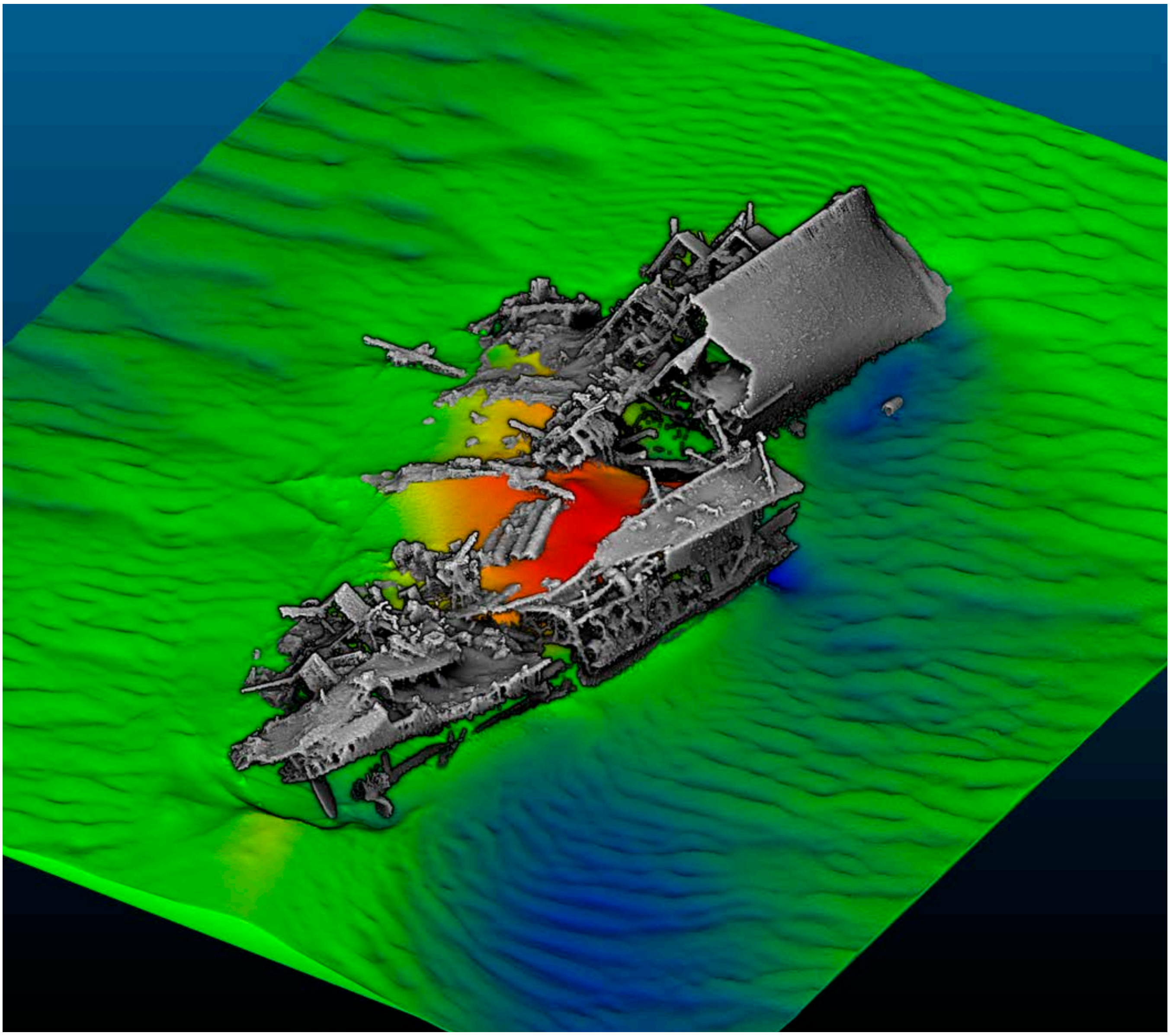
Historic England

Marine Geophysics

Data Acquisition, Processing, and Interpretation

Guidance Notes (2nd Edition)



Summary

This guidance has been written for commissioners, surveyors and end users of marine geophysical survey data in relation to the requirements for marine archaeology. Geophysical data is often, particularly in the case of marine development, collected for a number of different reasons, including route planning, engineering, resource assessment, the identification of unexploded ordnance, ecological studies and archaeology. Therefore, the outputs, including archiving and subsequent ease of access, need to be suitable for a number of end users in line with the policy of collect once, use many times.

Historic England also commissions geophysical survey to inform management strategies for designated historic shipwrecks, and for the purposes of supporting investigation of heritage assets that could be designated. This guidance explains the acquisition, processing and interpretation of survey data to established standards to deliver this requirement.

This second edition of marine geophysical guidance explains, in an accessible way, different techniques for conducting geophysical survey and the processing and interpretation techniques that can reveal information about the historic environment that might be encountered on, within and beneath the seabed around England.

Front cover: Front cover: Multibeam bathymetry of HMS *Keith* collected during the Operation Dynamo Project. © Drassm, multibeam processed by A. Rochat (Drassm) and M. James (MSDS Marine /Historic England)

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1. Introduction

In its broadest form marine geophysical survey is the use of sound, light, or variations of magnetic fields to make measurements, or images, of the seabed, or below it. A distinction is made between geophysical survey and hydrographic survey within relevant sections of this document. However, for ease of reference the term geophysical survey is used within this guidance to encompass both disciplines.

> Geophysical surveys measure and map physical properties of the sediments comprising the seabed and its underlying geology, whereas hydrographic surveys are used to measure and map the seabed depth and topography.

Geophysical surveys are commonplace in marine archaeology and are used by avocational and professional archaeologists alike, for prospection, assessment, monitoring, and during the marine development process. This guidance has been produced to replace previous guidance in response to advancing technologies, and more standardised methodologies. The significant increase in marine development since the First Edition has also led to a requirement for clear and concise guidance and standardisation in the collection, processing, and interpretation of geophysical data.

The guidance is aimed at those involved in the commissioning, collection, processing, and interpretation of geophysical data for archaeological objectives, including data collected as part of a wider scope that will be subject to archaeological interpretation. The guidance is not intended as an instruction manual for the operation of equipment, or the use of software: it is assumed the user of such equipment and software will be trained in its operation and familiar with the limitations. However, using these guidelines through the stages described should support the delivery of outputs as necessary for either archaeological assessment required by archaeological curators or as part of development-led assessment exercises.

This guidance has been written for different users of geophysical survey data. It contains technical concepts and terms required to accurately explain how survey equipment is used and the processing of the resulting data. The technical language used is consistent throughout the wider marine survey industry to ensure that the survey methods described are understood by those using or commissioning geophysical data. Technical terms are defined in the Glossary (Section 19).

1.1 The need for guidance

General methodologies for geophysical survey are well established and have been developed to meet the needs of the end user. For example, data are regularly collected for engineering, hydrographic charting, archaeology, benthic ecology, physical processes, prospection for oil and gas and to inform the development process for offshore developments. The development of larger offshore projects, most notably offshore wind farms, has led to a significant increase in the collection of geophysical data which has greatly increased our understanding of the marine environment, including the historic environment.

Particularly in the case of data collected for marine developments, this is often used and assessed by a range of disciplines to feed into the Environmental Impact Assessment (EIA) process. With archaeology being one of those disciplines, there is a requirement to ensure that data collected, and its subsequent processing and interpretation is suitable to characterise the area of the proposed development. During the survey planning stage, this guidance will ensure that any data collected meet the requirements for archaeological interpretation.

Across the wider marine archaeological sector, the collection of data to a common minimum specification will ensure suitability for not only the assessment being undertaken but comparison of datasets for ongoing monitoring. Common data formats will ensure suitability for, and access to, a wide range of users as well as ensuring agreed standards for data archiving. However, it is rarely the case that a ‘one size fits all’ approach can be taken and the type of data collected, and the specification should be appropriate to meet the archaeological objectives.

Clear, concise guidance is crucial at all stages of the geophysical survey process. Data not collected appropriately, or to a suitable specification, can result in a dataset that is not suitable for archaeological assessment. Data not processed appropriately can result in a loss of detail and resolution and data that are not interpreted appropriately can lead to an inaccurate assessment being undertaken.

1.2 Target audience and guidance structure

The target audience of this guidance is deliberately broad, representing the broad range and experience of those that may be involved with geophysical survey in relation to marine archaeology. This can include the commissioners of survey (including curatorial agencies and offshore developers), practitioners (including archaeological surveyors and survey contractors), and those undertaking the archaeological interpretation of the resulting data. All of whom will be working towards a common outcome of meeting the archaeological objectives.

To ensure suitability for the broad target audience, this guidance has been structured in such a way that it can be considered modular. Each section can be reviewed independently dependant on the requirements of the reader. A modular approach also allows for future revisions to be made as technology advances which may lead to, for example, changes in example specifications.

1.3 Form of the guidance

This guidance covers the four principal sensors used within marine geophysical survey: the multibeam echosounder (MBES), the sidescan sonar (SSS), the magnetometer, and the sub-bottom profiler (SBP). This document summarises the equipment, the uses, and the limitations, and provides guidance from survey planning through to final deliverables.

Whilst every effort has been made to produce this guidance in such a way as to minimise the impacts of advances in technology, certain areas may require revisions and updates. Should it be noted that revisions are required, readers should provide comments to Historic England in order that these can be implemented within future editions.

2. Light, acoustics and survey platforms

This section provides an introduction to light, acoustics, and survey platforms which underpin a number of the survey techniques discussed in this guidance. The magnetometer does not use acoustics, and the principles of operations are discussed within Section 6. The following sections then outline the positioning systems (Section 3) and the four primary techniques that are used in geophysical survey; multibeam bathymetry (MBES) (Section 4), sidescan sonar (SSS) (Section 5), magnetometer (Section 6) and sub-bottom profiler (SBP) (Section 7). For each technique a brief outline of the equipment is provided, and includes the common uses and limitations, survey planning, data outputs, and data processing. Assessment and interpretation of the resulting data are presented in Section 11.

2.1 Light based surveys

With the exception of the magnetometer, the primary sensors commonly used within the marine environment use acoustics, or sound, to image the seabed or beneath the seabed. This is in contrast to many survey techniques on land which use light to create images or produce data. Whilst some survey techniques such as bathymetric and subsea LiDAR and photogrammetry have applications in the marine environment, their limitations should be understood.

2.1.1 Limitations of light-based surveys

Light is a form of electromagnetic energy which propagates (or moves) as transverse waves (Figure 1), the waves move most effectively through a vacuum and as the density of the medium through which it is travelling increases, the effectiveness of the wave decreases.

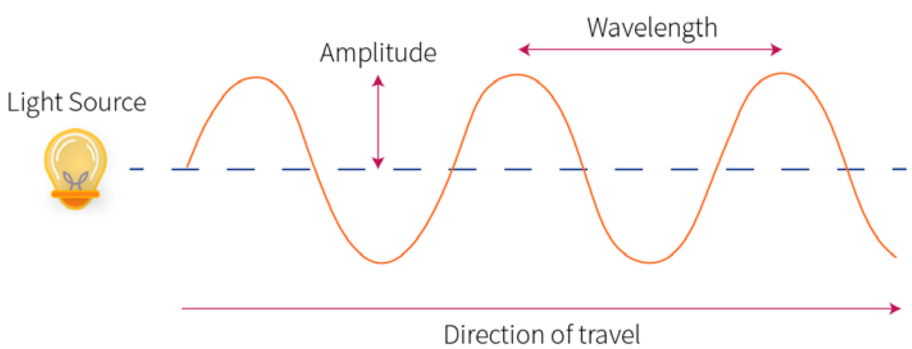


Figure 1:
Movement of light waves.

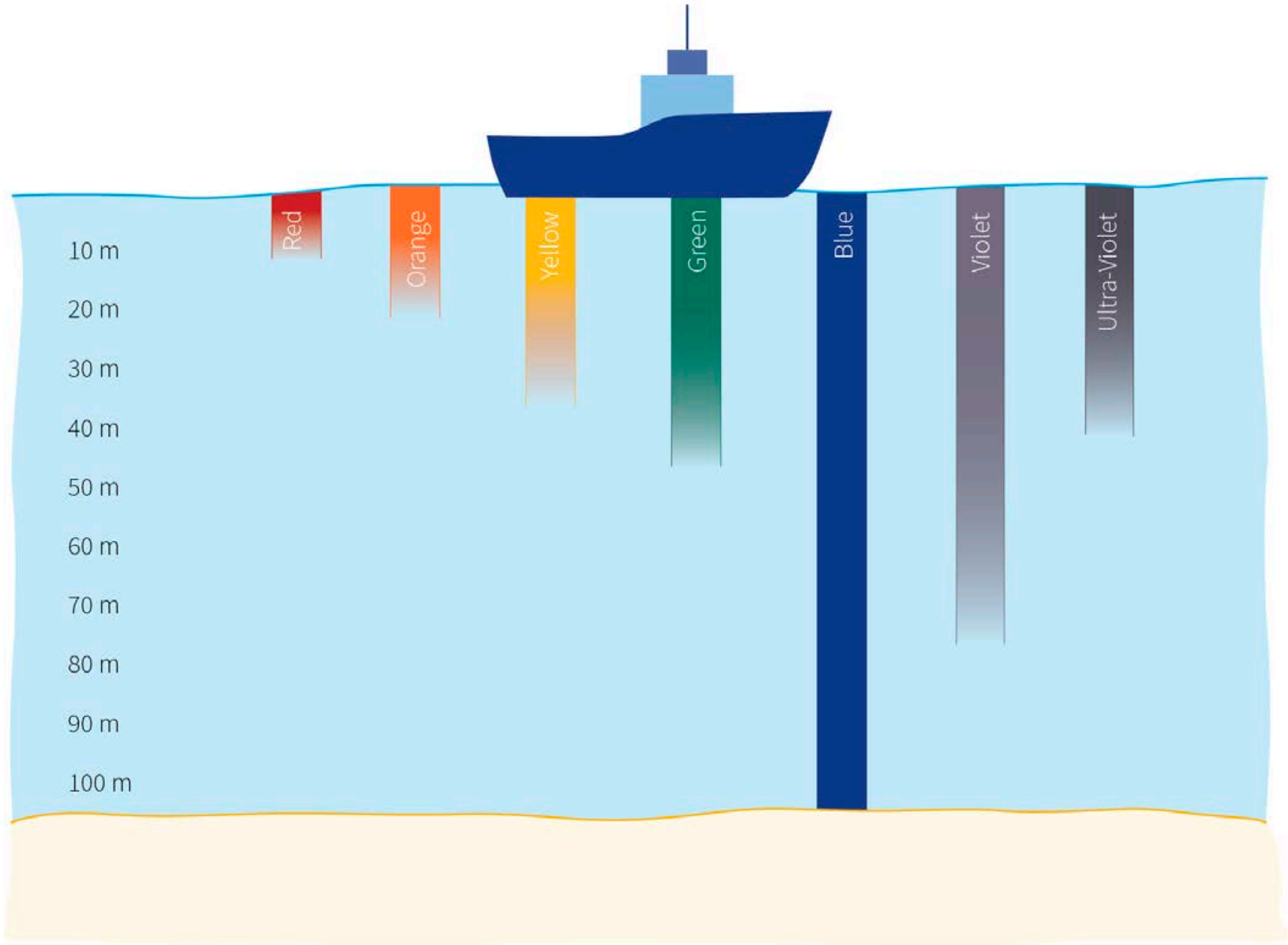


Figure 2: Loss of colour through water.

The propagation of light through water is limited, water absorbs light making its effective range much less than in air. Light is made up of different wavelengths, the longer the wavelength, the lower the energy, and the shorter the distance before absorption. Red is the first colour within the visible spectrum to be absorbed (Figure 2).

As well as the absorption of colour as light moves through the water column, the intensity of the light decreases exponentially with distance from the source; a process called attenuation. Attenuation is caused by the absorption and scattering of the light by suspended particles.

Whilst it is possible to use light-based survey methods underwater, the general restrictions will be based around the distance of the light source to the subject, the water clarity, and the ambient light. Whilst this guidance does not expand further on light-based survey techniques, a brief overview of bathymetric LiDAR, subsea LiDAR and photogrammetry is provided below.

2.1.2 Bathymetric LiDAR

Bathymetric LiDAR is an airborne technique that typically uses green lasers to create topographic maps of the seabed (or lakebed, riverbed, etc.) in areas of shallow water. The depth of water where the technique is effective will be dependent on the clarity, turbidity, and surface movement of the water, with the range below the surface being up to three times the Secchi depth, and typically to a maximum of 25 – 30 m in ideal conditions. Within UK waters the clarity is likely to be a significant limiting factor in the usefulness of the technique.

However, where the technique can achieve the required range below the surface to meet the archaeological objectives it can provide a useful dataset. Due to the shallow depth of water, it is suitable for obtaining data in waters where the deployment of other techniques may be restricted, and it provides a seamless dataset between the terrestrial and marine zones. The resolution of bathymetric LiDAR varies significantly dependant on the system used and the altitude and will be an important consideration when determining if the technique can meet archaeological objectives.

Airborne LiDAR in archaeological surveys, and the principles of its operation can be found in the Historic England guidance Using Airbourne LiDAR in Archaeological Survey (2018).

2.1.3 Subsea LiDAR

Subsea LiDAR uses the same principles as bathymetric LiDAR; however the sensor is deployed subsea rather being airborne. This may be statically on the seabed, or dynamically on a survey vessel, Remotely Operated Vehicle (ROV), or Autonomous Underwater Vehicle (AUV). Subsea LiDAR has similar limitations to bathymetric LiDAR in relation to water clarity, however the ability to decrease the range in relation to the target when deploying from an ROV or AUV can not only reduce this limitation but enable the collection of very high resolution data. In clear water, subsea LiDAR can be an effective technique for acquiring very high specification data to meet archaeological objectives.

The technique follows the same basic principles as terrestrial laser scanning, further information on which can be found in the Historic England guidance Advice and guidance on the use of laser scanning in archaeology and architecture (2018).

2.1.4 Photogrammetry

In its most basic form, and in relation to its application underwater, photogrammetry involves the collection of multiple overlapping photographs of all elevations of a feature. Using specialist software, the photographs are then stitched together to create a three-dimensional representation (model) of the feature. The inclusion of scales within the photographs allows the models to be scaled appropriately.

The models can output in a variety of formats including Digital Elevation Models (DEM) or photorealistic models. The data collection methods and processing techniques can result in high resolution data. Whilst commonly a diver-based technique, the collection of data by

ROV is becoming increasingly common. The technique is limited, like LiDAR, by the clarity of the water, however good results can be achieved even when clarity is less than optimal and wrecks the size of the *Titanic* have been successfully recording using the technique.

Further information on photogrammetry can be found in the Historic England guidance Photogrammetric Applications for Cultural Heritage Guidance for Good Practice (2017)[1].

2.2 Introduction to acoustics

Sound is a vibration that propagates as an acoustic wave, through a transmissible medium such as a solid, liquid, or a gas. Not all sound can be heard; humans have a general hearing range of between 20 Hz and 20 kHz. Frequencies below 20 Hz are called infrasound, and frequencies above 20 kHz are called ultrasound. Whereas light waves are transverse waves, acoustic waves are longitudinal waves.

In relation to underwater acoustics, two main types of acoustic wave should be noted;

- **Primary Waves** (P Waves) are longitudinal compressional waves which can propagate though most materials, including liquids.
- **Secondary Waves** (S Waves) are transverse shear waves that can only propagate through solids.

Vibrating objects underwater create sound pressure waves that travel through the water column by alternately compressing (compression) and decompressing (rarefaction) molecules (Figure3).

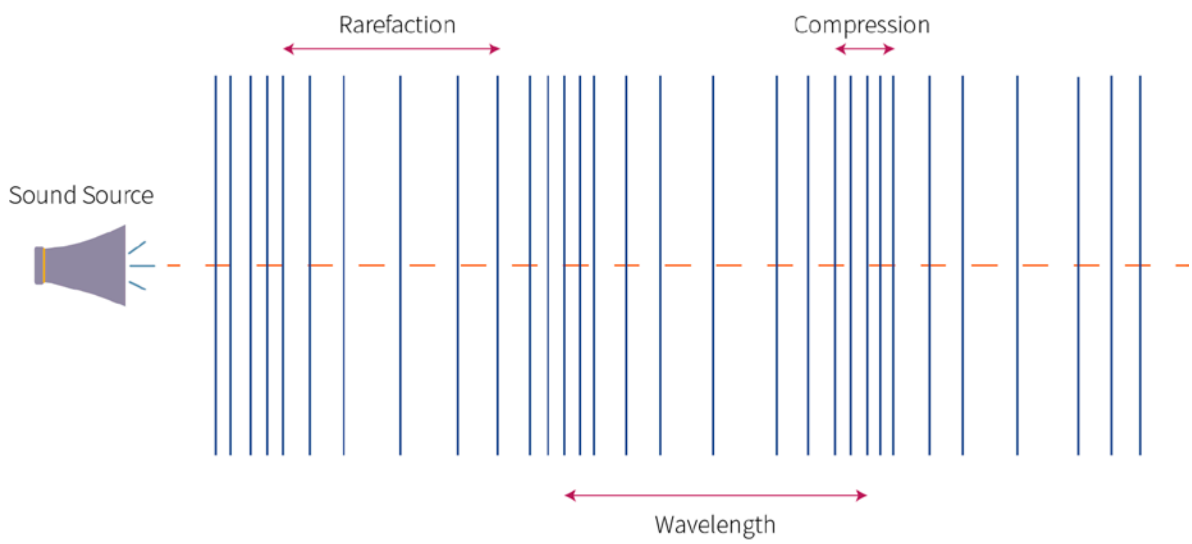


Figure 3: Movement of sound waves.

1 See Case Study 6: Underwater photogrammetric survey within Historic England (2017) Photogrammetric Applications for Cultural Heritage. Guidance for Good Practice. Swindon. Historic England

There are three main properties of a sound wave that are commonly discussed in relation to geophysical survey: wavelength, frequency, and amplitude.

- **Wavelength**
  - Wavelength is the distance between two points that are in phase, for example between two peak compressions or two peak rarefactions.
  - Wavelength is measured in Metres (m).
  - Wavelength = speed of sound (metres per second) (e.g. c. 1,500 m/s in salt water) / frequency of sound (Hertz) (1 Hertz (Hz) = 1 cycle per second).
- **Frequency**
  - Frequency is the number of occurrences of a repeating event per fixed unit of time.
  - Frequency is measured in cycles per second, expressed as Hertz (Hz) or Kilohertz (kHz), 1 kHz is equal to 1,000 Hz.
  - Frequency and wavelength are inversely proportional to each other; when one increases the other decreases.
- **Amplitude**
  - The amplitude of the sound wave is related to the amount of energy it carries. A high amplitude wave carries a large amount of energy; a low amplitude wave carries a small amount of energy
  - It is important to note that amplitude does not alter frequency, and frequency does not alter amplitude.
  - Amplitude is measured in Decibels (db).

Frequency is the property most commonly referred to in relation to geophysical equipment.

2.2.1 Understanding frequency

Prior to a discussion about the impact of frequency on geophysical survey outputs, it is important to understand the process of attenuation. Attenuation is the reduction in amplitude of the sound wave through scattering, absorption and distance travelled (as the wave front expands and the energy is spread over a larger area). The reduction in energy will reduce the distance the sound wave can travel.

Frequency will be discussed in relation to each piece of equipment within this section, however, there are a few generalised relationships that it is important to be aware of.

- Higher frequencies generally produce higher resolution data but have greater attenuation, meaning the effective range (the distance from which good quality data can be collected) is shorter.
- Lower frequencies generally produce lower resolution data but have lower attenuation, meaning the effective range is greater.

There will always be a compromise between range and resolution and surveys need to be planned accordingly.

Very low frequency sound can travel through the water column and continue beyond the seabed surface (remembering sound travels as vibrations): This is the principle behind sub-bottom profilers. In this instance, the lower the frequency the greater the penetration (the distance it can travel beyond the seabed), however, the general rule that the higher the frequency, the higher the resolution, is still applicable.

2.2.2 Speed of sound underwater

One of the biggest factors affecting geophysical survey is the speed at which sound travels through the water. Errors in the calculation of the speed of sound will cause errors in the data, particularly in the case of echosounders which calculate depth by the speed at which the soundwaves travel to the seabed and return.

The denser the material, the faster soundwaves will travel. The increased density of particles will mean that neighbouring particles are closer and therefore collide more frequently. Unlike light, sound travels faster through water than it does through air, and faster through saltwater than freshwater. On average, sound travels at:

- 343 m/s in air
- 1,480 m/s in freshwater
- 1,500 m/s in saltwater

The speed of sound does not remain constant through the water column, and is affected by three primary factors:

- **Temperature** - as the temperature increases so does the speed of sound.
- **Salinity** - as salinity increases so does the speed of sound.
- **Depth** - as depth increases, so does the pressure, and so does the speed of sound.

Typically, as the depth increases, the temperature decreases, and the salinity increases. These all have an effect on the speed of sound meaning that the speed of sound is not uniform throughout the water column. Two phenomena that can cause marked, and rapid, changes in the speed of sound are thermoclines (a distinct change in water temperature) and haloclines (a distinct change in the salinity, typically in locations where freshwater from rivers meets the saltwater of the sea).

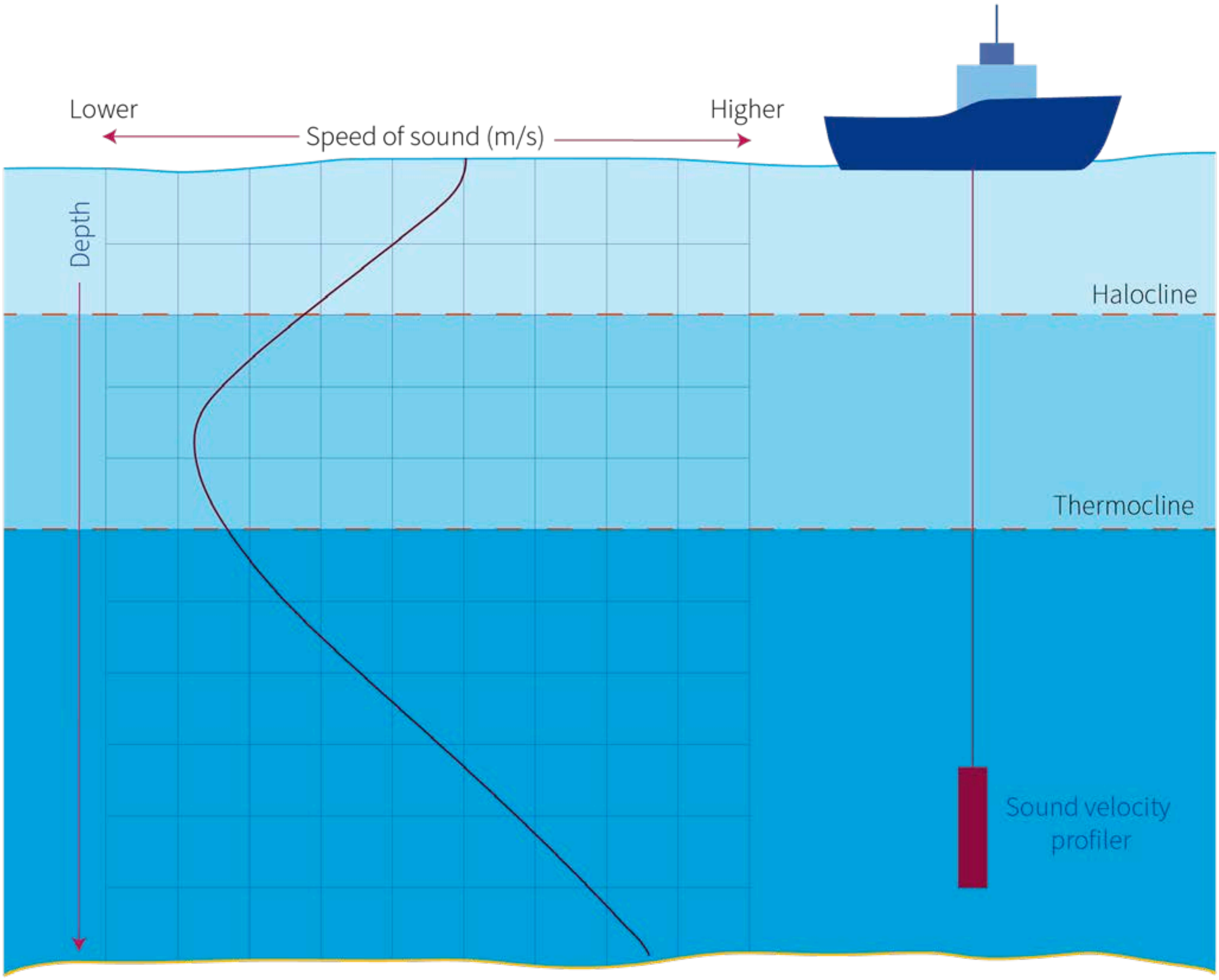


Figure 4: Changes in the speed of sound through the water column.

The speed of sound can be measured using a Sound Velocity Profiler (SVP). SVPs are discussed further in relation to multibeam bathymetry, however, in brief, an SVP is an instrument that is lowered through the water column which continuously records pressure (and therefore depth), along with the speed of sound (Figure 4). This data can then be applied to the survey outputs to correct the speed of sound through the water column. This is typically required for multibeam bathymetry surveys, for other techniques and estimation is usually sufficient.

The frequency of deployment of the SVP will be determined by the specification of the survey, the survey area, and the environmental parameters of the survey location, including proximity to fresh water sources, depth, etc. Typically, the frequency of deployment will be between every couple of hours and twice a day, or whenever the survey location changes.

2.3 Survey platforms

Traditionally, geophysical survey is undertaken from either ships or boats (vessels), with sensors either towed behind the vessel or mounted to it, further information is provided in Section 3. The vessel chosen for the survey is dictated by a number of variables including the equipment required to be mobilised, the personnel required and the distance from shore. The vessel may take the form of a kayak on a small inland lake through to a 70 m plus ship offshore.

As technology advances, different types of survey platform are routinely in use. These platforms have been developed, or modified, to increase efficiency (both time and resource) and improve data quality. The three most common of these are briefly discussed below.

It is outside the scope of this guidance to recommend the survey platform that should be used when undertaking geophysical survey other than to highlight that the chosen survey platform should enable the collection of data to a specification that meets the archaeological objects of the survey.

2.3.1 Remotely Operated Vehicles

Remotely Operated Vehicles (ROV) are uncrewed underwater vehicles attached to a support vessel by a tether. The tether allows an operator on the surface to manoeuvre the ROV underwater with a high level of precision. Large (work class) ROVs can weigh many tons and can be mobilised with a variety of equipment including MBES, SSS, cameras, scanning sonars, LiDAR and pulse induction (PI) sensors, all of which can be utilised to meet archaeological objectives. Smaller (micro) ROVs are available that can be deployed by one person. These can be mobilised with sensors including cameras, scanning sonars, and SSS, which can again be utilised to meet archaeological objectives.

The advantage of an ROV is that they can be deployed in close proximity to a feature, often increasing the resolution due to the closer proximity of the sensor, this is particularly the case with multibeam bathymetry (Section 4), furthermore the ROV is able to be rolled in order to direct sensors towards the sides of features. They do however, in most instances, require a support vessel and their use is primarily suited to the investigation of individual sites.

2.3.2 Autonomous Underwater Vehicles

Autonomous Underwater Vehicles (AUV) are uncrewed sub-surface vehicles that operate from, but independently of (with no tether), a support vessel. AUVs are programmed to run along predefined survey lines at a set distance from the seabed (altitude) and return to a specified location following completion. The duration of the AUV will depend on the size and specification, micro AUVs that can be deployed by one person may be able to operate for several hours, whilst larger AUVs may have a duration of several days. The sensors that can be mobilised will be dependent on the size of the AUV, but can include MBES, SSS, SBP, magnetometer, cameras and LiDAR.

The advantage of an AUV is that they operate subsurface and close to the seabed, potentially increasing the resolution of the data, they are also less susceptible to the motion of the surface and weather potentially resulting in higher quality data. As AUVs are uncrewed they can reduce the resources required in terms of support vessel size and personnel, with efficiency increased when deployed in multiples.

2.3.3 Uncrewed Surface Vessels (USV)

Uncrewed Surface Vessels (USV) are uncrewed survey vessels that are programmed to run independently along predefined survey lines. The duration of the USV will depend on the size and specification, micro USVs may be able to operate for several hours, whilst larger USVs may have a duration of several days. The sensors that can be mobilised will be dependent on the size of the USV, but can include MBES, SSS, SBP, magnetometer.

As USVs are uncrewed they can reduce the resources required in terms of personnel and can be deployed both from a support vessel or from shore, with efficiency increased when deployed in multiples. However, consideration should be given to the size, and sea keeping abilities, of smaller USVs as they are more susceptible to the impacts of motion than potentially much larger crewed vessels.

3. Positioning

Material of archaeological interest identified by geophysical survey needs to be accurately positioned to allow for proper management. Positioning systems can vary in application, and accuracy, and the appropriate type to use will depend on the specification of the survey and equipment being used. Furthermore, there are several different ways of presenting positions which need to be considered. This section introduces coordinate reference systems, vertical datums and positioning systems, and provides guidance as for the appropriate use in relation to different types of equipment.

3.1 Coordinate reference systems

In its simplest form, a Coordinate Reference System (CRS) is a grid from which measurements can be made from a single, pre-determined point (datum). On a flat two-dimensional surface this is achieved by measuring the horizontal (x) and vertical (y) distances from the datum (Figure 5). The process can be translated to three dimensions through the addition of a height measurement (z). Depending on the position of the datum in relation to the grid the x, y, and z measurements can be positive or negative. The concept is applicable over as small, or as large, an area as required, with the accuracy of the measured position consistent across the extents of the grid but dependant on the limitation of the technique for taking the measurements.

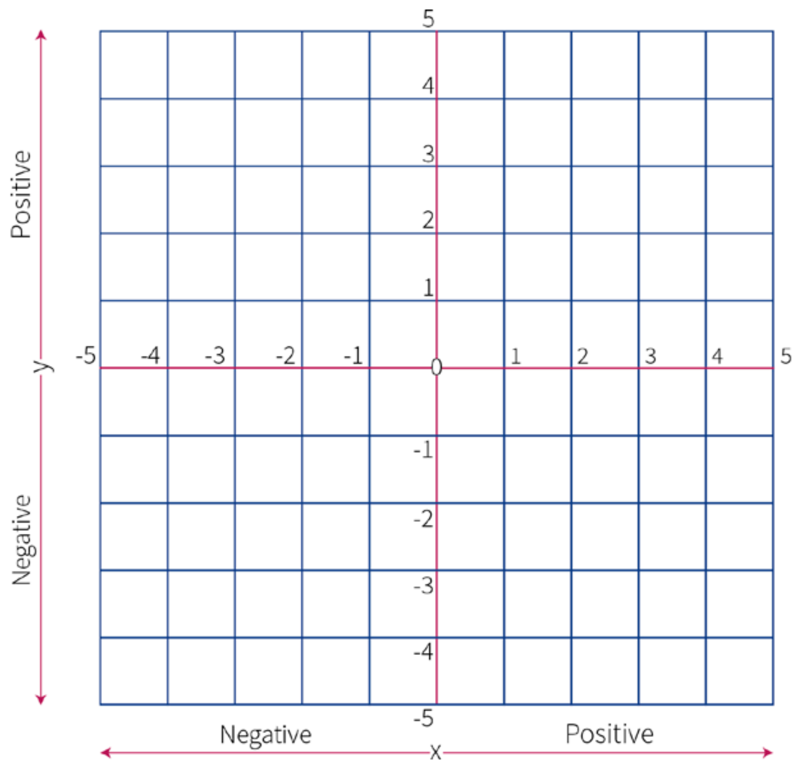


Figure 5:
Example of a coordinate grid.

Whilst theoretically simple, survey positioning is complicated by the fact that the Earth is neither a flat surface nor a perfect sphere. The intricacies of the theory behind certain elements of coordinate references are beyond the scope of this guidance and further information found in [A guide to coordinate systems in Great Britain]() published by the Ordnance Survey should be consulted. There are however some basic principles that need to be understood in advance of survey.

3.1.1 Ellipsoids and geoids

The Earth is not a perfect sphere; it increases in diameter around the equator and narrows in diameter between the north and south poles, so positions cannot be related to a sphere. Therefore, a reference surface, from which horizontal measurements can be made has to be defined. Reference surfaces are known as ellipsoids and are based on a gravitational best fit model of the Earth. Ellipsoids can be based on a model which best fits the Earth at a global scale such as the Geodetic Reference System 1980 (GRS80) from which the World Geodetic System 1984 (WGS84) CRS is based, or a model which best fits a localised area such as the Airy 1830 ellipsoid from which the Ordnance Survey of Great Britain 1936 (OSGB36) CRS is based.

The ellipsoid provides the best fit model for the shape of the Earth, but in order to provide consistent measurements of height, and depth from a defined datum another model called a geoid is used. Geoid models are based on Mean Sea Level (MSL) assuming the only factor affecting the level is the Earths gravitational field, and not taking into consideration, for example, tides. Geoids form the basis from which local datums are referenced. As with ellipsoids, they can be created at a global scale such as the Earth Gravitational Model 1996 (EGM96) from which WGS84 is based, or at a local scale such as the Ordnance Survey Geoid Model 1915 (OSGM15) which is referenced to MSL at Newlyn, Cornwall (recorded between 1915 and 1921) and known as the Ordnance Datum Newlyn (ODN).

Whilst the reference to ellipsoids and geoids is generally built into the CRS, it is important to note when referencing depth data to a datum, or reprojecting data and positions to a different CRS.

3.1.2 Geographic coordinate reference systems

The geographic CRS is based on the measurement of the x (longitude) and the y (latitude) in relation to the ellipsoid, and the height (z) in relation to the geoid. The measurements of longitude and latitude are made in degrees (°) based on the centre of the ellipsoid, with longitude being expressed as degrees east (positive) or west (negative) of the Prime Meridian (0°) and the latitude being expressed as degrees north (positive) or south (negative) of the equator (0°) (Figure 6). The equator is an invisible line running around the Earth (or the ellipsoid) at an equal distance between the north and south poles. The Prime Meridian is an invisible line running between the north and south poles and passing through Greenwich. The location is important to understand, whilst working in the United Kingdom there will be instances where data will be collected to the east and west (positive and negative) either separately, or potentially as part of one survey.

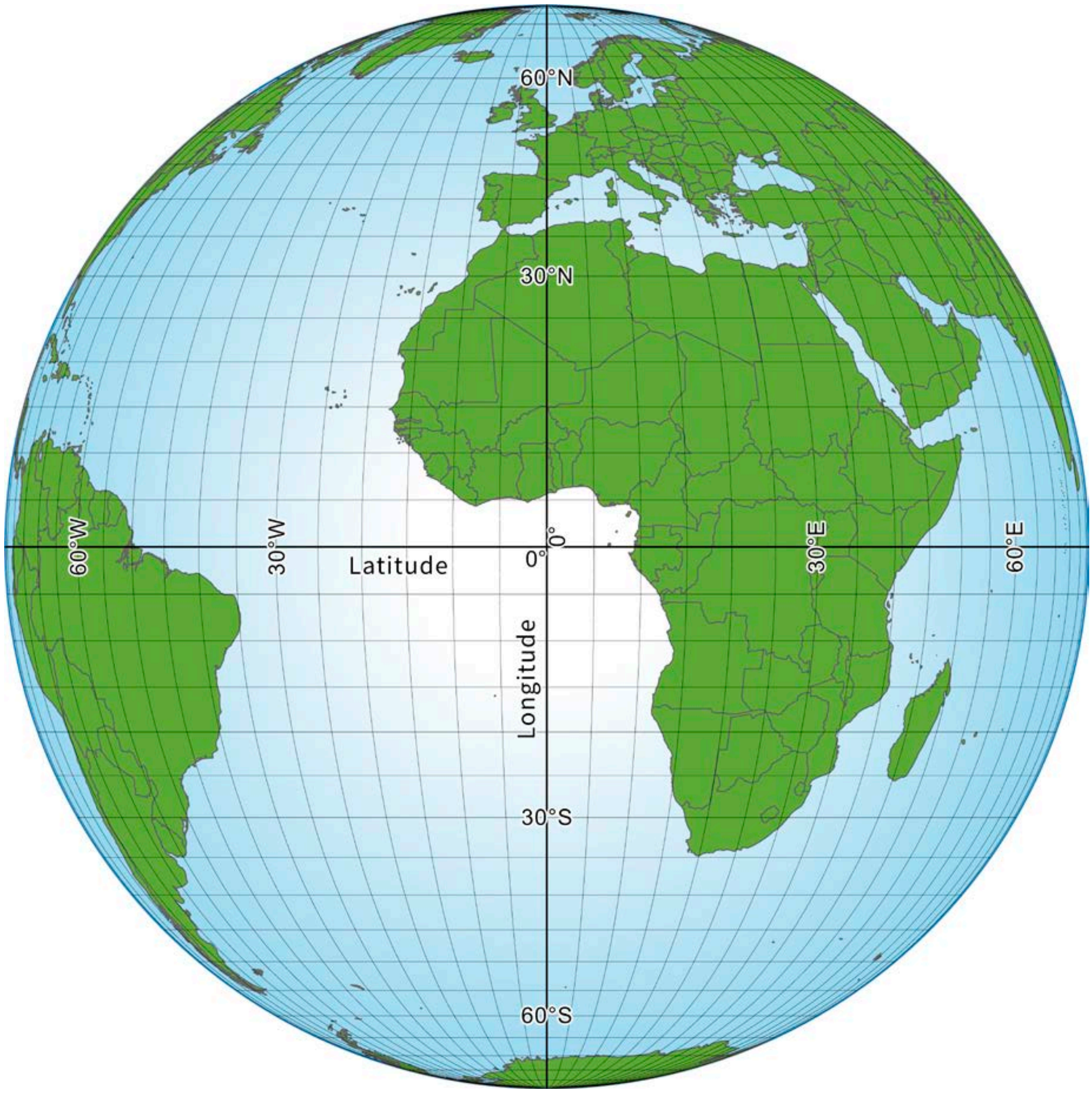


Figure 6: Lines of longitude and latitude.

The most widely used geographic CRS, and the standard for Global Navigation Satellite Systems (GNSS), is the World Geodetic System 1984 (WGS84), the use of which will be familiar to users of vessel navigation systems, handheld GNSS, and smartphones. The position can be presented in a number of ways, all based on the measurement of degrees, and sub-divisions of minutes and seconds.

Traditionally positions were presented in Degrees (°), Minutes (‘), and Seconds (“) (DMS) with the corresponding compass designation. Today most GNSS will display positions as Degrees (°) and Decimal Minutes (‘) (DDM) with the corresponding compass designation. The position can be simplified in terms of representation to Decimal Degrees (DD) which displays as a single decimal of the Degrees (°) and as either a positive or negative value, see Table 1.

Table 1: Example presentations of longitude and latitude.

Format	Latitude	Longitude
Degrees Minutes Seconds (DMS)*	51° 34' 1.092" N	001° 47'.38.508" W
Degrees Decimal Minutes (DDM)	51° 34.0182' N	001° 47.6418' W
Decimal Degrees	51.56697	-1.79403

* DMS may present seconds as decimals dependent on accuracy and should not be confused with DDM

Global coordinate reference systems are inherently inaccurate, albeit minimally, on a global scale due to the constant movement of the Earth's tectonic plates (continental drift). Whilst two positions taken on the same continent will retain relative accuracy, the absolute accuracy (the position on the Earth) will deteriorate with movement, as will positions taken across two continents. To combat this, continent specific geographic CRS have been developed. Of relevance to Europe, and the United Kingdom, is the European Terrestrial Reference System 1989 (ETRS89). ETRS89 assumes the Eurasian Plate does not move, and therefore both the relative and absolute accuracy is maintained at a European level. ETRS89 is based on the same ellipsoid as WGS84 (GRS80) and shares the same Prime Meridian. For surveying in Europe, ETRS89 is the preferred CRS, however both WGS84 and ETRS89 are commonly in use.

In addition, measurements of degrees, and sub-divisions thereof, do not result in uniform measurements of distance. For example, a measurement of one degree longitude at the equator is equivalent to approximately 111 km, at either the north or south pole one degree of longitude will not be measurable in terms of distance due to convergence. To enable the measurements of distance, data collected in a geographic CRS must be projected onto a flat surface or be collected with reference to a Projected CRS.

3.1.3 Projected coordinate reference systems

A projected (or planar) CRS (sometimes referred to as map projections) is one based on the projection of the spherical surface of the Earth onto a flat surface, with the addition of an invisible and regular grid from which x and y measurements can be made from a common datum. Projected CRS are based on geographic CRS, however due to the nature of creating a flat surface from a spherical one, a level of distortion will always be present and as such this is minimised though the projection of localised areas. Within Great Britain (terrestrially) the national projected CRS is OSGB36 (or the British National Grid (BNG)).

OSGB36 is not typically used within marine surveying, however it is noted here as in some instances, such as within the jurisdiction of ports and harbours or inland bodies of water, data may be required to be positioned in this format. Historic charting and data may also be held in OSGB36.

Figure 7: UTM Zones.

The most commonly used projected coordinate system in the marine environment is the Universal Transverse Mercator (UTM) projection. The UTM projection is made up of 60 zones each covering an area of 6° of longitude, with the projection and size of each zone designed to minimise distortion (Figure 7).

In the Northern Hemisphere measurements are made in metres from the intersection to the east of the western edge of the zone and north of the equator and are known as eastings and northings. It is important to note that measurements include a false measurement of 500,000 applied to the easting (false easting). In the Southern Hemisphere a false northing of 10,000,000 is applied to eliminate negative numbers. UTM projections can be applied to both WGS84 and ETRS89 which is the underlying geographic CRS. The United Kingdom is covered by three UTM zones, Zone 29 and Zone 30 to the west of the Prime Meridian and Zone 31 to the east of the Prime Meridian. Due to the same coordinate being replicated within each zone, it is essential that the UTM zone, and the location in the Northern or Southern Hemisphere is recorded, often presented, for example, as ETRS89 Z30N (Table 2).

Table 2: Example presentation of UTM projection coordinates.

Format	Northing (m)	Easting (m)
ETRS89 UTM Zone 30 North (ETRS89 Z30N)	5713566.28	583585.54

Whilst their use is less common, there may be a requirement for certain projects (including linear schemes) to use a custom, or bespoke, CRS which is locally defined.

3.1.4 EPSG codes

The international Association of Oil and Gas Producers (IOGP) Geomatics Committee maintains a public database of CRS and coordinate transformations known as the EPSG Geodetic Parameter Dataset (EPSG). Each CRS, and the associated parameters, are defined by a unique code (EPSG code) ensuring consistency, and the use of the correct CRS, between software packages associated with data collection, processing and interpretation. The EPSG codes of some common CRS within the UK are shown below (Table 3).

Table 3: Common EPSG codes.

CRS	CRS type	EPSG code
WGS84	Geographic	4326
WGS84 UTM Zone 29	Projected	32629
WGS84 UTM Zone 30	Projected	32630
WGS84 UTM Zone 31	Projected	32631
ETRS89	Geographic	4258
ETRS89 UTM Zone 29	Projected	25829
ETRS89 UTM Zone 30	Projected	25830
ETRS89 UTM Zone 31	Projected	25831
OSGB36 / BNG	Projected	27700
ED50	Geographic	4230
ED50 UTM Zone 29	Projected	23029
ED50 UTM Zone 30	Projected	23030
ED50 UTM Zone 31	Projected	23031

3.1.5 Geodetic transformation and reprojection

There may be instances where the CRS of the dataset is required to be changed, this may be to change from a geographic CRS to a projected CRS for data display, or to ensure a standardised CRS across a project. Whilst the complexities of geodetic transformations and reprojections are beyond the scope of this guidance, it is important to understand the basic principles to ensure data remains accurately positioned.

- **Geodetic transformations** – geodetic transformations are those that change the underlying geographic CRS (datum), for example this could be a change from WGS84 to ED50. In order to transform the data a mathematical model, specific to the two geographic CRS is required. The transformation models are usually built into data collection and processing software, as well as Geographical Information Systems (GIS) and is generally a straightforward and automated process. It is important to ensure that the models used are correct and are the most recent available.

- **Reprojection** – reprojection of data changes the projected CRS (map projection) but does not change the underlying datum (for example WGS84). As with geodetic transformations, this is generally a straightforward and automated process, but the projection is undertaken based on embedded parameters.

Within the UK, particularly close inshore, or within inland bodies of water, there may be a requirement to transform horizontal positions between OSGB36 and ETRS89. This is achieved through the use of the OSTN15 model created by Ordnance Survey (OS) which provides the most accurate transformations. The transformation is detailed here as there are limitations to its use offshore. The previous iteration of the model (OSTN02) had transformation values set to zero 10 km offshore, so was not able to be used past this point. The latest iteration of the model (OSTN15) does not have this limitation; however the accuracy is significantly reduced and is not recommended for use.

3.1.6 Vertical datums

In a terrestrial context heights (or elevation) are given in reference to a defined geoid. In the UK this is OSGM15 which is referenced to MSL at Newlyn, Cornwall (ODN). An observed height will therefore remain constant, irrespective of the state of the tide, and typically be referred to as the height above sea level.

Within a marine context the principle is similar, however measurements are presented as depths below a datum. Requirements for a datum stem from a need to not only measure depth accurately and consistently, but also to do so in a way that presents the minimum depths that might be encountered to ensure safety of navigation. The use of MSL (ODN) as the datum would only give an approximation of the depth. Within hydrographic survey in the UK, depths are referenced to the Lowest Astronomical Tide (LAT) to ensure the minimum depths are presented. LAT varies across the UK dependant on the tidal regime and the tidal range (the differences between high and low water) and therefore LAT as a datum varies by region and is referred to as Chart Datum (CD) for a defined region. A conversion between OSD and CD can be made based on publicly available tables.

The datums discussed, MSL, ODN, LAT and CD, are all tidal datums derived from average measurements, or predictions, of sea levels at a point in time. The measurement of depth, in relation to a datum, in the marine environment is complicated by the ever changing depth of water due to the influence of tides. Assuming the measurement of depth at a fixed point, and one tidal cycle, the variation in the measurement will be equal to the difference between high and low water.

In order for recorded water depths to be reduced to a common datum, and to provide an accurate representation of the seabed, the tidal variation needs to be applied to the resulting data. Whilst tidal predictions can be used, they are not generally considered to be suitable where a high level of accuracy is required. As such, the use of observed tides is recommended, this is typically achieved in two ways;

- **Tide gauges** – tide gauges use either pressure sensors or acoustics to continuously record the depth of water at a location. These are installed at ports and harbours or can be deployed at a survey location. The resulting data are time stamped and can therefore be applied to the recorded water depths. Due to the variation in tides in different regions, the closer the tide gauge is to the survey location the more accurate the data. Fixed tide gauges, such as those in ports and harbours, are usually referenced to ODN.

- **Ellipsoid** – using accurate GNSS height (z) data (derived from RTK) tidal heights can be calculated based on the height of the GNSS receiver from the ellipsoid. With the use of a fixed onshore reference station, and the comparison in heights, the variations can be applied to the recorded water depths – this can be achieved in real time with suitable corrections.

To reference the resulting depth data to a defined datum (ODN, CD, LAT, etc.), the difference between the ellipsoid and the datum needs to be known. Within UK waters Vertical Offshore Reference Frame (VORF) models are available to provide the ability to transform vertical height data between different reference datums, including ellipsoid, ODN, CD, and LAT.

The accurate recording of heights to a defined (and recorded) datum is critical. Not only in relation to charting and safe navigation, but to allow the ability to undertake monitoring of not only seabed dynamics such as scour and sand bank migration, but site stability and evolution.

3.2 Positioning systems

Having established the methods of presenting positions and the format in which they are captured, consideration must be given to how position data are collected, and how this is applicable to geophysical survey. The term GPS (Global Positioning System) is commonly used as a synonym for GNSS. However, GPS (which is owned and maintained by the United States) is just one example of a GNSS, with others including Galileo (Europe), GLONASS (Russia) and BeiDou (China). All operate in a similar way and differentiation is not required so the term GNSS should be used.

There are three primary real time positioning methods that will be briefly discussed: GNSS, Differential GNSS (DGNSS), and Real Time Kinematic (RTK) GNSS. A further method of increasing GNSS accuracy following a survey, Post Processed Kinematic (PPK), is also discussed.

3.2.1 Global Navigation Satellite System (GNSS)

Almost everyone will have had interaction with, or used a GNSS, even if they are unaware of it. It provides the positioning information in most consumer electronics, including smart phones, car satellite navigation systems, cameras, and vessel chart plotters.

In order to calculate latitude and longitude, signals from at least three satellites must be received. To calculate altitude, signals from four satellites must be received. However, the more satellites that signals are being received from the greater the accuracy. Conversely, the lower the number of satellites sending signals, the higher potential for errors. For a receiver to be able to receive signals, it must have a direct line of sight with the satellite, meaning not all satellites will be visible at the same time due to their location in the Earth's orbit (Figure 9). Furthermore, the visibility of satellites will depend on obstructions including topography, buildings, and dense forest. This is less of an issue in a marine context, but consideration should be given to potential obstructions to satellite view that may be caused by the vessel superstructure.

The horizontal accuracy of GNSS will depend on factors such as the specification of the receiver, atmospheric conditions, the number of visible satellites, and restrictions on the GNSS output signal. The achievable accuracy of an uncorrected single receiver can vary significantly, but is likely to be between 3.0 m and 15 m. The vertical accuracy of GNSS is typically significantly less: up to 2 to 3 times the horizontal accuracy.

It is worth noting that a single GNSS receiver cannot calculate heading unless it is moving. A GNSS compass is required to calculate heading whilst stationary. A GNSS compass uses two GNSS antenna separated by a fixed distance, with the relationship in positions used to calculate the heading. The greater the separation of the antenna, the more accurate the heading. When used within an integrated position and motion system (Section 3.2.2) a minimum of 2.0 m separation should be used, although for use with towed systems a separation of 0.5 m is generally acceptable.

3.2.2 Differential Global Navigation Satellite System (DGNSS)

Due to the inaccuracies detailed above, uncorrected GNSS data are not usually sufficient for use as a positioning system for geophysical survey. One method of data correction is the use of a Differential GNSS (DGNSS).

A GNSS receiver at a fixed position for a number of hours will record a spread of different positions as a result of atmospheric conditions and inherent inaccuracies within the equipment (Figure 8). Establishing a GNSS receiver (base station) at a known location allows the measurement, and recording, of variations, and thus errors, in signals. Corrections can then be applied to the GNSS data collected by a mobile GNSS (rover) resulting in improved accuracy.

Within the marine environment the most common way of receiving base station corrections is through a Satellite Based Augmentation System (SBAS). Within Europe the SBAS is the European Geostationary Navigation Overlay Service (EGNOS). Reception of SBAS corrections is dependent on the GNSS receiver (rover) being enabled to receive them. Typically, horizontal accuracies are discussed at around 1.0 m, however greater accuracies of ~0.3 m can be achieved under ideal conditions. Noting that the further the rover is from the base station(s) the lower the accuracy. The vertical accuracy of DGNSS is 2 to 3 times less than the horizontal accuracy.

