motion reference system
A comparison of all the major systems was recently undertaken for the Shallow Water 2005 Conference and, while many were of comparable standard one, the Applanix POS MV, although more expensive, gave measurably better results.

Choice of positioning system
Most surveys are reliant on calculating positions from constellations of satellites, the most common being the Global Positioning System (GPS), and the positional errors reduced by differential corrections transmitted from public or commercial base stations. A more accurate method of utilising GPS data is to exploit Real Time Kinematics (RTK) using corrections from a survey base station on the shore. In this way repeatable positions and heights can be obtained to within 1cm so that the results of similar surveys can be seamlessly integrated. The Applanix POS MV has RTK capability and currently provides the best solution for inshore archaeological work.

Accuracy of base station position.
If all the benefits of RTK are to be exploited then the base station on shore needs to be positioned to millimetric accuracy, with special attention paid to the height and to what datum it relates.

Distance from base station
The potential accuracy of a survey is better if the base station is relatively close to the site. A distance of less than 5km is ideal.

Choice of survey vessel
Most archaeologists use vessels of opportunity for multibeam surveys and they may not be ideal for the equipment that needs to be installed. The layout of the wheelhouse which allows computers, processors and screens to be positioned rationally is a big advantage when aiming for high quality surveys, as is having the ducting and apertures for cables. It is crucial to have the necessary range of in built power supply (often 12 and 24v DC and 240v AC) rather than ad hoc generators on the deck. Whatever is used adequate safeguards must be in place to prevent electrocution. A catamaran will often give a large wheel house for setting up survey equipment and is often seen to be more stable for surveying. However, their motion is 'short period' as compared to a more gentle rolling of a mono-hull. Modern motion reference units are better suited to compensating for slow rolling than rapid movements and so a trade-off must be made

Stability of the survey vessel.
This has two impacts on quality; personnel will be more comfortable and so more able to work to a higher standard if the platform is stable; similarly motion referencing systems have to work less and the output is therefore more accurate in such an environment. Inevitably large vessels are more stable than small boats in a given environment, but small survey boats are often necessary where manoeuvrability and shallow draft are required.

Effectiveness of the motion reference system.
As well as choice, the position of the system on a vessel is important. Ideally it should be placed at the centre of motion of the vessel, which is difficult to determine accurately and not always possible if machinery or other equipment is in the way. Another option is to place the system as close to the multibeam sonar head as possible. The ideal solution is to place both at the centre of motion of the vessel.

Rigidity of the mounting of the sonar heads.
When using vessels of opportunity, archaeologists often have to devise suitable sonar head mountings for each survey. Some flexing within a survey vessel is normal and so the greater the distance between the sonar head and the motion reference system, the bigger the problem. Another problem is unwanted flexing of the pole, particularly in side mounted systems, and so the mounting has to be properly designed and engineered. A firmer mount can often be made over the bow, which tends to be easier to set up on mono-hulled vessels, and forward motion helps to keep it secure and in place. A sonar head in its operational position seriously reduces most vessels' speed during passage making. Most removable mounting systems are not capable of withstanding the force of water against them at much above survey speeds and so it is advantageous to have a mounting design that allows for rapid recovery and redeployment. This ideally should have sufficient built-in accuracy when redeployed that the timeconsuming calibration of the system caused by misalignment on refitting is not necessary.

Accuracy of the measurement of the offsets between sonar heads, reference sensor and GPS antennas.

This is a significant problem during installation on most vessels of opportunity as bulkheads, decks, lockers, and equipment all get in the way. The most accurate solution is to take the vessel out of the water and use laser lines and a total survey station to minimise errors. Placing the motion reference sensor and one GPS antenna above the sonar head helps reduce the measurement problems but could introduce other disadvantages

Hydrodynamics of the sonar head.

This normally only becomes a significant problem at higher survey speeds (>6kn) and where the sonar head mounting is not strong enough to withstand the additional forces generated when there is no streamlining.

Noise generated by the survey vessel and its equipment.

A good survey vessel will have had these problems sorted but it may be necessary for the helmsman to switch off the vessels own echo sounder or other equipment which may cause causing interference. A good surveyor will check the data for extraneous noise before starting a survey.

Frequency of checks of the sound velocity throughout the water column

As well as constant monitoring of the sound velocity through water close to the sonar head, checks need to be made regularly through the water column with a separate sound velocity probe (SVP). This interval can vary with the local environment or the state of the tide and only by sensible testing can the rate of variation be established. Good surveyors know from experience the likely requirement in a given situation but, even where there are no detectable changes, test intervals of no more than 30 minutes are recommended for high quality work.

Operating frequency.

The higher the frequency, the shorter the range and so dual frequency systems can be useful if work has to be done in varying water depths. Generally speaking the higher the operating frequency, the better the definition, providing the design and manufacturing quality of the electronics is of appropriate quality. Frequencies of at least 400KHz are necessary for high definition work.

Pulse update rate.

Increasing the number of pulses a second generally increases the resolution but echoes from one pulse have to be received back by a multibeam system before the next pulse is transmitted. For example in a high quality high definition system such as the Reson 8125, the pulse rate is 40Hz for range settings of less then 7m and 12Hz for range settings of 30m.

Pulse width.

