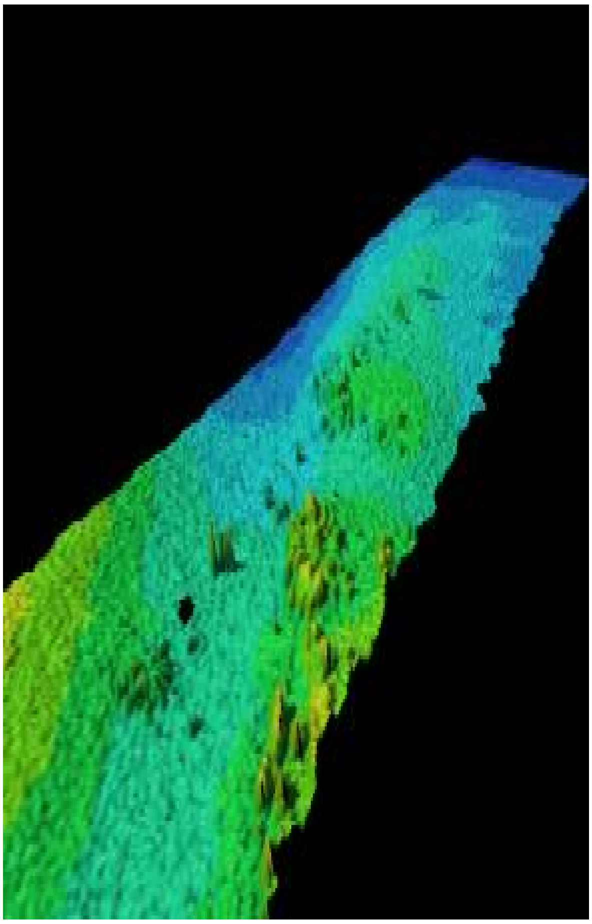
Innovative approaches to Rapid Archaeological Site Surveying and Evaluation (RASSE)

Artificial Test Site Report

For English Heritage

Project Number 3837



Multibeam image of Plymouth test site

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1. Introduction

1.1. This document constitutes a report of work carried out by the RASSE Project (hereafter called 'the Project'), at the University of St Andrews, during Year One of a three year research project for English Heritage (E.H.).

1.2. The work was conducted in accordance with a Project Design submitted by the University of St Andrews to E.H. (Bates et al., 2004)

2. Project aim and objectives

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

2.2. Towards this aim, the Project identified 12 objectives relating to academic research, curatorial management, and dissemination. Those 12 objectives are listed in Appendix I of the Project Design.

3. Summary

3.1. The purpose of this report is to summarise the methodology and results of a programme of sonar system testing on a survey of an artificial test site in Plymouth Sound

3.2. In brief, significant progress has been made on the following tasks mapped to objectives in the Project Design:

Task Number	Description	Objectives
Task M3-1	Preparation of artificial test site	1 and 4
Task M3-2	Testing sonar types and settings etc., on test site	4

Table 1: Tasks progressed in Year One

4. Tasks undertaken

4.1. Introduction

4.1.1. Objective 4 of the project design (Bates et al., 2004) concerns the development of methodologies to maximise the archaeological and environmental detail obtained by high resolution sonar

4.1.2. To meet objective 4, the Project established a test site in Plymouth Sound where a number of artefacts and other objects were deployed on the seabed. The site area was then used to test different sonar techniques for their ability to detect the various objects. The following sections review the sonar methods used and results of surveying.

4.2. Deployment of vessel and on site position fixing methodology

Survey vessel

4.2.1. The survey vessel for the 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 (figure 4.1).

4.2.2. The vessel was chosen because:

- It could effectively house all survey equipment within the wheelhouse
- Its size enabled it to manoeuvre effectively over the test sites
- The RASSE mounting framework for deploying the Reson 8125 sonar head bolted directly on to existing mounting points on the hull, thereby considerably reducing mobilisation time on the sites
- A mounting framework existed on the starboard side suitable for use with the Submetrix bathymetric sidescan
- It came with a skipper used to the requirements for careful, high definition survey works with high-speed transit capability enabled mobilisation and deployment of the sonar in Plymouth within a reasonable timeframe

Position fixing and orientation

4.2.3. For the test site work in Plymouth, 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.

4.2.4. 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.

4.2.5. 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.