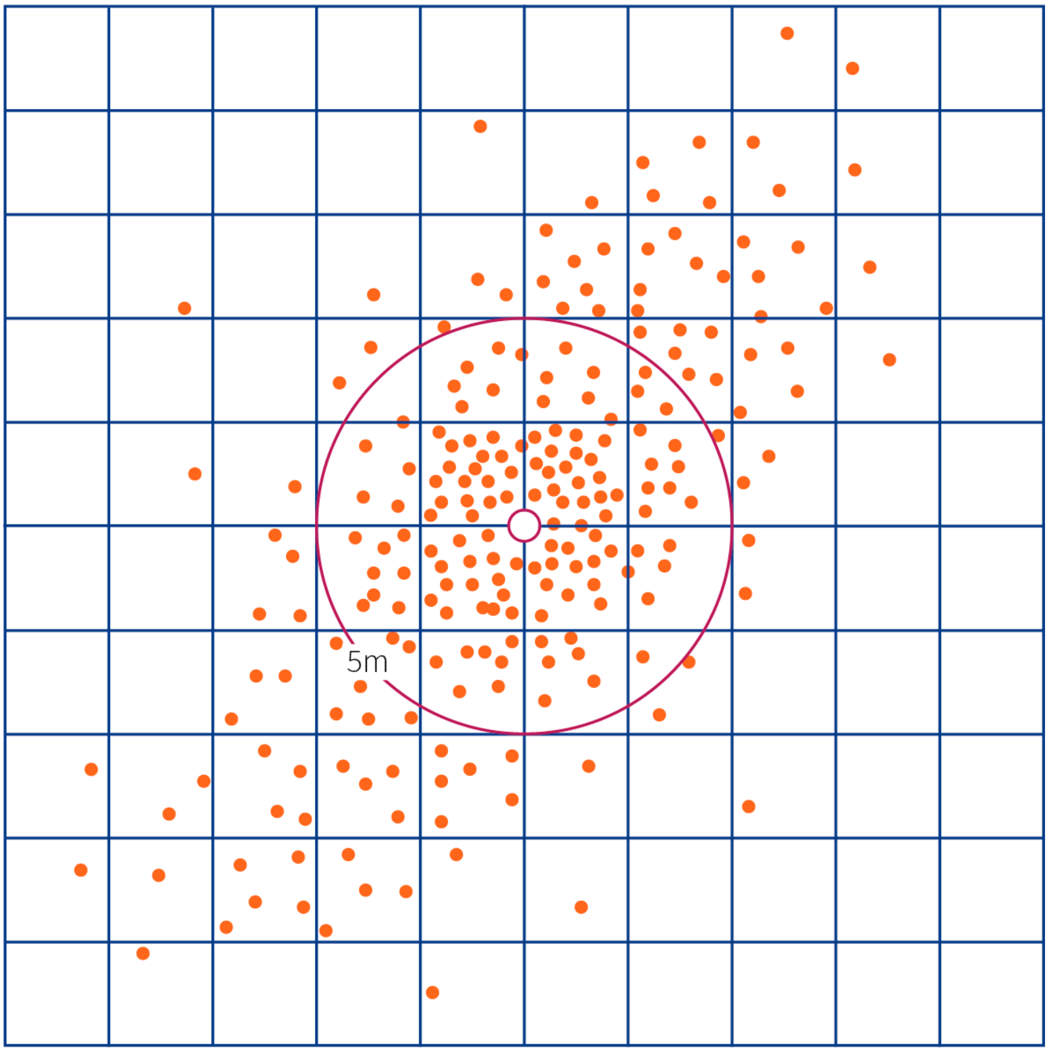
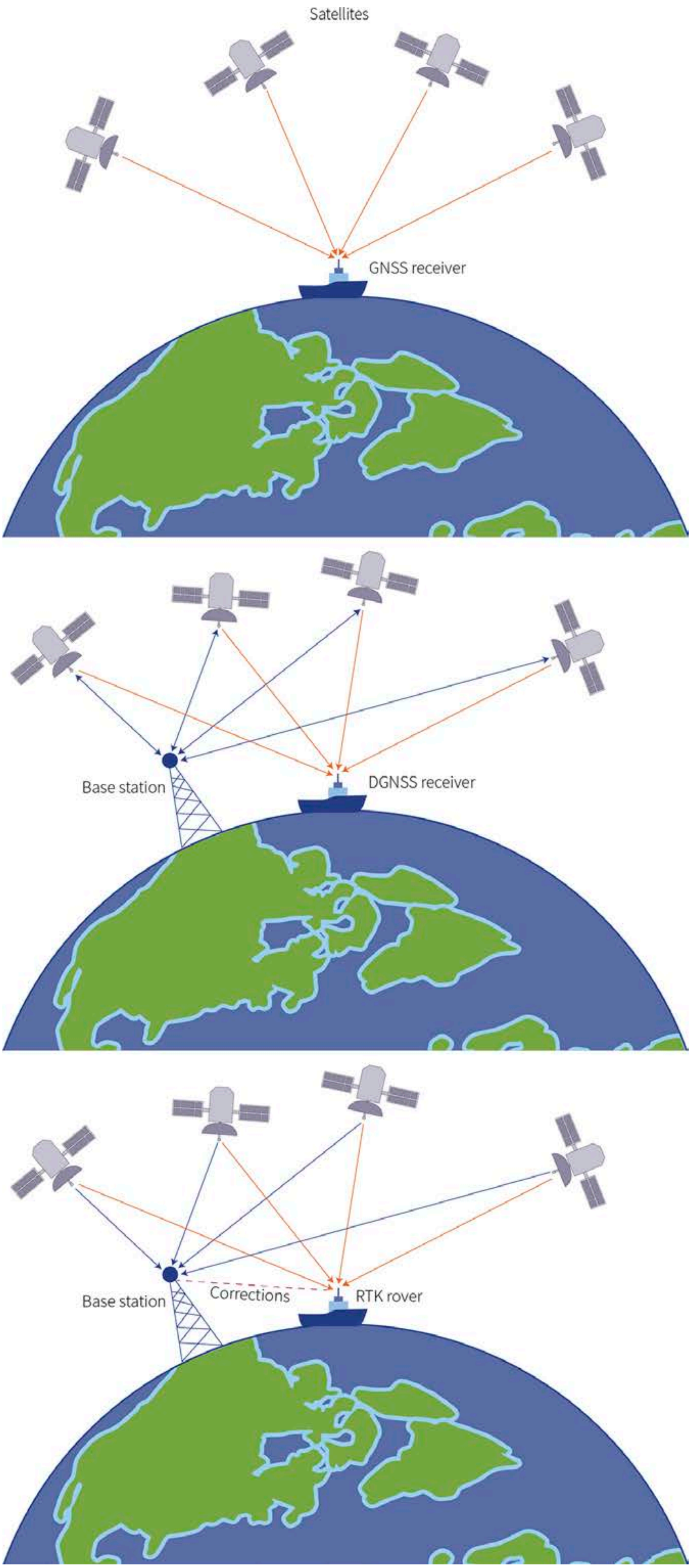


Figure 8: Scatter plot of GNSS positions collected over time.

For surveys using towed equipment, DGNSS is typically sufficient as it provides a level of positioning accuracy proportional to the actual estimated location of the equipment. DGNSS is not sufficient for the accurate measurement of heights, and therefore where accurate height data, or more accurate horizontal data, is required (typically vessel mounted equipment) more accurate Real Time Kinematic (RTK) corrections can be used (Figure 9).

Figure 9:
Top: GNSS configuration,
Middle: DGNSS configuration,
Bottom: RTK configuration.



3.2.3 Real Time Kinematic (RTK)

RTK is a form of differential correction as discussed above, and the basic principles remain the same; a base station collects data and the corrections from this are applied to the source data. There are two types of RTK correction solutions. The first is derived from a base station positioned at a known point that is ideally less than 20 to 40 km from the survey location and transmitted to a receiver (or rover) on the survey vessel (Figure 9). Typically, this provides the most accurate solution and accuracies of just a few centimetres can be achieved horizontally, with the vertical accuracy around two times the horizontal. The other method is the use of corrections derived from a network of RTK base stations, maintained by a service provider and distributed via an internet-based solution. This typically provides less accuracy than a dedicated base station and relies on coverage within the survey area. However, it is still superior to DGNSS.

If height data, which is critical for the collection of high quality multibeam bathymetry data, is being derived from GNSS then RTK positioning must be used. DGNSS and uncorrected GNSS have insufficient vertical accuracy.

3.2.4 Post-processed navigation

The three positioning solutions detailed above relate to positional data, with corrections being received in real time and applied directly to the data. Brief mention should be made of Post Processing Kinematic (PPK) software solutions. PPK is of particular relevance where real time corrections are not available, potentially due to being beyond an RTK network. PPK software enables the processing of recorded raw GNSS data with data recorded from reference base stations. The base station can include data from both the time of the survey but also in the periods before and after, allowing a more accurate model of atmospheric conditions and effects to be created. The combination of the different datasets allows for the potential to achieve accuracies within a few centimetres.

3.3 Sensor positioning

Positioning data, whether it comes from GNSS, DGNSS or RTK, gives the location of the antenna receiving the satellite signals. Often, such as on large survey vessels, the geophysical sensors may be some distance away from the antenna, by several metres to tens of metres. Therefore, accurate positioning of the geophysical sensors requires consideration of their horizontal and vertical offsets from the antenna. The method of establishing these offsets depends on whether the sensor is towed or attached to the vessel.

3.3.1 Towed sensor positioning

Whilst there are exceptions, sidescan sonars, magnetometers, and some sub-bottom profilers are usually towed behind the survey vessel, with data from the sensor relayed via a cable. The sensors are typically towed at a constant distance above the seabed (altitude), although some (particularly sub-bottom profilers) are towed at the surface or at a constant distance below the surface (depth). When the sensor is below the surface, there is no visual reference, nor is there the ability to attach a GNSS receiver to it, meaning that the position has to be calculated in a different way. This is done through either the calculation of layback (the distance behind the vessel) or through the use of acoustic positioning to obtain a more accurate position.

3.3.1.1 Layback

Calculating layback is the determination of the sensor position in relation to the point on the vessel from which the sensor is being towed (tow point). In turn, the tow point is referenced to the GNSS receiver through the measurement of offsets (Figure 10). The combination of the offset measurements, and the layback will describe the position of the sensor.

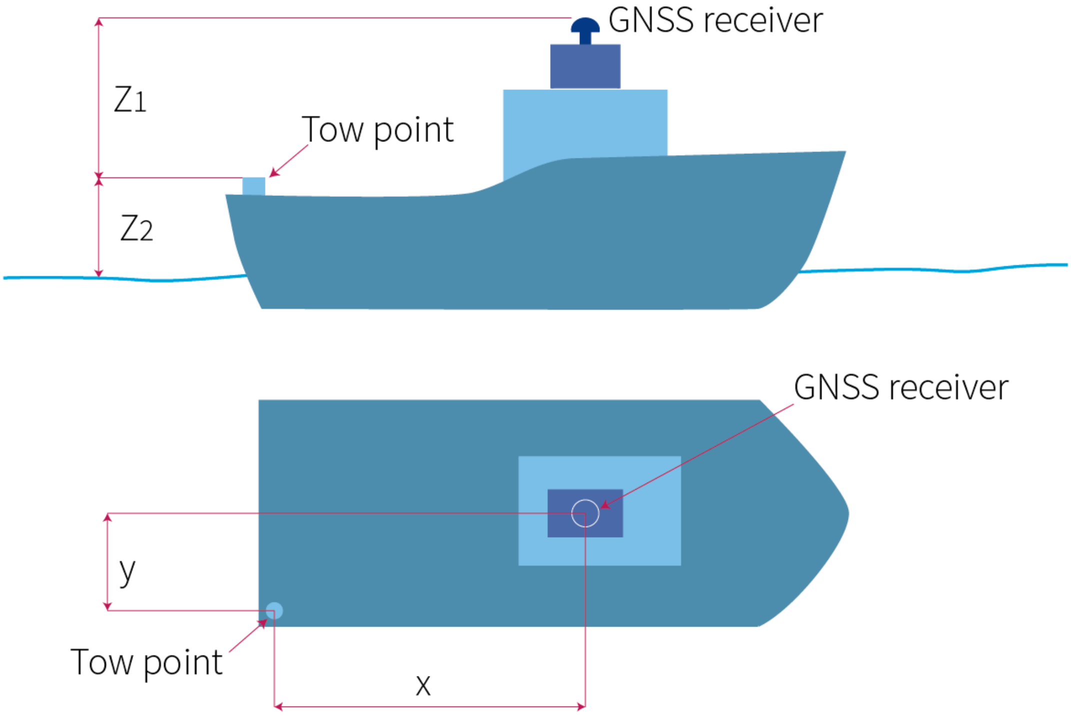


Figure 10: Tow point offsets.

The calculation of layback from the tow point is based on the amount of cable connecting the sensor to the vessel (cable out). Assuming the sensor and the tow point were on a horizontal plane, the layback would be equivalent to the cable out. However, the tow point is usually above the surface and the sensor will generally be beneath the surface, meaning the cable out will be greater in length than the layback.

There are several ways of calculating layback. In its simplest form, it involves a basic geometric calculation, with the main variables being: the depth of the sensor plus the vertical distance from the surface to the tow point (c), and the cable out (a), thus layback (L) can be identified using L=√(a2 – c2) (Figure 11). A separate calculation would have to be made to account for the distance between the vessel tow point and GNSS receiver, and the results combined for the true layback position.

Whilst layback provides a relatively good approximation of sensor position, it does have issues; the calculation assumes the sensor is positioned directly behind the tow point (which depending on currents it may not be) and it does not take into consideration any catenary effects on the cable which will reduce the layback from the theoretical position. Calculations to account for this second point can be made but require the altitude of the sensor to be known. Whilst manual calculation of layback can be time consuming, most data acquisition software will undertake the calculation automatically following the input of offsets and cable out measurement. It is important to note that the cable out figure and any layback calculations should always be recorded separately, even when entered into the acquisition software.

Layback calculations become less accurate as the depth of the sensor or length of the cable increases and so this method of positioning is most suited to shallow water applications and should not be used when high positional accuracy is required. It is however important to understand the principles as it remains a common method of sensor positioning for small scale surveys in shallow waters.

To achieve a higher, and more constant, positional accuracy an acoustic positioning system should be used, and should be considered the primary positioning method for offshore surveys.

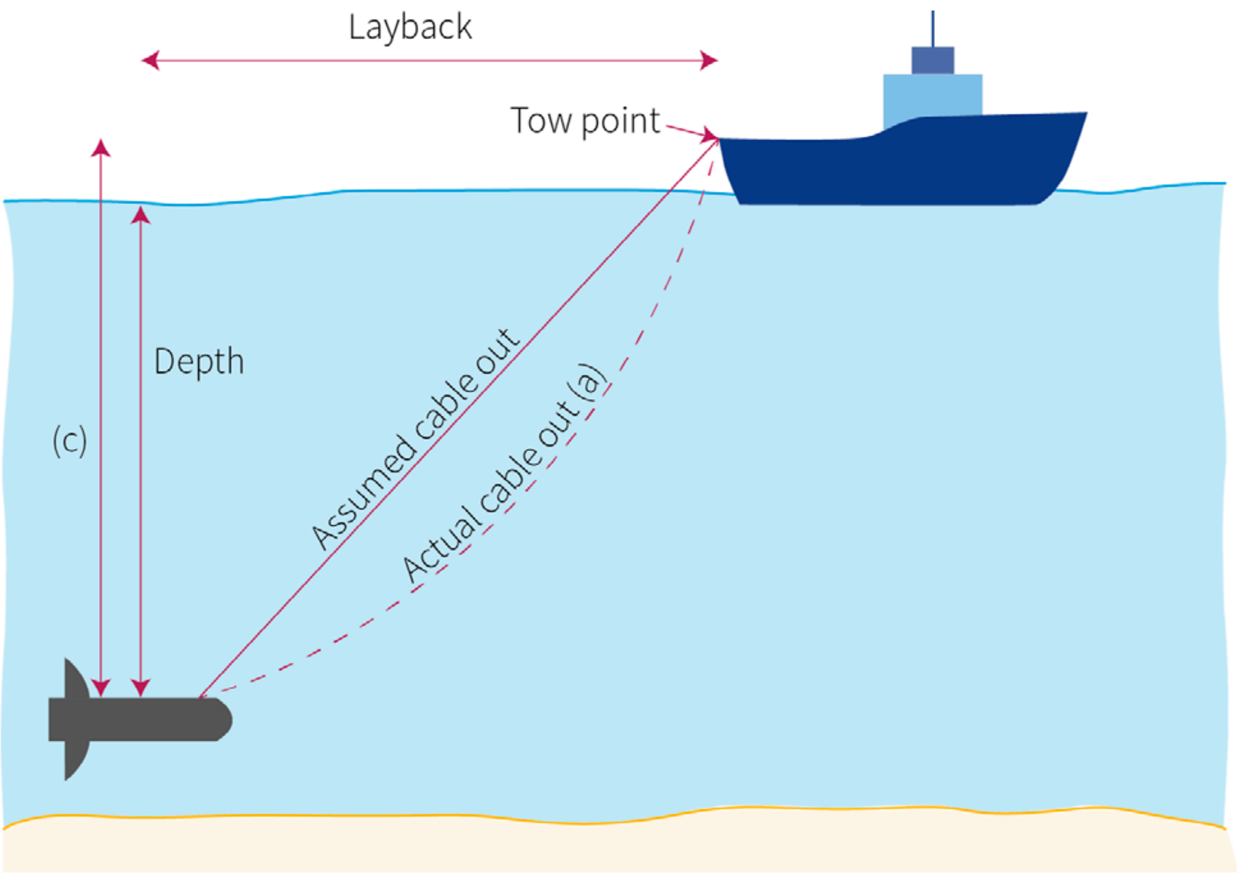


Figure 11: Towed sensor layback.

3.3.1.2 Acoustic positioning

There are three main types of acoustic positioning system;

- **Long Base Line (LBL)**
  LBL uses a network of acoustic transponders on the seabed at the extents of the survey area (the baseline). The position of a transducer (for example attached to an ROV, AUV, diver, etc.) is calculated through the measurement of offsets between it and the transponders.

- **Short Base Line (SBL)**
  SBL does not use transponders on the seabed, but instead uses a transducer fixed at the surface, typically to a vessel. The position of a transponder is calculated through the measurement of offsets between it and the transducers.

- **Ultra Short Base Line (USBL)**
  USBL is the most commonly used acoustic positioning system for towed sensors and is discussed below.

LBL and SBL are not commonly used to position towed sensors, however the use of LBL should not be overlooked with the increasing use of AUVs within the survey industry. The most commonly used acoustic positioning system for towed sensors is USBL, and this method is discussed here.

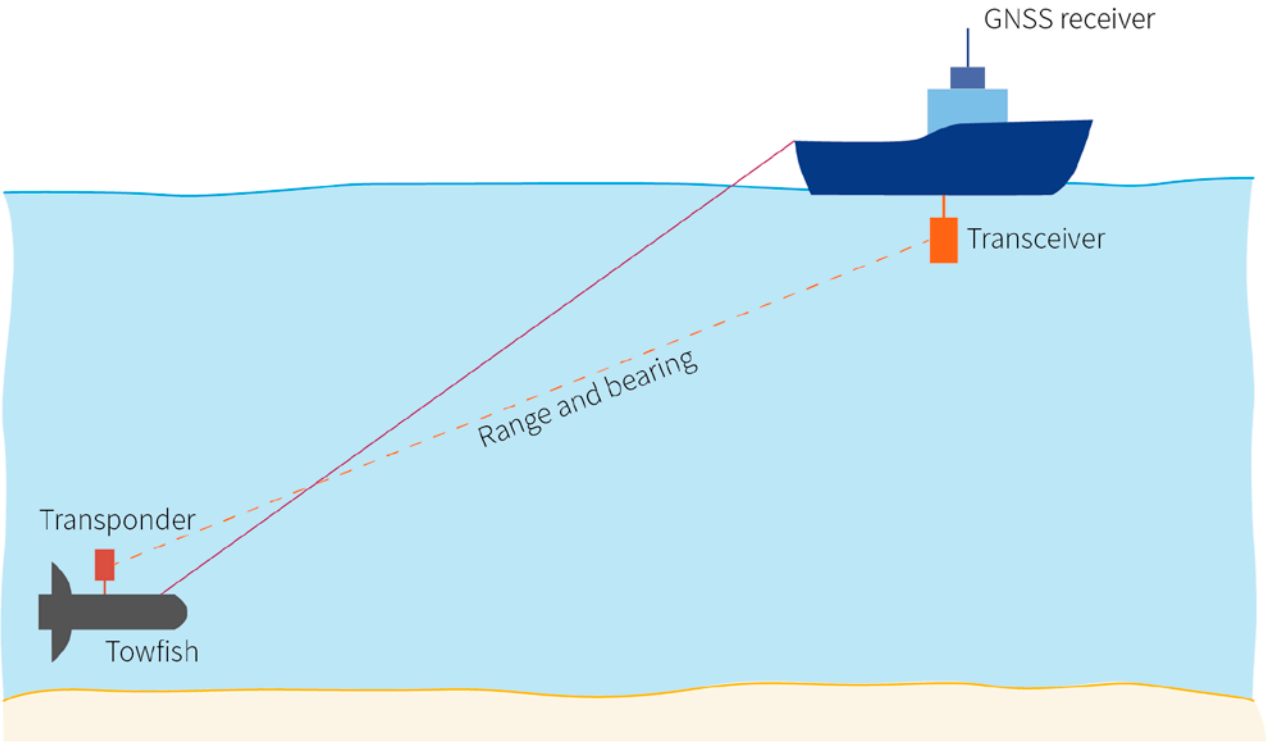


Figure 12: USBL configuration.

A USBL system consists of a transceiver mounted to the vessel, the location of which is known in relation to the GNSS position through the measurement of offsets, and a transponder mounted to the sensor, or more typically on the tow cable close to the sensor (Figure 12). The transceiver emits an acoustic pulse which is detected by the transponder, which then sends a reply pulse. The speed at which the pulse is returned allows a calculation of distance (range) while the bearing allows the direction in relation to the transceiver, and therefore the sensor position, to be calculated and inputted into the acquisition software. To achieve the most accurate position, the heading of the vessel and the motion should be applied to the data.

Specifications between systems vary but most can achieve an accuracy of between 0.1% and 5% of the slant range (the distance from the transceiver to the transponder), track multiple targets, and record positions between one and four times a second (1.0 Hz to 4.0 Hz). USBL systems are not limited to the positioning of towed geophysical sensors but are also used to position Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs), Remotely Operated Towed Vehicles (ROTV), used with multi sensor arrays, and even divers (Figure 13).

Figure 13:
Diver with USBL transponder.
© MSDS Marine

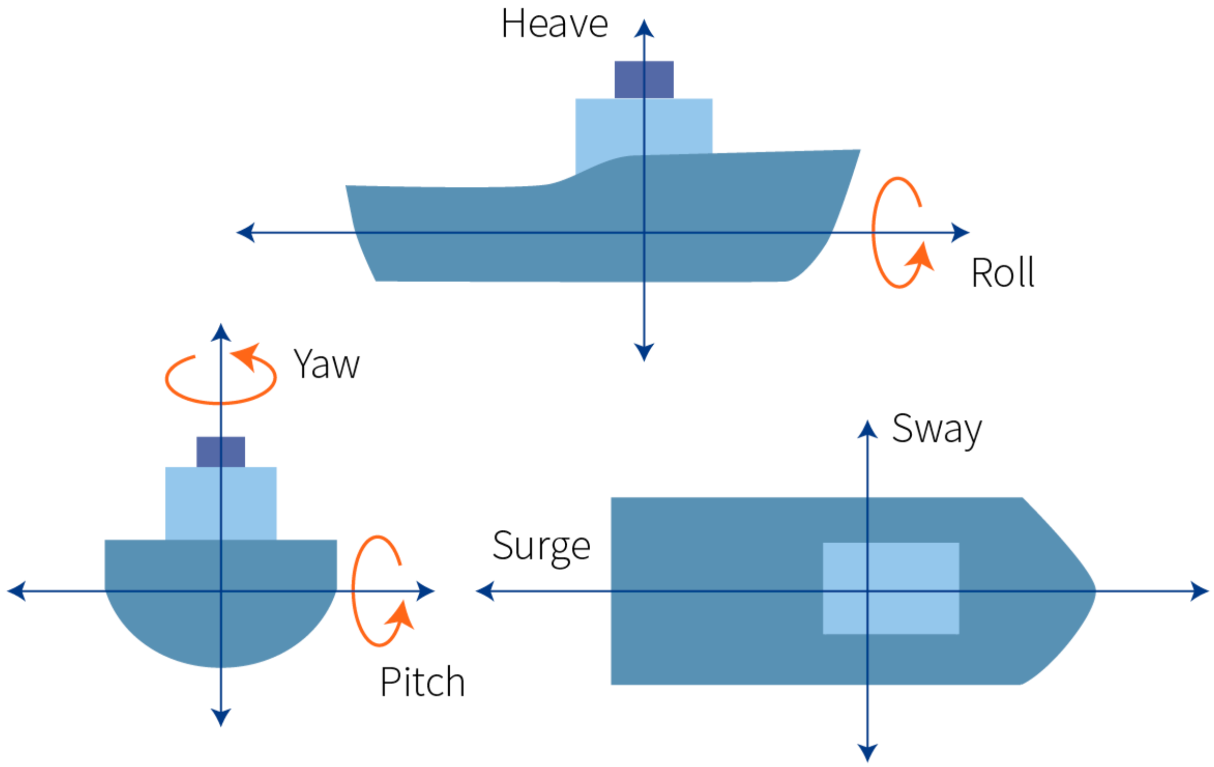


Figure 14: Vessel motion axes.

3.3.2 Vessel mounted sensor positioning

Sensors mounted directly on the vessel, including multibeam echosounders, some sub-bottom profilers, and USBL, not only need to have their position calculated in relation to the GNSS but also need to compensate for the motion of the vessel.

Vessels, ROVs, AUVs and other platforms that sensors may be mounted on do not move in one plane: the motion is measured against a number of axes. These are heave, pitch, roll, sway, surge, and yaw (Figure 14). The combination of movements will affect where the data are positioned. For example, not calculating heave will result in artificial depth measurements between the sensor and the seabed, and not calculating roll will mean the data will be positioned to the side of the vessel with an artificial depth.

The effect of vessel motion on the acquired data is compensated for through the use of an Inertial Measurement Unit (IMU), also known as a Motion Reference Unit (MRU). An IMU uses an accelerometer to measure acceleration along three axis and a gyroscope to measure angles along three axis, to a defined datum. Typically, the motion data, GNSS position, and heading data from very accurate heading sensors are combined (known as an integrated solution) and the position of the acquired geophysical data calculated based on these measurements.

To ensure the recorded motion is applied correctly to the data, it is imperative that the relationship (offsets) between the sensor, the IMU, and the GNSS are precisely known, along with the waterline and the centre of rotation (CoR) of the vessel. The CoR is a difficult position to determine, and can vary dependant on factors such as amount of fuel, deck modifications, etc. As such, measurements are usually made with reference to a Central Reference Point (CRP) (figure 15). Different software will require the input of different offsets and manufacturers' instructions should be followed, noting nuances between software packages. Following installation and the input of offsets, the position and motion system will need to be calibrated, which usually requires the making of a number of movements at sea so the positioning software can refine the offset measurements. The more accurate the offset measurements, the more accurate the calibration, and therefore the more accurate the data positioning. Calibration requirements relating to specific sensors can be found in the proceeding sections.

Consideration should be given to the use of a Dimensional Control (DIMCON) survey to accurately measure sensor positions and offset measurements. DIMCON surveys will typically employ three-dimensional survey techniques such as laser scanning or the use of a total station to create an accurate three-dimensional model from which measurements can be taken.

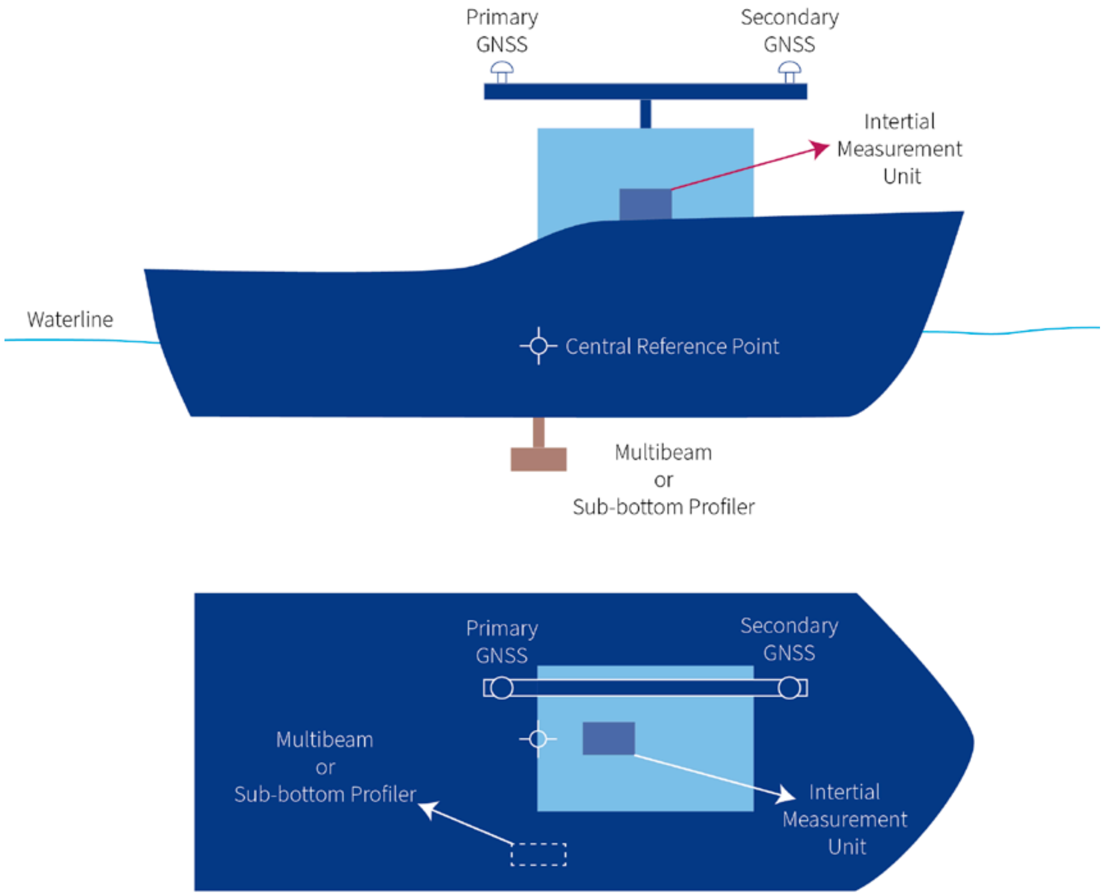


Figure 15: Position and motion sensor layout.

A typical, well calibrated IMU, GNSS compass, and RTK DGNSS should be able to produce:

- A horizontal positional accuracy of 0.5 m
- Roll and pitch accuracy of 0.03°
- Heading accuracy (2.0 m antenna separation) of 0.03°
- Heave accuracy of 0.05 m.

In addition, the IMU should be able to maintain a position output for a period of time through motion derived dead reckoning, even with a GNSS outage.

4. Multibeam echosounders

Multibeam echosounders (MBES) use sound to collect densely spaced measurements of seafloor depth and enable the production of detailed three-dimensional models of seafloor bathymetry. One of the primary uses is the plotting of water depths and the production of hydrographic (nautical) charts for the safe navigation of vessels at sea. The process of identifying water depths is centuries old. Traditionally vessels used a heavy weight (known as a sounding lead) attached to a long rope which was thrown overboard, with the depth measured on the rope when the weight hit the bottom.

The early 20th Century saw the development of the first echosounders which used soundwaves, and the measurement of the travel time between the source, the seabed, and the receiver, to measure depth (soundings).

Technological developments in the 1960's and 1970's led to the development of the multibeam echosounder. Continued development of the technology has resulted in the production of smaller, cheaper systems capable of recording over 1,000 soundings at a time, over a wider swathe and at significantly higher resolutions.

4.1 Uses within archaeology

The primary use of multibeam bathymetry is the bathymetric charting of the seabed and the production of charts for the safe navigation of vessels. As resolution and accuracy has increased, and costs and size of the equipment have decreased, the application of multibeam bathymetry within marine archaeology has broadened to include regular use for:

- archaeological assessment
- targeted archaeological surveys
- assessment of features relating to the palaeolandscape
- the high-resolution survey of archaeological features including shipwrecks
- assessment of seabed dynamics in relation to the stability and threat to the archaeological resource
- year on year bathymetric changes, and
- wide area surveys to identify locations of potential archaeological material

The resulting data can also be used to create accurate georeferenced site plans, plan further works in relation to working depths and areas of potential, and provide basemaps when using acoustic tracking to monitor the position of divers or remotely operated vehicles (ROVs). Due to the visually impressive possibilities available when processing data, it is a very valuable tool for public engagement.

Multibeam bathymetry is often a core technique of surveys undertaken in advance of construction activities, and is the predominant technique employed during Operations and Maintenance phases for asset integrity surveys.

The most common method of installation for a multibeam echosounder is fixed to a vessel, either permanently or on a removable mount, with precisely measured offsets between the GNSS antennas and the motion sensors (Figure 16). As such, and with proper calibrations, the positional accuracy of features on the seabed is considered to be extremely accurate.

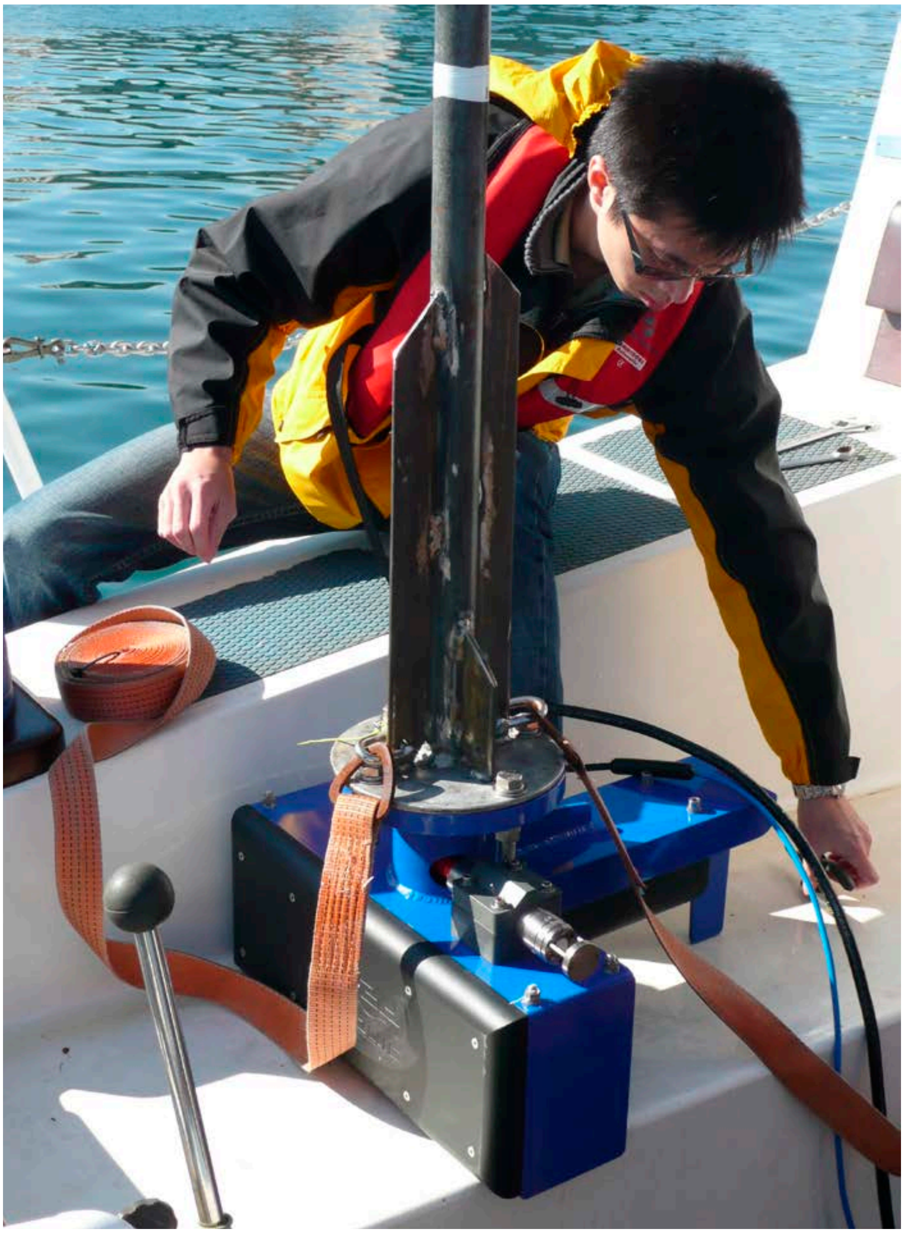


Figure 16:
Multibeam echosounder with attached sound velocity sensor.
© R2Sonic LLC

4.2 How it works

The term multibeam echosounder relates to the use of multiple acoustic pulses to create soundings (measurements of depth). Simplified, a number of acoustic pulses, or beams, arranged in a fan shape are emitted from a transmitter towards the seabed. The travel time of the pulse from the transmitter to the seabed and back to the receiver is recorded and the depth calculated. Most commonly the multibeam echosounder is mounted on a vessel, they can be mounted on Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs), and in some instances towed devices.

The fundamental principles of both singlebeam and multibeam echosounders are the same in terms of acoustic properties and the resultant data and follow the principles of acoustics discussed in Section 2. Initially it is important to understand the process by which a singlebeam echosounder collects data (Figure 17). This can then be applied to the multibeam echosounder.

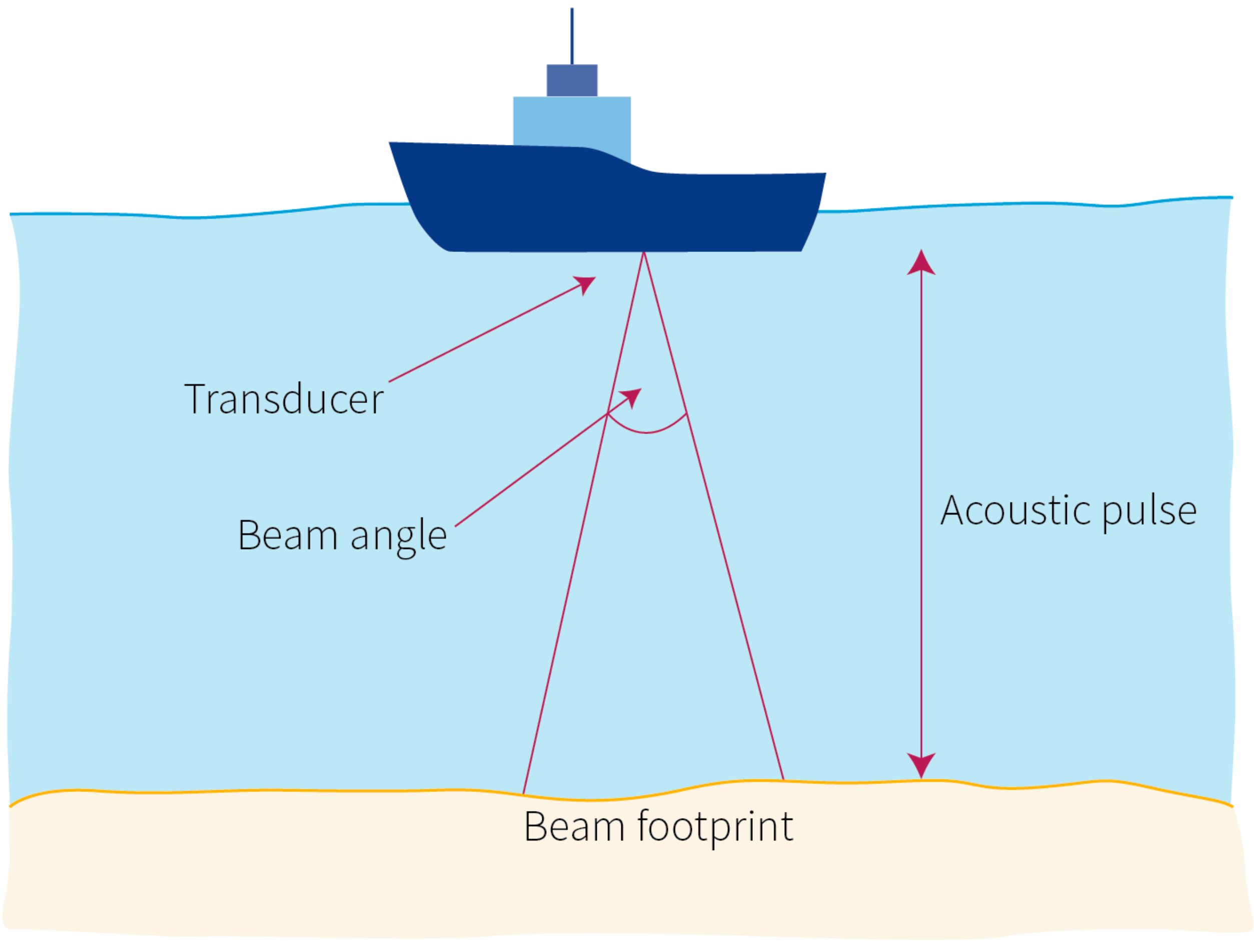


Figure 17: Singlebeam echosounder.

- An acoustic pulse is emitted from a transducer vertically towards the seabed. The pulse is reflected when it hits the bottom and the return recorded by the transducer. The time taken for the pulse from transmit to receive is known as the Two Way Travel Time (TWTT). This time can then be used to calculate the depth using the sound velocity (speed of sound) through water (approximately 1,500 m/s in saltwater) using the following equation:

  Depth = (sound velocity x time) / 2

- The depth is then recorded in relation to the GNSS position resulting in an x, y and z coordinate, where x and y relate to the position, and z the depth. Multiple readings are combined to create a three-dimensional point cloud.

Whilst a fairly straight forward concept, there are other factors to consider which are relevant to data resolution and quality.

- The acoustic pulse does not travel in a vertical column but spreads out as it travels away from the transducer, creating a cone shape and resulting in a circular 'beam footprint' on the seabed.

- The first seabed return in the beam footprint is the depth that is recorded, therefore the smaller the beam footprint, the higher the target resolution and greater the ability to distinguish between smaller features or changes in topography.

- The beam angle (beam width) defines the inside angle of the cone, and therefore the beam footprint: the higher the frequency the smaller the beam width that can be achieved, and thus the higher the target resolution. Whilst it varies between manufacturers beam widths are often around 10°. The depth of water will alter the beam footprint due to the spreading nature of the acoustic pulse (Figure 19). The deeper the water, the larger the beam footprint, and the lower the target resolution.

- The number of readings that are recorded over a given time period are known as the ping rate and is expressed in Hertz (Hz) (or cycles per second). Whilst the ping rate will vary with the specification of the system typically it will range between 1.0 Hz and 20 Hz. The effect of ping rate is important to understand as it effects data density along the track of the echosounder. For example, at a typical survey speed of 4.0 knots (approximately two metres per second) and a ping rate of 1.0 Hz, the along track distance between depth records would be 2.0 m. Noting also that depths are only recorded below the transducer, and therefore the horizontal measurement between depth records will depend on the survey line spacing.

Multibeam echosounders follows the same principle, however, the single transducer both transmitting and receiving a single pulse is replaced with a transmitter array and a receiving array. The transmitter and receiver array produces a number of beams in a fan shape perpendicular to the direction of travel. The transmit and receive angle of each beam is known, and therefore using TWTT, the sound velocity, and the angle, the depth can be calculated at a position not directly below the vessel. Each beam records a depth position simultaneously, resulting in a number of soundings extending across the fan shaped array.

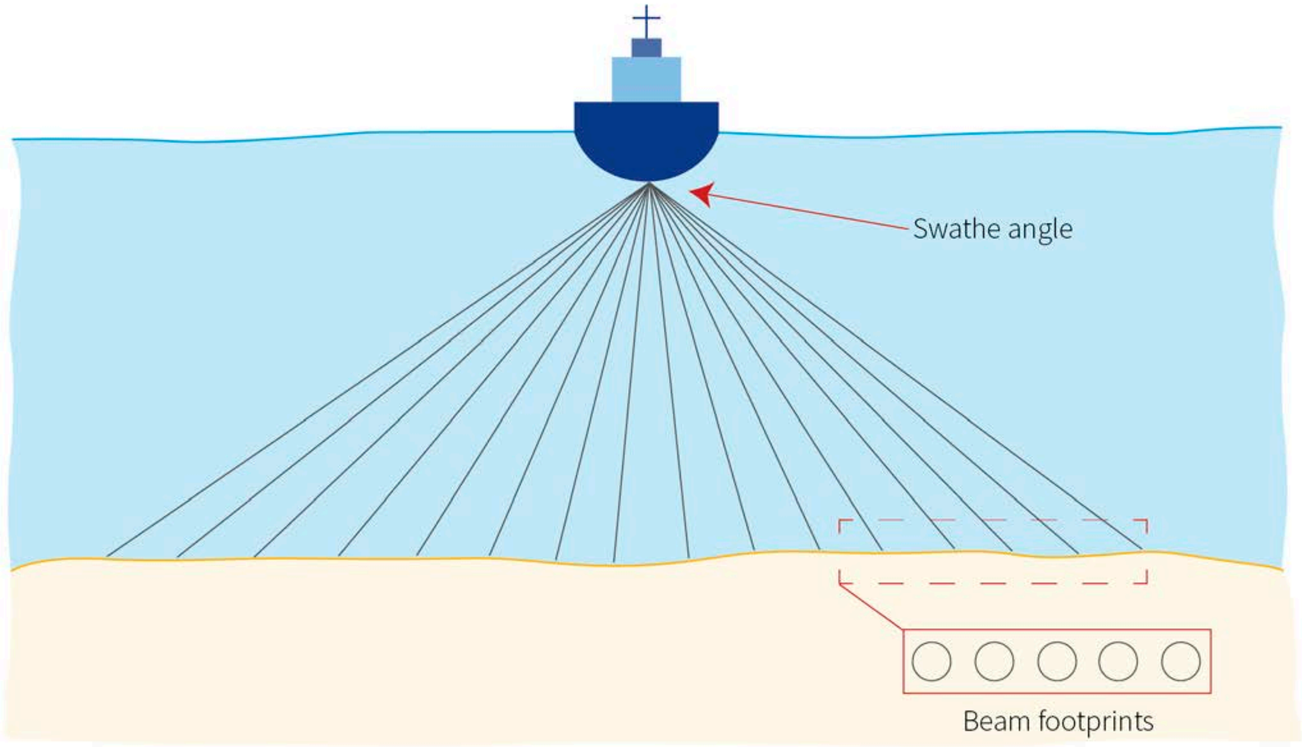


Figure 18: Multibeam bathymetry.

Options exist on most multibeam echosounders that can alter the distribution of the depth records.

- **Swathe angle** – the angle between the outermost port and starboard beams. The greater the angle the wider the swathe (or survey width) but the greater the distance between soundings (lower data density) and the lower the resolution across the swathe width and at the outmost beams. Swathe angles are usually user selectable and can typically range from 10° to 170°. Consideration should be given to the required data density, noting that reducing the swathe angle excessively so that the beam footprints overlap may not increase resolution (Figure 18).

- **Swathe steering** - most survey grade multibeam sonars have the ability to not only adjust the swathe angle, but also the direction of the swathe. Whilst for general survey this is not recommended it can have advantages when surveying along vertical faces such a quay walls, or the sides of shipwrecks. This feature can be automated to compensate for roll in the vessel maintaining a continuous swathe heading.

- **Bottom sampling method** – two primary settings determine the spread of soundings across the swathe and relate to the angle of the beams.

  - **Equi Angle** – all beams in the array maintain an equal angle, due to the greater distance the outer beams have to travel this has the effect of greater data density towards the centre of the swathe, deceasing towards the outer extents.

  - **Equi Distant** – all soundings maintain an equal distance from each other across the swathe. The setting assumes a relatively flat seabed and is not suitable for surveying vertical faces and the use is often limited by the swathe angle.

- **Ping rate** – like singlebeam echosounders the ping rate is measured in Hz, with a higher ping rate increasing the along track data density. Ping rate will be governed to some degree by water depth and therefore the range as applicable to the outermost beams, however manufacture specifications can exceed 50 Hz. A ping rate of 30 Hz, with a survey speed of 4.0 knots, will equate to an along track distance between depth records of approximately 0.07 m. Combining a narrow swathe angle and a high ping rate can result in a centimetric data density both along and across track.

- **Number of beams** – the number of beams within the swathe will vary between manufacturers, and therefore the number of soundings. The traditional number of beams is 256, however a number of manufacturers have implemented hardware and software solutions to increase the number of soundings to 1024. When reviewing specifications, it is important to understand whether the stated number of soundings are true soundings or interpolated.

- **Beam width** – like singlebeam echosounders the beam width will influence the beam footprint (Figure 19). However, the beam widths are typically much smaller with multibeam echosounders, increasing the resolution of each sounding. Unlike the singlebeam echosounder, beam widths are measured both along track and across track (which are not always equal) creating an oval beam footprint, which also changes shape as the distance from the swath increases. The majority of multibeam echosounders have beam widths of sub 1° x 1° at frequencies of around 400 kHz, decreasing significantly at frequencies around 700 kHz.

4.3 Resolution

The assessment of multibeam echosounder resolution is determined by a number of both technical and operational factors. Simply put, the higher the resolution, the clearer and more detailed the resulting image will be. Generally, the higher the frequency, and the smaller the beam footprint and the shorter the pulse width, the greater the resolution, but also the greater the attenuation so the shorter the range. The two areas that should be considered when assessing the suitability of a system are, range resolution and target resolution.

- **Range resolution** is the ability of the system to resolve two separate features that lie perpendicular to the transducer, but at different ranges. Range resolution is determined by the pulse length and the bandwidth, which are inversely proportion to each other. The shorter the pulse width, the smaller the distance between two objects that can be resolved.

- **Target detection resolution** is the ability of the system to accurately determine the depth of a single position on the seabed, and is directly related to the beam width, and thus the beam angle.

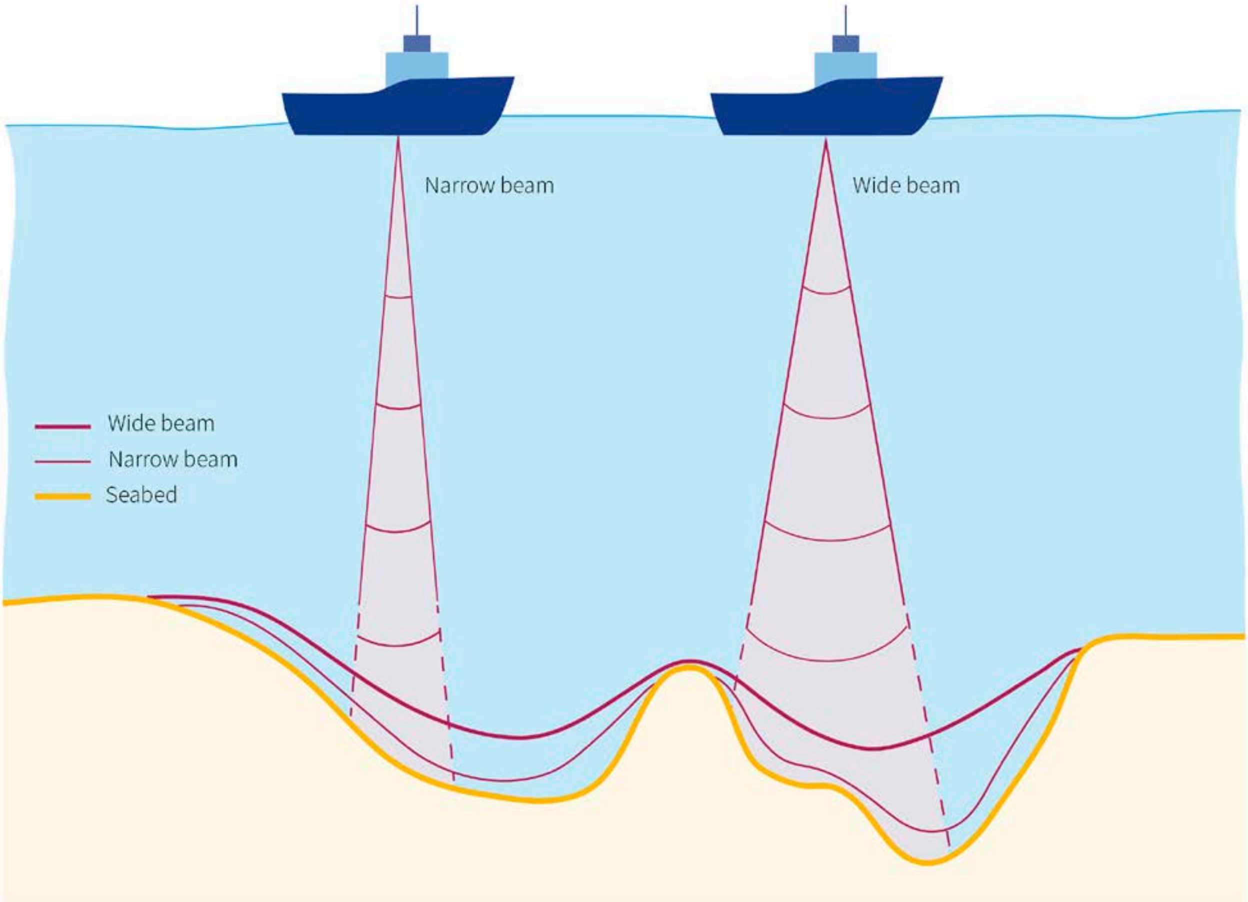


Figure 19: The effect of beam width, and beam footprint on resolution. The smaller the beam footprint, the more accurately the changes in topography can be resolved.

Survey speed, ping rate, and swathe angle also play an important part in the resulting data resolution. The more individual soundings collected over a feature (data density), the more accurate the representation of that feature will be, or the ability to ensonify a feature. Caution should be exercised during survey planning, as the collection of multiple lines of data over a single feature may increase the overall data density, but can compound errors in positioning, both through the limitations of the multibeam echosounder and the positioning system (Section 3). Data density will directly affect the resolution of the processed data outputs.

4.3.1 Other outputs

In addition to a three-dimensional point cloud, a number of other outputs can be derived from multibeam echosounder data.

- **Backscatter** – like with sidescan sonar the strength, or the amplitude, of the returning signal is recorded and this can be presented in a similar way. The strength of the return is an indication of the hardness of the surface from which it is reflected. The harder the surface, the stronger the return. Whilst typically not a replacement for sidescan sonar data for archaeological assessment due to the resolution being defined by the multibeam bathymetry data, and the lack of shadow helping to define features, it can for example provide meaningful high resolution seabed data for sediment characterisation. There are instances where backscatter data can aid archaeological interpretation, this can include areas where upstanding structures can create significant acoustic shadow, or where no sidescan sonar data is available.

