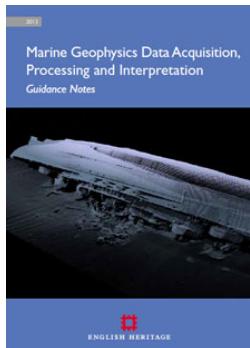




Historic England

Marine Geophysics Data Acquisition, Processing and Interpretation



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Although this document refers to English Heritage, it is still the Commission's current advice and guidance and will in due course be re-branded as Historic England.

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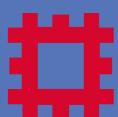
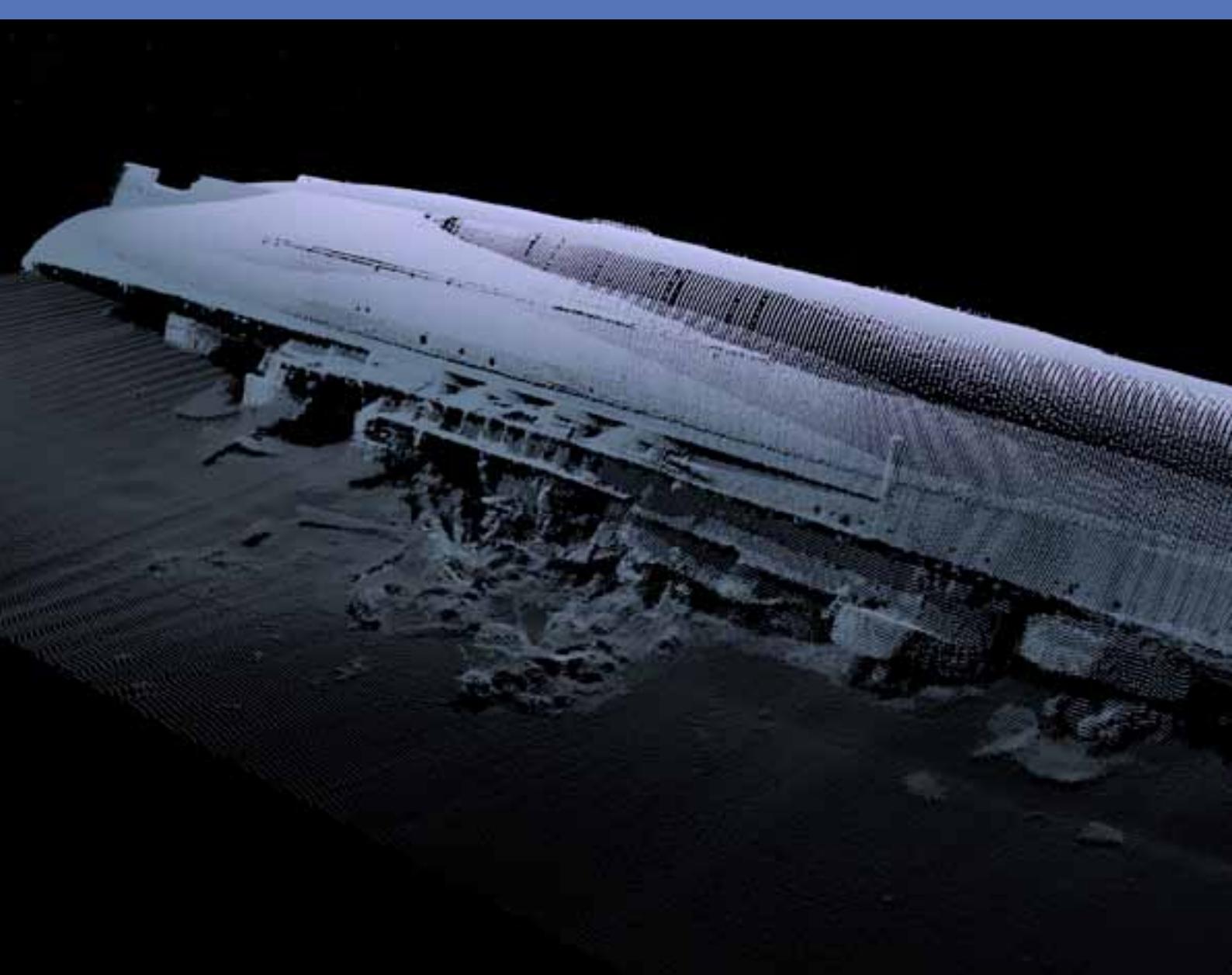
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2013

Marine Geophysics Data Acquisition, Processing and Interpretation *Guidance Notes*



ENGLISH HERITAGE

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List of acronyms

ADS

Archaeology Data Service

ALSF

Aggregate Levy Sustainability Fund

BGS

British Geological Survey

BMAPA

British Marine Aggregate Producers Association

BODC

British Oceanographic Data Centre

CEFAS

Centre for Environment, Fisheries and Aquaculture Science

COWRIE

Collaborative Offshore Wind Research Into the Environment

DBA

Desk-based Assessment

DCLG

Department for Communities and Local Government

DCMS

Department for Culture Media and Sport

Defra

Department for Environment, Food and Rural Affairs

DGPS

Differential Global Positioning System

DNH

Department of National Heritage

Doe

Department of the Environment

EH

English Heritage

EIA

Environmental Impact Assessment

ETRS89

European Terrestrial Reference System 1989

GEBCO

General Bathymetric Chart of the Oceans

GPS

Global Positioning System

GRS80

Geodetic Reference System 1980

HER

Historic Environment Record

HWTMA

Hampshire and Wight Trust for Maritime Archaeology

Hz/kHz

hertz/kilohertz

ICOMOS

International Council on Monuments and Sites

IHO/IHB

International Hydrographic Organisation/Bureau

IfA

Institute for Archaeologists

JNAPC

Joint Nautical Archaeology Policy Committee

JNCC

Joint Nature Conservation Committee

LBL

Long Baseline

LINZ

Land Information New Zealand

MAG

Maritime Affairs Group

MBARI

Monterey Bay Aquarium Research Institute

MCA

Maritime and Coastguard Agency

MEDIN

Marine Environmental Data Information Network

MESH

Mapping European Seabed Habitats

MEPF

Marine Environment Protection Fund

MMO

Marine Management Organisation

MoRPHE

Management of Research Projects in the Historic Environment

ms

milliseconds

nT

nanotesla

NIEA

Northern Ireland Environment Agency

NOAA

National Oceanic and Atmospheric Administration

OASIS

Online AccesS to the Index of archaeological investigationS

PPK

Post-Processed Kinematic

RCAHMS

Royal Commission on the Ancient and Historic Monuments of Scotland

RCAHMW

Royal Commission on the Ancient and Historic Monuments of Wales

REC

Regional Environmental Characterisation

ROV

Remotely Operated Vehicles

RTK

Real Time Kinematic

SAR

Synthetic Aperture Radar

SAS

Synthetic Aperture Sonar

SBL

Short Baseline

TWTT

Two-way Travel Time

UNESCO

United Nations Educational, Scientific and Cultural Organization

UKHO

UK Hydrographic Office

UKOOA

United Kingdom Offshore Operators Association

USBL

Ultra-short Baseline

USGS

United States Geological Survey

US MMS

United States Minerals Management Service

UTM

Universal Transverse Mercator

VENUS

Virtual Exploration of Underwater Sites

VORF

Vertical Offshore Reference Frame

WGS84

World Geodetic System 1984

Preface

These guidelines are part of the ALSF's dissemination of heritage information, which is managed by English Heritage. Previously the ALSF has funded studies of the potential and applicability of geophysical techniques for maritime archaeology, to provide basic information for and characterisation of wreck sites and submerged prehistoric landscapes. In preparing these guidelines we have assessed several projects: *Seabed in Prehistory: Gauging the Effects of Marine Dredging* undertaken by Wessex Archaeology (2008), which ultimately comprises four ALSF projects, 3876, 4600, 5401 and 5684, and the project archive comprises eight individual project reports; *Wrecks on the Seabed/Multibeam Sonar* by Wessex Archaeology (2007), which is again an amalgamation of three ALSF projects, 3324, 3594 and 3877; *Innovative Approaches to Rapid Archaeological Site Surveying and Evaluation*, Bates *et al* (2007) (ALSF project 3837); and High Resolution Sonar for the Archaeological Investigation of Marine Aggregate Deposits, Dix *et al* (2006) (ALSF project 3364). We have also consulted the English Heritage-funded Historic Environments project *Developing Magnetometer Techniques to Identify Submerged Archaeological Sites* by Cornwall Council (Camidge *et al* 2010) and the English Heritage publication *Geophysical Survey in Archaeological Field Evaluation* (2008). The conclusions of these projects, existing guidelines from archaeological and industrial sources and from other marine disciplines, and personal experience help provide guidance notes for a wide range of users.

This document provides information on the most commonly used geophysical techniques in shallow water surveying and guidance on the acquisition, processing and interpretation of geophysical data for the assessment of the archaeological potential of the marine environment. It is aimed at archaeologists (with or without previous geophysical knowledge), geophysicists/surveyors (with or without previous archaeological experience), and developers and planners, thus encompassing people working in industry, government, academia/research and the heritage sector. Targeting such a diverse audience means that these guidelines contain technical information that might seem obvious to one or other group. However, including different levels of information should make this document useful both to people unfamiliar with marine archaeological geophysics and to experienced surveyors or researchers.

We have tried to make these guidelines both practical and informative and able to be used alongside other guidelines and standards without major conflicts. It is impossible to produce fixed standards that can be used in all circumstances. Therefore, the surveyor and researcher should have some freedom to apply his or her own experience and adapt suggested strategies. We therefore stress that this document is for guidance, not a fixed standard or legislation. Our aim is to improve the consistency and quality of geophysical data acquired for archaeological purposes.

Further, these guidelines will have to be revised over time as techniques, methods, software, strategies and legislation change. We suggest that the users of this document report comments and contributions to English Heritage in order to improve and update it in future years.

Part I: Standards for geophysical survey

I Legislation, existing standards and guidance

It is beyond the aim of these guidelines to discuss all legislation, standards and guidelines relating to our underwater heritage. However, despite the fact that none of the existing legislation explicitly regulates the use of geophysical tools for underwater archaeological research, it is important to be aware of this legislation, as it can put restrictions even on non-destructive surveying.

This section lists current relevant acts, conventions, standards and guidelines. The reader is referred to the individual documents or to JNAPC 1995 *Code of Practice for Seabed Development* and to COWRIE/Oxford Archaeology 2007 *Guidance for Assessment of Cumulative Impact on the Historic Environment from Offshore Renewable Energy* for comprehensive contents summaries of such documents.

Currently the *UNESCO Convention on the Protection of the Underwater Cultural Heritage* (2001) is the only global convention concerned with maritime archaeology. Although the UK government has not ratified this convention, it has accepted the Annex of the document as 'best practice'. Rule 4 of the Annex explicitly encourages the use of non-destructive techniques and survey methods in preference to the recovery of objects. The geophysical tools and survey methods discussed in this document are prime examples of non-intrusive and non-destructive techniques that can be used to obtain historical and archaeological information.

On a European scale, the UK government has ratified the *European Convention on the Protection of the Archaeological Heritage* (European Commission 1992) and has signed the *Charter on the Protection and Management of Underwater Cultural Heritage* (ICOMOS 1996). Both documents encourage the use of non-destructive techniques in preference to excavation. Moreover, EU law (*EIA Directive* 97/11/EC – introduced in 1985, amended in 1997; European Commission 1997) requires an EIA to be conducted in advance of certain types of development (ie this often coincides with the license application). As part of the assessment, the direct and indirect effects on the historic environment need to be identified before granting a license will be considered. However, this document does not provide any information on the methods, techniques and strategies that should be adopted.

UK-wide, there are four relevant pieces of legislation dealing explicitly with the underwater cultural heritage, although none specifically mention geophysical surveying techniques:

- *The Protection of Wrecks Act* (Act of Parliament (UK) 1973)
- *The Ancient Monuments and Archaeological Areas Act* (Act of Parliament (UK) 1979)
- *The Protection of Military Remains Act* (Act of Parliament (UK) 1986)
- *The Merchant Shipping Act* (Act of Parliament (UK) 1995b)

On a regional scale there are the *National Heritage Act* (Act of Parliament (UK) 2002) in England, *The Historic Monuments and Archaeological Objects (NI) Order* (Act of Parliament (UK) 1995a) in Northern Ireland, and *The Planning (Listed Buildings and Conservation Areas (Scotland)) Act* (Act of Parliament (UK) 1997) in Scotland. However, in the near future, there may be some changes to the legislation regarding the protection of the marine historic environment in the UK. A draft Heritage Protection Bill was published in April 2008, which sets out the legislative framework for a unified and simpler heritage management and protection. It is based on proposals set out in a White Paper on *Heritage Protection for the 21st Century* (2007). At time of going to press this bill had been dropped from the government's legislative programme.

However, on 12 November 2009 the *Marine and Coastal Access Act* received Royal Assent and is making major changes to the frameworks governing economic

activity and conservation in the marine environment. This Act now forms the chief legislative instrument in the government's drive to achieve its vision for 'clean, safe, healthy, productive and biologically diverse oceans and seas'. The Act aims to introduce a forward-looking, strategic spatial planning system for the sustainable use, management and protection of the marine environment and its high-level objectives are outlined in *Our Seas – A Shared Resource. High level marine objectives* (2009a). The Act also saw the creation in April 2010 of the Marine Management Organisation, which acts as the marine planning authority on behalf of the UK government and as its regulator of most activities (see Defra 2009b *Managing Our Marine Resources: The Marine Management Organisation*). The MMO is tasked to work with English Heritage as the government's statutory advisor on the historic environment, on licensing and marine planning activities. The MMO needs to take account of both the marine heritage landscape and historic sites in developing marine plans and when determining licenses.

Besides legislation, a large number of guidelines have been issued, both on planning and EIA, and on the maritime historic environment specifically. Guidelines on planning and EIA in England specifically include

- *Planning Policy Guidance 16: Archaeology and Planning* (DCLG 1990)
- *Planning Policy Guidance 15: Planning and the Historic Environment* (DoE/DNH 1994)
- *Planning Policy Guidance 20: Coastal Planning* (DoE/Welsh Office 1992)
- *Offshore Wind Farms – Guidance Note for Environmental Impact Assessment in Respect of FEPA and CPA Requirements* (CEFAS 2004)
- *Environmental Impact Assessment: A Guide to Good Practice and Procedures – A Consultation Paper* (DCLG 2006)

Guidance on planning and EIA in Wales specifically includes

- *Planning Guidance (Wales): Planning Policy Section 5: Conserving and Improving Natural Heritage and the Coast* (Welsh Assembly Government 2011a)
- *Planning Guidance (Wales): Planning Policy Section 6: Conserving the Historic Environment* (Welsh Assembly Government 2011b)
- *Welsh Office Circular 60/96: Planning and the Historic Environment: Archaeology* (Welsh Office 1996a)

- *Welsh Office Circular 61/96: Planning and the Historic Environment: Historic Buildings and Conservation Areas* (Welsh Office 1996b)
- *Welsh Office Circular 11/99: Environmental Impact Assessment* (Welsh Office 1999)

Guidance on planning and EIA in Scotland specifically includes

- *National Planning Policy Guideline 5: Archaeology and Planning* (The Scottish Government 1994)
- *National Planning Policy Guideline 13: Coastal Planning* (The Scottish Government 1997)
- *Planning Advice Note 42: Archaeology – the Planning Process and Scheduled Monument Procedures* (Scottish Office Environment Department 1994)
- *Planning Advice Note 58: Environmental Impact Assessment* (Scottish Office Environment Department 1999)
- *Environmental Assessment Handbook* (Scottish Natural Heritage 2005)

Guidance on planning and EIA in Northern Ireland specifically includes

- *Planning Policy Statement 6: Planning, Archaeology and the Built Heritage* (DoE for Northern Ireland 1999)

Maritime historic environment guidance includes

- *Maritime Cultural Heritage and Seabed Development: JNAPC Code of Practice for Seabed Development* (JNAPC 1995 and amended versions in 1998 and 2008)
- *England's Coastal Heritage – A Statement on the Management of Coastal Archaeology* (English Heritage/RCHME 1996)
- *Conserving the Underwater Heritage* (Historic Scotland 1999)
- *Caring for our Coastal Heritage* (Welsh Historic Monuments) (Cadw 1999)
- *Taking to the Water: English Heritage's Initial Policy for the Management of Maritime Archaeology in England* (English Heritage 2002)
- *Marine Aggregate Dredging and the Historic Environment: Assessing, Evaluating, Mitigating and Monitoring the Archaeological Effects of Marine Aggregate Dredging*, Wessex Archaeology, commissioned by BMAPA and English Heritage (BMAPA/English Heritage 2003)
- *Coastal Defence and the Historic Environment* (English Heritage 2003)

- *Protecting our Marine Historic Environment: Making the System Work Better* (DCMS/Historic Scotland/Welsh Assembly Government/Environment and Heritage Service (Northern Ireland) 2004)
- *Protocol for Reporting Finds of Archaeological Interest*, Wessex Archaeology, commissioned by BMAPA and English Heritage (BMAPA/English Heritage 2005)
- *Ports: The Impact of Development on the Maritime Historic Environment* (English Heritage 2006a)
- *Historic Environment Guidance for the Offshore Renewable Energy Sector* (COWRIE/Wessex Archaeology 2007)
- *Guidance for Assessment of Cumulative Impact on the Historic Environment from Offshore Renewable Energy* (COWRIE/Oxford Archaeology 2007)
- *Accessing England's Protected Wreck Sites: Guidance for Divers and Archaeologists* (English Heritage 2010)

Most of these guidelines are aimed at planners and developers. They provide a good background to maritime archaeology and are a guide to good practice. They do not, however, offer detailed information or guidance on the exact geophysical methods, techniques, survey planning, processing and interpretation of data that should be followed. By contrast, a 'manual style' approach has been used in other disciplines and other countries. Examples of this include:

- *Standard and Guidance for Archaeological Geophysical Survey* (IfA 2011)
- *Geophysical Survey in Archaeological Field Evaluation* (English Heritage 2008)
- *Marine Monitoring Handbook* (JNCC 2001)
- *Guidelines for the Conduct of Benthic Studies at Aggregate Dredging Sites* (CEFAS 2002)
- *Review of Standards and Protocols for Seabed Habitat Mapping* (MESH 2007)
- *IHO Standards for Hydrographic Surveys Special Publication No 44* (5 edn) (IHB 2008)
- *Manual on Hydrography* (M-13) (IHB 2005)
- *Archaeological Damage from Offshore Dredging: Recommendations for Pre-operational Surveys and Mitigation During Dredging to Avoid Adverse Impacts* (US MMS 2004)
- *Archaeological Resource Surveys and Reports* (US MMS 2005)

The suggested guidelines in this document can be seen as a supplement to the general guidelines and standards of the maritime historic environment guidance documents

described above. These guidelines strive to provide a single, but flexible, protocol that can be used in all shallow-water environments (ie <200m: lacustrine, riverine and coastal), and that will assist the marine industry in the EIA process, as well as being useful to people in marine development, survey, research and heritage.

2 Geophysics and maritime archaeology

The underwater archaeological resource can be divided into two parts: (1) wreck sites, ie sunken ships and aircraft, and any material associated with such vessels, and (2) landscapes and sites, predominantly prehistoric but also more recent structures (eg harbours and quays), inundated by rising sea levels. Maritime archaeology is a non-renewable resource which is lost forever if destroyed. It is therefore important to preserve or record the artefacts as well as the context in which they are found. Preservation *in situ* should always be considered as a first option and non-destructive methods of investigation should be used wherever possible (UNESCO 2001). High-resolution geophysical instruments are fast and cost-effective tools that leave sites and artefacts undisturbed. They can therefore be used for the non-destructive detection, imaging, research, inspection and monitoring of submerged sites, whether they are exposed on or buried within a river, lake or seabed.

However, archaeo-geophysical survey is only part of a larger staged approach, which should always be preceded by a desk-based assessment (DBA), using the standards and guidance set out by the IfA (2012). Existing archaeological, geological and oceanographic databases should be consulted in order to study the nature and potential of the archaeological resource in addition to geological and hydrographical information (see section 3.1). An inventory and/or discussion of maritime archaeological sites can be found in:

- English waters: English Heritage Archive and HER
- Scottish waters: RCAHMS
- Welsh waters: RCAHMW
- The Regional Research Frameworks compiled by the Association of Local Government Archaeological Officers
- NI waters: NIEA

Furthermore, there are several government, museum, heritage and archaeological bodies holding maritime archaeological archives. A full list can be found in *Slipping*

through the Net? Maritime Archaeological Archives in Policy and Practice (IfA/MAG 2007). Subsequently in 2009, Hampshire and Wight Trust for Maritime Archaeology and the Institute for Archaeologists, with support from the Archaeological Data Service, undertook the project '*Securing a Future for Maritime Archaeology Archives*' (2009), which dealt with *Mapping Maritime Collection Areas, Review of Maritime Archaeological Archives and Access, and Analysing and Assessing Future Archive Creation*. The project should be regarded as the most recent overview of the state of the nation's maritime archaeology archives.

Since 2008 it has also been possible to gain access to the Historic Seascape Characterisation (HSC) maps which provide an understanding of the cultural processes shaping the present landscape in coastal and marine areas (<http://www.english-heritage.org.uk/professional/research/landscapes-and-areas/characterisation/historic-seascape-character/>). The HSC method has now been implemented along the following section of coastline: Liverpool Bay and waters off the Fylde; The Solent and waters off the Isle of Wight; Southwold to Clacton; Withernsea to Skegness; Scarborough to Hartlepool; Bristol Channel and Severn Estuary; The Irish Sea (English sector); Newport to Clacton and Adjacent Water; and Hastings to Purbeck and Adjacent Waters. Resources for the characterised areas are available from <http://ads.ahds.ac.uk/project/alsf/seascapes.cfm>.

If a geophysical survey is to be conducted over a protected wreck site, the appropriate survey license form should be obtained from:

- English Heritage (<http://www.english-heritage.org.uk/server/show/nav.1288>)
- Historic Scotland (hs.inspectorate@scotland.gsi.gov.uk)
- Cadw (Cadw@Wales.gsi.gov.uk)
- Northern Ireland Environment Agency (bh@doeni.gov.uk)

If archaeological sites are detected or imaged on geophysical data, national heritage bodies should be contacted for further advice:

- English Heritage
- Historic Scotland
- Cadw
- NIEA

This document represents the first set of guidelines specifically for the acquisition, processing and interpretation of marine geophysical data for archaeological purposes.

3 General guidance

Recommendations made in these guidelines represent the ideal planning stages and acquisition, processing and interpretation parameters for geophysical surveying of underwater archaeology. However, a clear distinction needs to be made between data collected specifically for archaeological purposes, and data acquired primarily for other purposes (eg pipeline survey) with predetermined survey line spacing and direction, which can subsequently be used for archaeological research (see Part III). In the former case it is highly recommended to follow the proposed guidelines, while in the latter case, the suggested guidelines will have to be adapted. Nonetheless, it is hoped that, where there is the freedom to change survey strategies, the recommendations made in this document will be taken on board.

3.1 Justification for a geophysical survey

Archaeological artefacts are a non-renewable resource. It is therefore important to preserve or accurately record any discoveries, together with the context in which they are found. Preservation *in situ* should always be considered as a first option and non-destructive methods of investigation should be used wherever possible. Therefore, from the viewpoint of maritime archaeological management, fast, cost-effective and non-destructive high-resolution marine geophysical tools offer great potential.

Despite the great potential of such tools, an archaeo-geophysical survey should always be a part of a larger staged approach and good planning of each stage should be the priority before doing fieldwork. The complete planning steps, from start-up to closure of a project, are based on the English Heritage (2006b) *Management of Research Projects in the Historic Environment* (MoRPHE) guides and can be found in Part II of these guidance notes. Important steps before the actual fieldwork should include the production of a project design detailing the aims and objectives, an outline of the planned stages, a justification for the choice of survey methods and an estimate of the time and resources required. At the start of each project, one should think carefully about the type of data that is needed and the reasons for the project in order to justify the use of geophysical equipment and shape the survey design.

A necessary step that should be performed before deciding on the need for a geophysical survey is a thorough DBA, as this will support or oppose the justification for such a survey. It is not only important

to research the archaeological potential of an area before surveying (see sources described above), but also to collate as much geological and oceanographic data as possible. Apart from published information and Admiralty charts, much of this information is presently available from online resources or can be purchased from data service companies. Data that are of particular use, include

- Bathymetric data: data sources include global data-sets such as the GEBCO 30 arc-second grid (*c* 1km grid spacing: www.gebco.net), ETOPO1 1 arc-minute grid (www.ngdc.noaa.gov/ngdc.html) and the SRTM30_PLUS 30 arc-second grid (http://topex.ucsd.edu/marine_topo/); regional data-sets including SeaZone Ltd. 1 arc-second (*c* 25m) grids developed in partnership with the UKHO (www.seazone.com), CMAP 6 arc-second grids (*c* 100m grids: <http://www.jeppesen.com/main/corporate/marine/lightmarine/gb/>) and Olex data acquired through the collation of 2,500 users contributing echo sounder data from all over northwest Europe (www.oce0andtm.com); and local swath bathymetry data-sets including Maritime Coastguard Agency Civil Hydrography Programme data via SeaZone Ltd, Channel Coastal Observatory data (www.channelcoast.org), and in Northern Ireland from the Joint Irish Bathymetric Surveys ([www.jetstream.gsi.ie/jibs/index.html](http://jetstream.gsi.ie/jibs/index.html)).
- Surface sediment, extant sub-bottom seismic data and bedrock information: BGS (www.maps.bgs.ac.uk); the UK DEAL website, a gateway to the UK Offshore Oil & Gas Industry (www.ukdeal.co.uk) and which represents an extensive archive of 2D and 3D seismic and well data; EU-SEASED (www.eu-seased.net) which contains both seabed samples and seismic data from European seas.
- Tide and Wave: Marine Environmental Data Information Network (www.oceanet.org); British Oceanographic Data Centre at the Proudman Oceanographic Laboratory (www.pol.ac.uk); Centre for Environment, Fisheries and Aquaculture Science (www.cefas.co.uk); and the Channel Coastal Observatory.
- Regional Environmental Characterisation (REC) reports, commissioned by the MEPF on behalf of Defra under the ALSF (www.alsf-mepf.org.uk).

A DBA not only avoids duplication of data-sets, but will facilitate survey planning by identifying data gaps and/or useful

geophysical/geotechnical data. When an EIA is required as part of a marine development, a full geological and oceanographic review has to be presented, independent of the archaeological potential of the development area. This review will either be the result of a separate DBA or newly acquired data. It is important that this information is made freely available to the archaeologist in charge of the archaeological assessment. Although this implies that archaeologists are only consulted after the acquisition of geophysical data, it is recommended that the companies requesting the EIA communicate with the archaeologist during the survey planning stage. This will ensure data are gathered that can serve archaeological, geological, oceanographic and biological purposes and avoid, in extreme cases, the need for repeat surveys for archaeological purposes.

3.2 Fieldwork

Before beginning fieldwork, the project manager should make sure that all legal requirements needed to survey the site are authorised. These include legal requirements to survey over protected wreck sites and access permission from landowners/local authorities if necessary (eg access to a pontoon or to set up an RTK antenna onshore). Also check if any protected sites are in the vicinity of the survey area.

The choice of techniques and survey strategy will mainly depend on the type and condition of the archaeological site and the purpose of the geophysical survey. First, a distinction needs to be made between two types of archaeological sites found in the underwater environment: wreck sites (ships and aircraft) and their associated materials; and sites that used to be on land, but are now inundated as a result of rising water levels. This second type includes prehistoric landscapes and more recent structures such as harbours or quays. The imaging and study of wreck sites needs a different approach than that of submerged landscapes.

Second, the purpose of the geophysical survey can be split into two broad types and several sub-types:

- 1 Large area and reconnaissance survey, where data are acquired to investigate the seabed and sub-surface geology, benthic habitats and archaeological potential. The techniques and survey strategies used will therefore be multi-purpose but need to be sufficient to give a clear indication of the archaeological potential of the area. These are typically the type of surveys performed as part of the consents or licensing process.

We can further sub-divide this group based on the commissioning industries:

- a Regional environmental characterisations – led by the aggregate companies through the ALSF-MEPF scheme but providing published outputs of regional information for all offshore users.
 - b Aggregate prospection and extraction – surveys at several stages, including resource assessment, Regional environmental assessment (traditionally done for each licensed area but becoming more site specific as the results from the RECs become widely available) and syn- and post-extraction monitoring.
 - c Pipeline and cable surveys – again both pre-laying and post-laying surveys are typical but with very narrow corridors of survey focused on the proposed cable routes.
 - d Wind farm development – requires pre-consent regional-scale surveys and environmental impact assessments; engineering, archaeology and unexploded ordnance surveys based on precise installation locations and post-installation monitoring.
 - e Coastal/harbour/river structures – The types of developments on coasts, harbours and rivers vary, ranging from dredging to engineering and construction works, and port maintenance and expansion. Each of these surveys needs a different strategy. In most cases a large area survey, assessing any buried or exposed site of archaeological potential is sufficient. However, a more detailed survey, might be desirable if the development is concentrated in a smaller area (<50m × 50m).
- 2 Small area surveys are often, but not uniquely, part of research-led projects and are aimed at more detailed archaeological interpretation and/or the advancement of the use of marine geophysical techniques for archaeology.
- The different approaches described here are also reflected in the data volumes acquired, with one of the major challenges to the commercial and regulatory sectors, as the larger projects such as the Round 1–3 windfarm operations are producing tens of Terabytes of data already and these figures are only likely to increase. Consequently, it will not

always be viable or appropriate to interpret the full data-sets (see section 7) and there may need to be a staged approach to the interpretation process.

3.3 General equipment statement

There are three principal geophysical techniques used for marine archaeo-geophysical surveys, all of which are deployed in conjunction with appropriate navigation equipment, which are described below and in more detail in Part III.