4.2.6. 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) [Latitude WGS84]	Northing (UTM 30) [Longitude WGS84]	Elevation (above WGS84 ellipsoid)
Sonardyne Turnchapel	418984.503 [50 21.843999 N]	5579730.800 [004 08.344867 W]	93.033

Table 2: Positions of the Sonardyne base station at Turnchapel

4.2.7. Vessel 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.

4.2.8. 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.

Datums

4.2.9. 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.

4.2.10. For the purposes of the Plymouth survey, the difference in height between the WGS 84 ellipsoid and ODN was calculated using proprietary software.

4.3. Sonar systems used

The RASSE project opted to test a selection of bathymetry (both beam forming multibeam and interferometric) and sidescan system types in 2005

Multibeam sonar (beam forming type)

4.3.1. 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.

4.3.2. 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 depth of water. 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.

4.3.3. 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.

4.3.4. 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 figure 4.3).

4.3.5. 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.

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

4.3.7. 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.

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

Multibeam Sonar data acquisition

4.3.9. 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.

4.3.10. 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.

4.3.11. 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.

4.3.12. 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

4.3.13. 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.

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

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

4.3.16. 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.

4.3.17. 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’.

4.3.18. Therefore single passes at slow speed were used to collect maximum detail of the Plymouth test site rather than combining the soundings from multiple passes to increase data density.

4.3.19. 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

4.3.20. 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.

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

Bathymetric sidescan (Interferometric multibeam system)

4.3.22. 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.

4.3.23. 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).

4.3.24. 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.

4.3.25. 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.

4.3.26. 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.

4.3.27. 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

4.3.28. 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.

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

Backscatter data from swath bathymetry

4.3.30. 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.

4.3.31. Backscatter datasets from the Swathplus were acquired for the Plymouth and *Stirling Castle* sites during the 2005 RASSE fieldwork.

Bathymetric sidescan post-Processing

4.3.32. 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.

4.3.33. 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.

4.3.34. 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'.

4.3.35. 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

4.3.36. 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

4.3.37. 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.

4.3.38. 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. 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.

4.3.39. 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*.

4.3.40. 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.

4.3.41. 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

4.3.42. 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.

4.4. Artificial test site preparation

4.4.1. The objective of setting up was to provide a test area for the refinement of techniques for mapping environmental context, and for maximising the detail obtained from high resolution sonar.

4.4.2. 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.

4.4.3. 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.

4.4.4. 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.

4.4.5. The RASSE 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 4.4). 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.

4.4.6. 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.

4.4.7. A list of the items deployed, their orientation with respect to the line, and their orientation with respect to the seafloor is given in Appendix A.

4.4.8. 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.

4.4.9. 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.

4.5. Survey

4.5.1. 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.

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

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

4.5.4. 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.

4.6. Post processing and analysis

4.5.1 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. Results

5.1. Summary

5.1.1. 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. Appendix A lists the various targets and Appendix B lists the success of detection with the multibeam sonar and the sidescan sonar. Each target that was located or identified is shown in the table in Appendix C. Two views of the site are shown in figures 5.1 and 5.2 from the multibeam and Klein 3000 sidescan survey respectively.

5.1.2. 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.

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

5.1.4. 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 5.3. Further analysis of the records has not been accomplished

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

5.2. Signatures of Individual Targets

Reference should be made to Appendix C with respect to the signatures for the following objects:

5.2.1. **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.

5.2.2. **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.

5.2.3. **$1m^2$ 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.

5.2.4. **Bicycle**

Multibeam – at 25m a ladies bicycle was positioned upright and at 45^{O} 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.

5.2.5. **Ceramic 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.

5.2.6. **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.

5.2.7. **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.

5.2.8. **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.

5.2.9. **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.

5.2.10. **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.

5.2.11. **$1m^2$ 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 the Fig.23 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.

5.3. Analysis - Multibeam

5.3.1. 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

5.3.2. 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.

5.3.3. 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.

5.3.4. 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.

5.4. Analysis – Sidescan Sonar

5.4.1. The information gathered during this test 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 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.

5.4.2. 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.

5.4.3. 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.

5.4.4. 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

5.5. Analysis - Bathymetric sidescan sonar

5.5.1. 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.

6. Conclusions

6.1. 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 6.1 and 6.2 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.

6.2. 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.

6.3. 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.

6.4. 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.

6.5. 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.

6.6. 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.

6.7. 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.

6.8. 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.

6.9. 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.

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8. Figures

Figure 4.1: Survey vessel Xplorer.