- **Water column data** – the depth data returned from a multibeam echosounder is dependent on the algorithm used to detect the seabed (or bottom) and will generally equate to the furthest, or strongest (highest amplitude) return. This process effectively filters out returns in the water column. Water column data is, as the name suggests, the data, or returns, collected within the water column (the area from just above the seabed to the surface) and are typically of lower amplitude. Water column data can be simply classed as lower amplitude returns that have not been correlated with the seabed and can include schools of fish or other organisms, gas leaks, bubbles, biological features and midwater material such as fishing nets. From an archaeological perspective, water column data can aid in the identification of fine features such as masts which may otherwise be filtered out.

4.4 Ancillary equipment

The collection of high quality, and accurate, multibeam bathymetry data requires data collected by a number of other external sensors.

4.4.1 Sound velocity profiler and sound velocity sensor

The calculation of accurate depths is based on the TWTT of an acoustic pulse through the water column which required knowledge of the sound velocity. Whilst for other techniques such as singlebeam echosounders and sidescan sonar an approximation based on the salinity of the water (i.e. fresh or salt water) can generally be used, with multibeam bathymetry even small changes in the sound velocity can have a detrimental impact to the resulting data and result in artificial measurements of depth. The effect will be exaggerated both with depth, and at the outer extents of the swathe as the distance to the seabed, and therefore the TWTT, increases. A sound velocity which is higher than the actual velocity at the time of the survey will result in a flat seabed appearing to curve upwards, and a lower sound velocity will result in a flat seabed appearing to curve downwards (Figure 20).

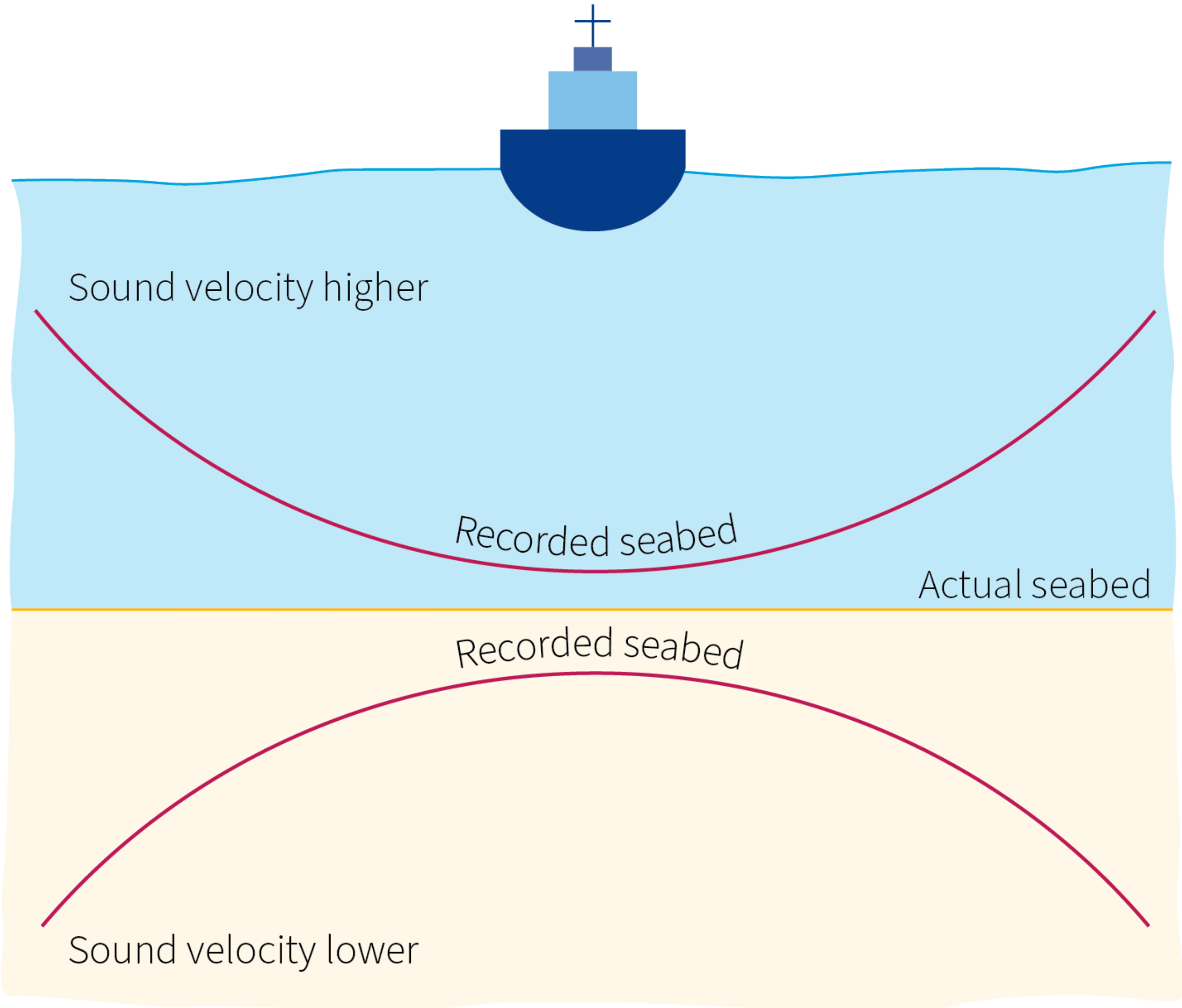
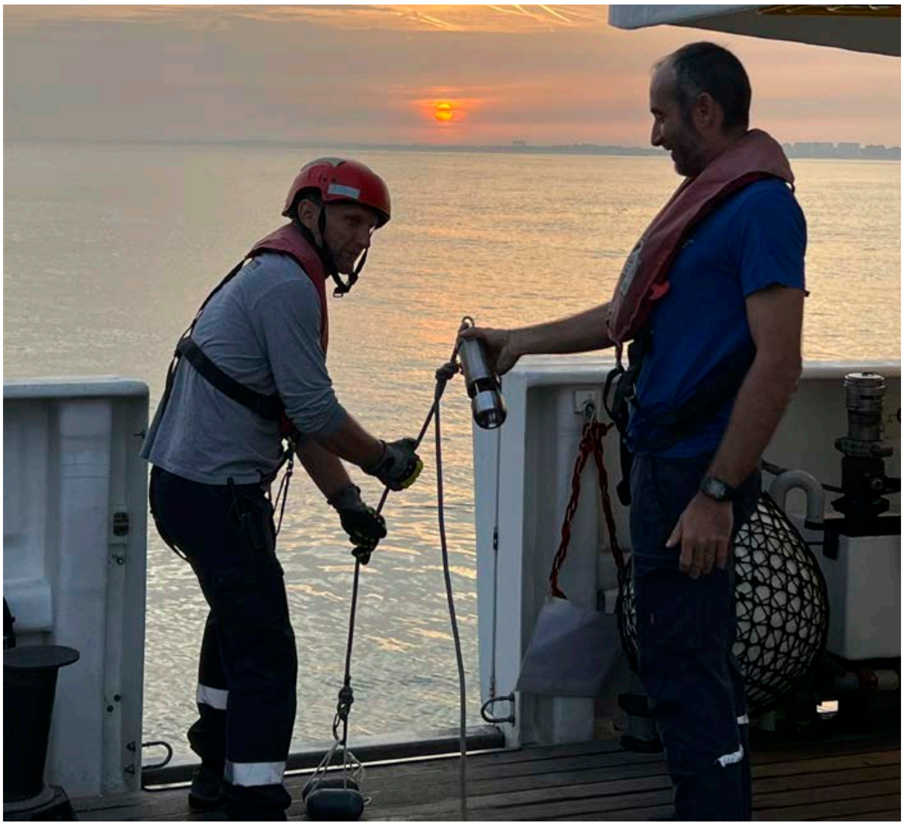


Figure 20: Sound velocity errors resulting in a false 'curved' representation of the seabed.

Figure 21: Deployment of a sound velocity profiler during multibeam bathymetry survey being undertaken with Drassm. © MSDS Marine



Sound velocity changes through the water column and hence data must be calibrated accordingly. To achieve this a Sound Velocity Profiler (SVP) is lowered slowly to the seabed (Figure 21). The SVP will record the sound velocity and depth at intervals and the resultant values are applied to the data. Profiles should be collected both pre and post survey, and at intervals throughout. The intervals will depend on the environmental conditions where there are notable changes such as freshwater outlets, increases in surface water temperature, changes in depth, or after moving to a new area.

In addition, a Sound Velocity Sensor (SVS) which continuously measures sound velocity at the same depth as the multibeam echosounder is generally deployed with the values imported into the acquisition software in real time.

4.4.2 Tidal corrections

Depths are calculated as distances from the multibeam echosounder to the seabed and are directly related to the surface of the waterbody on which the survey is being undertaken. Therefore, the effect of rising and falling tides needs to be accounted for. The greater the tidal range, the greater offset there will be in the data both between the start and end of a line and between adjacent lines. The most common methods for tidal corrections are the use of tide gauges deployed at, or close to, the survey site and permanent gauges which can be located in ports and harbours and the use of RTK height corrections (Section 3). Tide gauges record time and pressure, with pressure increases indicating a rising tide and pressure decreases a falling tide. The resulting data are then applied to the multibeam bathymetry data. RTK corrections, where available, negate the need for a tide gauge with height corrections either applied to the data in real time, or logged and applied during post-acquisition processing.

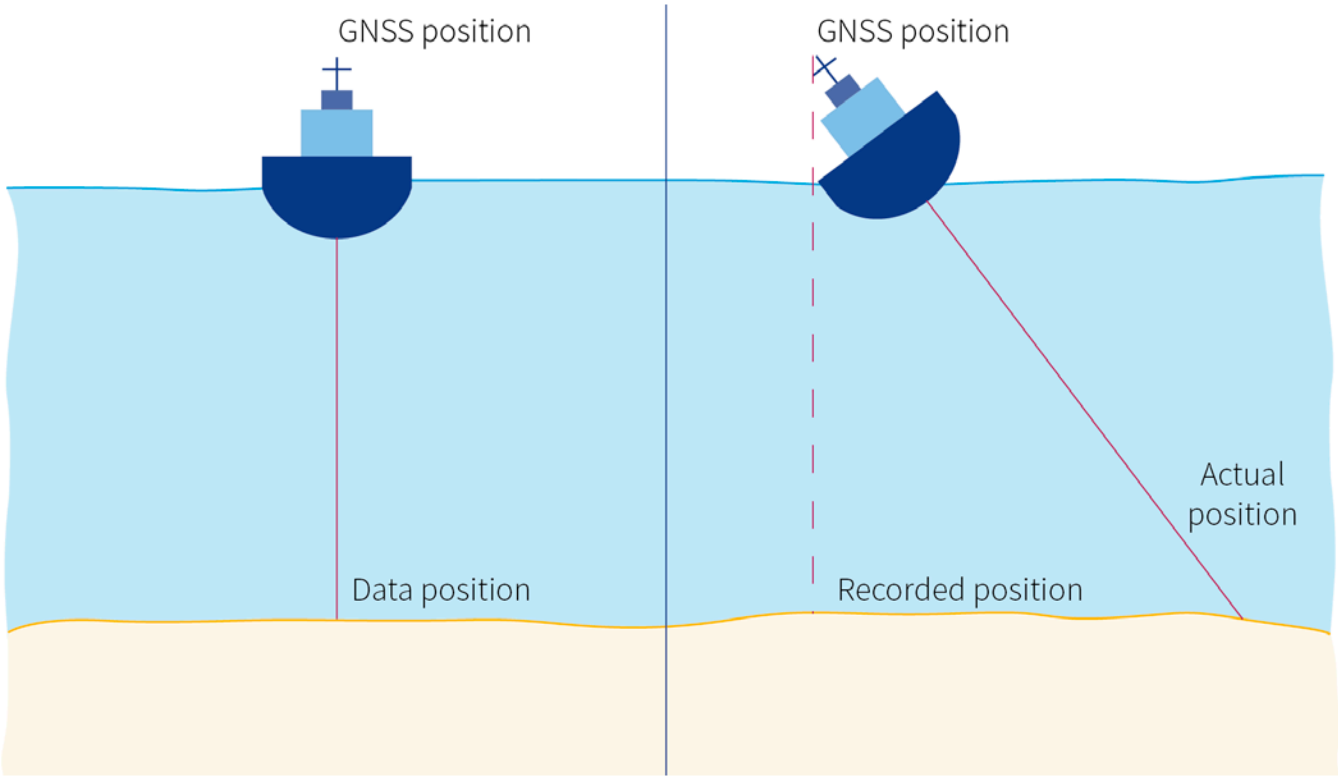


Figure 22: Offset errors in relation to vessel motion.

4.4.3 GNSS and motion sensors

GNSS and motion sensors are detailed in Section 3, however the importance is highlighted here due to the detrimental impact poor positioning and motion data have on data. With the multibeam echosounder typically fixed to a vessel the position of depth measurements will depend on the position and the motion, of the vessel. If the three-dimensional orientation of the vessel is not applied to the data, both the position and depth recorded will be incorrect (Figure 22). As such, multibeam echosounders should not be used without a well calibrated IMU.

Due to the significant volume of data points that can be collected over a small area of seabed, and the way in which the data are presented, the relative accuracy of data points between adjacent lines of data is critical to producing a high quality output. Therefore, typical GNSS and even DGNSS accuracies are often not suitable, and wherever possible GNSS corrections (either RTK or PPK) should be used.

4.5 Limitations

Within the marine construction industry multibeam bathymetry data are routinely collected and available for archaeological assessment. However, this is not the case for many amateur groups and marine archaeological organisations as the cost of owning the equipment is largely prohibitive, with costs for even a basic system being in the tens of thousands, and costs for survey grade equipment being in the hundreds of thousands. Hire costs are significantly more expensive than other geophysical equipment. Another limiting factor is the training and experience required to mobilise, calibrate, and operate the equipment which is a great deal more complex than with other geophysical equipment.

When considering a multibeam bathymetry survey, the following limitations should be noted:

4.5.1 Mobilisation

The mobilisation of a vessel with a multibeam echosounder is complex, particularly on vessels of opportunity (vessels that are not exclusively survey vessels). The quality of the installation will have a direct bearing on the quality of the data and permanent installations are likely to yield better results. Installations will require the multibeam sonar transducer, the GNSS antennas, and motion sensors to be fixed in relation to each other with offsets precisely known. Bespoke mounts or modifications to the vessel may be required to accommodate the equipment. This may preclude the use of smaller vessels such as rigid inflatable boats (RIBs).

Where equipment is mobilised onto a vessel of opportunity, consideration should be given to the additional time required to undertake the survey. The mobilisation time may mean that the survey of a single site scheduled to take a few hours, may require several hours or days overall.

4.5.2 Minimum object detection size

The minimum object detection size will depend on several factors including the specification of the system used (frequency, beam width, pulse width, etc.), and the data density (itself related to depth of water, vessel speed, and swathe angle). In general, the greater the data density usually the smaller the minimum object detection size.

4.5.3 Weather

Multibeam bathymetry is very susceptible to the effects of weather, typically more so than with towed equipment, as the motion of the vessel is transmitted to the equipment. The roll of the vessel will produce data that move in a zigzag across track to port and starboard and pitching of the vessel will produce data that is compressed and stretched along track. These can be corrected with automated compensation of the beam direction, but excessive movement will result in data that do not meet the specifications of the survey in regards data density and overlap.

4.5.4 Acoustic shadow

The effect of acoustic shadow is less marked than with sidescan sonar due to the acoustic source being directly above the seabed. Features, especially those which are upstanding, ensonified from one direction will have areas of no data along the side furthest from the acoustic source.

4.6 Survey planning

It should be noted that unlike the other techniques discussed within this guidance, there are international standards for hydrographic surveys produced by the International Hydrographic Organization (IHO) (Document S-44 – Standards for Hydrographic Surveys[2]), the data specifications for which are re-produced below in Table 4 (correct as of 2025). Whilst the aim of the standards is to harmonise the data used in the production of hydrographic charts and the safe navigation of vessels, they provide a good reference point when planning surveys for archaeological purposes and may be referred to survey specifications. However, it is important to note that dependent on factors such as water depth, these specifications (particularly Exclusive Order) may not be able to be met, conversely the specifications may not always be sufficient for archaeological interpretation dependent on the aims of the survey.

Table 4: International Hydrographic Organization (IHO) Standards for Hydrographic Surveys.

Criteria	Order 1a	Special Order	Exclusive Order
Area description (generally)	Areas where underkeel* clearance is considered to be critical but features of concern to surface shipping may exist.	Areas where underkeel* clearance is critical.	Areas where there is strict minimum underkeel* clearance and manoeuvrability criteria.
Depth THU {m} + [% of depth]**	5.0 m + 5% of depth	2.0 m	1.0 m
Depth TVU* (a) [m] and [b]**	a = 0.5 m b = 0.013	a = 0.25 m b = 0.0075	a = 0.15 m b = 0.0075
Feature detection [m] or [% of depth]	Cubic features > 2 m, in depths down to 40 m; 10% of depth beyond 40 m	Cubic features > 1.0 m	Cubic features > 0.5 m
Feature search {%}	100%	100%	200%
Bathymetric coverage {%}	≤ 100%	100%	200%

* Minimum water distance between a ship's hull and the seabed

** Total Horizontal Uncertainty

*** Total Vertical Uncertainty

Whilst survey planning is covered in Section 12, the following should be considered during the survey planning process to ensure optimal quality of data.

2 IHO 2020 Standards for Hydrographic Surveys Document S-44. https://iho.int/uploads/user/pubs/standards/s-44/S-44_Edition_6.1.0.pdf

4.6.1 Equipment selection

The equipment selected should be based on the ability to meet the objectives of the survey. Selection should take into consideration:

- **Frequency** - in general terms the higher the frequency the higher the resolution, and the smaller the minimum object detection size and more detail obtainable, but the shallower the depth that can be surveyed.

- **Equipment specifications** - frequency will generally be a good measure of the expected data resolution. Consideration should also be given to ping rate, the number of beams (both real and software based), and the beam angle. Specifications will differ across manufacturers and the intended use of the system.

4.6.2 Line planning

Survey line spacing should be planned to meet the objectives of the survey (Section 12). The predominant factors are data density and coverage, both swathe width and overlap. At a constant swathe angle, the swathe width on the seabed increases with depth due to the angle of the beams and this should be considered when planning survey lines. Whilst deeper water will give greater seabed coverage on a single line for a given swathe angle, the data density will be reduced.

For general line planning purposes, a swathe angle of 120° equates to a seabed coverage of 3.5 times the water depth, and therefore lines can be planned at three times water depth to achieve 100% coverage, or 1.5 times water depth to achieve 200% coverage (should the specification require it). The line spacing provides contingency for errors in line navigation and changes in seabed topography altering the swathe coverage. The use of 200% coverage has advantages in that not only is the data density increased, but features are ensonified along two sides, reducing the impact of acoustic shadow. Site specific data, or that collected specifically for the visualisation of shipwrecks, will generally require more bespoke line planning. Where possible lines should be planned to run:

- **Parallel to depth contours** - surveying parallel to depth contours will result in more consistent seabed coverage rather than data density increasing and decreasing with depth of water changes. Operationally this reduces the survey time as lines can be planned for a single depth, rather than the shallowest depth of a line. Running survey lines parallel to depth contours in shallow waters allows the depth of adjacent lines to be determined, reducing the risk of grounding the vessel.

- **In straight parallel lines, with turns being undertaken outside of the survey area** - the quality of the data is dependent on the ability of the survey vessel to maintain straight lines during data acquisition. Data collected during a turn will compress data on the inside of the turn and stretch data on the outside of the turn.

- **Parallel with the direction of the current** - to minimise the impact of cross currents on the vessel.

- **At a constant speed** - the speed of the survey should remain constant and will be determined by the aims of the survey and the ping rate of the system. A general speed of 4.0 knots can be used, noting that some systems can operate at much higher speeds. In some instances, it may not be possible for the survey vessel to maintain a consistent heading at a low speed and in this instance, consideration should be given to running all lines into the current to increase steerage. For wreck surveys, data should be collected at as low a speed as practical to increase data density.

It is good practise to collect cross lines perpendicular to the main survey lines at intervals across the survey area. Cross lines can help identify errors in tidal corrections.

4.6.3 Calibration

Equipment calibration certificates should be checked and confirmed they are in date prior to the commencement of the survey.

The process of calibration for multibeam bathymetry is beyond the scope of this guidance and is specific to both the equipment and the acquisition and positioning software used. The following summary is provided to enable a basic understanding of the process and enable the reader to ensure that correct procedures have been carried out when receiving data from third parties. Errors in calibration, or lack of calibration, are generally visible in the output data.

The system should be fully mobilised with the survey vessel alongside, the GNSS and the motion sensor fixed in place, and the multibeam sonar deployed and secured in the survey position. The spatial relationships between sensors and the CRP of the vessel, or offsets, should be measured as accurately as possible. Different offsets will be required for both the acquisition and positioning software. Care should be taken to ensure that the requirements of the software are met and the correct +/- value is used. All systems should be turned on and all inputs into the acquisition software confirmed. These are likely to include GNSS, motion, SVS, and the multibeam sonar transducer.

Two primary system calibration tests are required for multibeam bathymetry: one for the positioning and motion system in relation to the offsets between the motion sensor and the GNSS antennas, and one for any offsets and mounting angles in relation to the multibeam echosounder and the positioning system. Calibration of the positioning and motion system is typically achieved by performing a range of vessel movements at sea, with the software calculating any errors in offset measurements and adjusting them accordingly.

The offsets and mounting angles between the positioning and motion system and the multibeam echosounder are corrected using a series of patch tests. Patch tests require the collection of a number of lines of data, which are then compared and aligned, and offset corrections calculated. Patch tests are briefly summarised in table 5.

Table 5: Types of patch test for the calibration of offsets and mounting angles of a multibeam echosounder and associated positioning and motion systems.

Type of Test	Information
Roll Test	The roll test identifies angular errors along the x axis of the multibeam sonar. The test requires the collection of two lines of data on a flat seabed, in opposite directions and at the same speed, and along the same track. When viewing a slice of the resulting data roll errors will be visible with the two lines of data creating an 'X'.
Pitch Test	The pitch test identifies angular errors along the y axis of the Multibeam Sonar. The test requires the collection of two lines of data over a steep slope or seabed feature, in opposite directions and at the same speed, and along the same track. When viewing a slice of the resulting data pitch errors will be visible as an offset in the position of the slope or seabed feature.
Yaw (or heading) Test	The yaw test identifies angular errors along the z axis of the multibeam sonar. The test requires the collection of two lines of data over a steep slope or seabed feature, in the same direction and speed and parallel to each other. The lines of data must overlap at the position of the slope or seabed feature. When viewing a slice of the resulting data yaw errors will be visible as an offset in the position of the slope or the seabed feature.
Latency Test	The latency test is the only test not looking at angular offsets, but the latency of the GNSS position. Latency is typically not an issue as most installations use GNSS time synchronisation, however as an error can indicate underlying system issues, the test still needs to be undertaken to prove latency is zero or very close to it. The test requires the collection of two lines of data over a steep slope or seabed feature, in the same direction, along the same track but at different speeds. When viewing a slice of the resulting data latency errors will be visible as an offset in the position of the slope or the seabed feature.

Following the patch tests the calculated corrections will be input into the acquisition software where they will be applied to the data. It is good practise to undertake patch tests prior to the commencement of the survey; they can however be applied retrospectively. Patch tests need to be undertaken every time any offsets may be altered, even minimally.

4.6.4 Testing

The determination of a correct minimum object detection size can be achieved through the deployment of an object of known dimensions, corresponding with the required specification, and at a known position on the seabed. The actual process will depend on the survey parameters, but the following provides an example of a typical minimum object detection size test.

For this example, a swathe width of 70 m (20 m water depth) will be assumed. The test is undertaken under the expected survey conditions, including line direction and speed, and water depth.

Two lines of data are collected either side of the object at a fixed distance from the object (15 m) and in the same direction (e.g. north to south). Two further lines of data are collected at a fixed distance towards the edge of the range (30 m) and in the opposite direction (south to north). The process is then repeated with perpendicular lines (in this example, east to west and west to east). The minimum object detection size is confirmed both close to the centre of the swathe where the data density is greater and at the outer edges of the swathe where data density is sparser.

4.6.5 Survey outputs

Multibeam bathymetry data are recorded digitally during acquisition and are typically stored in a proprietary database format containing all data relevant to the survey. Prior to export, the following corrections should be applied:

- Application of corrected position and motion data. In some instances, these data may require processing, and this should be undertaken prior to export of the resulting data.
- Application of patch test corrections.
- Application of tidal corrections.
- Application of sound velocity corrections.

Corrected data should be exported at full resolution as delimited ASCII x, y, z files (where x and y relate to the position, and z the depth) (.txt, .csv, .pts, .asc, etc.) referred to as a point cloud. The data should be exported with each individual line as a separate file.

In addition, depending on equipment and software, backscatter data can usually be exported as .xtf files, for viewing, processing, and interpreting using the same process as for sidescan sonar. Survey outputs should always include metadata.

4.7 Quality control

Prior to the commencement of data processing, the data should be subject to a process of quality control. The process should establish the quality of the data in relation to suitability for archaeological interpretation, and whether the archaeological objectives of the survey have been met. Whilst data supplied by a survey contractor, typically in relation to marine development, will have been through a process of quality control, it is still important that quality control in relation to archaeological objectives is undertaken prior to any additional processing and interpretation. The results of the quality control assessment should be presented in the archaeological report (Section 14).

The quality control process should be ongoing. Issues with data may not become apparent until the interpretation phase when each line (or block) of data are viewed individually. The process for quality control will depend on the workflow of the organisation undertaking the work, as well as the software being used, but at a minimum the following should be considered:

4.7.1 Data quality

- Do the data show signs of external influences such as poor weather or sea state?
- Do the data show signs of incorrect, or absent, calibrations, including offsets?
- Do the data show signs of incorrect tidal corrections?
- Do the data show signs of incorrect sound velocity values?
- Do the data show signs of interference from other equipment including from simultaneous surveys (i.e. sidescan sonar or sub-bottom profiler), vessel engines, or vessel equipment such as echo sounders?
- Have the data been collected to a specification to achieve the minimum object detection size? In the absence of the survey of a test object of known size at varying ranges, this can be achieved, to a certain degree, through the measurement of features, such as boulders, identified within the data. Due to the minimum object detection size increasing with distance from the multibeam sonar this should be undertaken across the full range of the data.
- It is important to note whether the data have any other issues which may affect the ability to undertake archaeological interpretation? This can include, but is not limited to, the presence of natural or geological features including sandwaves, reefs, boulder fields, etc. that may either obscure the seabed through acoustic shadow, or for example in the case of boulder fields obscure the presence of archaeological material or make interpretation difficult. Although less common, the presence of other factors, such as large shoals of fish can all impact data quality and the ability to undertake archaeological assessment.

4.7.2 Coverage

- Has the survey achieved the required coverage, both in terms of the survey area and the coverage percentage? Most commercially available and industry standard processing software will plot the data, alongside a shapefile of the survey area to enable an assessment of coverage. If this function is not available, the data should be exported as a georeferenced mosaic and assessed within a Geographical Information System (GIS). The assessment of coverage percentage can again be assessed within most processing software, with the results presented graphically and numerically. It is important to note that coverage should be assessed only on the useable data following quality control.

4.8 Processing and visualisation

Prior to processing, a backup of the raw, or 'as supplied' data should be created as processing will result in the removal of data. Whilst most processing software will retain (or flag) deleted data this is not always the case and some point cloud editing software will permanently delete data.

Navigation data processing should be applied prior to the export of individual lines. The processing and visualisation workflow detailed below assumes exported data are free from offset and navigation errors. Whilst it is possible to adjust the positions of individual lines it is not good practice, and whilst relative positions may be more accurate, the certainty of the absolute accuracy will be decreased. The three main stages of multibeam bathymetry data processing are data cleaning, data gridding, and data visualisation.

4.8.1 Data cleaning and de-spiking

The collection of multibeam bathymetry data will generally result in the recording of spurious data points. These data points can be the result of a number of factors such as: incorrect sonar settings, interference from external sound sources such as other equipment and engines, vessel motion, and mobile objects in the water column including fish. Data cleaning and de-spiking is the process of removing these spurious data points. Caution must be exercised with the differentiation between spurious points, and those representing small features. This is especially important when cleaning data around shipwrecks, where points that may appear spurious may relate to small features extending from the main area of wreckage.

The workflow for the cleaning of the point cloud data will depend on the processing software used, but options will generally be available for either manual or automated cleaning. Cleaning should always be performed prior to data gridding as erroneous points may affect the averaging process:

- **Manual cleaning** – the cleaning of data manually requires the processor to review the dataset, either in two-dimensional slices or blocks, or three-dimensional point clouds, selecting points which are highly likely to be spurious, and either deleting them or flagging them for removal. Manual cleaning is the preferred method for data collected over shipwreck sites as it allows the processor greater control over the process. However, it should be noted that this process in itself requires a degree of interpretation. Over wide areas, manually cleaning data can be very time consuming, and depending on the requirements of the survey may not be proportional. A precautionary approach should always be used and data retained if the origin is uncertain.

- **Automated cleaning** – the process of automated cleaning uses a statistical approach to identify data points that are likely to be spurious, based on the position and distance from other points. The tolerances can be adjusted by the user resulting in a more, or less, aggressive process. Over large areas where the objective is the mapping of topography or the identification of larger seabed features (such as shipwrecks or large items of debris), an automated cleaning process can be acceptable. However, the original dataset should be retained and, where required (such as the assessment of a smaller feature within the wider area), the data cleaned manually as a separate dataset. Automated data cleaning should aim to achieve the desired results using the least aggressive settings and will require continued assessment of the data to ensure real data are not being removed.

For both methods it is critical that the data are not overcleaned as this will result in a loss of real data. It can also decrease the overall data density resulting in lower resolution data. Following data cleaning the individual lines of data can be combined to create a single point cloud.

If the data are going to be visualised and interpreted using the resultant point cloud without going through the data gridding process, the data should be exported as a delimited ASCII x, y, z file (where x and y relate to the position, and z the depth) (.txt, .csv, .pts, .asc, etc.) and clearly identified as cleaned data.

4.8.2 Data gridding

Data gridding involves the averaging of the data points within a point cloud to create a uniform distribution of data and, depending on the software, is a prerequisite to the continuation of the processing, and visualising process. Gridding can be undertaken on a single point cloud or can consider individual lines, with the resulting output being the combined and gridded point cloud.

Gridding is undertaken in the x and y planes (i.e. plan view) and to defined cell sizes. However, gridding will result in the loss of data points, the loss of data density and resolution, and the statistical handling of data which may not be a truly accurate representation of the seabed or feature. The advantages of gridding the data, particularly with large datasets, is the ability to create a georeferenced surface for visualisation, and in most instances a significantly reduced file size enabling a more effective use of the data within GIS software (Figure 23).

Whilst the archaeological interpretation of data relating to features such as shipwrecks should always be undertaken using un-gridded point cloud data, the use of gridded data for visualisation of shipwrecks (and the production of georeferenced images) and wide area assessments is considered acceptable as long as the limitations are understood and detailed within the survey report (Section 14). Where the aim of the assessment of a large area dataset is to identify the locations of features of potential archaeological interest, and where other datasets are available such as sidescan sonar, the use of gridded data is usually sufficient, but is dependent on the resolution.

The size of the grid will depend on the data density, and an assessment must be made of the data to understand this. The overall aim is to achieve a grid with the optimal cell size to meet the objectives, without having cells with no data points from which an average can be taken. For example, a data set with data points spaced at 0.1 m across track, and 0.2 m along track, could not be gridded at 0.1 m. The methods of averaging the points within the cell can be defined by the user but generally the following options are available: the mean, the shallowest point, or the deepest point. For archaeological assessment the mean is generally the preferred method.

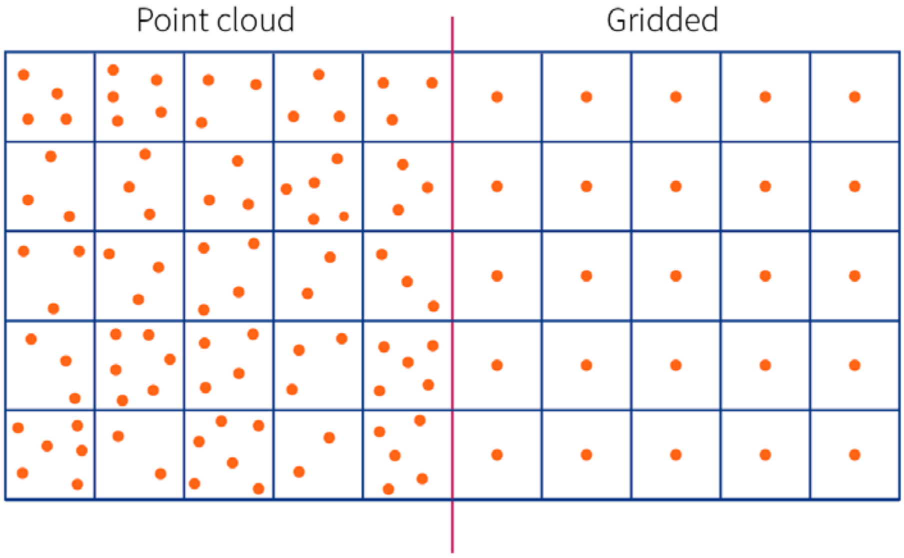


Figure 23: Example of the results of the gridding process.

The smaller the gridded cell size, the higher the resolution of the resultant output, and the truest to the original data it will be. The examples in Figure 24 are based on data collected over the wreck of the *London* and show the effect of cell size with the data gridded at 0.1 m, 0.25 m, 0.5 m, and 1.0 m. Note the data have had a surface applied which will be discussed in the visualisation section below. For characterisation surveys data should be gridded at a maximum of 1.0 m, for investigation surveys 0.25 m, and for shipwreck surveys 0.1 m should be aimed for.

The examples in Figure 24 have all been produced using the same colour scale for depth. Due to the nature of the gridding process not only do the levels of detail change, but subtle differences in the presented depths can also be seen due to the averaging of depth over different areas.

If the data are going to be visualised and interpreted using the resultant gridded point cloud, the data should be exported as a delimited ASCII x, y, z file (where x and y relate to the position, and z the depth) (.txt, .csv, .pts, etc.) with the cell size clearly identifiable in the title (such as _0.25m). Further visualisation may require the data to be exported, however depending on the software used, visualisation and exports may be able to be undertaken within the same package.

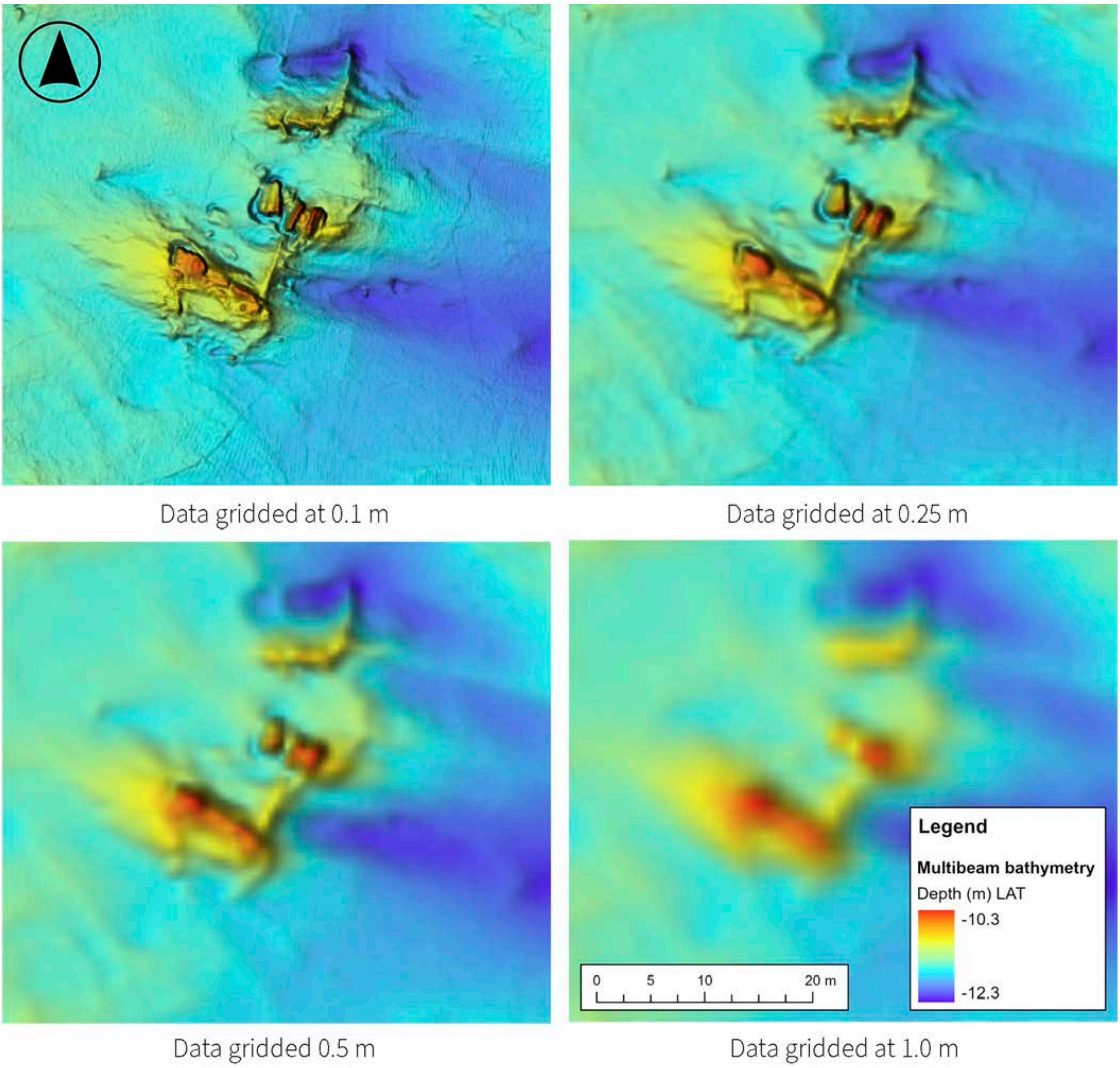


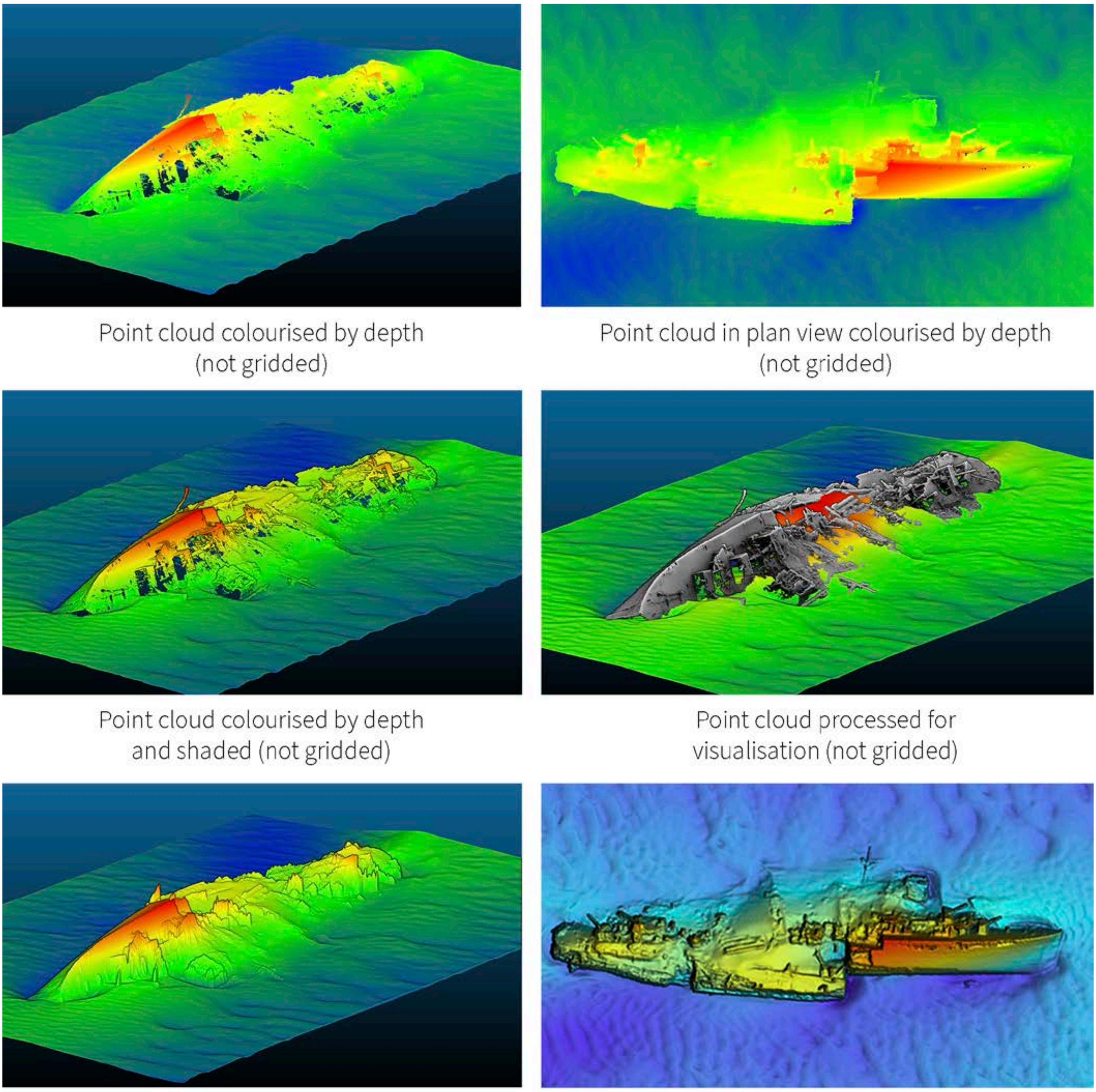
Figure 24: Example of the results of the gridding process. © MSDS Marine

4.8.3 Visualisation

Visualisation of the data will depend on the aims of the survey and the intended use of the data. As detailed, the requirements may vary between surveys undertaken over individual sites and those intended to cover large areas. The visualisation process must consider the intended use of the data and whether the exported formats are suitable. The three main types of visualisation are two-dimensional plan view images (usually georeferenced with a surface applied), in three-dimensions (with a surface applied), and in three-dimensions as a point cloud.

Most software will allow for the alterations of colour scales depending on depth and the application of effects such as shading, using a light source position to highlight features based on the shadow they create. These should be used to achieve the optimum presentation of the data to highlight features of potential interest. The visualisation of ungridded point cloud data will always give the most accurate representation of the data. The visualisation of a georeferenced two-dimensional image is more appropriate for use in GIS software.

The examples in Figure 25 are all based on high resolution data collected over the wreck of HMS *Keith* during the Operation Dynamo Project.



Point cloud colourised by depth (not gridded)

Point cloud in plan view colourised by depth (not gridded)

Point cloud colourised by depth and shaded (not gridded)

Point cloud processed for visualisation (not gridded)

Meshed surface colourised by depth, 0.1 m grid

Draped surface visualised in GIS, 0.1 m grid

Figure 25: Examples of different types of processed data.
© Drassm, multibeam processed by A. Rochat (Drassm) and M. James (MSDS Marine /Historic England)

The creation of a surface will produce either a mesh which directly links each point of data with straight lines, or a draped surface which will use the surrounding data points, and curved lines, to create a less angular surface. The higher the density of data points, the more accurate the resulting surface will be. Where there are no data points the software will typically interpolate between points which will create an unusual effect, and potentially obscure smaller features when viewing in an orientation other than plan view.

4.9 Processed outputs

The culmination of the data processing is the output of deliverables in relation the Method Statement (Section 10), and from which interpretation can be undertaken. The workflow for the production of outputs will vary depending on the processing software but all industry standard software should have the following options. To note, not all may be useful or applicable to the project but are included here for completeness.

4.9.1 Point clouds

Throughout the processing process, point clouds can be exported as a delimited ASCII x, y, z file (where x and y relate to the position, and z the depth) (.txt, .csv, .pts, .asc, etc.). At a minimum, a cleaned point cloud should be exported. Gridded point clouds should be clearly labelled as such. For a point cloud that has had visualisation effects applied, ASCII files are able to record certain information about each point, such as RGB colours and intensities. Whilst ASCII files are typically able to be read by a wider variety of software, binary formats such as .las and .laz can be considered. The format will depend on the requirements of the client and individual data storage workflows. It should be noted that some visualisation effects created in certain software, such as those within the point clouds visualised for assessment image, will require the finished product to be exported in a proprietary format.

Where data are being provided by a third party, such as in advance of marine development, or where data collected will be used by other organisations, data should be supplied and exported in industry standard, and non-proprietary, formats.

As point cloud data are three-dimensional, the presentation in reports (with the exception of three-dimensional .pdf's) will require orientation specific images to be created. Images should be exported directly from the software as opposed to taking screenshots, and should be exported to achieve a minimum of 300 dpi at the scale required, i.e. A3, A4, etc. Images should be exported in a common raster file format such as .jpeg, .tiff, or .png.

4.9.2 Surfaces

Surfaces should always be exported as a georeferenced raster image to enable use within GIS software, with .tiff being the preferred format (although other image formats are available). Some software may require the addition of a world file (georeferencing parameters accompanying an image) where it cannot read georeferencing data contained with the .tiff file. Should the option not be available at the time of export, open-source software is available that can retrospectively create a world file. Two types of georeferenced raster can be exported, one without elevation (or height/depth) data, and one with:

- **Rasters without elevation data** – rasters without elevation data will be a reproduction of the surface displayed during visualisation and will include the colour scale selected, and any effects applied during visualisation such as shading. Each pixel in the raster will have a set RGB colour. As the image does not contain elevation data a scale must be exported alongside the image, and preferably as a separate image file. The use of rasters without elevation data is not advocated, due to reduced usability, and should only be provided where there is a specific requirement.

- **Rasters with elevation data** – rasters with elevation data can be referred to as Digital Elevation Models (DEM) or floating point rasters and are the preferred format with each pixel having a z value, as opposed to an RGB colour. Elevation data within the raster allows for the manipulation of colour scales, shading, etc. within GIS software and can aid interpretation with the ability to alter the image presentation depending on scale.

Whilst .tiff is the preferred output for both raster types, other industry standard formats such as .flt, are acceptable and when receiving data from a third party will depend on the specified data output of the commissioning organisation. Surfaces can also be exported in proprietary formats, however this is not encouraged for data that will be used outside of the organisation collecting the survey data.

5. Sidescan sonar

Sidescan sonar (often abbreviated to SSS) uses sound waves to obtain high resolution, two-dimensional, imagery of the seabed.

The original concept of sidescan sonar focused on military applications, such as the identification of mines and submarines. Sidescan sonar has developed steadily since its initial conception, including evolving from using analogue to digital signals, and from recording the data on paper, to recording digital files that can be used and distributed much more easily. As is typical with technology, the costs and sizes have decreased significantly meaning that many dive charter vessels are fitted with small, reasonably priced systems that provide relatively good data in relation to the price. Equally, technological advances have meant that data originating from survey-grade equipment have increased in resolution and quality.

5.1 Uses within archaeology

A sidescan sonar is an acoustic imaging device that produces a two-dimensional image of the seafloor (Figure 26). The data from sidescan sonar has many uses and can include seafloor characterisation, environmental monitoring, search and recovery, the identification of debris and obstructions, and the identification of material of archaeological interest.

Early iterations of sidescan sonar were used to locate wrecks such as the *Mary Rose* off the coast of Portsmouth. As data have increased in resolution and quality, the archaeological applications have increased to include identification of much smaller anthropogenic material on the seabed, as well as larger wrecks. Sidescan sonar now forms a core component of many archaeological surveys.

5.2 How it works

Sidescan sonars emit high frequency sound pulses (or pings) sideways and downwards in a vertical fan shape from transducers located along the side of the instrument. The sound travels through the water and is reflected back from the seabed to the transducer where the amplitude of the return is recorded, along with the time between signal transmission and receiving the reflected signal. This time is used to calculate the distance from the transducer to the reflector, known as the slant range.

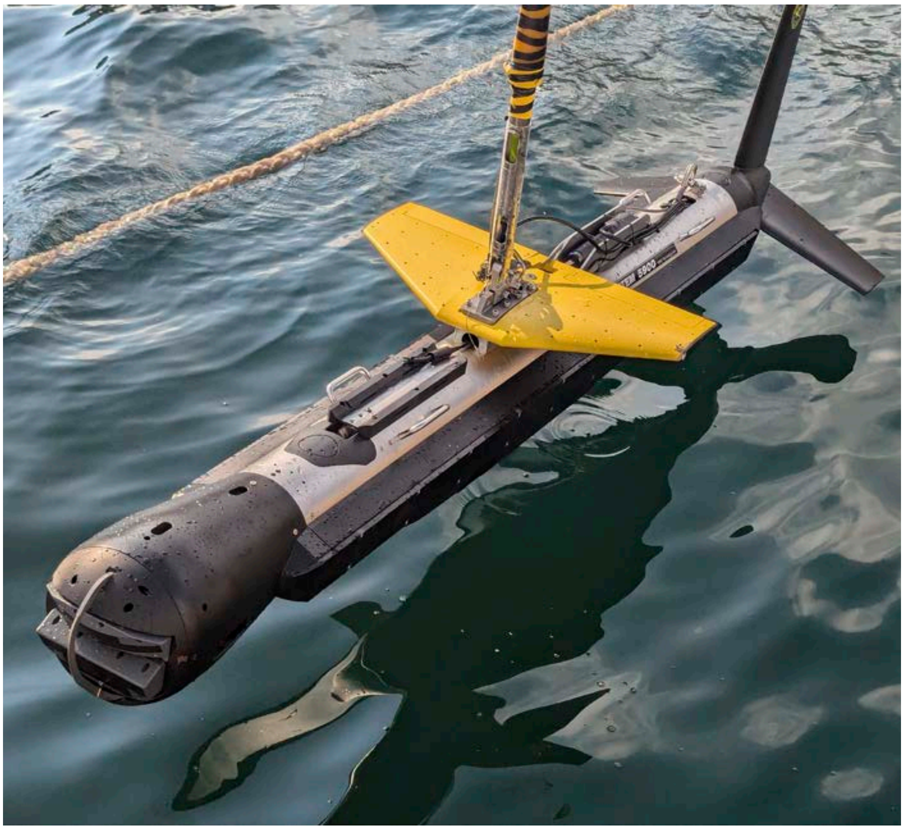


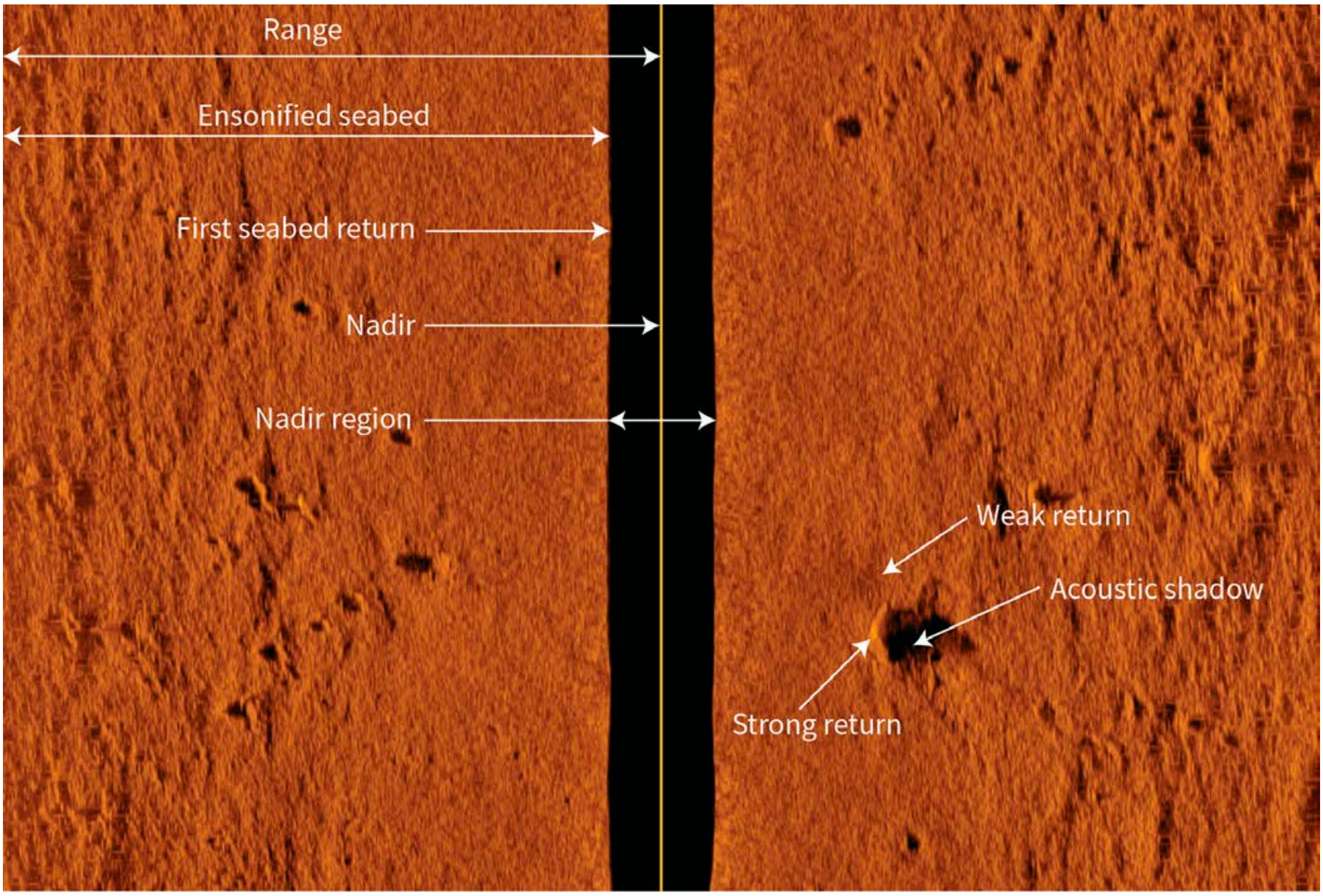
Figure 26:
Sidescan sonar.
© Klein Marine Systems, Inc

The amplitude of the returning signal, known as the intensity, is a function of the reflective properties (often characterised by the physical hardness) of the surface from which the sound is reflected. The reflected sound is known as backscatter.

Most commonly, the transducers are mounted on a towed device known as a towfish. They can also be mounted on, for example, remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), or directly onto a vessel.

The intensity is recorded, and each ping (or across track slice) is stitched together and displayed graphically using a graduated colour scale. The stitched together slices are viewed as a scrolling image known as a waterfall. It is common for most data collection software to be able to adjust colour scales and gains during data acquisition to enhance the visual representation of the data.