3.3.1 Navigation

DGPS navigational accuracy is a minimum requirement for maritime archaeological surveying. The vertical accuracy of DGPS, however, is not sufficient for the processing of bathymetric data, and tide gauge data must be used. Alternatively, RTK GPS or PPK GPS data can be used to offer centimetric horizontal and vertical accuracy. All navigation data should be recorded separately as a text (ASCII) file.

It is suggested that all marine navigational and positional data are acquired in ETRS89. All data should be tidally corrected to chart datum. Final maps should be created using the UTM projection (the UTM zone and ellipsoid used should be annotated in the map's legend).

3.3.2 Side scan survey

A side scan sonar system is an acoustic device which aims to produce a two-dimensional image of the seabed with near photographic quality. The system is nearly always towed behind the research vessel in a streamlined towfish and can only be used to image archaeological features that lie proud on the seafloor. At present, its main use is for the detection of shipwrecks, but it can equally be deployed for the characterisation of submerged landscapes where a relic land surface is believed to exist.

3.3.3 Bathymetric survey

Bathymetric tools measure the ocean's depth. There are two principal types of system: (1) single beam echo sounders, providing an image of the water depth along the track of the research vessel, and (2) swath bathymetry systems, providing water depth data across a large area of seabed. Single beam echo sounders are not recommended for wreck surveys. Swath bathymetry systems, on the other hand, can be used for both wreck and submerged landscape studies. Not only do such systems provide an image of the seabed, but the reflected acoustic signal (backscatter) can also be used to characterise the seabed.

3.3.4 Sub-bottom profiler survey

Sub-bottom profilers are seismic-acoustic systems that can detect and image structures buried within the sediments. The three systems most commonly used for high-resolution surveying are the boomer, pinger and chirp systems. Whereas the boomer system provides best results for coarser sediments, the pinger and chirp systems deliver greater detail for finer sediments. It is encouraged to use sub-bottom systems in the study of submerged landscapes.

Although sub-bottom data can provide useful information about buried wrecks, the exact location of the wreck site needs to be known in advance. It is not recommended to use sub-bottom systems for the detection of unknown wreck sites.

3.3.5 Magnetometer survey

A magnetometer can be used to detect metallic objects on or buried within the seabed. It does not provide an image of the object. Its main use is for the detection of wreck sites and associated ferrous material.

3.4 Data treatment

The processing of geophysical data generally involves improvement of the signal, by filtering out induced noise, and removal of artefacts created during data collection which could otherwise be interpreted as archaeological artefacts. However, the success of the data processing largely depends on the quality of the acquired raw data. If the acquired data are of very low quality, processing might not be able to improve it sufficiently for use in the detection of archaeological material. If the raw data are of unsatisfactory quality, a re-survey should be considered. For further details on data processing, see individual sections in Part III. Irrespective of the approach used, a record should be kept of all processing steps and archived together with the raw and processed data.

3.5 Data interpretation

Data interpretation (see section 7) should always be undertaken by an archaeological geophysicist and should be done after a thorough DBA of the known archaeology of both the offshore area and the adjacent land margin. Such geophysical data are often used to inform ground-truthing surveys. However, a lack of geophysical signals over a site does not automatically imply that no archaeological material is present. It is recommended that the interpretation is based on a combination of geophysical data (eg magnetometer data with side scan sonar imagery) together with geological, geomorphological and archaeological data.

The level of interpretation that can be undertaken will depend upon the initial data provided and the stage of the commissioned project. In the first instance, and particularly for the larger-scale projects, the marine archaeological geophysicist will be dealing primarily with secondary sources: extant survey reports, archive databases (see section 3.1) and picture images and maps of pre-processed data typically produced as part of the QA process by the survey company. The second level of data provision is typically gridded bathymetry, gridded magnetic data and in some cases gridded geological horizons (such as the bedrock surface) identified from the sub-bottom data and, finally, georectified images of sonar data. The third level of data delivery will be the same as the second but, in addition, raw/processed versions of sub-bottom and side scan data are provided to enable the interpreter to check directly features within the data.

Because of the volumes of data acquired it is common for a sub-set of the data to be interpreted first (for large projects typically 25%) in order to establish the regional palaeo-landscape morphology (eg the presence and course of palaeo-channels). Once major features are identified from this sub-sample, they can then be traced through the additional lines. Similarly, cross-referencing of the data against the known archaeological record such as that recorded in the UKHO wreck database, the English Heritage Archive and HERs allows focusing interpretation in the first instance on these sites to either confirm or not their presence. It is worth noting that in the offshore zone these newly acquired data-sets may represent the best data-sets as yet taken of much of the offshore archaeological resource.

Finally, when specific engineering plans for construction or extraction are developed and finalised, full analysis of all of the geophysical data in the area of actual impact, both during installation and as a product of post-installation changes in the sediment dynamic regime (eg the development of scour pits around individual wind turbines or bridge supports) is essential.

3.6 The survey report

Each survey report should at least include

- Title page
- Summary
- Background information
- Methods
- Results
- Conclusions
- Statement of indemnity
- Acknowledgements
- References and location of archive

It is important that the interpretations in the results section are supplemented with a map showing the survey location and individual survey lines, clear and fully annotated plots, and interpretation maps and diagrams (see section 7.1.2).

3.7 Data archiving and dissemination
All raw, processed and interpreted data should be archived systematically, together with the compiled metadata (see section 5.3.8). At present there is no requirement to archive marine geophysical data; we recommend that the advice given in *Geophysical Data in Archaeology: A Guide to Good Practice* (Schmidt 2002) is followed. English Heritage suggests that a digital record of all data is kept for five years following the completion of a project (MoRPHE Project Planning Note 1; English Heritage 2006c).

A copy of at least the summary of the survey report should be submitted to the administering heritage agency. A full survey report must be submitted if the survey was conducted over a protected site. English Heritage also recommends completing an OASIS record. The overall aim of the OASIS project is to provide an online index to the mass of archaeological grey literature that has been produced as a result of large-scale developer-funded fieldwork (for more details, see <http://oasis.ac.uk/>). Furthermore, it is advocated that the survey information is made as widely accessible as possible. The ADS have also recently developed marine archiving guidelines for large geophysical data-sets (Niven 2009).

Part II: Planning and reporting for a marine archaeo-geophysical survey

4 Archaeology and planning

Planning and preparation of the project stages are key to its success. A geophysical survey can either be a small facet of a larger archaeological project or the main focus of the research. No matter how small or large the contribution of geophysical survey, it is important that it is correctly integrated into the project proposal and subsequent project stages.

The *Management of Research Projects in the Historic Environment* (MoRPHE) (English Heritage 2006b) provides guidelines designed to support the planning and implementation of basic and applied research, and of development projects on the historic environment. It is the model for archaeological projects undertaken or funded by English Heritage, but represents

a good guideline for the archaeological profession as a whole. MoRPHE only covers the project management aspects of archaeological and historical work and should be used in conjunction with other standards and guidelines on specific procedures and techniques. In this document, the planning of an archaeological project is based, with respect to geophysical surveying, on a combination of MoRPHE and *Standard and Guidance for Archaeological Survey* (IfA 2009).

Note that subsequent sections are only guidelines and that the project manager should have the freedom to adapt these depending on the project context (eg threat-led versus commissioned research), complexity and existing in-house management procedures.

5 MoRPHE – a project's life cycle

5.1 Start-up and project proposal

A project begins with a formal or informal decision about a desirable or necessary piece of research. The decision might be part of a research agenda, organisational target or recommendation, or the result of a discussion among colleagues. For example, in a commercial bid, a brief might be sent out to tenders outlining the circumstances to be addressed and the scope of work required. Tenders respond with project specifications or a project proposal with a detailed schedule of work. Assessment of the proposal will lead to a decision on whether or not to proceed to the next stage – the initiation stage. For a project not centred on geophysical survey (eg a dive-based excavation survey of a shipwreck), use of and justification for geophysical methods should be considered at this stage and included in the project proposal. The proposal should outline the most suitable methods and include

- proposed project team, including suggestions for the geophysical experts who will be involved with the acquisition, processing and interpretation of the geophysical data
- estimated budget and timetable

In pure research, with no threat to the archaeology, a project proposal might not be needed, and one can go straight to the initiation stage and the writing of the project design.

5.2 Initiation and project design

The initiation stage should provide an effective and viable project design. The project proposal resulting from the start-up phase could form the basis of this more detailed project design. For a pure research project, the project proposal might be the first written part of the project. A project design should be a comprehensive, free-standing document that assumes no prior knowledge about the project and its circumstances. The style should be concise and include

- project name
- non-technical summary of the project
- background describing the context
(A more comprehensive DBA should be made at this stage. Information should be provided on the site location, context and description, including relevant geological and oceanographic information, designation number (eg English Heritage Archive), archaeological and relevant recent history of the site, ownership or legal limitations associated with the site and any wider project context. If any previous geophysical surveys/pilot studies have been conducted, these should be mentioned and their findings described.)
- research aims and objectives, including a detailed description of the objectives of the geophysical survey and how these fit into the greater aim of the project
- the motivation for carrying out the project, describing why the project should be carried out and why it should be carried out by the proposed project team
- project team (At this stage, a team comprising a project executive, a project manager and a number of project experts should be created. The structure of the team and the role of each member of the team should be described.)
- communications (Explain how the project team is to communicate with each other and how the team should communicate the results to the sponsor or client. A detailed timeline on planned internal and external review meetings should be included.)

- health and safety statement (A detailed risk assessment should be done for each aspect of the acquisition of the geophysical data and deployment of the instruments at sea. All personnel should be aware of the risks involved and measures that need to be taken. Depending on the research vessel used, the seagoing personnel might be required to attend a sea-survival course before sailing. Check with the helmsman well in advance of the planned survey whether this is a legal requirement.)
- methods statement (For the acquisition of the geophysical data, detailed information needs to be given on the technical aspects of the navigation system, on the type of geophysical instruments used, and on the line spacing and sample interval, together with a map of the suggested survey lines. Furthermore, information should be given on the anticipated processing that will be needed, together with the software that will be used for processing and interpreting the data. This statement should include the timetable for all the proposed project stages, with estimated start and end dates, and the expected outcome and product of each stage.)
- detailed budget, including staff costs, contractor costs, non-staff costs, overheads, and any other costs (For the geophysical survey, this should include the rental of the survey vessel, the rental of survey equipment – sometimes including an operator for the equipment – processing and interpretation time, and the possible purchase of software.)
- details on planned publication, dissemination and digital archiving of the raw data and the final products, together with the required metadata and documentation (At this stage consideration should be given to the requirements for archive preparation and deposition and the file formats that will be used for the secure archiving and dissemination of the geophysical data and final report.)

When a license is needed to survey over a designated site, contact the corresponding heritage agency; and where a new project is proposed, the project design must be sent to the heritage agency in order to obtain the necessary license (more information in *Accessing England's Protected Wreck Sites: Guidance for Divers and Archaeologists* (English Heritage 2010)).

This project design should be examined by the sponsor/client and by all those in the project team. Only when all personnel

involved are satisfied with a final draft of the project design can the Project Executive and sponsor authorise the decision to move on to the execution phase of the project.

5.3 Execution stages

Execution refers to the basic research stages. For a geophysical survey the most important are (1) DBA, (2) fieldwork, (3) data processing and analysis, (4) assessment of data potential for further analysis, (5) writing the survey report and (6) main project report, and (7) archive deposition and dissemination. Each of these stages should conclude with a formal review examining their outcomes against the original project design in order to authorise the execution of the next stage.

5.3.1 Desk-based assessment

A DBA should precede all geophysical fieldwork. It should examine existing archaeological, geological and oceanographic archives or databases. This procedure will avoid duplication of data and assesses the archaeological potential of the survey area. Although a DBA will already have been performed in order to write the project design, it is important that existing information is studied in great detail. Not only should information about the site be gathered, but papers and reports detailing geophysical investigations under similar conditions should be reviewed, as these can help with the preparation of the field work.

5.3.2 Fieldwork

The data collection is the central and most important stage of most archaeological surveys. Before going out to survey a site, it is important to check that all required permissions have been obtained; this is usually the responsibility of the project manager. A survey design and plan should have been set out in the project design, outlining the justification for the geophysical methods and techniques to be used and suggested survey lines or grids. This survey plan should be discussed with the helmsman beforehand and adjusted accordingly if necessary.

If the geophysical survey is part of a larger archaeological project, the survey should be timetabled well in advance of any planned destructive survey (eg underwater excavation) leaving sufficient time for geophysical data processing and interpretation. However, guided by findings made during the entire fieldwork stage of the project (destructive or non-destructive fieldwork) the geophysical team should be prepared to conduct another survey (more detailed or extending the area) at the end of the data collection stage if deemed use-

ful or necessary. There are three types of fieldwork, depending on the site and history of surveying in the research area: (a) pilot or test survey, (b) full survey and (c) site revisit. A guide to the choice of geophysical methods and detail on the actual fieldwork procedure for each technique forms Part III of these guidelines.

1 Pilot or test survey

Occasionally it can be beneficial and efficient to do a preliminary test survey to assess the suitability of the chosen geophysical techniques for the site evaluation. Such a pilot survey should not take longer than a day and is therefore mainly recommended for sites that are relatively easy to reach and close to a harbour, pontoon or dock where the survey team can board the research vessel with their equipment. The preliminary information acquired should help to decide which geophysical techniques will give the best results and aid the planning of the survey lines. This test will avoid wasteful deployment of resources. The test survey should also give a clearer picture of the archaeological potential of an area before deciding to collect further data. Depending on available resources, a pilot survey can also be part of the initiation phase – or even before the start-up stage – instead of during the execution phase, in order to investigate the potential of the project before committing to the full project. Additionally, pilot survey results can be included in the project design.

2 Full survey

Once the survey lines have been agreed and permissions acquired, the full survey can go ahead. Depending on the aims and objectives of the project, this survey might be a large or small area survey, detailed or more exploratory, using a single technique or a combination of methods. Key to any archaeological surveying is the ability to be flexible and to recognise when the survey strategy should be adapted in order to provide better results. The appropriate survey strategies for different types of archaeological sites are provided in Part III.

3 Site revisit

Sometimes the main field survey results suggest that an additional survey is desirable or necessary, possibly with the addition of ground-truthing results. The revisit could either be a more detailed survey of parts of the previously surveyed area or an extension of the previously surveyed area. It is important to include the possibility of such surveys into the project design and accompanying budget.

5.3.3 Data processing and analysis

The processing and analysis of the raw data can be done onboard or back onshore. The best option is often to perform crude processing and interpretation onboard, so that the survey strategy can be adapted if necessary. More detailed, labour-intensive data manipulation and analysis can be left for a later stage, back on land. Part III covers more details on specific processing and analysis procedures for each geophysical technique.

5.3.4 Assessment of data potential for further analysis

During the data processing and analysis it might become apparent that the geophysical data have further research potential, beyond the anticipated aims and objectives stated in the project design. This potential should be described in an updated project design or could be turned into a separate project proposal, depending on funds available. These results should be mentioned in the final project report and could be a separate publication.

5.3.5 The survey report

The survey report is the most important end product of the geophysical survey. As for the project design, the survey report should be a comprehensive, freestanding document. The statements made in the report about the results should be based on the assessment of the geophysical data, which was undertaken by suitably qualified marine geophysicists trained in archaeological interpretation, or by maritime archaeologists trained in the interpretation of marine geophysical data.

The minimum requirements for the report are

- project name, authors, contractor, client and data
- non-technical summary of the project
- background information and reason for the survey (aims and objectives as described in the project design)
- methods, including information on the types of equipment used, survey set-up, data processing and software used
- results (These should include an objective description of results as well as a discussion of the analyses and interpretations. These should be accompanied by plots of raw and processed data and interpretative diagrams. It should always be clear from the plots or accompanying figure captions, whether the display is showing raw, processed or interpreted data. In addition, each plot should be annotated fully, including scale bars, north arrows, grid coordinates (if applicable) and a key for any symbols and colour scales used.)

- conclusions, discussing the results in relation to the aims and objectives set out in the project design, the value of the geophysical data and the implications of the findings for the current and future research
- statement of indemnity
- acknowledgements
- references and the location of the archived data

5.3.6 The main project report

If the geophysical survey stands as an independent research project, then the survey report is often the main project report. If, on the other hand, the geophysical survey is part of a larger (archaeological) project, sections of the survey report should be included in the main project report, either within the report or as an appendix. The amount of geophysical data represented in the report will depend on the proportion of its contribution to the main project. It is important that the contribution of the geophysics is not ignored, even if results were inconclusive or negative. At the least, a summary of the survey report should be included. If the survey report is to become widely available at the dissemination stage, then a simple reference to the location of the survey report can be given.

5.3.7 End of project report

This report is mainly aimed at the stakeholders, informing them about the project's closure date, lessons learned, evaluation of the project, location of the archived material, outstanding issues and suggestions for future work.

5.3.8 Final (digital) archiving and dissemination

A comprehensive guide to the archiving of geophysical data is provided by *Geophysical Data in Archaeology: A Guide to Good Practice* (Schmidt 2002). Although aimed at terrestrial survey work, many of the concepts and ideas discussed in this guide can be applied equally to marine geophysical data for archaeological applications. This ADS guide is concerned with how to preserve the large amount of data that is being produced by a geophysical survey in a digital format so it is available for potential future reprocessing and re-interpretation, preventing duplication of existing information. All geophysical survey data are currently digital and are usually no longer accompanied by a paper print-out. Although the digital formats make processing and visualisation easier, they can be a challenge from an archival viewpoint; disks and other digital media eventually degrade and continuously changing technology means that

the data format or media may no longer be readable in the future. As such, the essence of digital archiving lies in short-term security measures, long-term preservation strategies and thorough documentation (Schmidt 2002). For example, secure backup, data refreshment and data storage; and migration from one medium and format to the next through changing technology.

In order to be re-usable, archived digital geophysical data must be fully documented and accompanied by technical documentation. It should include (Schmidt 2002)

- project background, methods and results
- description of the survey's coordinate system
- digital data documentation
- survey documentation (eg size of grids, traverse spacing, instruments used)
- a list of all file names with an explanation of codes used in file names
- data storage (eg format of data, how do the files fit together, hardware, operating system and software (version) used to create them)
- data analysis (eg filters applied to the data, images with interpretation drawings)
- description of known errors or areas of weakness in the data

There is currently no set requirement to archive and disseminate marine geophysical data for archaeological purposes. MoRPHE Project Planning Note 1 recommends that a digital archive is maintained for five years after project completion (English Heritage 2006c) and that an OASIS record is completed. At present, the only facility for digital deposition, dissemination and archiving is provided by the ADS and their guidelines are now available on line. For detailed information regarding the procedures and policies of this facility, the project manager should contact ADS – see <http://guides.archaeologydataservice.ac.uk/g2gp/Main>.

In the case of a survey for which a license was needed from the heritage agency, a copy of the site archive, containing the details of the research and geophysical survey data, must be offered to a suitable public repository so as to make it publicly available (eg the Historic Environment Record of the local county or country). A catalogue of the site archive should be made available to the appropriate heritage management agency.

Survey information should be made as widely accessible as possible. However, if there is any doubt that this might not be appropriate (eg to avoid looting or in the case of client confidentiality), dissemination should be discussed with the heritage agency

and/or client. If the survey information can be made public, the survey report can be turned into a peer-reviewed paper, which will reach a wider archaeological and scientific audience. The leading journals include *Archaeological Prospection*, *Geoarchaeology*, *International Journal of Nautical Archaeology*, *Journal of Archaeological Science* and the *Journal of Maritime Archaeology*. More public forms of dissemination include websites, and public lectures and presentations.

Part III: Practitioner's guide – techniques and geophysical instrumentation

6 Application of techniques

6.1 Navigation, positioning and datum

6.1.1 Navigation and positioning

Rapid technological innovations in the past two decades have made GPS the most widespread navigational and positioning method in the offshore sector. Satellite navigation has almost completely replaced older techniques such as the gyroscopic compass and radio beacon navigation (eg DECCA and LORAN). For this reason, the following section concentrates solely on GPS-based systems.

GPS, or officially NAVSTAR GPS (Fig 1a), was developed by the United States Department of Defense and has three main components: satellites in space, monitoring stations on Earth and the user's GPS receiver. At present, GPS has 31 active earth-orbiting satellites at a height of 20,200km in six circular planes, with orbit durations of 11 hours 57 min 58.3 sec. This configuration ensures that at least four satellites are constantly detectable at any time from any point on the Earth's surface, regardless of weather conditions. Each of these satellites broadcasts two signals combining three components: a carrier wave with short wavelengths (~20cm), ranging codes (C/A and P codes) with long wavelengths (~300m and 30m respectively) and a navigation message. For standard GPS, the C/A code and navigation message are used to calculate the longitude, latitude, altitude and time of the GPS receiver using a process called 'trilateration' (Fig 2). Each satellite broadcasts a signal that contains its position and time of transmission as a sphere. Two such spheres intersect in a circle, whilst three spheres intersect in two unique points. The fact that the Earth can be seen as a fourth sphere results in a single location in space with a known position. However, to improve the positional accuracy, a fourth satellite is needed. This is because the receiver's clock, often a quartz clock, is no match for the highly

accurate atomic clock inside each satellite and, therefore, needs to be calibrated to within a nanosecond of these atomic clocks. If this is not done, the positional accuracy would only be within hundreds of kilometres. Therefore, the information of a fourth satellite is received and the receiver's navigation device looks at a single time correction that would make all four signals intersect at one single point on the Earth's surface. This then gives the receiver atomic time accuracy and ensures metric positional accuracy. However, induced errors can, in a worst case scenario, reduce the final horizontal accuracy of GPS up to the order of several tens of metres. Factors causing such errors include ionospheric effects (the speed of the GPS signal is affected by atmospheric conditions in the ionosphere), ephemeris errors (errors in the positional information transmitted by the satellite), satellite clock errors (errors in the satellite clocks caused by noise and clock drift), multi-path distortion (the radio signal can reflect off surrounding terrain, buildings, and other similar factors), tropospheric effects (humidity in the troposphere affects the speed of the GPS signal) and numerical errors (caused by the finite precision of machine computation and truncation errors). The vertical accuracy is generally two to three times worse than the horizontal accuracy and is therefore often ignored by manufacturers and surveyors.

In order to correct for the various errors of GPS and to increase positional accuracy, Differential GPS (DGPS) can be used (Fig 1b). The system uses two receivers: one stationary receiver with a known position, and a roving station to take position measurements. These two receivers are sufficiently close to each other, in relation to the satellites in space, to have the same GPS errors. Because its position is known, the stationary receiver can calculate the timing errors for all visible satellites. This information is transmitted, mainly by ultra-high-frequency beacon transmitters, to all roving receivers and is used in combination with the collected GPS data to determine horizontal positions with accuracies between 1 and 5m. The vertical accuracy will again be approximately twice the horizontal accuracy and therefore cannot be used during data processing (eg for tidal corrections). Most UK differential beacons offer free differential services and the system works to within 2,000km of the fixed GPS receiver (a list of European Differential Beacon Transmitters can be found at <http://www.effective-solutions.co.uk/beacons.html>). At present, DGPS is a widely used system in the marine sector.

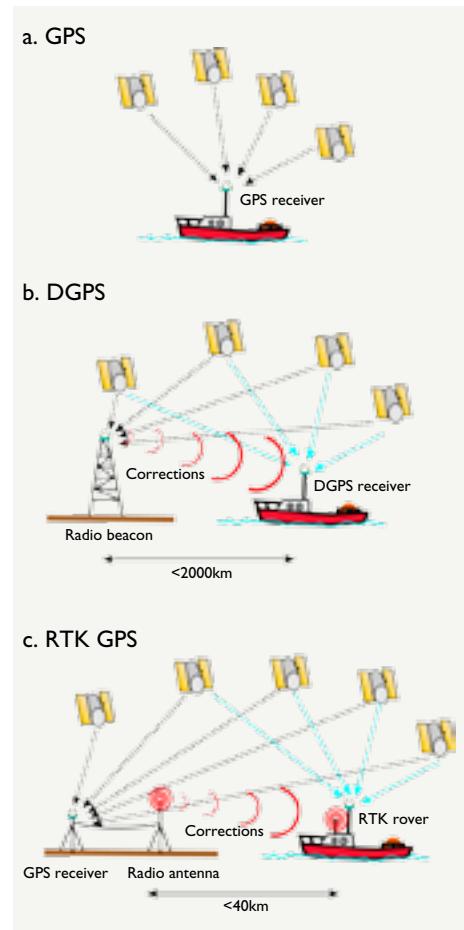


Fig 1 GPS-based navigation and positioning systems.

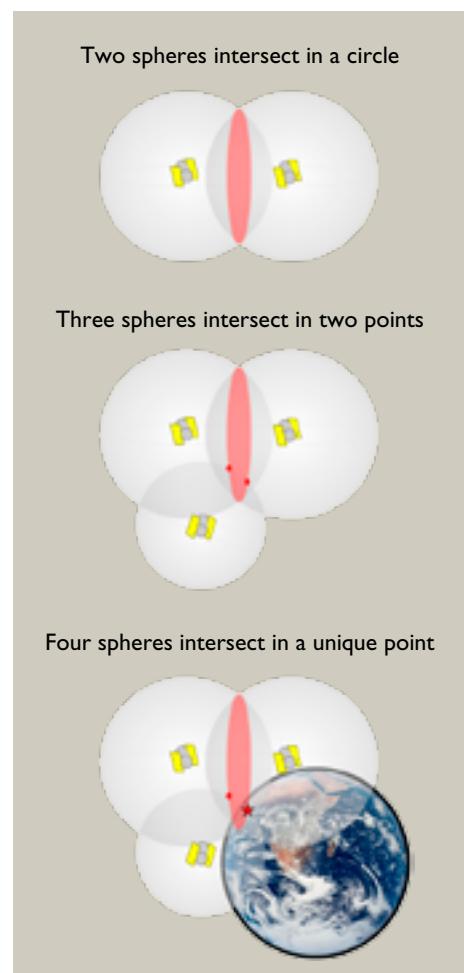


Fig 2 Principle of trilateration.

Sometimes metric accuracy is not good enough, and a horizontal and vertical centimetric position may be needed (enabling vertical measurements to be used during data processing). Such high accuracies can presently be obtained by a technique using carrier phase measurements, called Real Time Kinematic (RTK) GPS (Fig 1c). In the same way as DGPS, RTK uses a static monitoring receiver, placed at a known location, and a roving station. In contrast to standard GPS and DGPS, the monitoring station observes the phase of the much shorter, and more precise, carrier wave ($\sim 20\text{cm}$ versus $\sim 300\text{m}$ for the code wavelength) broadcast by the GPS satellites. The base station aligns this received short sinusoidal wave to a replica signal it generates itself. The receiver can estimate the travel time of the satellite's signal by determining the shift needed to line up the received and generated signals. However, because simple sinusoidal waves are being used, this lining up of the signals is ambiguous. That is, alignment can be achieved by shifting the signal over part of a wavelength or over any arbitrary number of full wavelengths.

The process of ambiguity resolution is complex and is referred to as 'initialization'. The more satellites the base station can track during initialization, the faster the process is completed. At least five satellites are needed to complete the initialization phase. After initialization, the information from only four satellites is needed. The base station then broadcasts a phase-corrected signal from its known position to the roving receiver via a radio link. The roving station in turn compares the received base station signal with its own phase measurements. This results in a millimetric relative position between base station and roving station, while the absolute position depends on the positioning accuracy of the base station. To obtain the corrections, the RTK system needs its own base station, rather than a free radio beacon broadcast. Additionally, the base station must be close enough to the roving station to avoid ionospheric delay of the broadcast-corrected signal and to account

for the relatively weak power of radio signals. A survey must take place within a maximum radius of 40km around the stationary receiver, although, in practice, this radius is often reduced to 20km.

It must be noted that the DGPS and RTK methods, described above, communicate the corrections to the rover in real time. However, it is possible to collect the GPS data without any corrections and then later process them to DGPS or RTK standard in the office. This process, called post-processing kinematic, needs specialised software and data from a reference station with a known location. Although this technique can be used without problems for mapping purposes, it cannot be used for accurate navigation.

In all cases it is important that the receiver antenna is located on the vessel in such a way that it is free from any obstructions, allowing a clear view of the sky (ie commonly on the highest point of the vessel). When the position of equipment used away from the survey vessel (eg towed equipment and ROVs) needs to be known very precisely, acoustic positioning systems can be used together with GPS, DGPS or RTK information. There are three primary acoustic positioning techniques: long baseline (LBL), short baseline (SBL) and ultra-short baseline (USBL) positioning.

The LBL technique consists of three or more transponders positioned at a known position on the seabed (Fig 3a). The distance between two transponders (ie the baseline) can vary from 100m to over 6km. A transceiver fitted on a surface vessel, ROV or towfish interrogates the transponder net using an acoustic signal. Each of the transponders responds with a unique acoustic reply, which is picked up by the transceiver. The elapsed time between interrogation and the received reply is used to calculate the position of the moving object, using triangulation, relative to the seabed reference coordinate system. Knowledge of the GPS positions of the acoustic network on the seabed then enables calculation of the absolute position. LBL systems are used for large area surveys.

For the SBL system, the transponder net on the seafloor is replaced by three or more transceivers fixed on the hull of a surface vessel, with baseline distances ranging from 10m to 50m (Fig 3b). Heading, pitch and roll must be measured continuously, because the transceivers are mounted on the ship, creating a coordinate system fixed to the vessel. A single transponder, mounted on an ROV or towfish, replies to acoustic signals transmitted by the transceivers, which, in turn, record the elapsed time between interrogation and response. The position, relative to the surface vessel, is then calculated as for the LBL technique. The SBL method is only rarely used.

