

12 Underwater Search Methods

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Searches can be divided into two types: those deploying a diver or a submersible and relying on the human eye or hand-held equipment, and remote-sensing surveys usually employing acoustic or magnetic equipment and remotely operated vehicles (ROVs) deployed from a boat, or other craft, on or above the surface. This chapter covers the first type of search. For detailed information about remote-sensing techniques, refer to chapter 13.

POSITIONING

Whatever search method is used, it is vital to know where you are and where you have been (see chapter 11 for position-fixing techniques). This will save time in search operations and will significantly enhance the information recorded. A search only has value if the position of the area covered and the identified targets, together with other pertinent observations, are accurately reported and recorded. Divers should complete detailed dive-logs, recording all information of potential interest for subsequent analysis.

COVERAGE

Unless a well thought-out sampling strategy has been devised, a common objective is 100 per cent coverage of

the selected area. Unfortunately 100 per cent is difficult to define in this context due to the varying degrees of efficiency for different techniques. For instance an extensive visual search may cover every square centimetre of the sea-bed but miss an object a few millimetres long, or a larger object camouflaged by a temporary dusting of light silt. Similarly, with remote-sensing techniques, magnetometer search-corridors separated by 50 m (163 ft) might be sufficient to detect a large wooden wreck containing iron cannon, but might not detect other smaller targets of archaeological significance, such as a single cannon.

It is important to realize that the fact that nothing has been detected during a search does not necessarily mean that nothing is there. The development of increasingly sophisticated remote-sensing equipment (see chapter 13) has made investigating the sea-bed a more reliable science, but there is still some way to go before it is possible to be certain of discovering all the available evidence.

SAFETY

Whichever search method is chosen, it is essential that team members are trained to undertake the technique safely. (Refer to chapter 6 for further information concerning safety on archaeological sites.) Many of the inherent problems associated with the following techniques, however, can be alleviated with planning and practice. This

could include carrying out a dry run (plate 12.1) to help perfect diver positioning, communications and an efficient recording technique.

DIVER SEARCH METHODS

These mostly depend on visual observations, but hand-held instruments and equipment, such as metal-detectors and cameras, can also be deployed. The speed and efficiency of any search is proportional to the size of the targets, visibility and experience of the divers in such techniques. Small objects on a muddy sea-bed are a challenge to locate. The search organizers must consider which method is likely to achieve the best results, taking into account the nature of the material being sought, scale of the search area, depth, sea-bed type, number of divers and time available. The choice of the search team is also important. It should be remembered that a large variation exists amongst divers in terms of ability to notice things on the sea-bed. This ability is related to factors, such as:

- familiarity with the area to be searched;
- anticipated target material (e.g. small ceramic fragments or large ships' timbers);
- training in the search techniques;
- experience in the search technique to be used;
- apprehension caused by diving factors;
- level of diving experience;
- concentration;
- aptitude;
- commitment;
- diving conditions and diver comfort.

Towed searches

The equipment associated with this method ranges from the simple (a diver holding on to a weight on a line) to the relatively sophisticated (involving towed vehicles with moveable vanes capable of altering attitude and elevation relative to the sea-bed). A common and inexpensive system uses a simple wing or board capable of sufficient movement to 'fly' the diver over changes in the sea-bed topography (figure 12.1). All these systems rely on the surface crew controlling and recording navigation and making due allowance for 'layback' between the diver and the boat. Alternatively, an underwater vehicle can pull the diver along. Diver propulsion vehicles (DPVs) vary in complexity from those with a simple electric motor driving a propeller held in front of the diver to mini-submersibles. The major drawback of these systems, apart from cost, is the difficulty of position-fixing. Surface marker-buoys attached to the diver can be tracked from the surface or, alternatively, it is possible to

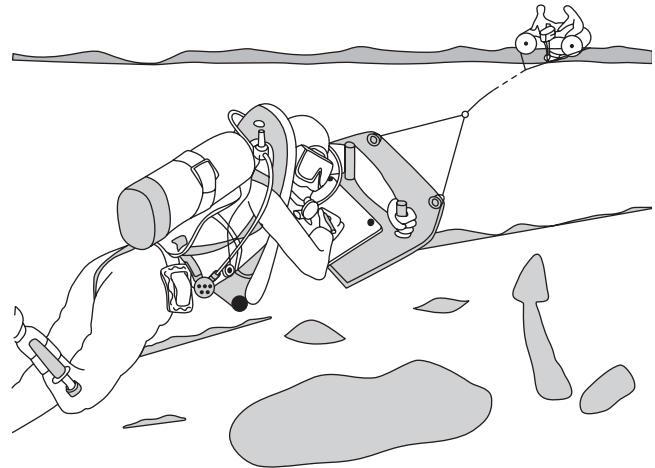


Figure 12.1 Towed diver search. (Based on original artwork by Ben Ferrari)

use through-water navigation systems based on acoustic transponders placed at known positions on the sea-bed.

The effectiveness of a towed-diver search will be dependent on visibility and speed of the diver over the sea-bed. At 1 knot the diver is covering just over 30 m (98 ft) a minute or 0.5 m (20 in) a second and this can be an effective way of covering relatively large areas of the sea-bed during one dive. In many circumstances, however, this will be too fast to allow observation to the required level of detail.

If the diver can control speed and even stop the forward movement to inspect potentially interesting sightings, the efficiency of the operation is dramatically increased. While rope signals are possible, diver-to-surface communications maximize the benefits of this method. Telephone-style (hard-wire) communications with the diver's microphone connected via wires to the surface tend to be clearer than through-water versions, which can be affected by water turbulence caused by the moving boat. The position of the towline relative to the propulsion unit must be taken into consideration when planning the search. With efficient communications it is possible for the surface team to log and plot observations made by the divers. Without communications, a less satisfactory alternative is for markers to be dropped on the sea-bed in the vicinity of any observation, which can subsequently be investigated further. These will then need to be accurately positioned so they can be relocated and assessed at a later date.

To reduce the inherent risks to the diver and to avoid pressure-related illness, very careful control of depth is important. This is often difficult to achieve when being towed. A solution is to use a diving computer that can accurately record the dive profile during the search.

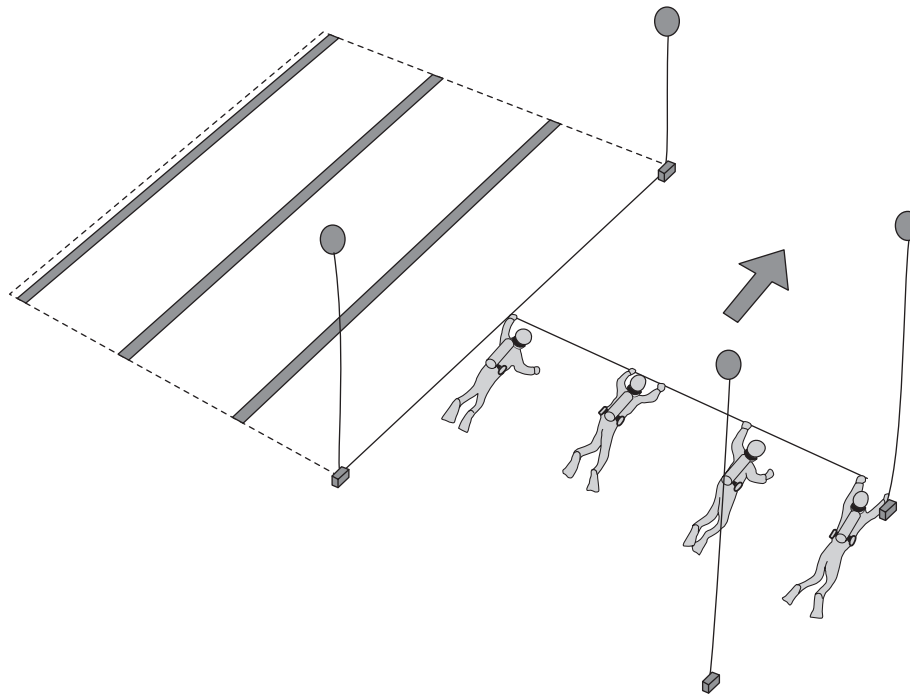


Figure 12.2 Swimline (freeline) search. (Based on original artwork by Ben Ferrari)

Many dive-computers have audible alarms to alert the diver in the event of a rapid ascent. In conditions of poor visibility, there should also be some capability for detecting potentially dangerous obstructions in the path of the towed diver. One solution is for the towboat to be equipped with forward-scanning sonar.

Swimline (freeline) searches

Practice, patience and perseverance are prerequisites for this method but it has been used with success on many archaeological projects in the past. The system relies on a string of divers, often between two and six, spaced along a tape-measure or graduated line at intervals equivalent to less than the limit of clear visibility, so that complete coverage is possible (figure 12.2). The search is usually undertaken with a ground-line to guide a controller. To enable positions of objects to be fixed, it is useful also to graduate the ground-line in convenient increments. This technique is in fact a large-scale offset survey (see chapter 14). These ground-lines can be as long as necessary (up to a kilometre has been known) and should be reasonably straight. To achieve this, they are probably best laid from a moving boat, keeping the ground-line under tension while it is being deployed. It can be difficult to lay long ground-lines precisely, but with practice it is possible. As long as the line is

straight, the positions of the two ends can be fixed (see chapter 11) so that there will be a record of where the search took place.

The main difficulty with this technique is maintaining the line of divers at right angles to the ground-line, which inevitably becomes more difficult in poor visibility. Another difficulty encountered with this method is maintaining effective communication between the divers to allow the line to advance smoothly. This problem increases proportionally to the number of divers on the line, and it is also intensified by poor visibility. Usually, if a diver needs to stop to make an observation, or is ready to move off again, this is indicated to the others by a code of signals along the line. With practice, it is possible to communicate quite complicated messages along the connecting line using a set of bells (short tugs) and pulls (long tugs). Standard rope signals can be found in many diving manuals and additional ones appropriate to the individual operation can be devised.

Another difficulty is the variation in dive duration between individuals at the same depth and in the same environment caused by dissimilar equipment and breathing rates. Matching the contents of the divers' breathing-gas supply will help. It is considered best practice to terminate the search when one of the divers needs to surface for whatever reason, unless a buddy diver can accompany the diver to the shore or safety-boat.

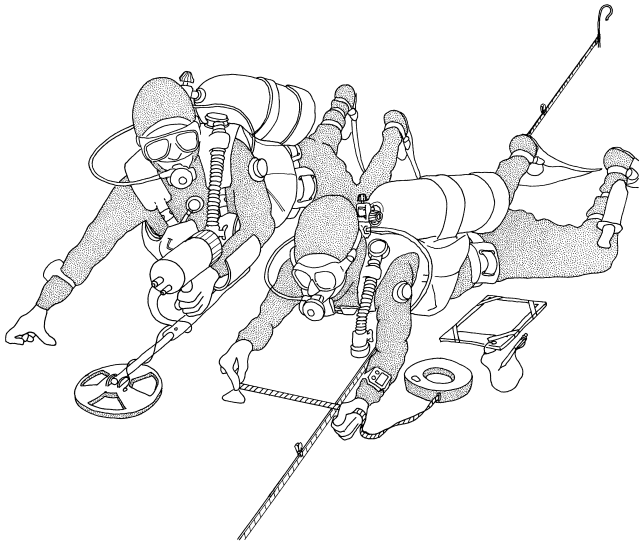


Figure 12.3 The offset method can be used to record the position of features in relation to jackstays and ground-lines. In this example a hand-held metal-detector is being used to locate metallic features. (Drawing by Graham Scott)

Plotting the position of observations during the search can be achieved in the same way as described when using the offset survey method. All that is required is to record the distance along the ground-line and a distance out at right-angles to the ground-line. To achieve a detailed survey two divers can move slowly forward using a short rigid rule or tape, at right-angles to the graduated ground-line (figure 12.3). Alternatively, markers can be dropped at points of interest and the position fixed later. If the number of markers needed by each diver is excessive, an alternative search method, such as the jackstay system (see below) may be more suitable.

Swimline searches are often more effective in clear, shallow water, but this technique can be deployed successfully in deeper water if consideration is given to using a secondary pair, or team, of divers to record the points of interest located by the search team. With discipline, good communication and rehearsed procedures this technique can be very flexible, allowing the search-line to be stopped periodically to record the nature of the sea-bed, or count the number of surface-indicators (potsherds, for example) to compile a distribution-map.

Jackstay (corridor) searches

This is a useful system if total coverage of an area of sea-bed is required during visual or metal-detector searches, but it requires more pre-search organization than the two methods outlined above. The minimum requirement is usually two long ground-lines laid parallel at a

convenient distance apart, often 10 m, 30 m or 50 m, and a further line, the jackstay, laid at 90 degrees between the two ground-lines. It is more efficient to use two jackstays to define a corridor because an area with defined edges can be more effectively searched. Once the area between the jackstays has been searched, another corridor is laid, usually by leapfrogging one line over the other (figure 12.4). It is important to take into account the potential safety implications of divers being separated during this part of the operation.

Fixing ground-lines to the sea-bed can be achieved with methods similar to those suggested for survey points (see chapter 14). In fact the ends of ground-lines are likely to be survey points. One of the problems with ground-lines is keeping them straight on the sea-bed. In shallows, water-movement may mean the line has to be weighted or pinned to the sea-bed to prevent unacceptable lateral displacement. Even in deeper water, ground-lines may have to be placed along the line of maximum prevailing current to help prevent sideways movement; and even then, fixing to the sea-bed is likely to be required if the lines are going to be used as part of a site coordinate system for locating observations.

The jackstays themselves are less permanent features and may only be in position for as little as 5 or 10 minutes, depending on the size and intensity of search. The method by which they are anchored must depend on the nature of the sea-bed, and that might be totally different from one end of the line to the other. Like many survey points, line fixing will probably rely on either the weight of an object, such as a 25 or 50 kg (55 or 110 lbs) metal block, or on a pin or other fastening forced into bedrock, an immovable boulder, or sediment. Even heavy weights can be pulled across the sea-bed with surprising ease (except when you want to move them yourself, of course), so it is common for a weight to be pinned to the sea-bed for additional security.

If the ground-lines and the jackstays are graduated, one of the ground-lines should be considered as a zero axis. The zeros of the jackstays can then be positioned on that line. It is difficult to keep the distance between ground-lines constant and therefore the other end of the graduated jackstay will not always coincide with the second ground-line at the required distance. Rather than spend unnecessary time making everything perfect, and without sacrificing offset-survey precision, simply concentrate on the line of the jackstay passing across the appropriate graduation of the ground-line. To do this, it helps if the jackstays are over-length. While ground-lines are usually made from rope or line (leaded line is useful), the jackstays are often tape-measures or, better still, thin plastic measuring lines that are available in 50 m (165 ft) lengths. In many circumstances it can be advantageous to

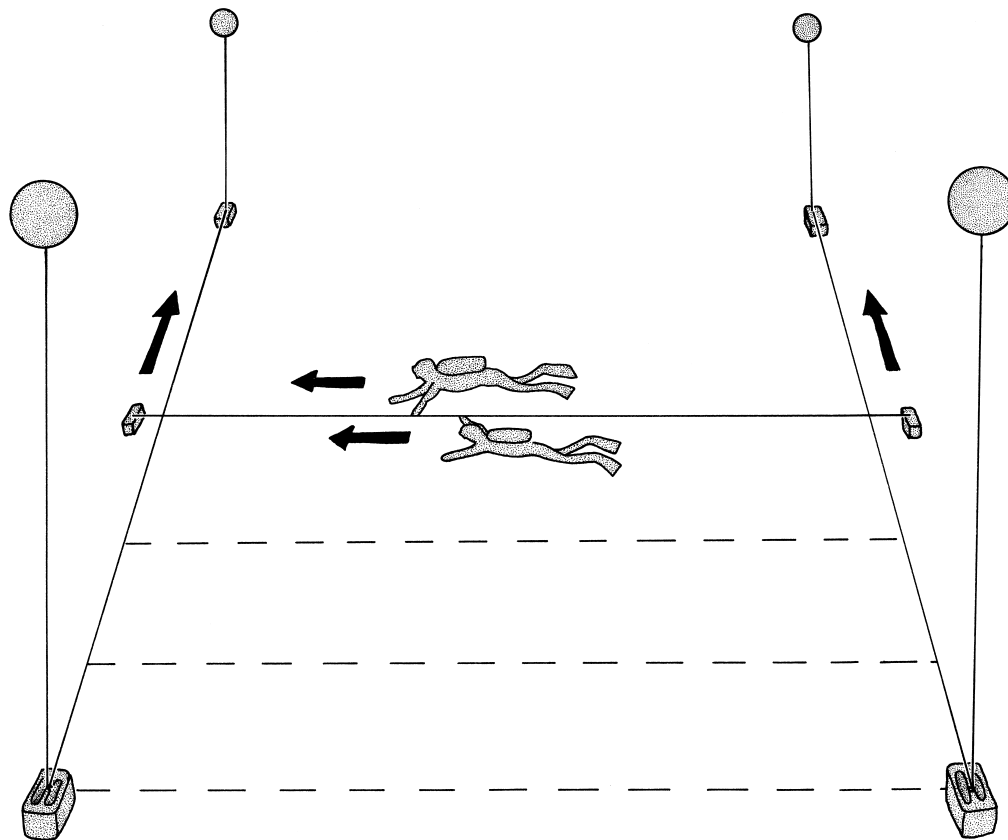


Figure 12.4 Jackstay (corridor) search. (Drawing by Graham Scott)

extend the length of these with about 2 m (6 ft) of elastic cord ('shock cord' or 'bungee-cord'). The advantage is that it keeps the line under permanent tension, therefore making it less of a problem should a diver accidentally apply pressure to it during the search. It also means that, provided there is sufficient elasticity, one end of the jackstay can be leapfrogged at a time with less expenditure of time and effort than if both ends have to be released before the line can be moved.

The normal width of the corridor between jackstays is between 2 and 8 m (6 and 26 ft), depending on the number of divers searching each corridor, visibility and the type and size of expected targets. Although searches with four divers can be organized between the jackstays, for intensive work a maximum of two divers for each corridor allows easier offset measurements to be taken from the jackstays, resulting in a precise location for each observation.

Experience has demonstrated that a 1 m (3 ft) wide strip for each diver in a 2 m (6 ft) wide corridor is suitable for very intensive sea-bed searches (perhaps using a metal-detector), almost regardless of visibility or nature of the sea-bed. In areas where the sea-bed is uniformly covered in fine sand or silt, the width of the search strip can be

greater. It can be as much as 6 m (20 ft) in certain circumstances, and even wider if the expected target is relatively large (e.g. a ship-sized ballast mound).

Grid searches

If an area needs to be searched thoroughly and features need to be located with precision, then the grid search has much to offer. The first step is to lay a series of ground-lines at 90 degrees to each other at an appropriate spacing to create a grid over the site. The size of the grid will depend on a variety of factors but is commonly between 2 m and 50 m (6–165 ft). Ground-lines left on the seabed for any time tend to get damaged or disappear. However, if the intersecting points or anchorage points have been adequately fixed, the grid could be reconstructed in future seasons, even if the actual lines have gone.

Once the grid has been established, the corridor-search technique can be easily deployed and the location of points can be readily identified by site coordinates with, conventionally, a series of numbers on both the horizontal and vertical axes with the zeros at the bottom left (south west) corner. Sometimes one of the axes is

replaced by letters to help those inexperienced in the use of coordinates as a way of expressing a position. By using an appropriate number of digits it is possible to define a location down to the nearest millimetre, although that would not normally be necessary.

Circular searches

This is a simple search system that can be useful in poor visibility or when the need to conduct a search suddenly arises. The method can use equipment that is normally carried by divers, such as a diver's marker buoy and a weight to form the down-line and distance-line. Even the boat's anchor could be used as a starting point. The technique does not, however, easily or efficiently lend itself to total sea-bed coverage because of the elliptical overlap created by linked searches (figure 12.5). It is useful for trying to locate a known object whose position has not been accurately recorded, or to extend a search area after an isolated artefact has been found. It can also be of use as part of a sampling strategy to assess different areas of the sea-bed before intensive searching begins.