- **Hard surfaces**
  - Strong return
  - High intensity
- **Soft surfaces**
  - Weak return
  - Low intensity



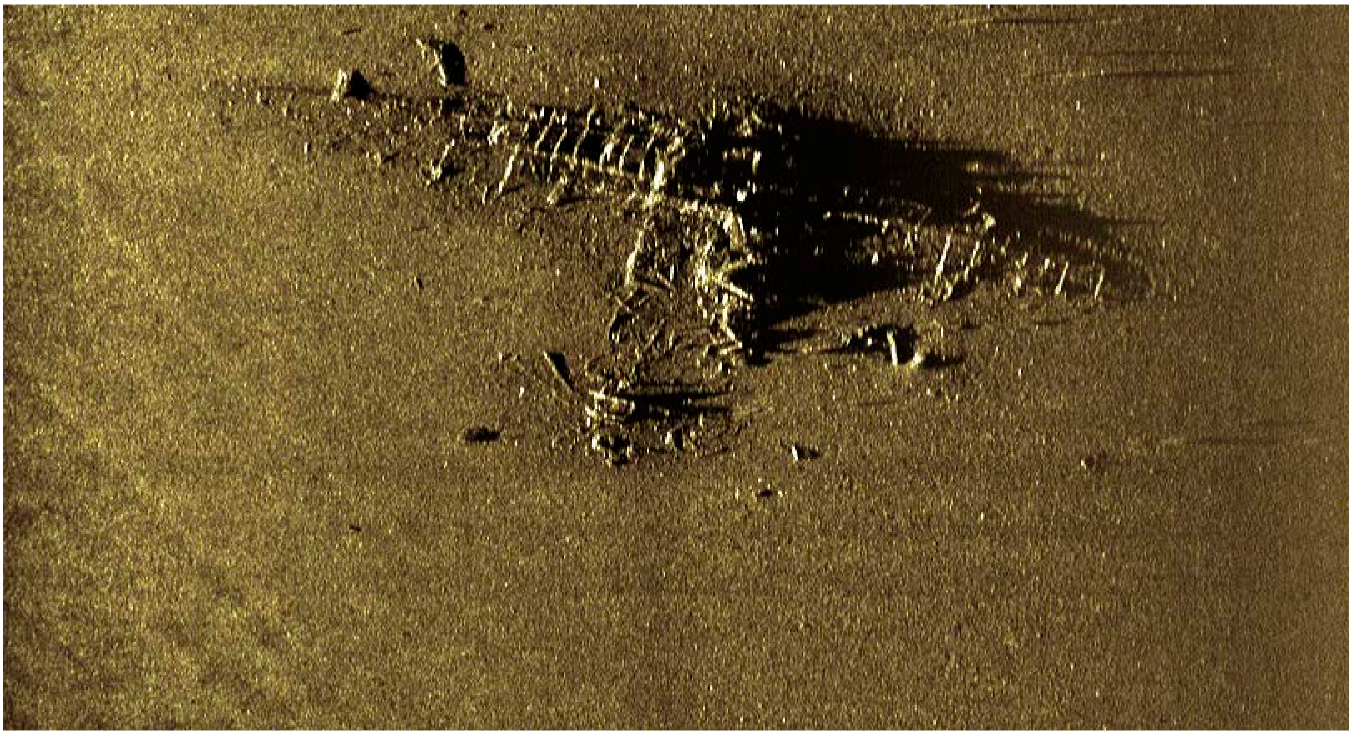


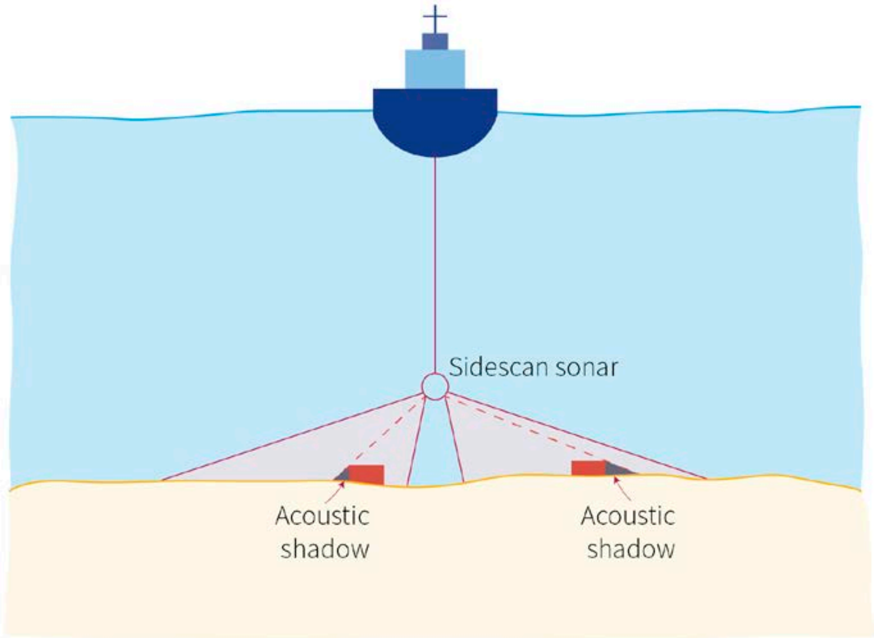
Figure 27: Above - sidescan sonar data as a waterfall. Below - sidescan sonar image of a crashed aircraft in the Sound of Mull. Noting that acoustic shadow is black.
© SOMAP, Annabel Lawrence, Mark Lawrence and Stuart Leather.

5.2.1 Acoustic shadow

Sound works in a very similar manner to light, in that solid objects will block sound, not allowing it to travel through. In the case of sidescan sonar, upstanding objects on the seabed will block the sound waves resulting in what is called acoustic shadow (Figure 28). Whilst acoustic shadow will cause areas of no data, this effect can highlight variations in topography and help visualise objects on the seabed, revealing their form and allowing the measurement of their length, breadth and height.

The height of the sidescan sonar above the seabed (known as the altitude), as well as the distance from an object, will affect the shape and dimensions of the shadow. Knowing the altitude of the sensor, the range to object, and the length of the shadow allows an approximation of the height of the object to be made.

Figure 28: Acoustic shadow.



5.2.2 Resolution

Simply put, for a given sample interval, the higher the resolution, the clearer and more detailed the resulting image will be. Generally, the higher the frequency, the greater the resolution, but also the greater the attenuation so the shorter the range. For example, a low frequency sidescan sonar of 50 to 100 kHz will collect data across a large area of seabed up to c. 500 m each side but at a low resolution, whilst a high frequency sidescan sonar of 400 to 900 kHz will collect data c. 100 to 50 m each side but at a high resolution.

The two types of resolution discussed in relation to sidescan sonar are ‘along track’ and ‘across track’ (Figure 29).

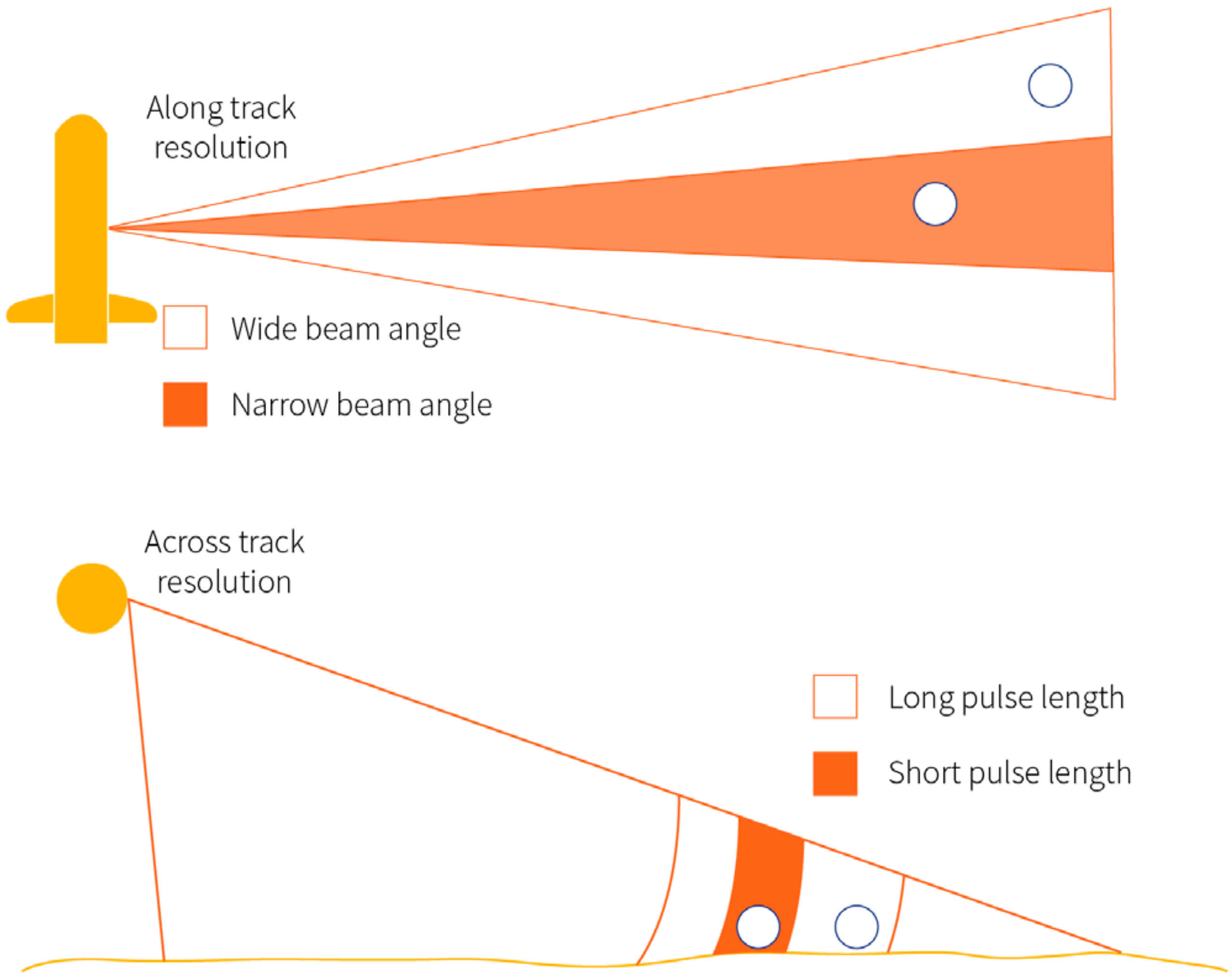


Figure 29: Along track and across track resolution.

- **Along track** resolution is the ability of the sonar to resolve two separate features that lie along the track of the sonar this is governed, in part, by the aperture (or beam angle) of the sonar, the higher the frequency, and the larger the transducer diameter, the smaller the beam angle. The smaller the beam angle, the smaller the beam width, which will result in a smaller area of seabed being ensonified with each ping, and therefore the smaller the distance between two features that can be measured whilst remaining separate in the data. The along track resolution decreases with distance from the transducer.

- **Across track** (or range) resolution is the ability of the sonar to resolve two separate features that lie perpendicular to the transducer. The primary factor that influences across track resolution is the pulse length. The higher the frequency, the shorter the pulse length. The shorter the pulse length the smaller the amount of seabed ensonified with each pulse, and therefore the smaller the distance between two features that can be measured whilst they remain separate in the data. The across track resolution remains almost the same across the range.

Ping interval (the time between each ping) will also affect survey resolution, the shorter the ping interval the more data acquired on a target at a constant speed. The data acquisition per target will also be determined by the vessel speed and line intervals so survey speed needs to be considered and planned to meet the objectives of the survey.

5.3 Limitations

Sidescan sonar is a very common technique and forms the backbone of many geophysical surveys due to its ability to identify small objects within the limits of its coverage, partially due to the angle at which the data is collected (grazing angle). When viewed in comparison with the other seabed imaging techniques, including multibeam bathymetry, there is significantly less ancillary equipment required reducing the mobilisation time. Sidescan sonar systems are often easier to operate than multibeam bathymetry systems and the processing workflow is also typically less time consuming and simpler. With systems available that are aimed at everyone from recreational boat owners through to professional surveyors it makes it a very versatile technique. However, there are significant differences in the data collected between the two systems and they should be considered complementary techniques and both may be required to be meet the objectives of the survey.

When considering a sidescan sonar survey, there are limitations that should be noted.

5.3.1 No data at the nadir

The nadir, the central point beneath the towfish, and the nadir region, the area either side of the nadir, are not covered during a single survey pass. The width of the nadir region is directly related to the altitude of the towfish, the higher the altitude the wider the nadir region. In order to have data coverage in this area the survey line plan must be equal to, or less than, the range.

5.3.2 Two-dimensional survey

Survey data originating from sidescan sonar are two-dimensional and are presented as a plan view image of the seabed. Whilst many sidescan sonar systems will record the depth and altitude at each ping, these data are not processed into a three-dimensional image and heights of features, or the presence of upstanding features, are identified through the assessment of acoustic shadow.

5.3.3 Positioning

Positioning techniques are discussed in Section 3. Being predominantly a towed technique, sidescan sonar is susceptible to external factors such as currents which can alter the calculated position of the sensor. Deeper water and large amounts of tow cable can further reduce the accuracy of layback calculations. To accurately determine the position an Ultra Short Baseline (USBL) system should be used.

5.3.4 Heading

The heading of the towfish, if not recorded accurately, can have an impact on the positioning of features. For example, towing the sidescan sonar perpendicular to the direction of the current will not only skew the position of the towfish in relation to the tow point (if not using USBL), but can also cause the towfish to twist or yaw, reducing the quality of the data and creating a rotational offset in the positioning of the data. The impact of heading can be offset through the use of an integrated compass; however, the accuracy of the compass should be noted.

5.3.5 Weather

Sidescan sonar is very susceptible to the effects of weather; Movement of the survey vessel, such as motion caused by waves, swell, or wind, can cause tugging on the tow cable which impacts the motion of the towfish. These movements will be visible as lines, striations, or noise within the data reducing the ability to undertake interpretation and assessment. Where the sidescan sonar is fixed to the survey vessel, either on the hull or on a survey pole, the effects of weather and vessel movement are exacerbated.

5.3.6 Obstacle avoidance

Depending on the depth of water, the amount of tow cable extending from the survey vessel can range from 10 m to over 100 m, with the towfish being towed a fixed distance above the seabed. Whilst the altitude of the towfish can be monitored, this is only possible at the location of the towfish making it susceptible to impact with the seabed where there are sudden changes in topography or where there are upstanding features such as wrecks. The potential for snagging on submerged hazards such as fishing gear, mooring chains, structures, etc. should also be considered.

5.4 Survey planning

Whilst survey planning, in relation to specifications, is covered in Section 12 the following should be considered during the survey planning process to ensure optimal quality of data:

5.4.1 Equipment selection

The equipment selected should be based on the ability to meet the objectives of the survey. Selection should take into consideration:

- **Range vs resolution**: in general terms the higher the resolution, the shorter the effective range. The objectives of the survey will determine whether wide area coverage or higher resolution data are the primary consideration.

- **Depth of water and environment**: for towed equipment, the deeper the water the more tow cable will be needed to ensure the correct altitude of the towfish, and typically the heavier the towfish required to ensure stability. At depths of water exceeding 25 m the additional weight of cable and drag through the water is likely to require the use of a winch to safely deploy and recover the towfish. Current, and/or poor sea states, may require the use of heavier equipment to minimise the impact to data quality.

5.4.2 Line planning

Survey line spacing should be planned to meet the objectives of the survey (Section 12), the predominant factors being the seafloor coverage percentage and the ensonification of the nadir region which will be determined by the usable range of the system. The useable range of the system will be determined by the frequency and the model of sidescan sonar. Where possible, lines should be planned to run:

- **In straight lines**, with turns being undertaken outside of the survey area. The quality of the resulting data will depend on the ability of the survey vessel to maintain straight lines during data acquisition. Data collected during a turn will compress data on the inside of the turn, and stretch data on the outside of the turn, as well as potentially causing the towfish to roll.

- **Parallel with the direction of the current** to minimise the impact of cross currents on the position, stability, or heading of the towfish. The ability of the survey vessel to maintain a straight line and follow line plans, will be reduced when traveling perpendicular to the current.

- **As far as possible parallel with the seabed topograph**y to avoid changes in altitude over the course of the line. In areas of shallow water, and along the coast, survey lines should be run parallel to the shore and working from deep to shallow to minimise the risk to the towfish. Shallow water surveys should aim to undertake the shallowest areas at the period around high tide.

- **At a constant speed**, the speed of the survey should remain constant, and will be determined by the aims of the survey and the ping interval of the system. A general speed of 4.0 knots can be used, noting that some systems can operate at much higher speeds. In some instances, it may not be possible for the survey vessel to maintain a consistent heading at a low speed, consideration should therefore be given to running all lines into the current to increase steerage.

- **At a constant altitude**, typically calculated as 10% of the range.

- **At a constant layback**, when the towfish is positioned using manual layback calculations the length of tow cable should remain constant on each line to ensure positional accuracy. However, large changes in topography may mean that adjustments need to be made. The use of USBL, and in some instances a cable out counter, may negate the need for a constant layback.

5.4.3 Calibration and testing

Prior to the commencement of the survey, calibration certificates (if applicable) of the equipment should be checked and it should be confirmed that they are in date. Calibration intervals will be determined by the manufacturer.

Prior to deployment, the system should be fully mobilised on deck and all inputs into the acquisition software confirmed. This can include GNSS, USBL, towfish, etc. The towfish should be confirmed as operational by performing a rub test, whereby the port and starboard transducers are rubbed in turn. When correctly connected, a signal will be visible in the acquisition software corresponding to the correct transducer.

Example minimum object detection size and positioning test

The determination of a correct minimum object detection size, and accurate positioning, can be achieved through the deployment to the seabed of an object of known dimensions, corresponding with the required specification, and at a known position, or the identification of an object within a multibeam bathymetry dataset, the size of which can be accurately measured. The following provides an example of a minimum object detection size and positioning test should it be required

The distances discussed will depend on the range of the sidescan sonar, for this example a range of 50 m will be assumed. The test should be undertaken under the expected survey conditions, including line direction and speed.

Two lines of data should be collected either side of the object at a fixed distance from the object (15 m) and in the same direction (e.g. north to south), two further lines of data should be collected at a fixed distance towards the edge of the range (40 m) and in the opposite direction (in this instance south to north). The process should then be repeated with perpendicular lines (i.e. east to west and west to east). From the resulting data the minimum object detection size can be confirmed both close to the transducers and at the outer edges of the range, as well as on both port and starboard channels. The plotting of the positions from all lines will allow for the identification of any offset errors, caused by tow point offset measurements, layback calculations, or USBL errors.

5.5 Survey outputs

Sidescan sonar data are recorded digitally during acquisition and depending on the manufacturer will either be saved as .xtf (eXtended Triton Format), which is considered the industry standard, or a proprietary format which will have a file extension unique to the manufacturer. Each survey line should be recorded individually, with acquisition stopped prior to the start of turns, and started following the completion of the turn. Data files will include, at a minimum, the acoustic data, the position and time of each ping and the heading.

It is important to understand where the position stored in the file relates to. Depending on how the system is set up this can be the GNSS antenna position, the tow point (defined through offsets in the acquisition software), or the position of the towfish calculated through layback, input during acquisition, from the tow point or recorded from a USBL system. Irrespective of the positioning system used, the length of cable out should be recorded separately, and outside of the acquisition software, for each line.

Files may also include;

- real time bottom tracking
- layback
- GNSS/or tow point position
- corrected position
- real time gain adjustments – to note, data should be exported with no gain adjustments applied. Whilst real time gain adjustments are useful for data visualisation during data acquisition, they should not be permanently applied to the export data.

5.6 Quality control

Prior to the commencement of data processing, the data should be subject to a process of quality control. The process should establish the quality of the data in relation to suitability for archaeological interpretation, and whether the archaeological objectives of the survey have been met. Whilst data supplied by a survey contractor, typically in relation to marine development, will have been through a process of quality control it is still important that quality control in relation to archaeological objectives is undertaken prior to any additional processing and interpretation. The results of the quality control assessment should be presented in the archaeological report (Section 14).

The quality control process should be ongoing. Issues with data may not become apparent until the interpretation phase, when each line (or block) of data is viewed individually. The process for quality control will depend on the workflow of the organisation undertaking the work, as well as the software being used, but at a minimum the following should be considered:

5.6.1 Data quality

- Do the data have any other issues which may affect archaeological analysis and interpretation? Do the data show signs of stretching or compression caused by poor weather, sea state, data being collected on turns, or the towfish not flying ‘smoothly’?

- Do the data show signs of interference from other equipment including from simultaneous surveys (i.e. multibeam bathymetry or sub-bottom profiler), vessel engines, or vessel equipment such as echo sounders?

- Does the quality of the data degrade towards the edge of the recorded range? Typically, this is caused by recording at a range greater than is appropriate for the frequency. Most commercially available software will allow importing, or trimming, of data to a percentage of the range. This will however affect the overall coverage of the data.

- Have the data been collected to a specification to achieve the minimum object detection size? In the absence of the survey of a test object of known size at varying ranges this can be achieved, to a certain degree, through the measurement of features, such as boulders, identified within the data. This should be undertaken across the full range of the data.

- Do the data have any other issues which may affect the archaeologist's ability to undertake archaeological interpretation? This can include, but is not limited to, the presence of natural or geological features including sandwaves, reefs, boulder fields, etc. that may either obscure the seabed through acoustic shadow, or for example in the case of boulder fields, obscure the presence of archaeological material or make interpretation difficult. Although less common, the presence of other factors, such as large shoals of fish and thermoclines, can all impact data quality and the ability to undertake archaeological assessment.

5.6.2 Positioning and navigation

- Whilst raw navigation data (including that embedded within the sidescan sonar data) will usually require some smoothing during processing, the general trend should be assessed for irregularities including large spikes, missing data, or notably wrong positions. This can include ensuring the data have been recorded in the correct coordinate reference system, both in relation to the area (i.e. correct UTM Zone) and as presented in the survey details.

- Have the correct layback and/or offsets been recorded? This can be achieved through the assessment of the position of features identifiable on multiple lines of data. Broadly speaking, large offsets along track indicate layback or tow point offset errors, and offsets across track indicate tow point offset errors. However, the effects of currents, both along track and across track, can cause positioning errors. Multibeam bathymetry data can also be used to establish errors in the positioning of sidescan sonar data through the co-location of seabed features.

5.6.3 Coverage

- Has the survey achieved the required coverage, both in term of the survey area and the coverage percentage? Most commercially available and industry standard processing software will plot the data alongside a shapefile of the survey area to enable an assessment of coverage. If this function is not available, the data should be exported as a georeferenced mosaic and assessed within a Geographical Information System (GIS). The assessment of coverage percentage can again be assessed within most processing software, with the results presented graphically and numerically. It is important to note that coverage should be determined following the assessment of data degradation at the extents of the range, and only the useable data included.

5.7 Processing and visualisation

Prior to processing, a backup of the raw, or 'as supplied', data should be created. Whilst most processing software will create a separate file for processed data (and thus not alter the source data) it is good practice to maintain an unaltered copy of the data.

It is important to understand the process of importing data, and any automatic adjustments that may be made by the software that will impact the resolution, or quality of the displayed image. The most common automatic adjustment is the down sampling of the across track resolution to reduce imported file size, commonly referred to as samples per channel. The options available will depend on the software, but it is important that no down sampling takes place during import as this results in a loss of across track resolution.

Different processing software will have different workflows, some with automated options and some with software specific processing features. Regardless of the software and workflow, the overarching process will be broadly similar. Caution, and an understanding of the process and the effect on the data are important when using automated processing features or those specific to individual manufacturers. While some features can result in visually pleasing images, they have the potential to reduce data quality and therefore reduce the appropriateness for archaeological interpretation.

The three main elements to data processing that should be undertaken prior to interpretation are as follows:

5.7.1 Navigation

Navigation processing ensures that data are positioned correctly, both relatively and absolutely. Whilst exported navigation data can be imported into most processing software, navigation data are most commonly contained within the sidescan sonar data and processed as a whole.

Navigation data consists of a position, heading, and time relating to each ping of sidescan sonar data. Recorded positions are affected by GNSS inaccuracies, as well as the heave, pitch, and roll of the vessel, and time gaps, which will not be translated to changes in position of the towfish. Hence the navigation data should be smoothed to provide a more accurate towfish track. The amount of smoothing required will depend on the quality of the navigation data, and the impact of factors discussed above.

Following import, the navigation data should be viewed and assessed for erroneous data points, which should be removed. The removal of erroneous data points will result in the interpolation of the navigation between last and first 'good' points. Depending upon the number of erroneous points there is the potential for the interpolation to create an artificial towfish track. Smoothing is undertaken following the removal of erroneous data points, the aggressiveness of the smoothing is altered by defining the number of pings between which smoothing is calculated. The number of pings should be kept as low as possible to reduce the creation of artificial towfish tracks.

Whilst less common on large scale surveys which typically use USBL, (and thus have corrected towfish positions) should it be required, layback (or cable out) and tow point offsets should be applied to each line of data and the resulting navigation corrected files assessed as per the quality control process. Wherever possible navigation accuracy should be assessed against multibeam bathymetry data.

5.7.2 Bottom tracking

Bottom tracking is fundamental to the effective, and accurate, processing and interpretation of sidescan sonar data. This process identifies the first acoustic return and thus the separation of the edge of the ensonified seabed and the nadir region. Accurate bottom tracking results in an accurate towfish altitude and thus more accurate georeferencing. It also forms the baseline from which gain and other corrections are applied and should be undertaken prior to the application of other processing. Bottom tracking can be recorded in real time during acquisition or applied during processing – often bottom tracking recorded during acquisition will require a certain degree of re-interpretation.

The processing of bottom tracking can be undertaken manually where the first acoustic return is identified and recorded along each line of data. However, most processing software can automate the process based on a range of user adjustable parameters, the accuracy of which is dependent on the quality of the data and the results should always be reviewed.

5.7.3 Gains and geometric processing

Raw sidescan sonar data display a marked difference in intensity between the first acoustic return and the far extents of the range, predominantly caused by signal attenuation and the non-linear effect of the signal. The options for normalising the image vary between processing software and the appropriateness of different processes will often depend on the data. The most common processes across most processing software are:

- **Beam Angle Correction (BAC)** – the application of BAC attempts to compensate for the decrease in return intensity with range by accounting for the beam angle. This is because backscatter intensity also varies with the angle at which the beams strike the seabed; beams at the far range tend to have a shallow angle and low intensity return.

- **Time Varying Gain (TVG)** – the application of TVG allows for the greater application of gain at the outer extents of the range and a lesser application of gain closer to the towfish as required to normalise the image. TVG is often based on a non-linear graph, or curve, which in its most basic form is user adjustable. It should be noted that TVG adjustments required may alter along each line of data which can have an impact to the overall presentation of the data. Most software will have an option for the automatic calculation and application of TVG along each line of data.

- **Speed correction** – the application of speed correction uses the recorded speed on the towfish (the survey speed), and the range, to present an image that maintains a 1:1 ratio along and across track.

- **Slant range correction** – the application of slant range correction is intended to adjust the geometry of the data, so that across track distances are more accurate. When the process is applied there is a noticeable difference to the presentation of the data in that the nadir region disappears and the port and starboard channels align.

Most processing software will have an option for normalising the data based on a range of user adjustable parameters, not only across track but along track and across the whole dataset, resulting in a largely standardised image. These automated processes often replace the need for other correction processes. The impact to data quality when using automated processing should be assessed as there is the potential for degradation of the displayed intensities masking changes in seabed composition.

Caution should be exercised when using various processing tools and filters that are available within most processing software. Whilst the use of such filters can produce visually pleasing images, incorrect use can affect the appropriateness of the data for archaeological interpretation.

5.8 Processed outputs

The culmination of data processing is the output of deliverables in relation to the Method Statement (Section 10). The workflow for the production of outputs will vary depending on the processing software but all industry standard software should have the following options. To note, not all may be useful or applicable to the project but are included here for completeness:

5.8.1 Mosaic

A sidescan sonar mosaic is the combination of the lines of data contained within the project into a single image. The production of a high-quality mosaic is dependent on high quality data processing to ensure a normalised image and with each line of data positioned correctly. The process of creating a mosaic is a straightforward process, however adjustments will generally need to be made to optimise the presentation and the final output.

- **Line choice** – the aim during the production of the mosaic is to present the data in as clear a way as possible whilst ensuring all the seabed is covered. Depending on the line spacing of the survey, it may not always be appropriate to include all lines of data within the mosaic. More lines create areas of overlap which can obscure features of interest or produce distracting seams. When choosing lines of data enough should be chosen to provide 100% coverage, including covering the nadir region. Priority should be given to using the best quality lines.

- **Line order** – following the selection of the lines making up the mosaic, the line order should be adjusted to bring to the front the lines that have the clearest image, or data showing the features of interest most clearly. The effects of acoustic shadow and the decrease of resolution with range are likely to be the predominant factors to consider. The data should be ordered in such a way as to cover the nadir region across the extents of the mosaic where the data coverage allows. Where a single line of data is split into several files due to length or file size, these should be displayed on the same level. Most processing software will create the mosaic based on the order in which the files were imported, or the order in the file tree.

- **Mosaic overlap method** – the default option for the creation of a mosaic is typically to overlap adjacent lines, and whilst not always the most visually pleasing option this will give the best representation of the data as no adjustments are made. Other options will result in additional processing to composite and visualise data from multiple lines. Two main issues arise with relation to archaeological interpretation unless the positional accuracy and data quality is exceptional. Firstly, features on the seabed can become blurred. Secondly, the mosaic can display the same feature in multiple positions, particularly with smaller features and where positioning errors exceed 1.0 – 2.0 m. The three primary methods of mosaic production are detailed below, although overlapping the data is generally the most appropriate method.

  - **Overlap** – sometimes referred to as coverup. The data are presented in a specified order, the topmost lines obscuring the lines beneath them. This should be the default option during the creation of mosaics.

  - **Transparency** – sometime referred to as shine through. The transparency of the data is adjusted so that the bottom most lines are visible through the lines above them, usually the transparency can be adjusted to create the desired effect. This option has the most potential for displaying a feature in multiple positions where there may be small differences in position.

  - **Average** – different options can exist for how the average is calculated, but effectively the software will create an average value for each overlying pixel and display this value. This option creates very normalised looking images and can be effective when assessing a wide area for features such as seabed sediment composition, or geological features. However, the averaging of values will result in the loss of detail and can, in some instances where there may be small differences in positions, result in features no longer being visible.

5.8.2 Export options

Following completion, the mosaic will need to be exported for use within GIS software or presentation in the survey report (Section 14). Commonly this will be in the form of a georeferenced .tiff file (preferred), but options are generally available for other image formats or .pdf. Consideration must be given to the intended use of the mosaic, and the required resolution, as the higher the resolution the larger the file size. When dealing with large areas, file sizes can be significant and sometimes beyond the limits of all but the fastest computers. To minimise the creation of unnecessarily large files, the resolution of the output should not exceed the maximum resolution of the input data. The export resolution is typically defined in pixels per meter (ppm), for example 10 ppm would equate to a 0.1 m resolution and 1.0 ppm would equate to a 1.0 m resolution. For general use, between 2.0 ppm and 4.0 ppm (0.5 m and 0.25 m resolution) provides a good balance between resolution and file size. Where the resulting file size of the mosaic would be unmanageable, options exist to export the image in blocks, known as tiles.

5.8.3 Processed lines

Following the completion of processing and the creation of the mosaic, the processed lines can be exported. Lines should be exported as .xtf files and clearly identified as processed data.

Processed lines can also be exported individually as images in a similar manner to the mosaic. Although there is generally little requirement to export line images for archaeological assessment, the smaller image size allows for the images to be exported at higher resolution and will display the whole of the track without being obscured by overlapping lines. Where lines are exported as images they should retain the same file name as the original data.

5.8.4 Tracklines

Tracklines of the towfish and/or the vessel can be exported to a GIS to show the extents of the survey, measure line spacing, and compare the actual survey with the planned survey. Tracklines should be exported as industry standard .shp files.

6. Magnetometry

Magnetometry differs from the other techniques discussed within this guidance. It does not use acoustics to collect data, is passive (it does not transmit a signal from which the return is analysed), it does not replicate the seabed or features on it, and the data collected are not directional unlike with acoustic techniques. Magnetometers are used to identify and plot, the presence of ferrous materials (those containing iron (Fe)) that may be located on or beneath the seabed.

This section of the guidance is intended to provide an overview of the technique, and the application within marine archaeology. Magnetometry at its simplest requires limited equipment but there are a significant number of variables that can have a detrimental effect to the resultant data. Camidge et al (2010) and Holt (2019) provide comprehensive analysis, and instruction, relating to the use of magnetometers for the identification of archaeological material on the seabed and the processing of data.

6.1 Uses within archaeology

Within marine archaeology magnetometers are used to identify the location of ferrous material (anomalies) that may lie on or beneath the seabed. The data can also be used to calculate estimations of mass, dimensions, and burial depth. Whilst magnetometers cannot provide a visual interpretation of the actual anomaly, they can identify areas of potential and when used alongside visual techniques such as multibeam bathymetry, sidescan sonar and sub-bottom profiler can aid interpretation.

Magnetometer survey is often a requirement to minimise the risk of interaction with potential unexploded ordnance (pUXO).

6.2 How it works

At a basic level, a magnetometer will take regular measurements of the strength of the Earth's magnetic field. Variations in the magnetic field strength caused by the presence of ferrous material will alter the magnetic field and these changes can be plotted to identify the location. Magnetometers used in the marine environment are usually towed due to a requirement to ensure the sensor is not subject to external ferrous influences, however their use on ROVs is increasing.

Figure 30: Magnetometer. © Marine Magnetics Inc.

6.3 Types of magnetometer

Technologies used within magnetometers vary, and the working principles are beyond the scope of this guidance, however three are typically used in the marine environment, each with their benefits and limitations:

- **Proton** – the proton, or proton precession magnetometer, is considered an entry level technology in archaeological work. Low costs have enabled their use by recreational dive boats, wreck enthusiasts, and avocational archaeological groups. Whilst still in production, they are typically limited in their low sensitivity (c. 1.0 nT/ √ Hz) and low update rates (c. 0.5 Hz or one reading every two seconds). Proton precession magnetometers are so named as they rely on the precession of protons to measure the Earth's magnetic field.

- **Overhauser** – the Overhauser magnetometer has largely replaced the proton magnetometer for archaeological survey outside of avocational or recreational groups. Whilst more expensive than the proton magnetometer, they are still typically affordable and benefit from higher sensitivity (c. 0.01 nT), higher absolute accuracy (c. 0.1 nT/ √ Hz), and higher cycle rates (c. 5.0 Hz or five readings every second). For general survey requirements they also have an advantage over the caesium vapour magnetometer in that surveys can be undertaken in any direction.

- **Caesium Vapour** – the caesium vapour magnetometer is the industry standard in relation to the location and identification of potential unexploded ordnance (pUXO) due to higher sensitivity (c. 0.004 nT / √ Hz) and significantly higher update rates (upwards of 20 Hz or 20 readings per second), however the absolute accuracy is less than the Overhauser magnetometer (<2.0 nT). They are however slightly more involved to set up and consideration needs to be given to the angle of sensors in relation to the Earth's magnetic field.

Due to the higher performance of Overhauser and caesium vapour magnetometers, the use of the proton magnetometer is not generally recommended for archaeological survey unless no other technology is available.

6.3.1 Earth's magnetic field

In order to understand the working principles of the magnetometer it is important to understand the Earth's magnetic field, and the localised impact of target material on it. The easiest way to visualise the Earth's magnetic field is by thinking of the Earth as a large bar magnet with its resulting magnetic field (Figure 31).

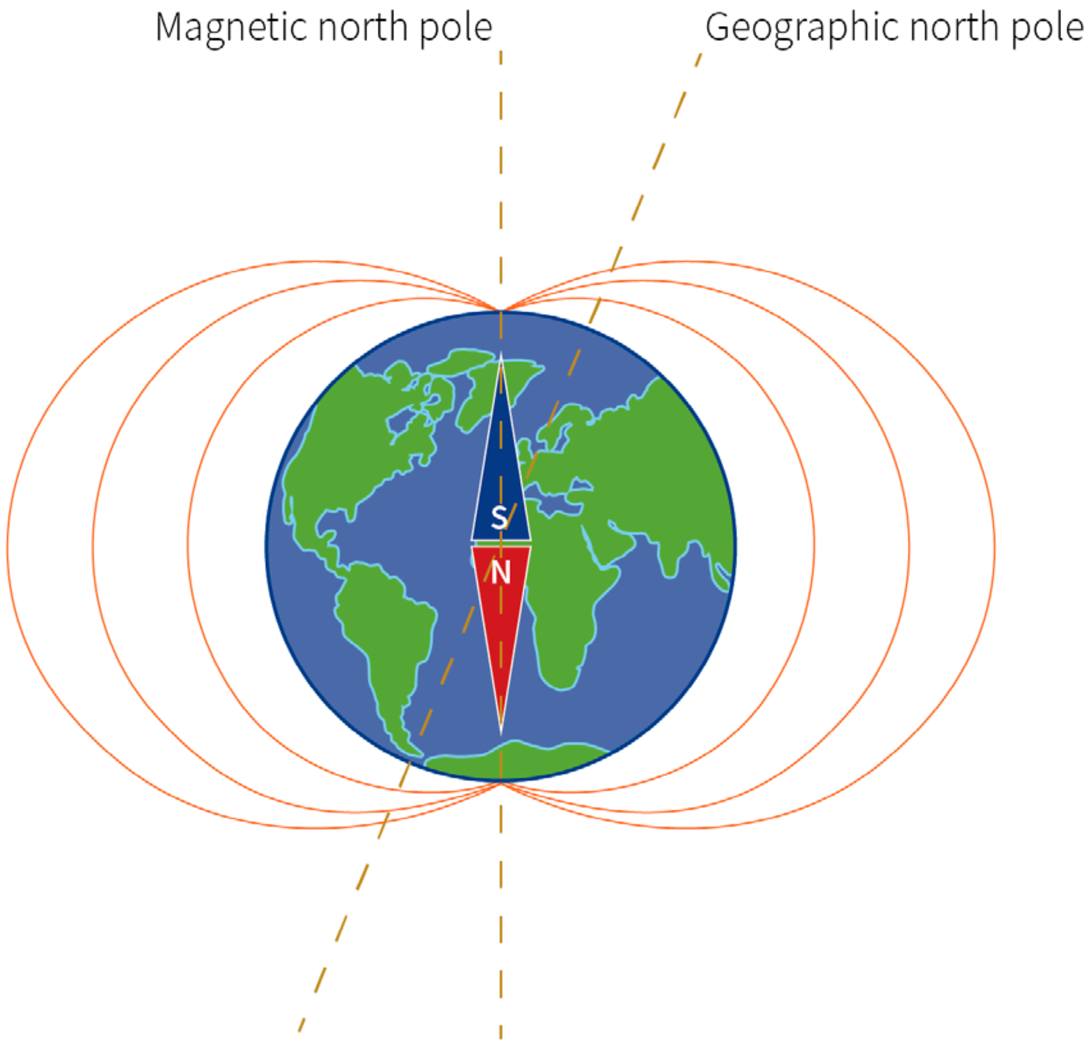


Figure 31: Earth's magnetic field.

The strength of the magnetic field is measured in Tesla (and usually expressed in nano Tesla, nT as variations can be very small). Field strength can also be measured in gammas which are equivalent to one nT. The strength of the magnetic field will be different depending on where in the world the survey is being undertaken. Whilst the strength of the Earth's magnetic field changes across the surface of the Earth, on a local scale they are unlikely to be noticed (Figure 32).

The Earth's magnetic field is also affected by changes in the upper atmosphere, solar storms and large ferrous objects, which may include the towing vessel or shipwrecks.

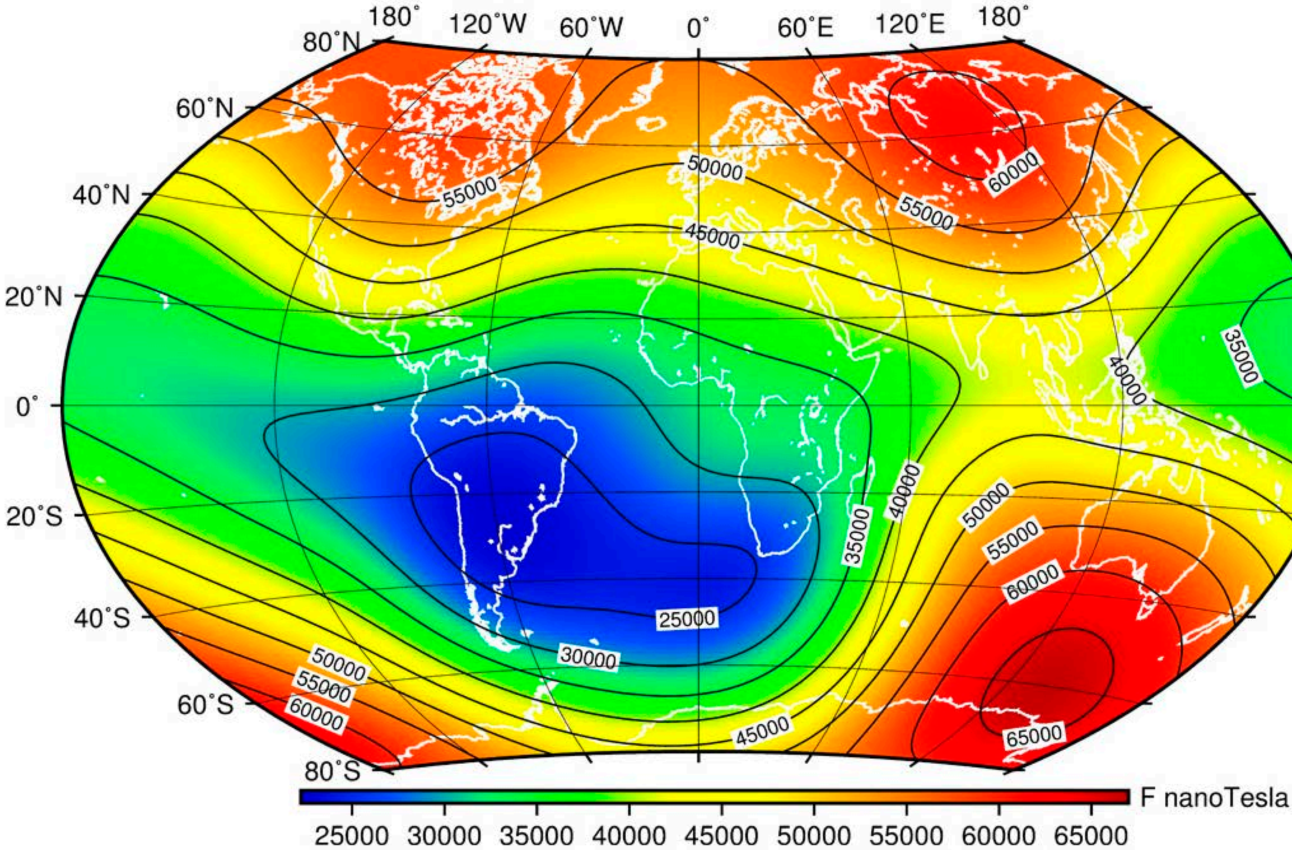


Figure 32: The Earth's background magnetic field. © BGS

6.3.2 Ferrous material

Non-ferrous material may have a remanent magnetisation that is influenced by the physical properties and shape of an object. Remanent magnetisation and increase in the magnetic susceptibility of soil is the basis of archaeological magnetometer surveys on land but is less relevant offshore. Ferrous material has magnetic properties that will locally distort the Earth's magnetic field, increasing and decreasing the strength, or amplitude, around it, the distance and amplitude depending on the mass of material. The changes in amplitude are measured by the magnetometer and recorded with each cycle. Whether the change in amplitude recorded by the magnetometer is greater or lesser (monopole) or both (dipole) than the mean of the Earth's magnetic field at that time and location will depend on where the magnetometer travels in relation to the material (or more accurately where in relation to the distortion of the Earth's magnetic field). Assuming the magnetic properties of the material are uniform, readings across a feature will produce a monopole anomaly, while readings along the length of a feature (passing over each pole) will produce a dipole anomaly. Hence the shape of an anomaly is determined by the orientation of a feature and the direction of travel over it. In addition, dipolar responses are anisotropic with respect to the Earth's magnetic field, giving a dipole reading in the north-south direction and either a monopole or symmetrical dipole in the east-west direction.

Whilst for individual items the results are generally likely to be coherent (i.e. a monopole or dipole), large concentrations of material, such as shipwrecks, or those made up of multiple components are likely to create a more complex anomaly (Figure 33). The complexity of the resulting data will typically depend on the specification of the survey.

The amplitude recorded by a single magnetometer will always be inclusive of the Earth's magnetic field strength, or background at that time and location. Where the background is 45,000 nT a measurement of 45,015 nT would indicate a 'positive' variation of 15 nT, a measurement of 44,075 would indicate a 'negative' variation of 25 nT (negative in this context being relative to the Earth's magnetic field). Monopole amplitudes are measured from the background to the peak with the position taken from the position of the peak. Dipole amplitudes are measured from the positive peak to the negative peak (PtoP), and the position measured from the intersection with the background between the peaks. For complex anomalies, where they cannot be separated, amplitude measurements are taken from the largest positive to the largest negative peaks, and the location in the centre of the overall anomaly. The dimension of the anomaly is recorded from the start of variation to the end of the variation.

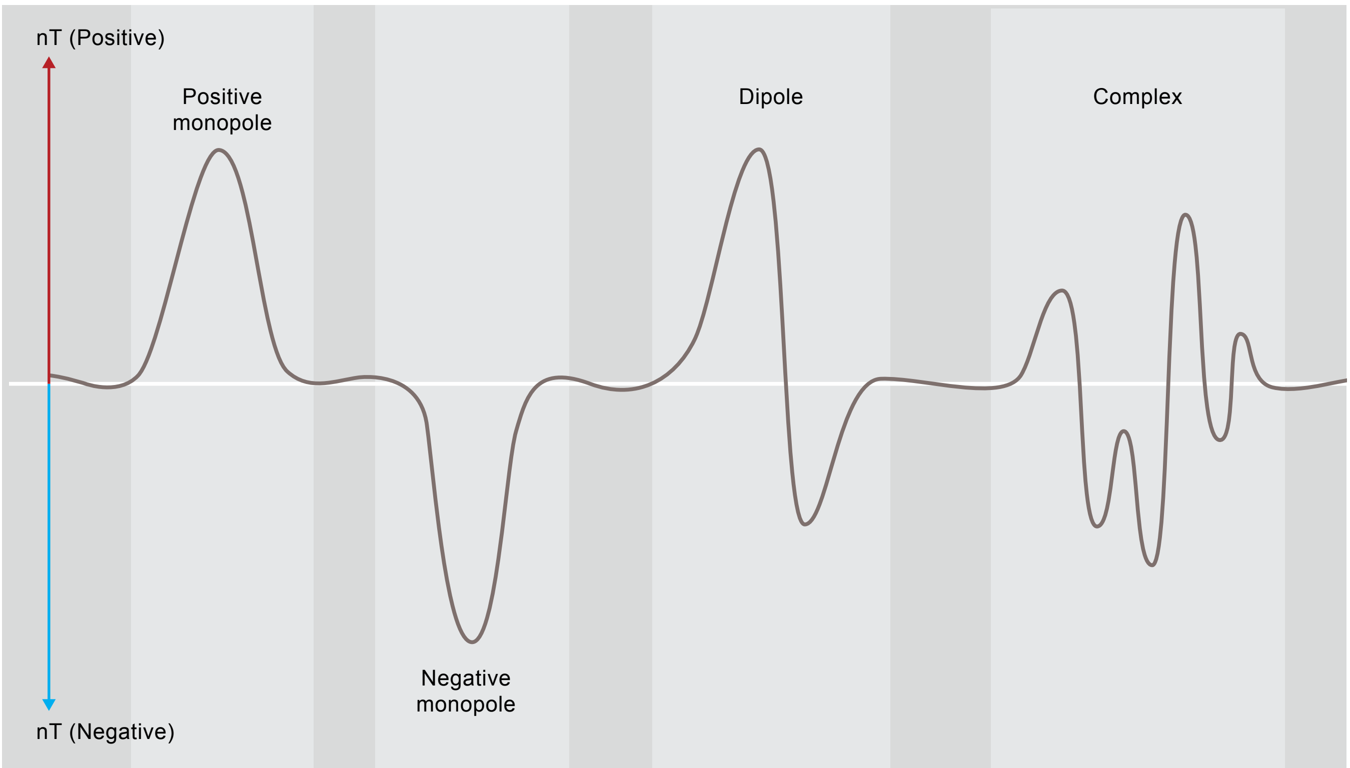


Figure 33: Types of magnetic anomaly.

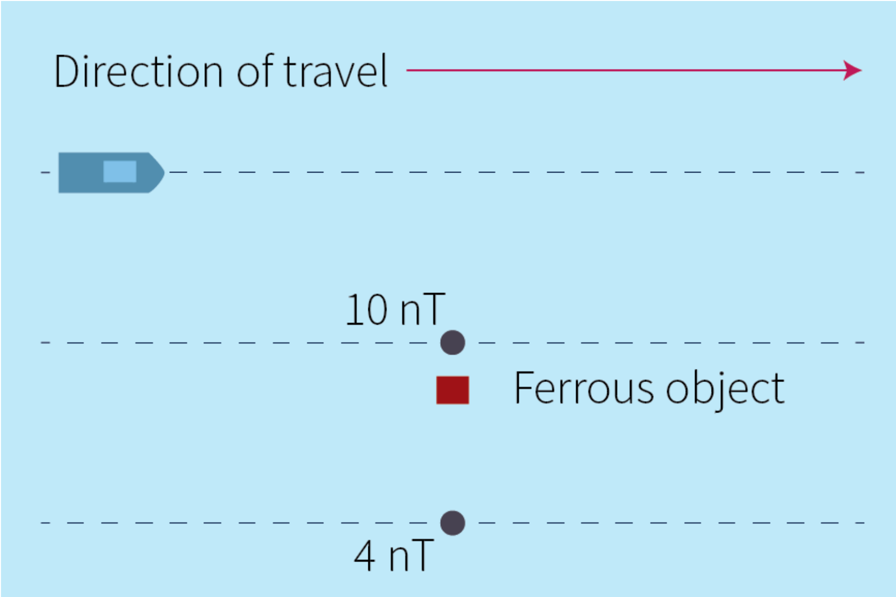


Figure 34:
Resolving magnetic anomaly positions.

6.4 Positioning of anomalies

The amplitude recorded by the magnetometer is not a direct measurement of mass, but a measurement of the variation in the Earth's magnetic field. As the distance between the magnetometer and the feature increases, the variation in the Earth's magnetic field decreases sharply with distance[3]. Therefore (and simplified), a magnetometer towed over a large ferrous object at a distance produces an anomaly similar to that produced by a small ferrous object much closer to the sensor.

The above assumes a single line of data being collected. However, the position of an anomaly can be refined through the collection of adjacent lines of data. For example, assuming three parallel lines of data 20 m apart with an anomaly of 10 nT identified on the centre line, if the anomaly is not visible on either the port or starboard line it can be broadly assumed that the anomaly lies within a distance of up to 10 m perpendicular to the direction of travel, either to the port or starboard of the centre line. Should an anomaly of 4.0 nT be identified on the starboard line, and perpendicular to the anomaly on the centre line, there is the potential for the anomalies to be related to the same feature with it being located between the two lines, and due to the higher amplitude closer to the centre line (Figure 34). However, it cannot be guaranteed that the two anomalies relate to the same feature. Closer line spacing will result in a higher confidence and the ability to resolve positions more accurately.

Manual calculations can be made to approximate the position of an anomaly identified on two adjacent lines, typically based on the application of Hall's Equation. These are discussed in Camidge et al (2010) and in Section 6.7.1 below. However, some processing software will undertake these calculations automatically.

3 Assuming a compact dipole feature, signal will decrease at a rate of 1/distance^3. With complex feature shapes, the signal will decrease anisotropically, but always very sharply.

6.5 Resolution

Resolution (or sensitivity) can be defined as the smallest difference in field strength measurable by the instrument. This is related to the sensitivity of the instrument and is set by the manufacturer.

The resolution is also influenced by the sampling interval (the number of readings, or data points, over a given distance along the track). The higher the sampling interval, the more data points that will be collected over a feature providing a more accurate representation of the anomaly size and position and therefore lower the chance of a feature falling between data points and not being identified.

6.5.1 Update rates and vessel speed

The update rate of the magnetometer is the frequency at which readings can be taken, measured in Hz with one Hz equal to one reading per second. The update rate is therefore directly related to the resolution of the resulting data. Technological differences in the way different types of magnetometer function will impact the update rate with proton magnetometers having the slowest update rate (c. 0.5 Hz) and caesium vapour magnetometers having the fastest (c. 20 Hz). The vessel speed will also affect the sampling interval as the faster the magnetometer is travelling the greater the distance between readings. The combination of update rate and vessel speed therefore determine the sampling interval. For example, assuming a survey speed of 4.0 knots (approximately two meters per second), the following sampling intervals can be achieved at the corresponding update rates:

- Proton magnetometer @ 0.5 Hz – 4.0 m
- Overhauser magnetometer @ 4.0 Hz – 0.5 m
- Caesium Vapour Magnetometer @ 20 Hz – 0.1 m

As can be seen, and without a significant decrease in survey speed, a proton magnetometer will only make one reading every 4.0 m producing very low resolution data. This alone typically excludes the use of the proton magnetometer for archaeological survey, with the exception of the identification of sites containing a significant amount of ferrous material. The faster the update rate, and the slower the vessel speed, the greater the ability to detect a smaller mass of ferrous material. For each magnetometer type increases in update rate reduce the sensitivity and increase noise within the data and therefore a balance must be achieved to meet the requirements of the survey specification (Section 12).

6.5.2 Accuracy and sensitivity

Alongside the update rate, two further specifications are also typically presented with equipment specifications and are measured in nT, these are:

- **Sensitivity** – this is a statistical calculation based on repeated measurements as a measure of how sensitive the magnetometer is to relative variations in the Earth's magnetic field. The proton magnetometer typically has a sensitivity of 1.0 nT/ √ Hz, meaning it is only able to detect changes greater that 1.0 nT. Overhauser and caesium vapour magnetometers have the highest sensitivities and are able to detect changes of less than 1.0 nT. In both systems, sensitivity will decrease with an increase in update rate (but still a much higher level than the proton magnetometer). A lower sensitivity will decrease the ability of the magnetometer to detect small anomalies.

- **Absolute Accuracy** – the absolute accuracy of the magnetometer is the ability of the magnetometer to accurately present the absolute value of Earth's magnetic field.

6.5.3 Noise

Noise is the recording of data points that do not represent a real or accurate measurement of the Earth's magnetic field. Noise typically relates to data points that are at the lower end of variations above the background and can mask smaller anomalies within the data. Readings that are abnormally high or low are referred to as spikes. Spikes in the data are less common and in most instances are easily removed during processing.

Noise can be caused by the magnetometer and its associated equipment, predominantly the power supply, but the quality of the magnetometer itself will have a bearing on the noise produced. Other source of noise can include using a low altitude towfish in an area of igneous geology, an area of increased dumping of ferrous rubbish, magnetometer update rate and non-linear movement of the magnetometer caused by either the towing method, the effects of weather and sea state and the survey vessel.

6.5.4 Masking

Masking within magnetometer data is caused when the size or shape of one anomaly masks the variations that are caused by smaller anomalies within close proximity. Within archaeology this is typically a consideration whilst attempting to identify outlying debris around iron or steel wrecks.