USBL is more commonly used. It is well suited for short-range navigational projects (Fig 3c). A single array of transceivers is mounted on the research vessel and replaces the multiple transceivers of the SBL system. The transceiver array sends out an acoustic pulse, which a transponder mounted on an ROV or towfish detects and replies to. The returned signal is received by the transceiver array. Phase comparison techniques (which determine the bearing relative to the transceiver) and the time lapse measurement between interrogation and response enable calculation of the position of the transponder relative to the survey vessel. Similar to SBL, the coordinate system is fixed to the vessel, hence, the heading, pitch and roll of the vessel need to be known. Furthermore, the USBL transceiver needs careful adjustment and calibration before use.

The relative accuracy of these systems depends on the transmitted frequency used, with low frequencies (8kHz–16kHz) obtaining relative accuracies between 2m and 5m, and high-frequency systems (200kHz–300kHz) obtaining accuracies $<0.01\text{m}$. The final, absolute, position of the towed equipment or ROV will depend on the accuracy of the transponder net on the seabed or on the navigational system deployed at the surface on the survey vessel (GPS, DGPS or RTK). Note that to obtain the best possible position, the velocity of sound through the water should be measured accurately.

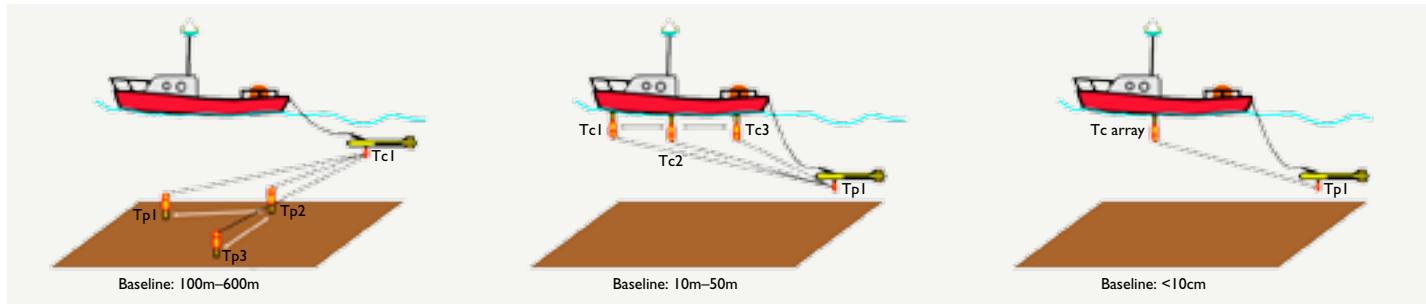


Fig 3 Acoustic navigation and positional systems.

The positional accuracy required depends on the type of survey proposed for the project and conducted. The accuracy possible depends on the survey equipment used. DGPS is currently the standard system used in shallow-water marine surveying and is a minimum requirement for the acquisition of geophysical data for submerged archaeological sites. Below, the positional system required for satisfactory results for different archaeological survey designs is described for each type of instrument.

If the acquired geophysical data cannot be accurately positioned during the processing and interpretation stage, it becomes useless. In all cases of surveying for archaeological purposes, positional accuracy of $\leq 1\text{m}$ is recommended. The navigational logging should be done at a rate of at least 1 fix per second and a real-time track display should be available for the helmsman to view. It is important to check the navigational data, which need to be of sufficient and consistent quality, during acquisition. In many cases it is possible to integrate navigational information directly with the geophysical data through the acquisition system. However, it is good practice to also log the navigational data separately as a text (ASCII) file as a back-up in case something goes wrong with the acquisition software or additional corrections or coordinate transformations are needed. In case the navigation is not directly recorded with the geophysical data, care needs to be taken that the acquisition system's clock is synchronised with the GPS clock of the navigation system.

6.1.2 Datum, coordinate system and projections

Geodesy – the science that aims to determine the shape and size of a simplified earth in order to define a terrestrial coordinate system – is a complex subject. There is no single agreed coordinate system, but, in practice, the modern GPS coordinate system is the most commonly used for marine surveying. Moreover, a clear distinction has to be made between a coordinate system used during the acquisition of the data (eg WGS84) and a coordinate system and projection used for post-processing and data presentation (eg UTM).

In order to define a coordinate system, a suitable origin and the direction of a set of 3D axes in relation to the earth need to be defined, together with a reference surface (ellipsoid or geoid) that best fits the earth with respect to its topography. The definition of such spatial relationship is called 'a geodetic datum'. The geodetic datum used for GPS is WGS84. It is a global, earth-fixed

Cartesian coordinate system represented by OXYZ Cartesian axes and a best-fit ellipsoid (GRS80) with their origin at the centre of the earth's mass. The direction of the axes, orientation of the ellipsoid equator and meridian of zero longitude coincide with the earth's equator and prime meridian as defined by the Bureau Internationale de l'Heure at midnight on 31 December 1983 (this was 102.5m east of the Prime Meridian at Greenwich). However, in reality, as a consequence of tectonic plate movement, all points on earth move with respect to this earth-fixed global coordinate system (in the UK coordinates change by about 25mm per year). Hence, WGS84 in itself is not suitable for mapping projects.

To deal with this problem, WGS84 has been adapted in various parts in the world to be useful for mapping but still compatible with GPS. To do this, a particular moment in time (ie an epoch) is selected and the WGS84 coordinates of several points in a region are stated at that epoch. Thus, to remove the effect of tectonic movement, a new datum is created, which initially coincides with WGS84 but then stays stationary while moving away from the WGS84 Cartesian axes and ellipsoid. In Europe, ETRS89 is such a realisation of WGS84 and is a datum that coincided with WGS84 in 1989. Anyone who receives DGPS corrections from European stations will obtain them in ETRS89. All Ordnance Survey coordinates and all Admiralty charts of the British Isles are currently being transferred to ETRS89 datum. It is therefore suggested that all marine navigational and positional data should be acquired in ETRS89. However, for surveys in close proximity to the shore, and where onshore and offshore archaeological, topographic and bathymetric data must be integrated, the UK National Grid system (OSGB36) is still used.

Bathymetric (vertical) datums on Admiralty charts, tidal prediction and tide gauge data are currently still provided in chart datum (CD). In the UK, chart datum refers to the lowest astronomical tide (LAT), and therefore varies regionally – ie different areas experience different magnitudes of tidal rise and fall, and hence each chart/map has an applicable CD. In addition, different countries may use different definitions for chart datum (eg mean sea level). The UK Hydrographic Office has noted that chart datum is not a sustainable vertical datum and, ultimately, aims to refer all heights and depths to ETRS89 datum, though this may not take place in the near future. At present, a homogeneous minimum sea surface is being derived and its relationship with ETRS89 and other

vertical datums are being modelled as part of the Vertical Offshore Reference Frames (VORF) project, sponsored by the UKHO. However, until such reference frames are fully established, it is suggested that data are adjusted and tidally corrected to chart datum (LAT). In order to be able to do this, tidal data need to be obtained. Such data will not only be used to adjust all acquired data to chart datum, but should also be consulted during the survey planning stage, especially for very shallow areas. Tidal corrections can be obtained from hydrographic models; however, it is likely that for most sites the regional models are not of sufficient accuracy to fully account for all local tidal variations. It is therefore recommended that either a tide gauge is deployed at the site for the duration of the project, or that data from a nearby permanent tide gauge (eg available from the BODC, Channel Coastal Observatory and UKHO; see the MEDAG data resource) is used to adjust the geophysical data or, more appropriately, that the survey is conducted using a full RTK GPS system for tidal height adjustment. The latter approach has the advantage that it compensates for both the influence of long-period swell and tides.

After data acquisition and processing, the results have to be presented on two-dimensional maps using a map projection. A map projection is defined as any function that converts ellipsoidal latitude and longitude coordinates to easting and northing coordinates. The axes for these eastings and northings (or plane/grid/map) are in metres. It should be emphasised that visual display is a final step and should not be used for computations: all computations should be done in latitude-longitude or Cartesian coordinates. There are several ways to project the earth's surface onto a flat plane; the most widely used is the Transverse Mercator Projection, which is a cylindrical map projection. On a global scale, the UTM projection is a recognised mapping standard (except for polar regions). The UTM system is divided into 60 longitudinal zones, each 6° in width extending 3° on each side of a central meridian. Each of these zones is a different projection using a different system of coordinates and, therefore, care should be taken not to combine objects from different UTM zones into a single map. Three UTM zones are used in the UK: zone 29 (central meridian 9°W), zone 30 (central meridian 3°W) and zone 31 (central meridian 3°E). Although the WGS84 ellipsoid is used as the underlying model of the earth for the UTM projection, the International 1924 ellipsoid is usually used in the UTM projection in Europe.

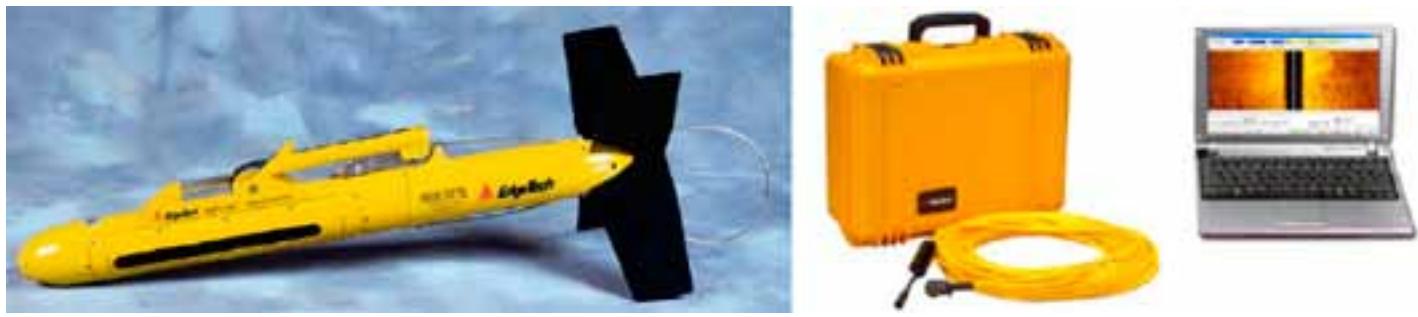


Fig 4 Side scan sonar system (Edgetech 4100 dual frequency).

As UTM is the most widely used map projection in the ever-more-popular GIS (Geographic Information System) software, it is suggested that all maps are created using the UTM projection. It is important, however, to annotate the UTM zone of the map and the ellipsoid (WGS84 or International 1924) used in the legend.

However, it is sometimes necessary to present the data in a more regional coordinate system. This is particularly true in the coastal zone where links need to be made with terrestrial information or data previously recorded in a regional coordinate system. In Great Britain, many of the older coastal data (geophysical, oceanographic or archival) are presented using the National Grid coordinate system. This consists of a geodetic datum using the Airy ellipsoid, a terrestrial reference frame called OSGB36 and a Transverse Mercator Projection using eastings and northings. OSGB36 was created by the triangulation of concrete pillars erected on prominent hilltops around the country between 1936 and 1953. Nowadays, the National Grid coordinates are no longer determined by the theodolite but by a GPS network. Transformation software, using the National Grid Transformation OSTN02 (freely available from <http://www.ordnancesurvey.co.uk/gps>), enables recorded ETRS89 positions to be converted to the National Grid with minimal errors, but is only effective to 10km offshore.

Note: Whether converting from WGS84 to UTM or to OSGB36 (or with extant data-sets in the opposite direction) the reader is referred to the conversion statements and parameters in UKOOA (1999).

6.2 Side scan sonar survey

6.2.1 Instrumentation – side scan sonar
A side scan sonar system is an acoustic device that aims to produce a 2D image of the seabed of near photographic quality. Although side scan sonar systems have been used commercially since the 1970s, they were initially too expensive for archaeological use. At that time their resolution was only just high enough to detect and locate larger sites. Since then, technological advances have made side scan sonars powerful enough and portable, requiring little power and able to display detailed information about a wide variety of sites. Until the recent emergence of high-resolution multi-beam sonars, it was the most commonly used geophysical system for maritime archaeology.

For a conventional side scan sonar two sets of transducers (one port and one starboard) are carried by a streamlined towfish, towed behind the survey vessel (Fig 4). The towfish ensures that the transducers are far enough from the noise generated by the vessel, increases the stability by reducing pitch and roll and enables the system to 'fly' within a few metres of the seabed. Each transducer transmits a fan-shaped acoustic pulse (ping) perpendicular to its travel-path. The transducers act as both source and receiver, which means that the transducer alternately switches between emitting and registering signals. The frequencies emitted can range from 100Hz (long range, tens of kilometres) to over 1MHz (short range, in metres). More commonly, side scan systems used for surveying in shallow water produce a frequency between 50kHz (medium range, hundreds of metres) and 500kHz (short range, tens of metres), with pulse

lengths of tens to hundreds of seconds. Systems that operate at two frequencies simultaneously (eg 100kHz and 500kHz) are being increasingly used. The generated side scan beams are narrow in the horizontal plane (along-track direction) and wide in the vertical plane (across-track direction) (Fig 5). For the dual frequency system, for example, the horizontal beam is smaller than 1° and the vertical beam can vary between 40° and 60° . Such angles enable the sonar to ensonify a narrow strip of the seabed while the sonar transmits vertically into the entire water column.

As the beam propagates through the water, it will eventually interact with the seafloor or with objects on it. Most of the energy is reflected away from the side scan sonar system as the result of specular reflection. A small portion of the energy is lost in the subsurface and another small portion, known as backscatter, reflects back to the side scan system. The amplitude of this returned signal is measured by the transducers, together with the travel time, amplified, recorded and displayed as a time series.

Data from different pings are stitched together to display a long continuous image of the seabed. The amount of backscatter is determined by three factors: the local morphology of the surface ensonified, the small-scale (sub-metre) roughness of the surface and the material properties of the seafloor. The image is created by a black-to-white display of the strength of the returning energy. Traditionally, the stronger the returning signals, the darker the tonality, with a lack of returning energy (eg a shadow behind an object) being displayed as lighter tones. However, this was a product of the thermal printers commonly used with the side scan systems of the time. Modern computer-based acquisition packages have no such limitation, so the current convention is to display shadows as black tones and strongly reflecting targets as light tones. The travel times give information about the distance travelled from the transducer to the seabed, called the slant-range, but should not be confused with the horizontal distance between the sonar and the target.

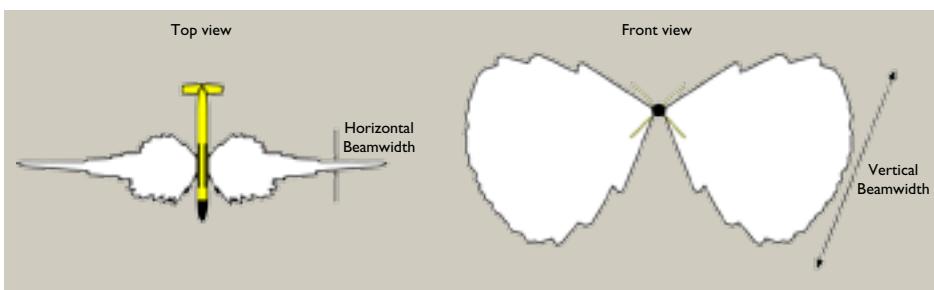


Fig 5 Typical horizontal and vertical side scan sonar beam pattern (modified from Fish and Carr 1990).

This configuration provides the archaeologist with imagery of semi-quantitative information on the morphology of the seabed equivalent to aerial photography and also a first-order-magnitude description of the material variability of the seabed (ie the distribution of different sediment types). Figure 6 shows an example, with commonly used key terms.

Side scan resolution is divided into transverse and range (Fig 7). Transverse resolution is the minimum distance between two objects parallel to the line of travel that is displayed as separate objects. This resolution is determined by the vessel speed, ping rate (dependent on the range setting) and width of the horizontal beam on the seafloor. Close to the towfish, the horizontal beam spreading is significantly smaller than farther away, where a wider area of the seafloor is insonified. The horizontal beam angle depends on the frequency and shape of the transducers: higher frequency and larger transducer diameters produce narrower beams. Close range and large ping spacing results in under-sampling, and features might be missed. In contrast, at far ranges separate objects might lie within the same sonar beam and appear as a single, smeared object.

Range resolution is the minimum distance between two objects perpendicular to the line of travel and is determined by the pulse length of the acoustic beam. Higher-frequency sonars produce smaller pulse lengths (ie the amount of time the sonar emits the acoustic pulse). This resolution is also a function of the display/recording mechanism – across-track spacing between data points corresponds to the swath width (range) divided by the number of points (pixels) recorded. By selecting a certain range the surveyor can control the resolution of each pixel size, depending on the digitisation rate of the system (eg a range of 50m provides a total swath width of 100m). The sampling digitisation rate can be between 8-bit and 24-bit – 8-bit corresponds to 2^8 samples and 24-bit to 2^{24} samples, hence 24-bit digitisation provides orders of magnitude higher fidelity.

The most limiting factor of conventional side scan sonar systems is the relatively poor transverse resolution caused by limits to the beam-forming process. As discussed above, the spatial resolution is different close to the side scan transducer than it is farther away, and becomes unacceptable beyond a certain point. Theoretically, the produced beam could be narrowed by either increasing the frequency used (which would result in more attenuation of the emitted beam)

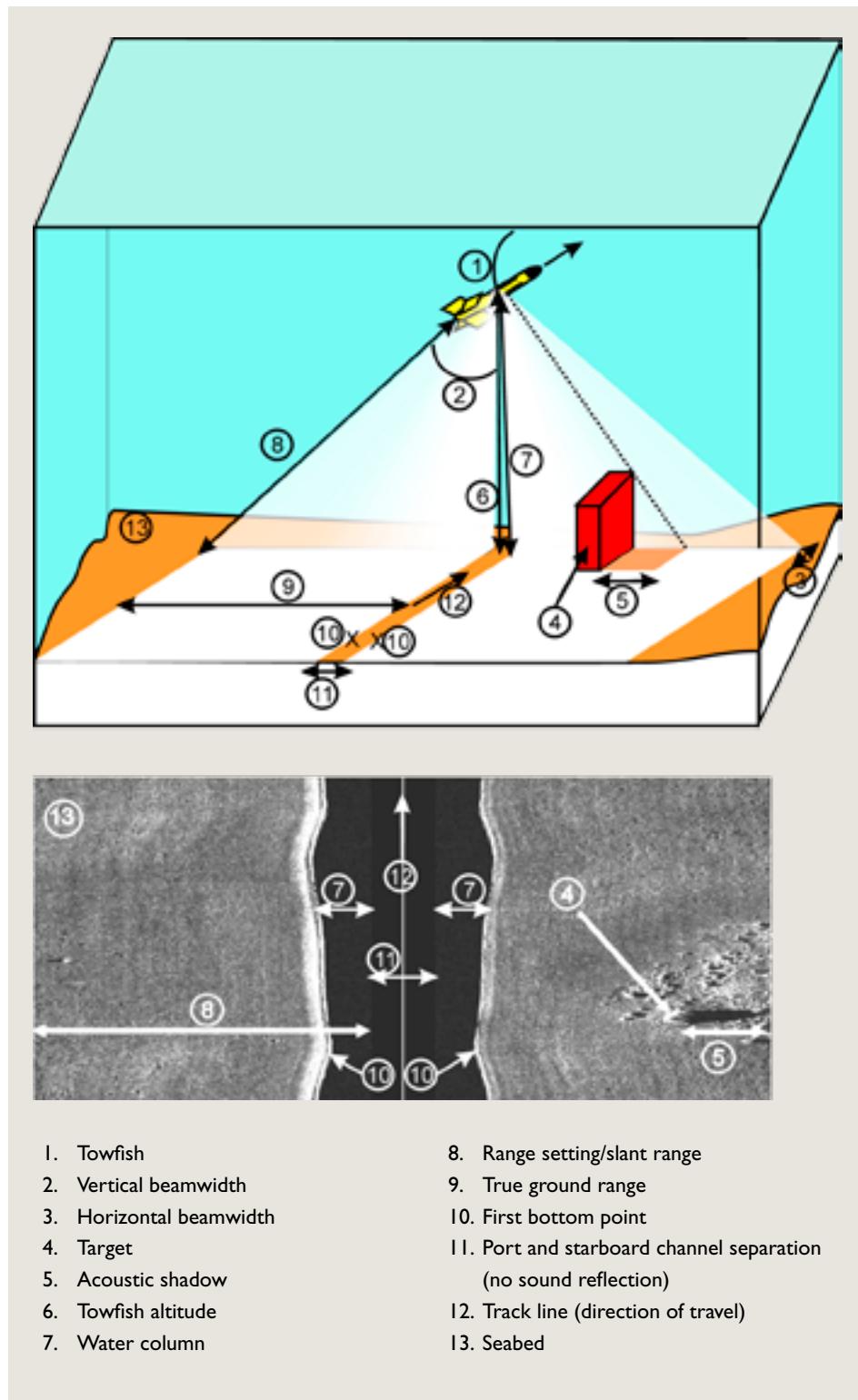


Fig 6 Key terminology for side scan sonar use.

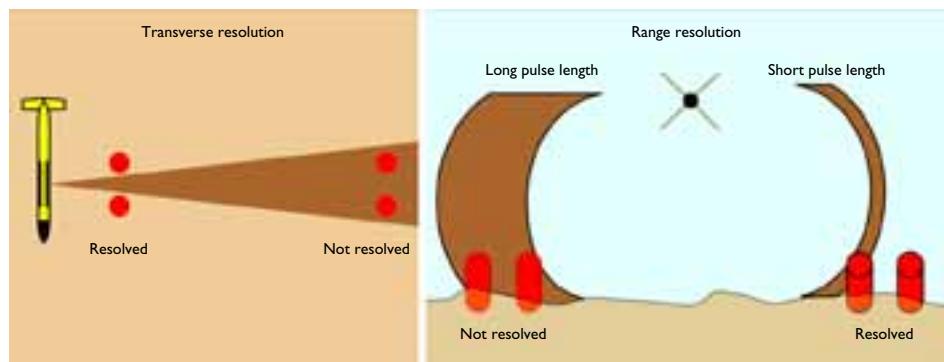


Fig 7 Side scan sonar transverse and range resolution principle (modified from Fish and Carr 1990).

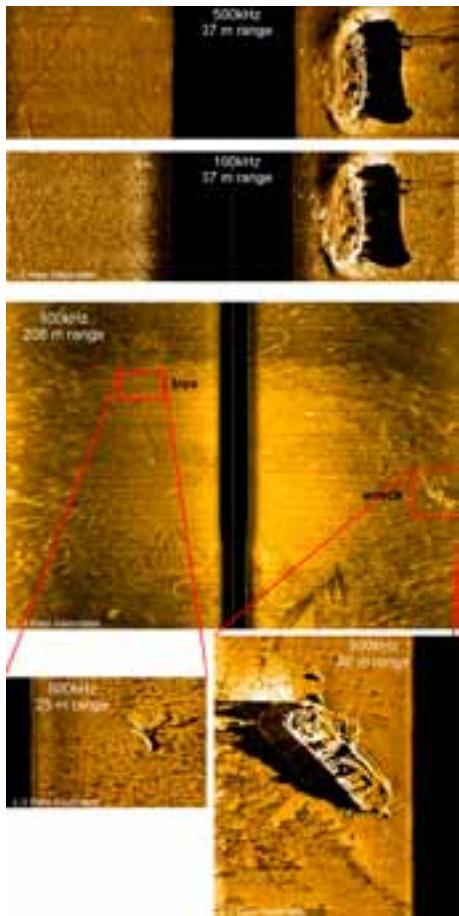


Fig 8 Difference in image quality depending on selected side scan sonar frequency and range (images available from http://www.l-3klein.com/image_gallery/image_gallery.html).

or increasing the array length (which would make deployment unfeasible). It has to be noted that side scan systems are most commonly described in terms of frequency and often the purchase of a particular system is based on frequency content. However, one should be aware that the beam angle and pulse width ultimately determine the resolution that can be obtained. Hence, a system with higher frequency does not automatically mean higher resolving power (eg Quinn *et al* 2005) (Fig 8).

This trade-off between resolution and range is being investigated and the disadvantages of a wide beam width have been turned into an advantage by the development of a synthetic aperture sonar (SAS; Fig 9), whose operation is comparable to that of the aircraft-borne synthetic aperture radar (SAR). The sonar system is made up of a towfish on which a pair of transducers, receiver arrays and motion sensors are mounted. The principle of SAS is to illuminate a single object on the seafloor several times with a wide-beam acoustic pulse as the sonar moves along a line, effectively creating a large array of synthetic transducers. As the returned signals are received, they are combined by post-processing. In order to achieve

this, the motion of the sonar needs to be known in great detail. The advantage of the system is the ability to obtain high-resolution imagery ($<100\text{mm} \times 100\text{mm}$), which is not range dependent, using relatively low frequencies ($<200\text{kHz}$) and without the need for excessively long arrays. The improved resolution, in comparison with the conventional side scan system, comes at the cost of increased computation, as the position and motion of the towfish need to be known exactly and used in the post-processing of the data. Furthermore, unlike SAR, SAS is still in development and needs to be deployed relatively slowly to obtain high resolution. Although there are SAS systems commercially available and fully operational (eg EdgeTech 4400-SAS, Kongsberg HISAS 1030) the system is still rarely used by the marine industry or by archaeologists. However, as seen in the progress made since the 1970s for conventional side scan sonar, further developments in SAS in coming years might mean it could become a valuable marine acquisition technique for archaeology.

Another recent advance is the commercial development of a 'multi-pulse' side scan sonar (eg EdgeTech 4300-MPX, EdgeTech 4700-DFX, Klein 5000 Series). A consequence of the narrow beam width of the traditional high-resolution side scan sonars is that the survey speed normally needs to be reduced to 5 knots or less to ensure full seafloor coverage along track. The 'multi-pulse' side scan system, however, emits several (normally four or five) simultaneous, adjacent parallel beams each side of the track, enabling 100% area coverage and increasing the operating speed to 10–16 knots.

6.2.2 Survey design – side scan sonar

1 General methods – side scan sonar

To avoid wasting transit time, before the research vessel departs, test the side scan system thoroughly by a 'rub-test'. Set up the system on land or on deck as it would be used in the water, triggered and rubbed on one side of the transducers. Then check whether a trace appears on the correct side (to check whether channels are correctly wired) and on only one side (to check for crosstalk between the transducers). Do the same with the other transducer and then again for the first transducer. This test confirms that the power and signal connections are intact.

The survey grid should be agreed with the helmsman before starting the survey. Conventionally, data are acquired by following alternate parallel lines running in opposite directions, generally with an overlap between adjacent lines. In areas with strong tidal streams, currents or swell, the side scan sonar should be towed with and against the current. Where currents are not a problem, the fish should either be towed parallel to the bathymetric contours or parallel to the physical directions of principal features of interest, if known (eg channels, sand banks, outcrops, wrecks). By surveying parallel to features elevated from the seabed, sufficient shadows are produced, which aids detection and interpretation. It is therefore useful to gain information on the nature of the seafloor and sea conditions in the area when planning the survey grid.

The side scan fish is normally towed from the side of the vessel from a crane or davit, or from the stern through an A-frame. When lowering the towfish into the water, reduce the vessel's speed sufficiently for safe deployment. Once the side scan system is in

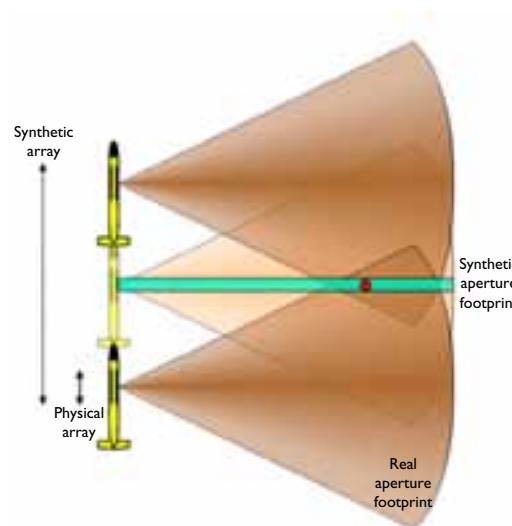


Fig 9 Synthetic aperture sonar principle and image example: German WW2 submarine U-735 submerged in 180m water depth in Oslo Fjord. Image taken at a range of c 200m with a theoretical image resolution of $3 \times 3\text{cm}$. (Image taken by Kongsberg HISAS 1030.)

the water, switch on the trigger and recorder and increase the vessel's speed to normal surveying speed. Then lower the towfish to the required depth above the seabed by paying out the tow cable. The ideal surveying speed for side scan survey is between 2.5 and 3 knots. These low speeds, however, can make it difficult for the helmsman to steer the vessel and keep it on the planned track. In practice, the survey speed should not exceed 4 knots in order to acquire sufficiently high-resolution data for archaeological purposes. It can be increased significantly (up to 10–16 knots depending on the system used) when data are acquired with a multi-pulse side scan sonar. During data acquisition, the sonar must be positioned close to the seafloor in order to obtain the greatest possible amplitude contrasts where objects cause the biggest shadows. Aim the side scan fish's height at one-tenth of the range setting when used on its own (eg range of 50m = height of 5m) to optimise the ensonifying geometry. When the side scan is used in conjunction with a magnetometer, determine the towdepth by whichever system needs the shortest distance to the seabed. This implies that the helmsman or surveyor needs to keep an eye on the water depth using the vessel's echo sounder and warn the side scan sonar operator when the towfish's depth needs to be reduced. Conversely, to ease interpretation, raising and lowering the towfish should be minimised, and hence aim at a compromise of ideal water depth versus frequent towfish movement.

When turning, the data are normally not of sufficient quality for recording, so increase speed to keep the towfish high enough above the seabed to reduce survey time. The longer the towcable (or the deeper the towfish) the wider the turns need to be to avoid contact with the seabed. During acquisition, keep an accurate survey log of details on the lay-back of the towfish, equipment settings and any events that occur during the survey. If possible, integrate navigation directly with the side scan data through the acquisition software, together with a lay-back correction. When a USBL system is used, the USBL position corresponds to the location of the side scan sonar, hence removing the need for lay-back corrections and improving the data's positional accuracy.