The system relies on a graduated line, often a tape-measure, being attached to a fixed point on the sea-bed. The divers swim round in a complete circle using either a compass (to take the bearing at the start and finish) or obvious marker on the sea-bed as a guide to when a circuit has been completed. A satisfactory solution is to set out a graduated, straight ground-line (running out from the centre of the search area) to act as a start/finish indicator. The distance between each circular sweep has to be related to the visibility and the type of target that the divers are expecting to find.

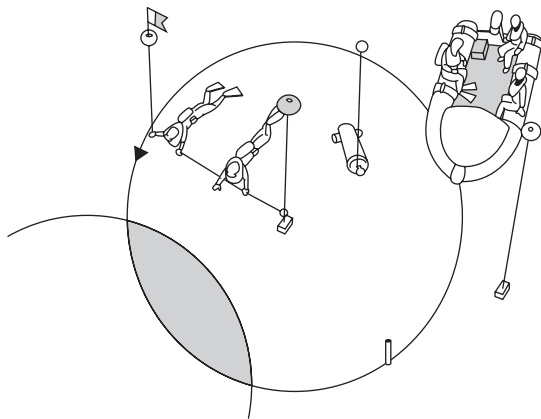


Figure 12.5 Circular search. (Based on original artwork by Ben Ferrari)

It is usual to begin in the centre and sweep at ever increasing diameters. Remember that the diver on the end of the line will be travelling further and faster than the diver closest to the centre-point of the search. However, starting at the maximum length of sweep can be more effective if a known object is thought to be upstanding from a flat seabed. One circuit should result in a snag if the target is in the circle. The distance line can then be followed back to the object. During normal archaeological searches such snagging is clearly not desirable. The problem of unwanted snags can be reduced if the distance-line is lightly buoyed at the mid-point. Some tension is usually maintained on the line to ensure that the diver keeps to the correct track. If the line catches on an obstruction, releasing the tension should allow it to rise and hopefully release itself from the snag. In very poor visibility, it is not always clear that a snag has occurred until the search pattern has been grossly distorted.

Once the position of the centre of the search area has been fixed, observations made during the search can be recorded by noting the distance from the centre and the magnetic bearing to it using a hand-held compass. In this way, each plot will be recorded but the level of accuracy will be as limited as surveying using the radial survey method (see chapter 14).

Metal-detector searching

Although these instruments are 'remote-sensing' devices and some types can be towed behind a boat, it is the numerous diver-held versions that have proved to be a valuable tool to many archaeologists. Unlike magnetometers (see chapter 13), they can detect both ferrous and non-ferrous metals, and those used under water usually work on the pulse-induction principle. Pulses of energy are emitted and produce a temporary magnetic field around the search-head. The rate at which this field decays is prolonged in the presence of metal. Comparison between the decay rate and the original pulses allows detection of metal objects of large mass to a maximum range of approximately 2 m (6½ ft), and objects the size of a single coin at a distance of approximately 10 cm (4 in).

Metal-detectors are used in three principal ways during archaeological work. First, during the pre-disturbance survey of a site, concentrations of metallic contacts and isolated responses can be mapped. The second way is to ascertain the approximate position of objects in a layer that is about to be removed. This can contribute to a very high recovery rate for metallic artefacts that might otherwise be overlooked because of their small size or poor visibility. The third use is to locate metal artefacts on bedrock which are either invisible because of a light dusting of silt or because they are hidden in holes and crevices in the rock.

Hand-held metal-detectors must be used systematically if they are to be an effective search tool. This usually entails total coverage employing the corridor or grid-search techniques as shown in figure 12.3. It is important that the search-head of the instrument covers every square centimetre of the area of sea-bed under

investigation. Investigating metal-detector responses by digging around an anomaly without regard to the other clues that might be disturbed is not a valid archaeological technique. Nor is any approach involving a diver with a metal-detector swimming in a random pattern over a site, looking for souvenirs.

Geophysical and Remote-Sensing Surveys

13

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- ◆ Multibeam swath systems
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- ◆ Sub-bottom profiling
- ◆ Magnetometry
- ◆ Integrated surveys
- ◆ Submersibles: ROVs and AUVs
- ◆ Aerial photography

Since the 1960s a variety of marine geophysical techniques have been used to investigate a range of submerged archaeological sites, with the principal aim of site prospection. More recently the emphasis of archaeological research has moved away from pure prospection towards a fuller understanding of individual sites in terms of detailed site mapping, the wrecking event, site-formation processes, and ultimately the development of heritage-management strategies for conservation and protection.

A significant advantage of geophysical surveying is the ability to collect large amounts of information quickly, often at some distance from the target. This allows search patterns to be much more widely spaced and undertaken at a greater 'speed over the ground' than could ever be achieved by divers. Some types of equipment can detect certain classes of information that are buried and out of the sight of divers. Furthermore, restricted underwater visibility and strong currents are less of a problem for geophysical survey instruments and, in many instances, they can be deployed in sea conditions worse than those in which divers can safely operate. However, these techniques should not be seen as ways of removing divers from underwater archaeological investigation, but as tools which can both enhance the effectiveness of diver investigation and extend the range of environments in which underwater survey can be undertaken.

Geophysical survey in archaeology is generally concerned with research and/or site management. This chapter

summarizes a range of geophysical instruments and techniques that can be useful in an underwater archaeological project, including:

- acoustic systems (see below);
- magnetometers;
- submersibles – remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs).

SEARCH PATTERNS, NAVIGATION AND POSITIONING

The search patterns appropriate to diver investigations of the sea-bed (see chapter 12) are also appropriate to larger scale investigations, the differences being in the scale of operations and the method of location control. For a marine geophysical survey it is essential to plan the track of the vessel so that there is total coverage of the search area. This usually involves the survey boat following parallel lines at set distances apart, the distance proportional to the coverage of the instrument and any overlap required. For intensive work, the overlap is often more than 100 per cent and, to guarantee total coverage and provide a different viewpoint, two corridor search patterns at 90 degrees, or even three at 60 degrees, to each other may be considered. Any decisions regarding line spacing and line direction will depend on the type of equipment

deployed and the nature of the sea-bed and environmental factors. For instance, in 10 m (33 ft) depth of water, an echo-sounder with a narrow-cone transducer might only cover a strip of seabed 1.8 m (6 ft) wide, considerably less than can be achieved with a sidescan system. If the sea-bed is fissured by deep gullies that need to be investigated acoustically, then the search pattern may need to be adjusted to allow transmitted energy to reach the bottom of the gullies. This consideration is not necessary with magnetometers (see below) as they are virtually omni-directional. Other factors that influence survey-line orientation include the proximity of shallows and obstructions, navigation buoys and fishing floats, shipping channels, the activities of other sea-users, the direction and strength of winds and currents, and variation in current direction and strength during tidal cycles.

To interpret any geophysical data acquired at sea, it is necessary to relate the observations to a geographical position; the more accurate the positioning, the more useful the data will be. For details of position-fixing techniques and technology, see chapter 11.

Currently, one of the most accurate ways of location control during marine surveys is for the position of the vessel to be displayed graphically on a computer monitor in front of the helmsperson. Specialist survey packages are often built into data collection software and allow an identified area to be quickly divided into survey lanes of appropriate separation and orientation. The helmsperson then 'steers' the cursor (representing the boat) down the selected line on the screen.

In good sea conditions, sidescan sonar can cover a swath up to about 1000 m (3250 ft) wide across the sea-bed whereas an echo-sounder with a narrow-cone transducer might only cover a strip 1.5 m (58 in) wide in 10 m (33 ft) of water. Such varying widths of sea-bed search highlight the difficulty of deciding what spacing is required between tracks to give a search pattern with 100 per cent coverage. It is important that the target type is known (or at least decided upon), the capabilities of the instruments deployed are fully understood and the environmental factors are considered – otherwise there could be gaps in the search area.

ACOUSTIC SYSTEMS

The most commonly used geophysical methods for marine archaeological survey are acoustic (sound or sonar) systems. These include echo-sounders, multibeam swath systems, sidescan sonars, sub-bottom profilers and bottom classification systems (see below). Which of the many available systems are chosen depends on the type of information required for a particular site. Important factors to consider are:

- Is it the morphology or the material make-up of the site that is important (or both)?
- Is qualitative or quantitative information required?
- Is the site of interest exposed and/or beneath the sea-bed?

No one system can provide all this information, and normally there will always be a compromise: in some instances it may be necessary to undertake multiple-instrument surveys to collect a wider range of information. Regardless of the methodology chosen, the survey should extend to include a meaningful proportion of the surrounding area so that there is the opportunity to put the archaeological site into its environmental context.

BATHYMETRIC SURVEY

An essential component of all investigations of submerged archaeological sites is the production of a detailed bathymetric (depth) chart. The degree of accuracy of the final presentation is dependent on both the geophysical technique used and the effective integration of a high-resolution navigation system. Attention must be paid to the coordinate system recorded by the navigation software. GPS data are conventionally output as geodetic coordinates (latitude and longitude) using the WGS84 datum. Where the survey is being undertaken as part of a seamless onshore–offshore investigation, it is common for the geodetic data to be converted to a metric coordinate system (e.g. UTM or OSGB36 for the UK). To ensure effective integration of the data, the archaeologist should always be aware of the vagaries of coordinate conversion (see chapter 11).

There are two primary systems for the acquisition of bathymetric data: narrow-track echo-sounders and wide-track multibeam swath systems. Whichever system is used, data quality is affected by the following factors.

Relative height of the sonar head: When taking a series of depth measurements with a transducer attached to a boat that goes up and down with the tide, the height variation has to be allowed for in the final bathymetric data. A simple way to allow for tidal variation is to check the depth reading over a fixed point on the sea-bed with the echo-sounder at regular intervals. Adjustments can be made to readings collected between checks to provide uniformity in the data. Often a tidal curve calculated from readings of a nearby tide-gauge is used to correct the depths. This works reasonably well if the tide-gauge is very close to the site but becomes less effective as the distance increases. It can be relatively simple to install a graduated board on a site as a tide-gauge, which can then be

visually monitored and readings noted manually. Alternatively, sophisticated instrumentation can be set up which records the data automatically and transmits a correction in real time to the survey boat. Obtaining tide-gauge readings from a nearby source may work for some projects, but it is rarely good enough for high-quality, very high-resolution surveys.

While it is relatively easy to measure height differences caused by the tide, differences created by waves and swell are much more difficult to measure. It is for this reason that the highest quality surveys tend to use RTK systems (see chapter 11), which continuously and accurately monitor the relative height of the sonar head. This allows all vertical variations, regardless of their cause, to be compensated for automatically in the data set.

Roll, heave, pitch and yaw: Another factor which needs to be considered is the way transducers move about as they follow the motion of the boat on the water. Groundswell can heave the boat up and down over considerable distances, which can cause problems with the depth readings if not taken into account. Similarly, waves can make the survey boat roll, pitch and yaw, which, in turn, can have a profound effect on the direction of the acoustic beam(s). For high-definition surveys, it is pointless to assume that transducers mounted on a moving boat always point directly down at the sea-bed. Most echo-sounders, except those specifically designed for professional surveys, do not have facilities for compensating for boat movement. As it is crucial to know exactly where the acoustic energy is directed when surveying, it is necessary to measure, to a very high degree of accuracy, movement in all four directions. This can be achieved with a motion-reference unit. While they are relatively expensive, they are an essential component of high-quality acoustic surveys in support of archaeological investigations.

Speed over the ground: A simple and effective way of improving the quality of geophysical surveys is to move slowly so that more data is collected in every portion of sea-bed. The biggest problem with adopting this simple technique is the difficulty of getting boats to steer accurately at slow speeds, but by heading into current or against the wind, natural forces can be used to help reduce the speed over the sea-bed. It is also possible to slow down survey boats by the use of drogues, but these can have an additional detrimental effect on steering.

ECHO-SOUNDERS

Conventional echo-sounder systems consist of a single, hull-mounted or pole-mounted transducer that acts as

both an acoustic transmitter and a receiver (transceiver). These systems produce an acoustic pulse with a single frequency within a typical range of 100–300 kHz and a frequency-dependent, vertical resolution on a centimetric scale. The echo-sounder transducer produces an acoustic pulse with a cone angle normally between 5 and 45 degrees, oriented vertically downwards, so concentrating the acoustic energy in a small circular area of the sea-bed (the radius of this circle being dependent on the water depth). The horizontal resolution of these systems is controlled by a combination of source frequency, cone angle and water depth. For example, a 200 kHz echo-sounder with a 10 degree cone angle has a footprint diameter of 1.8 m (6 ft) in a water depth of 10 m (33 ft).

The echo-sounder system does not provide direct measurement of depth, but calculates a value from the recorded two-way travel time. The resulting depth information can either be recorded digitally or via post-acquisition digitization of two-dimensional analogue traces. Depths are conventionally recorded in metres, with the actual figures displayed representing the distance from the transducer to the sea-bed. For bathymetric analysis of data from a near-shore environment, all values obtained must be corrected for both tidal variation and the depth of the transducer beneath the water surface.

One major disadvantage of narrow-track systems is that the distance between the lines of a survey-grid controls the effective horizontal resolution of the system. In a tidal environment, the closest survey-grid spacing normally achievable is approximately 5 m (due to the limits imposed by the survey boat manoeuvrability). Therefore, the highest possible horizontal resolution for the bathymetric data is ± 5 m. Bathymetric data are conventionally represented as profiles and/or two-dimensional contour plots.

Overall, the quality of echo-sounder surveys does not compare well with swath surveys and they take significantly longer to conduct, but they have the advantage of being less expensive and useful results can be obtained.

MULTIBEAM SWATH SYSTEMS

A development from echo-sounder technology is multi-beam swath bathymetry, which records depth measurements in a thin strip below and to the side of the boat, and repeats at up to 50 times a second as the boat moves forward. In one pass, this provides considerably more depth information about the sea-bed than could be achieved with a single echo-sounder. In the example given earlier, an echo-sounder at 10 m depth would cover a strip of sea-bed 1.8 m wide as it moves forward. A typical multi-beam swath system in a similar depth of water would

perhaps cover a track 55 m wide. When coupled with the exceptionally good vertical accuracy, it is no surprise that multibeam swath systems are now the instrument of choice for professional hydrographic surveyors.

Many of these sophisticated systems have large sonar-head arrays and, although they can be built into the hull of a large boat, archaeological work is often done from smaller vessels of opportunity, which means that the sonar-heads need to be mounted on frames attached to the boat or on towed floating platforms. With care, it is possible with temporary mountings to get close to the theoretical resolutions available from multibeam swath systems, which can be of the order of 5 mm horizontally and 6 mm vertically (plate 13.1). Such precision is ideal for detailed archaeological site investigations.

As soon as the water depth increases, or the range when mounted on an ROV or AUV, the ping-rate has to be reduced so that returning echoes are collected before the next pulse is transmitted. This means that survey boat speeds must be reduced to maintain the highest resolution. This also has an additional benefit because sonar-heads, when mounted on frames attached to boats, tend to vibrate as speed increases, reducing data quality. As a general rule of thumb, when aiming for the best quality multibeam swath-survey data, try to keep the survey boat speed down to below 4 knots (*c.* 2 m/s).

The data collected during multibeam swath surveys can normally be displayed in real time as a profile and as a colour contour plan, or as a complex three-dimensional image. After the survey, the millions of points of data will often include 'fliers' and 'spikes', acoustic returns caused by a variety of natural and physical phenomena. These are usually filtered out in post-processing but it is important that an archaeologist, or a surveyor with considerable archaeological experience, does this editing – otherwise archaeological features can be unwittingly removed.

The software available for viewing multibeam swath data usually has the facility to apply an artificial rendered surface to where the software thinks it should be. This is effective for normal sea-bed types (plate 13.2), but can be disastrous for archaeological evidence (plate 13.3). It is essential to view multibeam swath data of artificial material, such as wrecks, as point-clouds floating in space. Each point represents the *x*, *y* and *z* coordinates for each return for each beam at each ping and, with high-definition surveys, these can be very densely packed. Most of the proprietary multibeam swath data-visualization software packages allow these point-clouds to be looked at in three dimensions and rotated on the computer screen. This provides much more information than would be seen from stationary images because, currently, the human eye and brain are better than software for separating out and identifying features. It is also possible to produce profiles in any direction across a data set and

take measurements between any two points, which is a tremendous help when trying to interpret and understand a site.

Multibeam swath bathymetry is a standard survey tool for both site-specific work and for coverage of the larger expanses of the sea-bed necessary for submerged landscape reconstruction (plate 13.4). It makes sense to undertake a multibeam swath survey first, to collect basic information about where the major components of the site are, before committing resources to diver surveys with tape-measures and drawing frames. As geophysical surveys are not constrained in the same way as diving operations by pressure of water, underwater visibility and currents, it is even possible to collect excellent data on sites where diving surveys would be either ineffective or impossible.

The advantage of multibeam swath systems is that they provide baseline surveys very quickly and, in terms of the overall site, at very high levels of accuracy. Basic site surveys can be accomplished at rates more than 100,000 times faster than can be achieved by even the most experienced diving teams (plates 13.5 and 13.6). However, tape-surveys by divers tend to be more precise where the measured distances are less than 2 or 3 m ($6\frac{1}{2}$ –10 ft), and so are ideal for detailed archaeological surveys of small areas. For longer distances and relating various small areas of a site, there is nothing as quick and accurate as a high-definition multibeam swath survey, but it must always be seen as a complement to, rather than a replacement for, diver surveys.

Multibeam swath surveys are also very useful as a management tool because high-standard repeat surveys of a site are relatively simply achieved. This enables direct comparison between multiple surveys so that changes to sediments (plates 13.7 and 13.8) or changes to an archaeological site (plate 13.9) can be easily detected.

One perceived drawback of multibeam swath systems is the amount of data that such surveys can generate – up to 10 gigabytes in a day. Fortunately, advances in computer processing power and memory capacity have largely overcome this problem. Another potential drawback is cost, but systems are available for hire on a daily basis and it is not impossible to find a manufacturer or a grant-awarding body to pay for, or at least subsidise, the use of this important archaeological survey tool.

BOTTOM-CLASSIFICATION SYSTEMS

Multibeam swath and profiling echo-sounders were originally designed to give only quantitative data on the topography of the sea-bed. However, developmental work has resulted in attempts to extract proxy indicators of the material nature of the sea-bed from the returning echoes. There are a number of bottom-classification

(sea-bed discrimination) systems. Most are based on single-beam 'profile' technology and so give an indication of the material type at individual points. These systems look at either the shape of the sea-bed return directly or in conjunction with a multiple reflection of the sea-bed to determine both the 'hardness' and the 'roughness' of the bed. Thorough ground-truthing of these parameters is then used to determine the grain size of the sea-bed. The available literature on bottom-classification systems suggests they are capable of delimiting broad sediment types (bedrock, gravel, sand and mud) and indeed they have been used for some archaeological surveys (plate 13.10). For these systems to become really useful tools for imaging archaeological materials, research needs to be undertaken into both their sensitivity to the rapid changes of material type common on archaeological sites and the actual acoustic properties of typical archaeological materials. Archaeologists are actively researching the potential for extracting such information from multibeam swath bathymetry data, but the extraction of non-normal incidence backscatter to material type is a major challenge. It should also be noted that those systems based on single-beam acoustic sources suffer the same horizontal resolution problems described above for the single-beam echo-sounders.

SIDESCAN SONAR

Sidescan sonar is a method of underwater imaging using a wide-angle pulse similar to those of the multibeam swath bathymetry systems. Rather than calculating depth information from the returning echo, the sidescan sonar system displays the intensity of the sound scattered back to the tow-fish from the sea-floor sediments and objects exposed on the sea-bed. Sidescan data can be processed to provide undistorted images of the sea-floor in real time. The area of the sea-floor covered in a single pass is controlled by the surveyor altering the altitude of the tow-fish above the sea-bed. This can be done by adjusting either the speed of the vessel or the length of the tow-cable.