Figure 4.2: Reson 8125 Seabat multibeam system twin sonar head configuration and wheelhouse data acquisition hardware.

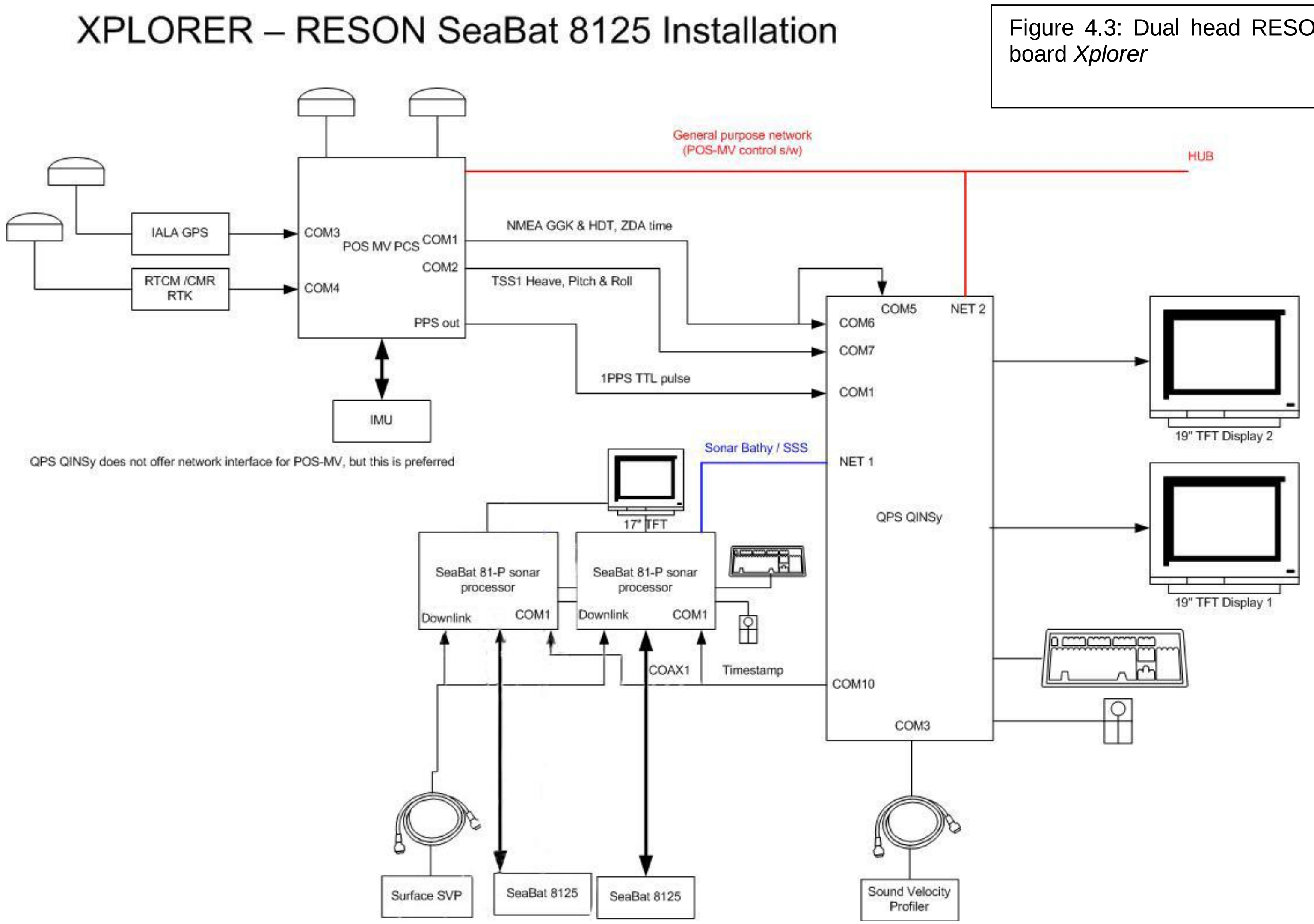


Figure 4.3: Dual head RESON Installation on board *Xplorer*

Figure 4.4 – a selection of test artefacts used at the Plymouth Sound test site