Although side scan sonar paper records are still commonly used and can be helpful to annotate features during a survey, data should be recorded digitally. While gain filters can be applied for real time display, recorded files should be raw data (ie no processing applied). There are several file formats for recording side scan sonar data,

including .xtf (eXtended Triton Format), SEG-Y and W-MIPS. The most commonly used is .xtf, and for ease of data transfer between different processing platforms it is recommended that all digital data are recorded in this format.

2 Wreck site survey design – side scan sonar

When surveying for wreck sites with a side scan sonar, a distinction should be made between reconnaissance surveys and detailed surveys of known sites. For both cases, however, a dual-frequency side scan sonar with a lower frequency of c 100kHz and a high frequency c 500kHz will yield the best results. If a dual-frequency system cannot be used, then a high-frequency system (~500kHz) is recommended. If time and resources permit, a maximum line spacing of 30m is recommended, with alternate lines running in opposite directions. However, when surveying a larger area for potential wrecks a maximum line spacing of 50m could be used, with alternate lines running in opposite directions. It is good practice to run some lines perpendicular to the general survey direction (ie every 200m–250m). A search coverage of 2× full seafloor (with 100% area overlap) is required in order to illuminate potential wreck material from opposite angles. A full seafloor coverage with 50% area overlap is acceptable if an extremely large area needs to be surveyed. The exact survey requirements for marine development projects will need to be determined on a case-specific basis in consultation with English Heritage. In combination with the suggested line spacing, a range setting of 50m will provide the required ground coverage. Range settings of >100m suffer from too much attenuation away from the transducers, especially for the higher-frequency channel.

In areas where currents do not dictate the survey direction, the survey direction should be determined by the physical features on the seabed. While, for geological purposes, the side scan should be towed parallel to the principal direction of natural features (channels, sand banks, outcrop), for archaeological wreck detection it is better to survey perpendicular to such features. In areas with large natural features on the seabed, surveying along axis might result in wreck material being positioned in the acoustic shadow zone. The chance of detecting artefacts in such environments is better when surveying perpendicularly to the conventional survey direction. This reiterates the importance of studying geological and oceanographic information as part of the DBA.

For large-area surveys, DGPS navigational accuracy combined with a lay-back correction should suffice. Not knowing the precise position of the towfish in the water automatically reduces the positional accuracy from several metres up to tens of metres, and would make RTK GPS positional accuracy a waste of resources.

When the (approximate) position of a wreck site is known or a potentially interesting anomaly has been detected during a reconnaissance survey, make a more detailed side scan survey. Initially, run a few lines to determine the exact position, extent and direction of the wreck as described above, or determine this from earlier surveys. The high-frequency channel (~500kHz) will give the most detailed information about the site.

Known wreck sites should then be 'boxed'; that is, acquire a minimum of four side scan lines, both along and perpendicular to the main axis of the wreck (in alternating directions). Use a maximum line spacing of 30m, with a maximum range setting of 50m; a coverage of 2× full seafloor search, with 100% area overlap, is essential. Keep the vessel's speed as low as practically possible. This way, an area of 150m × 150m, with the wreck site in the centre, is imaged in great detail. If the wreck material has been dispersed over a larger area, enlarge the 'boxed' area. Do this by increasing the number of lines, not by increasing the line spacing or the range setting. At all times aim to fly the side scan at a distance between 3m and 5m above the wreck site, but increase this distance if 3–5m would endanger the wreck. Centimetric accuracy might be required for such detailed surveys. If resources allow, using an onboard RTK GPS system is recommended; also the use of USBL tracking to track the side scan sonar system.

3 Submerged landscapes survey design – side scan sonar

Side scan data give a digital image of the present seabed and can only be of interest to submerged landscape research when used in conjunction with bathymetric and sub-bottom data. Acquiring side scan data for palaeolandscape evidence is similar to geological survey and should, therefore, be similar to the usual practices of the marine industry.

If possible, acquire data parallel to the bathymetry or parallel to the main axis of natural features (channels, sand banks, outcrop). Ideally, a dual frequency (100kHz and 500kHz) system should be used, for both frequencies might contain useful information. However, if a dual-frequency system cannot be used, then use a medium-range sonar (>50kHz) for large area surveys and

a high-range sonar (>450kHz) for detailed area surveys. Use a maximum line spacing of 50m, running lines in alternating directions with several perpendicular lines crossing the survey grid spaced 200m–250m. Keep the range setting below 100m (ideally between 50m and 75m) and aim to achieve 200% area coverage (100% overlap). Depending on time and resources, an area coverage of 150% may be acceptable (50% overlap). The side scan fish should be towed between 5m and 7m above the seafloor.

For large regional surveys, DGPS navigational accuracy can be used in conjunction with a measurement of the towfish's lay-back. When an interesting feature is detected on the side scan imagery, 'box' and survey as described above, preferably using RTK GPS combined with a USBL.

Finally, the line spacings described above are for research standard surveys and will vary with the different purposes of offshore survey.

6.3 Bathymetry survey

6.3.1 Instrumentation – bathymetry

Techniques to measure the ocean's depths changed significantly during the 20th century. Until the 1920s, bathymetry was determined by the lead and line method. In the 1950s, single-beam echo sounders were developed and have been used in hydrographic surveying ever since. Swath bathymetry systems have been tested from the 1960s and were first used commercially in the 1970s. However, only after the 1990s did the system gain popularity in the hydrographical and archaeological worlds. This section explains the principles of the acoustic bathymetric

survey systems, but mainly concentrates on swath techniques, as it is believed that these are now regarded as the standard survey tool for coastal and shelf surveying.

1 Single-beam echo sounders

These measure the depth to the seabed by recording the time a sound pulse takes to travel from the transducer to the seabed and back (Fig 10). The mean speed of sound through water (a typical value of 1480ms to 1500ms is commonly used) enables conversion of TWTT to depth: depth = (TWTT time/2) × the velocity of sound through water. The frequencies used by commercially available systems range from 10kHz to 200kHz. For high-resolution mapping, high-frequency systems with narrow beams (typically between 2° and 5°) need to be used in order for the circular footprint to cover a small enough area to obtain sufficient accuracy. The transducer, which acts both as a source and receiver, is normally mounted on either the bottom or side of the vessel's hull and only measures the depth vertically beneath it. The narrow beam echo sounders might need beam stabilisation (ie compensate for the roll, pitch and heave of the vessel) in order to measure the depth vertically below the transducer. A single-beam echo sounder survey produces an image of the seabed topography along the track of the vessel. However, to produce a bathymetric map, several parallel profiles are needed and, thus, significant interpolation between profiles is always necessary.

The principle behind swath bathymetry systems is to increase the seabed coverage and reduce survey time by using several

beams at different angles to the vertical. Such systems are available in a range of frequencies, varying from 12kHz to 500kHz. The highest-frequency systems provide centimetre-scale images of the seabed. Swath systems transmit a fan of ultrasonic sound, broad in the across-track direction (typically 120° to 150°) and narrow in the along-track direction (between 0.5° and 3°). The position of each echo can be computed from the angle and the travel time (ie the range) of the returned signal. Depending on how the angle and travel time pairs are determined, two different systems are recognised: beam-forming multi-beam echo sounders and interferometric or phase discrimination sonars.

2 The multi-beam sonar

This system uses a process called beam-forming to determine the depth to the seafloor (Fig 10). The system is made up of two transducer arrays, a transmitting array whose long axis is parallel to the direction of travel and a receiving array perpendicular to that. Each array produces a fan-shaped beam that is narrow in the direction of its long axis. The arrays are made up by a number of identical and equally spaced transducer elements, forming a fixed number (eg 126, 254 or 512) of transmitted and received beams at different angles (hence the name 'multi-beam'). Through a process called 'beam steering' the receiving array can be altered so that echoes from a number of directions can be received. Using beam steering, each receiver beam intersects the emission beam, resulting in a series of 'footprints' on the seabed along the ensonified area.

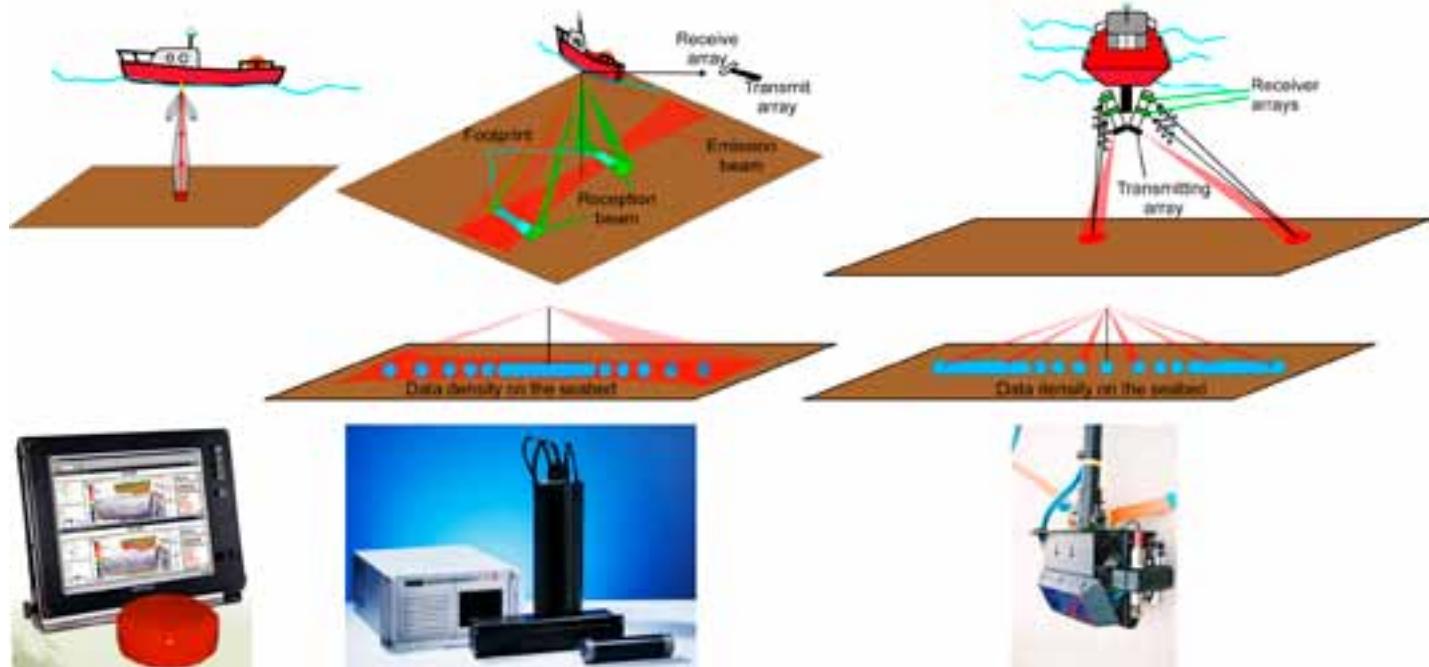


Fig 10 The three common types of bathymetry systems: single-beam echo sounder (eg Simrad EK60), multi-beam sonar (eg Reson Seabat 7125) and interferometric sonar (eg GeoAcoustics GeoSwath).

The echo arrival time of each footprint and the angle of the received beam, corresponding to that footprint, is then used to determine the depth to the seabed. Using this system, the seabed is sampled more densely at small angles than at higher angles. Therefore, the accuracy and resolution will be highest for the inner parts of the swath and will decrease with increasing swath width (Fig 10). The beam-forming process cannot distinguish between multiple travel times corresponding to a single angle. However, these multiple reflectors are often much weaker than the primary reflectors, hence in practice cause few problems.

3 An interferometric sonar

This consists of two sonar heads on a V-shaped structure (Fig 10). Each sonar consists of one transmitting array and at least two receiving arrays, parallel to each other and parallel to the direction of travel. Similar to side scan sonar, the transmitting transducer arrays produce a single beam that is wide in the vertical direction and narrow in the horizontal direction. The receiving arrays, spaced at carefully chosen fixed distances detect the backscattered signal at different arrival times. The travel times provide the range to the echo, while the phase difference measured between the signals at the different receivers determines the angle of arrival. The knowledge of both the range and the angle makes it possible to calculate the exact position of the echo. However, the interferometric system cannot distinguish between multiple angles with the same travel times. Consequently, in theory the system will struggle to produce an image of a steep seafloor or of complicated (upstanding) structures correctly. Manufacturers are developing ways to deal with this shortcoming, for example by assessing the strength of the reflected data.

In contrast to the multi-beam system, interferometric sonar receives thousands of beams. The density of the sounding locations is larger for the outer parts of the swath than for the inner parts (Fig 10). The high density of data points is reduced during the post-processing by calculating a mean grid. The interferometric sonar is also frequently referred to as a bathymetric side scan sonar, for the system can accurately record the amplitude (or backscatter) of the returned signal, and the data can be treated as a side scan record as well as offering bathymetric information.

For an independent comparison of the performance of the two types of systems in imaging a range of seabed features see Gostnell (2005) and Talbot (2006). From an archaeological viewpoint, the *Rapid Archaeological Site Surveying and Evaluation*

(RASSE) project (ALFM 3837) (2007) compared the two systems and proved that interferometric sonar is not as effective for detailed site investigation as multi-beam sonar, but recommended that a new generation of interferometric systems with increased resolution be tested in future investigations. Some commercially available systems are a combination of electronic beam-forming and the interferometric (phased array) method, providing equal footprint spacing across the sampled swath (eg atlas FANSWEEP 20). Swath systems are nearly always deployed fixed to the vessel, either hull-mounted or mounted on a rigid pole on the side or over the bow of the vessel.

To know the exact position of each recorded echo the vessel's movement and the velocity of the emitted sound through the water must be known with precision. Therefore, a motion sensor that measures the attitude (roll, pitch and heading) and heave must be installed on the vessel or swath system. Inertial sensors are most commonly used to determine the roll, pitch and heave, and the heading can be derived from accurate positional information (eg DGPS or RTK). It is important to know the exact position of the system in relation to this motion sensor.

Knowledge of the velocity of sound through water is necessary to convert the measured travel times to distances. This velocity depends on the temperature, salinity and pressure of the water and thus will vary laterally and vertically. Sound velocity can be measured using a sound velocity profiler or probe. The sound velocity probe is placed on the head of the swath system and continuously measures the velocity at the transducer face. The sound velocity profiler generates a sound profile through the entire water column and can only be deployed when the vessel is stationary. Measure these profiles at regular intervals during the survey; and take a minimum of two sound velocity profiles, at the beginning and at the end of the survey. For prolonged surveys and for surveys that cross areas of different water bodies, such as in estuaries, a higher frequency of measurements is recommended.

In contrast to the other geophysical systems discussed in this document, there are set international standards for the acquisition of hydrographic (bathymetric) data. These standards have been issued by the International Hydrographic Organization (IHO), with the latest release of the fifth edition of the Special Publication (IHO S-44) in 2008. The minimum standard requirements set out in these standards are summarised in Table 1.

6.3.2 Survey design – bathymetry

1 General methods – bathymetry

The biggest disadvantage of single-beam echo sounders is the relatively low coverage of the seabed, making it a less useful tool for archaeological prospection. Wrecks and artefacts in particular are rarely detected on single-beam data. Furthermore, although cheap to buy and run, it is not a time-efficient tool when used on its own. Nevertheless, the single-beam echo sounder is still used frequently by industry and for hydrographic purposes and could be of use to archaeologists when combined with other available data (eg side scan sonar images). The highest-quality data are obtained with a narrow-beam (high-frequency) echo sounder and using a well-constrained velocity of sound through the water (measured by a velocity probe) for depth conversion. Narrow-beam transducers, however, need corrections for the motion of the vessel. The standard followed for archaeological purposes should be at least IHO S-44 Order 1b, requiring a line spacing of $3 \times$ the average water depth or 25m, whichever is greater; for best practice we recommend a line spacing of 30m in water depths greater than 10m and cross lines at a minimum spacing of $1-10 \times$ the principal line spacing. The line spacing might have to be reduced in areas with high potential. DGPS navigational accuracy is a minimum requirement. The sounding rate (or ping or update rate) depends on the make of the system, but is normally between 5Hz and 20Hz. Because the transceiver needs to wait for the emitted signal to come back, this update rate is a function of the depth. Generally, for archaeological surveys in relatively shallow water, use an echo sounder with update rate capabilities between 15Hz and 20Hz and a vessel speed no faster than 4 knots (ideally between 2.5 and 3 knots). All data should be recorded digitally as x,y,z ASCII data.

Swath systems, in contrast to single-beam echo sounders, are technologically advanced systems: they need accurate calibration, installation and operation by experienced personnel. An experienced engineer should do the initial installation and alignment of the system.

Accurate calibration is important owing to the sensitivity of swath systems. On hull-mounted systems, patch tests should be performed periodically, while pole-over-side-mounted systems should be calibrated each time they are put in the water (for full description see IHO 2005, 170–4). However, solid-pole constructions should enable system recovery offshore and be able to return into the same position during and between surveys, reducing any need to re-calibrate. The calibration

Table I Summary of minimum standards for hydrographic surveys IHO S-44 5 edn

ORDER	SPECIAL	Ia	Ib	2
description of areas	areas where under-keel clearance is critical	area shallower than 100m where under-keel clearance is less critical but features of concern to surface shipping may exist	areas shallower than 100m where under-keel clearance is not considered to be an issue for the type of surface shipping expected to transit the area	areas generally deeper than 100m where the seafloor is considered adequate
maximum allowable total horizontal uncertainty (95% confidence level)	2m	5m + 5% of depth	5m + 5% of depth	20m + 5% of depth
maximum allowable total vertical uncertainty (95% confidence level) ¹	a = 0.25m b = 0.0075	a = 0.5m b = 0.013	a = 0.5m b = 0.013	a = 0.1m b = 0.023
full seafloor search ²	required	required	not required	not required
feature detection ³	cubic features > 1m	cubic features > 2m in depths up to 40m; 10% of depth beyond 40m	not applicable	not applicable
recommended maximum line spacing ⁴	not defined, as full seafloor search is required	not defined, as full seafloor search is required	3 x average depth or 25m, whichever is greater; for bathymetric lidar a spot spacing of 5m x 5m	4 x average depth

Notes:

¹ Recognising that there are both constant and depth-dependent uncertainties that affect the uncertainty of the depths, the formula below is to be used to compute, at the 95% confidence level, the maximum allowable TVU. The parameters 'a' and 'b' for each order, as given in the table, together with the depth 'd' have to be introduced into the formula in order to calculate the maximum allowable TVU for a specific depth:

$$\pm \sqrt{[a^2 + (b*d)^2]} \text{ where:}$$

a represents that portion of the uncertainty that does not vary with depth

b is a coefficient which represents that portion of the uncertainty that varies with depth; d is the depth

b x d represents that portion of the uncertainty that varies with depth

² For purposes of navigation safety, the use of an accurately specified mechanical sweep to guarantee a minimum safe clearance depth throughout an area may be considered sufficient for Special Order and Order Ia surveys.

³ A cubic feature means a regular cube each side of which has the same length. It should be noted that the IHO Special Order and Order Ia feature detection requirements of 1m and 2m cubes, respectively, are minimum requirements. In certain circumstances it may be deemed necessary by the hydrographic offices/organisations to detect smaller features to minimise the risk of undetected hazards to surface navigation. For Order Ia the relaxing of feature detection criteria at 40m reflects the maximum expected draught of vessels.

⁴The line spacing can be expanded if procedures for ensuring an adequate sounding density are used. Maximum line spacing is to be interpreted as the

- Spacing of sounding lines for single-beam echo sounders, or the
- Distance between the usable outer limits of swaths for swath systems.

tests should test for errors in position-time delay (latency – which is the delay between the time of the positioning system and the swath system) and for pitch, roll and azimuthal offset between the motion sensor and the swath system. If a pole mounting is used, its construction should be tested for robustness – and to avoid vibration – at survey speed.

To avoid wasting costly transit time, check the swath system, motion sensor, navigational system and velocity probe/profiler before sailing.

An experienced hydrographic surveyor should undertake the survey. However, even the most stringent hydrographic standards (IHO Special Order; Table 1), which require the identification of a cube

>1m, may not always be sufficient for archaeological purposes. Therefore, good communication between the hydrographer and an experienced maritime archaeologist is essential from the outset. Ideally, the hydrographic surveyor should have archaeological experience and an archaeological geophysicist should be present during the survey.

For archaeological investigations, keep the transmitted acoustic fan width to between 120° and 150° across the track direction, and between 0.5° and 1° along the track direction. The beam width on the seafloor depends on the depth of the water column. It varies between $3\times$ and $7\times$ the water depth for a multi-beam system, and between $12\times$ and $15\times$ the water depth for interferometric systems. Hence, the depth of the water column, in combination with the required coverage, determines the line spacing of the survey. In general, aim for IHO S-44 standards Order 1a, which requires a full sea-floor search, preferably with a 50% area overlap between survey lines.

It is good practice to include a few survey lines perpendicular to the principal survey direction. For areas with high potential, 100% area overlap might be necessary ($2\times$ full seafloor search). In areas with a relatively flat seabed, a pre-defined survey grid is recommended, one that the helmsman can follow in real time. In areas with a large variation in bathymetry, use a real time display of the ground coverage as a navigational guide rather than an outlined survey grid, bearing the required overlap in mind.

As with the single-beam echo sounder, the ping rate depends on the system used and on the water depth surveyed. Three pings per object are needed to avoid spatial aliasing (ie insufficient sampling of the data along the space axis). Interferometric systems incorporate more on-the-fly computing and therefore have a slower ping rate than multi-beam systems. For both multi-beam and interferometric systems, the ping rate usually varies between 5Hz and 40Hz in shallow water. There is often the choice to reduce the beam width (range) so as to increase the system's ping rate. Aim to use the highest ping rate possible and financially acceptable for the system and average water depth surveyed. When preparing the survey it is important to have a good idea of the rough bathymetry from Admiralty charts, previous surveys and online chart data, so that line spacing, direction and ping rate can be decided before going offshore. Survey speeds should not exceed 4 knots and, ideally, should be between 2.5 and 3 knots.

DGPS navigational data are sufficient for large regional reconnaissance surveys. However, in order to use the full potential of the high-resolution swath systems, RTK GPS navigation should be used, especially for detailed studies. Incorporate this positional data within the survey data through the acquisition system. Also record a raw navigational file (ASCII) separately.

Although several filters and other parameters can be defined during acquisition, the digitally recorded data should be unprocessed, raw data. Today, there is still no set standard data format for swath data, but most generic software processing systems can support a range of acquisition file types. It is therefore not appropriate to suggest a single acquisition format. A list of the most commonly found industry standard file formats can be found on <http://www.ivs3d.com/support/dataTypes.pdf>.

Single-beam and swath bathymetry data need tidal corrections. When DGPS navigational accuracy is used, the information of several tide gauges needs to be used when processing the data. The cross lines provide a way to check the tidal corrections. When acquiring RTK GPS positional data, use the recorded z values to correct the data.

2 Wreck site survey design – bathymetry

Single-beam echo sounder data only rarely detect wreck sites and therefore are not recommended for conducting specific wreck site surveys.

For reconnaissance surveys, at least a shallow-water swath system (95kHz–240kHz) should be used, but a high-resolution system ($>400\text{kHz}$) is recommended at all times (Fig 11a). If RTK GPS navigation is not an option, DGPS positional accuracy may be sufficient.

The survey line spacing will depend on the water depth, but at least 50% area overlap should be obtained. In areas with a large number of uncharted, archaeologically interesting wrecks, 100% area overlap should be considered ($2\times$ full seafloor search coverage). Survey speed should not exceed 4 knots.

Wreck surveys should aim to produce data that can be used to map detailed features of the site or as a baseline for future research (Fig 11b). Therefore, the data should be acquired with high-resolution ($>400\text{kHz}$) swath systems together with RTK GPS navigational positioning to achieve centimetric accuracy. In total, at least three lines should be acquired over the wreck, forming a star pattern: one line running along the long axis of the wreck, and two crossing lines over the centre of the wreck with angles c 30° to the long axis. Select a ping rate as high as possible for the water depth surveyed. Depending on the site width and water depth, it might be possible to consider decreasing the beam width in order to increase the ping rate and, hence, the resolution. If the wreck is in very shallow water or the material is widely spread, or both, several parallel lines should be acquired with a 100% area overlap ($2\times$ full seafloor search coverage). Survey the site at the lowest speed possible to record high data density (ideally 2–2.5 knots).

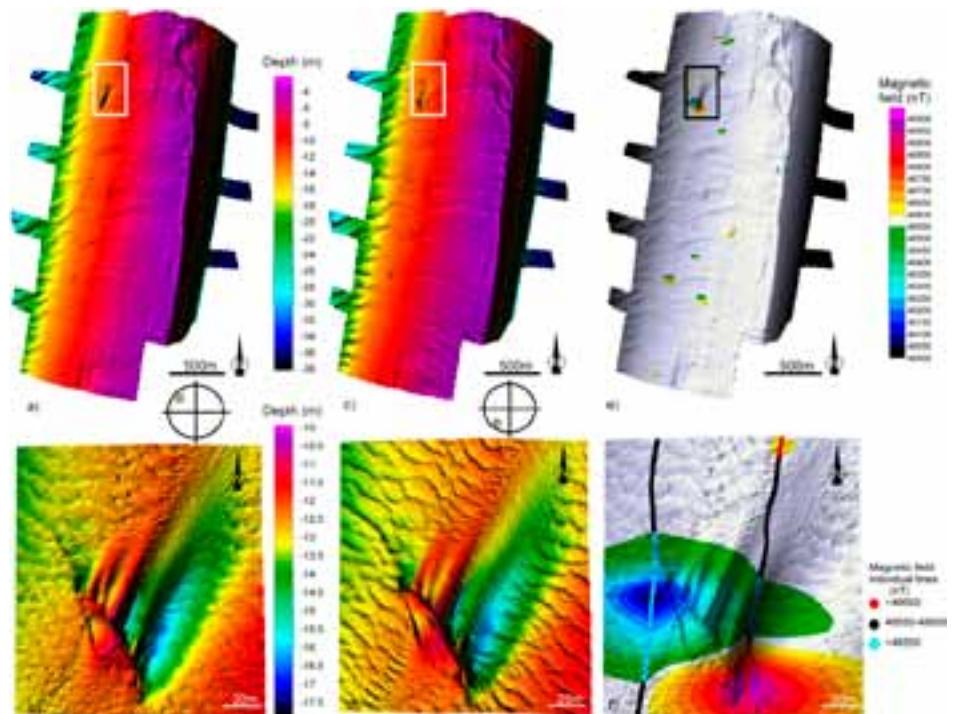


Fig 11 (a) and (c) Multi-beam data acquired over large area and consequently gridded at 10m bin resolution; (b) and (d) multi-beam data gridded at 0.5m bin resolution over an anomaly detected in (a) and (c). Note the change in appearance of the bed forms in (a-b) and (c-d) as the direction of the sun illumination is changed during the shading process (d); (e) and (f) magnetometer data acquired with 50m line spacing, and contoured before being superimposed on the multi-beam imagery (modified from Quinn 2006; multi-beam data acquired by Titan Environmental Surveys Ltd and magnetometer data acquired by Donal Boland).

3 Submerged landscapes survey design – bathymetry

Although single-beam echo sounder data are not the preferred tool for bathymetric surveys for submerged landscape research, they can be valuable when used in combination with other data. The frequency of the system will depend on the water depth and system available, but should ideally be $\geq 50\text{kHz}$. The minimum line spacing used should be IHO S-44 Order 1b standard ($3 \times$ the average water depth or 25m, whichever is greater; and cross lines spaced $15 \times$ the principal line spacing). However, a maximum survey grid $30\text{m} \times 30\text{m}$ is suggested when water depths are $> 10\text{m}$. The survey grid should be orientated so that the principal survey direction gives the best cross sectional view of features on the seabed (ie perpendicular to the main course of channels and crests of sand and gravel bars). A ping rate of 15Hz in combination with a vessel speed of 4 knots should ensure high enough resolution for large area surveys. For more detailed small area surveys (ie a few kilometres), reduce the line spacing to $10\text{m} \times 10\text{m}$, increase the ping rate to 20Hz and reduce the vessel speed to 2–2.5 knots. DGPS navigational data are sufficient.

Swath bathymetry gives a detailed image of the present-day bathymetry and might contain clues to the location of submerged landscapes. However, swath bathymetry should always be acquired in combination with sub-bottom systems in order to gain information about sediment thicknesses and stratigraphy. For large areas, the IHO S-44 Order 1a standard is advocated (preferably with a 50% area overlap), obtained with a shallow-water swath system (95kHz–240kHz). DGPS positional accuracy might be sufficient, but use RTK GPS when available and affordable. In areas with great depth variation, set the ping rate to survey the deepest section likely to be encountered. In the case of deep channels, follow their general course for the principal survey direction. The survey speed should not exceed 4 knots. When a smaller area (a few kilometres) with large potential is targeted, the survey lines should overlap 100% ($2 \times$ full seafloor search) and RTK GPS should be used. The survey speed should be reduced to 2.5–3 knots.

Note: The line spacings described in these sections are described for research standard surveys and will differ with the different purposes of offshore survey.

6.4 Sub-bottom profiler survey

6.4.1 Instrumentation – sub-bottom profiler

Sub-bottom profilers are acoustic systems traditionally used to image sediment layers and rocks beneath the seabed, providing information about sediment thicknesses and stratigraphy. Although these systems have been used for decades by the marine surveying industry, in general they are infrequently used in archaeology. However, the increasing interest in submerged landscapes has brought an increase in their use by archaeologists. Nonetheless, they are still not used regularly for detailed, site-specific investigations. The main reason is that they are difficult to interpret and do not provide sufficient detail. However, as with all the technologies discussed in these guidelines, technological advances in sub-bottom profilers, together with an adapted survey design, can provide valuable information about archaeological sites. More importantly, it is the only technique that can supply information about buried sites in a non-destructive manner.