Traditionally, a swath width equalling ten times the water depth was recommended but, while this may be adequate for basic sea-bed surveys, it does not always provide the optimum geometry for archaeological information. For detailed surveys, the angle at which the acoustic energy reaches the target is very important and running the same survey lines at very low and very high passes can often reveal very different, but complementary, information.

Sidescan sonar systems are available in a variety of types, depth ratings and operating frequencies. Recent developments that are now commercially available include 'Chirp' systems (so called because of the noise emitted),

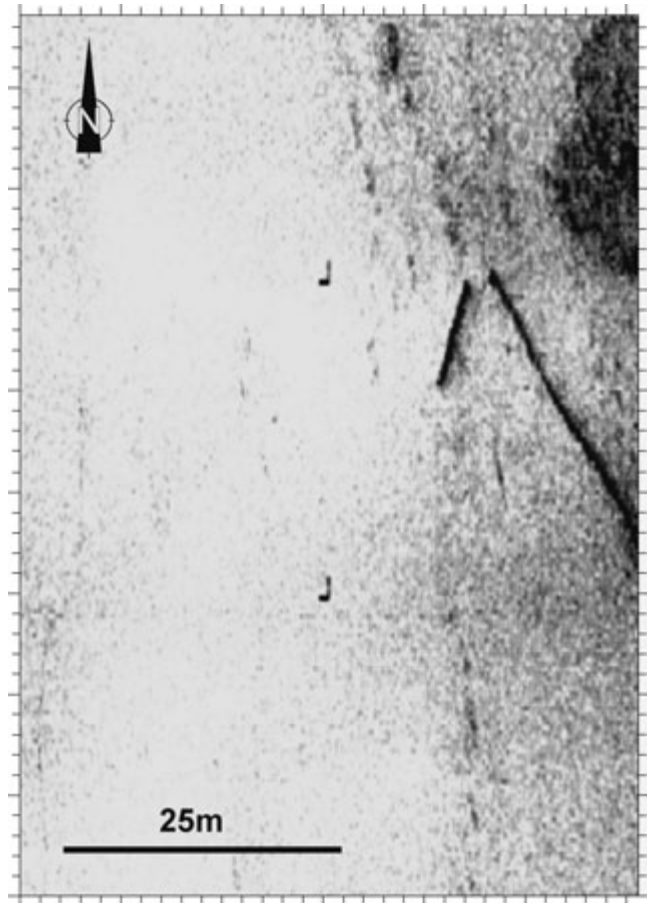


Figure 13.1 500 kHz sidescan sonar image of a v-shaped fish-trap from the River Barrow, County Wexford, Ireland. Data acquired using an EdgeTech Model 272-TD acquisition system. (Courtesy of the Centre for Maritime Archaeology, University of Ulster, Coleraine)

which utilize a sweep across a range of frequencies, and synthetic aperture systems, which provide excellent definition at longer ranges. Standard systems usually connect directly to a laptop computer to display the data. Such systems employ one of two industry-standard frequencies for imaging: 100 kHz and 500 kHz, although they may vary considerably from these, depending on the model and the manufacturer. In general terms, a 100 kHz operating frequency is chosen for regional surveys with swath widths in excess of 100 m (325 ft) per side. 500 kHz sources are generally used where a higher resolution is required, such as for shipwreck or waterside structure surveys (figure 13.1). Very high-frequency systems of up to 2.5 MHz provide even better definition but their effective range is limited, sometimes to less than 10 m (33 ft), and so are only useful on small, well-defined sites with excellent tow-fish positional control.

Material properties (primarily roughness characteristics) of the area being surveyed determine the strength of the echo (backscatter) from the sea-bed. Rock, gravel, wood

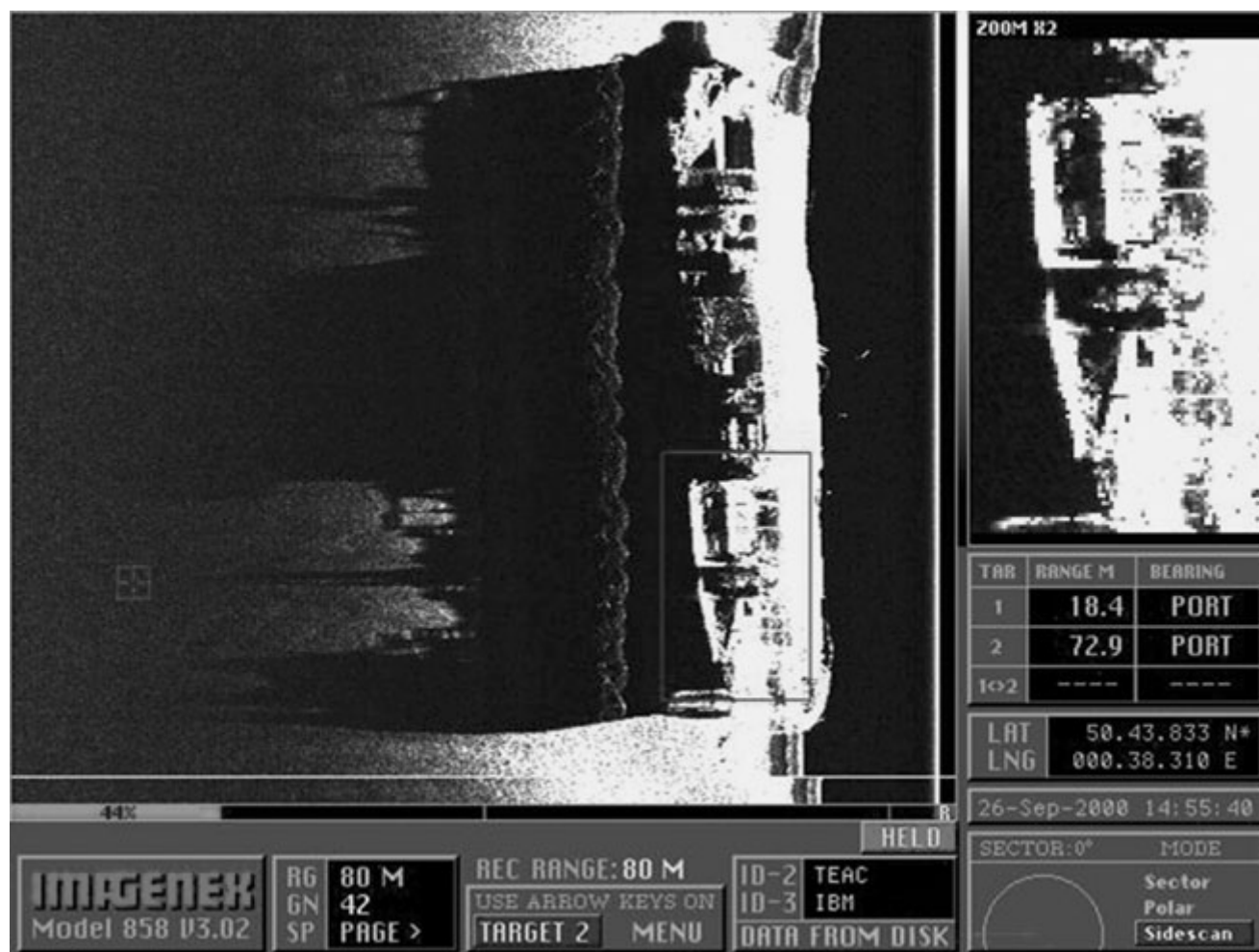


Figure 13.2 Sidescan sonar image of the SS *Stora* (1943) showing shadow detail complementing the backscatter information from the wreck. (Courtesy of ADUS, University of St Andrews)

and metals are better reflectors than finer grained sediments and will therefore be recorded as darker elements on the sonar record. Target shape, including sea-floor gradient, also influences reflectivity and backscattering. Arguably the most important phenomena on sidescan records for archaeological purposes are acoustic shadows, which provide a three-dimensional quality to what is essentially a two-dimensional survey. Acoustic shadows occur alongside objects that stand proud of, or are partially buried in, the sea-floor. In sidescan sonar data, shadows can often indicate more about the shape and nature of a target than the acoustic returns from the target itself (figure 13.2).

The majority of sidescan investigations follow a pre-determined survey pattern. Search patterns conventionally comprise a series of parallel survey lines with the lane spacing determined by survey requirements. The lane spacing must be less than the swath width of the sonar, thereby allowing for overlap between lines, ensuring 100

per cent coverage of the area. Although data has conventionally been displayed as a paper-trace, modern systems allow real-time data to be displayed through a computer and in conventional monochrome or almost any variety of colour mixtures the operator chooses. Software can then be used to identify the coordinates of any feature (geo-rectification) and, by measuring the length of the shadow and the height of the tow-fish, its projection above the seabed can be calculated. Geo-rectified sidescan images can be joined together in a mosaic to provide an image of large areas at the original resolution, thereby decreasing the trade-off between data resolution and survey coverage.

SUB-BOTTOM PROFILING

While sidescan sonar and multibeam swath bathymetry are the most effective techniques for finding and delineating archaeological objects exposed on the sea-bed,

many archaeological sites coincide with areas of high sedimentation. This can result in the partial or complete burial of structures, features and artefacts. While wrecks with substantial iron content may be found using magnetic surveying (see below), the only technique suitable for detecting buried wooden artefacts is sub-bottom profiling. Furthermore, marine archaeologists are increasingly interested in the identification of the environment or landscape in which such artefacts were deposited, and to understand this it is essential to look at both the surface and the sub-surface.

Two principal types of systems exist: those that produce a single-frequency pulse (such as 'Pingers' and 'Boomers') and those that produce a swept-frequency pulse ('Chirp'). The single-frequency systems suffer from a penetration-versus-resolution compromise. Put simply, higher frequency sources give better resolution but can penetrate only a short distance into the sediment; conversely, lower frequency systems penetrate further but give poorer resolution. The development of Chirp technology in the early 1990s attempted to address this conflict by producing a pulse that can penetrate decametres into the

sea-bed while still retaining decimetre resolution. It should be noted that the effectiveness of each system is dependent on the nature of the sediments being imaged, with coarser sediments (sands and gravels) being harder to penetrate than fine-grained sediments (silts and clays) (figure 13.3).

All sub-bottom profilers use a source that generates sound pulses that travel into the subsurface. These waves then reflect off boundaries or objects within the subsurface and are detected by an acoustic receiver (or hydrophone), which is usually mounted close to the source. Reflections occur where there are differences in density and/or sound velocity across a boundary. The returning echoes are then transmitted to a recording device, either a hard-disk or direct to paper printer (figure 13.4).

Sub-bottom profilers generate a data set that can be processed to give a cross-section in the direction of movement of the boat in two-way travel time (the time taken for the pulse to travel from the source to the reflector and back to the receiver). With additional knowledge of the speed of sound through the sediments present (obtained from *in situ* measurements of core

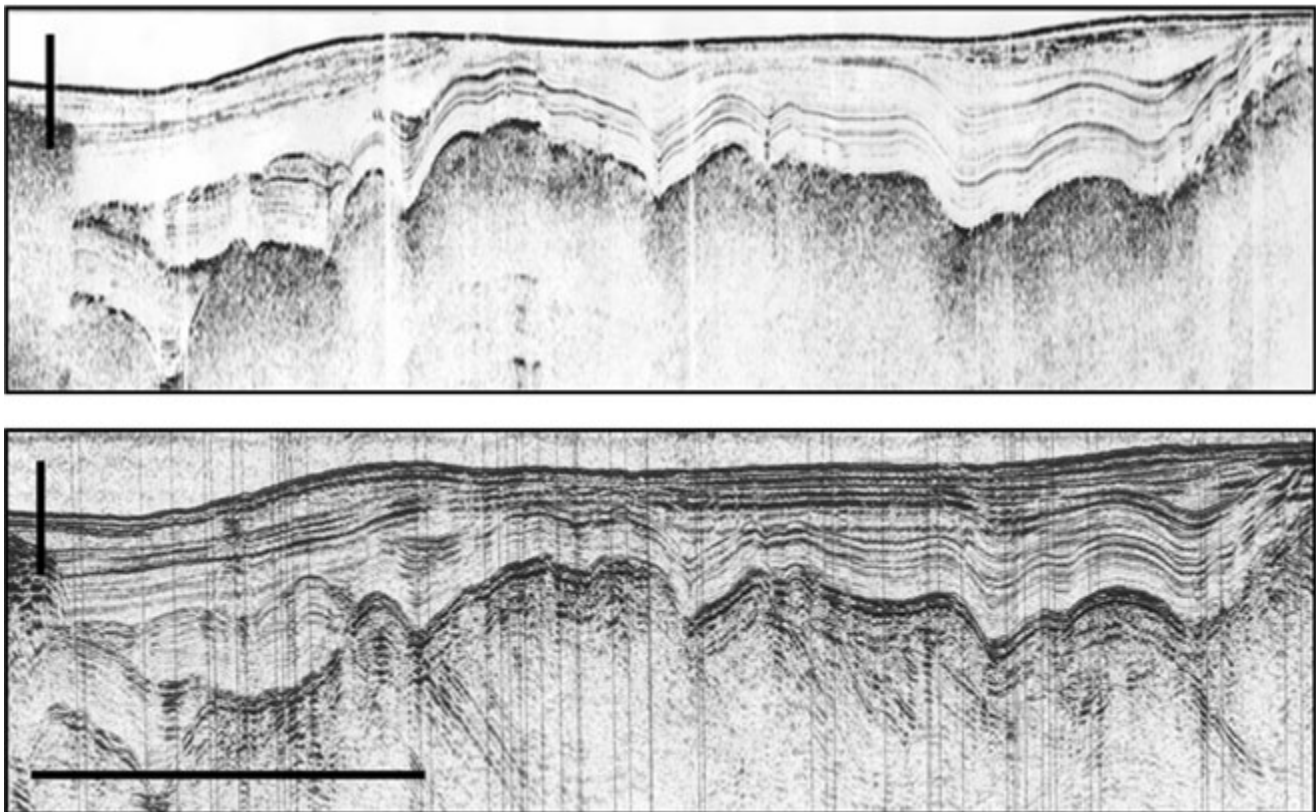


Figure 13.3 Chirp (top) and Boomer (bottom) image from the same location within Strangford Lough, Northern Ireland, showing the detailed layering within the upper, fine-grained sediments in the Chirp profile and the penetration through stiff glacial sediments into the basal bedrock from the Boomer section. Data acquired using a GeoAcoustics Chirp and Boomer system. Vertical scale bar represents c. 15 m (49 ft). (Courtesy of the National Oceanography Centre/University of Southampton)

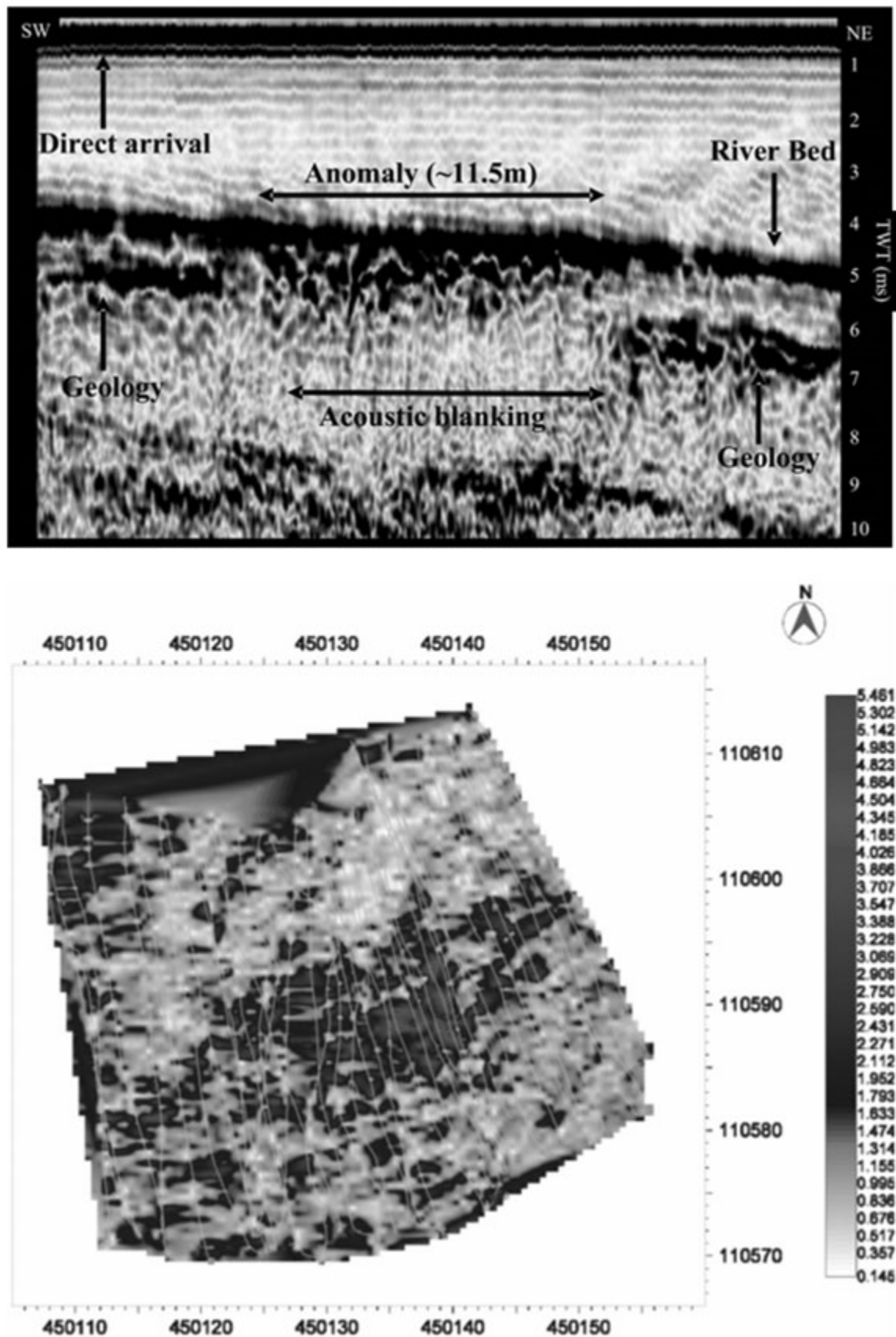


Figure 13.4 A two-dimensional profile and interpolated timeslice of the *Grace Dieu* (1439) wreck, River Hamble, Hampshire, UK. Data acquired using a 3-D Chirp sub-bottom profiling system, developed by the National Oceanography Centre and GeoAcoustics Ltd (UK). (Courtesy of the National Oceanography Centre/University of Southampton)

material or by comparison with standard empirically derived values), this cross-section can be converted to a depth section. Inevitably, the two-dimensional nature of the data results in sub-bottom data suffering the same coverage problems as described for echo-sounding. Recently, researchers at the National Oceanography Centre, UK, have developed a high-resolution 3-D Chirp system that is capable of acquiring a true 3-D volume of the sub-surface and has huge potential for the investigations of small-scale areas such as archaeological sites.

Pingers emit short pulses of a single high frequency (3.5 kHz for example), which gives a resolution of 0.3–0.5 m (12–18 in) and penetration of 20–25 m (65–82 ft). With such a system, the generation of the pulse and recording of the returning echoes are conducted within a single set of transducers, thus optimizing the horizontal resolution of the system. Boomer systems represent a single lower-frequency source, typically between 1 and 6 kHz. The boomer output pulse can be tailored to the survey's requirements, both in terms of the frequency of the pulse and the energy output. Boomer systems have a range of penetration of 50–75 m (165–246 ft) and an optimum vertical resolution of 0.5–1.0 m (18–39 in).