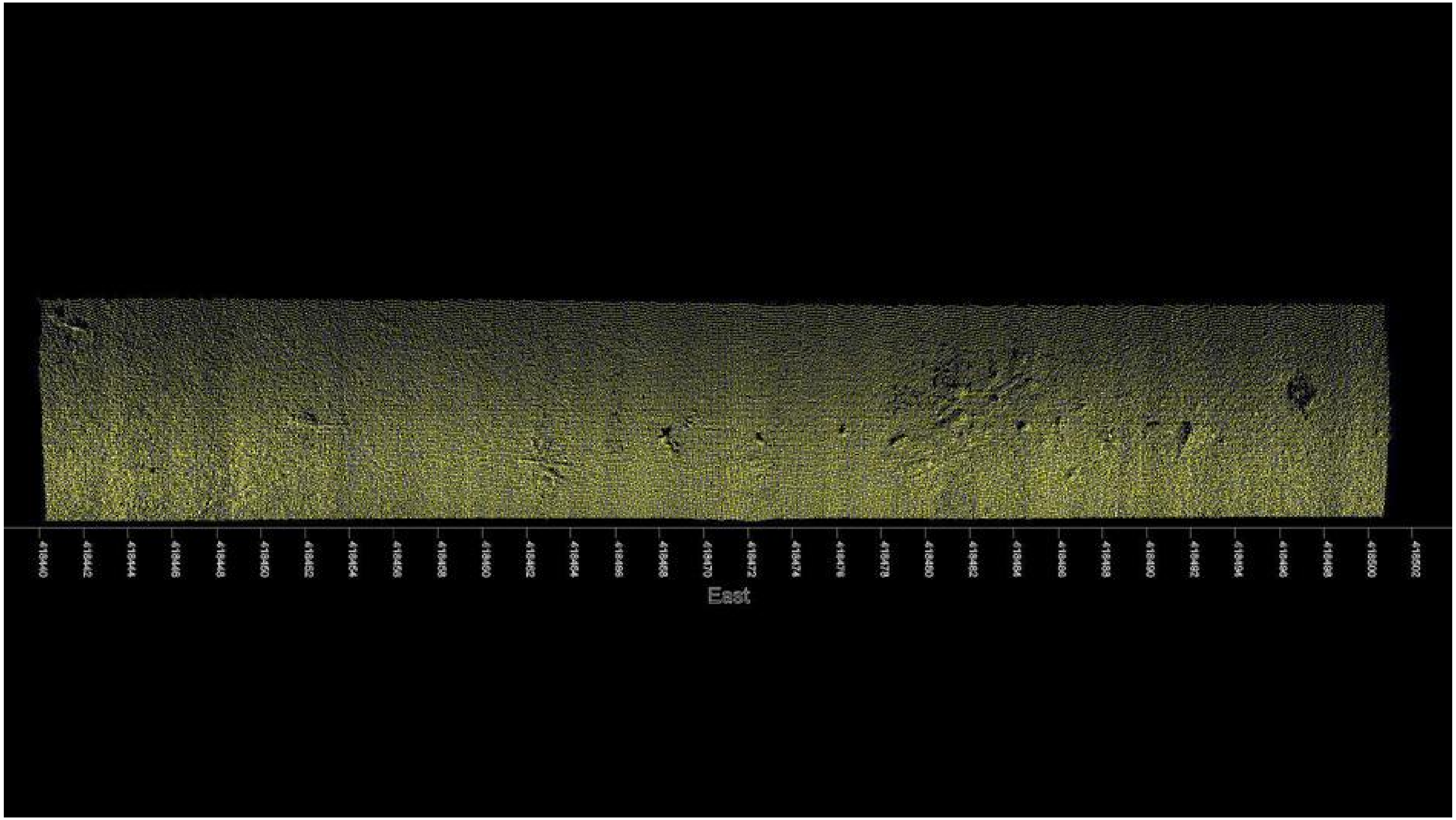


Figure 5.1 Image of **test site acquired with Reson 8125 multibeam sonar**

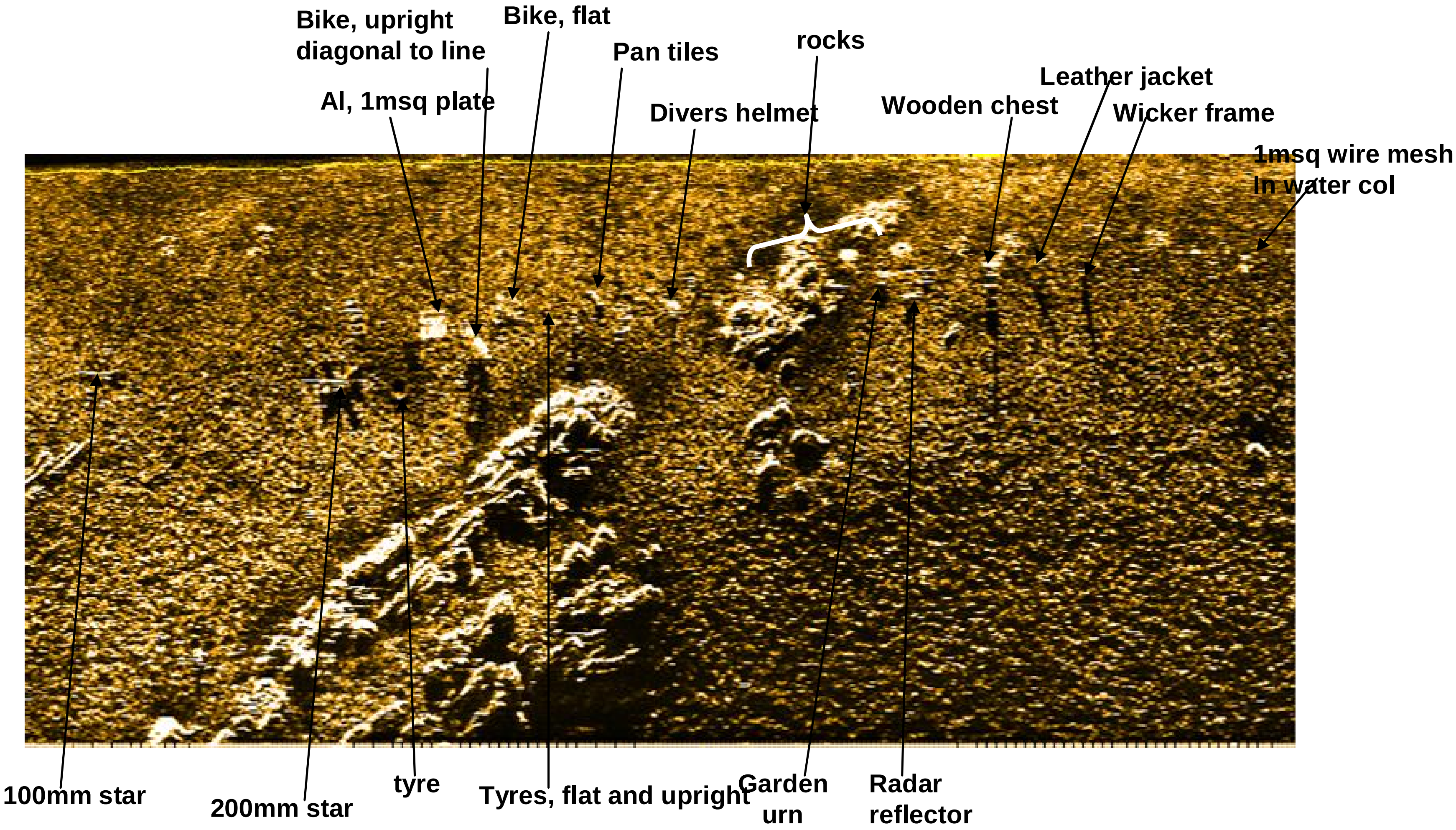


Figure 5.2 Image of test site acquired with Klein 3000 sidescan sonar

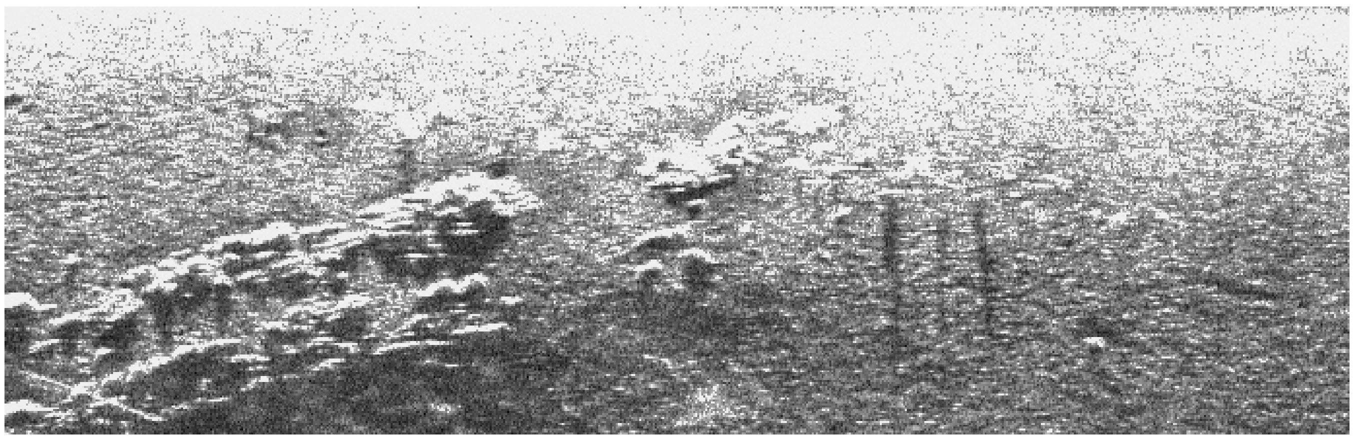