The technique of the sub-bottom profiler is similar to that used by single-beam echo sounders, but at lower frequencies, so that the sound waves penetrate the seafloor. At boundaries between layers of different acoustic impedance (ie the product of sound velocity and density), part of the seismic energy reflects back to a detector, part of the energy is transmitted through the boundary to deeper layers and part of the energy is lost through scattering. It is the impedance contrast between the layers that determines the amount of energy that is reflected back. Either the transceiver or a separate acoustic receiver (ie a hydrophone) towed directly behind the seismic source detects the reflected energy. The subsurface image is the result of the amplitudes (two-way travel times) of the reflected waves.

High-resolution seismic sources can be divided into four broad categories: implosive (watergun), explosive (sparkler), accelerating water mass (boomer) and controlled waveform systems (pinger, chirp and parametric sources). The latter two categories are most commonly used today for shallow-water surveys and, therefore, this section does not discuss the use of waterguns or sparklers. The choice of the seismic source depends on the trade-off between the resolution (requires high frequencies) and penetration (requires lower frequencies) needed for the survey.

1 Boomer

This seismic system is normally surface-towed behind the research vessel, mounted on a lightweight catamaran. The sound-producing element of the boomer is a

heavy-duty electrical wire coil, which is magnetically coupled to a rigid aluminium plate situated behind a rubber diaphragm. A capacitor bank is discharged through the coil and the resulting electromagnetic induction forces the aluminium plate rapidly downwards, setting up a compression wave in the water. The rubber member forces the plate slowly back against the coil after each violent repulsion. The resultant acoustic pressure pulse is broad spectrum in nature, within the frequency range of 200Hz to 15kHz (Fig 12). Energy levels range from 100 joules up to 5,000 joules per pulse. The combination of power and the frequency spectrum means that the wavelet emitted by boomer systems can easily penetrate beneath the seafloor to depths of 20m in sands, 60m in compact silts and up to 150m in soft mud. Generally, a vertical resolution of 0.5–1m can be obtained. However, recent technological developments, specifically the development of wider bandwidth systems, have increased the vertical resolution to $> 25\text{ cm}$ without processing. The ease with which power levels can be changed is an advantage of the boomer system, although it is disadvantageous in that the resolution and repeatability of the system is dependent on the choice of the energy level. Furthermore, the shape of the transmitted wavelet is often not well known, which can cause problems when processing the raw data. This type of system is the most commonly used system for marine industries surveying in shallow waters. A typical boomer seismic section, over a buried palaeo-channel system from the Thames estuary is shown in Fig 13.

2 Pinger

These systems are either mounted within the hull of a ship or in a towfish. The transducer of a pinger sub-bottom profiler is made up of a small piezoelectric element, which emits a short, single, high-frequency wavelet (ranging from $c 1\text{kHz}$ to $c 40\text{kHz}$) when activated by an electric impulse (see Fig 12). The most commonly used systems produce a narrow bandwidth frequency of 3.5kHz. The transducer acts both as a source and receiver. Pingers can only handle low-energy pulses (typically 10–60 joules). The low power output, combined with the narrow-frequency bandwidth, results in a limited penetration of only a few metres in sandy sediments, but up to 50m in muddy sediments. However, they offer high resolving power (up to 0.1m). Although pinger systems are still frequently used in the marine surveying industry, the availability of such systems has declined during the past few years as boomer and chirp technology has replaced them.

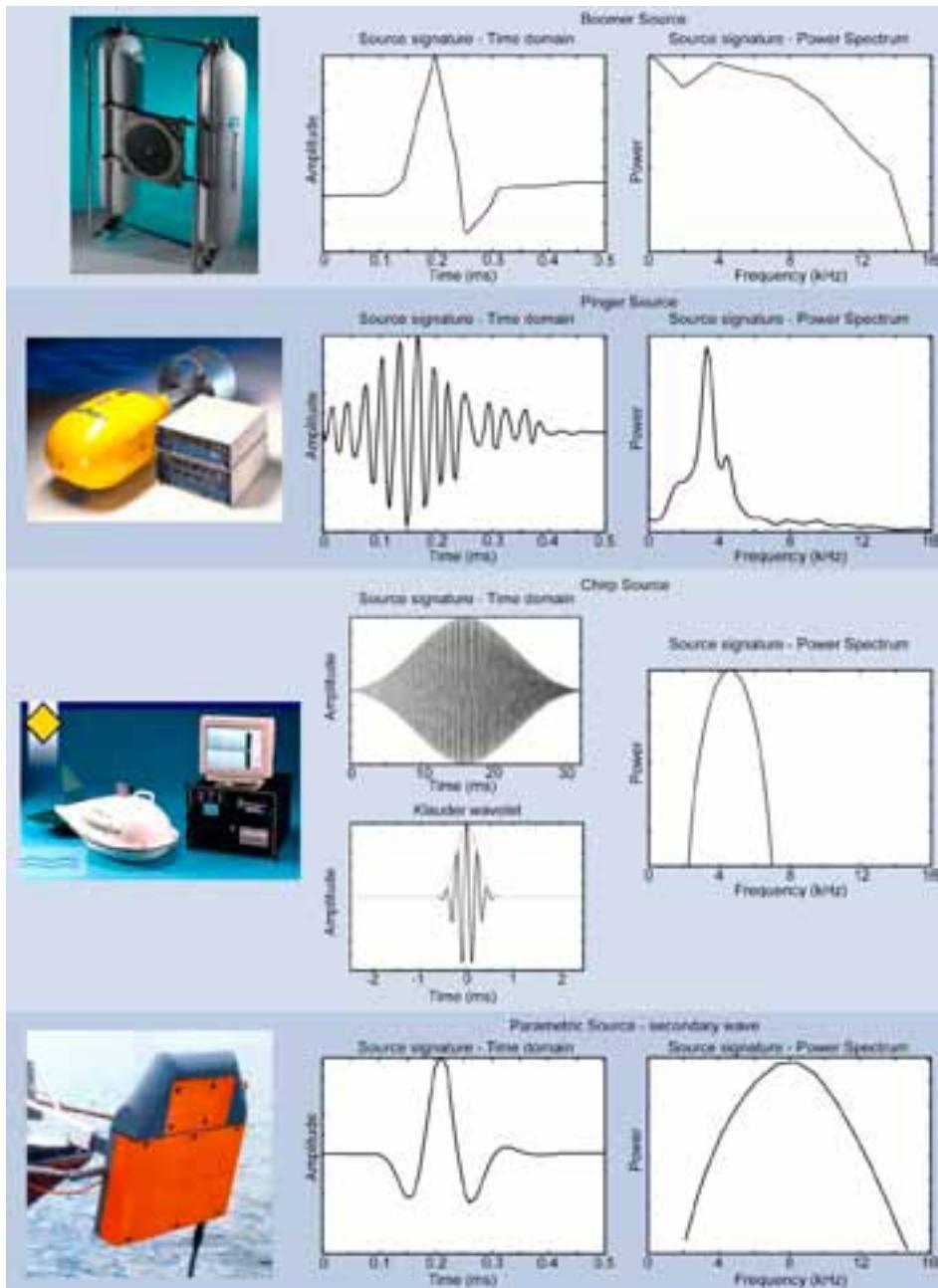


Fig 12 Source signature and power spectrum of the most commonly used high-resolution sub-bottom profiling systems: boomer (picture: Applied Acoustics AA 200); pinger (picture: GeoAcoustics GeoPulse 5430A); chirp (picture: Benthos CAP6600 Chirp II); and parametric (picture: Simrad Topas PS40).

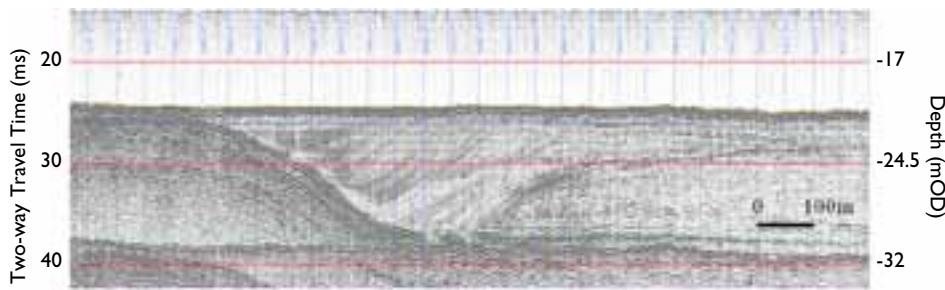


Fig 13 A boomer section across a section of buried palaeo-channel buried up to 12m beneath the current seabed. Data acquired as part of the MASLF-MEPF Outer Thames Estuary Regional Environmental Characterisation project (EMU Ltd, 2009).

3 Chirp

The development of the chirp system has begun to address the trade-off between resolution and penetration. The chirp system has a different amplitude and pulse frequency to that of a pinger. These values vary over time, creating a so-called

frequency-modulated (FM) sweep. The sinusoidal peaks and troughs are generated as the crystal expands and contracts. The FM pulses are computer generated and there are hundreds of waveforms (called 'sweeps') to choose, which can easily be stored in the electronics bottle connected

to the transducer. Sweeps are characterised by a wide bandwidth in the frequency domain, ensuring high resolution. They also have a long pulse length (typically 16ms or 32ms), enabling a relatively large amount of energy to be output despite the low-energy output per shot (between 6 joules and 64 joules). These characteristics ensure good penetration (see Fig 12). This long chirp pulse is compressed by cross-correlating the signal with a replica of the transmitted acoustic pulse, resulting in a much shorter 'Klauder' wavelet and maximising the output signal-to-noise ratio (SNR). Typical frequency ranges are 1.5kHz–7.5kHz and 1.5kHz–12.5kHz, but could be anywhere between 400Hz and 24kHz. Depending on the frequency used, vertical resolution of 10cm to 40cm can be achieved and penetration varies from 3m in coarse sands to >100m in fine-grained sediments. A major advantage of the chirp system is that the emitted pulse shape is well known and highly repeatable, aiding post-acquisitional processing and enabling quantitative sediment/object characterisation. The chirp system can be deployed either hull-mounted, surface-towed (mounted on a catamaran) or deep-towed (mounted in a towfish). The receiver (hydrophone) arrays can either be mounted on the tow vehicle or towed behind the chirp system.

The three systems described above are linear systems. Their acoustic output signal has the same frequency as the electrical input signal. For these systems, the beam width (ie the angle between the half-power or -3dB points of the conical beam) of the acoustic pulse is dependent on the frequency and the length of the transducer array: higher frequencies and longer arrays produce narrower beams. Hence, in order to obtain the best horizontal resolution (ie a small footprint on the seabed), a long array made of very-high-frequency transducers should be used. However, these high frequencies severely limit the amount of penetration, while large arrays are highly impractical, especially in shallow water and on smaller vessels. Consequently, the systems discussed earlier often have relatively poor horizontal (or spatial) resolution (generally >0.5m). This trade-off problem between penetration and horizontal resolution can be solved using a parametric sonar. A parametric source uses non-linear acoustics to create a 'virtual' low-frequency array with a small angular aperture. The source transmits two high, but close, frequencies (f_1 and f_2 , eg 100kHz and 105kHz), called primary beams, with high sound pressure. At high pressures the density of water and, consequently, the sound velocity behave

non-linearly, causing the primary beams to interact and convert some of the energy into waves at frequencies $2f_1$, $2f_2$ and $|f_1 \pm f_2|$. The most interesting wave, $|f_1 - f_2|$ (eg 5kHz), called the secondary wave, has the directivity pattern of the primary waves (high frequency, hence narrow beam width), while having a frequency low enough to penetrate up to 50m. Other advantages of the system are that the secondary beam pattern is virtually sidelobe free, reducing the disadvantageous ringing effects of other sub-bottom profilers in shallow water and the manageable size of the system. A major disadvantage is the poor conversion efficiency, which is typically <1% of the input energy converted into the secondary wave. The receiver can be the same as the transducer, or receivers can be integrated into the system separately. The sonar is normally mounted on the hull or deployed over the side of a vessel, mounted on a pole. The primary frequencies are usually close to 100kHz; secondary frequencies are between 4kHz and 12kHz, giving decimetric vertical resolution. This type of system has not been used much for archaeological purposes and needs more research. Despite a long record of use by other researchers, this technology is not common within the commercial sector and to date only a limited number of archaeological surveys have been undertaken using it.

6.4.2 Survey design – sub-bottom profiler

1 General methods – sub-bottom profiler

Deciding on the type of sub-bottom profiler to be used depends on the expected water depth and anticipated sediment type. In the shallow waters of the continental shelf, boomer and chirp systems are the most commonly used techniques. Boomer systems are recommended for survey areas dominated by sediments with a typical grain size larger than coarse sand. In areas with predominantly finer sediments, chirp sub-bottom profilers provide the best detail in the top few metres of the seabed (Fig 14).

Perform a pre-installation check before sailing. If safe to do so, and not damaging for the profiler, a dry test is the easiest and fastest way to check its performance, hydrophones, acquisition system and connections. A dry test should *not* be undertaken for a boomer system; a boomer system should only be triggered in water. The manufacturer's manual should give specific procedures to test and calibrate the system. A better, but more time consuming, way is to test the system with the profiler positioned in a test tank or dock. This makes it possible to test all parts of the system, check for noise and examine the repeatability of the source.

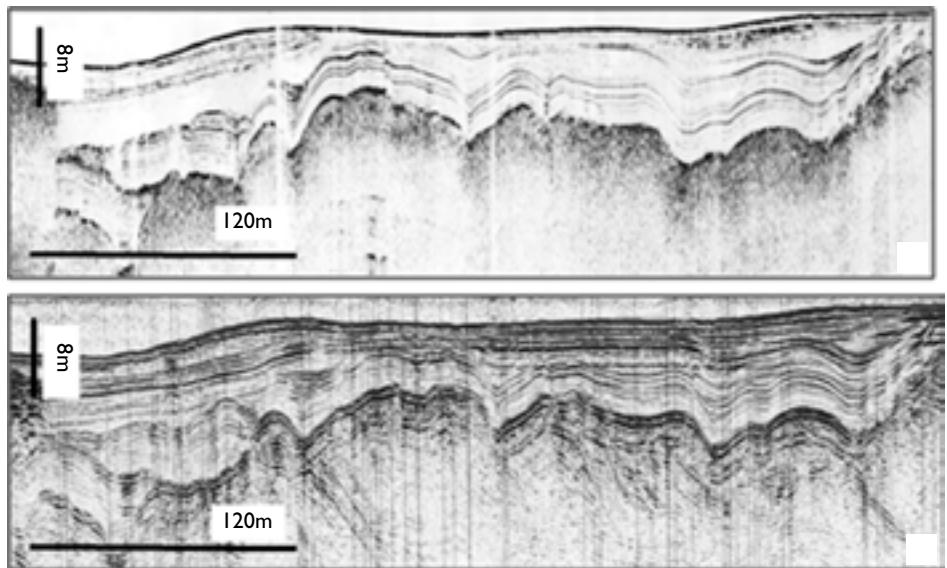


Fig 14 Chirp (a) and boomer (b) image from the same location within Strangford Lough, Northern Ireland, showing the detailed layering within the upper fine-grained sediments in the chirp profile and the penetration through stiff glacial sediments into the basal bedrock from the boomer section (data acquired using a GeoAcoustics Chirp and Boomer system; vertical scale bar represents c 8m; image courtesy of University of Southampton).

Most profilers are towed when surveying in shallow water. To avoid multiple reflections interfering with shallow parts of the data, it is suggested that the system is surface-towed, mounted on a catamaran, or towed just beneath the surface in a towfish. Note that catamarans and towfishes are often bulky and heavy – they require a crane or A-frame to lower them into the water, and sailing speed must be significantly reduced. Therefore, although a single person can acquire the data, enough people need to be on board to assist with launching and retrieving the system. Once the system is in the water, the vessel's speed should kept between 3 and 4 knots, and the tow cable should be paid out until the system is out of the vessel's wake.

The survey grid should be agreed on with the helmsman before starting the survey. In areas with strong tidal streams or currents, high-quality data can only be obtained when sailing with or against the currents. In these conditions, it is best to survey along a set of parallel lines with a maximum line spacing of 30m. If currents and tides are not a problem, follow a survey grid with a spacing of $30m \times 30m$. To get a good cross-sectional image, one grid direction should be perpendicular to the main or long axis of major features (eg channel, sand bank, wreck). The helmsman should be able to follow the survey lines on his monitor. For large area surveys, the grid spacing can be increased to 30m–50m for the principal survey line direction and to 1–10× the principal line spacing for the cross lines.

The ping rate can normally be selected manually and usually varies between 1Hz and 8Hz. The ping rate selected depends

on the length of the reflected trace that needs to be recorded. From an archaeological viewpoint, the top few metres of the seabed are the most interesting and, hence, a recorded trace length of 100ms–150ms should be long enough. In such cases, a ping rate of 4Hz–8Hz should be feasible. A shot interval of 2Hz is an absolute minimum for archaeological prospecting (ie a ping rate of 2Hz and a vessel speed of 4 knots will only provide information every 1m along the survey line). It is important to note down the recorded trace length, as this parameter might be needed when importing the data into seismic processing software.

DGPS navigation should be sufficient for the majority of sub-bottom profiling surveys. Normally, the catamaran's position is determined by calculating the lay-back with respect to the DGPS antenna on the vessel. However, in calm weather conditions and with a sufficiently long cable (with low attenuation), the DGPS antenna can be mounted on top of the catamaran, reducing the positional error. Integrate the navigational data directly with the acoustic data and set the acquisition systems clock to use the GPS time. When a lay-back is used, it is often possible to introduce this correction directly into the acquisition software. However, the raw navigational data should also be recorded independently as an ASCII file. Record all acoustic data digitally, in the industry standard SEG-Y format or .xtf format. Although filters (eg band-pass, gain) can be applied in real time to the acquisition software, these should only be used for display purposes during the survey; all data should be recorded as raw data.

Raw data are particularly important for chirp surveys: although it is recommended that the correlated signal is displayed during acquisition, the uncorrelated data should be recorded for future processing. Information about the data – navigation, date, trace number, trace length – is stored in the data header. Unfortunately, there is a variety of modern formats, particularly for the SEG-Y format, and it is therefore important to know what information is in which header for the acquisition system used. This information is supplied by the manufacturer of the system.

All surface-towed sub-bottom data must be tidally corrected and (unless RTK data have been acquired) this can be done using tide gauge information. When a grid of data has been acquired, the crossing points between different lines will indicate whether the tidal correction has been applied correctly.

2 Wreck site survey design – sub-bottom profiler

Sub-bottom profilers are the only systems able to completely detect buried wrecks or to provide more information about the depth of burial of partially buried wrecks. However, used on its own in a large area with unknown potential for buried wrecks, is like looking for a needle in a haystack. Sub-bottom profilers should only be used when the position of a wreck is known or when a detected anomaly (for example from magnetic data) needs to be studied in greater detail.

For detailed surveys of potential or known wreck sites, the chirp system with a wide -3dB bandwidth (thus providing high vertical resolution) is the preferred tool. If possible, survey a grid of at least 5m × 5m. One survey direction should be parallel and the other perpendicular to the main axis of the wreck or anomaly. In areas with strong currents, where only parallel lines can be surveyed, this spacing may have to be reduced depending on the size and orientation of the wreck and thus ensure sufficient passes over the site. Aim to cross the site at least five times.

During the detailed survey, keep the vessel's speed between 2.5 and 3 knots and the ping rate as high as possible (ideally 8Hz). Wreck sites are rarely buried deeper than 10m beneath the seabed. Therefore, depending on the water depth, the recorded trace length can frequently be reduced to 50ms–100ms, thus allowing a higher ping rate.

If possible, mount the DGPS receiver on top of the catamaran to give positional accuracy within a metre. Alternatively, a USBL system could be deployed.

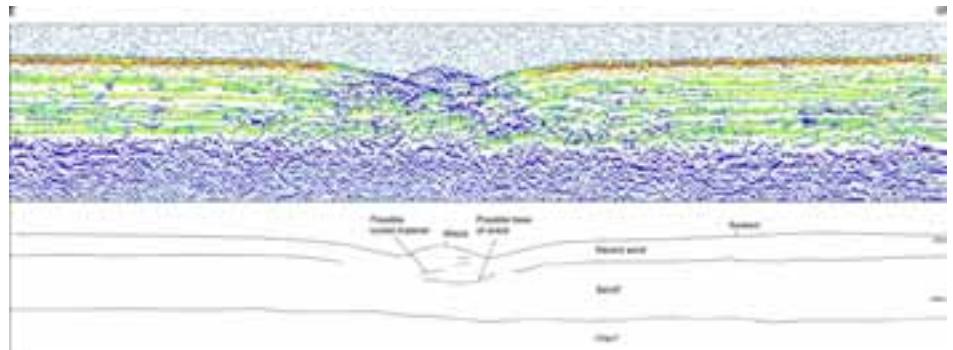


Fig 15 An example of a parametric sonar section over the Dunwich Bank wreck, offshore Suffolk. Courtesy of Wessex Archaeology and English Heritage.

In theory, the parametric sonar should be able to produce higher horizontal resolution than the chirp system. However, there is currently little information on the use of these sources for archaeological object detection and more data are needed to show whether this system can become a standard tool for archaeological research. An example of a recent parametric survey by Wessex Archaeology over the Dunwich Bank wreck, a post-medieval, partially buried wreck off the Suffolk coast, can be seen in Fig 15. This can be compared with the chirp imagery taken over the protected wreck sites, the *Grace Dieu* (see Fig 20) and the Yarmouth Roads (see Fig 26) in the Solent.

3 Submerged landscapes survey design – sub-bottom profiler

Sub-bottom profilers can also provide important data on submerged landscapes, as they can survey large areas relatively quickly and are non-destructive. In particular, when used in combination with core data, they can provide valuable data for the reconstruction of past environments.

Areas with predominantly coarse sediments (eg gravel terraces) are best imaged with the boomer system, while areas with finer sediments (eg intertidal muds and peat) are best imaged with chirp systems. It is therefore important to have an idea about the dominant sediment types within the area when planning the survey.

When surveying a large area, use a grid line spacing of 30m–50m, with cross lines at 1–10× the principal line spacing. One survey direction should be perpendicular to the long axes of prominent features (eg buried channels). Such features can be determined from previous surveys, if available. DGPS accuracy with a lay-back correction should be sufficient. It is a good idea to check whether there are any useful core data available from the area and to plan the survey accordingly (ie run at least one line over the core site). The survey speed should not exceed 4 knots.

When a smaller area is targeted, reduce the survey speed to 2.5–3 knots, the line spacing to a maximum grid size of 10m × 10m and, if possible, mount the DGPS antenna on the catamaran or use a USBL system.

Depending on the water depth and the depth of the sediment of interest, the trace length should normally not exceed 200ms, providing a shot interval of 4Hz.

Note: The line spacings described in these sections are described for research standard surveys and will differ with the different purposes of offshore survey.

6.5 Magnetometer survey

6.5.1 Instrumentation – magnetometer
Marine magnetometers measure the total amplitude of the Earth's magnetic field, but do not give any information about the direction of this field. In contrast to the acoustic methods discussed above, magnetometers do not transmit any signals, but rather measure geographical variations in the geomagnetic field. The total intensity of the magnetic field at the Earth's surface varies from 24,000nT in equatorial regions to 66,000nT at the poles; the geomagnetic field is c 50,000nT overall in the UK. Variations within the magnetic field are caused by a number of factors: solar activity may cause variations of c 20 nT; geological features of a few nT to several hundreds of nT; non-geological ferro-magnetic metallic objects (eg cannons) on or buried within the seabed of tens of nT; and metallic hulls of up to thousands of nT. The measured intensity of metallic artefacts on or buried within sediments depends on the material, size, shape, depth of burial and distance to the magnetometer. As the strength of the magnetic field is inversely proportional to the cube of the distance from the source, the magnetometer needs to pass the object as closely as possible and needs to be sufficiently sensitive to detect smaller, archaeologically significant, objects.

On land, diurnal, solar-caused variations of the Earth's magnetic field to the data can easily be corrected by placing a base station

magnetometer at a fixed location in the vicinity of the survey area and collecting the magnetic variations continuously. The recorded survey data can then be adjusted using the base station's observations.

At sea, a land-based base station is not accurate enough to provide the corrections and an ocean-based base station complicates survey logistics and increases costs. Instead, diurnal corrections can be assessed by planning the survey such that certain lines cross each other. The diurnal variation can be calculated by studying the variation in magnetic field intensity at the crossover points. This method can only be used if the data points are collected at exactly the same depths above the seabed.

By using magnetic gradiometers, regional and temporal variations are automatically removed from the data. A gradiometer measures the gradient, or first spatial derivative, of the magnetic field. Two sensors, separated by a fixed distance, both measure the total field strength. The difference in field intensity measured by the two sensors, divided by their separation distance results in a linear estimate of the gradient of the ambient field. The sensors can either be separated vertically or horizontally. The gradient resolves complex anomalies of shallow magnetic features into their individual elements, which can give information about the location, shape and depth of an object. Despite the advantages and the availability of gradiometers, they are currently only rarely used by the marine surveying community.

A more detailed review is provided by Camidge *et al* (2010). While this is a theoretical study of the acquisition, processing and interpretation of magnetic data for submerged archaeological sites, it includes an analysis of extant magnetic data-sets from known sites.

Currently, three types of magnetometers are used for maritime archaeological surveys: proton precession magnetometers, Overhauser magnetometers and optically pumped magnetometers.

1 Proton precession magnetometers

These instruments were almost always used, until recently. The sensor component of this system is a cylindrical container filled with a liquid rich in hydrogen atoms (Fig 16). The container is surrounded by a coil connected to a power supply, amplifier and frequency counter. When no current is running through the coil, the hydrogen protons align parallel to the ambient geomagnetic field. As a DC (continuous) current runs through the coil, a magnetic field is produced that is larger than and in

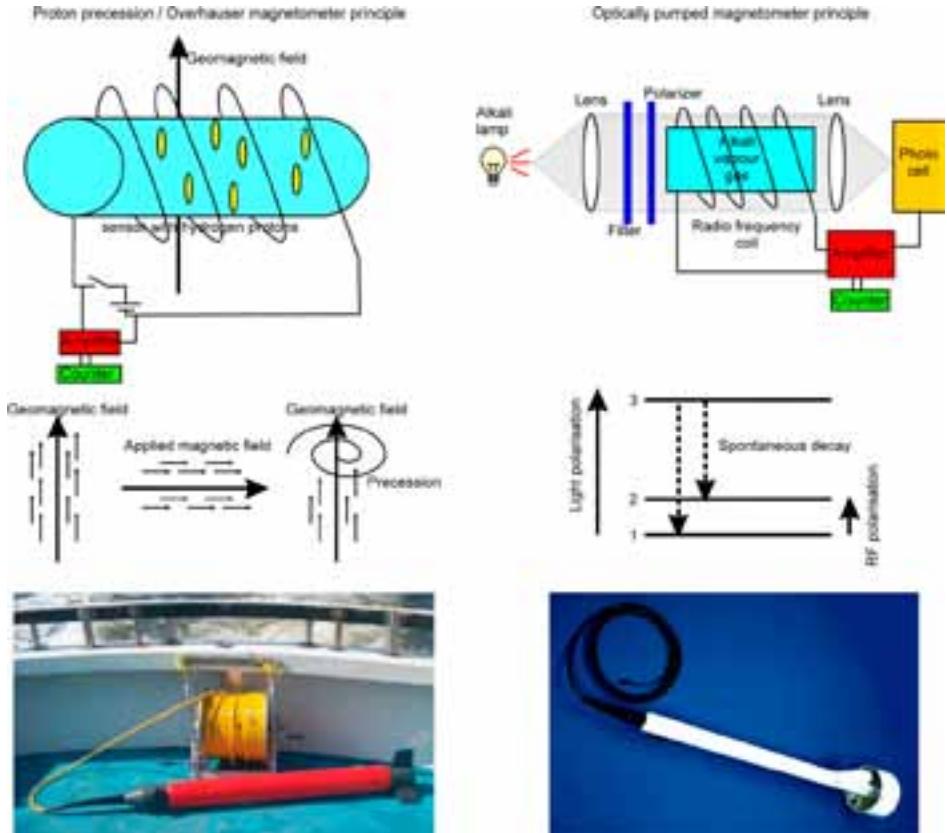


Fig 16 Principle of proton precession: Overhauser (picture Marine Magnetics 3000M Seaspy) and optically pumped magnetometers (picture Geometrics G-880).

a different direction to the geomagnetic field. This induced magnetic field causes the hydrogen protons to align along the direction of the applied field. The current is then turned off and the protons return to their original alignment by spiralling, or 'precessing', around the Earth's total magnetic field. This precession produces a time-varying magnetic field that in turn produces a small alternating current in the coil. The frequency of this AC (alternating) current equals the frequency of the precession of the nuclei, which is proportional to the strength of the total field. Hence, by measuring this frequency, the total magnetic field strength can be determined. Proton precession magnetometers are inexpensive, but have a relatively slow sampling rate (0.5–2.0 s) with sensitivities of 0.2 nT to 1.0 nT. It is important that the sensor's orientation is at an angle with the Earth's magnetic field during surveying. Unfortunately, proton precession magnetometers are sensitive to heading errors, where the resulting measured total magnetic field over an object varies depending on the orientation of the towfish.

2 Overhauser magnetometers

This type is an improved proton precession magnetometer that has recently begun to replace traditional instruments. A special liquid containing free, unpaired electrons is combined with the hydrogen liquid in the sensor cell. The sensor is irradiated with a

radiofrequency magnetic field, causing these unbound electrons to transfer their energy to the hydrogen protons (Fig 16). The resultant precession signals have a higher signal-to-noise ratio than for a normal proton precession magnetometer. The Overhauser magnetometer sensitivity is 0.015 nT/√Hz with an absolute accuracy of 0.1–0.2 nT.