This has a small but detectable influence on survey definition so, for highest quality, it may be necessary to reduce the pulse width to below that even recommended in the manufacturers handbook. We concluded that such guidance notes were not written for close quarter, high definition work but for the average survey situation.

Distance between sonar heads and the targets.

The pulse update rate (see 7.3.16 above) indicates the optimum range settings. Similarly, even though the beams are relatively narrow on the best equipment (0.5º cross track and 1º along track) this still has an impact on footprint size when, for instance, comparing a range of 5m with a range of 20m.

Speed over the ground.
This is one of the most important factors in achieving high definition surveys. The best multibeam survey detail is obtained at speeds over the ground of 1m per second or less, (approximately 2 knots). Such a low speed is difficult for many survey vessels to achieve and impossible for most helmsmen to consider.

Software used to interpret and display the results
Ideally the data once collected should be analysed using high quality software, such a Fledermaus, Terramodel Visualiser or QINSy. Flying around or rotating 3-dimensional images derived from the survey data is crucial for identifying features and objects of archaeological significance on the seabed or individual parts of upstanding structures. It is important to do this using basic point clouds rather than a visualised surface of the points data, because the rendering can obscure archaeological detail.

Environmental Factors

Sea state during the survey
The advantage to personnel of flat seas is obvious, but such conditions also have the advantage of making the motion reference systems less prone to error.

Maximum depth of water in the survey area
If the site is deep then it is a problem for hull-mounted multibeam systems to collect high definition data (See 7.3.18 above).

Depth variation in the survey area
If the site has great depth variations within it then the range settings have to cope with what is covered by the beams. It may be possible to treat the shallow areas separately to achieve high definition and then survey the deeper water separately to a lesser quality. If there is great depth variation in close proximity, such as in the case of deep gullies, the range normally has to be set to the deepest water otherwise there can be problems with noisy data. It is also difficult to ensure overall coverage of the bottom of gullies because of shadowing from the sides if the survey vessel doesn't follow the line of each gully, and exactly overhead.

Tidal regime during the survey
It is often possible to exploit the minimum depths at low water to get the sonar head close to the seabed to achieve the highest definition. Similarly, it is possible to survey areas at high water which may otherwise be inaccessible by the survey vessel. Such ploys obviously depend on the range of the tide, but the range itself can lead to variations in survey definition if conducted for more than a few hours.

Variation in current strength during the survey
Current strength can be exploited to bring the survey speed down for best results, but currents can also be sufficiently strong to throw a vessel off track unless the surveyor has set lines parallel to the direction of water flow.

Variation in current direction during the survey
Irregular variation can make area surveys along fixed tracks difficult but reverse direction flows can assist in keeping survey speed down by choosing to run every line against the current.

Cost Analysis
Anaysis of system useage and costs
A preliminary cost evaluation of each particular geophysical instrument used has been made in table 14

Table 14 cost analysis

Instrument	Specifications (frequency, depth or horizontal range, range/depth ratio	Application	Footprint @10m, 50m beneath sonar head, and at maximum beam angle	Equipment Cost*	Add on requirements	Addon costs (per day to EH contract)
Multibeam Sonar: Reson 8125 SeaBat	455kHz, 120m water depth, 1:1	Detailed survey Wide area survey	8x16, 45x90 68x16, 340x90	865	POSMV F180 SV Probe SV Sounder RTK dGPS	350 270 25 26
Bathymetric Sidescan sonar: SEA SwathPlus-H	468kHz, 75m water depth, 12:1	Wide area survey, detailed survey	3x19 , 3x96 3x19, 3x96,	300	POSMV F180 SV Probe SV Sounder RTK dGPS	350 270 25 26
Sidescan Sonar: Klein 3000	100/500kHz, 100/300m	Wide area survey	17x3, 3x3 17x3, 87x3	250	dGPS	30
Acoustic Ground Discrimination Sonar: SEA EchoPlus	28/200kHz	Wide area survey	$5.4m^2/3.1m^2$ $136m^2/38m^2$	45	dGPS	30

* this cost does not cover experienced personnel to operate the equipment or processing software costs

Appendix 2 – Technical specifications of sonar systems used during field work

Reson 8125 bathymetric multibeam

The Reson 8125 system has an operating frequency of 455khz, and can cover a 120º swath on the seafloor consisting of 240 dynamically focused beams (Figure 4.2). The 8125 uses focused true time delay beam forming to provide a high level of detail. Up to 240 soundings are collected with every pulse of the multibeam across the swath and this can happen up to 40 times per second depending on the range setting. The system is designed to record features up to 120 metres beneath the sonar head but at that depth, the point resolution is less than for shallower features.

Bathymetric sidescan (Interferometric multibeam system)

The Submetrix System 2000 bathymetric sidescan has 117 kHz sonar transducers with an effective survey depth of 150m which under typical survey conditions manifests itself as a $0.25m^2$ ensonified patch and 25cm depth resolution suitable for widearea surveying. Acquisition settings varied with transmit lengths of 8- 100cps (8-424usec), a ping rate of 3 - 5 per second and 2048 sample receiver length. After testing, it was decided to use the minimum pulse length (8usec) possible for the sonar with the highest ping rate (6 pings per second).

Sidescan sonar

The Klein 3000 sidescan operates on two frequencies, 100kHz and 500kHz and comprises a surface processing unit, a monitor and ‘fish’, deployed and towed from the stern of *Xplorer*.