Figure 5.3 Image of test site acquired with Edgetech sidescan sonar

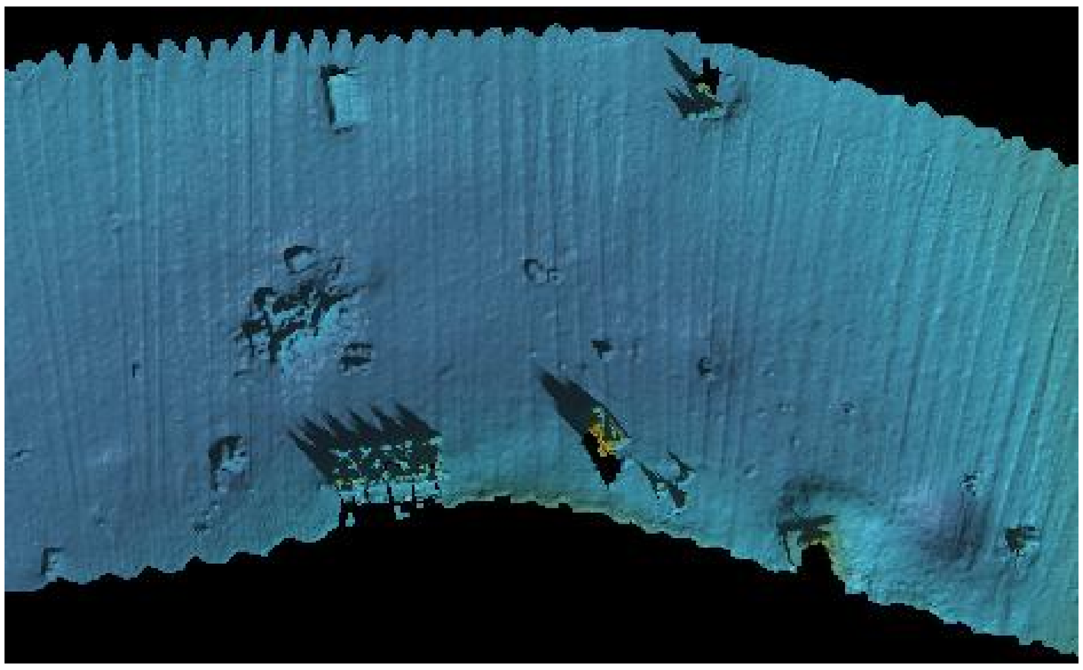


Figure 6.1 Multibeam image of Sonardyne test site

Figure 6.2 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

Appendix A

Test artefacts deployed at the Plymouth Sound site

Appendix B