Furthermore, the signals are non-decaying, which means that the polarisation and signal measurement can occur simultaneously, leading to an increased sampling rate (between 1 and 5 readings per second). This technique is also less prone to heading errors and requires less power consumption, making the Overhauser instrument lighter and more compact.

3 Optically pumped magnetometer

This is the third type of magnetometer, and has an even higher precision, with a sensitivity of 0.004 nT/√Hz and an absolute accuracy <2 nT. Its depolarisation is extremely rapid – up to 40 samples per second.

The operational process is known as optical pumping. An optically pumped magnetometer comprises a glass cell containing a vapour of alkali atoms (rubidium, caesium or potassium) and a polarised light source of the same element (Fig 16). Normally, electrons of these alkali atoms are positioned at two energy levels. As the polarised light is emitted through the vapour, electrons are bumped from these two

levels to a third level. However, electrons at level 3 are not stable and will spontaneously decay back to levels 1 and 2. When level 1 is fully populated (and level 2 is depleted) the cell becomes transparent and the absorption of the polarised light stops.

At this point, radio frequency (RF) power is applied to move the electrons back from level 1 to level 2, making the cell opaque again. The frequency of the RF field required to populate level 2 is a function of the ambient magnetic field. By measuring the light modulation as an effect of polarisation and depolarisation, together with the RF frequency, the total magnetic field can be determined.

The most commonly used alkali atom for marine surveying is caesium, hence the term caesium vapour magnetometer.

Recommendations from Camidge *et al* (2010) are included within the following sections.

6.5.2 Survey design – magnetometer

Magnetometers are mainly used to determine if anomalies detected on other geophysical data are related to ferrous wrecks, or to determine whether a known wreck is predominantly ferrous or wooden (see Fig 11e and f and Fig 17a–d). Therefore, they are of no use for submerged landscape research and are solely recommended for wreck survey designs. Magnetometers are mostly used in combination with side scan sonar. All three types are towed behind the vessel, at a distance of at least two ship's lengths, to avoid interference from the ship's magnetic field. It is important to record the time and position when a vessel other than the survey vessel passes in the vicinity of the magnetometer, as this will affect the recording of the magnetic field. If the impact on the data is detrimental, the line should be re-run. For this reason, it should be possible to view the data in real time, to maintain quality control and check for noise. Thus, it is often difficult to obtain magnetic data in busy areas such as shipping lanes and harbours.

Caesium vapour magnetometers are becoming more widely used and should be deployed when available. If an optically pumped magnetometer is practically or financially not feasible, give preference to an Overhauser magnetometer over the traditional proton precession magnetometer. For archaeological purposes, it is important to detect changes in the magnetic field rather than the absolute amplitude. The sensitivity of the system used should be <1nT.

The line spacing depends on the type of artefacts searched for. The intensity of the magnetic field caused by ferrous objects depends on the size of the feature and,

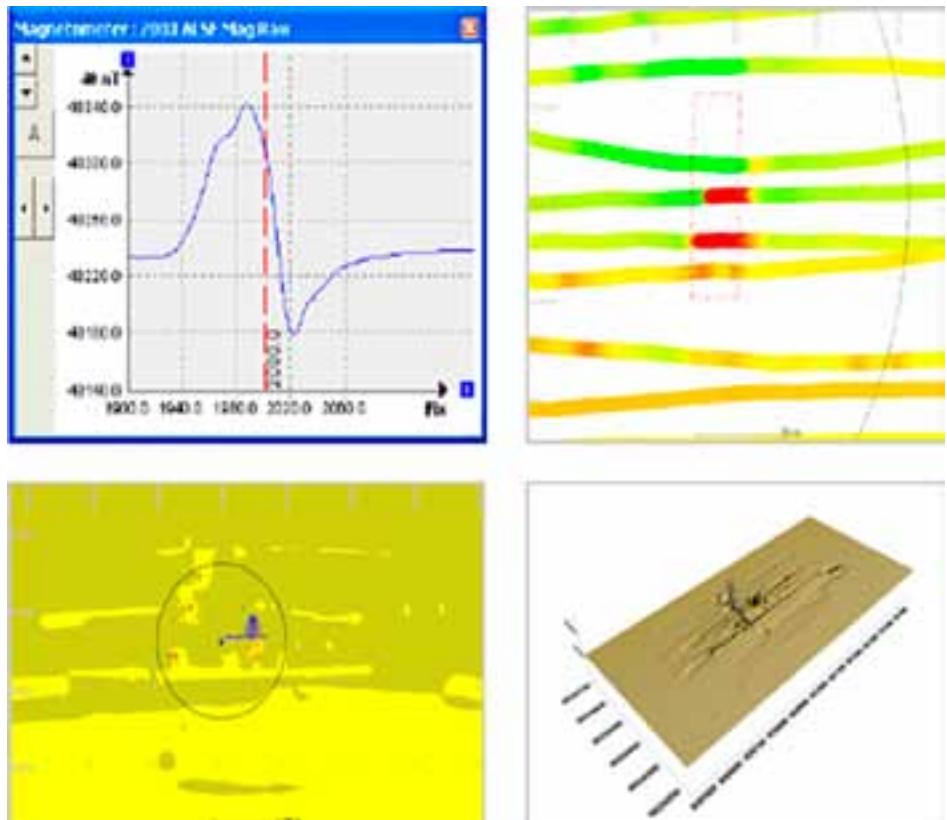


Fig 17 Different modes of representation of the recorded and processed magnetic field associated with the wreck of the *Hazardous* in Bracklesham Bay, Eastern Solent: (a) time-series plots; (b) colour weighted survey lines; (c) contour maps; and (d) 3D display. Images courtesy of Camidge *et al* 2010.

more importantly, decreases with the cube of the distance to the object. To calculate the distance to a ferrous object:

$$\Delta M = 10^4 \cdot \frac{A}{B} \cdot \frac{W}{D^3}$$

where ΔM is the change in field intensity (nT), $\frac{A}{B}$ is the length-to-width ratio of the object, W is the weight of the object in tons and D is the distance to the object (m).

In practice, the smallest change in the magnetic field that can reliably be detected is 5nT. From this, the distance at which an object can be detected can be calculated:

$$D = \sqrt[3]{\frac{10^4 \cdot \frac{A}{B} \cdot W}{5}}$$

for example:

- A 9kg (20lbs) cannon ball (ratio = 1) is detectable at 3m.
- A 100kg (2cwt) anchor (ratio ≈ 1) is detectable at 6m.
- A 2 ton cannon (ratio ≈ 5) is detectable at 27m.
- A 10 ton ship (ratio ≈ 5) is detectable at 46m.
- A 100 ton ship (ratio ≈ 5) is detectable at 100m.
- A 1,000 ton ship (ratio ≈ 5) is detectable at 216m.

Wooden warships nearly always have a large amount of iron on board (cannons, ammunition) and will therefore still be detectable, although the field intensity will be significantly smaller than for a ferrous hull. Wooden wrecks not carrying such objects often contain an amount of small iron fittings, but these are often difficult to detect.

For large areas with unknown potential, survey a grid with grid spacing of 30m–50m and cross lines at 1–10× the principal line spacing, with lines running north–south and east–west. In areas with a large potential for wreck sites, areas with many unidentifiable anomalies detected on other geophysical data or in an area where a large magnetic anomaly has been detected, reduce the line spacing to a maximum of 15m with cross-lines completed at a minimum of 5× the principal line spacing. The cross lines are not only needed to provide additional data, but also to correct for diurnal variations. Furthermore, the magnetometer should be towed at an altitude of 6m above the seabed, so that any target with a mass greater than 450kg can be detected on at least one run-line. It is important to tow the magnetometer at a constant height above the seabed, so it is advised that a depth sensor be attached to the magnetometer to control the instrument's altitude. At the start and end of each survey line, the magnetometer's depth should be recorded.

The sampling interval should be greater than 4Hz at a maximum vessel speed of 4 knots. Camidge *et al* (2010) recommend that surveys be conducted in calm sea conditions to minimise the impact of swell noise on the data. Navigational data should be integrated with the data through the acquisition system. DGPS data are sufficiently accurate, especially when the position is calculated from a lay-back measurement. RTK and USBL will give more accurate results, the latter being particularly useful in water depths >20m. Where USBL systems are not available, test lay-back calculations using a known anomaly and survey lines of opposing headings to quantify any along-track lay-back errors. Record the final data digitally and as x,y,z text (ASCII) files, with separate files for individual survey lines. Each file should include columns of data for raw (ie survey vessel) positions, lay-back corrected positions, raw (ie unfiltered) magnetic values, time/date stamps and towfish altitude. Where a towfish with a sonar altimeter has not been used, include fish depth and survey bathymetry. Where processed (ie filtered) magnetic values are included, these should be in addition to, not in place of, the raw magnetic values.

For ease of processing it is logically preferable if survey lines are oriented in an east–west direction to avoid possible heading corrections. Where lines are oriented approximately north–south, a heading-derived discrepancy of up to 30nT can be observed.

To study the advantages of magnetometer systems for submerged archaeological object detection we need more data. Magnetometers are generally relatively cheap, and therefore, it should be feasible to economically run two systems at the same time. The two sensors should be separated horizontally or vertically by no less than 1m and should be synchronised to within 1ms. Such systems are commonly deployed in pipeline inspection surveys either by towing sensors close to the seafloor or attached to an ROV.

Note: The line spacings described in these sections are from the recommendations of Camidge *et al* 2010 and will differ with the different purposes of offshore survey.

6.6 Integrated surveys

In theory, the acoustic systems described in earlier sections can be used simultaneously, making surveys more economical and effective. However, several limitations must be kept in mind during survey planning.

1 Systems working within the same frequency band can interfere with each other and introduce noise in the data.

For example, in high-resolution data acquisition for archaeological purposes, the instruments most likely to interfere with each other are, on the one hand, high-resolution swath systems (>400kHz) and the high-frequency channel of the dual frequency side scan sonar ($\pm 500\text{kHz}$), and, on the other hand, low-frequency echo sounders (10kHz–50kHz) and sub-bottom profilers (200Hz–24kHz). It is therefore not only necessary to test the instruments individually before leaving port, but also to check for cross-talk between instruments. This includes both the geophysical equipment used for the survey, and all systems on board the survey vessel. Therefore, instruments should be switched on one by one (not all at once) while checking for interference. If there is evidence that the vessel's echo sounder is interfering with the instruments, then the helmsman should switch it off during survey. If this is so, then use digital navigation charts or do a single-beam or swath bathymetry survey in advance, especially in very shallow areas or in areas with highly variable bathymetry. This is to confirm that the vessel's draft is shallow enough and to determine the depth that the side scan sonar and magnetometer can be towed. If this check is undertaken using a single-beam echo sounder, then follow the survey grid planned for side scan and magnetometer deployment.

2 Synchronise all survey systems to the GPS clock. In most cases the DGPS or RTK signal can be split into several channels and integrated into the acquisition computer. If a lay-back correction is used, it should be input independently into the acquisition system of each instrument. However, record the raw navigation data separately for future reference. If all systems cannot be connected to the incoming navigational signal, then synchronise the clock of the acquisition instruments with the GPS clock. Check the offset between the GPS and internal clocks at the start and end of each survey line, and adjust it accordingly.

3 Determine the survey direction by the sources most prone to the influence of tides and currents, and by the orientation of features on the seabed. If the strength of the current is an issue, then collect all data initially with and against the currents. Some cross lines should also be acquired, however. Although these may not provide good data for side scan sonars and sub-bottom profilers, they are needed to carry out corrections for diurnal variations on the magnetometer data. For shipwreck investigations base the location of the cross lines on observations

made on the side scan sonar data and pass the magnetometer over features of interest. For submerged landscape research it must be decided whether cross lines could provide additional information based on observations made from the sub-bottom data. Where tides and currents are not an issue, aim to acquire a regular grid of data. One direction should be perpendicular and one direction should be parallel to the main axis of the main geological or archaeological features.

4 The instrument that needs the narrowest line spacing determines the survey coverage and line spacing. For large reconnaissance surveys, a survey grid with a line spacing of 30m–50m \times 30m–50m (maximum up to 10 \times the principal line spacing) provides good coverage for all geophysical instruments. In the case of an individual wreck site, the site should be 'boxed'. To acquire the best data possible and because this box will generally measure <200m \times 200m it is best to do the survey in stages. Do the swath and side scan survey first, then an integrated sub-bottom and magnetometer survey using the standards described in the individual sections above. For a detailed submerged landscape survey, it is more economic (eg with respect to data quantity and processing costs) to do a wider-area survey with a swath and side scan sonar first, followed by a sub-bottom survey of selected areas at a line spacing of 10m \times 10m, rather than surveying at the narrow line spacing with the full suite of systems.

5 Determine the survey speed according to the system that needs the slowest acquisition speed. The ideal speed is 2.5–3 knots; do not exceed 4 knots. When a site needs to be surveyed with great detail, the helmsman should try to reduce the speed as much as possible while still being able to follow the planned survey lines.

6 The magnetometer is most commonly towed directly behind the side scan sonar, as their combined weight makes it easier to fly the systems close to the seafloor and improves stability. Some new side scan systems actually have an in-built magnetometer attachment, which means only one cable needs to be towed behind the vessel (eg Klein 3000 side scan sonar). When a range <50m is used for the side scan system, tow the systems <5m above the seabed. For a larger range, tow the systems >6m above the seafloor.

Several software programs are available for the simultaneous acquisition of multiple sensor surveys. These include those by CODA, TritonElics, OIC, Chesapeake and Hypack.

The same software can be used for preliminary processing of the individual data-sets, or each data-set can be exported for processing as described in previous sections. The main advantage of processing within one of the combined packages is that the processor is less likely to have a coordinate mismatch between data-sets.

6.7 Other systems

Obviously, new techniques are still being developed and existing methods are being improved. There are, however, other techniques currently in use in disciplines other than maritime archaeology (eg habitat mapping) that could provide additional information. As these techniques have been used rarely or not at all in archaeological studies, this section merely explains them rather than giving guidance on their use.

1 Lidar (light detecting and ranging)

This is one technique that has been applied in terrestrial, but not marine, archaeology (Fig 18). It is an airborne mapping technique that measures the backscatter and travel time of a laser pulse reflected off a land, water or seabed surface. The laser itself has a narrow beam, but a scan mirror mounted in front of the laser rotates and directs the laser pulse to the Earth, producing a conical sampling pattern with a swath width of c 30°. Airborne lidar bathymetry (ALB) or airborne lidar hydrography (ALH), which can measure seabed depths, is of particular interest to the marine sector.

The technique is mainly used for coastal surveying and monitoring of erosion and flooding. ALB or ALH emits two rays at different wavelengths: a near-infrared wavelength ray (between 1,047nm and 1,540nm), which does not penetrate the water column and, hence, reflects off the ocean surface; and a blue-green wavelength ray of 532nm, which penetrates the sea surface and reflects off the seafloor. By determining the difference in travel time between the two laser pulses, the water depth can be calculated with a vertical accuracy of c 150mm. The main advantage of this technique is its ability to survey seamlessly between the terrestrial and coastal environments. As a consequence, and because lidar's swath coverage is independent of the water depth, the technique can operate in water depths that are too shallow for more traditional acoustic bathymetry surveys (ie swath systems). Furthermore, lidar surveys are more cost-effective than hydrographic surveys because of two factors: the coverage rates (20–30km² per hour) are much

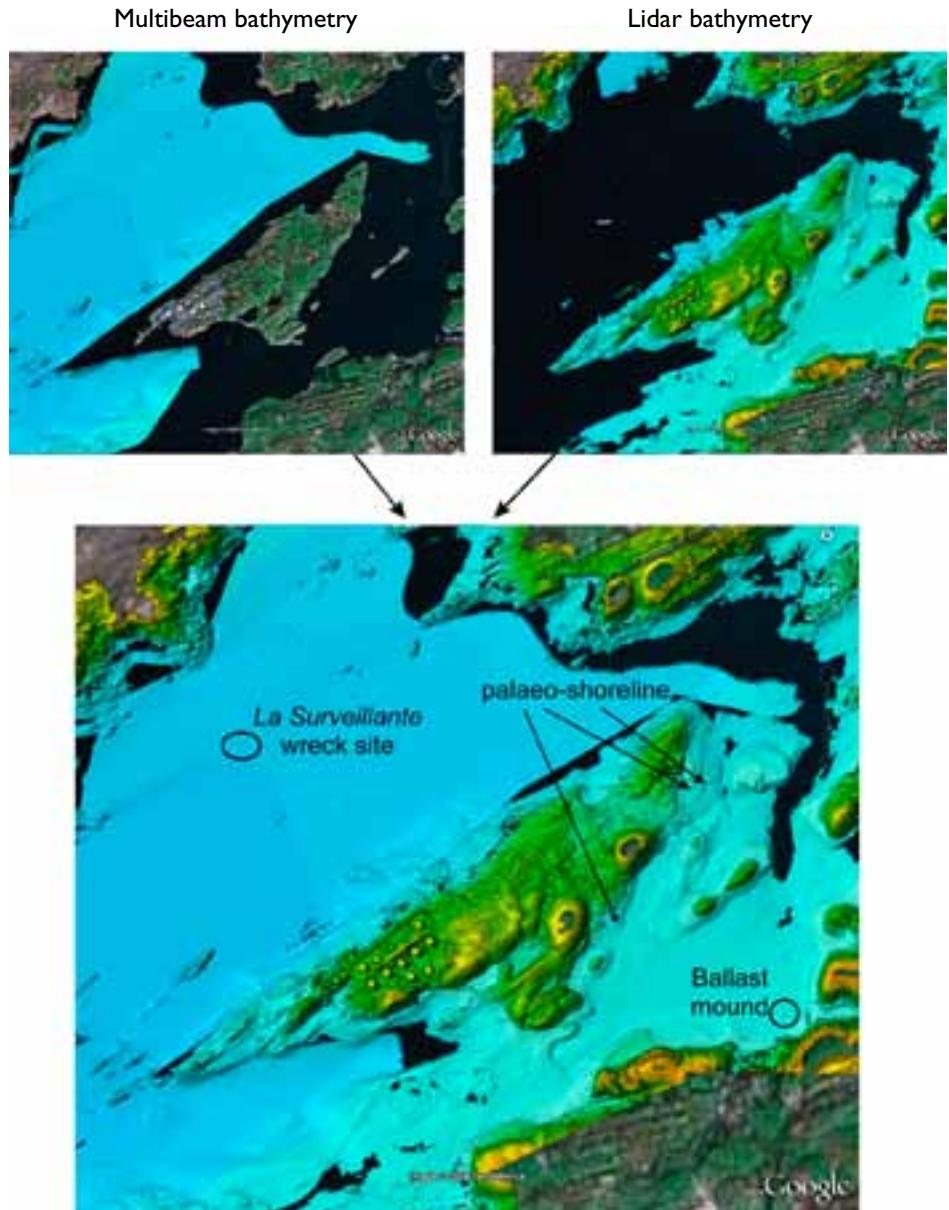


Fig 18 Seamless integration of multi-beam and lidar data in Bantry Bay, Ireland, superimposed in Google Earth. Data acquired as part of the Irish National Seabed Survey (INSS) and INFOMAR (INtegrated mapping FOr the sustainable development of Ireland's MArine Resource) programmes. (Data available from <http://www.gsi.ie/Programmes/INFOMAR+Marine+Survey/View+the+Irish+Seabed+in+Google+Earth.htm>.)

higher than for acoustic methods, and up to 3,000 pulses per second can be emitted and recorded, enabling high horizontal resolution (typically within a metre when using DGPS, sub-decimetric when using RTK GPS).

There are, however, some disadvantages in comparison with the acoustic systems. One is that lidar only works in relatively clear water. Turbidity, wave activity and algae blooms all affect water clarity and will reduce the operational depth to two to three times the Secchi disk depth (a Secchi disk, usually 200–300mm in diameter, is a white or black and white disk lowered into the water to visually measure its transparency). Another disadvantage is that lidar is sensitive to aerosols and cloud particles in the atmosphere and is therefore only effective in fair weather.

As for multi-beam processing, lidar final data (ie a digital terrain model) need to be corrected for tidal variations.

From a maritime archaeological viewpoint, lidar could be used as a tool for anomaly detection in very shallow water. The data can then be used to target certain areas for more detailed observations, either with acoustic or diving methods. However, at present, lidar data collected to IHO S-44 standards only require a spot spacing of 5m × 5m (standard 1b – see Table 1), which may result in data resolution that is too low for smaller archaeological object detection. The most important benefit is for the study of submerged landscapes, as it can link palaeo-landscapes currently exposed on the continental shelf to the present land surface, integrating maritime and terrestrial archaeology.

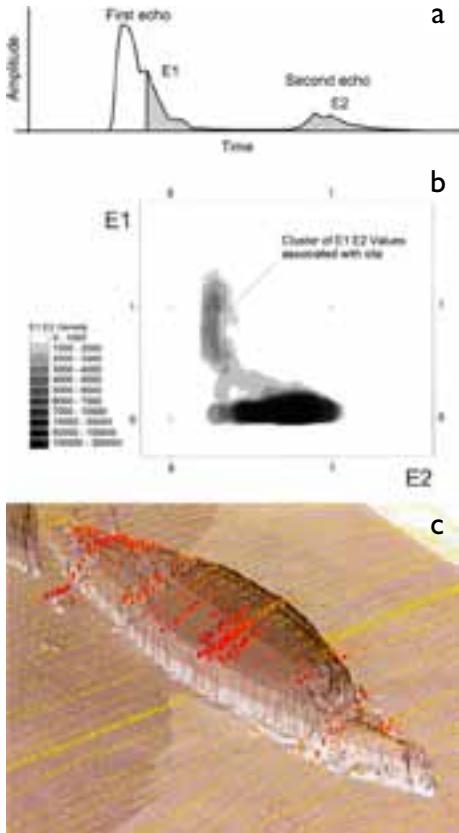


Fig 19 (a) Principle behind RoxAnn™ seabed classification system; (b) A density plot of E2 (hardness) vs E1 (roughness) for data points associated with the wreck of the *Markgraf*, Scapa Flow; (c) distribution of these clusters of points superimposed on a 3D swath bathymetry image of the vessel. After Lawrence & Bates, 2001.

2 Acoustic ground discrimination systems

In recent years the requirement for remote seabed classification for defence (eg mine hunting) and for environmental (eg habitat mapping), economic (eg fishing) and industrial (eg dredging) purposes has led to the development of relatively inexpensive acoustic ground discrimination systems (AGDS). Originally, and most commonly, the use of AGDS refers to single-beam seabed classification – using a single-beam echo sounder to remotely classify seabed bottom types. This is achieved either by attaching signal processing systems to an existing echo sounder or by installing an echo sounder transducer and signal processing software exclusively for seabed classification use. The latter set-up tends to have a wider beam width (12° to 50°) than that of echo sounders used for bathymetric purposes. AGDS looks at two main properties of the seafloor: the acoustic hardness (or acoustic reflection coefficient) and the acoustic roughness (or acoustic backscatter coefficient). As the cone of sound emitted by the echo sounder travels through the water column, the centre of the cone hits the seafloor first and is the source of most of the specular reflection. The signal strength of this specular return holds information on the hardness of the seafloor. The sound energy of annular rings around

the centre of the cone hits the seafloor later and produces a weaker echo as the result of backscatter. A smooth flat seafloor will return the signal largely unchanged, resulting in a large main peak with a short tail. Soft sediments will attenuate the emitted sound considerably and change the shape of the signal. Rough surfaces will produce an echo that decays slowly and produce more backscatter, resulting in a lower main peak but a longer tail. At present, the two most commonly used off-the-shelf acoustic bottom-classification systems are RoxAnn™, which is based on a multiple echo energy approach, and QTC-View™, which uses a first echo shape approach.

RoxAnn (SonaVision, Aberdeen) uses the second echo (E2) (Fig 19), or multiple, of the returned energy as a measure of the acoustic hardness: the sound is emitted by the transducer, reflects off the seafloor, travels up and hits the air–water interface, travels back towards the seafloor, reflects off the seafloor a second time and is then recorded by the echo sounder. Because this is a multiple return, the contribution of backscatter is negligible. The tail of the first echo (E1) is used as a measure of the acoustic roughness. E1 and E2 are consequently plotted against each other and data clustered together indicate areas of related bottom types. Each of the classes identified on the E1–E2 plot must be calibrated using samples before a spatial distribution map can be composed.

The QTC-View (Quester Tangent Corporation, Sidney BC, Canada) system examines the shape of the first echo by calculating parameters in the time and frequency domain. In total, 166 parameters are determined, which are then, by principal component analysis, used by the QTC software to determine three Q-values (Q1, Q2 and Q3). The three Q values are plotted on a three-axis plot and echoes with similar characteristics cluster together in classes in the three-dimensional Q-space. Two types of classification can be used. The supervised classification mode provides bottom classes by comparing them against chosen (ground-truthed) portions of the data-set. In the unsupervised classification mode, the software automatically provides the classification.

The result of these systems is an estimate of the seabed sediment type while the vessel is underway. It has to be noted that the classification is not absolute, because it is dependent on the characteristics of the echo sounder used. It is therefore essential to take seabed samples to calibrate the system. The AGDS gives best results for wider mapping purposes when it is used in conjunction with conventional side scan and sampling systems.

Current research is moving away from the single-beam echo sounder and is developing methods to use side scan and multi-beam backscatter values for seafloor classification. Much of the work to characterise the seabed using swath bathymetry is currently driven by the requirement for extensive and rapid biotope mapping and by fisheries assessment. The typical approach taken is to correct the raw backscatter data for absorption and refraction of the sound pulse in the water column and for the influence of the seabed's topography. A series of backscatter signals versus incident-angle profiles is produced for a series of flat, homogenous and calibrated seafloor sites, and these results are then compared statistically with corrected backscatter data acquired from the survey area.

Although the ground-discriminating technique is routinely used in industry and environmental research, it is currently under-researched for its potential in maritime archaeology.

3 Multi-channel and 3D seismic reflection surveying

The sub-bottom profilers discussed above (see section 6.4) assume the simplest and most common method of marine seismic reflection surveying: single-channel profiling in which a marine seismic/acoustic source is towed behind the vessel, triggered at a fixed rate and the signals reflected from the sedimentary column detected by a hydrophone streamer made of several receiver elements towed close to the source. The signals detected by the individual receiver elements are summed and a single trace is recorded.

Advances in sub-bottom techniques, mainly triggered by the offshore industry, have led to the development of multi-channel and 3D systems. These systems are now being adapted and are slowly finding their way into shallow-water surveying. During multi-channel reflection seismic surveying, a long hydrophone streamer made up of individual receivers is towed behind the source. Instead of instantly summing the received signals, each individual seismic signal received at each section is recorded as a separate trace. This way, recordings of reflected pulses are obtained at several offset distances from a shot point. This data can then be used to estimate the velocity of sound through the sedimentary column, which, in turn, can be used to convert the two-way travel time to true depths. After processing and stacking data points with a common position, the resulting profile will have an improved signal-to-noise ratio, a higher horizontal trace density and improved ability to discriminate among reflection events in comparison with traditional single-channel data.

The most recent advances in high-resolution reflection seismic data acquisition have been made in 3D surveying. The aim in traditional 2D surveying is to acquire a grid of data and to create a pseudo-3D image by interpolating between the lines. However, this method can give a false image, and objects buried between the grid lines will be missed. During 3D seismic data acquisition, multiple parallel streamers with a known separation distance are towed behind the seismic source and a series of closely spaced lines is run. During post-acquisition data processing a grid is chosen over the area and divided into bins; for high-resolution surveying the bin size should be smaller than $1\text{m} \times 1\text{m}$, or, for very detailed surveys, smaller than $0.5\text{m} \times 0.5\text{m}$. All data points within a bin are subsequently stacked and, normally, migrated. The finished product is a volume

of data that can be examined in any possible direction rather than as individual lines that need interpolation. The data provide a clearer and more detailed image of buried structures and features in comparison with traditional sub-bottom data. This technique, however, is not cheap and is generally not affordable in current archaeological budgets. Nonetheless, as the shallow-water marine industry is starting to recognise the potential of the technique and the technology evolves, it is predicted that archaeologists will benefit from such 3D systems in the future.

A 3D chirp system has recently been used successfully to image buried shipwrecks and offers great potential for visualising buried archaeological objects (Fig 20). In addition, the system can provide detailed stratigraphic information for reconstructing submerged, buried landscapes.

7 Processing and analysis of geophysical data

7.1 General data processing, presentation and interpretation

7.1.1 General geophysical data processing
The main purpose of processing marine geophysical data is to enhance the signal level over the background noise levels. Initial processing is typically accomplished using the same software as that used for data collection, or using software that enhances the geophysical data and provides a final interpretation of it. However, computational processing can never substitute for poor raw data; it is therefore important to try to acquire the highest quality data possible in the field. Processing of final data involves the following basic steps.

1 Data editing

Primary data editing is often accomplished during or immediately after acquisition. The editing typically includes the rejection of data that fall significantly outside a basic range of parameters that should be determined before the start of surveying. The parameters are applied to the digital data as a series of filters designed to eliminate data based on the following criteria:

- geographic position – The data fall outside the survey area. For example, it is common when using GPS and DGPS to record sudden jumps in the navigation to points outside the survey area. Such points can be easily recognised in most survey packages and the data associated with them can be flagged for omission.
- depth range – The data fall outside the site's expected depth range. Frequently, sonar systems will record noise from within the water column that would, if included faithfully, create topographic features with naturally unrealistic gradients and dimensions (vertical differences of tens to hundreds of metres over distances of less than a metre) and so these can be easily identified. For the majority of sonar acquisition the on-line display systems enable the easy discrimination between the more consistent high-amplitude seabed reflector and individual ping-related, water-column reflectors.