Chirp profilers are towed as close to the sea-bed as safety will allow, typically 5–10 m (16–33 ft) above the bottom, although if configured correctly they can operate in water depths as shallow as 2.5 m (8 ft). The frequency spectrum or bandwidth is wide for Chirp systems (typically between 6 and 10 kHz) and this is important as it controls the vertical resolution, with a practical vertical resolution of 20–30 cm (8–12 in) being obtainable at depths in excess of 30 m (98 ft).

For artefact identification, Chirp systems currently represent the best available technology, not only because of their good resolution but because suitable post-processing of data allows some degree of material characterization for buried objects. For landscape reconstruction, the Boomer system is considered the most reliable because it is capable of penetrating most sediment types found within the coastal zone and can thus guarantee some basic imagery of buried landscapes. However, in ideal circumstances both Chirp and Boomer should be deployed on a survey to ensure both detailed imagery of any fine sedimentary cover and penetration to bedrock.

MAGNETOMETRY

Magnetometers measure the strength of the earth's magnetic field and can detect variations in this field caused by the presence of objects containing iron and geological formations containing ferrous material. Modern sensitive systems can also detect weak magnetic signatures caused by ancient hearths and assemblages of ceramics. Marine

magnetic surveying is a well-proven technique and is often used for the location and detailed investigation of metal-hulled wrecks and wooden-hulled vessels that may have carried substantial ordnance or have some other ferrous component (plate 13.11). For inshore maritime archaeological research, three types of magnetometer are used. The proton precession magnetometer was the most widely used in the past, but is being replaced by the caesium (or optically pumped) and the overhauser magnetometer systems as the instruments of choice because they are both considerably more sensitive and so can detect smaller objects at greater range than proton systems.

The earth's magnetic field varies in intensity over the surface of the planet. At the poles, the field is concentrated and therefore has a high intensity – about 61,000 nT (1 nT = 1 gamma). At the equator, the field is quite weak, with a typical reading of 24,000 nT. In a localized area, the magnetic field tends to be even. If a ferrous mass or object is introduced into the area (e.g. an iron wreck), the lines of force are disturbed. Such local disturbances within the magnetic field are of potential archaeological interest and the amount of disturbance is a function of the mass of the object and its alignment.

Magnetometers for marine use are typically towed devices to avoid interference from the survey vessel. The minimum layback (distance between the stern and the tow-fish) can be ascertained by increasing the cable length until the boat stops registering as a magnetic anomaly. It may be necessary to carry out this procedure in more than one direction. The magnetic information is normally displayed as a numerical readout and as a graph, updated as the survey advances. The better systems generally use laptop computers to collect the data, rather than a dedicated logging device provided by the manufacturers. This has the advantage of being able to process the data quickly and, using appropriate software, produce informative graphical representations of the survey data, such as contour plots.

The proton precession magnetometer typically has a recording rate of 0.5–2.0 seconds and a sensitivity of 0.2–1.0 nT. Caesium and overhauser magnetometers have a faster measurement rate, typically 0.1 s, and sensitivities of at least 0.02 nT. These more sophisticated instruments can also be towed at higher speeds, tend to be more stable and are generally more effective for archaeological work than traditional proton precession magnetometers. The advantages of the proton type are a smaller relative size of tow-fish and they are cheaper to buy or rent.

One problem with magnetic surveying in coastal waters is the amount of detritus on the sea-bed from port developments and people's use and abuse of the coastal zone. Non-archaeological magnetic anomalies are abundant within developed areas such as ports. This is a particular problem at some sites, where objects such as

anchors, chains, cables and ordnance with large magnetic signatures can effectively mask archaeological anomalies. A more widespread but localized difficulty is background magnetism from geological formations, particularly where these are in tight folds that reach close to the surface a number of times in a survey area. Various techniques are available to reduce this problem, including multiple magnetometers set in a fixed array, which allows differentiation between very large masses such as ferruginous rocks (containing iron) or nearby steel wrecks and smaller signatures of potential archaeological significance.

INTEGRATED SURVEYS

Integrated systems are often used in mapping the underwater cultural resource. Integrated survey systems may comprise a combination of two or more of the following: bathymetric survey equipment, sidescan sonars, sub-bottom profilers and magnetometers. This integrated approach can lead to the acquisition of a large but effective data set. Generally, data is acquired in digital format

to facilitate offline processing and spatial integration (figure 13.5 and plate 13.12).

SUBMERSIBLES: ROVs AND AUVs

Remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) are examples of integrated systems. They can perform many of the tasks of a diver, including visual searches and photography, but are not limited in the same way by depth and time spent under pressure. These systems can host a suite of acoustic and video imaging data-collection devices with some underwater video systems incorporating image-intensifiers capable of showing greater detail on a surface monitor than the diver can see while under water.

ROVs are connected to a support ship via a cable and controlled from within the ship by an ROV pilot. Submersible technology is a field of rapid development but at the time of writing, deep-water ROVs can operate in depths of up to 6000 m (19,500 ft) while cheaper, shallow-water systems can operate in depths of around

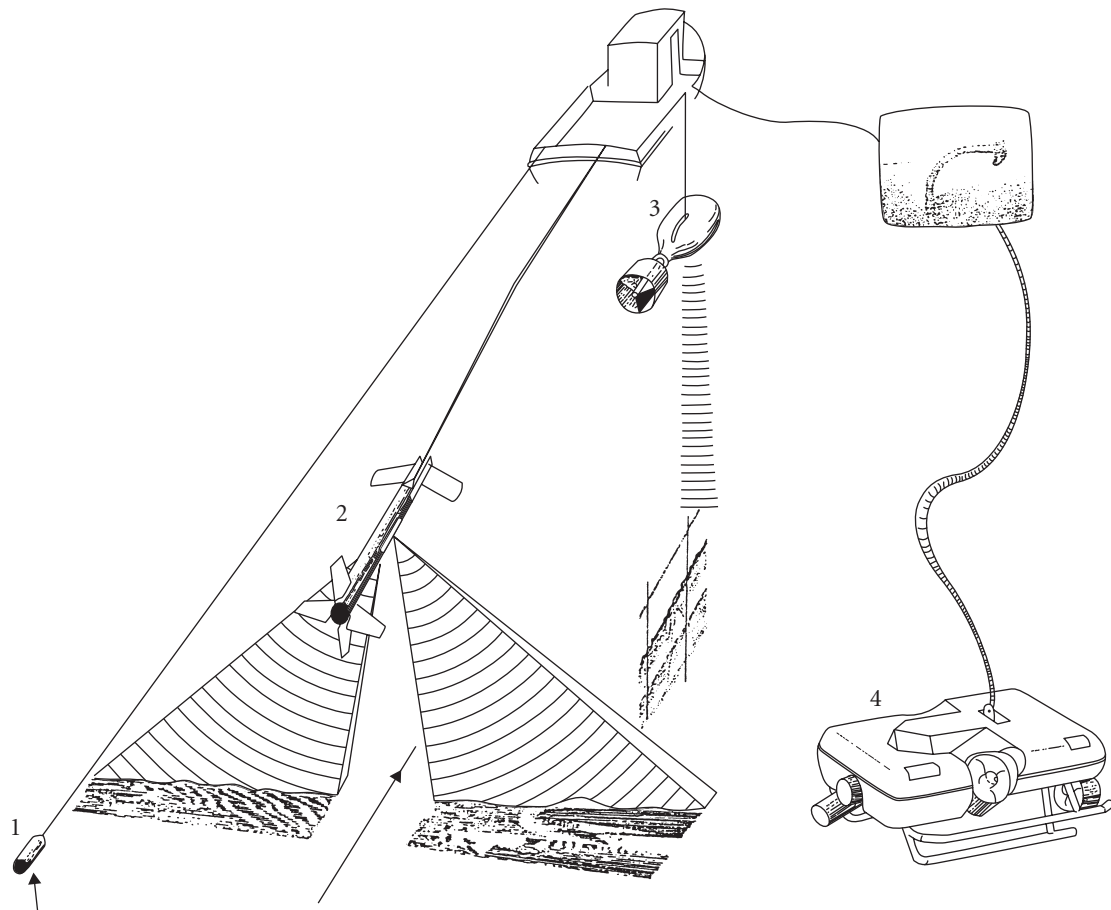


Figure 13.5 Geophysics equipment: 1) magnetometer, 2) sidescan sonar, 3) sub-bottom profiler, 4) ROV. (Based on an original drawing by Mark Redknap)

300 m (975 ft). AUVs, as their name suggests, are autonomous systems that function without remote control, tethers or cables. Their depth-rating at the time of writing is restricted by battery-life to approximately 3000 m (9750 ft).

AERIAL PHOTOGRAPHY

Aerial photography, particularly using modern digital cameras, is a successful method of investigation for

inter-tidal and foreshore research but has limited success in underwater research due to an inability to penetrate the water column successfully beyond, typically, 1 to 3 m (3–10 ft). Modern high-resolution digital cameras produce images in either colour infra-red (false colour) or true-colour mode. The size of the ground covered by each pixel can range from 10 to 50 cm (4–20 in) and above, depending on flying height and speed. Although this pixilation does not give images as obviously detailed as conventional film, digital images are easier to rectify and analyse.

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14 Underwater Survey

Contents

- ◆ Types of survey
- ◆ An initial sketch
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- ◆ Installing survey points
- ◆ The principles of survey
- ◆ Survey using tape-measures, grids and drafting film
- ◆ Vertical control (height/depth)
- ◆ Drawing/planning frames
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- ◆ Three-dimensional computer-based survey
- ◆ Acoustic positioning systems
- ◆ Positioning the site in the real world

It has been shown elsewhere in this book that fieldwork should be undertaken with clear aims and objectives that are defined in the project design. It may be that the survey alone answers the questions posed by the project design, so an accurate site-plan can be the end product of the fieldwork rather than just one phase of a project.

The aim of this section is to give an introduction to basic survey techniques used in underwater archaeology. The techniques described here are the same as those used in archaeology on land, as well as in civil engineering and building work. Surveying is not the same as searching; divers looking for wreck remains are searching, while divers recording the positions of those remains are surveying. The purpose of a survey is to produce an accurate picture of the site, usually as a two-dimensional plan (figure 14.1) with supporting descriptions and measurements. In essence, this is an attempt to re-create, on paper or in a computer, the site as it exists now, and before it is disturbed. The site-plan must be an accurate representation, so it is not acceptable to simply sketch or guess where things are.

TYPES OF SURVEY

Surveys on archaeological sites can broadly be divided into four types:

- 1 assessment survey;
- 2 recording survey (including pre-disturbance and excavation surveys);
- 3 monitoring survey;
- 4 topographical survey.

The end product for each survey type is the same – the site is recorded to a known level of detail and accuracy.

An assessment survey provides information on which a fieldwork strategy can be based. It can be used to find the extent of the site before embarking on a more detailed pre-disturbance survey (see below). It can also provide information on the range, type and stability of archaeological material surviving on the site. This is important because such information can affect decisions about what action should be taken and when. Such a survey could help decide the location of primary survey

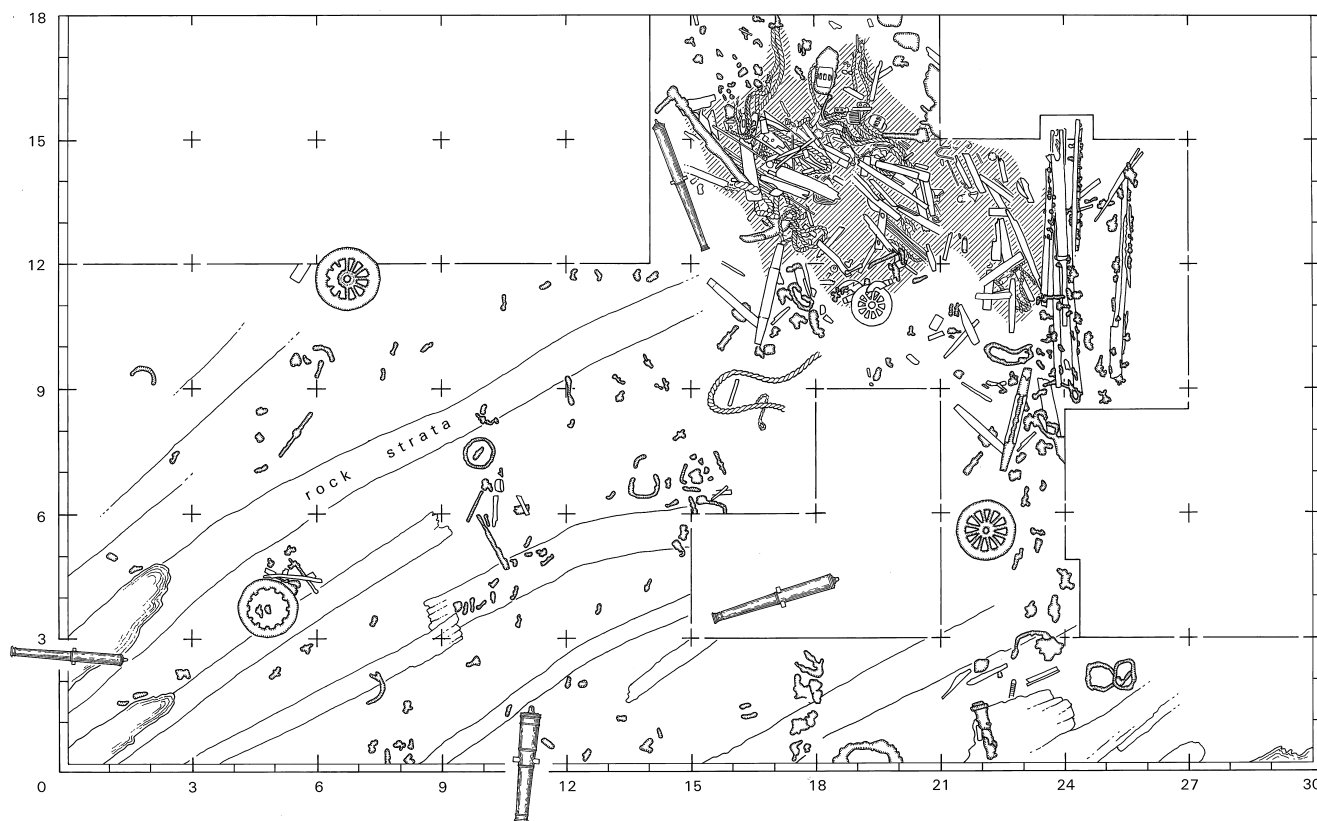


Figure 14.1 Excavation plan of part of the Spanish Armada wreck *La Trinidad Valencera* (1588), a scattered site on a flat, sandy sea-bed. The excavation limits are shown within a grid framework, and the locations of prominent objects shown. The extent of a major deposit of organic material is shown by hatching. (Colin Martin)

points. The aim of an assessment survey is to get a rough idea of the extent and layout of a site as quickly and efficiently as possible. Position accuracy is less important than speed, as the plan can always be improved at a later date. As a minimum, the assessment survey should result in a paper plan, drawn to scale, showing the significant features on the site, sea-bed type and an outline of the topography, as well as any information requested in the project design (figure 14.2).

Recording surveys include pre-disturbance and excavation surveys. These require high position-accuracy so careful planning, recording and processing are needed and they take time to do correctly. A common question regarding pre-disturbance surveys is, 'how much information should be recorded?' The simple but daunting answer is, 'as much as possible without disturbing the site'. The more information that can be collected through non-destructive pre-disturbance surveys, the more effective future work on the site is likely to be. This applies to both the planning of further work on site and avoiding unnecessary damage to archaeological material.

A pre-disturbance survey is an essential step in ensuring that a complete record of the site is made. A pre-

disturbance survey is not undertaken for the sake of it; the work will provide useful information on the condition of the site at that time. The results can be used as a benchmark for future monitoring (see chapter 17) if no further work is to be done, or can be a record of the original condition of the site if it is to be altered or destroyed by intrusive investigations such as excavation. The information collected during the pre-disturbance survey can help to ensure that the appropriate funds, conservation facilities and expertise are arranged well in advance of any disturbance to the site.

If intrusive investigation is considered to be the most appropriate way forward for an archaeological site, then recording during excavation is an essential continuation from where a pre-disturbance survey left off. Pre-disturbance survey results are developed during excavation as more artefacts, structure and stratigraphy are uncovered.

Monitoring surveys are designed to monitor how the site changes over time. Using an existing survey, a monitoring survey compares those parts thought most likely to indicate change. Typical examples might include monitoring the position, attitude and remains of a

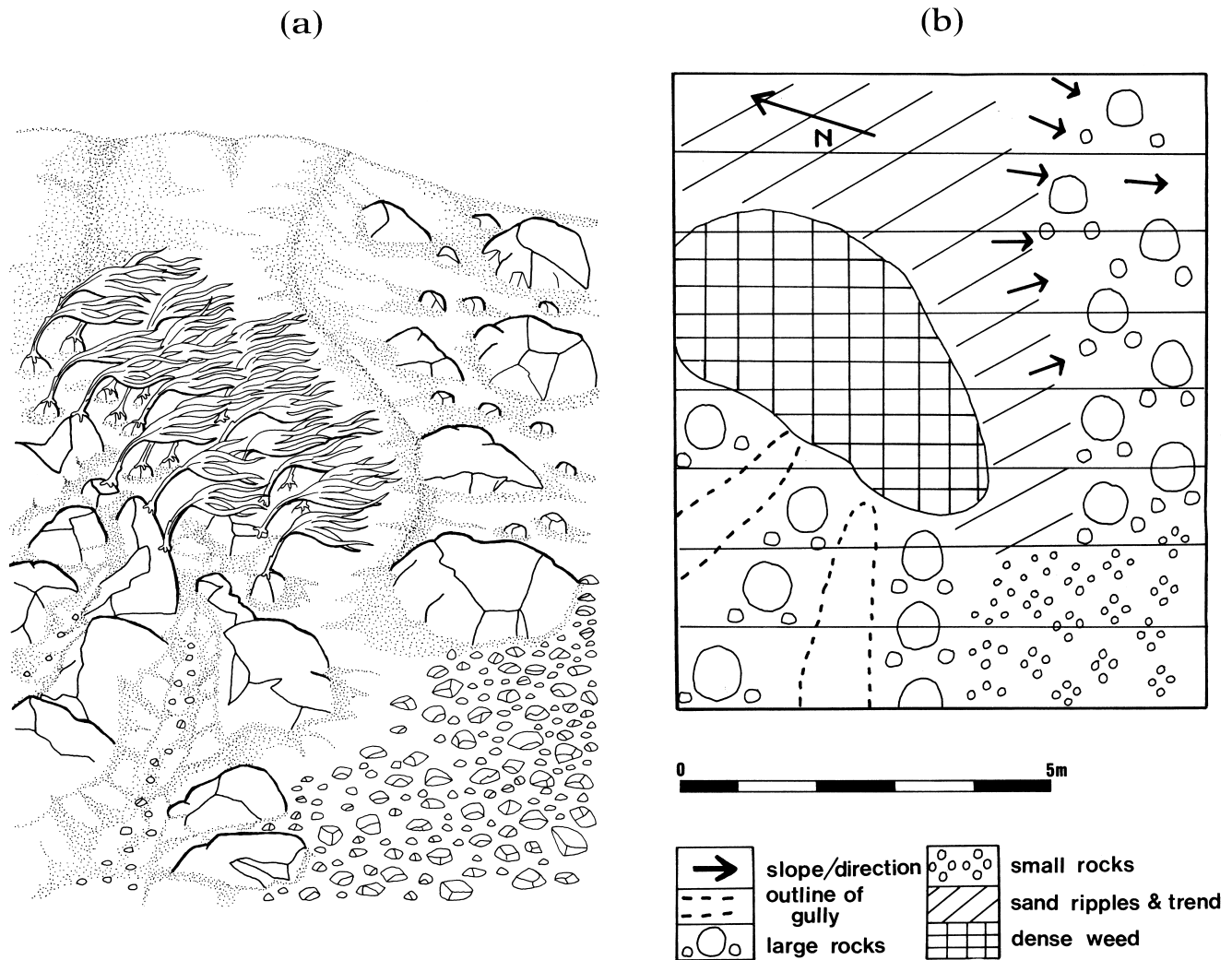


Figure 14.2 Translating the visual image into written record: the sea-bed (left) can be depicted by the use of symbols as shown on the right. (Based on original artwork by Ben Ferrari)

sternpost on an exposed site, or the depth of burial of a site under the sea-bed (see chapter 17).