6.5.5 Geology

Magnetometers record variations in the Earth's magnetic field caused by magnetic material. This includes metallic iron and steel and a number of minerals with magnetic properties (predominantly iron oxides). In addition, materials can be magnetised by heat, chemical action or sedimentological processes known as remanence. Thermoremanence is an important principle in magnetometer surveys on land but is less relevant in marine magnetometry. The impact of geological materials and remanent materials on magnetometer data at sea will vary dependant on the type, iron content, and distribution of the geological features. It can present as small variations in the background over a wide area, or more significant variations potentially causing masking, over a more localised area.

6.5.6 Diurnal variation

Diurnal variation is the short term changes in the Earth's magnetic field due to the rotation of the Earth and the orientation in relation to the Sun. The effect is a variation in the background which can be noticeable when surveys are undertaken over the course of a day, or on different days. Similar short term variations can be caused by solar flares and electrical currents in the ionosphere.

Processing of the data can filter, or remove, the effects of diurnal variation on the background. In some instances, the deployment of another magnetometer in a fixed position near the survey site, typically onshore, to record the background and any variation can be used. The resultant variations caused by diurnal variation can then be removed from the survey dataset.

6.5.7 External influences

As magnetometers are susceptible to fluctuations in the Earth's magnetic field all around them, data are susceptible to the influence of external material which can affect the quality of the survey data. Influences can be from ferrous materials being inadvertently used as part of the coupling system, or more significantly from the survey vessel. Most vessels used in magnetometer survey will have ferrous material in some form, either from the construction, or within engines and fixtures and fittings. The amount of influence this will have on the magnetometer will depend on the mass, and the distance from the magnetometer, and therefore dictates the distance the magnetometer needs to be towed behind the survey vessel. The overarching guidance is that the magnetometer should be towed at a distance greater than the influence of the survey vessel. In practise this may be between 2.5 and 4.0 ship lengths behind steel hulled vessels, with the required distance behind nonferrous hulls being less but depending on the mass of ferrous material onboard.

6.6 Limitations

Magnetometer survey used to be a very common technique within recreational diving and exploration due to the low cost of the proton magnetometer in relation to acoustic techniques, and many shipwrecks were identified as a result. With the increasing availability of low-cost acoustic techniques, recreational use of magnetometers has decreased significantly. Within marine development their use is prevalent, especially prior to construction, to aid in the identification of pUXO and it forms a core component of the pre-construction data collected for offshore wind farms.

When considering a magnetometer survey, the following limitations should be noted:

6.6.1 Interpretation

The magnetometer does not give a visual representation of the actual object. Assuming the successful removal of the effects of geology, identified anomalies are likely to be of anthropogenic origin. However, using magnetometer data alone does not allow for the interpretation of whether the material is of archaeological interest, only that is has ferrous contents. There are exceptions and assumptions that can be made but a program of further investigation would be required to establish the origin of the anomaly if only magnetometer data are available.

6.6.2 Identifiable material

The only material a magnetometer can detect is that with a ferrous content, limiting the detection of certain material that may be of archaeological interest, including but not limited to wooden shipwrecks and aircraft components, which are typically aluminium. Whilst a proportion of wooden shipwreck assemblages will include some ferrous material such as guns, anchors, structural components, and cargoes, there are many examples where this is not the case and therefore the wreck will not be identifiable in the data. Aircraft wrecks are similar. Typically, construction is of aluminium with some steel structural elements, fixtures, and engine components which whilst identifiable will produce only a small anomaly in relation to the overall size of the aircraft. Where wooden wrecks and aircraft are broken up and distributed across the seabed, the concentration of ferrous material in one place is reduced. The result is a number of smaller anomalies spread across a wide area. It is theoretically possible that a magnetometer could detect a large non-metallic, ferrimagnetic object such as a cargo of bricks, but instances will be rare.

6.6.3 Positioning

Positioning techniques are discussed in Section 3. As a towed technique magnetometer surveys are susceptible to external factors such as currents which can alter the sensor position when compared to the expected position determined through layback calculations. Deeper water and large amounts of tow cable can further reduce the accuracy of layback calculations and with no visual references on the seabed the accuracy can be difficult to determine. To accurately determine the position an Ultra Short Baseline (USBL) system should be used. Additionally, towing the magnetometer perpendicular to the direction of the current will not only skew the position of the magnetometer in relation to the tow point, but can also cause the magnetometer to roll and yaw, introducing noise into the data.

6.6.4 Weather

Magnetometer data are susceptible to the effects of weather. The movement of the survey vessel, such as motion caused by waves, swell, or wind, can cause tugging on the tow cable which impacts the motion of the towfish. These movements impact the quality of the data and introduce noise into the data reducing the ability to undertake interpretation and assessment. Where the magnetometer is towed close to the surface, wave motion will have a direct impact on the towfish.

6.6.5 Obstacle avoidance

Depending on the depth of water the amount of tow cable extending from the survey vessel can range from 30 m to over 300 m, with the magnetometer being towed a fixed distance above the seabed. Whilst the altitude of the magnetometer can be monitored on some systems, this is only possible at the location of the instrument itself, making it susceptible to impact with the seabed where there are sudden changes in topography or where there are upstanding features such as wrecks. The potential for snagging on submerged hazards such as fishing gear, mooring chains, structures, etc. should also be considered.

6.7 Survey planning

Whilst survey planning, in relation to specifications, is covered in Section 12 the following should be considered during the survey planning process to ensure optimal quality of data, and suitability for further interpretation.

6.7.1 Minimum object detection size and line planning

The most important parameter when planning a magnetometer survey is establishing the minimum size of object that is required to be reliably detected. The minimum object detection is the minimum mass (kg) that is required to be reliably detected by the magnetometer, at a given amplitude (nT) and will depend on the aims of the survey. This will depend on the material to which the survey relates and could be based on a requirement to identify a shipwreck of 100 tonnes, or an anchor of 500 kg. The minimum object detection will depend on the distance of the magnetometer from the seabed, and therefore the object.

Holt (2019) calculated the maximum detection distances for a range of common ferrous objects typically found within the archaeological record. The distances were based on the use of the Hall Equation and assume a minimum reliable anomaly detection amplitude of 5.0 nT. The value of 5.0 nT is considered a standard measurement within the marine environment and takes into consideration the inherent noise within the data. However, where the effect of noise is minimal anomalies as low as 3.0 nT may be able to be identified with confidence. For survey planning purposes, 5.0 nT should be used as a minimum value when calculating the minimum object detection.

The Hall equation:

The Hall equation is a quantitative method of calculating the amplitude of a magnetic anomaly based on an object's size, weight, shape and distance from a magnetometer. The equation can be expressed as

$$\Delta M = 10.\frac{a}{b}\frac{w}{d\text{\textasciicircum}3}$$

Where ΔM is the amplitude of the magnetic anomaly (in nT), a is the length of the object (in m), b is the width of the object (in m), w is its weight in kilograms and d is the altitude of the sensor above the target (in m).

In archaeological prospection, the equation is most useful when rearranged to calculate the mass of a given magnetic anomaly:

$$w = \left(\frac{\Delta M}{10} \cdot \frac{a}{b}\right) d^3$$

In the case of an unknown object, the physical size of the object is unknown and so for simplicity it can be assumed to be spherical. The ratio of would be 1, leaving the equation as

$$w = \frac{\Delta M}{10} . d^3$$

It is important to note that the distance in this equation represents the distance from sensor to object, not the altitude of the sensor above the seabed nor the distance between the object and the survey line.

The Hall equation makes a number of assumptions as noted above, meaning the equation as presented here will only give a rough approximation of the mass of any feature.

Table 6: Example detection distances (at 5 nT), reproduced from Holt, 2019.

Object	Mass	Distance
20lb round shot	9 kg	2.7 m
32lb round shot	14 kg	3.0 m
Small anchor	100 kg	6.0 m
Large anchor	500 kg	10 m
Small iron gun (9 lb)	1,250 kg	14 m
Medium iron gun (18 lb)	2,000 kg	16 m
Large iron gun (42 lb)	3,250 kg	19 m
Iron ballast	10,000 kg	27 m
Small iron wreck	100,000 kg	58 m
Iron wreck	100,000,000 kg	126 m

There are a few points to note with the minimum object detection and maximum detection limits in relation to line planning, and it must be understood that all calculations are theoretical, and contingency should be applied. Using a 500 kg object as an example, the magnetometer would record a 5.0 nT variation at a distance of 10 m, which is the detection limit. Past this distance either a lower variation or a null value would be recorded. Closer than this distance and a higher variation would be recorded.

When using the maximum detection distance, it is not sufficient to use the value as the altitude for the magnetometer as the distance to the seabed will increase with perpendicular distance from the magnetometer. Instead, a practical altitude should be used, generally not more than 6.0 m for archaeological survey, and the seabed coverage calculated where 500 kg of material can be detected at an amplitude of 5.0 nT or greater.

$\text{Coverage}^2(\text{m}) = 2.\sqrt{(\text{Slant range Minimum Distance}^2(\text{m}) - \text{Altitude}^2(\text{m}))}$

In the example in Figure 35, a 6.0 m altitude has been used for the magnetometer which would allow the detection of a 100 kg object directly below the magnetometer. With a maximum range of 10 m to detect a 500 kg object this will equate to a distance on the seabed of 8.0 m from directly below the magnetometer to the object.

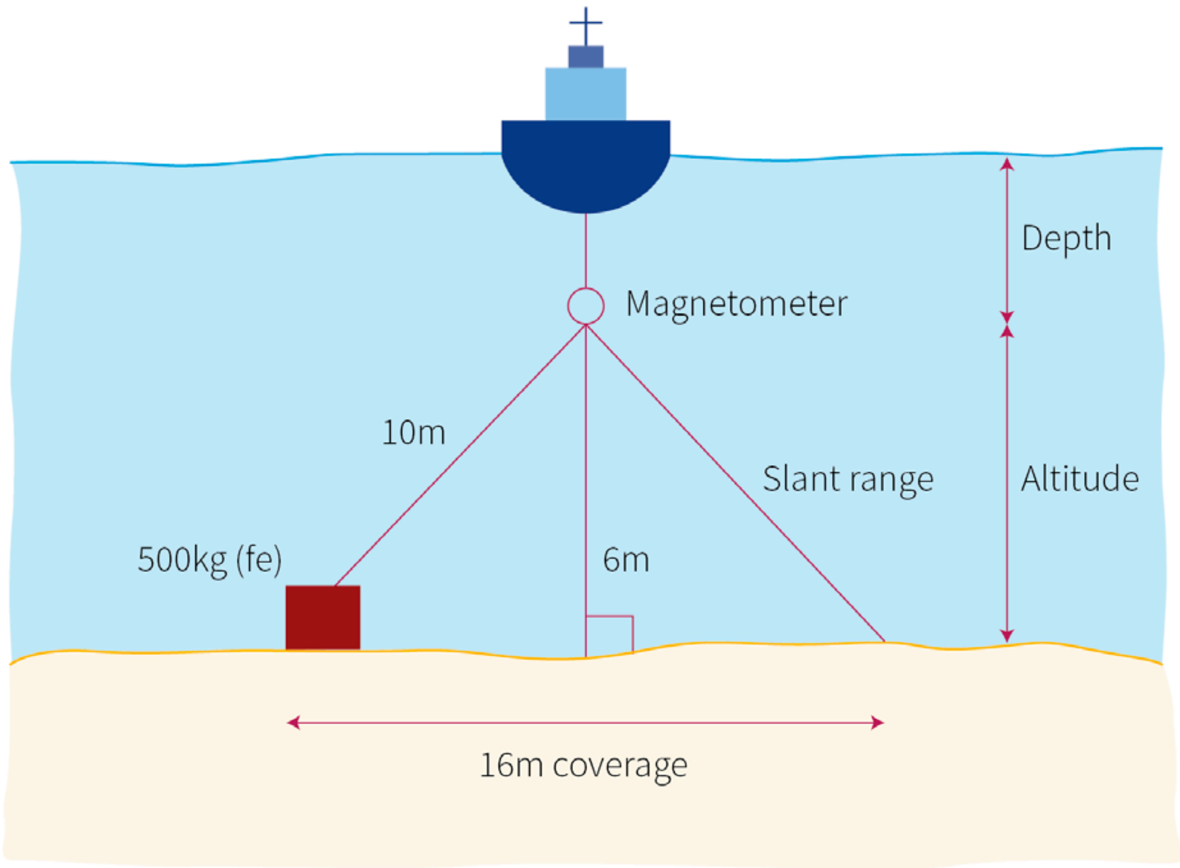


Figure 35: Magnetometer coverage.

The resultant coverage of 16 m (8.0 m either side of the magnetometer) will also be the minimum line spacing that needs to be used to achieve 100% coverage of the seabed where a 500 kg object will be identifiable as a minimum variation of 5.0 nT. The anomaly position will be accurate (across track) to +/- 8.0 m if it is not seen on adjacent lines.

When applying the same principle to the calculation of minimum object detection in relation to planned line spacing it can be seen that the theoretical minimum object detection significantly decreases, and the theoretical positional accuracy significantly increases as the line spacing decreases. Table 7 below shows calculations of minimum object detection size in relation to line spacing. Calculations are rounded to one decimal place, and all assume a magnetometer altitude of 6.0 m, a minimum detection amplitude of 5.0 nT, and 100% coverage at the specified minimum object detection. No contingency has been applied to the figures.

Table 7: Calculations of minimum object detection size in relation to line spacing.

Line Spacing	Slant range	MOD	Accuracy (+/-)
50 m	25.7	8,487 kg	25 m
20 m	11.7	800 kg	10 m
10 m	7.8	237 kg	5.0 m
5.0 m	6.5	137 kg	2.5 m
2.0 m	6.1	113 kg	1.0 m
1.5 m	6.0	108 kg	0.75 m

Reducing the altitude will decrease the minimum object detection, for example at an altitude of 4.0 m, and a line spacing of 5.0 m, the minimum object detection would be 52 kg with a positional accuracy of +/- 2.5 m. This does however come with an increased risk to equipment and collision with the seabed, and it is more difficult to maintain shallower altitudes, which should be considered during survey planning.

Line planning should also give consideration to the objectives of the survey. As detailed above there may be a requirement to detect all anomalies of a certain size, but in some instances the objective may be to characterise an area to determine what is likely to be encountered. Further information on survey specifications is given in Section 12.

6.7.2 Equipment selection

The equipment selected should be based on the ability to meet the objectives of the survey. Selection should take into consideration the following:

- **The type of magnetometer** - the use of the proton magnetometer is generally not considered appropriate for professional archaeological data collection. The slow update rate leads to a sparse distribution of data along the track at a typical survey speed of 4.0 knots. Most archaeological surveys required a sampling interval of at least every 0.5 m (4.0 Hz at 4.0 knots), increasing to every 0.2 m (10 Hz at 4.0 knots) for the identification of smaller anomalies such as the remains of aircraft. Overhauser magnetometers can record data at 4.0 Hz. Caesium vapour magnetometers can collect data at 20 Hz.

- **Magnetometer configuration** - the guidance so far has only discussed the use of a single magnetometer. Whilst typically not employed by smaller archaeological organisations, the techniques below are commonly used within the survey industry. For archaeological assessment, the use of either the Transverse Gradiometer, or a multi sensor array is only likely to have positive benefits to the data collected.

    - **Transverse Gradiometer (TVG)** - the data collected from the deployment of two magnetometers at a fixed, and known, distance from each other, either vertically or horizontally, can be processed as gradiometer data which measures the field gradient between the magnetometers (Figure 36). This can remove the effect of diurnal variation and reduce the effect of geological features. The data can also be processed to compute the quasi-analytical signal (known as the analytical signal). The analytical signal can have advantages when viewed graphically as it reduces the visual complexity of the anomaly as well as reducing the effects of geology, this aids with the clearer identification of smaller features and a more accurate estimation of horizontal position. In addition, the dataset is simplified due to the presentation of values as positive only. Furthermore, the data can be processed as independent datasets, increasing coverage and allowing, for example, estimates of anomaly position to be made using appropriate modelling.

Figure 36:
Two magnetometers configured as a horizontal Transverse Gradiometer (TVG).
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- **Multi sensor array** - a multi sensor array is a number of magnetometers, usually four or five, towed at a fixed distance from each other and usually with the use of a frame. Some frames will have the ability to alter the altitude of the array without having to alter the amount of tow cable out or altering vessel speed. The use of such equipment is common in the identification of pUXO as it allows a shallow altitude to be accurately maintained. The data can be processed in a method similar to TVG, but fundamentally it maintains a very small line spacing between data lines, without having to achieve near impossible, and incredibly time consuming, closely spaced parallel vessel tracks. Assuming five magnetometers with a spacing of 1.5 m, the line spacing for the vessel to run would be 7.5 m to achieve a line spacing of 1.5 m across the entirety of the survey area. The result is either a survey that in theory will be completed in 20% of the time, or assuming the line spacing of 7.5 m is a constant, a survey that will have a significantly smaller minimum object detection and more accurate anomaly positioning.

- **Depth of water and environment** - for towed equipment, the deeper the water the more tow cable will be needed to ensure the correct altitude of the towfish, and typically the heavier the towfish required to ensure stability. At depths of water exceeding 25 m the additional weight of cable, a potential requirement to weight the magnetometer, and additional drag through the water is likely to require a winch to safely deploy and recover the towfish. Current, and/or poor sea states may require the use of heavier equipment to minimise the impact on data quality.

- **Altitude** - during magnetometer surveys the measurement of the altitude is critical both to retrospectively calculation the MOD and to ensure the survey remains within the defined specification. Two common methods are a pressure sensor on the magnetometer to calculate depth or an integrated altimeter. With a pressure sensor, the depth recorded by the magnetometer can be subtracted from the total water depth to obtain the instrument altitude. This requires accurate water depth measurements to be taken with the data time stamped so that calculations can be made, and errors of just a few metres can significantly alter the calculation of the instrument altitude. The preferred method is the use of an integrated altimeter which provides regular and accurate measurement of the magnetometer altitude.

6.7.3 Line planning

Survey line spacing should be planned to meet the objectives of the survey (Section 9), the predominant factors being survey purpose and minimum object detection. Where possible lines should be planned to run:

- **In straight lines**, with turns being undertaken outside of the survey area. The quality of the resulting data will depend on the ability of the survey vessel to maintain straight lines during data acquisition. Data collected during a turn can also cause the magnetometer to roll.

- **Parallel with the direction of the current** to minimise the impact of cross currents on the position, stability, or heading of the magnetometer. The ability of the survey vessel to maintain a straight line, and follow line plans, will be reduced when traveling perpendicular to the current.

- **Parallel with the seabed topography** as far as possible to avoid changes in altitude over the course of the line. In areas of shallow water, and along the coast, survey lines should be run parallel to the shore and working from deep to shallow to minimise the risk to the magnetometer. Shallow water surveys should aim to undertake the shallowest areas at the period around high tide.

- **At a constant speed**, the speed of the survey should remain constant and will be determined by the aims of the survey and the update rate of the system. A general speed of 4.0 knots can be used, noting that some systems can operate at much higher speeds, or the objectives of the survey may not require the collection of dense data. In some instances, it may not be possible for the survey vessel to maintain a consistent heading at a low speed, consideration should therefore be given to running all lines into the current to increase steerage.

- **At a constant altitude**, not exceeding that from which the minimum object detection has been calculated.

Cross lines should be collected perpendicular to the main survey lines to allow for correlation and the assessment of overall positioning accuracy. Cross lines can also be used to correct for the effects of diurnal variation. The cross line spacing will depend on the specification, but 10% of the main line spacing is usually sufficient.

6.7.4 Calibration and testing

Prior to deployment, the system should be fully mobilised on deck and all inputs into the acquisition software confirmed. This can include GNSS, USBL, and magnetometer outputs. Magnetometers, depth sensors, and altimeters may all require calibration. Calibration certificates of the equipment (if applicable) should be checked and confirmed to be in date. Intervals and methods vary between manufacturers and instructions should be followed prior to, or as part of, the deployment process.

The determination of a correct minimum object detection size and accurate positioning can be achieved through the deployment to the seabed of an object of a known ferrous mass, equivalent to the minimum object detection at a known position – the process is often known as a Surrogate Item Trial (SIT). The actual process, and the requirement for it to be undertaken, will depend on the survey contractor or the requirements of the client, but the following provides an example of a suitable minimum object detection size and positioning test.

Prior to the deployment of the known object, the area of seabed selected should be surveyed to ensure it is free from anomalies that may affect the test results. Following deployment of the known object, eight lines of data should be collected directly over the object. Two lines, in opposite directions, should be collected in the orientation of the planned survey, directly over the object and at an altitude corresponding with the maximum detection range. Two lines should be collected in the same orientation, with one set at an altitude below the minimum detection range, and one set above the minimum detection range. Two lines should be collected at a perpendicular orientation and at an altitude corresponding with the maximum detection range.

From the resulting data, the minimum object detection size, and minimum detection distance, can be confirmed. The plotting of the positions from all lines will allow for the identification of any offset errors caused by tow point offset measurements, layback calculations, USBL errors, and potentially current.

6.8 Survey outputs

Magnetometer data are recorded digitally during acquisition and, depending on the manufacturer, will either be in ASCII format, or a proprietary format which will have a file extension unique to the manufacturer. Each survey line should be recorded individually, with acquisition stopped prior to the start of turns, and started following the completion of the turn. Data files will include at a minimum the amplitude reading, the altitude and/or depth, the position and time of each reading, the heading, and the signal strength.

It is important to understand where the position stored in the file relates to. Depending on how the system is set up this can be the GNSS antenna position, the tow point (defined through offsets in the acquisition software), or the position of the Magnetometer calculated through layback, input during acquisition, from the tow point or recorded from a USBL system. Irrespective of the positioning system used, the length of cable out should be recorded separately, and outside of the acquisition software, for each line. Files may also include:

- layback
- GNSS/or tow point position
- corrected position

If collected in a proprietary format, the data should be exported as delimited ASCII files (.txt, .csv, .asc, etc.). The data should be exported with each individual line as a separate file.

6.9 Quality control

Prior to the commencement of data processing, the data should be subject to a process of quality control. The process should establish the quality of the data in relation to suitability for archaeological interpretation, and whether the archaeological objectives of the survey have been met. Whilst data supplied by a survey contractor, typically in relation to marine development, will have been through a process of quality control it is still important that quality control in relation to archaeological objectives is undertaken prior to any additional processing and interpretation. The results of the quality control assessment should be presented in the archaeological report (Section 14).

The quality control process should be ongoing. Issues with data may not become apparent until the interpretation phase, when each line of data are viewed individually. The process for quality control will depend on the workflow of the organisation undertaking the work, as well as the software being used, but at a minimum the following should be considered:

6.9.1 Data quality

- **Noise** - is the level of noise acceptable and within the tolerances required to still be able to identify anomalies of minimum object detection at the calculated amplitude for the minimum detection distance?

- **Spikes and dropouts** – spikes are erroneous readings, typically of an amplitude significantly above or below background. Dropouts are caused by an interruption in signal, or no reading being taken. Typically, they will result in a zero reading or no data.

- **Data collection** - have the data been collected to a specification to achieve the minimum object detection? In the absence of the survey of a test object of known mass at varying altitudes, this will have to be undertaken theoretically in relation to the line spacing and altitude.

- **Other issues** - does the data have any other issues which may affect the ability to undertake archaeological interpretation? This could include, but is not limited to, the presence of geological features, or significant ferrous anomalies masking smaller anomalies. Modern anthropogenic features such as that relating to infrastructure, or even other vessels passing close by will also affect data. Where these are visible during the survey their positions should be recorded.

6.9.2 Positioning and navigation

- Whilst raw navigation data (including that embedded within the magnetometer data) will usually require some smoothing during processing, the general trend should be assessed for irregularities including large spikes, missing data, or notably wrong positions. This includes ensuring the data has been recorded in the correct coordinate reference system, both in relation to the area (i.e. correct UTM Zone) and as presented in the survey details.

- Have the correct layback and/or offsets been recorded? This can be checked through the assessment of the position of anomalies identifiable on multiple lines of data. Broadly speaking, large offsets along track can indicate layback or tow point offset errors, while offsets across track indicate tow point offset errors. Where multibeam bathymetry or sidescan data are available these should be used to correlate anomalies with visible features on the seabed.

6.9.3 Coverage

- The survey should achieve the required coverage, both in term of the survey area and the coverage percentage (based on the percentage of seabed where the minimum object detection can be achieved). Most commercially available and industry standard processing software will plot the data as lines, alongside a shapefile of the survey area to enable an assessment of coverage.

- The quality control process should highlight and record areas where the data does not meet the specification of the survey, particularly in relation to altitude as this will have an impact on the minimum object detection. For a high specification survey where the minimum object detection is critical, such as within areas of high archaeological potential, or where precise positioning of anomalies is required, data that fall outside of the survey specification should be recollected.

6.10 Processing and visualisation

Prior to processing, a backup of the raw, or ‘as supplied’, data should be created, as some software used will alter the source file. Whilst some software will save processed data in a proprietary format (and thus not alter the source data) it is good practice to maintain an unaltered copy of the data.

The primary purposes of data processing are to correct navigational and positioning errors, enable the visualisation and measurement of anomalies, and assess potential relations with other anomalies identified. Processing should be undertaken with caution, however, as while some processing procedures can result in data that looks good, they have the potential to remove data which may represent features of interest and therefore reduce the appropriateness for archaeological interpretation.

In its very simplest form, the processing and visualisation of magnetometer data can be undertaken in a spreadsheet editor with an option to display data graphically as a time series plot. A number of commercially available software packages (some free to use) that not only simplify the overall process but reduce the number of manual calculations required and can produce visual outputs for presentation of the data are also available.

The main elements of data processing that should be undertaken prior to interpretation, and export of deliverables, are as follows:

6.10.1 Navigation

Navigation processing ensures that data are positioned correctly, both relatively and absolutely. Navigation data consist of a position and time relating to each magnetometer reading. Recorded positions are affected by GNSS inaccuracies and the heave, pitch, and roll of the vessel. These will not be translated to changes in position of the magnetometer; hence the navigation data should be smoothed to provide a more accurate magnetometer track. The amount of smoothing required will depend on the quality of the navigation data, and the impact of factors discussed above.

Following import, the navigation data should be viewed and assessed for erroneous data points, which should be removed. This will result in the interpolation of the navigation between last and first 'good' points. Depending upon the number of erroneous points there is the potential for the interpolation to create an artificial towfish track. Smoothing is undertaken following the removal of erroneous data points, the aggressiveness of the smoothing is altered by defining the number of pings between which smoothing is calculated. The number of pings should be kept as low as possible to reduce the creation of artificial towfish tracks.

Whilst less common on large scale surveys which typically use USBL and thus have corrected magnetometer positions, layback (or cable out) and tow point offsets should be applied to each line of data when required and the resulting navigation corrected files assessed as per the quality control process.

6.10.2 De-spiking

The data should be cleaned of spikes and drop outs. Both are usually easily identifiable within the data as single points that do not fit the general trend of the data, i.e. a single significantly higher reading than the background, or a single zero reading. The process of de-spiking will remove the data points and interpolate between the readings either side. The process can be undertaken manually, or with the use of statistical filters. Whether undertaken manually or using an automated process, caution should be exercised with the removal of data points, particularly where the update rate is slow, as a single reading could represent an anomaly of interest. Where the data are characterised by a significant number of spikes or drop outs, this might indicate an underlying problem with the system or the survey methodology and conditions. Where there are excessive spikes or drop outs, this has the potential to impact the overall specification of the survey due to a decrease in along track resolution.

Noise, especially high frequency instrument noise, can also be reduced at this stage using a low pass filter. A low pass filter will remove higher frequencies whilst leaving the lower frequencies resulting in the smoothing of small variations within the data.

6.10.3 Correction of diurnal variation

The effect of diurnal variation on the Earth's magnetic field can be corrected in a number of different ways. Base station data can be collected and used to remove diurnal variation from the collected data. More commonly, diurnals variations are removed by normalising the background for each line to a generalised baseline or residual. This can be achieved through the use of crosslines where the primary lines can be adjusted to, or through, an automated statistical calculation, which is undertaken within the processing software.

6.10.4 Background and regional variation

The magnetometer will record the total field measurement at a position and time. This includes the Earth's magnetic field, the effect of any regional geological variations, and the variations caused by features on and below the seabed, and diurnal variation as detailed above. The variation caused by features of potential interest, excluding the Earth's magnetic field and regional variations, is known as the residual field and can be separated from the background using a series of filters and estimations of best fit.

For the purposes of archaeological assessment, it may not always be necessary to remove the background effect of regional geological variations. Changes are often gradual, over a large area and of a low amplitude, meaning anomalies can still be identified against the background. Where the effects of regional variation are more noticeable, they can often be removed through the application of a high pass filter. The process of filtering will also alter the shape and peak to peak measurement of anomalies that may be of interest, so caution must be exercised when using filtering, particularly in relation to the identification of smaller anomalies and calculations of mass.

6.10.5 Visualisation

The processed magnetometer data can be visualised in a number of different ways (Figure 37). The most appropriate method will be defined by the aims of the survey.

- **Time series plot** – the most basic method of viewing magnetometer data is a time series plot, from which variations, both positive and negative, can be viewed and identified. Positions, and measurements can be taken from the plot, and the results presented spatially using a GIS. Some software will allow for simultaneous assessment with the cursor position in the time series plot being displayed on a georeferenced image of other data. Point data can be displayed spatially by importing the residual field data into a GIS and applying a colour scale based on the amplitude.

- **Contour plot** - a contour plot will interpolate the data between lines to produce a visual representation of the data across the whole survey area, much in the same way as depths are presented on a nautical chart. The distance between contours will depend on the changes in amplitude recorded. However, care is required as data will be presented as an interpolated surface, creating a misleading impression of the integrity of datasets collected with a wide line spacing. Contour plots work well when the line spacing is reduced below 5 m, however, their usefulness in anomaly identification can be limited, and at wider line spacings can give the impression of much greater coverage than there is, with no anomalies lying between lines. Contour plots can be presented in two or three dimensions.

- **Gridded outputs** - data can be presented graphically as a surface, through a process of gridding, where the data are averaged into cells of a pre-determined size. Each cell can then be coloured based on its amplitude and a selected colour scale. As with a contour plot, care is required as data will be presented as an interpolated surface, creating a misleading impression of the integrity of datasets collected with a wide line spacing. Gridded data are useful for considering data over a wide area and for examining anomaly distribution, but do not display small features or feature shape well. The gridded values (i.e. the value from which the colour is derived) can be based on several different inputs from the processed data, the most common being Total Field, Residual, Altitude, and where calculated the Analytical Signal. The assessment of an altitude grid is especially useful to identify graphically where the altitude has not met the specification. The gridding of data will result in averaged, and in some instances interpolated data, and therefore the process and the resulting limitations must be understood. As with the graphical presentation of individual records, diurnal variation and regional geological variations should be removed so a normalised background value is presented. When gridding data, the first value that needs to be considered is the along track distribution of records, or the resolution, which will typically be between 0.5 m and 0.2 m. This is the minimum cell size that should be used to avoid over interpolation of data. The second value is the across track resolution, which is equivalent to the line space. Consideration must be given to the fact that with wide line spacing data will be interpolated between lines, creating a false visualisation of the actual anomaly. When dealing with narrow lines spacing (c. 2.0 m), or that collected with a multi sensor array, gridding at 1.0 m will produce a largely accurate map of anomalies, and their positions.

6.10.6 Processed outputs

The culmination of the data processing is the output of deliverables in relation to the method statement (Section 10) from which interpretation can be undertaken. The workflow to produce outputs will vary depending on the processing software but all industry standard software should have the following options. To note, not all may be useful or applicable to the project but are included here for completeness.

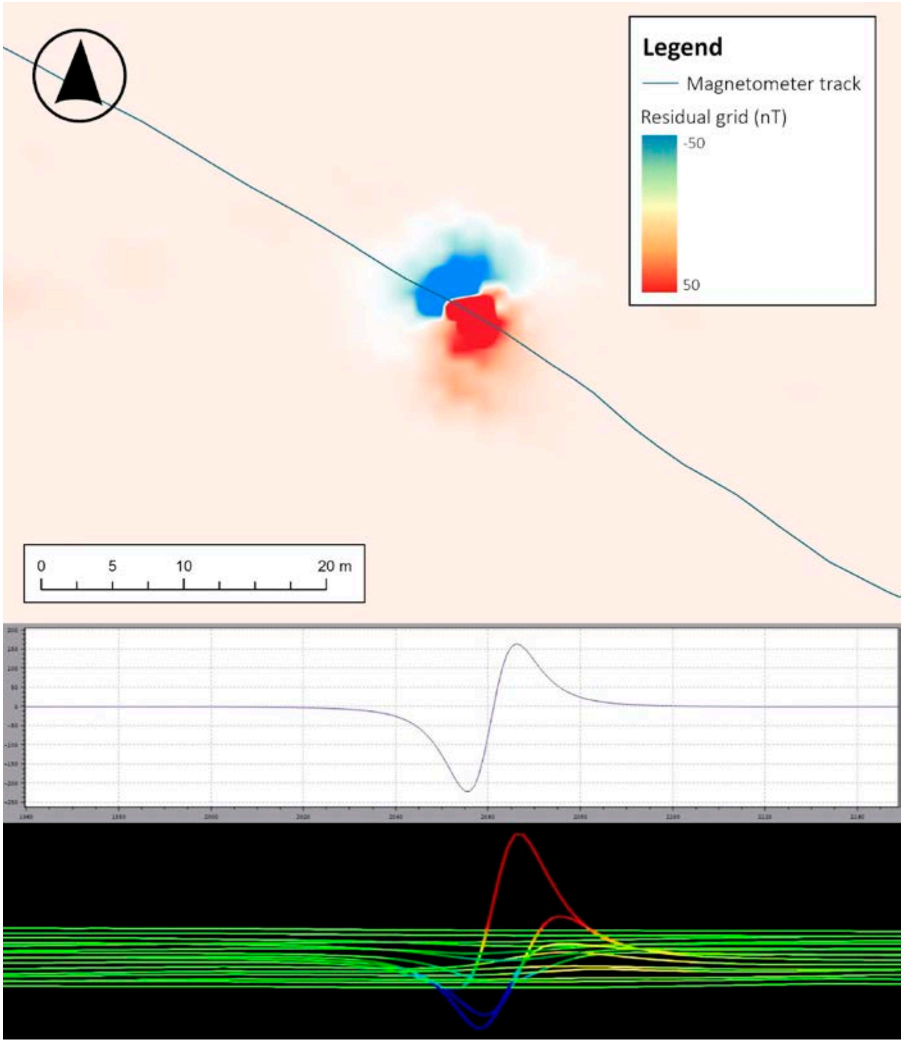

Figure 37:
Magnetometer residual data displayed as a gridded raster, time series plot and a three-dimensional visualisation including adjacent lines. Note, only a single line of data is shown on residual data raster to correspond with the time series plot.
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6.10.6.1 Processed Magnetometer data

Processed magnetometer should be exported as delimited ASCII files (.txt, .csv, .asc, etc.). The data should be exported with each individual line as a separate file, with each file containing at a minimum the total field, the position and time of each reading, the heading, the altitude and the signal strength.

It is important to understand where the position stored in the file relates to. Depending on how the system is set up this can be the GNSS antenna position, the tow point (defined through offsets in the acquisition software), or the position of the towfish calculated through layback, input during acquisition, from the tow point or recorded from a USBL system. Irrespective of the positioning system used, the length of cable out should be recorded separately, and outside of the acquisition software, for each line.

Files may also include;

- layback
- GNSS/or tow point position
- corrected position

Lines should be exported and either suffixed with an identifier (such as _PROC) to show they have been processed or exported to a folder clearly identifying processed data.

6.10.6.2 Interpolated contour plots

Interpolated two-dimensional contour plots should be archived as industry standard .shp files, with vector information relating to the amplitude of each contour. Three-dimensional contour plots should be exported as a delimited ASCII x, y, z file (where x and y relate to the position, and z the amplitude) (.txt, .csv, .pts, .asc, etc.). Interpolated data should be exported and either suffixed with an identifier (such as _INT) to show they have been interpolated or exported to a folder clearly identifying interpolated data. Data should be archived along with appropriate metadata detailing processing flows.

6.10.6.3 Gridded data

Gridded data should be archived in a non-proprietary format. Typically, either as a delimited ASCII x, y, z file, where x and y relate to the position, and z the variable altitude or amplitude (.txt, .csv, .asc, etc.), in grid format (.grd, .grid, etc.) or as a georeferenced raster to enable use within GIS software. A geoTiff is the preferred format. Two types of georeferenced raster can usually be exported, one without z data (amplitude or altitude), and one with z data.

- **Rasters without z data** – rasters without z data, where each pixel has an RGB colour, will be a reproduction of the surface displayed during visualisation and will include the colour scale selected. As the image does not contain z data a scale must be exported alongside the image, and preferably as a separate image file. The use of rasters without z data is not advocated due to reduced usability, and should only be provided where there is a specific requirement.

- **Rasters with z data** – rasters with z data, or floating-point rasters where each pixel has a z value, are the preferred format. The z data within the raster allows for the manipulation of colour scales, shading, etc. within GIS software and can aid interpretation with the ability to be able alter the image presentation depending on scale.

Whilst .tiff is the preferred output for both raster types, other industry standard formats such as .flt, are acceptable and when receiving data from a third party and will depend on the specified data output of the commissioning organisation. Surfaces can also be exported in proprietary formats; however, this is not encouraged for data that will be used outside of the organisation collecting the data and should not be used for archiving.

6.10.6.4 Tracklines

Exporting tracklines of the magnetometer and/or the vessel will result in data of a small file size that can be used within a GIS to establish the extents of the survey, measure line spacing, and compare the actual survey with the planned survey. Tracklines should be archived as industry standard .shp files.

7. Sub-bottom profiler

Sub-bottom profiling, or seismic reflection, uses low frequency sound waves (generally below 12 kHz) to image geological features buried beneath the seabed. This includes geological features such as sedimentary layers, oil and gas fields, and bedrock beneath the seabed, as well as buried infrastructure such as pipelines, and features such as shipwrecks and pUXO. Seismic reflection as a technique has been used for sub surface investigation since the 1920's, with significant technological advances in the 1960's and 1970's increasing its use within offshore industries. The development of the technique has largely been driven by the hydrocarbon industry in the prospection for oil and gas. Where other geophysical techniques such as multibeam bathymetry and sidescan sonar use high frequency acoustics (generally above 100 kHz) to map the surface of the seabed, sub-bottom profilers use the lower frequency acoustics to penetrate past the seabed, mapping changes in sub-surface composition.

As noted, this section of the guidance is intended to provide an overview of the technique, and the application within marine archaeology. As will be seen, the overall technique is broadly consistent in its operation, but the range of equipment varies greatly depending on the required outcomes, predominantly in relation to depth of penetration and resolution.

7.1 Uses within archaeology

Within archaeology the predominant use of the sub-bottom profiler is within the assessment and interpretation of submerged palaeolandscapes (ancient landscapes now submerged and buried as a result of sea level changes), in particular the identification of geological units with favourable environmental conditions for anthropogenic occupation within the Quaternary period (which covers the last 2.58 million years). The Quaternary is divided into two epochs;

- the Pleistocene (2.58 million to 11.8k years ago)
- the Holocene (11.8k years ago)

Early hominin evidence in Great Britain currently suggests a presence from c. 970k years ago, meaning that some Quaternary deposits have the potential to contain archaeological material or provide information about the contemporary environments within which hominin activity took place.

Although falling outside the scope of this guidance, the archaeological assessment of sub-bottom profiler data should be informed where possible by the results of geotechnical investigations in the development of a final deposit model.

Sub-bottom profiling techniques can have other uses within archaeology that can include the location of buried features identified in magnetometer data; the identification of buried features not seen within other datasets; the establishment of extents of partially buried features and using certain techniques the three-dimensional modelling of sub-surface features.

7.2 How it works

Acoustically, the sub-bottom profiler is in essence a type of singlebeam echosounder that emits a compression wave, at a frequency low enough to move (propagate) through the water column and then past the surface of the seabed. Here it interacts with sub-bottom conditions to create reflected energy that is then propagated back to a listening device (receiver) also at, or near the sea surface. The transmitting of a single acoustic wave is known as a shot, with the distance between shots known as the shot interval. The amount and distribution of the reflected energy is controlled by contrasts in acoustic impedance that are a function of the acoustic velocity and density of the material (sediment) through which it passes. The boundary in acoustic impedance contrast is called a seismic reflector which is typically a layer that is associated with a sedimentary boundary, or it could be a point reflector such as a discrete buried object, for example a boulder or anthropogenic feature.

7.2.1 Types of sub-bottom profiler

Sub-bottom profiling systems have either co-located transmitters and receivers or consist of a separated transmitter and acoustic receiver (hydrophones) or series of receivers. There are several different systems for creating the acoustic energy, namely pinger, chirp, parametric, sparker, boomer and airgun sources (Figure 38). In general, the choice of a particular system is made based on the desired penetration depth and resolution of the target sub-bottom features, as well as the likely sediments to be encountered. Penetration and resolution are a function of the system itself and the nature of the sediment through which the acoustic energy penetrates.

Controlling parameters of the transmitter include the output power, the signal frequency and the acoustic pulse length. The intensity of the return energy that is recorded is controlled by attenuation of the primary signal as it passes through the subsurface. For the transmitter, increased output power gives greater penetration into the substrate however shallow water and coarse grained or hard substrates can result in noisy data with multiple, repeat reflections. The attenuation of acoustic energy, and therefore bottom penetration, is inversely related to frequency. Lower frequency (longer wavelengths) and longer pulse lengths result in greater penetration but with lower resolution, and thus less chance of discrimination between adjacent, thin reflectors. Higher frequency signals have shorter wavelengths which are more easily absorbed and thus penetration is generally less, however they can often discriminate finer sub-surface layers. In general, the coarser-grained a material the more it absorbs energy and frequency.

Recording the acoustic energy is accomplished by co-located piezoelectric receivers for the high-resolution sonar, with separate piezoelectric elements usually towed in a single hydrophone or a string of multiple hydrophones for the lower resolution sonar. Occasionally, the use of an array of hydrophones is used to acquire multi-channel data, however this requires a more complex acquisition setup and processing of the data.

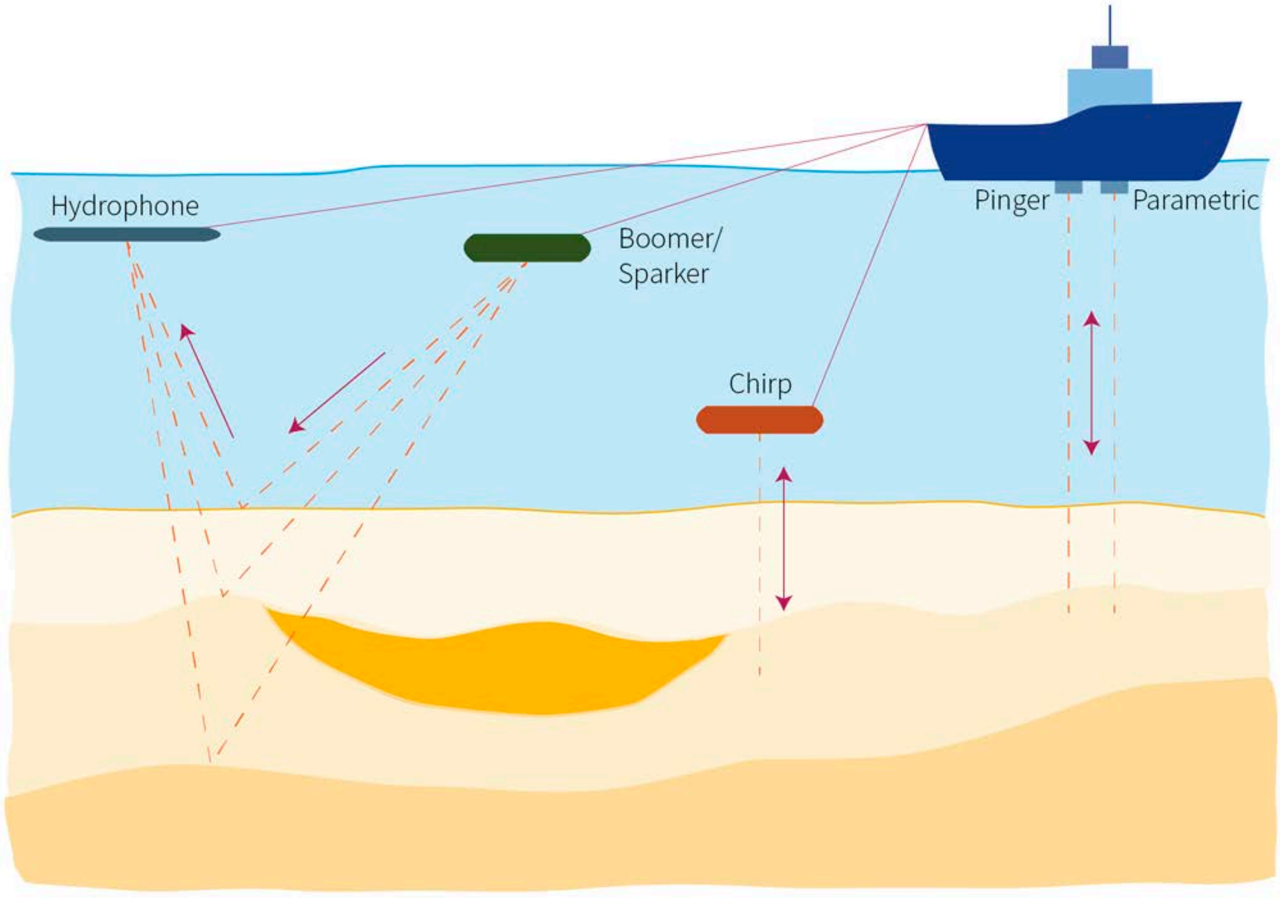

Figure 38: Types of sub-bottom profiler.

Each type of sub-bottom profiler will have characteristics that can aid in the outcomes of the survey, but there will always be a trade-off between resolution and depth of penetration. Particularly with surveys undertaken to inform marine development, there may be a requirement to collect a high resolution, shallow penetration dataset, alongside a lower resolution, deeper penetration, dataset. The operating parameters of the common sub-bottom profilers used to meet archaeological objectives are given in Table 8 below, and the operational characteristics in the following bullet points:

Table 8: Operating parameters of common sub-bottom profilers.

System Type	Pulse Type	Operating Frequency	Penetration Range	Vertical Resolution	Mount Configuration
Pinger	Single	2 - 20 kHz	3.0 - 30 m	0.1 - 0.3 m	Vessel or tow
Chirp	Swept	2 - 20 kHz	5.0 - 50 m	0. 05 - 0.3 m	Vessel or tow
Parametric	Dual interference	2 - 22 kHz	5.0 - 50 m	0.05 - 0.2 m	Vessel or tow
Boomer	Single	500 Hz - 5 kHz	10 - 100 m	0.2 - 0.5 m	Tow
Sparker	Single	30 - 300 Hz	10 - 800 m	0.15 – 1.0 m	Tow
Airgun	Single	10 – 300 Hz	10 – 5,000 m	0.5 – 1.0 m	Tow

- **Pinger** - the pinger type sub-bottom profiler operates with an energy source of between 10 - 60 Joules (J) at frequencies between 2 kHz and 20 kHz (generally around 3.5 kHz). The energy is produced by electrical to mechanical transformation and flexing of a piezoelectric crystal. Pingers can be deployed either as single units or as multi-unit arrays and mounted either on a towed sledge or as a hull-mount. Penetration depths are typically up to tens of metres with decimetre resolution, although coarse substrates can reduce this significantly. Pingers produce a high resolution dataset but are limited in penetration range.

- **Chirp** - a chirp system transmits a sweep of frequencies typically in the range of 2.0 kHz to 20 kHz in a single pulse. Each pulse has a much longer length than with a pinger and thus, despite their relatively low-energy output per pulse (6 - 64 J), a greater total amount of energy can be imparted to the signal. Further, because the long signal is compressed by a process of cross-correlation, improved signal to noise ratios allow for resolution down to approximately 0.05 m. Chirps are available in both towed and hull mounted configurations. Chirp, like pingers, produce a high resolution dataset, but with a slightly higher penetration range.

- **Parametric** - parametric echosounders are dual frequency profilers which broadcast two signals of slightly different frequency simultaneously. The interference between the signals produces a low frequency signal that can ‘carry’ the higher frequencies and thus higher resolution data (decimetre) can be generated at greater distances from the source than would be typical with other systems. An additional advantage of the parametric sonar is that the signal is virtually sidelobe free, thus reducing the ringing effects observed with other systems in shallow water. The systems can be towed however most are hull-mounted (Figure 39). The quality and resolution of data typically associated with parametric sub-bottom profiler data in shallow deposits means they are a good technique for the assessment of buried shipwrecks.

- **Boomer** - boomer plates discharge energy stored in a capacitor through a coiled spring acting against a copper plate. This produces a compression wave that travels through the water. The plate is mounted on a towed, floating sled behind the survey vessel. Typically, a single plate system is used however, if further energy is needed then this can be gained using multiple plates. Energy is recorded by a towed hydrophone array. The boomer system operates with an energy source of between 50 J and 300 J at frequencies up to approximately 5.0 kHz with typical penetration depths of up to 100 m when penetrating fine grain sediments (e.g. silt-sand) and a penetration depth of up to 50 m when penetrating coarse grain sediments (e.g. gravel).

- **Sparker** - as its name suggests a sparker system discharges an extremely high electric charge stored in a capacitor bank across an electrode in the water. The discharge produces a vapor bubble which rapidly expands then collapses, making an acoustic pulse of frequencies between 30 Hz and 300 Hz. Sparkers can be operated either as single electrodes or electrode arrays. Where high resolution (HR), or ultra high resolution (UHR) data is required, smaller sparker systems with frequencies in the range of a boomer can be utilised to provide resolutions of up to 0.15 m.

- **Airgun** – an airgun source consists of one or more pressurised chambers that release compressed air as a bubble that then collapses to produce the energy. Airgun operations require large air compressors in addition to the electronic control systems and are usually operated in arrays together with multiple hydrophone receiver elements. Typical frequencies of between 10 Hz and 300 Hz are possible thus penetration to kilometres in the sub-surface.

Figure 39: Parametric sub-bottom profiler. © Innomar Technologie GmbH

7.2.2 Two dimensional (2D) multi-channel seismics

The types of sub-bottom profiler detailed so far are referred to as single-channel, or more commonly single-channel seismics (SCS), and comprise a sound source and a receiver. Multi-channel seismics (MCS) however, comprise a sound source and multiple receiving elements distributed evenly in a neutrally buoyant cable known as a streamer. The main advantage of MCS over SCS is the quality of the subsurface image that can be derived after processing of the recorded data.

For MCS data an image of the subsurface is created midway between the source and receiver, known as the Common Mid Point (CMP). The CMP will be halfway between the sound source and the receiving element along the survey line. For different source-receiver pairs the CMP will differ (Figure 40), but as the survey moves along a two-dimensional track multiple CMPs are imaged in the subsurface at the same point. This allows a CMP gather to be constructed from the recorded data at the same subsurface point, each with a different source-receiver pair. Each CMP gather is summed digitally (stacked) resulting in two-dimensional seismic reflection profiles along the survey line with a significant increase in data quality when compared to SCS data. Typical imaging for offshore windfarm development analysis is 1.0 m spaced measurements to a depth of c. 100 m below seabed.

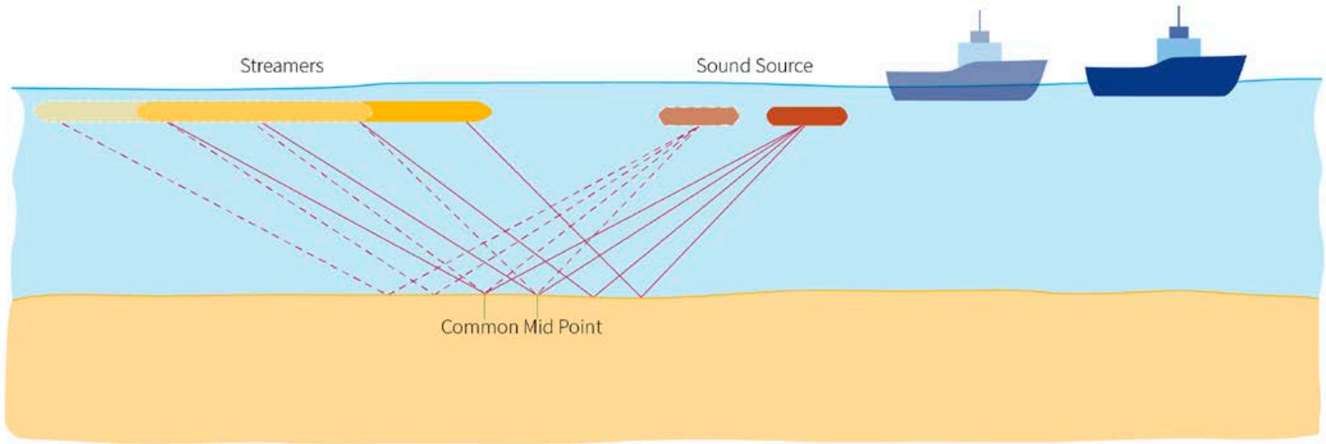

Figure 40: Two-dimensional multi-channel seismic data collection.

7.2.3 Three dimensional (3D) multi-channel seismics

Both SCS and MCS data are collected along pre-determined survey lines, the distance between which is dependent on the objectives of the survey. The resulting data provides a two-dimensional dataset comprised of a number of lines of data. The data can then be interpolated between the lines to create an estimation of the overall sub-surface environment. Whilst this may be suitable in many instances, there is the potential for features to not be identified due to their location falling between the pre-determined lines.

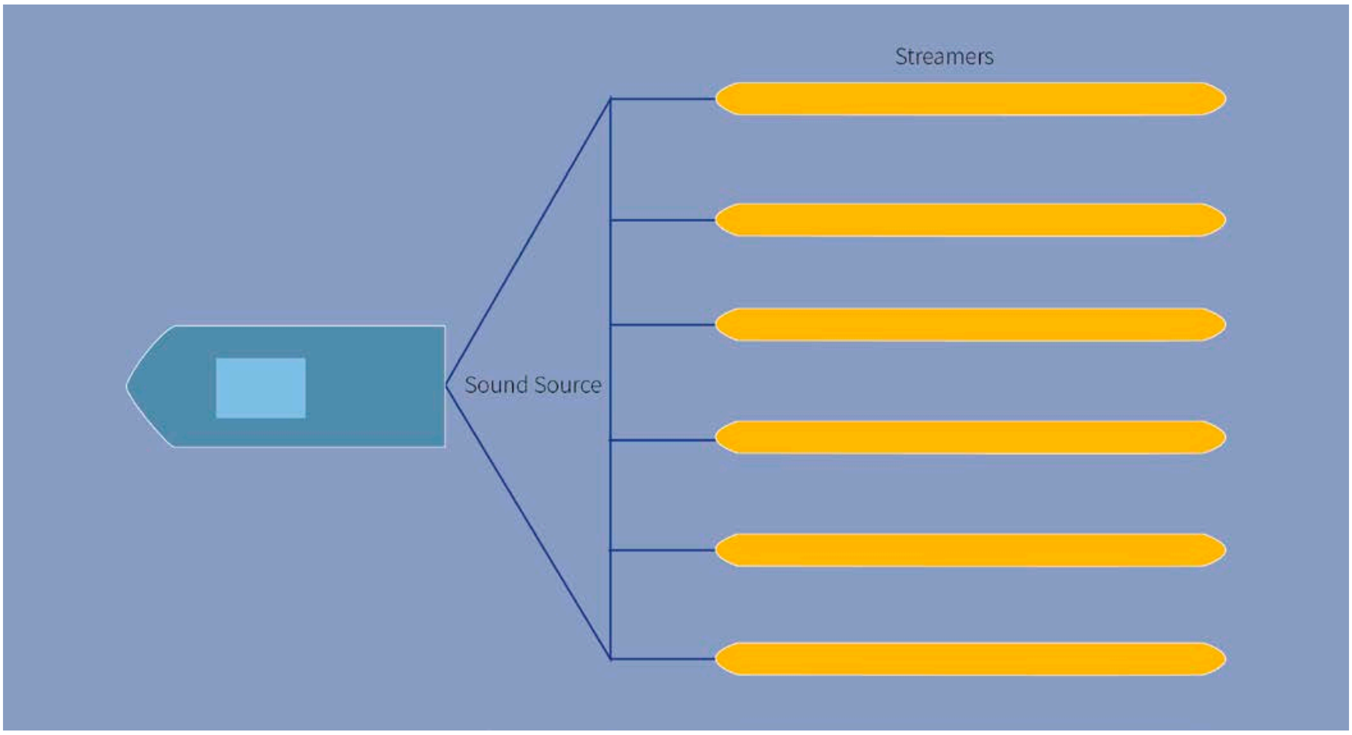

Figure 41: Three-dimensional multi-channel seismic streamer array.