2 Noise reduction

With the increased use of digital data acquisition, the use of noise reducing techniques in post-survey processing has become more widespread. In the past all these acoustic-based techniques typically relied on analogue filters designed to exclude specific unwanted parts of the frequency spectrum to reduce

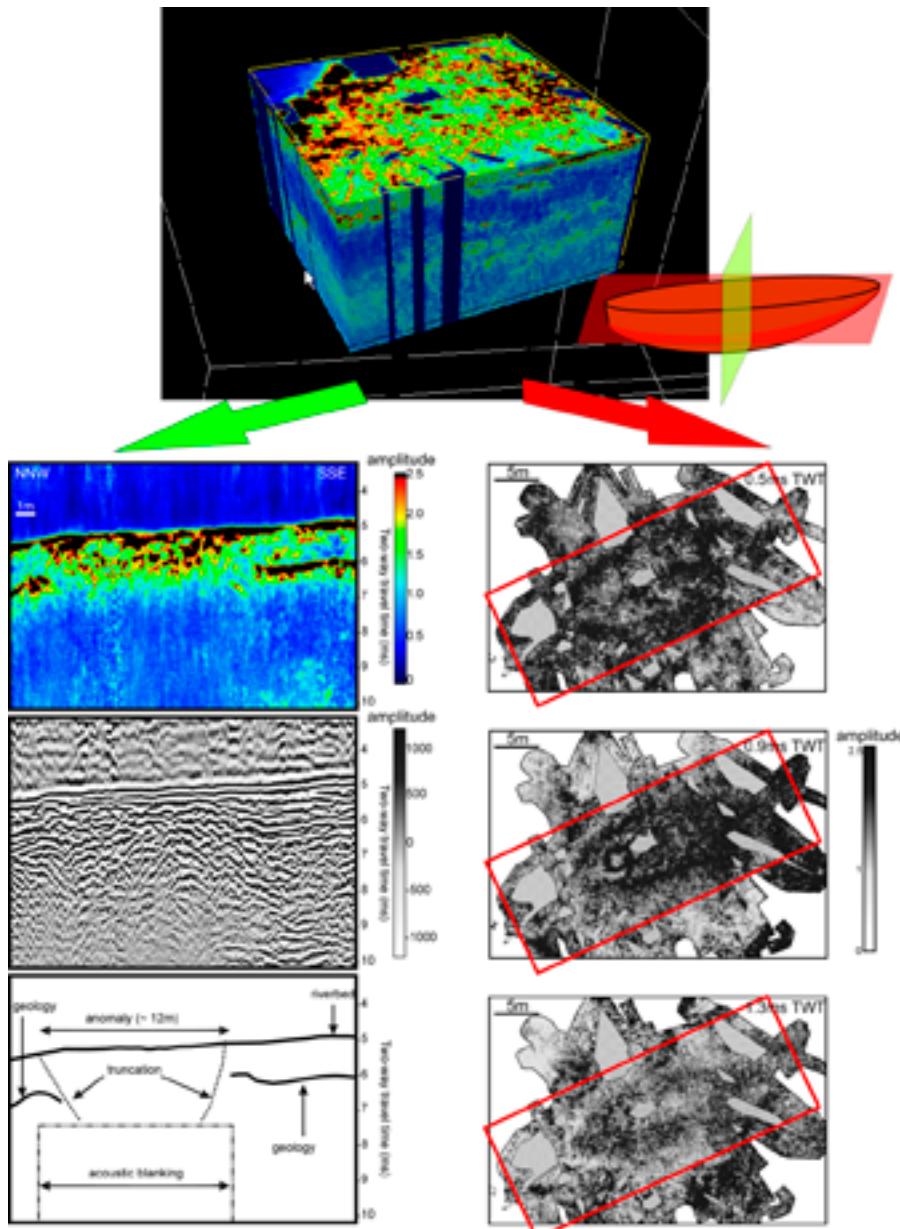


Fig 20 3D data volume acquired with a 3D chirp system over the wooden buried wreck of the Grace Dieu: (top left) a typical vertical section showing enveloped correlated data, (middle left) raw correlated data and (bottom left) acoustic interpretation; (top right) horizontal cross sections 0.5ms (~38cm), (middle right) 0.9ms (~68cm) and (bottom right) 1.3ms (~98cm) TWT beneath the river bed (modified from Plets et al 2009).

noise during a survey. However, once applied in acquisition the analogue filter permanently loses the unwanted part of the spectrum and thus it is essential to be absolutely confident during acquisition that the correct filter has been applied. Digital filters are designed to mimic the analogue counterparts, but with the advantage that they do not permanently affect the data. Thus, during processing it is common to test a range of filter settings in order to determine the most appropriate for enhancement of the data over background noise.

7.1.2 General geophysical data presentation
 Graphical representation of the digital geophysical data is essential and a routine part of all marine geophysical surveys. Graphical displays aid not only the understanding of the geophysical data but also provide a method for further quantitative analysis of the data. Several display methods are available and each has advantages and limitations. While traditional methods of display rely on final images for reports, advances in computer graphics in the last decade can provide computer-aided representations of geophysical data beyond static images. To produce such 3D representations requires some degree of sophistication in computing power and often also specialised knowledge of specific computer programs. The full scope of these aspects is beyond these guidelines, and the field is developing at a pace that would make specific recommendations redundant in a short time. Therefore, only the more traditional display methods are discussed in detail.

The choice of a particular display type follows similar reasoning to that used to choose displays for terrestrial geophysics. However, the amount of data typically collected in marine surveys is often orders of magnitude greater than that for land sites, and consequently the sophistication of software needed increases. The most commonly used types of data presentation are:

1 Line and trace plots

Representation of geophysical data as line or trace plots was the usual form before the development of digital data formats. The method lends itself to marine geophysical data, as marine surveys typically follow lines using global positioning systems. Using such representations for marine data, however, is limited almost exclusively to magnetic data and sub-bottom seismic profiling (see Fig 13) because the results from bathymetry and side scan data are more appropriately shown as contiguous surfaces (eg see Fig 11a-f). To present magnetic data, line tracks or

trace plots of vertical profiles with horizontal distance along the line are plotted parallel to each other, and are usually offset by the relative position in the field.

2 Contour plots

Contour plots are the most common form of marine geophysical data representation. In particular, they are used for contouring seabed depth, for showing buried palaeo-landscapes and for plotting and contouring magnetic signature through magnetic field strength (see Fig 11f). Contour plots show a surface created from the original data points to show a continuous surface extrapolated between points. There are several methods of creating the surface: minimum curvature, kriging, nearest neighbour and triangular irregular networks. Typically, the resulting contour map comprises contours filled by a colour-coded surface. The colour coding can be used to enhance particular ranges or intervals within the data and thus emphasise certain features. In addition to contouring the raw Z values, derivative values such as seabed gradients, single direction slope angles and signal amplitude are also increasingly contoured. This method is inappropriate to marine magnetic investigations, as the line interval between measurement stations tends to be >10m, so small, isolated anomalies are rarely recorded.

3 Grey-scale plots (grey-tone plots)

Grey-scale plots are the most commonly used display method for terrestrial archaeology, but are rarely used for marine data except for side scan sonar data. Grey-scale plots divide the area into rectangles (pixels), each with a user-defined dimension appropriate to the size of the area and to the resolution of the geophysical instrument. A value scaled to the geophysical measure is associated with each rectangle and represented by a grey tone or shade. Because extrapolation of a rectilinear surface of grey tones across the survey area fills in missing data, surface discontinuities tend to be smoothed out. The use of shadow to enhance the final plot can further emphasise data anomalies, especially linear anomalies.

4 Three-dimensional views and other computer manipulation

Isometric plots can be viewed using a horizon perspective to enhance their three-dimensionality. This presentation method resembles a 2D contour plot in producing an artificial surface between the data points that can be further enhanced using 'sun-illumination' (see Fig 11). The surface can also be draped with values from other methods, for example draping

a bathymetric surface with the magnetic map response (see Figs 11f) or with the amplitude data from a side scan sonar. A limitation with 3D views is that they usually obscure background information with foreground information.

5 Point cloud viewing

Point clouds are simply x,y,z co-ordinates that locate a data point in 3D space. Several software manufacturers have programs for working with point cloud data (eg Terramodel (Trimble) and Fledermaus (IVS)). A major advantage of point cloud representation is that only the original data are shown, by comparison to contour and grey-scale plots, which rely on interpolation and thus create data in order to fully populate a geometric grid. A difficulty, however, is that in showing all the data, background data points often become visually merged with foreground data points, causing confusion within the image. This can cause perception difficulties when a large number of points (typically many million) are viewed in the same scene. Software developed by ADUS (<http://www.wrecksight.com>) addresses these perception problems through a combination of depth cueing devices (methods to determine what points are close and which are farther away) such as the use of colour ramps, opacity maps and occlusion objects (Flack and Rowland, 2006 and Fig 21). A key feature of point cloud data display is enhancement of 3D perception through digital cinematography. In particular, camera movement over the scene significantly improves the perception of depth and detail. This effect can be enhanced by adjusting nearer points to move faster than points farther away from the viewer.

7.1.3 General geophysical data interpretation

The final data presentations described above are normally used for interpretation. However, the data can also be exported in other forms for further manipulation and analysis. If this is to be done, the original data must be geo-referenced. Typical data output formats include .jpg and .tif images with their appropriate geo-reference files as .jpw and .tfw files, and ASCII files for bathymetric models in x,y,z format.

The interpretation of geophysical data for archaeological purposes requires the interpreter to have knowledge of archaeology, geophysics, geology and geomorphology. It is therefore suggested that a qualified marine geophysicist trained in archaeological interpretation or a maritime archaeologist trained in marine geophysical interpretation

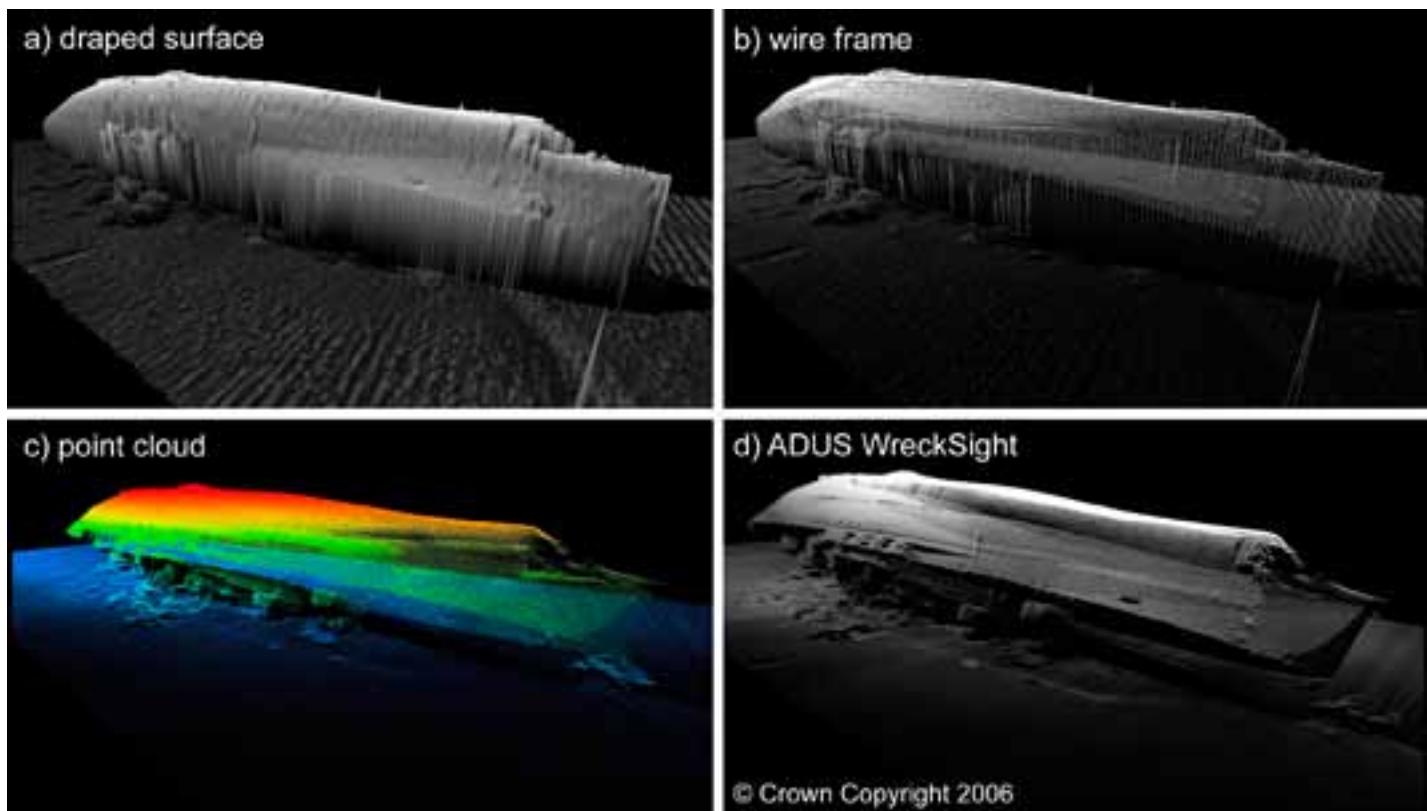


Fig 21 Different representations of high-resolution multi-beam data acquired in 2006 over HMS Royal Oak (imagery courtesy of ADUS Ltd; www.adus-uk.com).

undertake such data interpretation. It is important to interpret as objectively as possible and not to over-interpret the data; to recognise real, potentially archaeological anomalies versus natural features or data ‘artefacts’ caused during data acquisition or processing.

The interpretation is an important section of the survey and main project report. It is essential that the interpretation is accompanied by good graphical presentation of the results, showing the reasoning behind the interpretation. Note that ground-truthing after the survey can offer important information during interpretation.

An important feature of modern marine geophysical data is that data-sets taken at different times can be compared. For example, changes to a wreck site caused by site disintegration can be monitored over time by comparing different side scan or multi-beam bathymetry data-sets. To do this, it is essential to collect the repeat data using similar positional accuracies, and that the data are collected with equivalent equipment and methods. It is additionally recommended that an area close to the site is surveyed as a control point, where seafloor conditions have not changed between the surveys. There are several software programs for conducting the analysis of repeat monitoring on a site; the most commonly used ones include GIS by ESRI (ArcGIS), MapInfo and Golden Software’s Surfer (Quinn and Boland, 2010).

7.2 Side scan sonar processing, presentation and interpretation

7.2.1 General side scan sonar processing, presentation and interpretation

Side scan sonar data processing can be done using one of several commercially available software packages or freeware packages available from government institutions. A number of companies have outlined recommendations for such work, and some information protocols are also available from IHO standards (S-44 and S-57). However, no internationally recognised standards are available for data processing and interpretation. No matter which software package is chosen, procedures follow a similar sequence intended to enhance the signal data over background noise. The original survey objectives, however, determine the method for display of the final results. These fall into three basic types: reconnaissance surveys, wreck site surveys and regional landscape surveys.

Basic data processing includes

- initial-signal manipulation to remove the water column
- addition of a time variable gain (TVG) to increase the signal level at later time offsets from the original pulse
- slant-range correction to correct to true ground distances
- speed compensation for survey speed variation

- beam-angle correction for compensation from a decrease in beam intensity with range due to decreasing grazing angles and signal attenuation

After initial processing, individual gain control can be applied separately or jointly to both the port and starboard transducers and the gain varied throughout the survey project with the aim of producing a consistent amplitude response over the entire data-set. The correct application of gain is especially important if the data are to be mosaicked into a geo-referenced map of seafloor condition. Geo-referencing side scan sonar data is achieved by taking into account the position of the sonar calculated from the boat’s position and either lay-back calculations or by the deployment of a short base-line transducer on the sonar head to record the direction of travel and the roll, pitch and heave of the sonar. With simple side scan systems all of this information is not always available; thus the mosaic is only as good as the stability of the sonar platform and knowledge of its position and attitude. Processing for a geo-referenced image is achieved by re-projecting the digital image onto the seafloor in its true spatial position. Since this requires re-digitising the sonar record into a raster image, the quality of the original image is sometimes reduced. For this reason it is often better to view wreck sites without mosaicking the image.

Similarly, slant-range correction to display approximate horizontal distances also results in a loss of display of the water column, which can be a significant disadvantage in interpretation, particularly of individual targets. Consequently, use both slant-range corrected and uncorrected images in interpretation.

There are several important points to note when producing a mosaic of the seafloor. The shadows behind objects can cause significant problems in a mosaic or map because they represent areas of no data; thus shadows from one line can mask data from an adjacent line. Although a survey overlap up to 200% is recommended, using all of the overlap in the final display is not. Options exist in most processing packages for using adjacent lines to overlap consecutive swaths, to average the amplitudes between overlap swaths or to 'shine through' the highest contrasting swath. In addition, individual swaths can be separately masked to combine certain parts of one line with parts of adjacent lines. For example, it might be that the data are degraded at far offsets and at nadir, creating a permanent clip that filters out this data. No one technique is recommended, as each project will vary depending on the target and the acquisition objectives, so trial and error must prevail.

The final side scan sonar output presented is an image representation of the reflectivity or backscatter amplitude of the seafloor (ie a grey-scale plot). The amplitudes are typically represented in the computer as black and white display (although to optimise the image it is essential to sample the colour scale at the same frequency, eg 8- or 24-bit, as the actual geophysical data) or as a false colour spectrum. For side scan sonar data the pixel size is usually dictated during acquisition and the amplitude recovery enhanced during processing for final display, using the most appropriate mapping of grey-scale amplitude. Light tones represent upstanding objects and hard surfaces where there is significant backscatter; dark tones typically represent areas with low backscatter, shadows, hollows and a soft seafloor. The side scan output can be presented as an individual swath (either slant-corrected or uncorrected) or as a mosaic.

During the interpretation of either wide-area mosaic images or individual swaths, additional analysis tools can be applied to the data. These include enhancements similar to those found in most digital image packages, such as image sharpening, photo capture and image

zooming. These features are usually linked to a database so that the mosaic can be systematically analysed for targets, a set of target images produced and all stored together with their location information in a database for the project.

For wide areas it is typical to produce a mosaic of the area where the images are interpreted in terms of differing textural response across the seafloor. These geo-referenced image mosaics are typically viewed using some form of GIS, so they can be integrated with other ground-truth information. Using these, the human eye can identify characteristics of different parts of the resulting image and these can be related back to known ground-truth control. The image is then classed into areas with similar backscatter response.

There are a number of seafloor classification algorithms that automatically classify different seafloor conditions. These algorithms have been developed over the last decade in response to the routine use of side scan sonar and multi-beam sonar in wide-area survey. The development has been largely stimulated by the deep ocean community (*see, for example, Blondel and Murton 1997*) 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*). To date, the use of such automatic classification routines has not been actively applied to wide-area archaeological prospecting or to site characterisation. However, it has been tested on sites (*see, for example, Bates et al 2007*). Two companies currently offer dedicated classification software for marine data: Questar Tangent Corp., Canada (*see, for example, Preston et al 2004*) and Geoacoustics, UK (*see, for example, Müller et al 2007*).

Both companies attempt to use a statistical approach to classify the seafloor based on the backscatter (side scan grey-scale) images. The software attempts first to compensate an image from the side scan sonar to exclude regions of poor data quality and where the side scan acquisition parameters changed pulse length or frequency. It next divides the image into rectangular patches dependent on the overall image dimensions and the resolution of the survey. It extracts a set of features from the backscatter intensities for each rectangle and applies multivariate statistics 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 software analyses the three components for clustering in a three-dimensional space. Then it analyses a catalogue of where these plot in space, then stores and applies the boundaries to the clustering to the whole data-set to produce a classed image. The technique has found considerable success in classification of seafloors with highly contrasting conditions, such as between rock areas, sand and mud. However, testing has been too limited to date to fully appreciate its potential success with marine archaeological sites.

7.2.2 Side scan sonar processing, presentation and interpretation for wreck sites

After processing the data for standard amplitude corrections, wide-area survey data are typically mosaicked to provide a map of the whole survey area. Adjacent swaths are used in their entirety, with the 'shine-through' enabled to give the strongest ensonified object most relevance.

We recommend that for individual wreck sites a number of individual swaths are analysed together with the final mosaic, as these will tend to show the highest-resolution images of the site and thus the most site details. In addition, when the swaths have been acquired from different directions along the site, it is more likely that the whole site will be imaged.

For wreck sites with upstanding objects the side scan sonar images give photo-like representations that can be interpreted directly from relatively raw sonar records. Software enables objects to be measured along the track length and across it, together with an estimate of the object's height based on the length of shadow. Even without complete georectification the position of the object can be read directly from the side scan image. If the data are of a quality to enable making a mosaic, then the data can be used to produce a geo-referenced image that can be draped on a bathymetric model of the site (Fig 22).

Store the final mosaic images as geo-referenced .tif or .jpg images together with their location information stored as world files .jpw or .tfw. For final interpretation, it is usual to load the images into a GIS system for comparison with other ground-truth data, such as video, still images or diver observations.

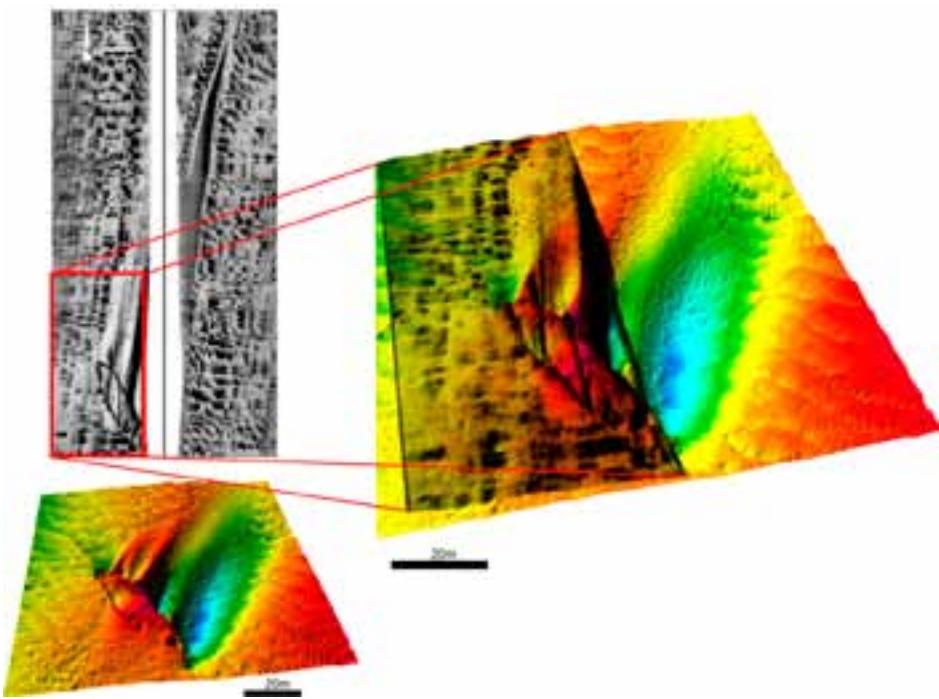


Fig 22 Side scan sonar data (top left) (500kHz, 150m swath) and three-dimensional terrain model (bottom left) of the wreck site generated from multi-beam bathymetric data acquired on the Arklow Bank wreck site; right: side scan imagery draped over the bathymetric data (modified from Quinn 2006; multi-beam data acquired by Titan Environmental Surveys Ltd and side scan sonar data acquired by Donal Boland).

7.2.3 Side scan sonar processing, presentation and interpretation for submerged landscapes

Side scan sonar is not the preferred method for the study of submerged landscapes. If data are available, however, it will improve the interpretation of other geophysical data by characterising the seabed deposits. Processing follows a similar path to that for wide-area survey. It is therefore important to maintain a consistent approach to amplitude response and to review overlaps between individual swaths before automatically accepting them for inclusion in the data-set. For extremely-wide-area survey, the size of the final geo-referenced images can become extremely large and thus quite unwieldy with even the latest computer power. It is recommended for these cases that the data are sub-divided into area blocks less than 30MB in size. For such wide-area surveys, the data are generally presented as a mosaic, while detected anomalies on the mosaic can be shown in the individual swath.

The interpretation of such wide-area surveys for landscape research can be improved greatly if the side scan sonar data can be draped over bathymetric data. If no bathymetric data are available, the data can mainly be used to differentiate seabed conditions in the area, which can eventually be linked to ground-truthed sedimentological information. In addition, a database can be constructed with all detected anomalies, detailing a visual description, positional information, size and a possible interpretation.

7.3 Bathymetry processing, presentation and interpretation

7.3.1 General bathymetry processing, presentation and interpretation

Typically, there are three steps for processing single-beam sonar data acquired using digital acquisition navigation software such as Hydropro Coastal. The first step is to filter the data for spurious points based on navigation errors (sudden large changes in the GPS-derived location) and errors from sudden changes in depth. Depth changes can be caused by noise in the water column from air bubbles or by objects such as fish. Most navigation programs provide automatic filters for such errors. However, if the depth data have been recorded into a simple ASCII text file in the format of x,y,z, then running filters can be designed within standard spreadsheet programs. The second step is to export the bathymetry data to a text file containing the edited soundings and their spatial locations. The bathymetry data should be exported with a coordinate system appropriate to the project specifications. Step three is to display the bathymetric data as a point data-set (Fig 23a) or to extrapolate them into a gridded surface using other proprietary software, such as Surfer (Golden Software) or a GIS program. Alternatively, the bathymetry data can be gridded and interpolated to create a bathymetric surface image, which can then be viewed and analysed in a 3D visualisation program (eg IVS Fledermaus) (Fig 23b). This surface can then be combined with other data-sets (eg sub-bottom data), further

improving interpretation. It is important to choose the binning parameters for gridding the data carefully, to find the right balance between over-interpolation (smoothing the data) and under-interpolation (leaving data gaps). Because seabed coverage with single-beam sonar is generally low, the data are used mainly to interpret the general bathymetry of the area. It will not be possible to detect individual objects using this method.

The major processing and interpretation steps for multi-beam sonar and swath sonar are similar. For both techniques, processing is best accomplished by a trained hydrographic surveyor with experience in marine archaeological geophysics. There are several standards and protocols for multi-beam sonar, including IHO standards S-44, MESH Standards and Protocols for Seabed Habitat Mapping and Land Information New Zealand (LINZ). Processing with various commercially available software programs (Table 2) follows two steps. The initial acquisition and processing are usually done with the same software. This processing makes basic geometrical corrections, cleans the data and projects it into an appropriate geographic system. Then the data are exported for use with other software for enhanced data editing and data amalgamation into whole-area volumes (Fig 23c-d). The steps are:

1 Preliminary data manipulation

Application of offsets after patch test

Corrections for offsets between the various components of the multi-beam sonar system (the sonar head, the DGPS, the motion reference unit, the sound velocity probe) are usually applied in the field following initial survey set-up and the patch test. If not, then such correction must be done during processing.

Application of sound velocity profiles

Sound velocity measurements obtained during acquisition are extrapolated and applied to the data spatially and temporally.

Tidal corrections

Using tide gauge data or GPS RTK information to correct the data to chart datum.

TVG normalisation for amplitude information

If amplitude or backscatter data are to be used, then a preliminary TVG function is typically applied at this stage. This procedure compensates for large amplitudes near nadir vs low amplitudes at far offsets.

Export data

After initial processing further data manipulation is typically conducted after the x,y,z data are exported to a point cloud

visualisation program such as Fledermaus or Terramodel. Data can be viewed line by line within these programs.

2 Further data manipulation

Data are edited for spurious points: water-column noise, depth soundings below the seafloor, navigation errors and invalid motion reference unit values. Points or whole swaths are rejected or adjusted for tidal mismatches. Rejection of low amplitude (noisy) data at the far offsets (outer beams) is also typically necessary. Many routines have been written for the automatic filtering of data: most are designed for hydrographic survey, where the objective is to construct a seafloor surface for navigation purposes. Therefore, in applying automated filtering take care that the archaeological information is not filtered out. Manual data manipulation is therefore advisable over known wreck sites.

Data export and interpretation

After final data editing the data-sets from individual survey lines can be combined into

a single file for one bathymetric model of the whole survey area or split into subsections if the data file becomes very large. Data are exported as text ASCII x,y,z, files and as images (.tif and .jpg with appropriate location files). The text files can be further visualised in point cloud programs or used for extrapolation. Full-coverage bathymetric data are usually displayed as a surface in a 3D visualisation program (eg IVS Fledermaus, ArcGIS), where it can easily be interpreted for general seabed bathymetry or anomalies. Additional visual manipulation techniques used today include:

- hill-shade representations, obtained by setting a position for a hypothetical light source and calculating the illumination values of each cell in relation to neighbouring cells. These can be used on their own to aid interpretation or as an underlay to a semi-transparent, colour-coded bathymetry to provide a pseudo-3D effect (eg Fig 24a and b)
- slope analysis and display, which presents the maximum rate of change

of slope between each cell and its neighbours, presented as an angle in degrees (Fig 24d)

- aspect analysis and display, which identifies the down-slope direction (relative to north) of the maximum rate of change in value from each cell to its neighbours, as calculated in the slope raster.

These methods can effectively interpret both wreck sites and submerged landscapes. Further, the accuracy of modern swath bathymetry survey provides the potential for the creation of difference plots when you can extract one survey data-set from another to quantitatively record bed level change (Fig 24c).

7.3.2 Bathymetry processing, presentation and interpretation for wreck sites

Processing multi-beam and swath bathymetry sonar data over wreck sites follows the procedures described above. For wreck sites, pay specific attention to careful manual editing of data before combining it to create a full bathymetric model of the site.