Target detections

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

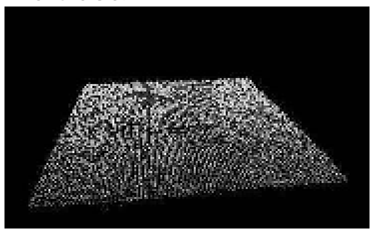
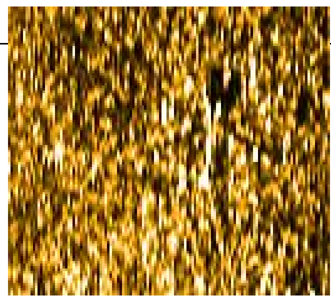
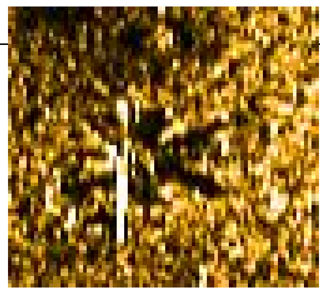
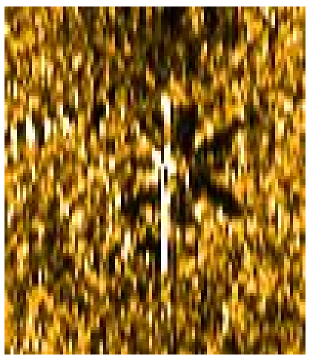
M - Reson 8125 multibeam, S - Klein 3000 sidescan