The deployment of multiple MCS streamers and sound sources in parallel, at a known separation and accurately positioned, allows for much finer spatial sampling of the subsurface. Similar to two-dimensional MSC, CMP gathers are created. However, due to the positioning of multiple parallel receivers the CMPs will be distributed both along the survey line and across the width of the array (Figure 41).

In contrast to two-dimensional MCS which presents data as linear profiles, the processing of three-dimensional MCS creates a horizontal grid of equal sized cells (bins) over the survey area, each CMP gather within each bin is then stacked producing a true three-dimensional volume of data. The volume can then be interrogated from all angles and sliced across any plane for interpretation. The spatial resolution of the resulting data will be dependent on the survey specification and the bin size, however spatial resolutions of 0.5 m can be achieved.

Whilst the above three-dimensional survey techniques predominantly relate to sparker, boomer and airgun sources, multi-transducer chirp and parametric systems have been developed. These systems use multiple transducers to record high density data, typically of a better vertical resolution than sparker, boomers and airguns, but with a reduction in subsurface penetration. These dense data are gridded to create three-dimensional volumes, the results of which can be used effectively in the assessment of buried features, such as wrecks, where two-dimensional techniques would not provide the required level of detail in order to undertake effective archaeological assessment.

7.3 Resolution

The assessment of resolution, with regards to sub-bottom should consider the vertical resolution and the horizontal resolution. Noting that the predominant factor behind the suitability of a system is likely to be the depth of penetration.

7.3.1 Vertical resolution

Vertical resolution is the ability of the system to resolve individual and closely spaced reflectors, or horizons. The vertical resolution is determined by the pulse length, and the frequency or wavelength. Typically, individual units can be resolved with ¼ to ⅛ of the dominant wavelength. High frequency systems can typically achieve a vertical resolution <0.3 m, and low frequency systems <1.0 m.

7.3.2 Horizontal resolution

Horizontal resolution, and individual target discrimination, is dependent on the beam footprint, with a smaller beam footprint resulting in higher horizontal resolution. Higher frequencies and longer arrays produce narrower beams and thus the highest horizontal resolution data (smallest footprint) will require a long array of high frequency transducers. Much in the same way as a singlebeam echosounder, or multibeam echosounder, the horizontal resolution will decrease with depth because of the conical nature of an acoustic wave. Horizontal resolution is an important consideration, particularly when trying to identify small, buried features, however at a palaeolandscape level the requirement may be less due to the size of the deposits.

These limitations are partially addressed with the use of parametric sonar that uses a non-linear acoustic signal.

7.3.3 Ping rates and vessel speed

Ping rate, or the frequency at which a profile is taken (sample interval), is measured in Hz, with a higher ping rate increasing the along track data density. Ping rate will be governed to some degree by water depth (deeper water requires a slower ping rate to allow for the increased TWTT to avoid overlapping signals), but also the system selected. Although it varies greatly, parametric sub-bottom profilers can achieve ping rates of up to 50 Hz. The required ping rate will depend on the aims of the survey, for a detailed survey of a buried shipwreck, ping rates should be kept high, for the assessment of a palaeolandscape survey they can be lower but should aim to achieve a profile at least every meter. A survey speed of 4.0 knots, and a ping rate of 2.0 Hz will equate to an along track distance between profiles of approximately 1.0 m.

7.3.4 Definitions of resolution

The nomenclature for resolution in relation to sub-bottom profiler surveys varies between different practitioners, developers and survey companies. A standardisation of terms is detailed in ISO 19901-10:2021 *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 10: Marine geophysical investigations*, and further definitions have been proposed by Cook, et al. (2024). The definitions are presented below

- Medium resolution (MR)
    - ISO 19901 – not defined
    - Cook et al. – data collected at a frequency range of 5 to 180 Hz at a sample interval of 1 to 2 milliseconds (ms)
- High resolution (HR)
    - ISO 19901 – data collected at a frequency range of 75 to 300 Hz
    - Cook et al. – data collected at a frequency range of 20 to 375 Hz at a sample interval of 1 ms
- Ultra high resolution (UHR)
    - ISO 19901 – data collected at a frequency range of 250 to 800 Hz
    - Cook et al. – data collected at a frequency range of 50 to 600 Hz at a sample interval of 0.5 ms
- Ultra ultra high resolution (UUHR) or extremely high resolution (HER)
    - ISO 19901 – data collected at a frequency range of 750 to 2,000 Hz
    - Cook et al. – data collected at a frequency range of 250 to 5,000 Hz at a sample interval of 0.0625 to 0.125 ms

The definitions detailed above predominantly relate to two-dimensional linear surveys (both SCS and MCS), and do not provide equivalent definitions for three-dimensional surveys where the resulting resolution is defined by the bin size.

It is not within the scope of this guidance to make recommendations for definitions for resolution nomenclature. However, the above provide a broad guide but attention should be paid to the equipment and survey specifications to ensure that the data is of a suitable resolution to meet the archaeological objectives.

7.4 Ancillary equipment

The collection of high quality, and accurate, sub-bottom profiler data requires data collected by several other external sensors.

7.4.1 Tidal corrections

The distances to the seabed (the first return) are recorded as distances from the sub-bottom profiler and are directly related to the surface of the waterbody on which the survey is being undertaken. Therefore, the effect of rising and falling tides needs to be accounted for. The greater the tidal range, the greater offset there will be in the data both between the start and end of a line and between adjacent lines. The most common methods for tidal corrections are the use of tide gauges deployed at, or close to, the survey site and permanent gauges which can be located in ports and harbours and the use of RTK height corrections (Section 3).
Tide gauges record time and pressure, with pressure increases indicating a rising tide and pressure decreases a falling tide. The resulting data are then applied to the sub-bottom profiler data. RTK corrections, where available, negate the need for a tide gauge with height corrections either applied to the data in real time, or logged and applied during post-acquisition processing.

7.4.2 GNSS and motion sensors

GNSS and motion sensors are detailed in Section 3, however their importance is highlighted here due to the detrimental impact poor positioning and motion data will have on sub-bottom profiler data. Where the system is mounted to the vessel, the position of the resulting data will depend on the position and the motion of the vessel. If the three-dimensional orientation of the vessel is not known, or not applied to the data, this will result in mis-calculated depth positions. This is applicable to both vessel mounted and towed systems, however, the effect is exaggerated when the system is mounted to the vessel.

Motion can occur due to both wave and swell interference. Historically, data has been filtered for swell using software algorithms however in shallow water or in situations with complex (confused) seas, typically experienced in near shore survey, then measuring the actual motion of the source and receiver will result in higher quality data.

7.4.2.1 Towed systems

When using a towed system (either surface or subsurface), it will be susceptible to external factors such as currents, which can alter the calculated position when layback calculations are used to determine the position. Deeper water and large amounts of tow cable can further reduce the accuracy of layback calculations. To accurately determine the position, an Ultra Short Baseline (USBL) (Section 3) system should be used for subsurface towed systems, and a dedicated local DGNSS used with a surface towed system.

7.5 Limitations

Sub-bottom profiler is the only technique that allows the visual representation of features below the seabed and therefore is a requirement for archaeological surveys where the aim is the investigation of the palaeolandscape. Whilst other techniques may have options for both the survey industry, and recreational users, this is less so with sub-bottom profilers. A limiting factor is the training and experience required to undertake not only the data acquisition, but the eventual interpretation, which can be a more complex and involved process than with the other techniques.

When considering a sub-bottom profiler survey, the following limitations should be noted.

7.5.1 Mobilisation

The different ways in which a sub-bottom profiler will be mobilised will depend on whether the system is mounted directly to the vessel, towed on the surface or towed. Where the sub-bottom profiler is mounted to the vessel, the mobilisation can be complex, particularly on vessels of opportunity (non-survey vessels). Installations will require the sub-bottom profiler, the GNSS antennas, and the motion sensors to be fixed in relation to each other with offsets precisely known, and therefore bespoke mounts are often required, and in some instances, modifications may need to be made to the vessel to accommodate the equipment. Depending on the equipment, this may preclude the use of smaller vessels such as Rigid Inflatable Boats (RIBs). The quality of the installation will have a direct bearing on the quality of the data and permanent installs are likely to yield better results.

Where the system is towed, consideration should be given to the size of the vessel required, a small system can weigh upwards of 30 kg in air, with weights and towing requirements increasing significantly for larger systems. The weights and sizes of some of the towed equipment may mean that launch and recovery systems, A-Frame, winches, etc., may be required to enable deployment.

7.5.2 Weather

Sub-bottom data acquisition is very susceptible to the effects of weather, typically more so with vessel mounted systems than towed equipment as the motion of the vessel directly impacts the equipment. Whilst the data position can be corrected using a motion sensor or swell filter, the quality of the recorded data is likely to be poor in bad weather, and potentially be unable to meet the requirements of the survey in regards to the ability to resolve features.

7.6 Survey planning

Whilst survey planning, in relation to specifications, is covered in Section 9 the following should be considered during the survey planning process to ensure the optimal quality of data.

7.6.1 Equipment selection

The equipment selected should be based on the ability to meet the objectives of the survey and due to the wide range of sub-bottom profiler systems available this should be given careful consideration. Where the selection of the most appropriate equipment is not fully understood, then advice should be taken. There are however some general considerations;

- **Penetration vs resolution** - in general terms the higher the resolution, the shallower the effective penetration. The objectives of the survey will determine which system is suitable. However, it may be that there is a requirement for the use of two systems, a low frequency system to achieve the required penetration, and a high frequency system to achieve a higher resolution in the uppermost section.

- **Depth of water and environmen**t – for subsurface towed equipment, the deeper the water the more tow cable will be needed to ensure the correct altitude of the towfish, and typically the heavier the towfish required to ensure stability. At depths of water exceeding 25 m the additional weight of cable and drag through the water is likely to require a winch to safely deploy and recover the towfish. Current, and/or poor sea states, may require the use of heavier equipment to minimise the impact to data quality.

7.6.2 Line planning

Survey line spacing should be planned to meet the objectives of the survey Section 12. However, unlike sidescan sonar and multibeam bathymetry, and three-dimensional techniques aside, line planning is designed to achieve the distribution of two-dimensional slices required to meet the objectives, rather a percentage of surface coverage. The line spacing will typically depend on the size of the target geological feature, or indeed a more modern feature such as a buried shipwreck. Cross lines (or tie lines) are required to ensure that interpretations made across lines can be tied together to ensure an accurate representation of the feature and confirm tidal corrections.

Targeted surveys of, for example, buried shipwrecks or buried occupation sites, may require line spacing of a few metres to upwards of 10 m, dependent on the size of the feature. However, given the limitations of two-dimensional survey, consideration should be given to the use of three-dimensional techniques in these instances.

Where possible lines should be planned to run;

- **Perpendicular to the orientation** where the orientation, or the structural grain, of the geology or feature is known.

- **In straight lines**, with turns being undertaken outside of the survey area. The quality of the resulting data will depend on the ability of the survey vessel to maintain straight lines during data acquisition.

- **Parallel with the direction of the current** to minimise the impact of cross currents on the position, stability, or heading of the towfish or vessel. The ability of the survey vessel to maintain a straight line, and follow line plans, will be reduced when traveling perpendicular to the current.

- **Parallel with the seabed topography** as far as possible for subsurface towed equipment. In areas of shallow water, and along the coast, survey lines should be run parallel to the shore and working from deep to shallow to minimise the risk to the equipment. Shallow water surveys should aim to undertake the shallowest areas at the period around high tide.

- **At a constant speed**, typically c. 4.0 knots, however manufacturing specifications should be adhered to, and some systems will be able to operate at higher speeds. In some instances, it may not be possible for the survey vessel to maintain a consistent heading at a low speed and this instance consideration should be given to running all lines into the current to increase steerage.

- **A constant altitude** should be maintained for subsurface towed equipment. To ensure optimal data quality the length of tow cable should remain constant on each line, however large changes in topography may mean that adjustments need to be made.

7.6.3 Calibration

Prior to the commencement of the survey calibration certificates of the equipment, if applicable, should be checked and confirmed they are in date. Calibration intervals will be determined by the manufacturer.

For towed equipment, and prior to deployment the system should be fully mobilised on deck and all inputs into the acquisition software confirmed (this can include GNSS and USBL). The method for checking operation varies between manufacturers and instructions should be followed, prior to, or as part of the deployment process. It should be noted that some systems require immersion in water when in use to avoid damage to the equipment, and therefore a dry test is not always possible.

Vessel mounted systems should be fully mobilised with the survey vessel alongside, the GNSS and the motion sensor fixed in place, and the sub-bottom profiler deployed and secured in the survey position. Offsets should be measured as accurately as possible, and for permanent installations the use of a total station to measure sensor positions and offsets should be considered. In their simplest form the offsets are the measurements between each sensor (Section 3) and in relation to the CRP of the vessel. However, different offsets will be required to be input into both the acquisition and positioning software and care should be taken to ensure measurements are correct, the requirement of the software is met and the correct +/- value is used. All systems should be turned on and all inputs into the acquisition software confirmed.

Calibrations are generally required for the positioning and motion system in relation to the offsets between the motion sensor and the GNSS antennas. Calibration of the positioning and motion system is typically performed by performing a range of vessel movements at sea, with the software calculating any errors in offset measurements, and the offset measurements adjusted accordingly.

Whilst not strictly calibration, acquisition settings will need to be adjusted during mobilisation to ensure optimal data acquisition. Settings can include those related to ping rate, frequency, power, pulse length and gain, but note that some settings will affect the quality of the recorded data, whilst others can be changed during processing. All acquisition settings, and adjustments made during the survey, should be recorded.

7.7 Survey outputs

Sub-bottom profiler data are recorded digitally during acquisition and, depending on the manufacturer, will generally either be in SEG-Y format, or a proprietary format which will have a file extension unique to the manufacturer. Each survey line should be recorded individually, with acquisition stopped prior to the start of turns, and started following the completion of the turn. Data files will include, at a minimum, the acoustic data, and the position and time of each ping.

It is important to understand where the position stored in the file relates to for towed systems. Depending upon how the system is set up, this can be the GNSS antenna position, the tow point (defined through offsets in the acquisition software), or the position of the sub-bottom profiler calculated through layback, input during acquisition, from the tow point or recorded from a USBL system. Irrespective of the positioning system used, the length of cable out should be recorded separately, and outside of the acquisition software, for each line.

Files may also include;

- layback
- GNSS/or tow point position
- corrected position
- real time gain adjustments – to note, data should be exported with no gain adjustments applied. Whilst real time gain adjustments are useful for data visualisation during data acquisition, they should not be permanently applied to the export data

If collected in a proprietary format the data should be exported as SEG-Y files. The data should be exported with each individual line as a separate file.

7.8 Quality control

Prior to the commencement of data processing, the data should be subject to a process of quality control. The process should establish the quality of the data in relation to suitability for archaeological interpretation, and whether the archaeological objectives of the survey have been met. Whilst data supplied by a survey contractor, typically in relation to marine development, will have been through a process of quality control it is still important that quality control in relation to archaeological objectives is undertaken prior to any additional processing and interpretation. The results of the quality control assessment should be presented in the archaeological report (Section 14).

The quality control process should be ongoing. Issues with data may not become apparent until the interpretation phase when each line of data are viewed individually. The process for quality control will depend on the workflow of the organisation undertaking the work, as well as the software being used, but at a minimum the following should be considered.

7.8.1 Data quality

- **Penetration** - has the survey achieved the required level of penetration and is it possible to resolve reflections and features extending to the depth of interest. Where the specification was to be able to resolve complex units, and sub-units, can this be achieved?

- Does the data show signs of **external influences** such as poor weather or sea state?

- Does the data show signs of **interference from other equipment** including from simultaneous surveys (i.e. multibeam bathymetry, sidescan sonar, or other sub-bottom profilers), vessel engines, or vessel equipment such as echo sounders?

- Has the data been collected using appropriate **acquisition settings**?

- Does the data have any **other issues** which may affect the ability to undertake archaeological interpretation? This can include, but is not limited to, the presence of natural or geological features, gas blanking (shallow gas restricting penetration), etc. that may impact the penetration (particularly high frequency systems).

7.8.2 Positioning and navigation

- Whilst raw navigation data (including that embedded within the sub-bottom profiler data) will usually require some smoothing during processing, the general trend should be assessed for irregularities including large spikes, missing data, or notably wrong positions. This can include ensuring the data has been recorded in the correct coordinate reference system, both in relation to the area (i.e. correct UTM Zone) and as presented in the survey details.

- Have the correct layback and/or offsets been recorded? This can be achieved through the assessment of the horizons identifiable on multiple lines of data. Broadly speaking, large offsets along track indicate layback or tow point offset errors, and offsets across track indicate tow point offset errors. However, the effects of currents, both along track and across track, can cause errors. As such, wherever possible towed sub-bottom profilers should be positioned using USBL. Where multibeam bathymetry is available this can be used to correlate with the seabed as identified with the sub-bottom profiler data.

7.8.3 Coverage

- Has the survey achieved the required coverage, both in term of the survey area and the line spacing? Most commercially available and industry standard processing software will plot the data as lines, alongside a shapefile of the survey area, to enable an assessment of coverage.

The quality control process should highlight, and record, areas where the data does not meet the specification of the survey.

7.9 Processing

Prior to processing, a backup of the raw, or 'as supplied', data should be created as some software used will alter the source file. Whilst some software will create a version in a proprietary format, and thus not alter the source data, it is good practise to maintain an unaltered copy of the data.

The primary purpose of data processing is to correct navigation and positioning errors and perform image enhancement so that features and reflections of interest are clear and interpretable. Different processing software will have different workflows, some with automated options, and some with software specific processing features. Regardless of the software and the workflow, the overarching process, or result on the data, will be broadly similar. As such, a simplified overview of the results expected to be achieved is presented within this section. Caution, or at least an understanding of the process and the effect on the data, should be exercised when using automated processing features or those specific to individual manufacturers. While some features can result in data that looks good, they have the potential to remove data which may represent features of interest and therefore reduce the appropriateness for archaeological interpretation.

The main elements to data processing which should be undertaken prior to the interpretation and export of deliverables are as follows;

7.9.1 Navigation

Navigation processing ensures data are positioned correctly, both relatively and absolutely. Whilst exported navigation data can be imported into most processing software, navigation is most commonly contained within the sub-bottom profiler data and processed as a whole. Navigation data consists of a position and time relating to each sub-bottom profiler record. Particularly with DGNSS data, the recorded positions will not follow a straight line and are affected by GNSS inaccuracies, as well as the heave, pitch, and roll of the vessel which will not be translated to changes in position of the sub-bottom profiler. As such, the navigation data should be smoothed to provide a more accurate sub-bottom profiler track. The amount of smoothing required will depend on the quality of the navigation data, and the impact of factors discussed above.

Following import, the navigation data should be viewed and assessed for erroneous data points, which should be removed. The removal of erroneous data points will result in the interpolation of the navigation between last and first 'good' points. Depending on the number of erroneous points there is the potential for the interpolation to create an artificial sub-bottom profiler track. Smoothing is undertaken following the removal of erroneous data points, the aggressiveness of the smoothing is altered by defining the number of pings between which smoothing is calculated. The number of pings should be kept as low as possible to reduce the creation of artificial towfish tracks.

Should it be required, layback (or cable out), and tow point offsets should be applied to each line of data and the resulting navigation corrected files assessed as per the quality control process. This will be less necessary on large scale surveys which typically use USBL, and thus have corrected sub-bottom profiler positions.

7.9.2 Bottom tracking

Bottom tracking is fundamental to the effective and accurate processing and interpretation of sub-bottom profiler data. Bottom tracking is the process of identifying the first acoustic return and thus the boundary between the seabed and the water column. Accurate bottom tracking creates the datum from which depths to features and reflectors are measured. Where multibeam bathymetry data is available it should be used to align the bottom track to the seabed. The seabed forms the baseline from which gain, nadir region removal, and other corrections are applied and should be undertaken, prior to the application of image enhancement processes. Bottom tracking can be recorded in real time during acquisition or applied during processing – often bottom tracking recorded during acquisition will require a certain degree of re-interpretation.

The processing of bottom tracking can be undertaken manually, where the first acoustic return is identified and recorded along each line of data, however, most processing software is able to automate the process based on a range of user adjustable parameters which overall tend to be fairly accurate, although the better the data quality the better the results.

Where motion data has not been collected, and therefore the motion of the sensor has not been corrected, the process of bottom tracking may include the use of a software based swell filter to reduce or attempt to correct the impact of motion on the data.

7.9.3 Image enhancement

When sub-bottom profiler data are visualised without any corrections made to the data, there will be a marked difference in the displayed intensity between the first acoustic return and the far extents of the range, predominantly caused by signal attenuation and the non-linear effect of the signal. The options for correcting and normalising the image vary between processing software and the appropriateness of different processes will often depend on the data. The most common processes, and the order in which they are applied, across most processing software are;

- **Band pass filtering** – the application of a band-pass filter allows a certain range of frequencies to pass through while attenuating frequencies outside that range. In the context of sub-bottom profiler data, this filter is applied to the received acoustic pulse to remove frequencies outside of the input bandwidth. Typically, the application of band pass filters is used to remove noise from the data, both from the sensors itself, but also that originating from external sources.

- **Time Varying Gain (TVG)** – as sound travels through the water column and the sub-surface sediments, the process of attenuation will cause a reduction in the amplitude of the signal. The application of TVG allows for increases in gain towards the depth of penetration and decreases in gain closer to the seabed as required to normalise the image. TVG is often based on a non-linear graph, or curve, which in its most basic form is user adjustable. It should be noted that TVG adjustments required may alter along each line of data which can have an impact to the overall presentation of the data. Most software will have an option for Automatic Gain Control (AGC) which aims to adjust gains across to the data to result in a common amplitude.

- **Water column muting** – to reduce water column noise and to aid visual presentation, the data above the bottom tracked seabed can be muted.

- **Stacking** – stacking is a statistical application that averages the values of records, either over a specified distance or number of records. Stacked data can either be presented with average values or minimum/maximum values for each record.

Caution should be exercised when using various processing tools and filters that are available within most processing software. Whilst the use of such filters can produce visually pleasing images, the incorrect use can cause degradation of image quality, the loss or alteration of the source data, and impact the appropriateness for archaeological interpretation.

7.10 Visualisation

The visualisation of sub-bottom profiler data, prior to the interpretation of horizons and the identification of features (Section 11) is through along track cross sections, or profiles. Profiles will be viewed as either two way travel time (TWTT) of the acoustic signal, or the depth, along the vertical (z) axis and time or distance on the horizontal (x) axis. Data are recorded as TWTT; to display the data in relation to depth a velocity function must be applied. The velocity function must consider both the velocity through the water column and the sub-surface sediments.

Where the velocity is not known, approximations are typically used. For the speed of sound though water this is approximately 1,500 m/s for saltwater and 1,480 m/s for freshwater. Below the seabed and for saturated sediment, an average velocity of between 1,500 and 1,800 m/s is used. The combination of the TWTT and the speed of sound, allows the depth to be calculated, and presented.

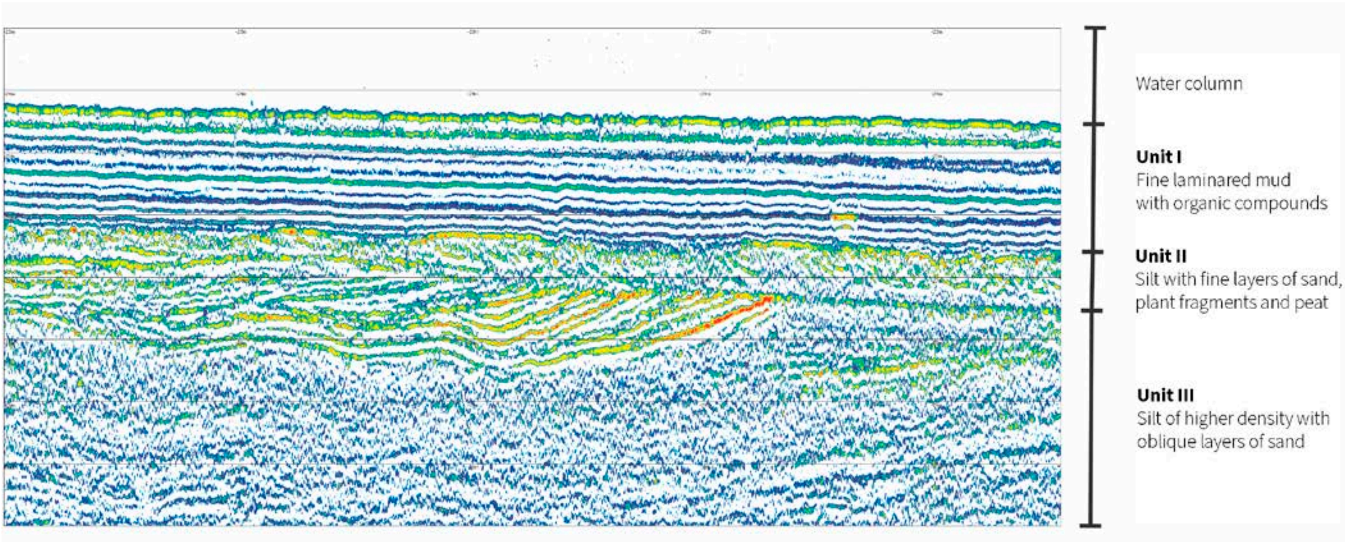

Figure 42: Sub-bottom profiler section showing different units beneath the seabed.
© Innomar Technologie GmbH

The two-dimensional data are used to interpret reflections which represent boundaries between different sedimentary layers or units (referred to as horizons) along the length of the profile (Figure 42). Interpretations are digitised, along with the bottom tracked seabed, to give values of the identified horizons (surfaces) below the seabed, either as depth or as TWTT.

Should the line spacing be sufficient, the individual horizons can be interpolated and gridded to provide contiguous projected surfaces, as either depths below the seafloor or elevations in true space. Noting that with wider line spacing comes greater interpolation and thus a greater chance the gridded surface does not match the true position of the horizon. Within offshore developments there is a growing trend towards the collection of three-dimensional seismic data for some objectives resulting in the production of very high resolution (small bin size) three-dimensional volumes. Where this data is available it is likely to yield the best results in relation to the creation of ground models and should be considered for archaeological assessment.

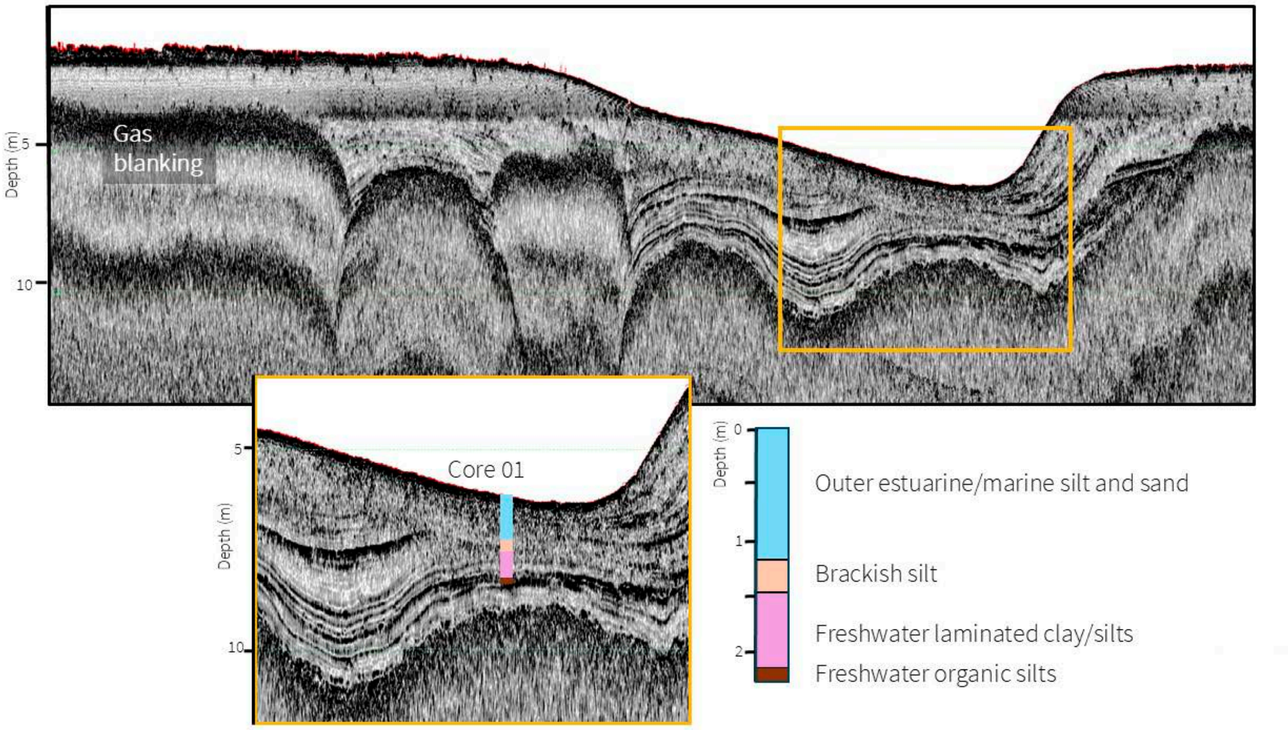

Figure 43: Sub-bottom profiler section showing ground-truthing using a geotechnical core. © Prof R Bates

7.10.1 Gridded outputs

Assuming a suitable line spacing, the horizon data can be presented graphically through a process of gridding. The gridding process will interpolate the horizons between lines, creating a contiguous surface, which can be displayed in either two or three-dimensions. The gridded surfaces can be exported as plan view rasters with each cell being coloured, based on the depth below seabed and the selected colour scale (Figure 44). Unless the survey lines are sufficiently closely spaced, the data between the lines will be an interpolation, creating a false visualisation of the horizon. However, at a landscape scale this is typically less of an issue for archaeological assessment than the interpolation of say multibeam bathymetry data where the objective is to identify smaller features.

7.10.2 Contour plot

A contour plot will interpolate the data between lines to produce a visual representation of the data across the whole survey area, much in the same way as depths are presented on a nautical chart. The distance between contours will depend on the depth below seabed recorded (Figure 44).

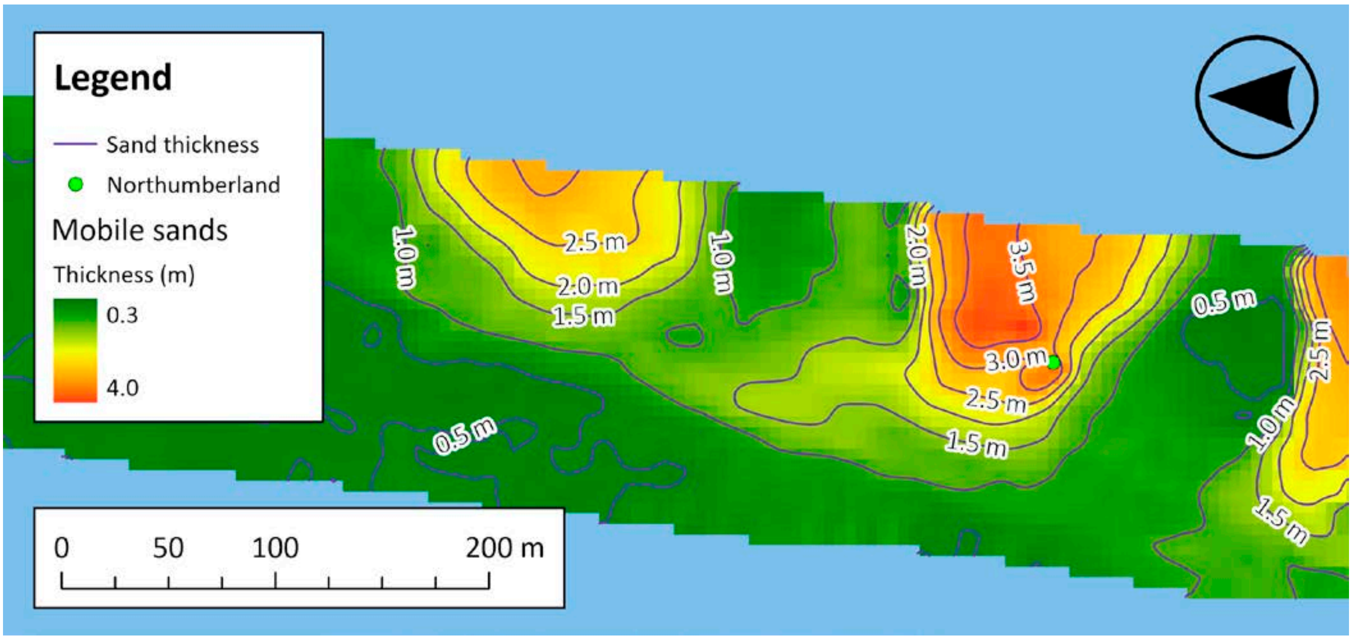

Figure 44: Thickness of mobile sands around the wreck of the *Northumberland*. Presented as contours and a gridded raster coloured by thickness. © MSDS Marine for Pascoe Archaeology, funded by Historic England

7.11 Processed outputs

The culmination of the data processing is the output of deliverables in relation to the Method Statement (Section 10), from which interpretation can be undertaken. The workflow for the production of outputs will vary depending on the processing software but all industry standard software should have the following options. To note, not all may be useful, or applicable to the project but are included here for completeness:

7.11.1 Processed sub-bottom profiler data

At a minimum, processed sub-bottom profiler data should be exported in SEG-Y format. The data should be exported with each individual line as a separate file containing the processed acoustic data. Lines should be exported and either suffixed with an identifier (such as _PROC) to show they have been processed or exported to a folder clearly identifying processed data.

7.11.2 Gridded data

Gridded data should be exported in a number of formats depending on the use, typically and preferred is a georeferenced raster. Two types of georeferenced raster can usually be exported, one without z data (TWTT or depth below seabed), and one with z data.

- **Rasters without z data** – rasters without z data will be a reproduction of the surface displayed during visualisation and will include the colour scale selected. As the image does not contain z data a scale must be exported alongside the image, and preferably as a separate image file.

- **Rasters with z data** – rasters with z data, or floating point rasters are the preferred format. The z data within the raster allows for the manipulation of colour scales, shading, etc. within GIS software and can aid interpretation with the ability to be able alter the image presentation depending on scale. The use of rasters without z data is not advocated, due to reduced usability, and should only be provided where there is a specific requirement.

Whilst .tiff is the preferred output for both raster types, other industry standard raster formats are acceptable. When receiving data from a third-party, the format will generally depend on the specified data output of the commissioning organisation. Surfaces can also be exported in proprietary formats; however, this is not encouraged for data that will be used outside of the organisation collecting the data.

7.11.3 Interpolated contour plots

Interpolated two-dimensional contour plots should be exported as industry standard .shp files, with vector information relating to the amplitude of each contour. Interpolated data should be exported and either suffixed with an identifier (such as _INT) to show they have been interpolated or exported to a folder clearly identifying interpolated data.

7.11.4 Tracklines

Exporting tracklines of the sub-bottom profiler, and/or the vessel, will result in data of a small file size that can used within a GIS to establish the extents of the survey, measure line spacing, and compare the actual survey with the planned survey. Tracklines should be exported as industry standard .shp files.

8. Marine development

Within England, the majority of geophysical data that undergoes archaeological assessment is collected as part of the marine development process. Marine development can include, but is not limited to, offshore wind farms, cable installation, pipelines, aggregate extraction, seaweed farms, dredging, and port and harbour developments.

These developments can physically impact the seabed and therefore may negatively impact material of potential archaeological interest. The archaeological resource is finite, and any damage, either through primary or secondary impact, is permanent. Geophysical surveys can form the basis data are used to of determining the potential archaeological resource and assessing its corresponding archaeological significance, in order that appropriate mitigation strategies can be implemented, and once implemented, monitored as to their effectiveness

Data are collected at different stages of marine development, often to specifications that enable their use within a number of different disciplines. This section broadly outlines the marine development process and provides guidance as to the phases of development where archaeological assessment of data should be undertaken. Due to the varied requirements for marine developments, survey specifications are not given in detail, with the overarching guidance being to seek marine archaeological input during the planning stages. However, example specifications that meet the requirements of different phases of development are given in Section 12.

Figure 45: Service Operation Vessel (SOV) supporting the Westermost Rough Offshore Wind Farm. © Historic England

8.1 Consenting

8.1.1 Introduction

Detailed discussion of legislation for marine development is beyond the scope of this guidance. However, the following is provided for context in relation to phases of works where the archaeological assessment of geophysical data may be required. The consenting process, and regulatory bodies, are those for English waters. Although there are commonalities in processes, particularly within the UK, where developments fall outside of English waters, or where developments cross borders, country specific requirements should be identified.

8.1.2 Marine Licences and Development Consent Orders

Marine development that impacts the seabed will, in most cases, be required to go through a consenting process, the requirements of which will depend on the scale of the development. For developments not classed as Nationally Significant Infrastructure Projects (NSIPs) consent is generally administered through a Marine Licence issued under the Marine and Coastal Access Act (2009) by the Marine Management Organisation (MMO), who will enforce the licence and any post-consent licence conditions. For projects classed as NSIPs consent is through a Development Consent Order (DCO) under the Planning Act (2008). A DCO is issued by the relevant Secretary of State on the recommendation of the Planning Inspectorate (PINS). The DCO may include provision for a Deemed Marine Licence (DML), or a Marine Licence may be consented independently.

The NSIP examination process uses National Policy Statements with reference made to published English Marine Plans. National Policy Statement e.g. Renewable Energy Infrastructure (EN-3) (published 2023), details the consideration necessary about the historic environment as might be encountered and appropriate mitigation strategies.

8.1.3 Environmental Impact Assessment

Marine Licence or DCO applications must include sufficient information from which a decision can be made as to the potential effect the development may have on the environment, including the historic environment. Furthermore, applications for a Marine Licence require the completion of a Marine Plan Policy Assessment (MPPA) where specific consideration of heritage assets must be detailed under a specific Marine Plan Area Policy, such as the South West Inshore and South West Offshore Marine Plan SW-HER-1;

> Proposals that demonstrate they will conserve and enhance the significance of heritage assets will be supported. Where proposals may cause harm to the significance of heritage assets, proponents must demonstrate that they will, in order of preference:
>
> a) avoid
> b) minimise
> c) mitigate -any harm to the significance of heritage assets.

If it is not possible to mitigate, then public benefits for proceeding with the proposal must outweigh the harm to the significance of heritage assets.

Where a development is deemed to have a potential significant effect on the environment, or the type of development is included within Schedules A1 and A2 of The Marine Works (Environmental Impact Assessment) Regulations 2007, it is likely to require an Environmental Impact Assessment (EIA).

Not all Marine Licence applications will require EIA but may, to align with relevant marine plan policies, require the archaeological assessment of geophysical data. In such instances, the method for archaeological assessment will remain the same, with the objectives of the survey being proportional to the potential impact of the development.

There are four primary phases undertaken during the consenting process in relation to EIA within the UK.

8.1.3.1 Screening

Screening is the process by which it is determined whether a project falls within the remit of the EIA regulations and if it is likely to have a significant effect of the environment and therefore require assessment.

8.1.3.2 Scoping

Scoping determines the extent of issues to be considered, and reported on, together with the sources of information they will use during the production of the Environmental Statement (ES).

8.1.3.3 Preliminary Environmental Information Report (PEIR)

As part of the NSIP consenting process the Preliminary Environmental Information Report (PEIR) Stage provides preliminary, and early, information on the likely significant environmental effects, and the mitigation required to offset these effects.

8.1.3.4 Environmental Statement

The ES is the assessment and presentation of the likely significant environmental effects, and the mitigation required avoid, reduce or where possible offset these effects. The marine historic environment ES chapter will be accompanied by an archaeological technical report, an outline Written Scheme of Investigation (WSI), and a Protocol for Archaeological Discoveries (PAD).

- **Archaeological technical report**
  The archaeological technical report underpins the ES chapter and details the historic environment baseline from which the likely significant effects, and mitigation, can be determined. The report may be presented as a standalone report or included with the ES chapter depending on length, requirements, etc. The baseline, which includes the known resource and an assessment of the potential resource, is established through a Desk-Based Assessment (DBA) which includes, but is not limited to:

- A review of Historic Environment Records (HER).
- Other records that may relate to the historic environment, such as those from the United Kingdom Hydrographic Office (UKHO) and the British Geological Society (BGS).
- The results of previous studies.
- The archaeological assessment of geotechnical data (both project specific and historic).
- The archaeological assessment of geophysical data (both project specific and historic).

The geophysical data acquired by the development project should be of a specification suitable to characterise the location within which the development is proposed in order to produce an environmental baseline. The data should cover the extents of the application area and be of a sufficient specification to identify receptors that may require mitigation, or identify what receptors are likely to be within a given area, along with preliminary modelling of the palaeolandscape.

The specification of the data should be guided by the objectives of a characterisation survey, an example of which is provided in Section 12. Specifications should however be proportional to the development, noting that in some instances there will only be direct interaction with the surface seabed in approximately 10% of the application area.

The technical report should clearly present data gaps, and limitations of the survey, along with presenting recommendations for additional survey works that may be required prior to any impacts.

Whilst typically, the technical report is produced to underpin the ES chapter, depending on the timescales of related surveys it (or versions of) may be used to support the process of screening, and scoping or a potential pre-application submission process.

- **Written Scheme of Investigation**
  An outline WSI is typically produced during the EIA process to support the DCO application and is submitted alongside the ES chapter, technical report and other associated appendices. Broadly speaking, the WSI may present summarised results of the ES chapter and any technical reports, which in turn informs the mitigation requirements, and their implementation, through the lifecycle of the development. The WSI includes summary methodologies for activities that may require archaeological involvement, which will direct and form the basis of more detailed activity specific method statements. The outline WSI is updated to a ‘final’ WSI post consent.

The WSI can be considered as the core overarching mitigation document for a development, the implementation of which is generally specified in a licence condition. Guidance for the production of WSIs for offshore wind farms has been published by The Crown Estate (TCE), although there are general principles which are applicable to most seabed development projects[4].

- **Protocol for Archaeological Discoveries**
  A PAD is typically produced during the EIA process. It forms a component of the mitigation process, and its use is applicable to all stages of marine development. A PAD outlines the process in which unexpected finds, or potential finds are to be reported when identified and the decision-making process by which further archaeological assessment should be implemented. It is important to understand that the application of a reporting system does not mitigate for impact and damage to an archaeological site, it is only a system to support timely and efficient communication between key identified parties.

  Guidance to support the drafting of a PAD for the offshore wind energy sector has been published by The Crown Estate[5], it is important to note that reporting protocols should be designed according to the type of seabed development e.g. extractive, such as dredging, or construction. The PAD system should also be applicable for any discoveries of archaeological interest that occur during geophysical survey. It is important to note that established procedures for reporting discovery of wreck to the UKHO and/or the Receiver of Wreck (RoW) should always be followed.

8.1.4 Post-consent

Once consent has been granted, either through a Marine Licence or a DCO with a DML, the development is likely to be subject to licence conditions related to the historic environment. Typically, they will outline a requirement for the implementation of the WSI and the PAD. The WSI may outline a requirement for the archaeological assessment of post-consent geophysical data, the specification and extent of which will be detailed within a Method Statement which will be produced in consultation with the archaeological curator prior to formal agreement with a regulatory authority e.g. the MMO (Section 10).

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4 Wessex Archaeology, 2021. Archaeological Written Schemes of Investigation for Offshore Wind Farm Projects. The Crown Estate

5 Wessex Archaeology, 2014. Protocol for Archaeological Discoveries: Offshore Renewables Projects. The Crown Estate

Archaeological assessment of geophysical data is likely to be required for the following activities/datasets, noting that not all may be applicable, and the extent of works will depend on the results of the ES and the requirements outlined in the WSI:

- **Pre-construction (or pre-impact) survey data**
This is typically collected for the purpose of design finalisation and for assessment in relation to pUXO. The data are subject to archaeological assessment as they are typically collected to a higher specification, but over a reduced footprint relating to the extents of the area of impact. The specification of the data should be commensurate with an investigation survey, an example of which is provided in Section 12.

- **Post-construction monitoring data**
This is typically collected following the installation of infrastructure, and at regular intervals to monitor integrity. For developments such as aggregate extraction, licence conditions may require periodic monitoring due to the continued impacts to the seabed. The specifications of the data will depend on the requirements of the developer in discussions with the archaeological curator, and any licence conditions.

- **Pre-remedial/decommissioning data**
Where remedial, or decommissioning, works to installed infrastructure are required, data is usually collected to inform the process. The archaeological assessment of this data will depend on the requirements of the WSI and will consider the archaeological potential of the area, the proximity to receptors, the nature of the works, the time elapsed since the last review of data, the seabed dynamics, and previous impacts. The specifications of the data will depend on the requirements of the developer, and any licence conditions.

- **Bespoke investigations**
Bespoke, or targeted, investigations may be required at all phases of a development, for example where a feature of archaeological interest (usually a shipwreck) is identified that may impact the development, where mitigation needs to be refined, or where new features are identified post-construction. The specification of the data will depend on the requirements of the survey but is likely to be commensurate with shipwreck specific survey, an example of which is provided in Section 12.

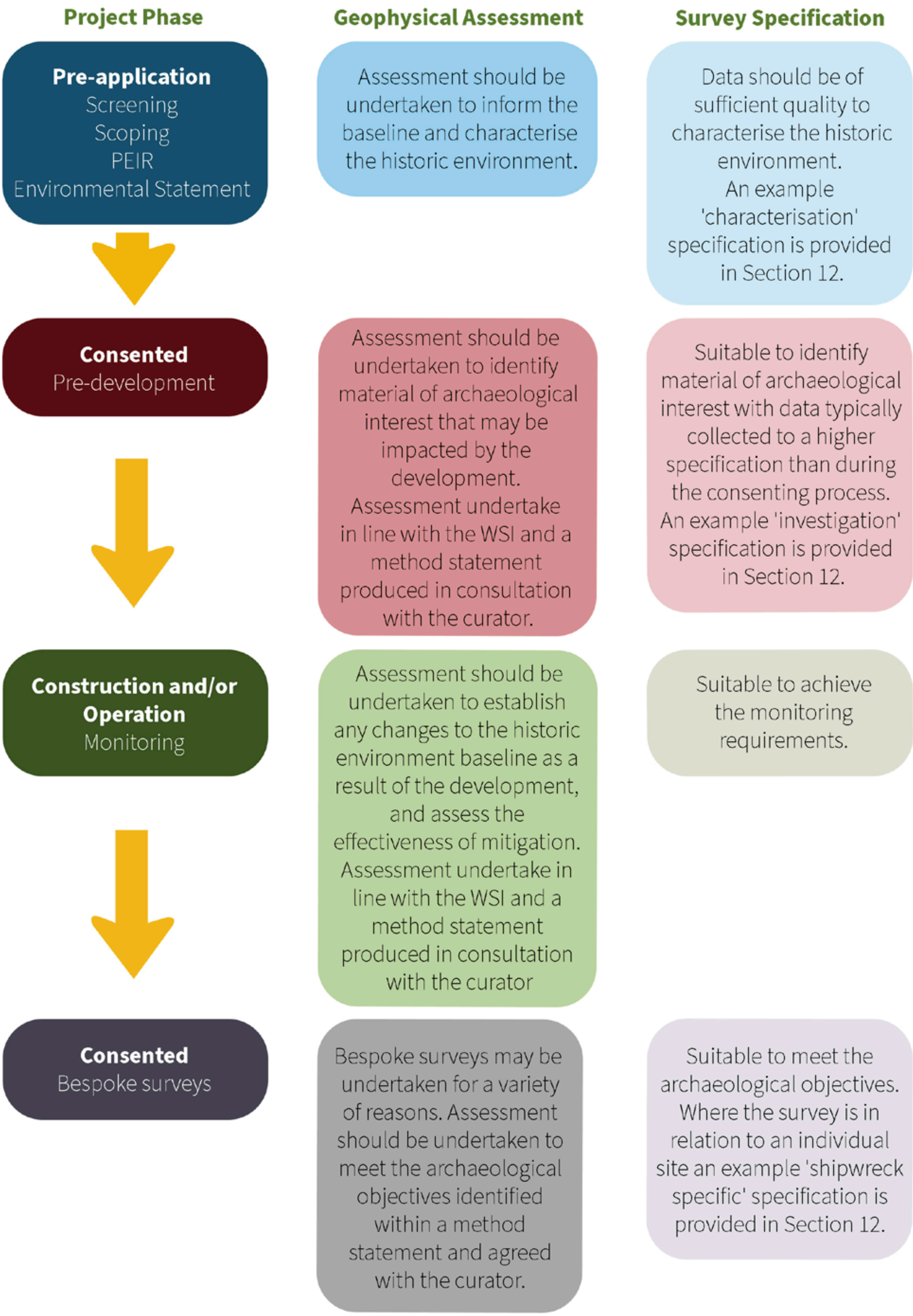

Figure 46: Integration of the archaeological assessment of geophysical survey data into the marine development process.

8.2 Survey strategy

The survey strategy, and therefore the archaeological assessment requirements, for large scale marine development projects generally follows the phases outlined above. Data collected at each stage supports not only archaeological assessment, but a number of other disciplines including engineering, benthic ecology, pUXO identification, and marine and coastal processes.

The overall strategy will depend on the requirements and scale of the development. Smaller developments, such as aggregate extraction, capital and maintenance dredging, or the development of seaweed farms, may combine phases and undertake one survey that meets the requirements of multiple phases. Surveys strategies should be practical, appropriate and proportionate to the development and the potential impacts.

8.2.1 Archaeological input into survey planning

Advice should be sought from a suitably qualified and experienced individual or organisation prior to the commissioning of geophysical survey. During the consenting process the individual or organisation is typically engaged directly by the developer or their environmental consultants. Following consent, the individual or organisation is typically retained by the developer and referred to as the ‘Retained Archaeologist’. It should however be noted that the Retained Archaeologist may not always be the most appropriately qualified to provide advice, and this may be sought from an alternative contractor or individual as required.

It is recommended that organisations are registered with the Chartered Institute for Archaeologists Registered Organisation scheme, commonly referred to as being a CIfA RO, or equivalent body. A CIfA RO may employ a multi-disciplinary team of accredited professionals, for example marine archaeologists, geologists, geophysicists and geoarchaeologists, in order to provide robust advice. Where advice is being provided by an individual, they should have demonstratable experience in the collection, processing and interpretation of geophysical data for marine archaeological assessment and a robust understanding of the marine development process and the requirements at each phase. It is recommended that individuals are accredited with CIfA, or another suitable marine or archaeological organisation which may include those in relation to marine geophysics or geology. It is the responsibility of the developer to ensure that appropriate and robust advice is sought and at the appropriate time.

The provision of appropriate and robust advice during the planning stages of surveys will allow the developer to make informed decisions based on the potential risk, ensure appropriate specifications are met through each phase, and make amendments to survey design at an early stage, where required. Advice should be sought in good time, prior to the commissioning of surveys, to ensure that consideration can be given to archaeological requirements (including data deliverables) during the commissioning process.

The provision of advice should be informed by:

- The scale and nature of the development.
- The phase of development (consenting, post-consent, monitoring, etc.).
- The results of previous assessments where undertaken.
- The archaeological potential of the development area.
- The overall survey strategy for the development and associated project timeframes for the completion of each stage.

The following inset box provides guidance for factors that should be considered by the marine archaeologist when providing advice as to survey specifications. Examples of specifications for characterisation, investigation, and shipwreck specific surveys can be found in Section 12. However, these are given as examples only and individual project specifications should be tailored to the project requirements to ensure an appropriate and proportional survey.

It is recommended that the advice provided be summarised by the archaeologist as a technical note and be retained by the developer.

Archaeological considerations

Survey specification

- Is the survey specification and design suitable to meet the archaeological requirements of the phase to which it pertains, together with any licensing obligations?
- If not suitable, how can the survey design be revised to ensure it is able to meet the archaeological requirements? For example, the following should be considered;
- Positioning (surface and subsurface – see Section 3)
    - Sensors
    - Coverage
    - Minimum detection size
    - Penetration
    - The sea state the survey is conducted in

- What are the limitations of the survey, and therefore what is the risk (from an archaeological perspective) to the project with the proposed specifications and survey design?
- How can any risks be mitigated? For example, the following should be considered;
  - Additional survey requirements
  - The overall survey strategy for the development
  - Detailed Desk-Based Assessment (DBA)
  - Survey techniques other than geophysical and hydrographic, for example, survey undertaken by divers, remotely operated vehicle or drop down video etc.
  - If the data is to be used to produce a baseline, consider when it was acquired in relation to when development impacts are planned to commence. Too great a gap between baseline and construction may present risks to the historic environment, especially in areas with a dynamic seabed.

Data requirements

- Are the data deliverables suitable to meet the requirements of archaeological assessment? Consideration should be given to;
  - Data formats
  - Level of processing
  - Data delivery method, and timescales

8.3 Aims and objectives

The aims and objectives of the archaeological assessment of geophysical data will change depending on the phase of the development, and the purpose for the assessment.

Broadly, the principal aim within a marine development context is to establish the presence of materials of known, or potential, archaeological interest, palaeolandscape features and deposits of geoarchaeological interest.

The identification of material and deposits of potential interest allows for the determination of whether a project may have a negative (or positive) effect on the historic environment, and for strategies to be recommended to mitigate any negative effects that may be caused.

The objectives can be summarised as follows:

- To establish the presence of anthropogenic material of archaeological potential.
- To interpret any identified anomalies and identify their archaeological potential.
- To understand the impacts of the development and recommend mitigation strategies for any sites, features and/or anomalies appropriate to their archaeological potential.
- To understand the seabed environment and composition.
- To establish the palaeolandscape potential.
- To recommend mitigation strategies in relation to the palaeolandscape and landforms/ deposits of palaeoenvironmental interest, and
- To recommend further works that may be required and their specifications.