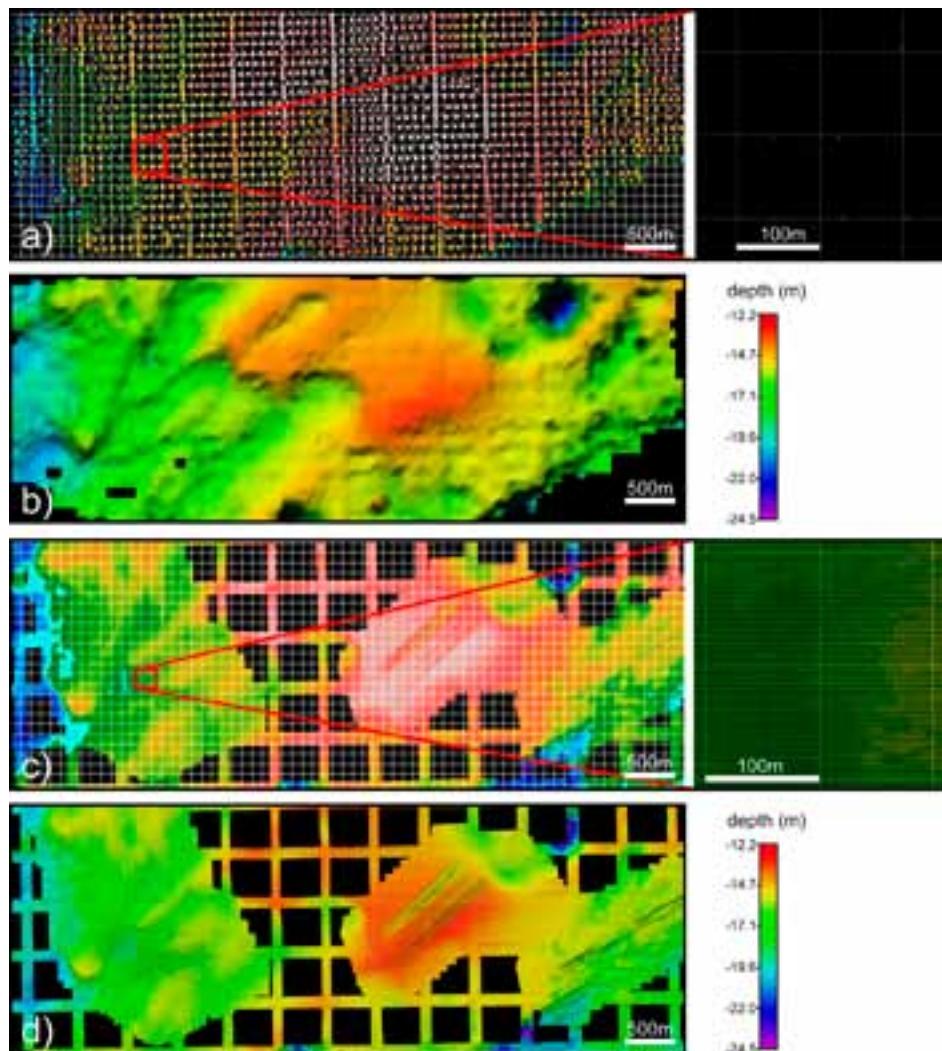


Fig 23 (a) Single-beam and (c) multi-beam data density over Owers Banks; (b) interpolation and shading of single-beam data using a gridded bin resolution of 50m; and (d) gridding and shading of multi-beam data using a 1m bin resolution. Note the difference in the degree of detail that can be observed from the multi-beam data in contrast to the single-beam image (data courtesy of the Resource Management Association).

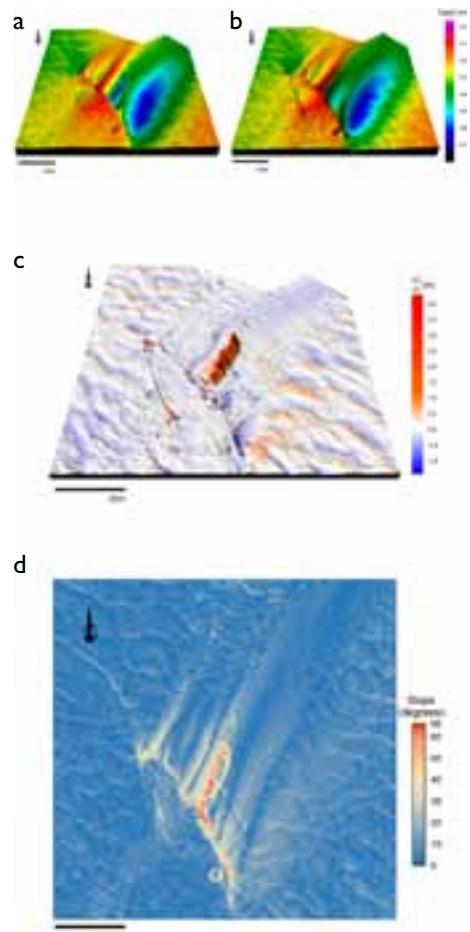


Fig 24 Composite graphic representing: (a) 3D terrain model of the wreck site generated from multi-beam data acquired on 12.08.03; (b) 3D terrain model of the wreck site generated from multi-beam data acquired on 23.08.03; (c) 3D surface produced by subtracting the data-sets presented in (a) and (b) showing areas of accretion (red) and erosion (blue); and (d) slope analysis of the multi-beam data showing steepest slopes in red and gentler areas in dark blue (modified from Quinn 2006; multi-beam data acquired by Titan Environmental Surveys Ltd).

Table 2 Standard commercial software packages for swath bathymetry acquisition and processing

SOFTWARE	COMPANY	USE
HIPS and SIPS	CARIS Ltd, US	data processing and visualisation; supports a wide range of multi-beam systems
Isis MB-Logger BathyPro	Triton Imaging Inc, US	data acquisition and processing
HYSWEEP	Hypack Inc, US	data acquisition and processing
CARAIBES	Ifremer, France	data acquisition and processing
Fledermaus	IVS Ltd, US	data post-processing and visualisation
Neptune	Kongsberg Simrad, Norway	data processing for data only; UNIX based
Poseidon	Kongsberg Simrad, Norway	multi-beam backscatter processing and mosaicking
Triton	Kongsberg Simrad, Norway	multi-beam backscatter seabed classification software; UNIX based
MB Systems	Lamont-Doherty Earth Observatory of Columbia University (L-DEO), Monterey Bay Aquarium Research Institute (MBARI), US	data processing and visualisation; supports a wide range of multi-beam systems; UNIX based
QINSy	Quality Positioning Services BV (QPS), Netherlands	data acquisition and processing
QTC Multiview Multi-beam	Quester Tangent, Canada	backscatter seabed classification software
PDS2000	Reson nl, US	data acquisition and processing

In the case of a wide-area survey, all survey lines can initially be combined into one bathymetric surface and scanned for seabed anomalies. Put together a database detailing the position, appearance, dimensions and possible interpretation of each anomaly. If a potential wreck has been detected, the anomaly should be studied in greater detail as an individual site.

Even with the best of motion-reference units providing information to adjust each individual data point, for individual wreck sites it is often advisable to export data only from individual line passes rather than combining multiple passes, as degradation in data quality is often observed when data are combined from more than one line. As the highest possible resolution must be achieved for individual wreck surveys, it is advisable that each individual swath of data is analysed point by point. This is especially the case on deeper wreck sites, where the number of pings per site is limited, and key wreck features are sometimes represented by only a few individual points. Extrapolation into a continuous surface is therefore not recommended other than for final visual display. Point cloud representations are likely to show more useful data for scientific analysis (see Fig 21).

Interpretation of multi-beam and swath bathymetry data for wreck sites should not only concentrate on the obvious character-

istics (depth, size, position, particular recognisable features), but should also look at the wider environment in which the wreck is positioned (scour, bedforms), as this can inform the archaeologist about the present and future state of the site. Therefore, when monitoring seafloor change around an archaeological site is required, wide-area bathymetric models form the basis of many projects. It is essential to apply tidal corrections accurately to measure true change by subtracting one gridded data-set from another. Each data-set must also be converted to a raster with equivalent bin sizes between each data-set, or individual data-sets must contain the depth information at coincident geographic locations. Extrapolation and re-projection are necessary for each method.

7.3.3 Bathymetry processing, presentation and interpretation for submerged landscapes

Processing for wide-area surveys follows the protocols set out in section 7.3.1. As discussed, where a bathymetric model of a large area is required, the grid spacing must be chosen carefully. The choice of grid spacing, sonar frequency, water depth (and hence ping rate) and survey speed all determine the number of pings on the seafloor. To produce a final continuous, digital bathymetric terrain model it is common to combine, or average, individual

pings within larger area units known as bins (rectilinear areas on the seafloor oriented with respect to the project's local coordinate system – usually the WGS84 grid). The main determining criteria for bin size are the size of the smallest feature of archaeological interest that must be resolved within the survey area and the raw data density (ie binning should not occur at a scale finer than the statistical average distance between data points). Generally, bin size must be at least one-third the size of the smallest feature of interest in order to avoid spatial aliasing. Data binning is usually done within the processing software (eg Caris, Fledermaus). After setting the bin size, the software averages individual data points within each bin and produces a grid data-set with evenly distributed data points. This gridded data can be exported as an ASCII text file containing location information and depth. The gridded data form the basis of further analysis for extrapolation into a bathymetric model, either within the processing software or in a GIS package.

The most appropriate presentation of bathymetric data for landscape research is as a 3D surface. This can be used in a 3D visualisation program for interpretation, where it can be combined with other marine geophysical data and even with a terrestrial digital elevation model, to enable wider and seamless landscape interpretation (see Fig 18 and Fig 25).

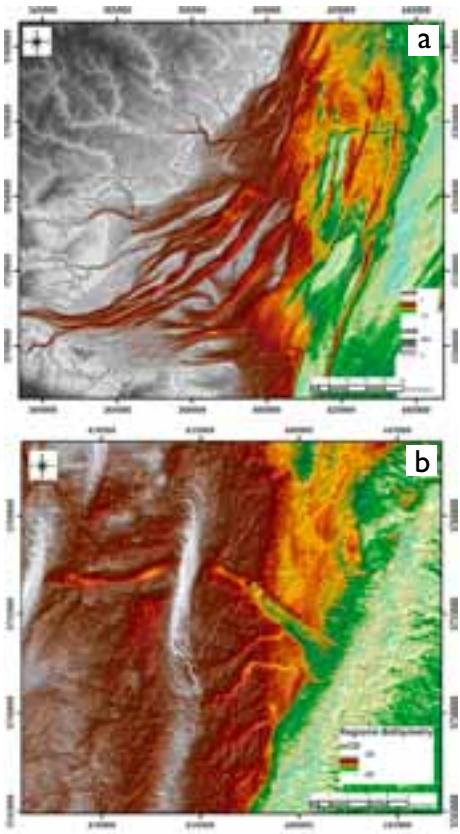


Fig 25 Combination of SeaZone Ltd bathymetric data (30m x 20m bin size) and OS Panoramic Topographic data (50m x 50m bin size) for the Thames Estuary. (a) shows evidence of offshore palaeo-channels of the Thames and Medway river systems; major sandbanks in the Inner Estuary and eroded deeps related to the Anglian Glaciation (Dix and Sturt, 2011). (b) shows a sub-area of (a) and the presence of second- and third-order stream systems submerged in water depths of -20 to -55 mCD. (Bathymetry courtesy of the British Crown and SeaZone Solutions Ltd. All rights reserved. Product Licence 052008.012 and 092009.22. Topography reproduced with the permission of Ordnance Survey © Crown copyright and database right 2013. All rights reserved. Ordnance Survey Licence number 100024900)

7.4 Sub-bottom profiler processing, presentation and interpretation

7.4.1 General sub-bottom profiler processing, presentation and interpretation
Although it is possible to undertake many stages of processing of sub-bottom data, there are several basic techniques that can be applied to the majority of sources typically used. A number of commercial, Windows-based packages specifically for processing high-frequency sub-bottom data are available, for example Chesapeake SonarWiz.sbp, CODA, Edgetech Discover, IXSEA Delph Seismic and Octopus. In addition, the freeware, Unix-based package SEISUNIX developed by the Center for Wave Phenomena at the Colorado School of Mines for lower-frequency multi-channel seismic processing can be easily used with high-frequency data to undertake a range of sophisticated processing. Most of these systems undertake four principal processing operations: band-pass filtering, acoustic-gain control, time-variable gain and stacking.

Band-pass filtering is the most common operation in high-frequency seismic processing. It is used to remove frequencies outside the bandwidth of the input pulse. These unwanted frequencies are typically associated with acoustic noise from the instrument, boat or other marine sources (including cetaceans). The successful application of these filters depends on knowledge of the frequency content of the data. This can either be assumed from the frequency content of the outgoing pulse (as determined from the system configuration; eg see Fig 12) or, ideally, from being able to analyse the frequency content of the actual data. The latter can be important because attenuation of the pulse as it passes through sediment/archaeological materials typically results in a downward shift of the dominant frequency and a narrowing of the bandwidth owing to a preferential removal of the higher-frequency components. Few current commercial high-resolution processing software packages enable computation of the frequency spectrum, so these operators are primarily based on assumed source frequency. The application of band-pass filters is particularly important for boomer systems that in raw format are frequently associated with low-frequency noise (tens of Hz), which swamps the actual data.

Automatic gain control (AGC) and time variable gain (TVG) are operators that attempt to mitigate the decrease in amplitude of the signal as it propagates away from the source owing to geometric spreading and attenuation of the pulse caused by the water column and the sub-surface sediments. AGC algorithms set the maximum amplitude within a specified time window to a preset value. The time window is automatically moved down the time section, equalizing the amplitudes to the preset value for each new section. The result is that the amplitude range of the seismic trace is approximately the same throughout the entire section. However, it is important to note that applying AGC destroys the relative amplitude information that may be required to undertake quantitative analysis of the acoustic properties of individual reflectors.

TVG, by comparison, applies an exponential gain operator to every seismic trace. Consequently, each trace is amplified down the time section by a regularly increasing factor instead of by a variable amount tied to a moving window. Many of the commercial, high-frequency processing packages currently use an operator that is effectively an amalgam of both of these approaches, so it is important to be aware of the implications for quantitative analysis.

Stacking in the context of 2D sub-bottom profiling is a simple process of averaging a number of adjacent traces in order to smooth the along-track section. The number is best defined by ping rate and survey speed, so you do not average over too great a section of seabed. Stacking can be particularly useful to enhance the continuity of reflectors and to deal with small breaks in the data.

Instantaneous amplitude/reflection strength is an operator that is commonly applied to chirp data for image enhancement. Effectively this operator rectifies the data so that all amplitudes are positive, and applies an envelope to the data to smooth the time section and enhance interpretability. As with AGC the destruction of the original properties of the acoustic pulse, in this case any polarity information, negates any potential quantitative analysis of the data at a later stage.

Deconvolution In addition to these fairly common processing steps it is possible to enhance sub-bottom data further through a filtering operator such as deconvolution. Deconvolution is particularly good at compensating for inherent changes in the acoustic properties of the signal: lengthening of the wave, shift in dominant frequency and reverberation effects (common in shallow water) as it passes through the sub-surface. There are several approaches to deconvolution, some of which rely on creating algorithms based on the source signature (and therefore are theoretically best suited for use with sources that output well constrained pulses, such as the chirp systems); others create predictive filters based on the acquired data.

Migration is another currently under-used processing step. It attempts to reconstruct a seismic section so that reflection events are repositioned to their correct surface locations, at a corrected two-way travel time. This process is necessary because although a standard sub-bottom profile trace presents each reflection point as though it is located directly beneath the mid-point between the transducer and the hydrophone, in reality this is not the case unless the reflector is horizontal. If the reflector is dipping along the survey line the actual reflection point is displaced in an up-dip direction, while if there is dip across the survey line the reflection point is displaced out of the plane of the section. Migration also improves the horizontal resolution of the data by focusing energy that is otherwise spread over an area of the bed by the pattern of the acoustic pulse.

At present deconvolution and migration are rarely used in commercial data processing, but are freely available in SEISUNIX.

Multiple removal Note that many manufacturers do offer additional processing options, in particular multiple removal. This operator attempts to suppress the multiple reflections of the seabed and strong subsurface reflectors that are common in shallow water, high-resolution sub-bottom data. At present these features merely suppress all data at fixed time windows predicted on the depth of the seabed reflector, and thus remove both real and artefact components. It is therefore strongly advised that these should not be used.

Sub-bottom seismic sonar data are typically collected along survey lines for 2D seismic and in a grid layout for 3D seismic. The seismic data are collected as a sequence of reflection times for an acoustic wave to travel from a surface instrument to a subsurface layer and back to the surface again. Seismic sections are therefore recorded as a series of two-way travel times with information gathered along individual line tracks, plotted and displayed as a 2D panel or trace plot. Interpretation of subsurface horizons can be done directly on

the panel after appropriate processing to enhance the individual horizons or layers. The panels are typically displayed individually, but can also be loaded into 3D interpretation software such as Kingdom Suite, IXSEA and SEISUNIX, which integrate the panels with a base map to create a fence-diagram of the sub-surface. Presentation in this format enables extrapolation of horizons between individual lines.

reflector or as an area of chaotic reflectors breaking up the more continuous reflectors representing the local geology (see Fig 26a and b). With sufficiently close survey line spacing it is possible to reconstruct in some detail the structure of individual wrecks, as has been done for the Yarmouth Roads protected wreck site in the West Solent. This can be identified by either contouring the amplitude variability of the wreck-reflecting horizon (Fig 26c) or by manually picking the horizon reflector (Fig 26d).

7.4.2 Sub-bottom profiler processing, presentation and interpretation for wreck sites

Sub-bottom profilers will only be effective in showing the detail of a buried wreck when its position is known and when it has been surveyed with a very narrow line spacing. Processing involves all basic steps described in section 7.4.1 and the data are most often presented as a line-trace plot. There are relatively few studies on the use of sub-bottom profilers for shipwreck detection. Where these have been successfully imaged, the buried part of the wreck is imaged either as a discrete strong

7.4.3 Sub-bottom profiler processing, presentation and interpretation for submerged landscapes

Together with bathymetric data, sub-bottom data can offer important information on submerged landscapes. Data processing follows the steps described in section 7.4.1. The individual lines of the sub-bottom data can be displayed individually as trace plots, or they can be viewed in 3D (combined with bathymetric data), which aids interpretation. Features of particular importance include palaeochannels, peat layers, lake

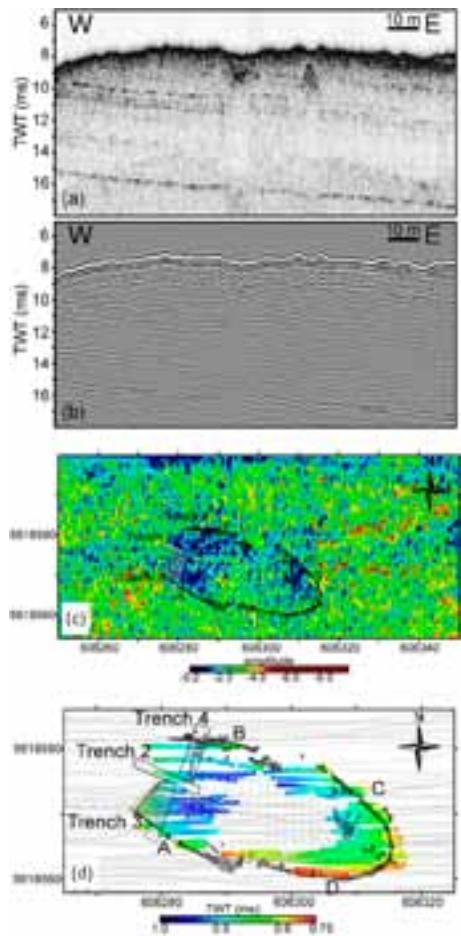


Fig 26 Yarmouth Roads wreck: (a) correlated chirp section of wreck site with reflection strength applied; (b) correlated chirp section – on both images the acoustic blanking caused by the presence of timbers is clearly visible; (c) amplitude map of selected bedrock reflector indicating very low amplitudes beneath the shipwreck, produced by acoustic blanking of the timber material above; (d) individual picks showing depth (in TWT ms) beneath sea-level of the wreck reflector against a diver site plan (Plets et al 2007).

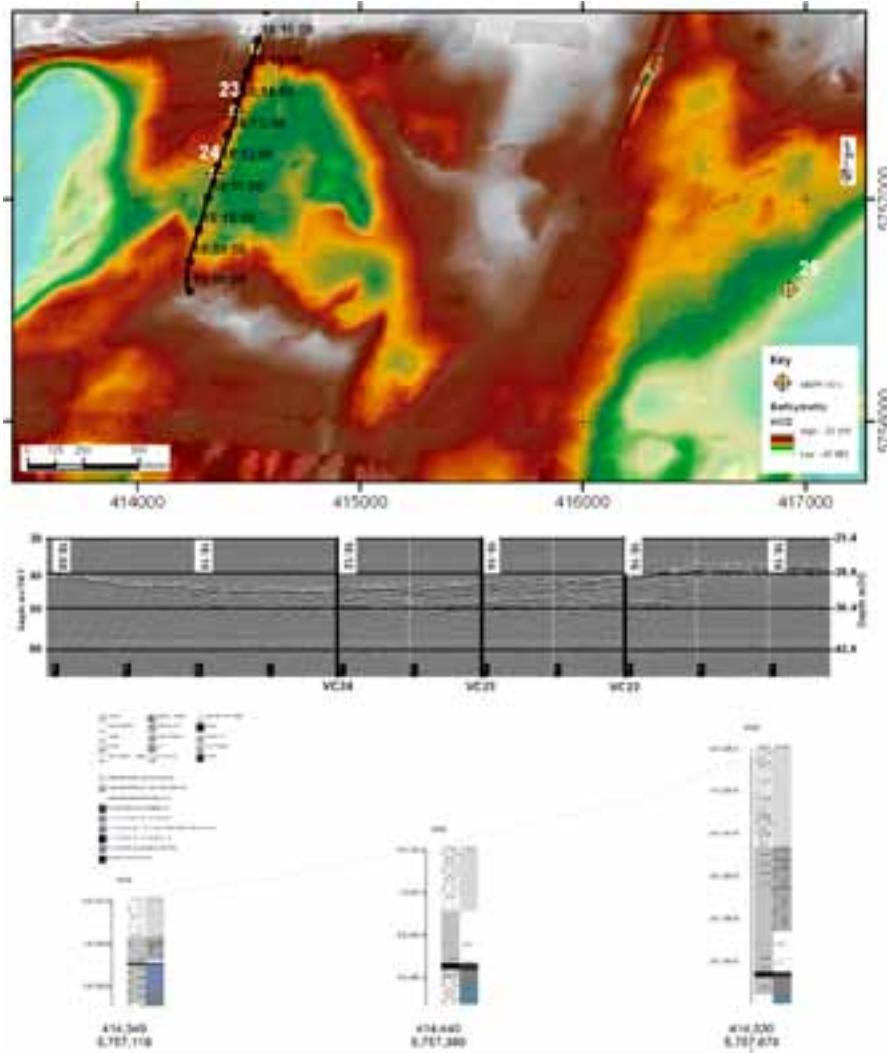


Fig 27 A combined image of geophysical and geological data-sets from the Outer Thames Estuary. (a) Combined SeaZone Ltd. and swath bathymetry data, showing location of three vibrocores taken across a buried channel seen in seismic section. (b) The prominent reflector in the seismic section is from the peat horizon identified within the core logs shown in (c). Image after Dix and Sturt (2011), from data acquired as part of MEPF-ALSF project 09/P126.

basins, lagoons and any other geomorphological feature that would have formed in terrestrial, lacustrine or near-coastal environments. Ultimately, the geophysical data need to be compared with actual core material, taken at targeted locations identified from the seismic section. Figure 27 shows the compilation of swath bathymetry, SeaZone data, sub-bottom data and core lithological and stratigraphical analysis from a cross section of one of the Thames Estuary submerged palaeo-channels. In this example an ancient (<450ka) incised palaeo-channel has been filled with sediments associated with the last Holocene marine transgression (Dix and Sturt, 2011).

7.5 Magnetometer processing, presentation and interpretation

As discussed above, the main use of a magnetometer is for the detection of shipwrecks. It will provide little information when used for submerged landscape research.

Initial processing of magnetic data is done within the acquisition software program. A lay-back calculation must be applied to the data in the same manner as it is for data derived from a side scan sonar. Within most survey packages basic editing follows for location errors due to navigation jumps (from bad GPS fixes) and static shifts in survey lines (for example because of the sensor orientation with respect to the survey vessel and to the Earth's magnetic field – ie the heading correction). This effect is typically seen in the data as alternate striping of parallel survey lines when they are acquired in two directions rather than one direction. Data amplitude adjustments can also be made at this stage if the depth/height from the seafloor changes rapidly during the survey. The diurnal field must be removed, based on a model of diurnal changes measured locally. For most surveys the use of an onsite base station is not possible, so information from cross lines must be used. To calculate the diurnal model the differences in data values are plotted as a function of time during the survey. A smooth curve is then fitted to this data and the curve applied to the raw data as a time-based amplitude adjustment. Removal of the regional field is not usually necessary for small site surveys, for the variation is not large enough to mask the local influence of spot or point anomalies from archaeological sources. Similar to land-based magnetic surveys, marine magnetic surveys can also be adjusted for the latitude-dependent influence on the magnetic anomaly. This influence on the shape of the anomaly, and in particular on

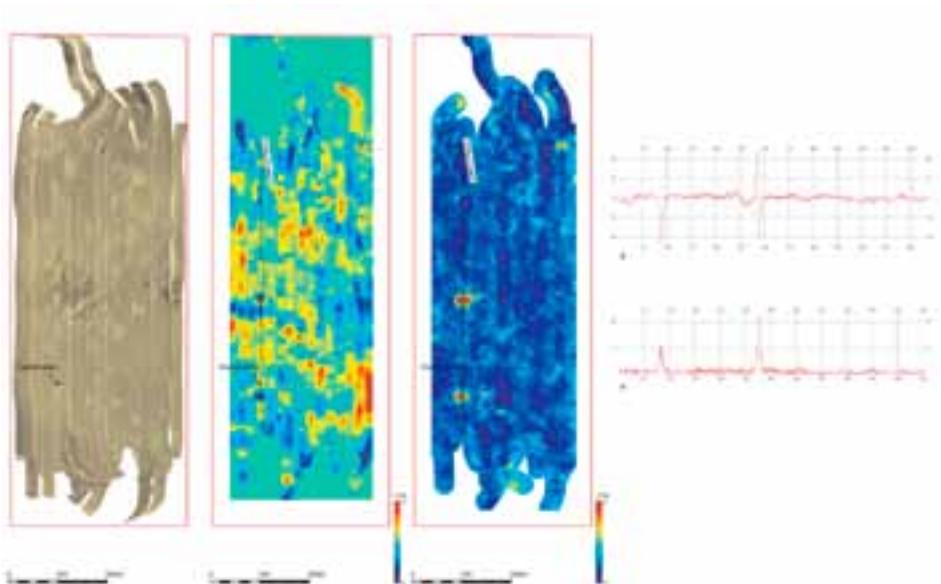


Fig 28 Different modes of representation of the recorded and processed magnetic field associated with a charted wreck: (a) side scan sonar image; (b) contour map of total field; (c) contour map of magnetic gradiometer data; (d) profile data of total magnetic field; and (e) magnetic gradiometer data. Images courtesy of Wessex Archaeology and Cadw, 2010.

the displacement of the anomaly from its source, can be expressed as a phase-angle shift between the Earth's magnetic field and that derived from the anomaly. The necessary correction, referred to as 'reduction to the pole', is a firmly established technique for linear transformation filtering and is usually accomplished within the magnetic processing software.

Many of these systems can also suffer from a range of noise effects, including power supply and other electrical noise sources, instrument noise, contamination (eg the effects of passing ships and navigation buoys) and wave-induced noise caused by the induction of seawater moving in the regional magnetic field. These effects can be particularly problematic if looking to detect very small anomalies of only a few nT, but can be removed/reduced using a combination of low-pass filtering (removal of high-amplitude signal content); despiking (removal of discrete values using a filter designed on the level of anomaly to be detected and the overall signal-to-noise ratio of the data – this approach is not recommended for low sampling rate systems); and spatial filtering (either simply from comparison with metadata in the case of passing ships, or using 2D spatial filters created for terrestrial magnetometry surveys, albeit this can only be of use on very closely spaced (1–2m) survey lines).

The final output from a marine magnetometer survey is an ASCII text file with location information, depth and adjusted magnetic value (x,y,z values). These data can then be represented in a number of standard ways, usually plotted as line surveys. Figure 28 shows a survey over

a charted wreck by Wessex Archaeology for Cadw. Figure 28a shows a side scan mosaic over the area which shows no surface expression of any wreck material at the charted position, but a clear bedrock exposure to the north. Plotting either as a colour-coded nt grid of the total field (Fig 28b) shows areas of extensive positive and negative anomalies but it is difficult to distinguish between anomalies associated with ferrous material on the wreck and the background magnetic signature related to the bedrock geology. Plotting the data as a magnetic gradiometer plot significantly reduces the ambient signal, and the anomaly associated (c 30m N) with the chart wreck position is clearly identified (Fig 28c), along with another stronger anomaly c 200m to the north. These data can also be presented as individual profile plots of both the total magnetic field data (Fig 28d) and the magnetic gradiometer data (Fig 28e). Any detected anomaly can indicate the presence of ferrous material on or buried within the seabed. As described in section 6.5, the change in the magnetic field intensity, in combination with the distance to the anomaly, can be used to estimate the amount of ferrous material present. This can give a first indication of the type of wreck: eg a steel or iron wreck will have a stronger magnetic signal than a wooden wreck with iron fittings and ferrous ammunition on board. Interpretation of these anomalies is greatly enhanced when they are overlaid on a bathymetric model or a side scan survey mosaic, especially if the material lies exposed on the seabed. In the case of buried material, sub-bottom data may confirm the presence and extent of a ferrous object.

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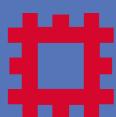
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