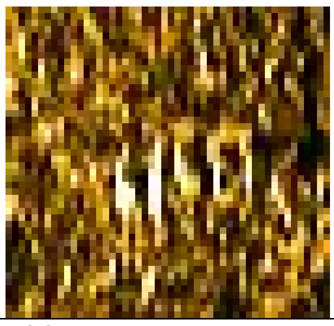
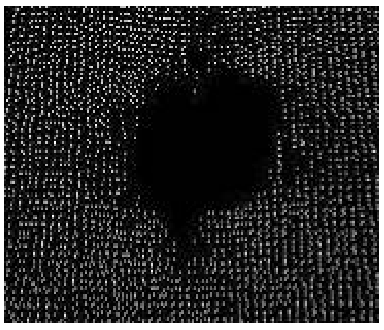
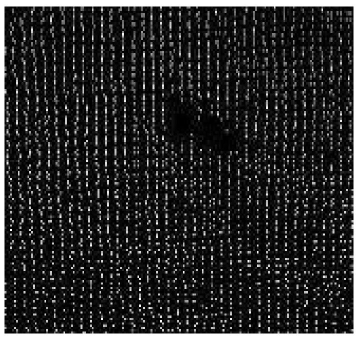
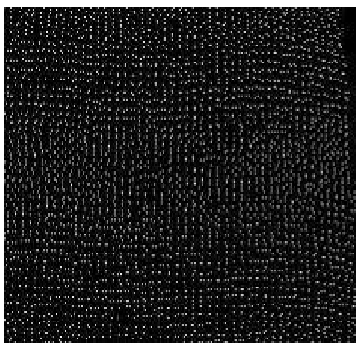
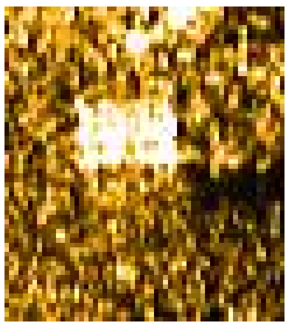
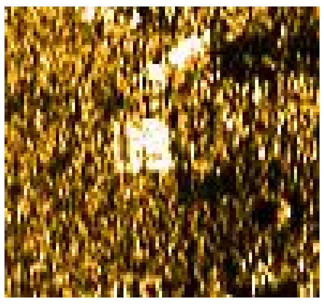
Target		Divers hat		Garden Urn		Radar reflectors		Flowerpots		Wooden Chest		Leather Coat		Timber		Wicker Triangle		Aluminium mesh and tubes	
Sonar run	Line Offset	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S
Line 0 over targets	0m	yes		yes		yes		yes		yes		yes		yes		yes		yes	
Ln3 -25m range	10m north		yes		yes		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