8.4 Archaeological Assessment of the Resulting Data

The requirements for the archaeological assessment of data will depend on the phase of survey for which the data was collected.

- During the consenting process, the archaeological assessment methodology must be suitable to enable the characterisation of the historic environment to support the application process.

- Post consent, the archaeological assessment methodology must be suitable to identify material of archaeological interest that may be impacted by the development, and be in accordance with agreed method statements (Section 10) produced in relation to the WSI, where one has been produced.

Guidance for the archaeological assessment of geophysical data are detailed in Section 11. Reporting requirements are detailed in Section 14.

9. Heritage led survey

This section provides guidance on the practical application of geophysical survey where heritage is the primary driver. This may include surveys commissioned by archaeological curators, research and prospection by academic institutions, or self-funded organisations and individuals.

The scope of these surveys will vary greatly depending on the project aims, and as such it is not possible to provide detailed survey specifications for all scenarios. However, adherence to the guidance and consideration of the information presented will ensure that data are not only suitable for the purpose intended but will provide baseline data that can be reused as required, adding value to the survey.

Whilst this chapter is not specifically aimed at marine development (see Section 8) where geophysical surveys typically have a wider data collection strategy, it provides useful guidance where a survey is carried out primarily to meet archaeological objectives. This may include archaeological monitoring of a site or detailed survey to inform bespoke mitigation. At the post-consent stage these works will be guided by the WSI and/or a method statement.

9.1 Desk-based Assessment

Prior to the commencement, and even planning, of geophysical survey a Desk-based Assessment (DBA) should be undertaken. The DBA will refine the research question, inform the aims and objectives of the survey, and aid in the determination of a suitable methodology including the geographical scope. Detailed guidance on the productions of DBAs is outside the scope of this guidance, however the following should be considered to inform future geophysical survey.

Existing geophysical, geological, and archaeological datasets should be assessed to establish the archaeological baseline, informing the requirement to undertake additional survey including the sensors that may be required and the geographic scope. The establishment of a baseline will also allow for the monitoring or changes to sites between surveys. Existing datasets can include, amongst others, bathymetry data available from the ADMIRALTY Marine Data Portal maintained by the UKHO, geological data available from the BGS, and offshore data available from the Marine Data Exchange maintained by the Crown Estate.

It may be the case that assessment of existing datasets alone will be sufficient to answer the research question, removing the need to undertake further survey work, alternatively the data may inform strategies to allow for a more targeted and effective approach.

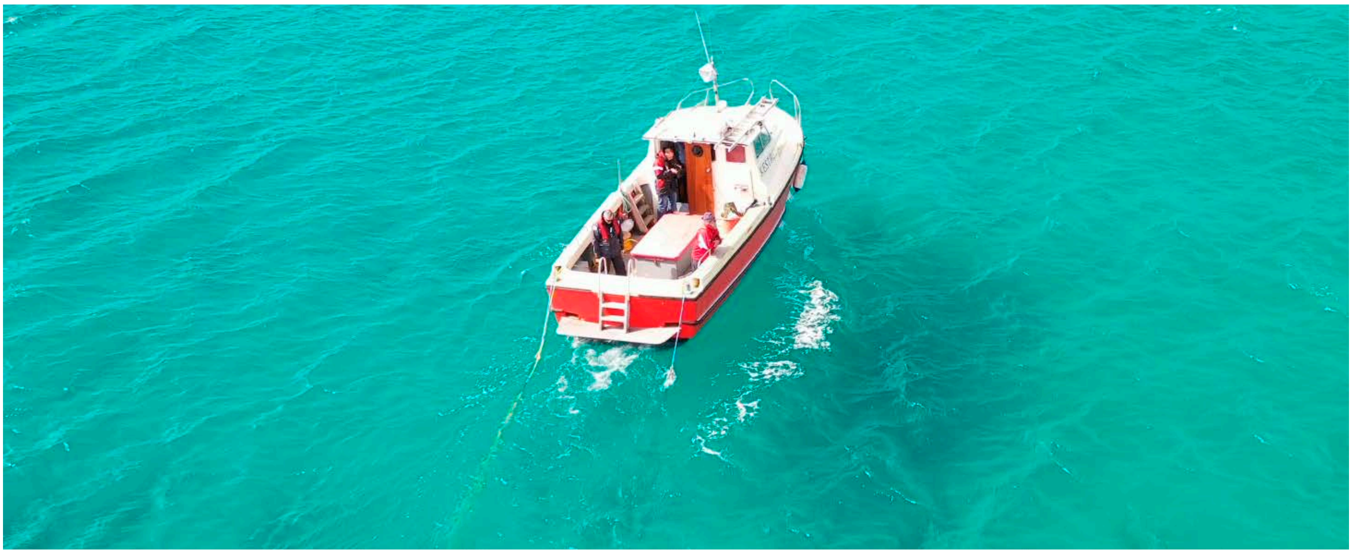

Figure 47: Sidescan and magnetometer survey being undertaken as part of a research project commissioned by Historic England on HMS *Colossus*. © CISMAS

9.2 Aims and Objectives

The aims and objectives of the survey will depend on the research question(s) that the survey has been designed to answer. A project design, or method statement, should be produced outlining the aims and objectives, and how they will be achieved[6]. Further guidance on the production of method statements, and the detail they should include, is presented in Section 10.

Geophysical surveys and their aims, outside of those undertaken as part of the marine development process, will typically fall into two categories: prospection, and site-specific surveys.

9.2.1 Introduction to prospection

The broad aim of a prospection survey is to locate or identify material of potential archaeological interest on or under the seabed or assess the potential for such material to exist within a given area. This can include anthropogenic material such as shipwrecks, cargoes, aircraft, structures or evidence of human activity, or the identification of areas with the potential for submerged prehistoric remains. This is typically achieved through a lower resolution survey. As noted in Section 2, lower resolution surveys usually allow greater coverage than high resolution surveys but at the expense of identifying only larger features.

The example characterisation survey specification given in Section 12 is commensurate with that which should be considered for prospection.

6 Historic England (2015) Management of Research Projects in the Historic Environment: The MoRPHE Project Managers' Guide

9.2.2 Introduction to site specific surveys

The broad aim of a site-specific survey is to obtain a greater level of detail at a local level about a specific site or area than is already available. This can include, but is not limited to;

- resolving complex stratigraphy
- accurate localised mapping of sub-surface features such as palaeochannels
- monitoring change on shipwreck sites
- the creation of georeferenced site plans
- establishing debris fields
- collecting data for public engagement

This is typically achieved through a specification with a narrow line spacing and generally at a higher resolution than used for prospection.

The survey specification for site specific surveys will vary depending on the aim, however the example specifications for investigation survey and shipwreck specific survey provide a robust starting point.

9.3 Data collection strategy

The data collection strategy for site specific surveys will vary greatly, primarily depending on the overarching aim. Whilst surveys undertaken during the marine development process (and particularly large developments) will routinely deploy several different techniques concurrently, for research projects consideration will usually need to be given to several factors including:

- Equipment availability
- Vessel capability
- Expertise required
- Data processing requirements

Outside of marine development it is rarely possible to deploy a full suite of techniques, and therefore careful consideration should be given to the selection of equipment which will achieve the required results. The four most common techniques, their uses, and their limitations, are presented in Sections 4 to 7. It is recommended that the reader seek advice from a professional, accredited and experienced marine archaeological service, and/or marine survey contractor.

General guidance is presented for data collection in relation to palaeolandscape prospection, palaeolandscape site specific survey, shipwreck prospection, and shipwreck site specific survey. Noting in each instance that the survey specification must be designed to meet the aims of the survey and must be presented within a method statement (Section 10).

9.3.1 Palaeolandscapes

The primary technique for the identification and mapping of the palaeolandscape is the sub-bottom profiler which allows the mapping of sub-surface features, including geological units and features. It is recommended that multibeam (or single beam) bathymetry is collected concurrently, or a recent dataset utilised, to enable the sub-bottom profiler data to be aligned with the seabed, and for the identification of features which may be visible on the surface. The requirement for this will depend on the area of interest.

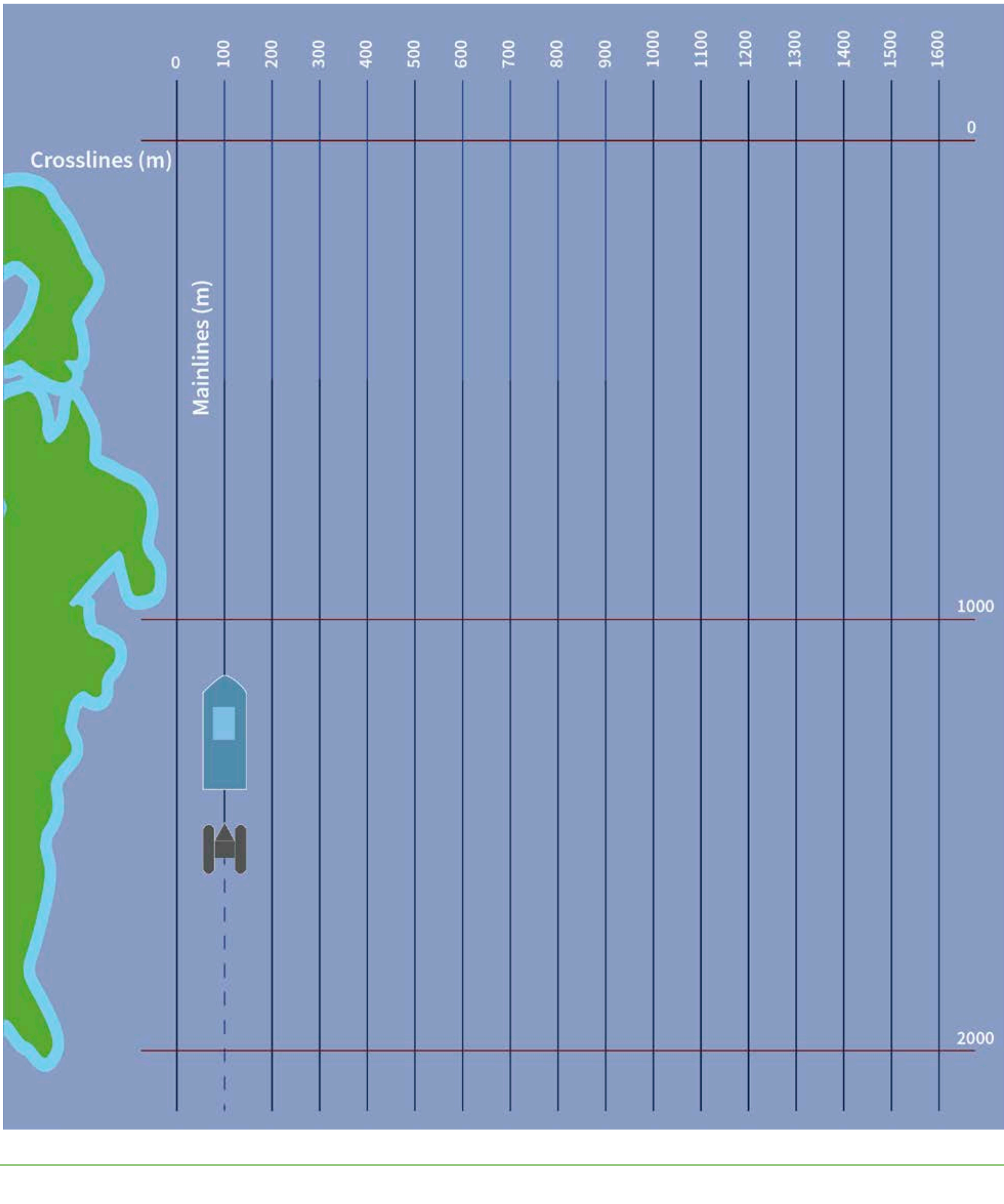

Figure 48: Example sub-bottom profiler prospection line spacing.

9.3.1.1 Palaeolandscape prospection

Unlike multibeam bathymetry and sidescan sonar, the sub-bottom profiler will only give a visual image (seabed and sub-surface) directly below the transducer, therefore it is not possible to define a line spacing to achieve a coverage percentage. Instead, the line spacing must be determined based on the anticipated changes in the sub-surface geology, with main lines orientated perpendicular to these changes. The geographical scope for prospection, in relation to the palaeolandscape, can be in the magnitude of hundreds of square kilometres, so sub-bottom profiler line spacing is critical to ensure efficiency in relation to the aims.

There is no general guide to line spacing as this will be determined by the aims of the survey. Line spacing may range from main line spacing of between 50 m and 100 m, and cross line spacing of between 500 m to 1,000 m for small areas or complex geology, whilst for large areas a grid of up to 1,500 m x 1,500 m line spacing may be suitable (Figure 48). Where, for example, multibeam bathymetry data are being collected concurrently (at 100% coverage, plus overlap), in water depths less than c. 40 m this is likely to dictate the line spacing.

The type and specification of the selected sub-bottom profiler will depend on the requirements of the survey and is dictated by the depth of penetration, and resolution, required. In general terms, the higher the frequency the higher the vertical resolution, but the shallower the penetration.

9.3.1.2 Palaeolandscape site specific survey

Following an initial prospection survey or desk-based research, there may be a requirement to undertake a higher resolution survey at a local scale. This may be to accurately map the extents of identified features such as palaeochannels or areas of potential habitation, to resolve complex stratigraphy, or to achieve greater penetration. Line spacing will typically be narrower than that used during prospection surveys but will depend on the aims of the survey. Where the aim is the mapping of features, they should be planned perpendicular to the length. Cross lines should be planned at 10 times the spacing of the main lines, however, consideration should be given to an equal grid depending on the shape of the feature, and the density of data required.

9.3.2 Shipwrecks and other archaeological sites

Whilst the focus of this section is shipwrecks, it is equally applicable to submerged structures and other large anthropogenic features including aircraft. The technique(s) selected will be determined by the type of material expected (i.e. iron, steel, timber, stone, etc.), the expected size, and whether there is likely to be evidence on the surface of the seabed.

9.3.2.1 Shipwreck prospection

For prospection the three main techniques that are generally considered are multibeam bathymetry, sidescan sonar, and magnetometer. Sub-bottom profilers only collect data beneath the transducer(s) so their use in prospection is limited. Assuming the prospection survey involves the identification of shipwrecks or material that has features proud of the seabed, the two primary techniques that will be considered are multibeam bathymetry and sidescan sonar, each with their own advantages and disadvantages:

- Magnetometer data can be useful in prospection surveys for the identification of large ferrous anomalies, such as wrecks containing guns or a significant amount of iron, or those constructed of iron or steel. However, the typically wide line spacing used during prospection will significantly increase the minimum object detection size. Magnetometer data are of particular use in aiding the interpretation of seabed features identified in other datasets.

- Sidescan sonar is generally easier to deploy than multibeam bathymetry. The data are less time consuming to process and ranges each side of the survey line can comfortably reach 100 m whilst still being operated at a high frequency (400 kHz to 500 kHz), allowing a resolution suitable for the identification of features >0.5 m. Whilst the minimum object detection for sidescan sonar is quite small, as a two-dimensional technique there may be instances where a slight mound, potentially indicating a buried shipwreck, might not be visible.

  When line planning, consideration should be given to the nadir region where features may be obscured due to the lack of data. For prospection of large features, a line spacing of two times the range minus 10% is generally sufficient (equating to 100% coverage minus the nadir region). Where the feature may be obscured by the nadir region line spacing should be the range minus 20% (equating to 200% coverage including the nadir region) (Figure 49). The reduction in line spacing, compared to the range, is to mitigate the effects of errors in line keeping and towfish movement. Crosslines should be collected at ten times the mainline spacing.

- The use of multibeam bathymetry can have advantages, both in terms of seabed coverage across the full width of the swathe, and the collection of a three-dimensional dataset. However, the minimum object detection is typically larger than with sidescan sonar and increases with water depth. For the prospection of wrecks, a minimum object detection of 2.0 m is likely to provide sufficient detail and is within the capabilities of most multibeam sonars operating at a frequency of >350 kHz. Line spacing should be planned to achieve 100% coverage, with sufficient overlap to mitigate the effects of roll, and errors in line keeping. The line spacing will depend on depth, at a swathe angle of 120°, coverage is equivalent to c. 3.5 times the water depth and survey lines should be run at approximately 3.0 times the water depth.

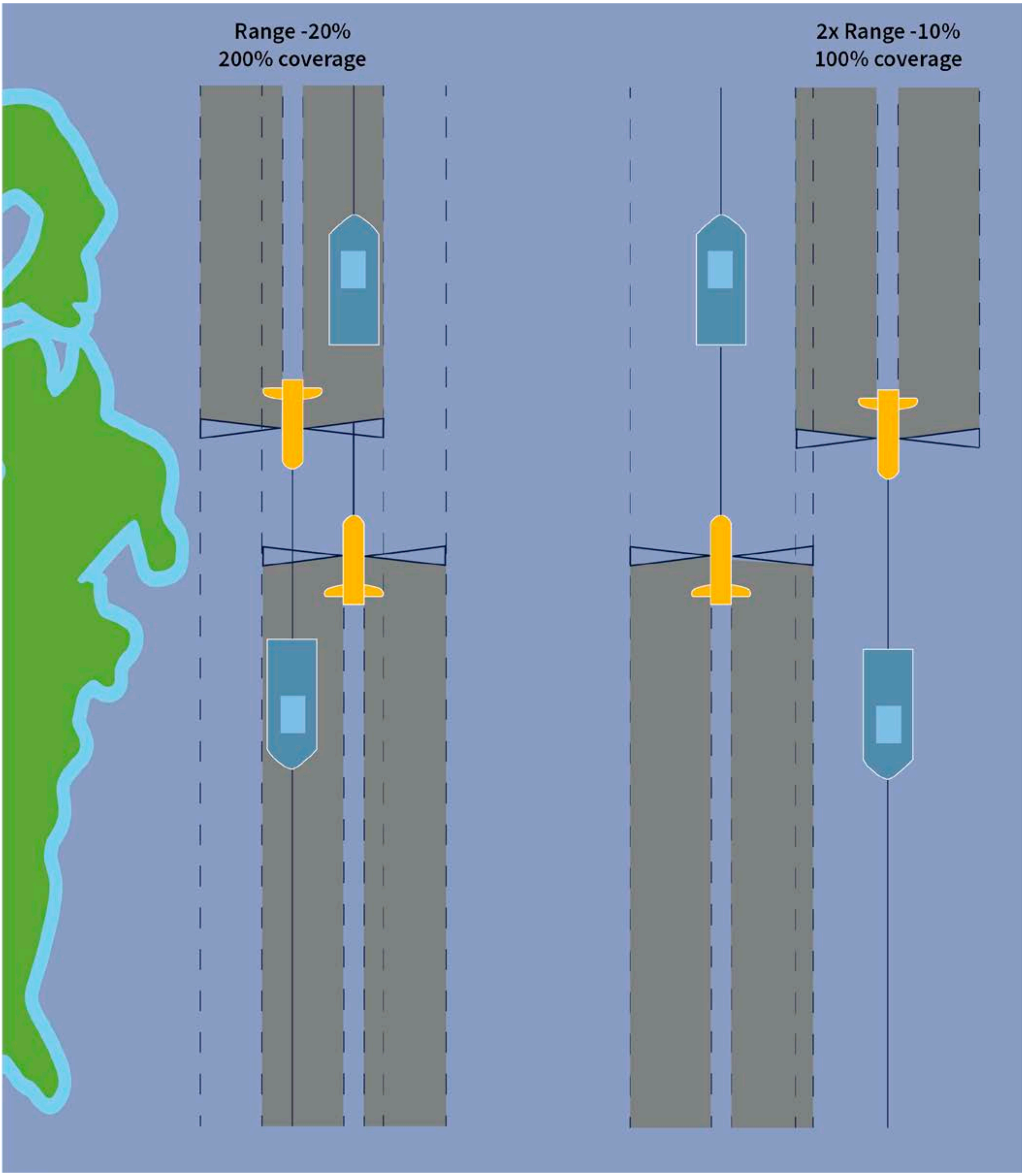

Figure 49: Sidescan sonar line spacing and resulting coverage.

9.3.2.2 Shipwreck site survey

Following a prospection survey, desk-based research, or as part of the monitoring or management requirements, higher resolution survey at a localised site (shipwreck) scale may be required. This may be to collect further information from which to fulfil the research question(s), or to collect higher resolution data to provide a higher level of detail. It may also be that the site was identified in other survey data and interpretation or planning for further works would benefit from three-dimensional data. Alternatively, the site could have been identified visually in previous data but is partially buried and would benefit from sub-bottom profiler survey to establish the buried extents or a magnetometer survey to identify outlying debris.

Whilst this guidance is focused on geophysical techniques, there should be an awareness that other survey methods may (both in terms of resources and output) result in going towards answering research question(s) in a more effective way. Other methods, such as diver or Remotely Operated Vehicle (ROV) surveys may be better suited to shipwreck site investigations. Such as utilising photogrammetry, Electro Magnetics (EM), visual inspection or manual recording techniques.

For geophysical survey the specification will depend on the aims, but the following guidelines should be applied:

- **Survey speed** – where possible, the survey speed should be reduced to 3.0 knots, increasing data resolution and density. Where the effects of currents mean that reducing to a low speed affects steerage, consideration should be given to running all lines into the current.

- **Multibeam bathymetry** – multibeam bathymetry data should be collected at the highest resolution available, in general terms the use of frequencies <350 kHz are not suitable for the detailed survey of shipwrecks. Very high frequency systems (c. 700 kHz) are available which result in a significant increase in resolution, however they are more susceptible to noise and erroneous data points, especially within the potentially contorted forms of steel wrecks. Additionally, the water depth in which they can be used effectively is limited. Therefore, the use of very high frequencies should be trialled onsite prior to data collection. The data collection methodology should be aimed towards the ensonification of all components of the shipwreck including, where possible, upstanding, or inverted features such as the hull. This can be achieved by making use of the angular distribution of the beams (Figure 50). Each shipwreck will be different, but the following is a good guide from which to base the survey design, noting that line planning will often have to be undertaken on site, and adjustments are often needed as the survey progresses.

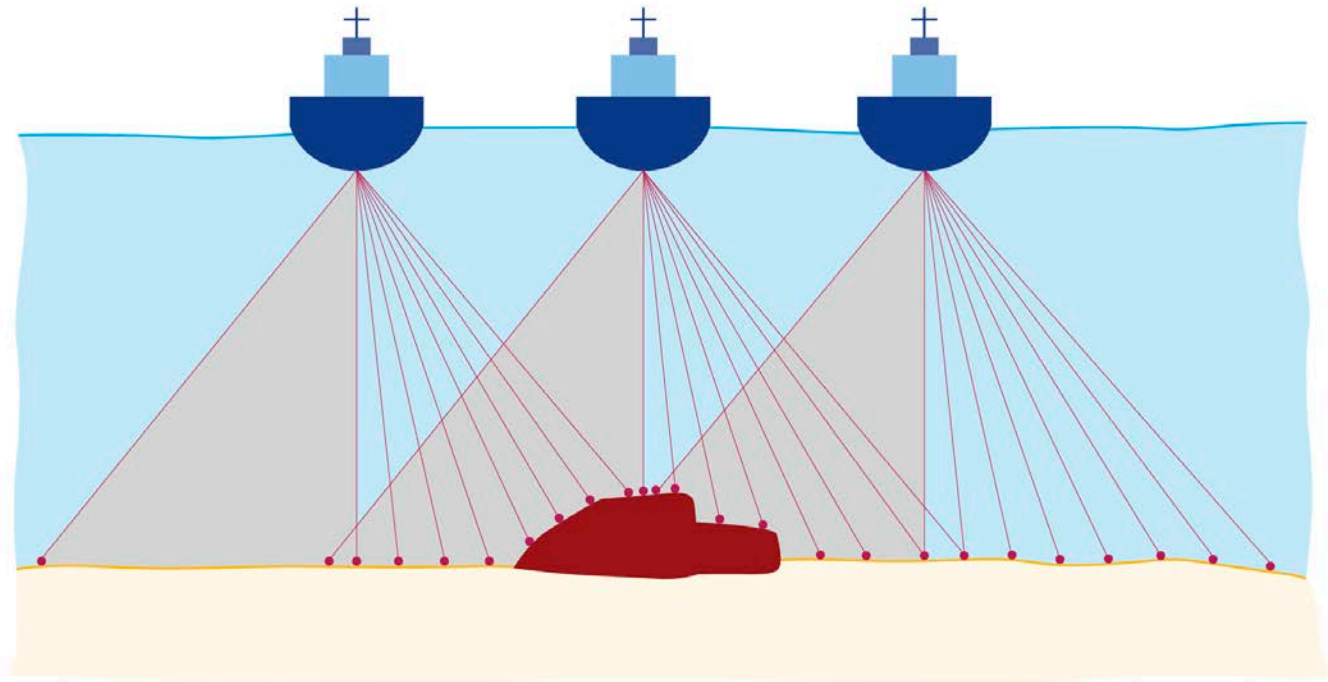

Figure 50: Multibeam bathymetry coverage.

The survey should achieve a minimum of 200% coverage of the shipwreck. In depths of less than 30 m, full coverage at a cell size of 0.1 m should be achieved, and in depths of less than 50 m full coverage at a cell size of 0.25 m. Most acquisition software will allow for a visual representation of coverage, both visually as data filled cells, or data density. Initially, a line of data should be collected over the site, typically at a wide swathe angle, from which the position and orientation can be used to plan the lines for the survey. The line plan should include a line directly over, and along the centre line of the shipwreck, with adjacent lines and coverage extending to a minimum of 100 m in all directions from the extents of the site, and at a line spacing to achieve the specification in the depth of water. Cross lines should be collected across the site, at a line spacing designed to achieve an additional 100% coverage. Following data collection, the data should be assessed to establish whether any additional lines are required to ensonify any upstanding, or inverted, elements. Where additional data is required, this can be achieved by planning lines to make best use of the angles of the beams, whilst also narrowing the swathe angle and rotating the swathe towards the upstanding elements.

- **Sidescan Sonar** – sidescan sonar data should be collected at the highest resolution available, and at a minimum frequency of 400 kHz but ideally higher, such as 900 kHz where available. For a 400 kHz, or similar, system, the range should be reduced which will increase the along track resolution. The data should be collected away from the outer extents, where resolution is reduced. Initially, a line of data should be collected over the site. This would use the full range, from which the position and orientation can be used to plan the lines for the survey.

For shipwrecks, a line of data should be collected along each side of the shipwreck, aiming to image the whole site in one pass on both lines. The lines should start and stop at least 100 m from the shipwreck but should be extended if debris is noted during collection. A minimum of two further adjacent lines should be collected each side, ensuring that the nadir region of the adjacent line is covered by adjacent lines. At a range of 50 m, a line spacing of 40 m (range minus 20%) will achieve the desired outcome of 200% coverage, including the nadir region. It is good practice to collect cross lines to aid in the assessment of navigation offsets and the visualisation from different angles. For sites <100 m this should be directly over the centre, with longer sites cross lines should also be collected at each end.

- **Magnetometer** – magnetometer use on a previously identified shipwreck is typically limited to establishing the extents of any debris field or, for example, the identification of ferrous items such as guns or anchors that may aid in the assessment of the wrecking process. As is critical with all magnetometer surveys, the minimum object detection must be determined to effectively plan the line spacing. In most instances to identify material within a debris field, a line spacing of 10 m, an altitude of 6.0 m, and an update rate of 4.0 Hz will be sufficient, giving a minimum object detection of approximately 250 kg, and an across track positional accuracy of +/- 5.0 m. Where small items of debris are required to be identified, such as those from an aircraft, a line spacing of 5.0 m and an update rate of 10 Hz should be considered, as should the use of a towed array and a specification more in line with that used for the identification of pUXO.

Figure 51: CISMAS undertaking magnetometer survey of HMS *Colossus* during a Historic England funded research project. © CISMAS

- **Sub-bottom profiler** – within a shipwreck context, the use of a sub-bottom profiler is predominantly for the identification of the extents of buried, or partially buried shipwrecks, or to help understanding of the depth of burial. Shipwrecks are likely to be buried just beneath, or at minimum distances from the seabed so the use of high frequency, low penetration, systems such as Pinger, Chirp or Parametric are recommended to gain the highest vertical resolution possible. This should be combined with a fast ping rate to increase along track data resolution. For two-dimensional surveys parametric sub-bottom profilers are recommended due to the data being less noisy, with excellent vertical resolution, and a significantly higher ping rate than other systems. However, the use of three-dimensional systems are likely to obtain the best overall results and their use should be considered.

Surveys should be undertaken using a grid, as opposed to parallel lines, to enable the identification of material evenly across the site, as well as ensuring linear features are identified. The size of the grid will depend on the size of the site, with smaller sites potentially requiring a grid of a few metres, to larger sites where 5.0 m to 10 m may be sufficient. Three-dimensional systems based on Chirp technology, or multi-transducer systems, can collect high density data which can be processed into true three-dimensional outputs.

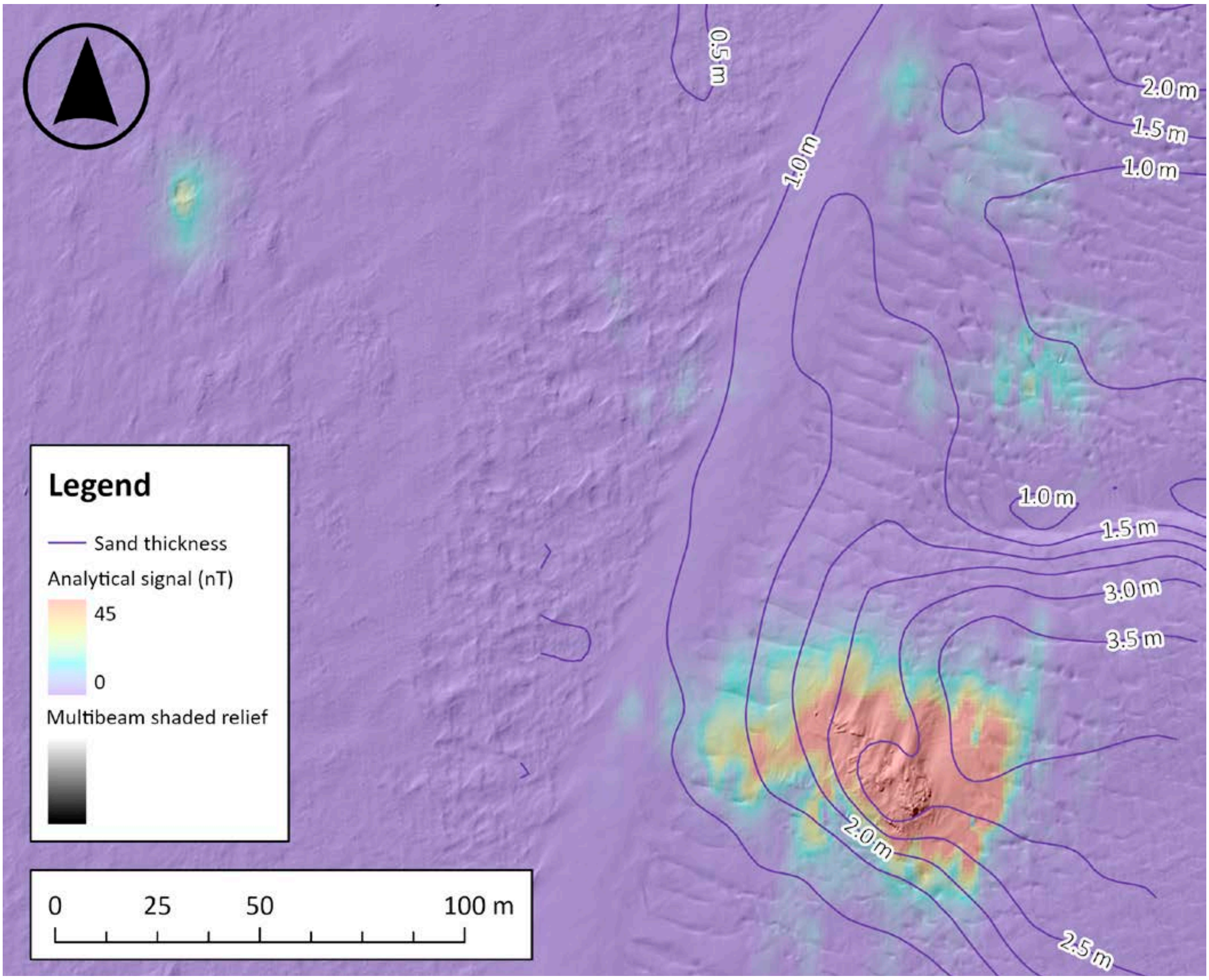

Figure 52: Example of multiple datasets used during interpretation. Hill shaded multibeam bathymetry overlain with a magnetometer analytical signal grid, and contours representing thickness of deposit derived from a sub-bottom profiler. Data collected over the wreck of the *Northumberland*.
©MSDS Marine for Pascoe Archaeology, funded by Historic England

9.4 Survey planning

9.4.1 Licences and permissions

Some geophysical surveys may be exempt from a Marine Licence; however it is the responsibility of the surveyor to establish if a Marine Licence or other permissions or consent is required, including for heritage assets that might be subject to statutory protection, or where geophysical surveys may impact marine mammals. Particular attention should be paid to permissions that may be required when undertaking survey operation within ports and harbours and where Vessel Traffic Services (VTS) are established. VTS are maintained by port authorities within their area of jurisdiction and include vessel separation schemes and restricted areas.

For geophysical surveys that are being undertaken over scheduled monuments a licence is likely to be required under Section 42 of the Ancient Monuments and Archaeological Areas Act 1979 for magnetometer and sub-bottom profiler surveys. The application and administration of licences is the responsibility of Historic England.

Whilst not a legal requirement under the Protection of Wrecks Act (1973), it is best practise to inform Historic England using their online reporting form when undertaking survey operations over protected wreck sites[7] in English waters.

9.4.2 Archaeological input into survey planning

Advice should be sought from a suitably qualified and experienced individual or organisation to steer data collection, processing, and interpretation of geophysical data during the survey planning process to ensure an appropriate specification is agreed to meet the aims and archaeological objectives of the survey.

When planning a survey, the following should be taken into consideration:

9.4.2.1 Survey specification

Is the survey specification and design suitable to meet the aims and answer the research question(s)? If not suitable, how can the design be revised to ensure it is able to meet the archaeological requirements? The following should be considered:

- Positioning (surface and subsurface – see Section 3)
- Sensors
- Coverage
- Minimum detection size
- Penetration

7 https://historicengland.org.uk/advice/planning/consents/protected-wreck-sites/applying-for-licensing/

What are the limitations of the survey, and therefore what is the risk (from an archaeological perspective) to the project with the proposed specifications and survey design?

How can any risks be mitigated? The following should be considered:

- Additional survey requirements
- Detailed Desk-Based Assessment
- Survey techniques other than geophysical survey, for example, survey undertaken by divers, remotely operated vehicle or drop down video, etc.

9.4.3 Data requirements

Are the data deliverables suitable to meet the requirements of archaeological assessment? Consideration should be given to:

- Data formats
- Level of processing

9.4.4 Curatorial Input into survey planning

For surveys commissioned by curatorial agencies, the methodology and the specification will either be provided by, or approved through, a project design or method statement. This document will include all the pertinent information required by the curator to approve the specification. Example contents are detailed in Section 10.

9.5 Archaeological assessment of the resulting data

The requirements for the archaeological assessment of data will depend on the aim of the survey and the research question(s) to be answered and should be in line with the project design. The archaeological assessment may be as simple as the plotting of positions of features identified during a prospection survey, or as detailed as the assessment of the wrecking process and distribution of a debris field of a shipwreck, using data from multiple techniques (Figure 52) or the creation of accurate georeferenced site plans (Figure 53).

The assessment should be undertaken by, or under the guidance of, a qualified, and experienced, marine archaeologist with a proven background in the collection, processing, and interpretation of geophysical data. The assessment should be undertaken in line with the project design. Where changes are required to be made to the specification, this should be discussed and agreed with Historic England.

Guidance for the archaeological assessment of geophysical data are detailed in Section 11.

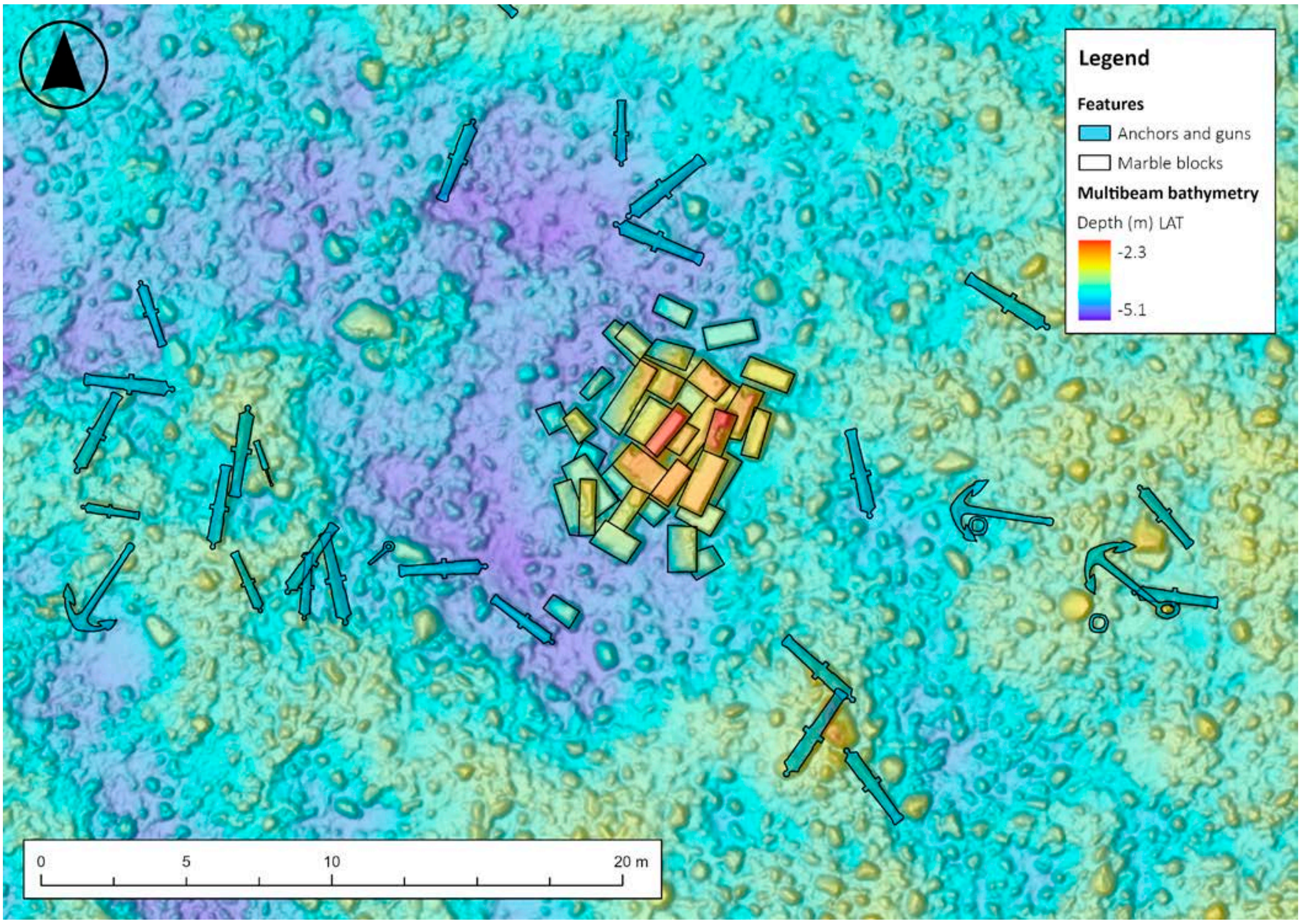

Figure 53: Multibeam bathymetry data used as a basemap to create an accurate, georeferenced site plan.

10. Method statements

The production of a method statement (within the context of the marine development process or a project design (within the context of Historic England commissioned projects), is the primary mechanism for which the methodology for the collection, processing, and interpretation of geophysical data can be agreed with the archaeological curator.

Method statements should clearly define the aims of the survey, how they will be achieved, and the deliverables. Whilst being succinct they should contain enough technical detail to demonstrate that the specification of the survey is suitable to meet the archaeological objectives. Where a method statement is being produced as part of the marine development process, it should make reference to the WSI[8] where applicable.

The contents of the method statement will depend on several factors including the aims of the survey, the techniques to be deployed, and the intended outcome. However certain information must be included, and the structure below is an example of how this can be achieved.

10.1 When is a method statement required

In the context of the marine development process the requirement to produce archaeological method statements for post-consent geophysical surveys will be detailed within the WSI. A method statement will guide individual surveys to ensure that archaeological objectives are met. Geophysical survey method statements for archaeological purposes are not typically produced pre-consent where the scope is driven by the overarching project requirements for EIA. However, where clarification is required from the archaeological curator, they can be a useful exercise to agree specifications and methodologies in advance.

Where data is being collected by, or on behalf of, a third party (such as a developer or geophysical survey contractor) the method statement should be produced when the specification of the survey is known. This may be prior to the appointment of a geophysical contractor if the broad specification of the survey has been established or following the appointment of a geophysical contractor where further details of the survey are potentially known. This highlights the importance of archaeological input during the planning phases to ensure that the survey specification is suitable to meet the required archaeological objectives.

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8 The Crown Estate, 2021. Archaeological Written Schemes of Investigation for Offshore Wind Farm Projects.

Method statements should be approved by the archaeological curator prior to the survey commencing, with sufficient time allowed for curatorial review and the addressing of any comments that may arise.

10.2 Method statement production

The method statement should be compiled by the archaeological contractor. Within the context of the marine development process, it is likely to require input from the client, and potentially their geophysical contractor, to ensure the presentation of the appropriate specifications.

Where information is not known, for example where the geophysical contractor has not be appointed, this should be noted within the method statement.

10.3 Method statement template

Table 9 below provides an example structure and suggested content for a method statement.

Table 9: Example structure and suggested content for a method statement.

Summary	Things to consider
1 Introduction	
The introduction should provide a brief overview of the project.	• The name of the project. • The organisation producing the method statement and any external expertise that has been provided in the compilation. • The client. • Document reference, version and date. • The purpose of the method statement.
2 Location	
This section should define the location and the status of the project.	• The distance in m or km, and the direction, from an identifiable location on shore, usually a town or a named location. • Whether the project falls within inshore waters (up to 12 nm from the normal tidal limit (NTL)), or in offshore waters (between 12 nm and 200 nm from the NTL). • The size of the survey area, or the development in m^2 or km^2. • The legal or consenting status of the site or the development and any licenses or permissions that may be required. • A figure showing the location of the project, clearly showing the location in relation to a landmass or other recognisable feature.

Summary	Things to consider
3 Aims and Objectives	
The aims and objectives of the project should be clearly, but concisely, stated.	• Aims focus on what the project intends to achieve. • Objectives focus on how the aims will be achieved. • Reference to relevant research frameworks.
4 Methodology	
The methodology should contain all the information about how the survey will be conducted, how the data will be processed, and how the assessment and interpretation will be undertaken. The suggested sub-sections will ensure that all key information is included.	
4.1 Data Collection	

This section should include information related to data collection.	• Who will be collecting the data?
	• When will the data collected?
	• The specification of the survey, including:
	  ◦ The sensors to be used (including positioning)
	  ◦ Frequencies/ranges/penetration
	  ◦ Deployment method
	  ◦ Line spacing
	  ◦ Coverage
	  ◦ Expected resolutions
	  ◦ Minimum object detection size
	  ◦ The coordinate reference system
	• Data deliverables.
	• The format the data will be output in, both raw and processed.
	• Where pre-planned, figures should include coverage, and/or line plans, of all sensors.

4.2 Data Processing	
The data processing workflow for each sensor should be provided.	• Software to be used, including version number. • Input data format. • Corrections to be applied. • Settings to be applied, including gains and filtering. • Output data format. • Final resolution.

Summary	Things to consider
4.3 Archaeological Assessment and Interpretation	
The archaeological assessment and interpretation workflow for each sensor, and all sensors combined should be provided.	• The assessment parameters, including thresholds, scope, and area. • How the data will be reviewed. • How the data will be assessed. • The assessment criteria. • Software to be used, including version number. • Additional data sources that will be consulted. • Data output formats.
4.5 Mitigation	
Although mitigation falls outside the scope of this guidance, it will typically form part of the Method Statement.	• Mitigation criteria (what should be subject to mitigation). • Mitigation strategies that will be considered.

5 Deliverables	
The expected deliverables from the survey, including the report, should be clearly defined.	• Deliverables. • Deliverable formats. • Distribution. • Timescales. • Data management plan. • Archiving.

11. Interpretation

The archaeological interpretation of geophysical data follows on from the data collection and data processing phases. It is the mechanism by which the archaeological aims and objectives of the survey will be met. The requirement for interpretation will be detailed within the method statement (Section 10) and will depend on the project aims. With a significant number of variables, software packages, and data outputs, this section can only provide general guidance. Examples of archaeological interpretation can include:

- The identification and spatial distribution of sites identified during the survey.
- The identification of anthropogenic features, and the assessment of archaeological potential.
- The identification of geological units, or sub-seabed sediments, and the assessment of archaeological potential.
- Site formation processes and assessments of change.
- The monitoring of threats.
- Site specific assessments.

11.1 Data suitability

Exported data formats, in relation to geophysical survey, will change from the as collected (raw) data, through to the final processed deliverables. The data format, or formats, used will depend on the requirements of the interpretation, and each should be considered on its own merits. The processing that data may have been subject to should be understood as they can affect interpretation.

Table 10 below details six primary data outputs that are typically available following geophysical survey.

Consideration should be given to different data formats and the limitations of each for interpretation in relation to the aims. Achievable results will be dictated by the survey specification and the data format. For example, if the aim is the identification of all anthropogenic debris >0.3 m, this will generally require the interpretation of navigation corrected sidescan sonar data. If the aim is to plot the spatial distribution of iron or steel shipwrecks, this may be achievable through the review of a multibeam bathymetry dataset that has been processed, gridded, and exported as a geoTIFF.

Third party interpretations made by survey contactors can inform the archaeological interpretation processes where appropriate, and where the limitations are understood. However, archaeological analysis, including the assessment of potential, must be undertaken by a suitably qualified and experienced practitioner. This will be a marine archaeologist suitably trained in the interpretation of geophysical data, or for example a geophysicist or a geologist, suitably experienced in archaeological interpretation.

Table 10: Geophysical data outputs.

Data Type	Description
Raw	Raw data are data that are in the original, as collected, format, with no adjustments made or processing undertaken. Typically, the data will contain embedded navigation data or will be supplied with separate time stamped navigation files.
Navigation corrected	Navigation corrected data will be in its collected format. The difference between raw and processed navigation corrected data is that the navigation will have been processed, ensuring the data are positioned correctly. No other adjustments or processing will have been completed.
Processed	Processed data will have had changes made that will, in most cases, alter the original data. With the potential removal, or averaging, of data the ability to undertake archaeological interpretation may be affected including an increase in the minimum object detection size. The impact will however depend on the level of the processing undertaken and the software used.
Gridded or sub-sampled	Processed data can also include gridded, sub-sampled, or interpolated datasets. The resultant data will have been reduced in resolution (spatial and temporal), with the as collected positions of datapoints either removed, altered, or new data points created through the averaging process.
Mosaics and files in geoTIFF format	Georeferenced images are typically the final output of most geophysical data processing. They allow a visual representation of the collected data. Where they have been created from gridded data they are typically produced at the native resolution, i.e. one pixel is equal to one grid square. Files in geoTIFF format should include z data such as amplitude, altitude, depth, or depth/time below seabed, enabling alterations to colour scales, and shading within GIS software, as well a data extrapolation and analysis.
Third party Interpretations	Interpretations made by third parties (survey contractors) typically form a deliverable of marine development surveys. The interpretations may include geological horizons, seabed features, or magnetic anomalies. As with processed data deliverables, the limitations should be understood, and the data from which interpretations have been made should always be available for independent review.

11.2 Data quality

The quality of the data directly influences the ability to undertake an effective archaeological assessment. As detailed in previous sections, data should be subject to a quality control process to ensure suitability for interpretation, recording any issues which may impact the assessment in relation to the aims of the method statement. Examples may include a shallower penetration of sub-bottom profiler data than expected; magnetometer altitude higher than the specification increasing the minimum object detection size, or the effects of weather in sidescan sonar data producing data artefacts obscuring large areas.

The presentation of the data quality will depend on the organisation interpreting the data and producing the report. This is typically in the form of assessment against pre-determined criteria, a discussion, or a combination of both. The assessment should be presented within the report as clearly as possible. To allow the reader to identify the limitations of the interpretation easily, the inclusion of examples should be considered. The assessment of data should be made and presented in relation to each dataset independently. The assessment criteria presented in Table 11 can be a good starting point where no organisational guidance is in place.

Table 11: Data quality assessment criteria.

Quality	Description
Very low quality	Data that have multiple or significant issues with quality or navigation, that cannot be corrected, or of a quality so low that archaeological interpretation cannot be undertaken.
Low quality	Data that has some issues with quality or navigation that cannot be corrected. The data are suitable for archaeological interpretation, but with a notable reduction in the ability to undertake archaeological interpretation to the required specification.
Good quality	Data that has correctable, or minor issues with quality or navigation. Overall, the data are suitable for archaeological interpretation to the required specification.
Very good quality	Data free from quality or navigation issues above acceptable tolerances. The data are suitable for archaeological interpretation, to the required specification, across the extents of the survey area.

11.3 Data interpretation

The interpretation of geophysical data is, by its very nature, subjective. However, with experience and by analysing the form, size, and characteristics of an anomaly, a reasonable assessment as to the potential origin can be achieved. It should be noted that there may be instances where an anomaly may exist on the seabed but not be visible in the geophysical data, or visible as a form that may suggest a different type of feature, even when data has been collected to an appropriate specification. This may be due to several reasons, such as being too small for detection, being covered by sediment or obscured by other features, for sensor specific reasons such as large magnetometer anomalies obscuring smaller ones, or gas blanking (shallow gas restricting penetration) within sub-bottom profiler data affecting penetration.

Data interpretation parameters will be defined within the project design or method statement and should be adhered to throughout the interpretation process. For marine development projects, the parameters will be informed by the stage of the development. For example, survey data resolution sufficient for environmental characterisation of a proposed development area will potentially be different to the higher resolution required for detailed design and delivery, prior to construction.

The archaeological assessment of geophysical data is a specialist task and should be undertaken by a professional, accredited and experienced person. This may be a marine archaeologist with a proven background in marine geophysical data collection, processing and interpretation, or a marine geophysicist/geologist under the direction or supervision of a marine archaeologist.

There may be instances where interpretations of data have been undertaken by third parties commensurate with the specification required for further archaeological assessment. Following quality control, there may be instances where these outputs are acceptable for use subject to further archaeological interpretation. Their use can avoid the replication of effort between end users of data and therefore result in a reduction of time and expenses and ensure continuity across the project. For example, magnetic anomalies identified for the purposes of further interpretation as to the identification of pUXO (assuming all anomalies within the specified range for archaeological assessment are identified) will typically result in an anomaly dataset that would correlate with magnetic anomalies picked by an archaeologist.

The crucial step is the interpretation of those anomalies, including the distribution, for archaeological potential which must be undertaken by an archaeologist. In comparison, the use of seabed features identified in sidescan sonar data by a third party would not be considered acceptable, due to this requiring archaeological interpretation.

The following examples assume the data have been processed as in the proceeding sections. However, it should be noted processing software generally allows for interpretation, and processing and interpretation may be undertaken concurrently. A further assumption made is that the data being assessed are of the highest resolution achievable. Measurements can be taken in most data processing and/or interpretation software, and whilst largely accurate, discrepancies can be noted due to several factors.

11.3.1 Multibeam bathymetry

The minimum object detection size of multibeam bathymetry data is typically larger than with sidescan sonar data. Often the primary use during archaeological assessment is seabed characterisation and the corroboration of anomalies identified within other datasets. This can include the visualisation of anomalies that may otherwise be obscured by shadow.

Several software packages allow the concurrent assessment of multibeam bathymetry and sidescan sonar data. Where this is not possible, multibeam bathymetry data should be viewed on a user defined block-by-block basis. All anomalies of potential archaeological interest should be identified. Each anomaly should be accompanied by a position, description, length, width and height measurements, and an image. Results should be exported as a .shp file containing the above information. Images should be at a size covering the extents of the anomaly and at a resolution where detail from which the interpretation is based can be seen. This would be the resolution of the source data.

Over large areas the interpretation of multibeam bathymetry data is not practical in three-dimensions with a navigation corrected point cloud and thus requires a dataset that can viewed in two-dimensions. This is most easily achieved using gridded data exported as a geoTIFF. An appropriate colour scale and shading should be applied to highlight anomalies that may be of archaeological interest. Where there is doubt as to the origin of an anomaly, an assessment of the navigation corrected, but un-gridded dataset, should be made, and therefore the dataset should always be available within the data deliverables.

Third party interpretations, including the assessment of images of features that may have been captured during interpretation for other purposes, should not be used for archaeological assessment. Such datasets lack context and cannot confirm that all anomalies have been identified. It is often the case that slight nuances within the data or distribution patterns of features will be identified by an archaeologist as of potential archaeological interest but may not be identified during the interpretation of the same data for other purposes.

11.3.2 Sidescan sonar

Sidescan sonar is an effective technique for the identification of anthropogenic anomalies on the seabed due to the ability to ensonify small features. Therefore, accurate interpretation is essential. Sidescan sonar data should be reviewed on a line-by-line basis by a marine archaeologist, using raw or navigation corrected data, and all anomalies of potential archaeological interest identified. Each anomaly should be accompanied by a position, description, length, width and height measurements, and an image. Results should be exported as a .shp or .csv file containing the above information. Images should be exported at a size covering the extents of the anomaly and at a resolution where detail from which the interpretation is based can be seen. Ideally this would be the resolution of the source data.

The mosaicing of sidescan sonar data nearly always results in a loss of resolution, a reduction in the percentage of the overall dataset that can be viewed (due to the overlap between lines), and the loss of the ability to adjust gains to ensure the optimal presentation of data. The use of mosaiced data for the identification of anomalies is therefore not recommended.

Third party interpretations of sidescan datasets, including the assessment of images of features that may have been captured during interpretation for other purposes, should not be used for archaeological assessment. Such interpretations lack context and cannot confirm that all anomalies have been identified. It is often the case that slight nuances within the data or distribution patterns of features will be identified by an archaeologist as of potential archaeological interest but may not be identified during the interpretation of the same data for other purposes.

11.3.3 Magnetometer

Magnetometer data indicates the presence of ferrous, and thus usually anthropogenic, material both on, and under the seabed. Where line spacing allows, typically to a specification for the detection of pUXO, magnetometer data can provide accurate positions of ferrous anomalies. These may not be visible within sidescan sonar or multibeam bathymetry datasets.

Archaeological interpretation of magnetometer data can be the most subjective when assessing archaeological potential. Where there is no surface expression in other datasets, a large magnetometer anomaly could represent buried material of archaeological interest or equally modern debris. A distribution of small magnetometer anomalies over a large area could represent a debris field of archaeological interest, or small items of modern debris commonly found on the seabed. Therefore, interpretation should always reference the archaeological potential of the area. For example, known shipping lanes or navigational hazard locations have the potential for an increase in the density of shipwrecks.