A topographical survey aims to record the shape and characteristics of the sea-bed. The same principles are used; what makes this different is the need to cover a wide area. Recording the shape of the sea-bed usually involves recording the depth or height of the sea-bed at known positions. If the measurements are made at regular intervals over the site, then a plan can be produced showing the depths as contours. Details concerning the surface of the sediments and bedrock lying under water should include information about relative heights of features. Recording topography in detail is time-consuming if it is to be done accurately. Sometimes, more can be gained in a reasonable time by sketching the site and adding spot-depths at known features.

Accurate wide-area topographic maps and 3-D models are usually created using a multibeam echo-sounder (see chapter 13). There are standard ways of describing types of sea-bed and sediment. For further information, readers are referred to *Seasearch Observation Form Guidance Notes* (www.seasearch – Seasearch Recording), which provide detailed practical information on how to record such information (see also table 14.1).

AN INITIAL SKETCH

The first step in any survey is to create a sketch of the site, as this will form the basis for any future work. A good sketch can very quickly provide a large amount of information about a site and this can be invaluable in the

Table 14.1 The sea-bed itself can be categorized by the size of individual grains within the sediment. (After Wentworth, 1922 or see http://en.wikipedia.org/wiki/Particle_size_%28grain_size%29)

<i>Sediment type</i>	<i>Particle size (mm)</i>
Clay	up to 0.004
Silt	from 0.004 to 0.06
Fine sand	from 0.06 to 0.2
Medium sand	from 0.2 to 0.5
Coarse sand	from 0.5 to 2.0
Fine pebbles	from 2.0 to 8.0
Medium pebbles	from 8.0 to 16.0
Coarse pebbles	from 16.0 to 64.0
Cobbles	from 64.0 to 256.0
Boulders	over 256.0
Bedrock	N/A

early stages of a project. Some form of sketch is essential before further work can be planned, as the size and shape of the site need to be known. The sketch should aim to give an overview of the main features, both topographical and archaeological, as well as any problems or potential hazards, and should help to decide where control points (see below) should be fixed. In later stages of a project, simple sketches can be extremely useful for recording the associations of objects (as can photographs). However, a sketch will have much more value if it is drawn at the site, and not later on dry land.

A checklist of information to record can be written on the slate before the dive. If the sketch was drawn under water on plastic film, it can if necessary be copied onto another sheet on land, either by hand or by photocopying or scanning. With an accurate sketch, future activity on the site can be thoroughly and efficiently planned.

If visibility is bad, then it may be easier to do a radial survey with a compass and tape-measure. The radial survey is a simple technique requiring a single diver with a tape-measure and compass. One end of the tape is attached to a control point in the middle of the site and the diver swims around the site recording the distance and bearing of each feature from the central point (figure 14.3). This, of course, works best on flat sandy sites with little weed-cover. It is simple enough for use on deep sites, provided that the tape is checked for snagging. Its main limitation is the inaccuracy of the measurement of bearing, especially as distance from the control point increases. Radial surveys are drawn up using a scale rule, a pair of compasses and a circular protractor. A point is marked in the middle of a piece of paper, which represents the central control point. After the selection of a suitable scale, a line (representing the recorded distance from the control point) is drawn from the central control

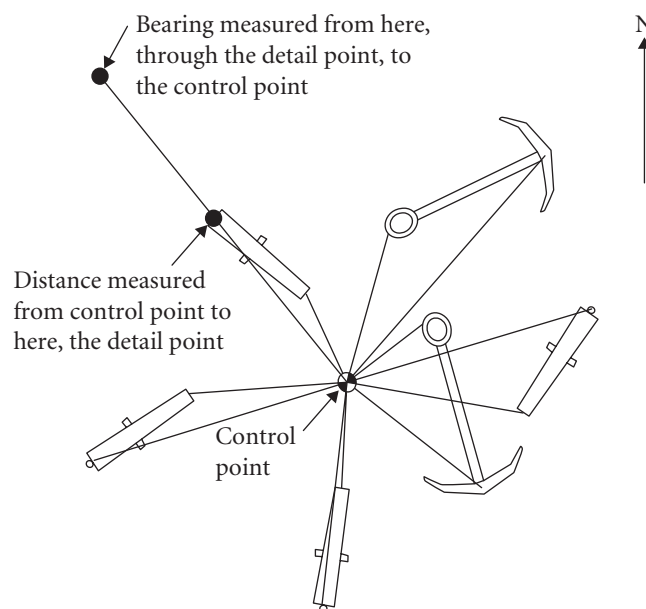


Figure 14.3 Radial method of survey, where the distances and bearings of features are measured from a central control point. Although accuracy diminishes with distance, the bearing shown here is measured from the extended point indicated because the effect of the iron gun's magnetic field on the compass has to be minimized

point at the appropriate bearing for each surveyed feature. For more about drawing up survey results, see below.

PLANNING

It is essential that all site work is well planned before it begins so that work on site is efficient, safe and problem-free. The actual amount of time the team will spend on site and under water is usually very short compared with the time spent planning and in processing the measurements. The first step is to define the scope of work, based on the project design (see chapter 5). The level of detail and accuracy required defines the type of survey to be undertaken and the techniques that can be used, so both should be specified in the project design. The scope of work will also depend on any work done previously. If the site has not been recorded at all, then an assessment is required; if an assessment has been done then subsequent work can be based on the previous results.

The level of detail and content of the survey depends on a number of related factors:

- Requirement – what needs to be recorded?
- Time – what is it possible to record in the available time?
- Equipment – what tools are available?

- Expertise – what skills are available?
- Environment – what can actually be recorded?
- Funding – what funding is available?

Requirement: What needs to be recorded depends on the aims laid out in the project design, which itself should take account of the other factors listed here and what information already exists (see chapter 5). For work where no change to the site is being made, a varying degree of recording can be considered because the work could be repeated to a higher standard if required. Where excavation is taking place, then ‘everything’ should be recorded, to a level determined by the archaeological director and set out clearly in the project design.

Time: How much can be recorded and the methods that can be used are determined by the time available on site, which itself depends on the time allocated to the project and working conditions on the site. It is important to plan how much time is likely to be spent working under water, and how much time might be lost due to poor weather or adverse tidal conditions. If working time is likely to be short, then the aim should be to do a simple survey using simple techniques – a little useful data is much better than no data at all. On average, it takes approximately 5 minutes to make a single tape-measurement under water. This time can be reduced or increased depending on variables such as depth, size of site, temperature, visibility, and experience.

Equipment: Most underwater survey methods use the same basic tools: the tape-measure and drawing board. Advanced tools such as acoustic positioning systems (see below) are not commonly available but they are occasionally used in support of underwater archaeological work and so should be considered in the project planning phase. It is important to ensure that the appropriate diving equipment is chosen to enable the diver to carry out the work safely and comfortably. A small rigid inflatable boat may enable the project team to get to the site quickly but a larger, hard-hulled boat may enable the team to spend all day on site in comfort. The ability to process results on site is a significant attraction of larger boats, as it allows for the correction of mistakes and collection of additional measurements there and then.

Expertise: It is essential to consider early in the project whether or not the team has the appropriate archaeological, surveying, and diving expertise to carry out the survey safely and accurately (see chapter 6). If additional skills are needed, they are readily available in the form of training, books, the internet, advice or recruitment of extra team members. The Nautical Archaeology Society provides training in many aspects of underwater archaeology to

a range of skill-levels. If any team member needs a refresher, the survey techniques to be used can be practised on dry land beforehand.

Environment: The location and conditions on the site can limit how much can be recorded. Sites with features scattered over a wide area are more difficult to survey accurately. As a general rule, any group of features separated by more than 30 m (98 ft) should be treated as a separate site. In good visibility, it is possible to position control points further apart, therefore reducing the work involved in setting up control. In very poor visibility, there may be a limit to what divers can achieve (e.g. checking that the tape is not snagged takes longer in poor visibility). In strong currents the tape will bow, so control points will need to be located closer together to reduce the length of each measurement. More points will therefore be required to cover a site and survey work must be scheduled around periods of slack water.

Funding: Most of the limitations mentioned above can be solved by spending more money. However, most teams have a limited budget, which determines what equipment can be used and how much time can be spent on site. It should be remembered that an acceptable survey is normally achievable with limited resources.

SETTING UP A BASELINE/CONTROL POINTS

The basic principle of surveying is to be able to work out the position of a survey point from some other point or points, using known features to position the unknown ones. On land the positions of known points are often provided in the form of triangulation or ‘trig’ pillars, unfortunately these do not exist under water so they must be created. To start a survey, all that is required is to measure the distance between two primary survey points on the site. As yet, the location of the two primary survey points in the real world is not known. They are assigned arbitrary coordinates so they can be drawn (to scale) on a plan. These two points are now ‘known’ control points; with a ‘baseline’ drawn between them, they form the start of a site-plan. By measuring the distances and/or angles from both these points to other fixed points on the site, the other points can be plotted relative to the two initial control points on the plan. It is then possible to draw up a network of survey-points joined by distance measurements. The site-plan of points and distances is drawn to scale and represents the archaeological site lying on the sea-bed.

Most archaeological sites will require more than two control points, which will form a control point network. These points are the framework on which subsequent survey work is built. Permanent, fixed points are placed

around the outside of the site and, if the site is large, possibly through the middle as well. A minimum of two points is necessary for manual recording (with a third advisable in order to make checks), and a minimum of three (or four with checks) for three-dimensional computer recording (see below), although more are usually used. The horizontal positions of control and detail points are defined using rectangular x, y coordinates, irrespective of the method used to survey them. The origin (0, 0 point) can be put anywhere on the real site, but it is easier if the origin is taken to be the extreme south and west of the area, thereby making the coordinates for all points on the site positive. If the site extent is unknown and it may extend further to the south-west, then it may be useful to put the origin a long way off the site. To achieve this, the coordinates of the extreme south-west point on the site can be given a large number such as 1000, 1000. This is known as a 'false origin'.

To avoid confusion, the survey team should standardize the units and conventions to be used. It is recommended that coordinates, distances and depths should be given in units of millimetres, metres and kilometres. Angles should be given in degrees. The way numbers are written down should also be standardized. It is recommended that distance and depth measurements are written in centimetres or millimetres, because distances in metres require decimal points, which can easily be lost when transcribing numbers from forms.

INSTALLING SURVEY POINTS

Once the position for each of the survey points has been decided, the next step is to install them on site. Where feasible, control points should be made as permanent as possible. Setting up new control points each diving season not only wastes time but may compromise accuracy.

Three types of survey point are used:

- 1 Primary control points are established in the planning phase and are the main reference points for the survey.
- 2 Secondary points may be added later to solve line-of-sight problems or to reduce measurement lengths.
- 3 Detail points are the points on artefacts and features used to position these objects.

Primary control points are the most important, and at least two primary control points must remain after the work has been completed so that any further survey can be related to the earlier one. Primary points should not be placed on the artefacts or structure of the site (both because archaeological materials should not be damaged and

because they might move), but should be fixed firmly and securely to the sea-bed. Some recent re-surveys of sites have re-used points installed more than 20 years ago. Secondary control points can be placed on rigid structures or artefacts that are unlikely to move. It is not so important to ensure the permanence of these points, as they could be re-established by measurement from the primary points.

For permanent fixings into rock, large galvanized steel or stainless steel coach-bolts can be used, or the bolts (spikes) used to hold train rails onto sleepers. For even more permanent attachment, the bolts can be cemented in using specialist underwater cement or a mixture of sand and cement held together with a little water and PVA glue (which stops the cement washing away while it is being applied). This mixture can be applied from a plastic bag like toothpaste. Climbing pitons, if made of a suitable metal, can also be used, driven into crevices in the rock. Enough of the bolt or piton should be left visible to provide a secure attachment for a tape-measure loop. If the bolts are too big then tapes can be temporarily attached using releasable plastic cable-ties.

Installing anything permanent on sand and mud can be difficult, especially if the sand itself moves, so a compromise is usually required. Long lengths of steel reinforcing-bar can be driven into the sea-bed and the longer the length of bar, the more stable it will be. Scaffold tubing can also be used (driven into the sea-bed with a stake-driver, sledgehammer or air probe), or the metal supports designed to protect and firmly locate the bases of fence posts. If there is a danger that the post will be knocked during diving work, then any excess length should be cut off. The actual point used for measuring on any post, bar or tube must be clearly identified; attaching a plastic hook to the bottom works well. It is better not to measure to the top of the post as any movement in the post will increase the further up you go. Clearly, it is important to check what is just under the sea-bed before the survey point is installed to avoid damaging the site.

Attaching control points to the wreck or structure itself is to be discouraged because it can easily damage the very object of the recording process. Where this cannot be avoided, it should be done with care and, ideally, should be attached to wood with no features (such as joints, treenails or decoration). Points attached to objects held in place simply by their own weight only work well on low-energy sites; any movement must be less than the intended survey accuracy. Extremely heavy objects do not always work well either; they move as they settle into the sea-bed or as scouring takes place. Brass screws are easy to fit and last a considerable length of time under water. Nails and cup-hooks are quick to install but tend not to last very long, and should be used only for temporary work. Large cable-ties or tie-wraps have been

used to securely attach plastic shower-curtain hooks to cannons and anchors.

All survey points should be clearly marked in a way that will last for as long as the points are needed. One of the most common mistakes made when recording measurements is to measure to the wrong control point. The marking method chosen for primary control points should be designed so that it remains visible, even after a few years of marine growth has accumulated. Each point needs a label clearly identifying its name or number. For primary control points, the labels should be large and securely fixed on the point or very close to it. Labels made from plastic sheet with the point's name cut out seem to work well, as the name is still readable even if covered in marine growth. For secondary and detail points, less expensive garden-tags can be used; if the point name is engraved with a hot soldering iron then the label can be read after several years under water.

Finding the points can be a problem, especially on large sites or those with poor visibility. For points fixed to rock, the area around the point can be cleared of marine growth with a wire brush to make the point more visible. Additional ideas that have worked include bright plastic markers designed for survey points on land, or animal ear-tags, and using any durable tape or paint on the point itself or a float above it if there is weed cover.

Features and artefacts can often benefit from having a label attached, particularly cannons and anchors. When positioning any artefact, a record should be made of the point or points on the artefact that were actually positioned – a simple sketch is usually enough. Where a surveyed point on a feature or artefact is to be repositioned later, the point should be marked. Techniques that have been used include: white map-pins for temporarily marking points and defining edges or corners of objects in photographs; silicone sealant for attaching survey points to corroded metal structures in the inter-tidal zone; yellow crayon to mark crosses for points or for adding labels to iron or concreted items. Alternatively, the join in the cable-tie can be used as the point to be positioned.

THE PRINCIPLES OF SURVEY

Survey is about depicting features in a symbolic way, and showing the three-dimensional relationships between them (though usually the result is shown on a flat surface). This could, for example, involve the relationship between a natural feature, such as a gully, and the archaeological features and objects deposited within that gully, but equally the relationships between the various objects and features in the gully. The degree of accuracy required relates to what is being shown, and what methods are employed to show it (including the scale).

All survey is based on measurements and bearings, which can be combined to build up a complex picture. There are two basic methods: offsets and ties/trilateration.

Offsets

Offsets are measurements that position features relative to a tape baseline fixed between two control points. An offset measurement positions a feature using a single measured distance at right-angles to the baseline from a known point, and is simple and effective over small areas. Two divers are needed for these methods, one at each end of the tape-measure. Like radial surveys, the positions are usually only given in two dimensions although spot-depths can also be recorded. Offsets are most frequently used for assessment surveys, for recording detail or in confined areas such as rock gullies.

The first step is to set out a tape-measure baseline between two control points, which runs through the centre of the area to be recorded, and with a clear line of sight between the two points. Distances are measured from this baseline, horizontally or vertically, to features on the site using a tape-measure or measuring rod. Vertical offsets are often used for measuring profiles of ships' timbers (figure 14.4 and plate 14.1). To position using an offset, a measurement is made from the feature to the point where the offset measurement meets the baseline at a right-angle (figure 14.5(1)). The right-angle point can be found by swinging the 'offset' tape-measure and finding where the distance to the baseline is the shortest (figure 14.5(2)). In poor visibility it may be useful to have

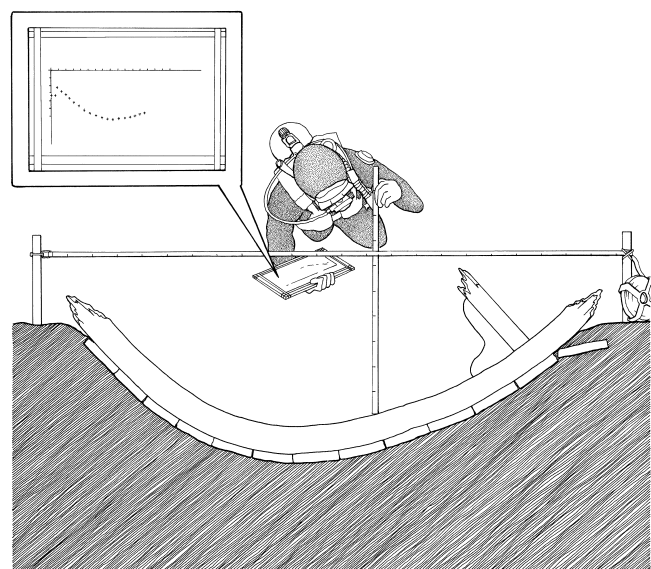


Figure 14.4 Recording the profile of a wreck using vertical offsets from a horizontal datum. (Drawing by Graham Scott)

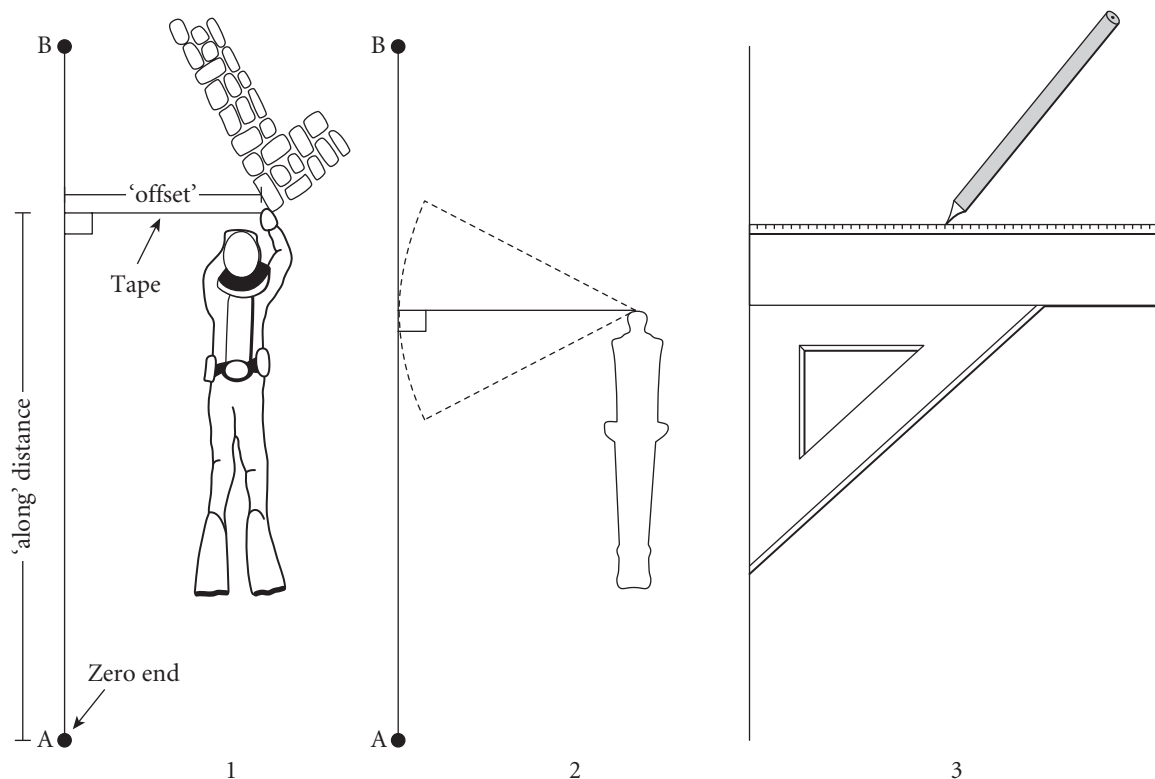


Figure 14.5 1) Offset method; 2) a method of establishing a right-angle, 3) plotting offset results. (Based on original artwork by Ben Ferrari)

a second diver swim up and down the 'offset' tape to ensure that it is not snagged.