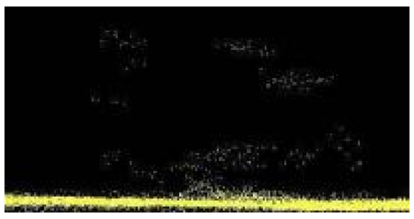
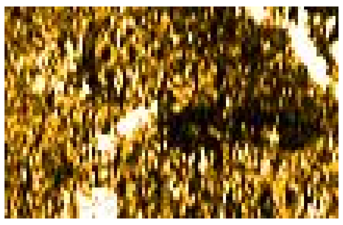
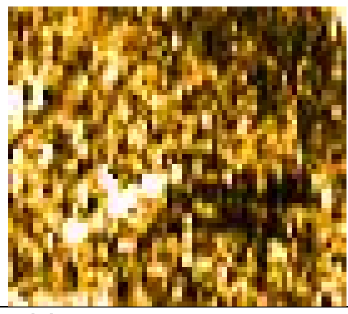
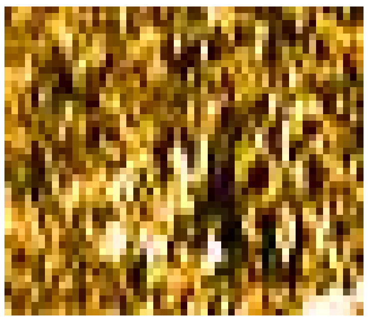
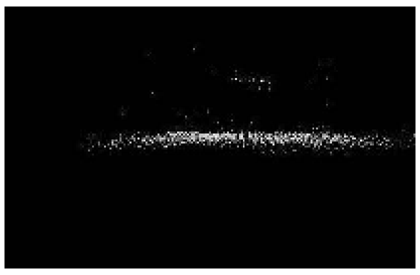
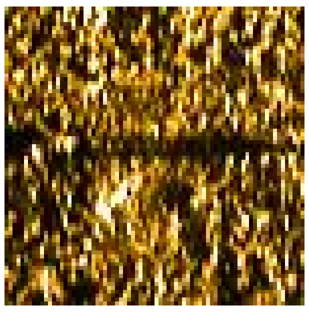
M - Reson 8125 multibeam, S - Klein 3000 sidescan

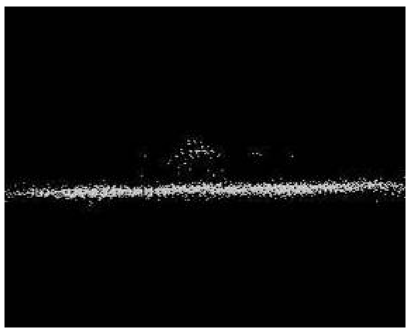
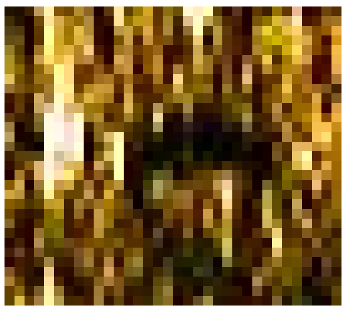
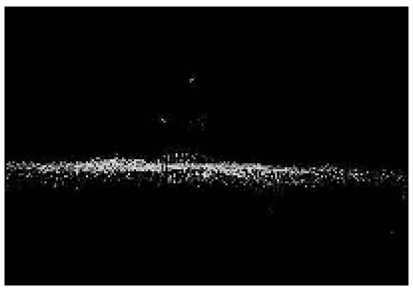
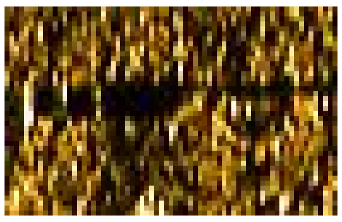
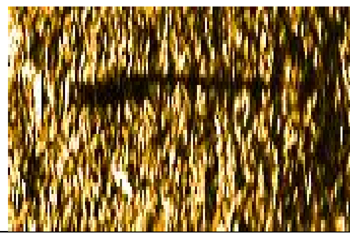
Appendix C

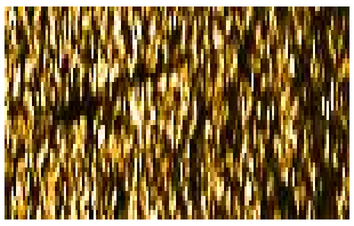
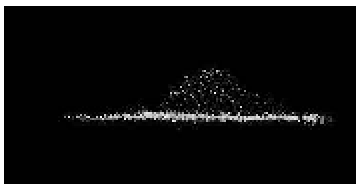
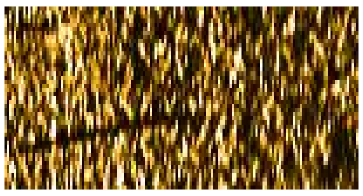
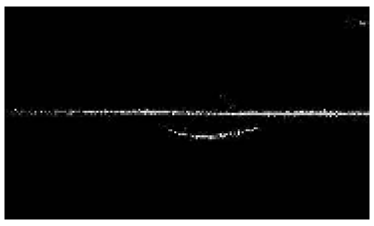
Target objects for Plymouth Test site
Reson 8125 Multibeam images from Terramodel of single passes over the test site
All Klein 3000 images rotated to show sidescan fish to the left of the image

100mm Star 	Multibeam 	
200mm Star 	Multibeam 	 
Large Tyre 	Multibeam	

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