The interpretation of magnetometer data should aim to identify all anomalies above the amplitude from which the minimum object detection size was calculated so that further interpretation can be undertaken. Where noise in the data allows, smaller anomalies should also be identified. Interpretation should be undertaken using time series plots, alongside grids or contours (total field and residual), the combination of both providing not only the location of the anomaly on each line, but the overall extents, and the wider distribution. Several software packages allow the concurrent assessment of magnetometer data alongside multibeam bathymetry and sidescan sonar data, which can aid in interpretation. All anomalies should be identified and recorded with the position, the amplitude, the type (i.e. dipole, positive monopole, negative monopole), the length along the track, the width following assessment of multiple lines, and an estimation of ferrous mass. Where the software package does not allow for the calculation of mass, and where manual calculations of ferrous mass for each anomaly would not be feasible (i.e. across the extents of a large development) a clear statement should be made outlining the minimum object detection at a range of amplitudes to allow for the assessment of potential. Results should be exported as a .shp file containing the above information.

Magnetometer data differ slightly from the visual techniques, in that initial interpretation relies less initially on the assessment being of archaeological potential and more with determining the presence of ferrous material. Establishing the presence of ferrous material will then be followed by archaeological assessment of the dimensions and distribution of ferrous mass to establish the archaeological potential.

Magnetometer data in relation to marine development, particularly offshore wind farms, is typically collected to identify pUXO, with the specification for collection, processing, and the identification of anomalies being commensurate with the requirements for archaeology. The archaeological assessment of anomalies identified by a third-party for the purposes of the identification of pUXO can be considered if the processing and anomaly picking parameters are understood, align with the archaeological requirements and a quality control process is undertaken.

Navigation corrected data should always be available (including for the quality control process) and should be reviewed. Where there is doubt as to the shape or distribution of an anomaly, or in areas of high potential, there may be a requirement to consider smaller anomalies than the minimum threshold. This is particularly pertinent where there is a high potential for aircraft crash sites, as these can often result in a wide distribution of small anomalies.

11.3.4 Sub-bottom profiler

Sub-surface data acquired from sub-bottom profilers is key to understanding the palaeolandscape and prehistoric archaeological potential within the survey area. It should however be noted that interpretation is best achieved alongside the assessment of geotechnical samples, and therefore the interpretation process can be protracted and subject to refinements over a longer period than with other datasets. Interpretation should also consider bathymetry data for the assessment of the current seabed topography, and the identification of surface features in relation to the palaeolandscape. Interpretation should always be made with reference to existing data, including geological maps from the British Geological Society (BGS), the results of previous studies, and extant geotechnical data collected within the wider area.

The archaeological interpretation of sub-bottom profiler data should aim to identify and map sedimentary units and features based on their seismic character and likely depositional environment. Interpretations should be correlated with known geological formations in the area, using existing data, such as that from the BGS. The level of assessment that may be required, including reviewing a percentage of the dataset (i.e. not every line), will be determined by the palaeolandscape potential of the survey area, and may vary between regions. A broad scale assessment of the area may highlight areas of greater archaeological potential, or complexity, that may require the review of additional data to resolve.

Interpretation techniques will be dependent on the type of data and the spatial alignment (i.e. two- or three-dimensional, line spacing, etc.). However, for a typically two-dimensional dataset interpretation should be undertaken on a line by line (or profile by profile) basis using navigation corrected data with all horizons, changes in lithology, and features recorded. Records should include descriptions of the acoustic properties and the depth below seabed. Units should be correlated between lines, and cross lines. The results should be built into a ground model, with horizon grids, isopachs and isochrons exported to allow the identification of extents, depths, and thickness over the survey area. The resultant data should then be correlated with existing geological data and be subject to geoarchaeological assessment to establish the archaeological and palaeoarchaeological potential of each unit, sub-unit, or feature. Images should be taken of profiles, or sections of profiles, of potential archaeological interest. These should clearly display the depth below seabed or elevation, the interpretation, and the start and end positions.

The line-by-line interpretation of sub-bottom profiler data should be undertaken by a marine archaeologist with demonstratable knowledge of Quaternary stratigraphy, or a marine geophysicist/geologist under the direction or supervision of a marine archaeologist. The extent of the assessment, both geographical and percentage of data viewed, should be informed by the archaeological potential as defined by the desk-based assessment. Following a quality control process, the results and select profiles from third-party interpretations can be used to inform the assessment of potential and therefore the extents of targeted assessment. Whilst third-party interpretations will present main geological units, and features, they may not always interpret small-scale nuances in the data that may indicate archaeological potential, and any limitations should be understood.

Due to the intrinsic link between the interpretation of geophysical data and geotechnical material, the overall interpretation strategy to produce a sedimentary ground model should be detailed within an archaeological Written Scheme of Investigation where appropriate. Consideration should be given to overall timescale for delivery of a final ground model which will be related to the phase of the development to which the interpretation relates, the level of assessment required and the timescales of the geophysical and geotechnical campaigns.

11.3.5 Combined assessment

Following the assessment of all available survey data, a combined assessment should be undertaken through a correlation exercise which should amalgamate duplicate anomalies that are either seen on different lines of the same dataset, or those that are seen across different datasets. Further, the combined assessment will develop an understanding of the extent of a feature that may be partially buried, or span across two or more lines of data. Typically, this is undertaken within a GIS platform or geophysical software, with the results of the individual assessments imported in .shp file or .csv format, along with files in geoTIFF format created from grids or mosaics.

Data from the United Kingdom Hydrographic Office (UKHO), including the positions of wrecks and obstructions, Historic Environment Records (HER) and National Marine Heritage Record (NMHR) data, as well as all other relevant data such as third-party assets should be imported, and assessed concurrently to ensure that any additional information is drawn upon. This will ensure that anomalies are not unnecessarily identified as having archaeological potential when their origin can be identified. The resultant remaining anomalies assessed as having archaeological potential should be compiled into a gazetteer and exported as a shapefile containing all relevant information.

The use of other available datasets should be considered, including bathymetry data available from the ADMIRALTY Marine Data Portal maintained by the UKHO, geological data available from the BGS, and offshore data available from the Marine Data Exchange maintained by the Crown Estate. This data can provide additional context to interpretations and aid in the assessment of, for example, seabed dynamics or changes to a site over time.

11.4 Artificial Intelligence and automated anomaly identification

At a basic level, automated anomaly or feature detection has been available within geophysical software for some time. This can be, for example, the identification of magnetic anomalies through variations in magnetic field strength, the identification of boulders in sidescan sonar data based on high amplitude returns with corresponding areas of acoustic shadow, or the identification of the seabed (bottom tracking) and horizons in sub-bottom profiler data. Although software dependant, the automated process is typically constrained by parameters defined by the user. The effectiveness of these processes is determined by not only an understanding by the user of the parameters, but also to a large degree the quality and complexity of the data.

Sizable increases in data quantities relating to offshore developments, and particularly the construction of offshore wind farms, is leading to an increased use of automated processes. Artificial intelligence (AI) (the concept of enabling a machine or system to sense, reason, or adapt) and Machine Learning (ML) (enabling machines to learn from data to undertake specific functions) is being developed to increase both the accuracy and efficiency of these processes. With more data collected and input, the more accurate the results will likely be due to the learning process.

Caution should be exercised with the results of automated processes. Whilst, for example, the automated identification of magnetic anomalies is commonplace, and largely relies on identifying changes in the magnetic field that would be identified manually, there is no reliable automated process (at the time of writing) that can accurately identify material and features of archaeological interest in other datasets. Archaeological interpretation is subjective, and requires not only on assessment of the data, but experience, a wider knowledge of the archaeological potential of the area, and an understanding of the archaeological objectives.

12. Example specifications

This section provides examples of the specifications of geophysical surveys that would meet the requirements for archaeological characterisation (prospection), investigation and site specific surveys. The examples provide a robust starting point when planning or commissioning surveys and allow an assessment of the suitability for archaeological interpretation of data collected by a third party.

As noted throughout this guidance, the specification for surveys will be determined by the aims of the survey and the suitability to answer research questions. The practical applications for geophysical survey where heritage is the primary driver are discussed with examples in Section 9, and information specific to marine development is discussed within Section 8. Whilst frequencies, range, and line spacing have been detailed below, the main driver for the specification is the minimum object detection size. Where positioning or data cannot meet the specification, clear statements should be made as to the reasons why, and what action will be taken in order to support analysis and interpretation.

12.1 Introduction

To ensure the accessibility of this guidance and avoiding over complication, it deliberately only focuses on the four primary techniques: sidescan sonar, multibeam bathymetry, magnetometer, and sub-bottom profiler. These techniques are accessible to a wide range of users, and the technological concepts broadly easily understood. It is noted that derivatives of these such as Synthetic Aperture Sonar (SAS), Interferometric Sonar (IS) and 3D Chirp are available, as well as other more specialist techniques such as those using pulse induction or light-based techniques, all of which have certain beneficial applications but an assessment must be made as to whether they meet the specifications for interpretation as defined below.

Whilst all of the four techniques are detailed in each example specification, there may be instances where not all are required to meet the aims of the survey or where surveys are undertaken in phases.

12.2 Notes of the use of the specifications

Geophysical survey is undertaken to support a wide range of objectives. In some instances, archaeology may be the primary driver, however the vast majority of geophysical data is collected in support of offshore development projects where the specification will be incorporating a large number of variables including the nature, location and phase of the project, the requirements of other stakeholders, and the overall data collection strategy. This may include additional phases of survey or different sensors driving the line spacing.

As such it is not possible to provide example specifications that will be applicable to all projects at all stages and thus those given below should be considered a starting point from which planning can be based. This highlights the importance of obtaining robust advice during the planning process to ensure the data collected is suitable to meet archaeological requirements.

12.3 Survey types

The survey types summarised below correspond with those presented in Section 8 and Section 9.

12.3.1 Characterisation (prospection) survey

12.3.1.1 Marine development

A characterisation (prospection) survey refers to surveys undertaken pre-application to inform the EIA process. The data should be of a specification suitable to characterise the location within which the development is proposed in order to produce an environmental baseline. The data should cover the extents of the application area and be of a sufficient specification to identify receptors that may require mitigation, or identify what receptors are likely to be within a given area, along with preliminary modelling of the palaeolandscape.

Surveys during this phase have the potential to deviate from the example specification due to the overall survey strategy of the development. However, the example provides a robust specification that would meet the requirements of EIA.

Where there is a requirement to significantly reduce the specification of the survey, appropriate advice should be sought, either from an appropriate individual or organisation, or the archaeological curator. Where there has been a reduction in the specification, the archaeological technical report (Section 8) should detail the limitations of the survey and how, for example, data gaps will be addressed pre-impact.

12.3.1.2 Archaeological survey

The broad aim of a characterisation (prospection) survey is to locate or identify material of potential archaeological interest on or under the seabed. This can include anthropogenic material such as shipwrecks, cargoes, aircraft, structures or evidence of human activity, or the identification of areas with the potential for submerged prehistoric remains.

The chosen specification will be linked closely with the research question(s). However, the example provides a robust specification that would meet the requirements of a general prospection survey.

Table 12: Example characterisation (prospection) survey data collection specifications.

Multibeam bathymetry	
Positioning	DGNSS with corrections, either RTK or PPK
Minimum cell size	1.0 m in water depths < 40 m 2.0 m in water depths >40 m
Example IHO Standard	IHO Special Order <40 m IHO Order 1a >40 m
Frequency	>350 kHz
Swathe angle	Depending on depth and to achieve specification
Line spacing	Based on swathe angle to achieve coverage requirements
Coverage	100%
Navigation corrected data format	ASCII as individual lines

Sidescan sonar	
Positioning	DGNSS and USBL (<5% slant range)
Minimum object detection size	1.0 m in any direction
Frequency	High frequency band >400 kHz
Range	<150 m
Line spacing	Based on range to achieve coverage requirements
Altitude	<10-15% of range
Coverage	100% excluding the nadir region (although may vary dependant on the objectives)
Navigation corrected data format	xtf

Magnetometer	
Positioning	DGNSS and USBL (<5% slant range)
Minimum object detection size	~1,500 kg beneath the sensor
Update rate	>4.0 Hz
Sensor spacing	Concurrent with other sensors or between 50 – 100 m (although may vary dependant on the objectives and survey strategy). May be 'piggybacked' with sidescan sonar
Altitude	<15 m
Navigation corrected data format	ASCII as individual lines

Sub-bottom profiler	
Positioning	DGNSS and USBL for towed systems (< 5% slant range) DGNSS for vessel mounted systems
Vertical resolution	0.1 - 0.3 m for high frequency systems 0.5 - 1.0 m for low frequency systems
Penetration	For developments below maximum depth of scheme impact and ideally a minimum of 10 m. Where the impact is shallow, the base of the first unit should be resolved. For research dependant on the objectives
Frequency	Depending on system and required penetration and resolution
Line spacing	Concurrent with other sensors or between 50 – 100 m (although may vary dependant on the objectives and expected geological conditions)
Ping rate/shot interval	Depending on system >1.0 m
Navigation corrected data format	SEG-Y

12.3.2 Investigation survey

12.3.2.1 Marine development

An investigation survey refers to surveys undertaken pre-construction (or pre-impact) to inform design finalisation, assessment for pUXO, and where required to address data gaps and refine environmental assessments made pre-consent. In relation to marine archaeology the data should be collected with the potential area of impact and be of a specification appropriate to identify marine archaeological receptors that may be impacted by the development and make recommendations for robust mitigation.

The survey should be commensurate with the archaeological potential as determined during the EIA process, and proportional to the impact.

Specifications should take into consideration that archaeological material may be buried, and in the instance of wooden wrecks and aircraft, may be associated with limited amounts of ferrous material. The example specification provides a robust starting point from which planning can be undertaken. The survey should be undertaken in line with the WSI and method statement produced in consultation with the archaeological curator.

12.3.2.2 Archaeological survey

Following a prospection survey the research questions(s) will, if required, guide the next phase of survey. This however is likely to be commensurate with a site specific survey. The investigation survey may not be required, but the example provided may be used in instances where, for example, a higher specification survey is required during prospection, or where the research question covers a wider geographic area.

Table 13: Example investigation survey data collection specifications.

Multibeam bathymetry	
Positioning	DGNSS with corrections, either RTK or PPK
Minimum cell size	0.5 m in water depths <40 m 1.0 m in water depths >40
Example IHO Standard	IHO Special Order <40 m IHO Order 1a >40 m
Frequency	>350 kHz
Swathe angle	Depending on depth and to achieve specification
Line spacing	Based on swathe angle to achieve coverage requirements
Coverage	100%
Navigation corrected data format	ASCII as individual lines

Sidescan sonar	
Positioning	DGNSS and USBL (<5% slant range)
Minimum object detection size	0.5 m in any direction
Frequency	High frequency band >400 kHz
Range	<100 m
Line spacing	Based on range to achieve coverage requirements
Altitude	<10-15% of range
Coverage	200% including the nadir region
Navigation corrected data format	.xtf

Magnetometer	
Positioning	DGNSS and USBL (better than 5% slant range)
Minimum object detection size	~100 kg beneath the sensor
Update rate	>10 Hz
Sensor spacing	<10 m
Altitude	<6.0 m
Navigation corrected data format	ASCII as individual lines

Sub-bottom profiler	
Positioning	DGNSS and USBL for towed systems (< 5% slant range) DGNSS for vessel mounted systems
Vertical resolution	0.1 - 0.3 m for high frequency systems 0.5 - 1.0 m for low frequency systems
Penetration	For developments below maximum depth of scheme impact and ideally a minimum of 10 m. Where the impact is shallow, the base of the first unit should be resolved. For research dependant on the objectives
Frequency	Depending on system and required penetration and resolution
Line spacing	Concurrent with other sensors or between 50 – 100 m (although may vary dependant on the objectives and expected geological conditions)
Ping rate/shot interval	Depending on system >1.0 m
Navigation corrected data format	SEG-Y

12.3.3 Site specific survey

12.3.3.1 Marine development

The example specification allows for the collection of high resolution data, that will meet the requirements of the majority site specific surveys that may be required during offshore developments. However, there may be instances where it may be more appropriate to use additional techniques or deployment methods, such as those associated with ROVs, to meet the archaeological objectives.

12.3.3.2 Archaeological survey

Following a characterisation (prospection) survey, desk-based research, or as part of the monitoring or management requirements, higher resolution survey at a localised site scale may be required. This may be to collect further information from which to fulfil the research question(s), or to collect higher resolution data to provide a higher level of detail. It may also be that the site was identified in other survey data and interpretation or planning for further works would benefit from three-dimensional data. Alternatively, the site could have been identified visually in previous data but is partially buried and would benefit from sub-bottom profiler survey to establish the buried extents or a magnetometer survey to identify outlying debris.

The specification and sensors used will be dependent on the research question(s). The example specifications allow for the collection of high resolution data, that will meet the requirements of the majority of archaeological site specific surveys. However, there may be instances where it may be more appropriate to use additional techniques or deployment methods, such as those associated with ROVs or divers, to meet the archaeological objectives.

Table 14: Example site specific survey data collection specifications.

Multibeam bathymetry	
Positioning	DGNSS with corrections, either RTK or PPK
Minimum cell size	0.1 m in water depths <30 m 0.25 m in water depths <50 m 0.5 m in water depths >50 m
Frequency	>350 kHz consideration should be given to systems capable of >700 kHz
Swathe angle	Depending on depth and to achieve specification
Line spacing	Based on swathe angle to achieve coverage requirements
Coverage	200%
Navigation corrected data format	ASCII as individual lines

Sidescan sonar	
Positioning	DGNSS and USBL (< 5% slant range)
Minimum object detection size	0.3 m in any direction
Frequency	>400 kHz – higher frequency preferred
Range	<50 m
Line spacing	Based on range to achieve coverage requirements
Altitude	<10-15% of range
Coverage	200% including the nadir region
Navigation corrected data format	.xtf

Magnetometer	
Positioning	DGNSS and USBL (< 5% slant range)
Minimum object detection size	~100 kg beneath the sensor
Update rate	>10 Hz
Sensor spacing	<10 m
Altitude	<6.0 m
Navigation corrected data format	ASCII as individual lines

Sub-bottom profiler	
Positioning	DGNSS and USBL for towed systems (< 5% slant range) DGNSS for vessel mounted systems
Vertical resolution	0.1 - 0.3 m for high frequency systems 0.5 - 1.0 m for low frequency systems
Penetration	Penetration depending on aims
Frequency	Depending on system and required penetration and resolution
Line spacing	Depending on aims. 10 – 30 m for small areas
Ping rate/shot interval	Depending on system >1.0 m
Navigation corrected data format	SEG-Y

13. Data deliverables

The guidance for data deliverables relates to those required for archaeological interpretation, and the expected formats as well as those that should be delivered following archaeological interpretation, and from which the resulting report should be based.

The list is not exhaustive, and the overarching principle is that data should be delivered in industry standard formats and be able to be imported into most commercially available software packages. Proprietary data formats, or those tied to a single software package, are not recommended unless the software used is the industry standard, and its use is almost exclusive.

Figure 54: An Uncrewed Survey Vessel (USV) undertaking a multibeam bathymetry survey. © Uncrewed Survey Solutions

13.1 Data deliverable formats

The tables below give guidance on data formats that can be considered standard outputs. Deliverables should be agreed with the client, the end user, and/or the archaeological curator, prior to the commencement of survey operations. In some instances, multiple file formats have been provided for the same output, which one that is supplied will be linked to the survey requirements, the survey contractor, and the end user.

Raw data have not been included within this section as they are typically collected in proprietary formats. GIS file formats listed here are industry standard. Note that some file extensions may be the same between software packages but may not be compatible; certain grid files are a good example of this. In addition, file headers can vary between the same format files depending on the acquisition and processing software.

Data formats that are not considered best practice have not been included here, for example geoTIFF with no embedded elevation data. Geodatabases containing many of the gridded, sub-sampled, and visual outputs, interpreted outputs, and some of the processed data are becoming more common, particularly in relation of largescale developments and their use enables effective and efficient data management. However, they have not been included within this section, as the component parts (or types of output, including point, lines and rasters) should align with the outputs detailed below. Furthermore, geodatabases are typically specific to a particular software and therefore cannot be considered appropriate for all end users, clarification must therefore be obtained prior to delivery.

Table 15: Navigation corrected data formats.

Technique	Data Format
Multibeam bathymetry	ASCII as individual lines (.txt, .csv, .pts, .asc, .xyz)
Sidescan sonar	eXtended Triton Format (.xtf)
Magnetometer	ASCII as individual lines (.txt, .csv, .pts, .asc, .xyz)
Sub-bottom profiler	SEG-Y (.sgy, .segy)
Trackplots	Shapefiles (.shp), vector (.dxf, .dwg)

Table 16: Processed data formats.

Technique	Data Format
Multibeam bathymetry	ASCII as individual lines (.txt, .csv, .pts, .asc, .xyz) ASCII as point cloud (.txt, .csv, .pts, .asc, .xyz, .las)
Sidescan sonar	eXtended Triton Format (.xtf)
Magnetometer	ASCII as individual lines (.txt, .csv, .pts, .asc, .xyz)
Sub-bottom profiler	SEG-Y (.sgy, .segy)
Trackplots	Shapefiles (.shp)

Table 17: Gridded, sub-sampled, and visual output data formats.

Technique	Data Format	
Multibeam bathymetry	Gridded point clouds	ASCII (.txt, .csv, .pts, .asc, .las)
	Digital Elevation Models	GeoTIFF (.tif, .tiff) Other formats (.flt, .bag)
	Contours (if required)	Shapefiles (.shp)
Sidescan sonar	Mosaic	GeoTIFF (.tif, .tiff)
	Coverage maps	GeoTIFF (.tif, .tiff) Shapefiles (.shp)
Magnetometer	Gridded processed data	ASCII (.txt, .csv, .pts, .asc, .las)
	Altitude, total field, residual and analytical signal grids	GeoTIFF (.tif, .tiff) ASCII grid (.asc) Other formats (.grd)
	Contours (if required)	Shapefiles (.shp)
Sub-bottom profiler	Outputs at this stage, including the ground model, are likely to be proprietary (see interpreted deliverables) SEG-Y (.sgy, .segy)	

Table 18: Interpreted output data formats.

Technique	Type of Output	Data Format
Multibeam bathymetry	Identified anomalies (points)	Shapefiles (.shp) Gazetteer (.csv)
	Identified anomalies (areas)	Shapefiles (.shp)
	Identified anomalies (linear)	Shapefiles (.shp)
	Anomaly images (if required)	Raster (.tif, .jpg, .png)
Sidescan sonar	Identified anomalies (points)	Shapefiles (.shp) Gazetteer (.csv)
	Identified anomalies (areas)	Shapefiles (.shp)
	Identified anomalies (linear)	Shapefiles (.shp)
	Anomaly images (if required)	Raster (.tif, .jpg, .png)
Magnetometer	Identified anomalies (points)	Shapefiles (.shp) Gazetteer (.csv
	Identified anomalies (areas)	Shapefiles (.shp)
	Identified anomalies (linear)	Shapefiles (.shp)
	Anomaly images (from plot/raster) (if required)	Raster (.tif, .jpg, .png)
Sub-bottom profiler	Identified anomalies (point reflector) (if required)	Shapefiles (.shp) Gazetteer (.csv)
	Profiles (complete/part) (if required)	Raster (.tif, .jpg, .png) Document (.pdf)

13.1.1 Reports

All geophysical data collected by a third party should, at a minimum, include an operations report outlining the data collection parameters and specification, and the results of calibrations. Data that have been processed should be accompanied by a processing report outlining the methodology, the parameters, and all changes that have been made to the data. Data that have been interpreted should be accompanied by an interpretation report outlining the methodology, parameters, and with a clear presentation of the results. Depending on the scale of the survey, the reports may be presented as a combined report, or separate reports. Reports should be supplied in a format able to be read in Microsoft Word, or as .pdf.

14. Archaeological reporting

The culmination of any geophysical survey and archaeological assessment is the production of an archaeological technical report. Whilst reports may be produced for several different purposes, there are minimum sections that should be included, and minimum levels of information that should be presented.

This section provides guidance on the report sections required, along with examples of the information and figures that should be included. It is noted that report structures may vary dependant on the author, the client, and the intended use, however the following serves as a basic report structure:

14.1 Archaeological technical report template

Table 19 below provides an example structure and suggested content for an archaeological technical report.

Table 19: Example structure and suggested content for an archaeological technical report.

Summary	Things to consider
1 Introduction	
The introduction should provide a brief overview of the project.	• The name of the project. • The organisation writing the report. • The client. • The legal, or consenting, status of the site or the development. • Document reference, version and date. • The purpose of the report. • The contents of the report.
2 Location	
This section should define the location and the status of the project.	• The distance in metres or km, and the direction, from an identifiable location on shore, usually a town or a named location. • Whether the project falls within inshore waters, up to 12 nm from the normal tidal limit (NTL), or in offshore waters, between 12 nm and 200 nm from the NTL. • The size of the survey area (or the development) in m2 or km2. • A figure showing the location of the project, clearly showing the location in relation to a landmass or other recognisable feature.

Summary	Things to consider
3 Aims and Objectives	
The aims and objectives of the project should be clearly and concisely stated.	• Aims focus on what the project intends to achieve. • Objectives focus on how the aims will be achieved. • Reference to relevant research frameworks.
4 Methodology	
The methodology should contain all the information about how the survey was conducted, how the data were processed, and how the assessment was undertaken. The suggested sub-sections will ensure that all key information is included.	
4.1 Data Collection	

This section should include information related to data collection.	• Who collected the data?
	• When were the data collected?
	• The specification of the survey, including:
	  • The manufacturer and model of any sensors used (including positioning)
	  • Frequencies/ranges/penetration
	  • Deployment method
	  • Line spacing
	  • Coverage
	  • Expected resolutions
	  • The coordinate reference system (CRS)
	  • Data deliverables
	  • The format of any raw data collected, or the format they were supplied in
	• Where data were supplied in a processed format this should be detailed.
	• Figures to include coverage, and/or line plans, of all sensors.

Summary	Things to consider
4.2 Data Quality and Limitations	

A statement on the data quality, and any limitations, should be provided. Depending on the overall report structure this may be more appropriate within the results sections.	• The quality of the positioning.
	  • Does the navigation have any significant errors?
	  • Do individual lines of data from the same sensor align?
	  • Do data from different sensors align?
	• The quality of the data, noting degradation caused by:
	  • Motion and weather.
	  • Interference (other sensors, vessel, etc.).
	  • Inappropriate settings (recorded range too great, etc.).
	  • Survey speed.
	• Limitations of the data:
	• Coverage.
	• Resolution/penetration.
	• Topography/acoustic shadow.
	• Suitability to meet the aim of the project requirements.
	• Figures.
	• Data image examples if required.

4.3 Data Processing	
The data processing workflow for each sensor should be provided in enough detail that the results, or the final datasets, can be reproduced within reason.	• Software used and version number. • Input data format. • Corrections undertaken. • Settings applied, including gains and filtering. • Output data format.
4.4 Archaeological Assessment and Interpretation	
The archaeological assessment and interpretation workflow for each sensor, and all sensors combined should be provided. Whilst this will depend on the aims and objectives of the project, the following are provided for consideration.	• The assessment parameters, including thresholds, scope, and area. • How data were reviewed. • How data were assessed. • The assessment criteria. • Software used and version number. • Additional data sources consulted. • Data output formats.

Summary	Things to consider
5 Results	

The results will depend on the aims and objectives of the project and will guide the reporting format.	● Results should clearly align with the aims and objectives of the project.
	● Results should be presented clearly, but concisely with tabulated results and summaries used to enable easy extraction of data.
	● What was not achieved (this can be as important as what was achieved).
	● Figures provide a visual representation of geophysical data and should be used within the results section to demonstrate the results, particularly in relation to the aims and objectives. Consideration should be given to:
	  ● Location and spatial plots
	  ● Visual representations of data

6 Mitigation (primarily for development projects)	
Recommended mitigation should be presented clearly.	● Mitigation criteria, including anomalies of archaeological interest and the palaeolandscape. ● Tabulated information including the positions, and extents of any exclusion zones. ● Details of other mitigation measures and how they should be implemented. This should include mitigation for the palaeolandscape. ● Figures showing the spatial extents of any recommended mitigation. ● Figures showing the spatial distribution of any recommended mitigation.
7 Recommendations for Further Work	
Recommendations for further work that may be required should be made. Additional works are not restricted to geophysical survey, but can include: ● ROV and/or diver survey or ground truthing ● Intrusive investigations ● Geotechnical investigations ● Desk-based Assessment and/or assessments of significance	● Were the aims and objectives met? ● Any limitations in the data that mean additional works are required to meet the aims and objectives. ● Future planned survey strategy. ● Ongoing or future monitoring that may be required.

Summary	Things to consider
8 Conclusion	
The conclusion should summarise the technical report, presenting the key results and recommendations. Conclusions should be succinct, not introduce new information, and be able to be read and understood in isolation from the main body of the report.	• Key results. • Recommendations if applicable.
9 Figures	
Figures form a core component of a geophysical technical report and are often required to be able to present results clearly. Figures should present the contents clearly and should avoid trying to show too much in one image. Figures should be scaled appropriately to clearly illustrate the points of discussion in the text. An example figure is given in Figure 55	• Administrative details. • Author. • Date. • Revision. • Quality assurance. • Figure details. • Project title. • Figure title. • Technical details. • Scale. • Coordinate reference system. • North arrow. • Legend. • The legend should identify all data presented within the figure. • Colour scales should be included where data is presented as a raster.

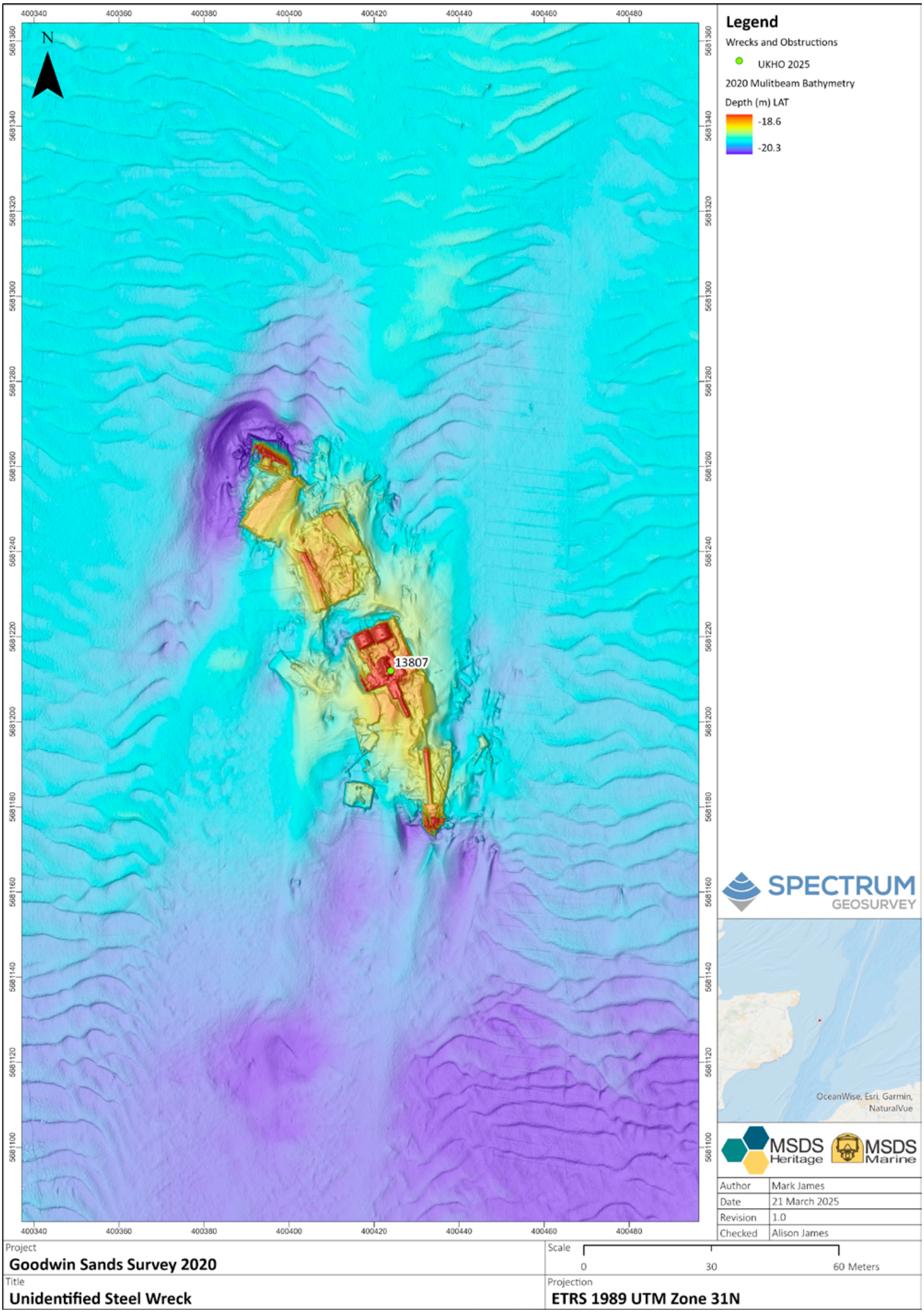

Figure 55: Example figure including pertinent information. © MSDS Marine

15. Archiving

While data collection strategies, equipment, and reporting structures will vary, methods of archiving and long-term data retention should be standardised to ensure the data is preserved and accessible. Archiving of geophysical data allows for the reuse of data and helps build the growing repository of available knowledge about the seabed.

A data management plan that includes provision for archiving should be embedded in the original project design, agreed with the archaeological curator and completed as part of the reporting process. Any relevant metadata should be included with the archive to support future applications. There are different repositories that can archive and subsequently facilitate access to marine geophysical data, depending on the format of the data. It can be beneficial to identify the repository prior to undertaking geophysical works to help structure the data outputs and streamline the submission process.

This section provides guidance on the data archiving process, associated metadata, and the data repositories and agencies that provide data storage and standards.

The CIfA Dig Digital Toolkit[9] should be consulted for further advice on digital archiving. The Dig Digital guidance aims to provide support for those creating digital data in archaeology, helping archaeologists manage digital data throughout projects and enabling the production of complete, ordered and stable archives that meet professional standards.

15.1 Metadata

Metadata is data about the geophysical data and is integral to the archiving process. It refers to the information that provides context, structure, and details about data. Metadata can include information on the data's sources, creation dates, size, formats, owners, access permissions, retention policies, and governance. Metadata requirements should be considered from the outset of the project and include early liaison with the planned archive repository over requirements. Archiving of geophysical data will and should include data pertinent to the project, and the structure of the metadata should follow that required by the repository.

9 https://www.archaeologists.net/work/toolkits/dig-digital

Metadata can include but is not limited to:

- Date the data was collected
- Why were the data collected
- Quality control
- Final data deliverables
- Files in geoTIFF format
- Figures
- Track plots
- Navigation
- Notes and/or progress reports
- GIS Projects
- Shapefiles
- Geodatabases
- Project Report or Summary
- Data collection parameters
- Contactor details
- Vessel details
- Equipment details and specifications
- Project datums (including coordinate reference systems (CRS), vertical datums, transformations)
- Owners (if any)
- Data access permissions
- Intended life cycle

15.2 Data Standards

15.2.1 Data Reuse – Collect once, use many times

Collection of marine geophysical data can be a costly endeavour, both in terms of economic and environmental parameters. Data collected during marine geophysical survey should be as widely accessible as possible, although there may be caveats to this depending on the reason for the data collection. Good practice in data archiving, storage, and dissemination encourages a policy of collect once, use many times. When marine data is stored properly it can be safeguarded for long term use.

Data standards improve the efficiency of data storage, retrieval, and security and should follow the principles of FAIR data to optimise the reuse of data. The FAIR guidelines are intended to improve the (F)indability, (A)ccessibility, (I)nteroperability, and (R)euse of digital data[10]. They promote interoperability, long-term accessibility, data integrity, and compliance, ultimately ensuring that archived data remains valuable and usable throughout its lifecycle. The Archaeology Data Service (ADS) provide a series of guidance for best practice on digital data standards, collection, and storage, including those for marine survey. At the time of writing this guidance, the ADS marine survey guide to good practice was due to be updated and will form an important guide in future.

15.2.2 Data Repositories and Archives

Data repository bodies should be consulted for guidance on data structure, formatting, and limitations prior to project completion and data submission.

Adherence to data standards and FAIR guidelines facilitates collaboration, allows for integration with other datasets, and supports the long-term preservation and reuse of valuable marine geophysical information. Data reuse facilitates the accumulation of knowledge over time. By building on previously collected marine data, researchers and the commercial sector can contribute to a comprehensive understanding of marine environments and processes. Historical data can be compared with new observations, aiding in the identification of trends, changes, and potential impacts on marine ecosystems. Following the latest guidance on data archiving promotes efficiency, collaboration, and long-term positively impacts marine research by maximising the utility of existing data and ensuring its accessibility, transparency, and adherence to established standards.

The Chartered Institute for Archaeologists (CIfA) provides further guidance on the creation and deposition of geophysical data archives (CIfA 2020).

Relevant data repositories include:

15.2.2.1 OASIS

OASIS is an online reporting form enabling archaeological and heritage practitioners to provide information about their investigations to regional Historic Environment Records (HERs) and respective national heritage organisations. As well as being an information-gathering tool, researchers may share reports with HERs for public release in the Archaeology Data Service (ADS) Library.

15.2.2.2 Marine Environmental Data & Information Network (MEDIN)

MEDIN is a partnership of UK organisations committed to improving access to and stewardship of UK marine data. MEDIN are funded by a consortium of 15 sponsors and partnered with over 50 organisations from both the public and private sectors.

MEDIN have complied data guidelines, metadata standards, and controlled vocabularies to ensure consistancy and the effective sharing and reuse of data.

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10 https://www.go-fair.org/fair-principles/

MEDIN signpost data submission to the MEDIN Data Archive Centers (DACs) which is appropriate to the data type. The MEDIN portal allows users to find information on marine datasets held at the DACs.

15.2.2.3 Archaeology Data Service (ADS)

The ADS is a repository for archaeology and heritage data generated by UK-based fieldwork and research. The ADS provide guidance and advice in relation to data, and metadata, standards. The ADS, in addition to making the reports available online for access to the wider public, undertakes the curation and archiving of the digital files, ensuring long-term preservation.

The ADS, alongside Historic Environment Scotland (HES) and the Royal Commission on the Ancient and Historical Monuments of Wales (RCAHMW), are the combined accredited MEDIN Data Archive Centre for the marine historic environment.

15.2.2.4 British Geological Survey (BGS)

The BGS is an independent UK research organisation for geological survey and global geoscience, providing geoscientific data, information and knowledge. The BGS is the accredited MEDIN Data Archive Centre for seabed and sub-seabed geological and geophysical data covering the UK Continental Shelf (UKCS) area which includes Sidescan Sonar, Sub-bottom Profiler, and bathymetric derived backscatter.

15.2.2.5 United Kingdom Hydrographic Office (UKHO)

The UKHO is an executive agency sponsored by the Ministry of Defense (MoD) and is a provider of hydrographic and geospatial data. The UKHO are responsible for fulfilling the UK government's obligation to provide hydrographic products and services for safe navigation in UK waters. The UKHO is the accredited MEDIN Data Archive Centre for bathymetric data.

15.2.2.6 Marine Data Exchange

The Marine Data Exchange (MDE) is a repository of freely available offshore data, including geophysical data, originating primarily from offshore development. The MDE is maintained by The Crown Estate (TCE) in partnership with Crown Estate Scotland (CES), a requirement of offshore renewable agreements is that data is deposited with the MDE.

16. Further Reading

16.1 Historic England: Publications and Webpages

Coastal and Marine Planning
https://historicengland.org.uk/advice/planning/marine-planning

Managing the Marine Historic Environment
https://historicengland.org.uk/advice/planning/marine-planning/marine-historic-environment

Historic England 2015 Marine Licensing and England's Historic Environment
https://historicengland.org.uk/images-books/publications/marine-licensing-and-englands-historic-environment/heag025-marine-licensing

Historic England 2018, Using Airbourne LiDAR in Archaeological Survey
https://historicengland.org.uk/images-books/publications/using-airborne-lidar-in-archaeological-survey/

Historic England 2018, 3D Laser Scanning for Heritage. Advice and guidance on the use of laser scanning in archaeology and architecture
https://historicengland.org.uk/images-books/publications/3d-laser-scanning-heritage/

Historic England 2020, Deposit Modelling and Archaeology. Guidance for Mapping Buried Deposits. Swindon. Historic England.
https://historicengland.org.uk/images-books/publications/deposit-modelling-and-archaeology/

Historic England Introduction to Heritage Assets – Ships & Boats
https://historicengland.org.uk/listing/selection-criteria/ihas/

Historic England 2021 Commercial renewable energy development and the historic environment Historic England Advice Note 15
https://historicengland.org.uk/images-books/publications/commercial-renewable-energy-development-historic-environment-advice-note-15/heag302-commercial-renewable-energy-development-historic-environment

16.2 Acts of Parliament

Act of Parliament (UK) 1973 Protection of Wrecks Act
https://www.legislation.gov.uk/ukpga/1973/33/pdfs/ukpga_19730033_en.pdf

Act of Parliament (UK) 1979 Ancient Monuments and Archaeological Areas Act
https://www.legislation.gov.uk/ukpga/1979/46/pdfs/ukpga_19790046_en.pdf

Act of Parliament (UK) 1986 Protection of Military Remains Act
https://www.legislation.gov.uk/ukpga/1986/35/pdfs/ukpga_19860035_en.pdf

Act of Parliament (UK) 1995a Historic Monuments and Archaeological Objects (Northern Ireland)
https://www.legislation.gov.uk/nisi/1995/1625/contents/

Act of Parliament (UK) 1995b Merchant Shipping Act
https://www.legislation.gov.uk/ukpga/1995/21/data.pdf

Act of Parliament (UK) 1997 Planning (Listed Buildings and Conservation Areas) (Scotland).
https://www.legislation.gov.uk/ukpga/1997/9/contents

Act of Parliament (UK) 2002 National Heritage Act
https://www.legislation.gov.uk/ukpga/2002/14/data.pdf

Act of Parliament (UK) 2009 Marine and Coastal Access Act
https://www.legislation.gov.uk/ukpga/2009/23/pdfs/ukpga_20090023_en.pdf

16.3 Other Publications

BMAPA/English Heritage 2003 Marine Aggregate Dredging and the Historic Environment: Assessing, Evaluating, Mitigating and Monitoring the Effects of Marine Aggregate Dredging
https://www.wessexarch.co.uk/sites/default/files/projects/BMAPA-Protocol/BMAPA-EH-Guidance-Note-April-2003.pdf

BMAPA/English Heritage 2005 Protocol for Reporting Finds of Archaeological Interest
https://bmapa.org/documents/fullreportingprotocol2005.pdf

Bournemouth University 2009 Refining Areas of Maritime Archaeological Potential (AMAPs) for Shipwrecks [data-set]. York: Archaeology Data Service [distributor].
https://archaeologydataservice.ac.uk/archives/view/amaps_eh_2009

CEFAS 2004 Offshore Wind Farm – Guidance Note for Environmental Impact Assessment in Respect of FEPA and CPA Requirements
https://www.cefas.co.uk/publications/files/windfarm-guidance.pdf

Chartered Institute for Archaeologists 2020a Standard and Guidance for Archaeological Geophysical Survey.
https://www.archaeologists.net/codes/cifa

Chartered Institute for Archaeologists 2020b Standard and Guidance for Historic Environment Desk-based Assessment.
https://www.archaeologists.net/codes/cifa

Chartered Institute for Archaeologists 2023 Standard and Guidance for Archaeological Field Evaluation.
https://www.archaeologists.net/work/standards

Chartered Institute for Archaeologists/MAG 2007 Slipping Through the Net? Maritime Archaeological Archives in Policy. https://historicengland.org.uk/images-books/publications/slipping-through-the-net/slippingthenet/

Cooper, V and Gane, T 2016, The Assessment and Management of Marine Archaeology in Port and Harbour Development, Wessex Archaeology, Salisbury
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https://www.biofund.org.mz/wp-content/uploads/2018/11/F1349.Cowrie-Ciarch-Web.pdf

COWRIE/Wessex Archaeology 2007 Historic Guidance for the Offshore Renewable Energy Sector.
https://www.wessexarch.co.uk/sites/default/files/field_file/COWRIE_2007_Wessex_%20-%20archaeo_%20guidance_Final_1-2-07.pdf

DHCLG, 2023 National Planning Policy Framework.
https://assets.publishing.service.gov.uk/media/669a25e9a3c2a28abb50d2b4/NPPF_December_2023.pdf

Historic England 2015 Accessing England's Protected Wreck Sites: Guidance for Divers and Archaeologists.
https://historicengland.org.uk/images-books/publications/accessing-englands-protected-wreck-sites-guidance-notes/heag075-guidance-notes-for-divers-and-archaeologists/

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Gribble, J. and Leather, S. for EMU Ltd. 2011 Offshore Geotechnical Investigations and Historic Environment Analysis: Guidance for the Renewable Energy Sector. Commissioned by COWRIE Ltd (project reference GEOARCH-09)

ICOMOS 1996 Charter on the Protection and Management of Underwater Cultural Heritage. https://admin.icomos.org/wp-content/uploads/2023/10/underwater_e.pdf

JNAPC 2006 Maritime Cultural Heritage and Seabed Development: JNAPC Code of Practice for Seabed Development. https://jnapc.org/publications/

Ordnance Survey 2020, A Guide to Coordinate Systems in Great Britain https://www.ordnancesurvey.co.uk/documents/resources/guide-coordinate-systems-great-britain.pdf

UNESCO 2001 Convention on the Protection of Underwater Cultural Heritage. https://unesdoc.unesco.org/ark:/48223/pf0000126065

Society for Underwater Technology (SUT) Offshore Site Investigation and Geotechnics Committee (OSIG) 2022 Guidance notes for the planning and execution of geophysical and geotechnical ground investigation for offshore renewable energy developments

Wessex Archaeology 2008 Annex to the Protocol Guidance on the use of the Protocol for Reporting Finds of Archaeological Interest in Relation to Aircraft Crash Sites at Sea. https://www.scribd.com/document/2174360/Annex-to-the-Protocol-Guidance-on-the-use-of-the-Protocol-for-Reporting-Finds-of-Archaeological-Interest-in-Relation-to-Aircraft-Crash-Sites-at-Sea

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https://www.thecrownestate.co.uk/media/3917/guide-to-archaeological-requirements-for-offshore-wind.pdf

18. Acronyms

ADS	Archaeology Data Service
AGC	Automatic Gain Control
AUV	Autonomous Underwater Vehicle
BAC	Beam Angle Correction
BGS	British Geological Survey
BMAPA	British Marine Aggregate Producers Association
CD	Chart Datum
CES	Crown Estate Scotland
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CIfA	Chartered Institute for Archaeologists
CIfA RO	Chartered Institute for Archaeologists Registered Organisation
CMP	Common Mid Point
CoG	Centre of Gravity
CoR	Centre of Rotation
COWRIE	Collaborative Offshore Wind Research into the Environment
CRS	Coordinate Reference System
CRP	Central Reference Point
db	Decibels
DBA	Desk-based Assessment
DCMS	Department for Culture, Media and Sport
DCO	Development Consent Order
DD	Decimal Degrees
DDM	Degrees Decimal Minutes
DDV	Drop Down Video
Defra	Department for Environment, Food and Rural Affairs
DGNSS	Different Global Navigation Satellite System
DGPS	Differential Global Positioning System
DIMCON	Dimensional Control
DML	Deemed Marine Licence
DMS	Degrees Minutes Seconds
EGNOS	European Geostationary Navigation Overlay Service
EIA	Environmental Impact Assessment
ES	Environmental Statement
ETRS89	European Terrestrial Reference System 1989
FAIR	Findable, Accessible, Interoperable, Reusable
FEED	Front End Engineering Design

GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRS80	Geodetic Reference System 1980
HE	Historic England
HER	Historic Environment Record
HES	Historic Environment Scotland
HR	High Resolution
Hz / kHz	Hertz / kiloHertz
ICOMOS	International Council on Monuments and Sites
IHO	International Hydrographic Organization
IMU	Inertial Measurement Unit
IS	Interferometric Sonar
JNAPC	Joint Nautical Archaeology Policy Committee
JNCC	Joint Nature Conservation Committee
LBL	Long Baseline
LiDAR	Light Detection and Ranging
MBES	Multibeam Echosounder
MCA	Maritime and Coastguard Agency
MCS	Multi Channel Seismics
MDE	Marine Data Exchange
MEDIN	Marine Environmental Data Information Network
MMO	Marine Management Organisation
MOD	Minimum object detection size
MoRPHE	Management of Research Projects in the Historic Environment
MPS	Marine Policy Statement
MPPA	Marine Plan Policy Assessment
MRU	Motion Reference Unit
ms	milliseconds
MSL	Mean Sea Level
NMHR	Marine Heritage Record
nT	nanoTesla
NTL	Normal Tidal Limit
NPPF	National Planning Policy Framework
NSIP	Nationally Significant Infrastructure Project
OASIS	The online system for reporting archaeological investigations and linking research outputs and archives
ODN	Ordnance Data Newlyn
OWF	Offshore Wind Farm
PAD	Protocol for Archaeological Discoveries
PEIR	Preliminary Environmental Impact Report
PINS	Planning Inspectorate
PPK	Post-Processed Kinematic
PPM	Proton Precision Magnetometer

PtoP	Positive peak to the negative peak
pUXO	Potential Unexploded Ordnance
RAMS	Risk Assessment Method Statement
RCAHMS	Royal Commission on the Ancient and Historic Monuments of Scotland
RCAHMW	Royal Commission on the Ancient and Historic Monuments of Wales
RCHME	Royal Commission on the Historic Monuments of England
ROV	Remotely Operated Vehicle
ROTV	Remotely Operated Towed Vehicle
RTK	Real Time Kinematic
SAS	Synthetic Aperture Sonar
SBAS	Satellite Based Augmentation System
SBL	Short Baseline
SBP	Sub-bottom Profiler
SCS	Single Channel Seismics
SIT	Surrogate Item Trial
SSS	Sidescan Sonar
SVP	Sound Velocity Profiler
SVS	Sound Velocity Sensor
TCE	The Crown Estate
THU	Total Horizontal Uncertainty
TVG	Time Varying Gain
TVG	Transverse Gradiometer
TVU	Total Vertical Uncertainty
TWTT	Two-way Travel Time
UHR	Ultra High Resolution
UKHO	United Kingdom Hydrographic Office
UKOOA	United Kingdom Offshore Operators Association
UNESCO	United Nations Educational, Scientific and Cultural Organisation
USBL	Ultra-short Baseline
USV	Uncrewed Survey Vessel
UTM	Universal Transverse Mercator
UXO	Unexploded Ordnance
VTS	Vessel Traffic Services
WAAS	Wide Area Augmentation System
WGS84	World Geodetic System 1984
WSI	Written Scheme of Investigation

19. Glossary

The definitions in this glossary are specific to marine geophysics and hydrography and may differ from more general definitions.

Altitude	The height of a sensor above the seabed. Knowledge of the altitude of a sensor, together with the horizontal distance from the survey line allows the slant range to be calculated.
Analytical signal	The analytical signal (or, more correctly, the quasi-analytical signal) is the difference in the Earth's magnetic field between two instruments deployed at a fixed distance from each other. Thus, the analytical signal removes the effects of diurnal variation and can reduce the effects of large scale geological variations.
Anomaly	An anomaly is a local variation of an otherwise uniform signal response. In the context of marine geophysics, the word anomaly is often used to indicate the feature causing the variation as well as the variation itself.
Attenuation	A decrease in the amplitude or energy of a sound or light wave.
Backscatter	The amplitude of sound reflected from the seabed (or another feature).
Coordinate Reference System	A grid from which measurements can be made from a single, and pre-determined, point.
Coverage	The extent of the seabed covered by a particular survey, usually expressed as a percentage. If lines overlap, this percentage can be more than 100% (so 200% means that the entire survey area is covered at least twice).
Ellipsoid	A mathematical model of the shape of the Earth.
Front End Engineering Design	Front End Engineering Design (FEED) is a method of engineering design where the majority of design and expected costs are met before implementation.

Gain	Gain is a mathematical method of increasing the amplitude of a signal. This can be controlled automatically (i.e. with software determined parameters) or manually.
Gas blanking	Shallow gas restricting penetration.
Gazetteer	A list of sites or features of interest.
Geoid	An irregular model of the Earth considering mean sea levels and gravitational variations.
Georeferenced	Georeferenced data record data position in addition to other variables.
GeoTIFF	A georeferenced Tagged Image File Format image.
Ground model	A two- or three-dimensional representation of the seabed (bathymetry) and sub-surface geology.
Hydrography	Measuring and mapping the depths of the seabed.
Horizon	The boundary between different geological strata.
Layback	Layback is the calculated difference between vessel position and sensor position in a towed survey.
Magnetometer	An instrument which measures the strength of a magnetic field.
Marine geophysics	Study of the physical properties of the seabed, usually its magnetic field strength and the relative acoustic impedances of sub-seabed layers.
Method Statement	A document detailing the intended methodology of an operation from start to finish. It can incorporate a risk assessment (in which case it is called a RAMS).
Multibeam Echosounder	An instrument that uses sound to create a three-dimensional map of the seabed bathymetry
Nadir	The point on the seabed directly below the instrument.
Nadir region	The area directly beneath a sidescan sonar where there is a gap in the data.

Processed data	Processed data have undergone some digital treatment, usually to aid interpretation and/or visualisation.
Processing flow	The processing flow is a record of any data processing carried out on data, together with the relevant parameters for each step.
Project Design	The Project Design is a document which details the processes, resources and deliverables for a project.
Proprietary data format	A proprietary data format can only be read by the software in which it was created and cannot easily be read by other software without conversion.
Prospection	Prospection is the search for previously unknown features of interest.
Raw data	Raw data are the data collected by the instrument, without any processing.
Receptor	Receptors are features of interest such as shipwrecks or preserved landscapes.
Residual field	The residual field is the magnetic field strength calculated from subtracting calculated or averaged background magnetic field from the total field.
Resolution	Resolution is a measure of the degree of detail that can be identified by an instrument.
Retained Archaeologist	The retained archaeologist is a member of a project delivery team advising on any archaeological remains uncovered over the life of the project.
Secchi depth	A measurement of water clarity based on the visibility of a black and white disk lowered through the water column.
Sidescan Sonar	An instrument that used sound to create a two-dimensional representation of the seabed.
Slant range	The distance the instrument and a point laterally offset from it.
Sub-bottom Profiler	An instrument that uses sound to create a representation of the sub-seabed stratigraphy.

Thermocline	A thermocline is a distinct, rapidly changing temperature layer in a large body of fluid, like an ocean or lake, that separates warmer surface water from colder, deeper water.
Total field	The total field is the Earth's magnetic field as measured by the magnetometer at a given point.
Workflow	The workflow is the series of steps required to complete a task or project.
World file	Georeferencing parameters accompanying an image.
Written Scheme of Investigation	The Written Scheme of Investigation (WSI) is a planning document detailing all stages of an archaeological investigation.

19.1 Contact Historic England

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