In this case two distances are recorded – the 'offset' distance from the feature to the baseline and the 'along' distance from the zero end of the baseline to the start of the offset (figure 14.5). The position accuracy of offset measurements is limited by the fact that it is difficult to estimate correctly the right-angle with the baseline, and it is therefore only suitable for use in good visibility and when close to the baseline. Long tape baselines can move sideways and do not provide a stable reference for the offset measurement.

Ties/trilateration

This works by creating a triangle, taking two measurements from a feature to two chosen points (control points) on a baseline (figure 14.6). It is most accurate when the triangle is as close as possible to equilateral. Although this cannot be achieved precisely, the angle of the tapes at the feature should be between 30 and 120 degrees: this is known as the angle of cut.

As much as possible should be drawn up under water, so that details can be added and errors can be identified and fixed. Drawing up a plan-view on dry land, based on

either method, requires a scale ruler, a pair of compasses and a set square. For both methods, select a suitable scale based on the length of the baseline and the size of the paper, draw the baseline to scale, and label the control points. For offsets, mark the scaled measurements along the baseline (from the appropriate control point) using the scale ruler. A set square can then be used to mark the distances out from the baseline (offsets) (figure 14.5(3)). When drawing up ties measurements, set the compasses to the correct measurement and draw an arc from one control point and another arc of the right length from the other control point. Where the two arcs cross is the third point (figure 14.6). Once completed it will be clear why angles which are too acute or too obtuse do not produce an accurate result, as the point where the two lines cross will not be as clear as when they cross at closer to the ideal 60 degrees. Drawing up on a computer uses the same principles.

The trilateration method does not need to be limited to baselines. It can be carried out directly from any two control points on a site. It can also be used to tie in additional control points and is particularly useful for recording isolated finds. For an area with tightly packed archaeological material, a grid frame is usually used (see below).

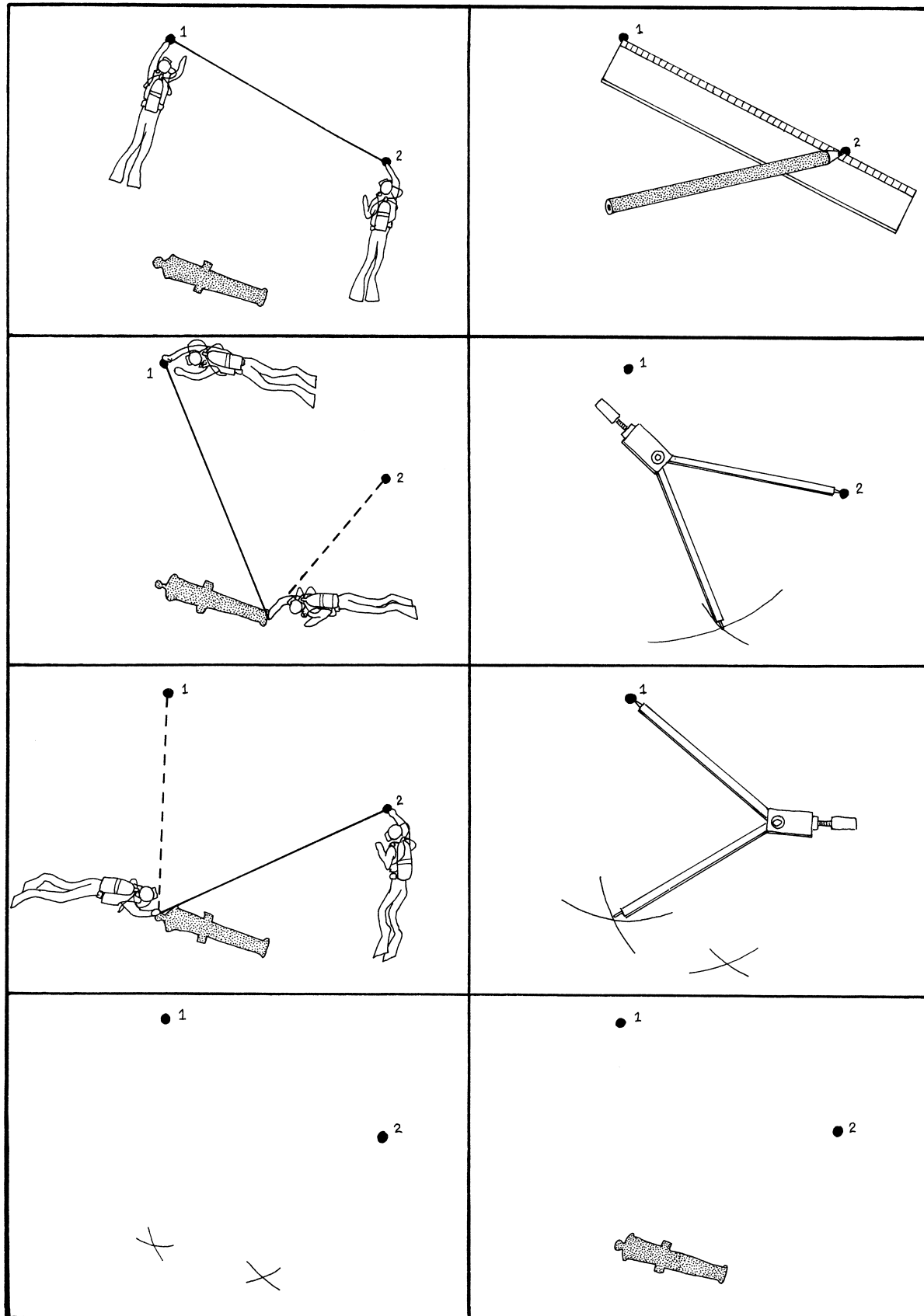


Figure 14.6 Ties/trilateration: survey and drawing up results. (Drawing by Graham Scott)

SURVEY USING TAPE-MEASURES, GRIDS AND DRAFTING FILM

With control points installed on the site, it is now possible to collect measurements that can be used to calculate the positions of the points. Each point on a site has a position given in three dimensions: x and y horizontally and z for depth or height. Positioning under water is largely a matter of measuring distances between objects. The most typical tools used for this are the tape-measure, the drawing frame and the rigid rule.

A small drawing board called a slate or clipboard is most often used for recording measurements under water. The slate should be slightly larger than A4 size. Plastic sheet of 3–5 mm thickness is usually sufficiently rigid. The slate should sink rather than float so, if necessary, a small strip of lead sheet can be attached to the bottom. It should have a short lanyard with a clip to attach it to the diver. If a slate is to be carried in a net bag, then the corners should be rounded. When carried in a bag with other equipment, the danger of figures smudging must be guarded against. A pencil should be attached to the slate with a lanyard long enough to allow it to be used comfortably anywhere on the slate. Propelling pencils made of plastic work well under water (soft (2B) leads are recommended). Ordinary pencils break easily when waterlogged.

The measurements are written on a sheet of plastic or drafting film attached to the slate with clips or electrical tape (plate 14.2). Standard waterproof forms can be made by photocopying a paper form on to drawing film (75 micron plastic paper will pass through most photocopyers and printers). Each form should have space for the site name, the site code, the date, a dive reference number, diver's name, estimated visibility and current, plus room for a small sketch. Numerous different types of form can be created – for distance measurements, offset measurements, depth measurements, blank forms for sketches and forms with square grids for drawing frames. Write clearly in capitals and avoid smudging work. Use standard units and conventions, which should be agreed beforehand. Any recording forms that have measurements on them should be well looked after. The forms are the primary record of any work and should be kept even after they have been processed. Keeping a notebook with day-to-day accounts, speculations and ideas about the site is often useful, as the notes can be helpful later when the measurements are being processed.

Many different varieties of tape-measure are available with different materials, lengths and designs. A tape-measure suitable for survey work under water is no more than 30 m (98 ft) long and has graduations as fine as the site-plan requires. Open-frame tapes are better as they can be easily rinsed after use and dismantled to

remove silt and grit. Yellow tapes look good in photographs, whereas white tapes tend to flare in bright light and are harder to read.

The most common type of tape-measure is made of glass fibre-reinforced plastic and those with stainless steel or plastic fittings will last the longest. Fibreglass tapes are cheap and readily available from builders' merchants but they do stretch with use. Steel-cored tapes look very similar but stretch very little, although they are slightly more expensive and can kink if not handled properly. A typical steel-cored tape is accurate to about 6 mm at 30 m in ideal conditions whereas a fibreglass tape is only accurate to 30 mm at 30 m. The achievable accuracy does depend on the conditions under water, as any water-movement will tend to make the measurement less accurate. Measurements over 30 m are not recommended as this length of tape is difficult to manage and sag in the tape makes the measurements insufficiently accurate.

Given that fibreglass tapes will stretch, the correct amount of pull has to be used to ensure the correct distance is recorded. The weight of the tape itself tends to make it sag so measurements will tend to be slightly long; in pulling the tape straight the diver may end up pulling it too much and record a short measurement. Any water movement will make the tape bow outwards and this has the same effect as sagging, so where possible take measurements at slack water. It is possible to measure the correct tension but this is difficult to do under water and is very time-consuming. Getting the correct tension can only come with practice, but it is more important to be consistent with the amount of tension used. It is important to train divers in the use of these techniques on land before they use them under water.

The free (zero) end of the tape should be hooked on to a control-point and unwound in the direction of the point to be measured. Pull the tape tight over the point to be measured and record the distance at the centre of that point. The names of the relevant points should be clearly recorded on the form along with the measurement itself. Care is needed here, as a mistake can be made when the measurement is written down and when it is read by whoever is processing the measurements. The results should be recorded on a form clearly enough for someone who has never visited the site to be able to process the results. It is often necessary to refer back to the recording forms during processing to help decide whether a measurement should be rejected. A number of factors affect the quality of measurements: working in low visibility, strong currents and deep water all tend to produce more frequent mistakes.

Tapes are prone to being snagged on other objects between the two points being measured. Where both ends of the tape cannot be seen the tape should be checked for snags before the measurement is taken. Where practical,

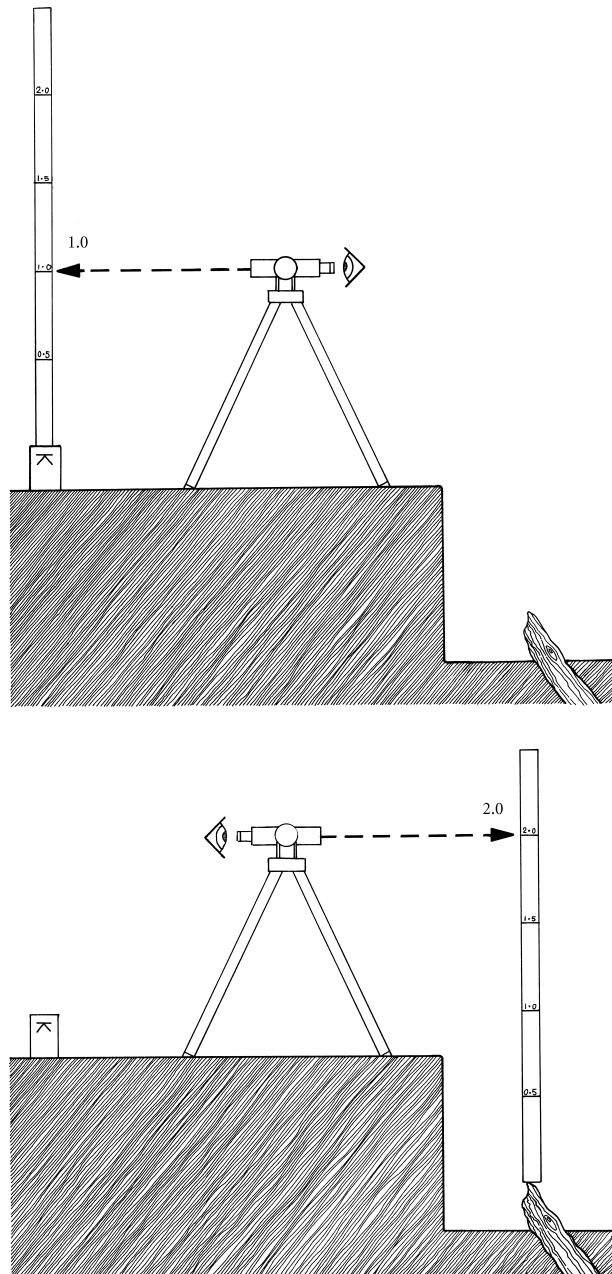


Figure 14.7 The principle of levelling to establish relative heights/depths. For example, if the benchmark is at 6 m: top image shows the level is $6 + 1 = 7$ m above chart datum; bottom image shows the level is 2 m above timber; therefore, top of protruding timber is $7 - 2 = 5$ m above chart datum. (Drawing by Graham Scott)

work in pairs where one diver takes measurements while the other ensures that tapes are not snagged. Avoid pulling tapes to free them from snags as this can damage them. Each tape being used for recording should be checked against an unused tape-measure at 15 m and 30 m (49 and 98 ft) lengths under normal tension. Any difference larger than the required accuracy for the survey indicates a problem and the tape should not be

used. The tape-measure used as the standard should be steel-cored rather than fibreglass and ideally should not be used under water to avoid damage.

VERTICAL CONTROL (HEIGHT/DEPTH)

The other component of a survey position is height or depth. In survey terms, this is called vertical control and the principles described here are similar to those used for levelling on land (figure 14.7). The most common tools for measuring depth or height are the digital depth-gauge and the dive-computer. These instruments measure the depth of water and display it on a screen, usually to a resolution of 0.1 m (4 in). A dive-computer takes time to settle to the correct measured value, so allow time for this before recording each depth measurement. The depth-sensor reading is affected by large changes in temperature, so measurements will change as the computer cools or warms up during a dive. If the temperature difference between air and water is very different, keep the computer out of the sun or put it in a bucket of sea-water for about 30 minutes before the dive. Some are more accurate than others, so try to use the same computer for all depth measurements. Waves and tides affect any instrument that measures depth. Underwater surveys are frequently done relative to a point on the sea-bed because this cancels out the effects of tides. A permanent feature on the site is nominated to be the depth reference or temporary benchmark (TBM) for all depth measurements (figure 14.8).

Other tools which may be useful in underwater survey include:

- rigid 1 m (3 ft) long rules and plastic folding rules for recording detail;
- a diver's compass for finding magnetic north;

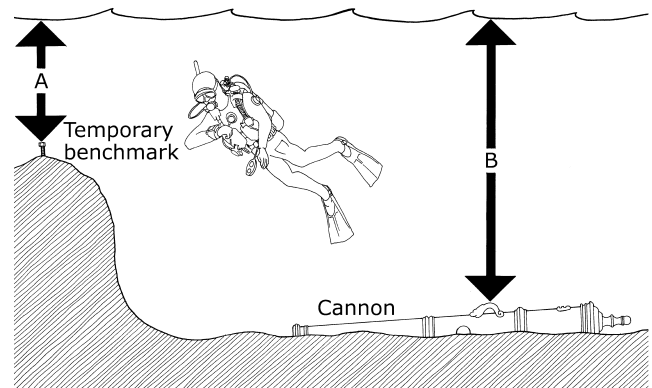


Figure 14.8 Depth of cannon ($= B - A$) relative to a temporary benchmark. (Drawing by Graham Scott)

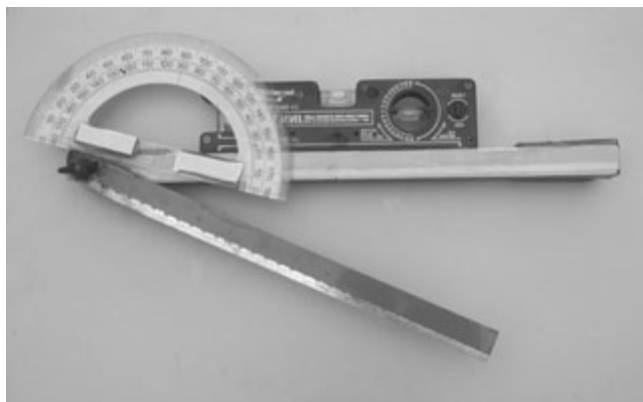


Figure 14.9 A simple clinometer made with items from a DIY store. (Colin Martin)

- a clinometer (figure 14.9 and plate 14.3) for measuring the tilt of ships' timbers and structure;
- large callipers for recording the thickness of objects such as timbers or the diameter of cannons;
- plumb-lines for vertical offset measurements.

If divers are not carrying out scale recording under water, then the sooner the measurements can be transferred from the diver to the site-plan the better, so that dud measurements can be re-measured as quickly as possible, before they distort or hold up the overall plan.

DRAWING/PLANNING FRAMES

Drawing or planning frames are used to quickly and accurately record small areas of a site in detail, and can be used vertically as well as horizontally for recording sections and areas of standing structure (figure 14.10, plate 14.4 and plate 14.5). A typical drawing frame is a 1 m rigid square made from metal or plastic tubing subdivided into squares of 100 or 200 mm using thin cord or elastic. A 200 mm spacing (5×5 sub-squares) allows the user to judge which square an object is in by eye. A 100 mm spacing (10×10 sub-squares) involves counting to ensure the correct sub-square is being worked on. The diver should be directly above each square as it is drawn to avoid parallax error. Double-stringing the frame is an effective way to ensure that this happens, as when both sets of strings are in line, the diver knows s/he is in the correct position. Drawing is done directly onto a drawing board, with the shape of the frame and its sub-divisions drawn to scale on it.

Alternatively, if a sheet of transparent acrylic or PVC is laid over a drawing frame, the detail can be drawn directly on to the sheet using a wax crayon or Chinagraph

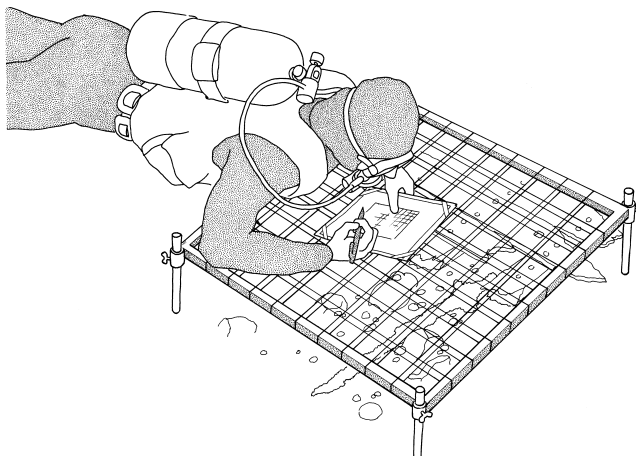


Figure 14.10 A double-strung frame helps counteract distortion caused by not being directly above the subject. (Drawing by Graham Scott)

pencil. Back on the surface, hand drawing, photography or scanning can be used to scale down the drawn squares. Or the squares can be traced off at the same scale onto drafting film.

Steel reinforcing mesh with 100 mm spacing can be used as a drawing frame in 1 m $\times$ 1 m or 2 m $\times$ 1 m sections. These frames have the advantage of being robust and can be left on site between dives. However, care is needed in using steel mesh frames because they are heavy and can damage delicate artefacts, structures and diving equipment. The use of a drawing frame is a simple technique and very accurate over small areas but the frame must be accurately positioned. Designs vary but the frame must be portable, must not distort, and the strings must be tight. In use horizontally, the frame needs adjustable legs and spirit levels on both sides.

Where an area larger than one drawing frame needs to be recorded, it is essential to position each frame accurately so all the separate drawings can be fitted together. If survey control is not used, then errors will accumulate through the recording process, leading to distortions in the final plan. Frames can be placed along a tape baseline if a strip of sea-bed is to be recorded. Sometimes positioning the ends of this baseline is sufficient to position the frames on the plan. For larger areas, the corners of each frame can be positioned relative to the control point network; however, this can be time-consuming. A third method involves putting labelled markers (control markers) over the site, positioned relative to the control point network – plastic survey markers are ideal for this. There must be enough control markers for at least two to appear in each frame as it is drawn and the markers, along with their names, must be shown on each drawn square.

To ensure that there is coverage of an area, it is recommended that some overlap is created between frame squares. The overlap can be useful in aligning adjacent squares when drawing up the survey but this should not be the only method for positioning squares when drawing up because this could lead to large distortions in the site-plan. Before moving a frame, markers can be placed to indicate the corners of the area just drawn so the next frame can be aligned accordingly.

The frame must be placed close to the subject so detail can be seen. In poor visibility the operation will be slower but should not be any less accurate. A set of symbols and conventions can be developed for each project so that various materials and features are represented in the same way on each drawn square. Recording using drawing frames produces lots of small squares to form a site-plan. The original drawings should not be inked over or stuck on to the main site-plan because the originals are the primary record and should be kept as a check on the final plan. Each original drawn square should have the following additional information marked on it: site code; date drawn; name of diver; magnetic north direction; individual or dive reference number; location description.

To draw up the plan by hand, a site-plan of the same scale as the squares is required, showing the position of the control markers. Each square can then be aligned on its appropriate marker and drawn onto the plan. To draw up a planning frame survey using a computer involves producing a computer-generated plan of the site. The plan should show the position of the control markers. The original drawings can then be scanned and overlaid onto the site-plan digitally. Although it is possible to fit the drawing squares together simply by lining up features on the edges, this is not recommended. It is important that control markers and/or survey points are included in the plan – otherwise the overall shape of the plan tends to distort and the accuracy of the plan will be unknown.

GRID-FRAMES

Another method for controlling positions on a site is to erect a grid-frame over the entire site, or the part of the site actively being worked on. The frame is usually made up of strong metal or plastic poles attached to each other to form a rectangular grid securely fixed to the sea-bed. Each square can be clearly labelled and colour-coded to indicate different areas on the site. Points on the grid itself then become the control points for the survey: placed high up above the sea-bed, they are ideally placed for making measurements. Control points and their labels are added as the frame is constructed. The frame has the advantage that control points can be put where they are needed, not just where the site dictates. Alternatively, a graduated

movable bar with movable vertical measuring rod can be moved up and down the grid frame and be used for recording the positions of points on the site.

A grid-frame works well if the site is small – otherwise the grid becomes too impractical to install. It can be used, however, on the part of a larger site that is actively being worked. The frame can be constructed on land and taken out to the site or it can be built from components on site. The site should be in a relatively protected place because storms, fishing activity or ships' anchors can move, damage, or even destroy the grid-frame. Because of the investment in time required, grid-frames are usually only used where a significant amount of work is to be done on a site over one long period.

A high degree of survey accuracy can be achieved using a grid-frame. It is likely that each point on it will need to be positioned under water, even if it has already been positioned on land, because the shape of the frame may distort during deployment on site. A distortion of 10 mm in any one point would be noticeable in a set of adjusted distance measurements. A few external control points should also be installed around a grid-frame so that its position can be re-established between seasons or if it gets moved accidentally. A grid must be carefully levelled before it can be used or the depths of each control point measured and dealt with in processing.

A rigid grid-frame of, for example, 5 m sides can be used as a framework within which to position 1 m square drawing frames. Rigid grid-frames are sometimes installed over trenches during excavations and these can be used simply as support for divers and may not necessarily be used for survey control. Rope grids can be used, but they suffer from poor positioning accuracy if they are larger than about 10 m square. These are useful for quick surveys but can be time-consuming to install and difficult to position accurately.

Site-plans can be drawn at any orientation but sometimes it can be more useful to align them so that north is upwards on the plan. To align the site, it is necessary to measure the bearing (angle from north) of something large on the site that appears on the site-plan: a baseline between two control points is ideal for this. The bearing measurements can be made using a diver's hand-held compass held alongside a tape-measure laid between the two control points. On completion, the plan can be rotated so that the baseline is at the correct bearing. Measuring the orientation of an iron or steel wreck is difficult, as the magnetic effect of the wreck will affect the compass measurements. In such cases, it may be preferable to use a heading derived from surface GPS positions (see chapter 11). Measurements from a compass will be given relative to magnetic north; if the magnetic variation is known at the site then the bearing can be corrected and the site-plan can be oriented relative to true north.

PROCESSING MEASUREMENTS AND DRAWING UP THE SITE-PLAN

Chapter 19 summarizes information that must be included on each survey drawing and site-plan. The site-plan is created using sketches and measurements collected from a site. The plan may be drawn by hand or on a computer. The advantage of computer-generated plans is that printed copies can easily be made, they can be printed at different scales, and the level of detail shown can vary as the work progresses. If the site has not been recorded before, the sketches or assessment survey results can be turned into a basic site-plan. In doing this, missing information is often identified and additional work can be planned.

If a recording survey is being undertaken, then the first step is to add the control points that were installed around the site to the site-plan. If a previous site-plan has been created from an assessment survey, then measurements may be needed from the new control points to a couple of the main features on the site, to align the previous site-plan with the control points. Once the control points have been established, the features can be added to the plan as they are recorded and processed.

The advantage of drawing up site-plans on paper or plastic film is that it requires few tools other than paper, pencils, scale ruler and dividers/compasses. Measurements made under water can be scaled down and drawn directly onto the paper. There are, however, a number of drawbacks with using paper:

- only one 'fair' copy of the site-plan exists so its loss or damage can be catastrophic (although this can be overcome by regular digitization);
- the plan has to be redrawn if the site changes due to environmental effects or excavation; unless a fair copy is made, this destroys the previous site-plan;
- large pieces of paper are usually involved and these require the use of large drawing boards or tables;
- if the site is extended the new drawing may be off the edge of the existing paper plan;
- paper shrinks and stretches as humidity changes, though drafting film is more stable.

The reasons listed above mean that it is preferable to draw site-plans on a computer. Personal computers are now very common, as are the computer-aided design (CAD) programs used to draw site-plans. These can be drawn in two or three dimensions, can cover any area and can be plotted at any scale. Layering facilities in these programs allow plans to be plotted with selected subsets of the information visible. Processing the measurements made on site also becomes easier and the positions of points

calculated by survey processing programs can be readily imported in bulk. A number of suitable CAD programs exist and deciding which one to use is largely a matter of personal choice. It is recommended that one of the more common programs is used or one that uses a standard file format such as 'drawing exchange format' (DXF). This allows the site-plan to be shared easily and minimizes the risks associated with 'future proofing' (see chapter 8).

Drawing the site-plan in one computer program separates it from the rest of the information recorded about the site. To keep all of the information together in one place requires a geographic information system (GIS). GIS programs run on personal computers and provide the combined capabilities of a CAD drawing program and a database. The GIS program can be used to draw the site-plan and to record information about finds, control points, measurements, dive-logs and anything else relevant to the site itself. As with CAD drawing programs, there are various GIS programs available. Any of these programs can be used to record information about a site but cost and complexity vary widely. To date there is only one GIS designed specifically for marine archaeology work and this is the 'Site Recorder' program from 3H Consulting Ltd. Like other GIS programmes, Site Recorder can record information about the site and be used to draw site-plans but it also includes archaeology-specific tools such as the ability to process survey measurements (plate 14.6).

It is essential that the site-plans and site information be copied and stored in a secure archive. If the site is destroyed accidentally or deliberately (by excavation), then the plans may be the only record of the site itself. Paper records should be copied photographically or digitally and deposited separately with team members and the authorities responsible for the site. Digital records can also be deposited with professional archive organizations such as the Archaeology Data Service in the UK (see chapter 19).

THREE-DIMENSIONAL COMPUTER-BASED SURVEY

Sites with little height variation can be recorded by adding contours to the two-dimensional plan. When dealing with a very three-dimensional site, such as substantial remains of a ship's hull, then three-dimensional recording is needed, and is probably best done by using a computer program. Three-dimensional (3-D) trilateration or 'direct survey measurement' (DSM) uses direct distance and depth measurements to position features on a site. Distances are measured directly from control points to features and any difference in depth is dealt with in the processing (figure 14.11). The 3-D trilateration technique has a number of advantages: it can be very accurate, it can

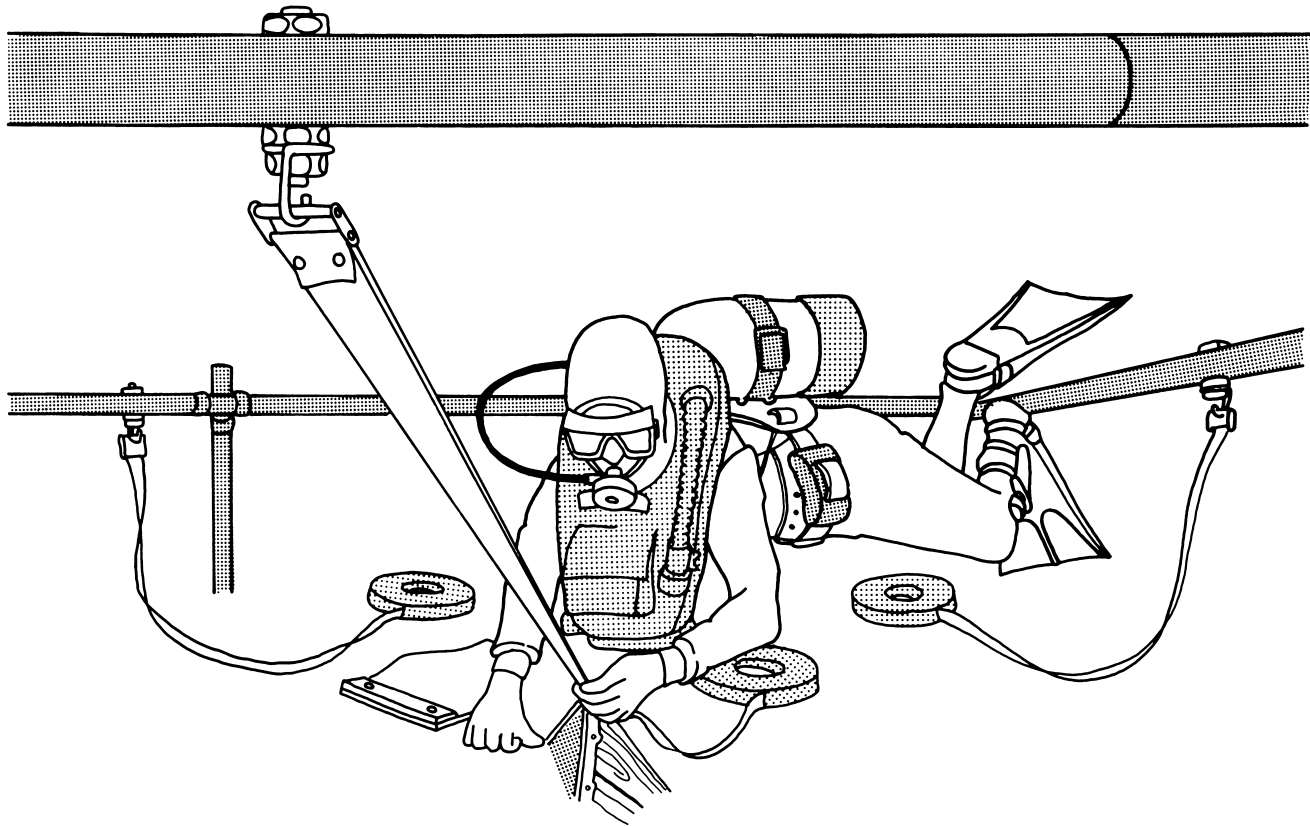


Figure 14.11 A diver taking DSM measurements. (Drawing by Graham Scott)

record positions in three dimensions and it is very easy for divers to take the measurements. In addition, standard survey processing techniques can be used to compute the positions of the features and also show how good those positions are. The main drawback with this technique, however, is that it requires a computer program to compute point-positions efficiently from the measurements.

The problem of positioning a point in three dimensions can be simplified by separating the horizontal position from the height or depth. Most underwater sites are three-dimensional and the tools available to survey them are usually limited. A tape-measure can be used to measure the distance between points so that those points can be drawn on a site-plan. But what if there is a big difference in height between the two points? In such cases, the distance measured is a slant distance and not a horizontal distance that can be drawn on a piece of paper. It is straightforward but time-consuming to correct each slant distance to a horizontal distance, so a technique that uses slant distances is preferable. A very high degree of accuracy can be achieved using 3-D trilateration, as this is the most accurate and reliable technique that uses tape-measures. A good survey point position computed using this method can be as accurate as 20 mm (95%), though this is dependent on the accuracy of the control point network.

Three-dimensional trilateration requires a network of survey control points to be established around and inside the site. This network of points is the framework on which the whole site-record is built. These control points are used for the same purpose as the concrete triangulation pillars (trig points/trig stations) found on the tops of hills and mountains. Trig points are used for providing survey control across countries and control points are used to provide the same control across a site. The main or primary control points should be established around the outside of the site. These points should be placed where they will not be removed if the site is excavated. If a network of survey control points is not used, it can be difficult to make the measurements fit together or to prove the accuracy of any survey. If the position accuracy specified in the project design is not achieved in the control network – or, worse still, not even measured – then the subsequent survey work can never achieve the required accuracy.

The first step in establishing the network is to plan the positions of the control points based on the current knowledge of the site. Planned positions for the control points are often based on the results of a previous assessment survey. Next, the positions of the control points are calculated using distance measurements between them, plus depths for each point. The calculated positions

of the control points are then considered to be fixed, so the addition of subsequent detailed measurements cannot alter the positions of the control points. Measurements from four or more control points can be used to position detail points on features such as artefacts and structure.

Survey work on land is based on triangles because the tools used for land survey, such as theodolites, measure angles. Survey under water is largely done with tape-measures, measuring distances rather than angles. If three points are set out on land and the angles between them measured and added together, the total should add up to 180 degrees. If the total is not 180 degrees, then the difference is a measure of how good the angle measurements were. Unfortunately, this does not work with tape-measurements, as three distance measurements will almost always fit together, so a 'braced quadrilateral' is used instead. The braced quadrilateral or 'quad' is made from four control points in a square or rectangular shape, with the sides and both the diagonal distances measured (figure 14.12). If the positions of the points are plotted onto a piece of paper, the four points can be positioned using five of the six measurements and the sixth measurement is the check. In most cases the check measurement will not fit perfectly and the size of the difference gives an idea of how well the other measurements fit together. If the check measurement is significantly different to the value expected, there is a mistake in one of the six measurements.

A complete control network can be as simple as just these four points. However, if tape-measurements are kept to less than 15 m (49 ft), this can only cover a small area of a typical site. To cover a larger area, a number of quads joined at the edges are used (figure 14.13). Avoid placing control points less than 5 m (16 ft) apart, as this will not improve the survey but will waste a lot of time in positioning the extra points. Install the control points high up so they have a clear line-of-sight to as much of the site as possible but note that high points with a good line-of-sight are often the most easily damaged.

Once a couple of quads are joined then it is possible to measure between points in adjacent quads. The net-

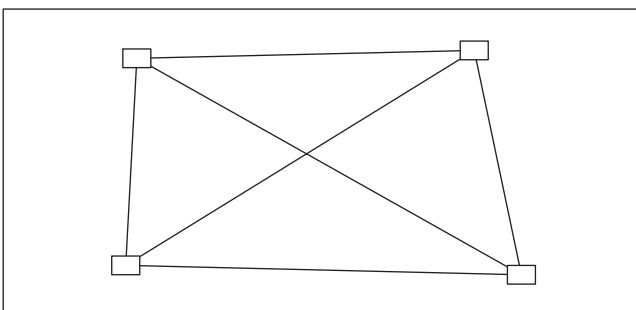


Figure 14.12 Braced quadrilateral (3-D survey)

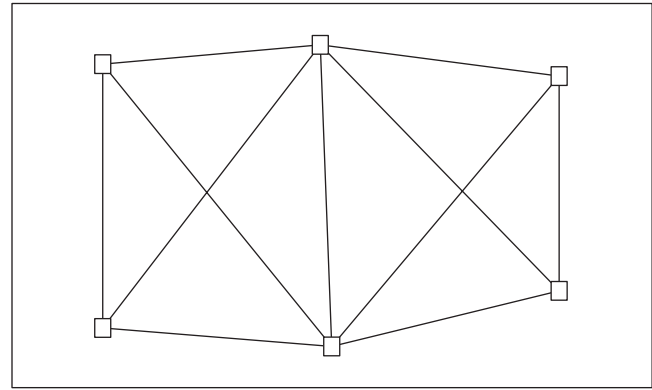


Figure 14.13 Joining quads (3-D survey)

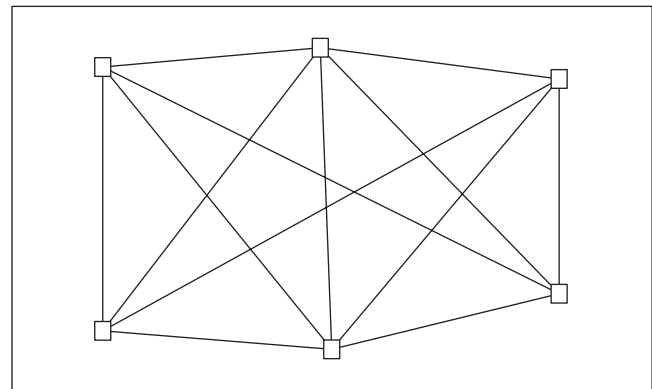


Figure 14.14 Measuring between quads (3-D survey)

work in figure 14.13 has the barest minimum number of measurements to be able to compute the positions of the points in three dimensions. If a mistake occurs in one of the measurements, it will be difficult to find and fix. By adding more measurements, as in figure 14.14, more information about the positions of the points is available, so any measurements that are mistakes should be easier to find. Sets of quads can be extended to cover large areas but, on very large sites, they can be time-consuming to set up. In some cases, it is easier to treat groups of features more than 30 m (98 ft) apart as separate sites.

The best network shapes for surveying are circles and ellipses (figure 14.15). Circular shapes can be used but not many sites are circular, so in most cases an elliptical network is required. The ratio between the length and width of the ellipse should ideally be less than 2:1 (less than twice as long as it is wide). To achieve this sometimes requires extra 'outrigger' bracing points to be placed either side of the site. It is essential that all control points for a site be connected together into one network. Separating parts of the site into smaller, unconnected networks will cause problems when drawing up. Where the extents of the site are not entirely known, the control point network may need

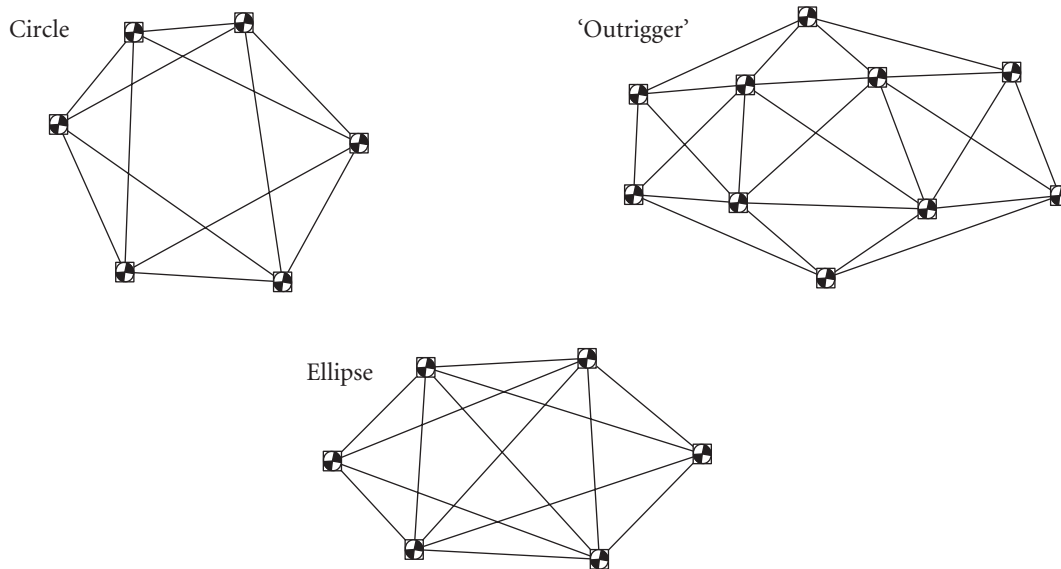


Figure 14.15 Good control-point network shapes (3-D survey)

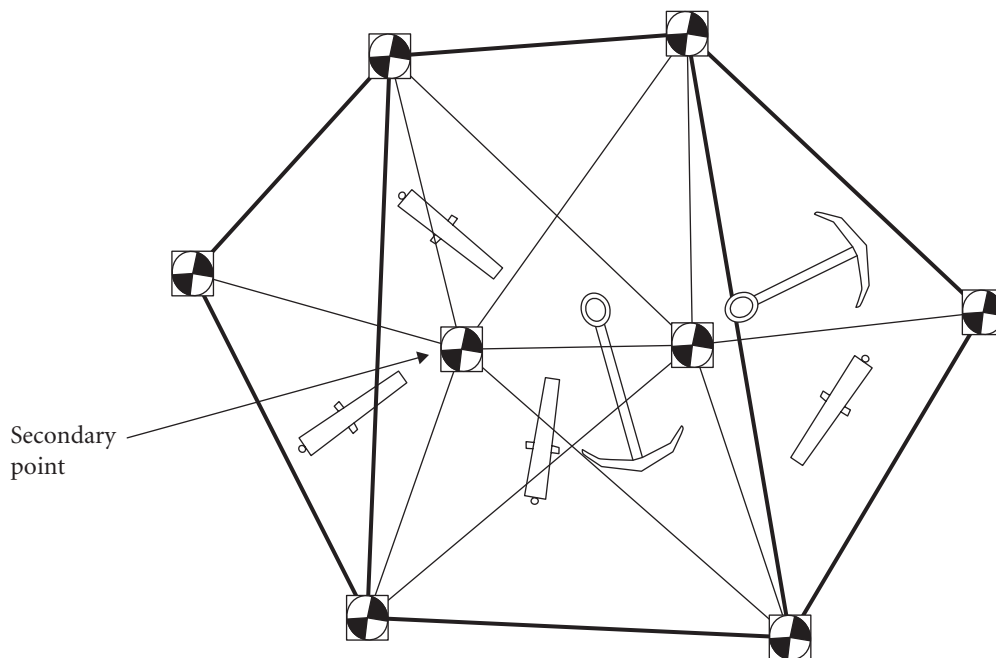


Figure 14.16 Secondary points (3-D survey)

to be extended as more of the site is discovered. The overall shape of the control point network should remain circular or elliptical after it has been extended. Where the site is large, secondary points can be placed within the site so that long tape-measurements are avoided (figure 14.16). On some sites, these points can be permanent and fixed to the sea-bed; however, this may not always be possible.

Secondary points fixed to structure or large artefacts can be used to span the gap between the two sides of the site

(figure 14.16). Long, thin networks or networks with a very pointed shape should be avoided because the position error will be large for the points furthest away from the main body of the network (as shown in figure 14.17, which illustrates poor configurations of control points). The angle between measurements to a point should be no smaller than 45 degrees and no larger than 135 degrees for a good control-point network shape.

It has been demonstrated that six distance measurements are used to position four control points, with one

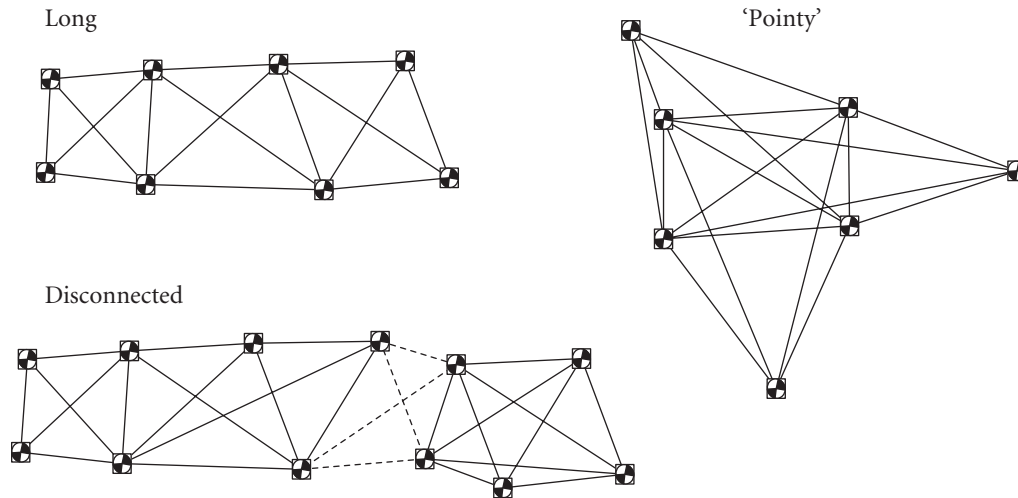


Figure 14.17 Poor control-point network shapes (3-D survey).

measurement used as a check. It is possible to plot the four points at the same height by hand and to determine how different the check measurement is from the expected value; this value is called the residual. If the points are at different heights then the depths can be measured and the measurements can be corrected for the difference using Pythagoras' theorem and the points can be plotted.

When there are more than four points, or more than one check measurement is made, then a problem occurs. The points can be plotted in a number of different places depending on which measurements are used. There are no rules to say which measurements should be used, so statistics are employed. A mathematical technique called 'least squares' can be used to compute the best answer for any given set of measurements. This is known as 'adjustment'. The technique is mathematically intensive and is best done using a dedicated computer program. Most sites using 3-D trilateration utilize the 'Site Recorder' or 'Site Surveyor' software from 3H Consulting Ltd or 'Web for Windows' (DSM), although other programs can also be used.

The computer program takes in initial guesses or estimates for the positions of the survey points, along with measurements between the points. From this, the software calculates new positions for the points on the site along with some position-accuracy information for each point. Based on the new positions for the points, the programme can also give an idea of the quality of the measurements or how well the measurements fit together.

Because many sites are essentially flat, the distance measurements tell us very little about the depths of each point. This is why it is essential to measure the depth of each control point and detail point, and to include these measurements when processing. When the calculated position accuracy for each of the control points is within

the accuracy specified in the project design, this phase of the work is complete. At this stage it is essential to 'fix' the positions of all of the control points in the computer program so that the addition of further points and measurements does not affect the carefully calculated control point positions.

With the control points carefully positioned, they can be used to position detail points on the site. The detail points are added to features, artefacts and structure, so, by positioning the detail points, the positions of the features themselves can be calculated. To position detail points, a direct distance measurement is needed from each detail point to the four nearest control points. Ideally the measurements should be made from points all around the detail point rather than from one side only (figure 14.18).

Distance measurements between detail points on the same object can be used, such as the distance between the detail points at each end of a cannon. However, measuring distances between detail points on different objects should be avoided. This is because the objects themselves may be moved as the site is worked on and it also makes processing much more difficult because it is harder to find incorrect or 'blunder' measurements. Mistakes in measurements between detail points will affect the position of both of the points, so one incorrect measurement can alter the positions of a whole chain of detail points linked together by measurements. A blunder measurement between a detail point and a 'fixed' control point will only move the position of the detail point, constraining the effect of the blunder measurement to one detail point only. As with control points, it is essential that a depth measurement be made at each detail point.

The computer program used for processing or 'adjusting' the measurements will calculate the position of each

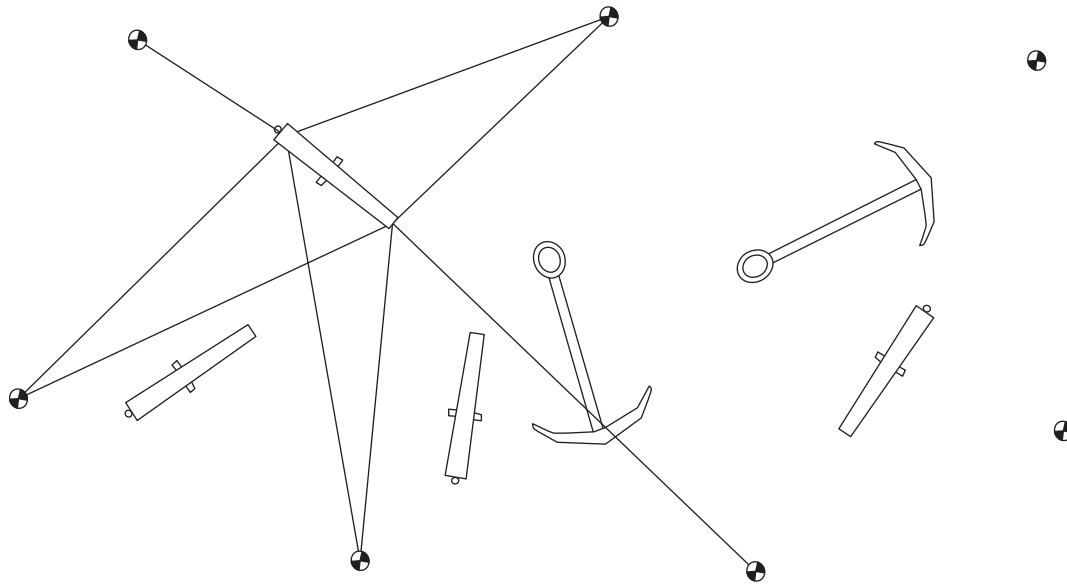


Figure 14.18 Positioning detail points on features using control points (3-D survey)

of the control points. These positions can be plotted on paper charts or imported into a CAD or GIS program. These adjustment programs show the positions of control points and detail points graphically on a chart, completing a significant part of the drawing up. Instructions for the use of any of these software packages is beyond the scope of this book but can be found in the manuals provided with each program.

ACOUSTIC POSITIONING SYSTEMS

An underwater 'acoustic positioning system' (APS) can provide positions under water like the Global Positioning System (GPS) does on land and on the water's surface. APSs are widely used for survey work in the offshore oil and gas industry, positioning ROVs, divers and remote-sensing tow-fish. These systems position objects under water by replacing distances measured using tape-measures with distances measured using pulses of ultrasonic sound-waves. They can be very accurate, can work effectively over very large areas and can continuously report the position of a diver under water. The main drawbacks of these systems are that they are expensive and the higher quality systems can be complicated to use.

APSs have been used for marine archaeology projects for many years. In 1972, the visible timbers of the *Mary Rose* were surveyed using an acoustic distance-measuring system. In recent times, the use of the APS has become more common and they are now in regular use by archaeology teams all over the world. Two types of APS are applicable to marine archaeology: 'long baseline'

(LBL) systems and 'ultra-short baseline' (USBL) systems. Both types of system use a personal computer on the surface to calculate and display the positions of the objects being tracked in real-time and in three dimensions. This allows the dive supervisor, archaeologists and ROV pilots to see the position of the divers and ROVs under water. By connecting the APS to a geographic information system, the position of the divers can be displayed live on the site-plan, allowing the site to be recorded in real-time.

An LBL system works in a very similar way to the way that 3-D trilateration is achieved using tape-measures. Four or more acoustic transponder beacons are deployed on the sea-bed for the APS and these do the same job as the control points installed around the site for 3-D trilateration. Acoustic signals measure the distance from a transceiver unit on the diver to each of the beacons. The diver's unit can also measure its depth so this and the distance measurements are used to compute the diver's position using exactly the same mathematics used for 3-D trilateration. LBL systems can be used in depths between < 5 m and 1500 m, and provide the same high accuracy whatever the depth. As LBL systems require a network of beacons to be set up on the sea-bed, the area that can be covered in one deployment depends on the size of the network and this is itself dependent on both the system being used and the depth. Typical sizes for high-accuracy work in shallow water (< 50 m) would be $100 \text{ m} \times 100 \text{ m}$, but in deeper water this can be increased to $1000 \text{ m} \times 1000 \text{ m}$. Position accuracy depends on the quality of the system and how well the positions of the beacons have been calculated. Typical position accuracy for a low-cost system can be 500 down to 100 mm, while the best-quality system can

reliably position to within 30 mm. The object being positioned has to be connected to the surface by a cable, as the transceiver needs to communicate with the computer system on the surface. This is less of a limitation than it may appear because divers using these systems need to be in voice communication with the surface and this usually requires a cable.

A USBL positioning system can position divers and ROVs relative to a boat on the surface. An acoustic transceiver is fitted to the end of a rigid pole and deployed in the water over the side of the boat. The transceiver on the pole receives acoustic signals from a transponder beacon on a diver and these can be used to calculate the distance and direction of the diver relative to the boat. By combining these measurements with the boat's position, provided by a GPS receiver, the position of the diver in the real world can be calculated. The position accuracy of USBL systems is dependent on the distance between boat and diver – the positions get less accurate the further the diver is from the boat. As the USBL system is attached to the boat, there is no limit on the area that can be covered because the boat can simply be moved. Often these

systems are used to track ROVs, allowing the boat to follow the ROV anywhere, similar to having a dog on a lead. Because the position accuracy is dependent on the distance between boat and diver, accuracy is usually specified in terms of percent slant range (distance); however, a typical working figure would be 1 m accuracy at 100 m. Unfortunately, the accuracy of the system is very much dependent on the quality of the GPS receiver and compass and motion reference unit, which also have to be fitted to the vessel. USBL systems are seen as being easier to use than LBL systems, but they require careful installation and calibration to get the best results.

POSITIONING THE SITE IN THE REAL WORLD

For simplicity, sites are often recorded using local co-ordinates that are not referenced to points in the real world. For projects where the site itself is associated with features on land, or where remote-sensing data have been collected, it becomes necessary to determine where the site is in the real world so as to relate the survey data

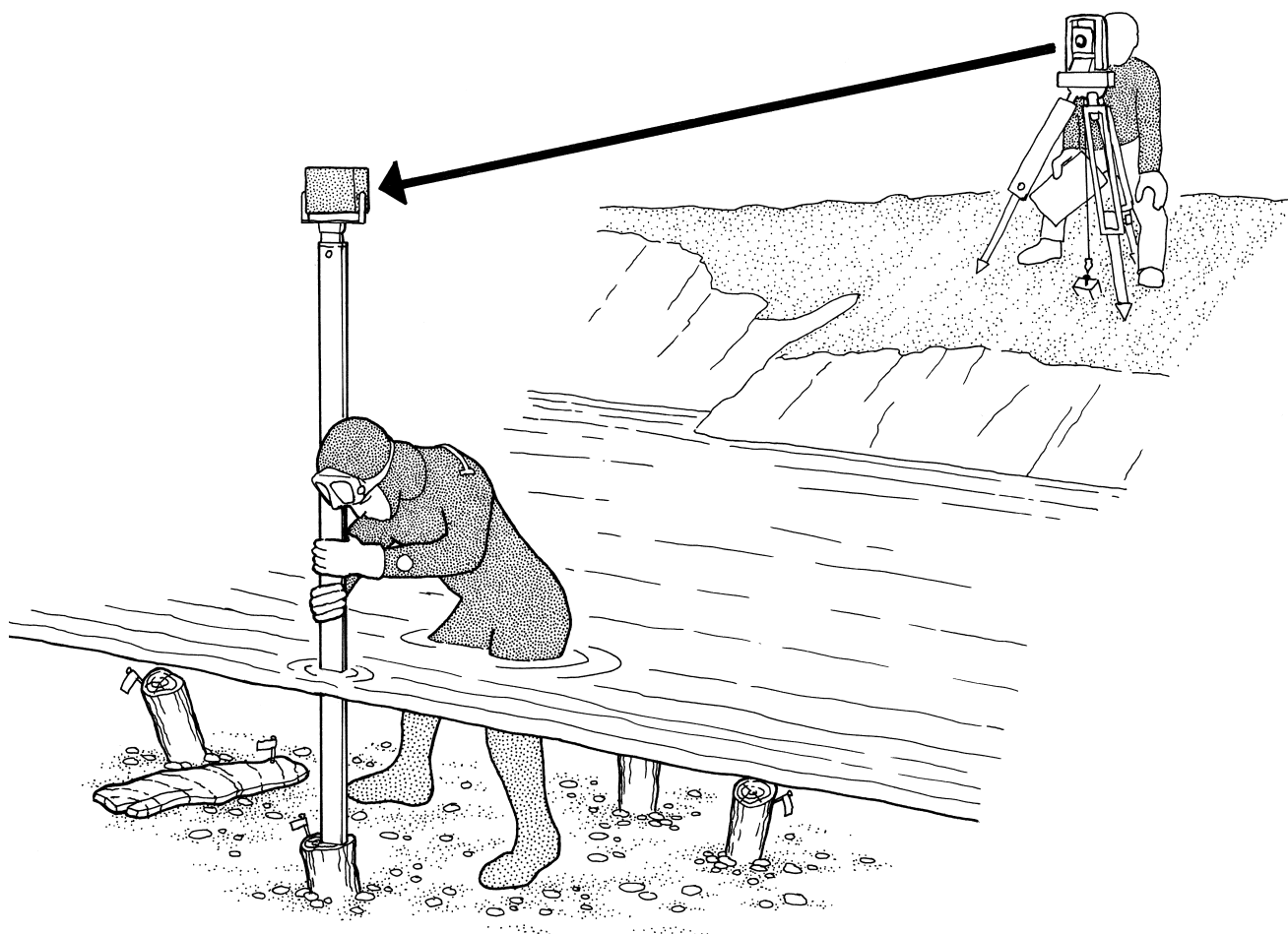


Figure 14.19 Surveying a submerged site in shallow water using a shore-based total station. (Drawing by Graham Scott; after Morrison, 1985, fig. 5.2)

to the National Grid or latitude/longitude. The methods of obtaining a position on the surface of the sea have been described earlier in the book (see chapter 11); this leaves the problem of accurately relating a point on the sea-surface to a point on the sea-bed. In shallow water, poles long enough to reach the surface can be placed on control points and their positions fixed using a 'total station' (figure 14.19) or DGPS ('differential global positioning system' – see chapter 11). In deeper water, a large buoy on the surface tied to a control point or heavy artefact can also work well. If the buoy is large, the rope can be tensioned, keeping the buoy above the point to be positioned;

this method works best at slack water on a flat calm day. Any methods more elaborate than a simple surface buoy may be wasted effort, unless the surface positioning system is very good, because the amount the buoy moves from a position directly over the point is likely to be less than the accuracy of the surface position. To obtain a very accurate (300 mm/12 in absolute) position-fix in deep water, an acoustic positioning system can be used. This involves placing a transponder beacon on the point to be positioned. The APS positions the beacon by combining acoustic range measurements, depth measurements and positions from a DGPS receiver.

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