11. Terrestrial and waterborne geophysical survey for road schemes

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Electrical resistance twin-probe array (Kevin O'Callaghan)

Introduction

Geophysical methods provide a non-invasive, non-destructive means of investigating and defining subsequent excavation targets in areas of known or suspected archaeological potential. Terrestrial methods rely on measuring contrasts in the properties, such as magnetism and electrical resistance, of buried archaeological features and the soils in which they lie. For submerged sites, contrasts with host sediments are measured in properties such as sound velocity and magnetism. The choice of method, order and mode of deployment is governed by the site type, the archaeological objectives, available archaeological, geological/morphological information, the nature of potential targets and the area under investigation.

Terrestrial geophysical survey methods

Archaeological targets and survey layouts

An understanding of the potential size and nature of archaeological targets, their archaeological context, local soils and geology/morphology is important in the design of a

Fluxgate gradiometer with handheld trigger (Shane Rooney)

geophysical survey strategy and in the interpretation of subsequent survey results. The size of potential targets will influence the spacing between the survey lines and the distance between readings (stations) taken along the survey lines so as to ensure the survey area is adequately sampled. This is especially important in reconnaissance surveys where a line and station spacing of 5 m or 10 m is normally used. Generally, the line and station spacing for detailed follow-up surveys is either 0.5 m and 0.5 m, 1 m and 0.25 m, 1 m and 0.5 m, or 1 m and 1 m respectively, depending on the target and method used. In order to systematically map a prospective area, survey lines are generally laid in 'survey blocks' or grids measuring 10 m x 10 m, 20 m x 10 m or 20 m x 20 m.

Accurate surveying is very important in archaeological and geophysical field survey. A global positioning system (GPS) operating in differential mode (DGPS) and/or a total station should be used to locate stations, transects and to set out survey grids. All surveys should be either carried out in, or tied to, the National Grid.

Potential targets, both in rural and urban settings, can be buried from a few centimetres to perhaps 10 m beneath the ground surface. Archaeological features susceptible to discovery by geophysical survey are very varied in size and typically range from a few centimetres to greater than 10 m. Features can be metal pins, silted or burnt post-holes, slag associated with furnaces, stone-lined cavities, charcoal and cracked stone from a burnt mound and silted ditches and/or buried walls associated with earthen mounds or walled enclosures. The geological context in which these archaeological features are likely to be found can have a large influence on the choice of a suitable geophysical method. Soils and gravels derived from certain igneous or metamorphic bedrock, or the bedrock itself, can possess a strong magnetic signature. The latter may mask responses due to archaeology when surveying using magnetic methods.

An understanding of potential archaeological targets and context, and the host soils and geology, will lead to an understanding of whether there is a likely physical property contrast between the target and host. If a contrast exists, and it can be measured, it can be said that the response due to the target is anomalous when compared to that of the host or background. The geophysical response due to the target is then called an anomaly. In addition, knowledge of the type and performance characteristics of the geophysical instruments to be deployed is needed in order to confirm that the contrast can be measured.

Magnetic gradiometry

Magnetic methods rely on the fact that materials can be inherently magnetic or be magnetised in the Earth's magnetic field. The ability of materials such as rocks, soils and buried archaeology to be magnetised is governed by their magnetic susceptibility. The latter is largely influenced by the presence of certain iron oxides and, in certain archaeological features, the degree to which these oxides have become magnetically enhanced by processes such as burning.

The primary magnetic method used in archaeological investigations is magnetic gradiometry using a fluxgate gradiometer. This method measures the change in vertical magnetic gradient caused by the presence of buried objects and features which have an appreciable magnetic susceptibility when compared to that of the soil in which they are buried. The survey can be carried out on a reconnaissance basis by systematically scanning an area along lines spaced 5 m or 10 m apart and manually noting the location of anomalous variations in gradient. In should be recognised that scanning on lines 10 m apart could result in a weak magnetic feature, perhaps up to 9 m in diameter, not being resolved. If scanning without digital recording is carried out, it is not possible to produce a map or trace showing the instrument readings. This has implications for quality control and/or later analysis of the scanning survey.

Anomalous areas found from scanning are usually then subject to a conventional grid survey which digitally records data at 0.25 m or 0.5 m intervals along lines spaced 0.5 m or 1 m apart. Grid surveys can be particularly effective in mapping buried walls, ditches and industrial areas where burning has occurred. In addition, surveys carried out in the vicinity of known archaeological sites can sometimes reveal hitherto hidden features (Fenwick *et al.* 1999). The effective depth of investigation of the method, when using an instrument with fluxgate sensors spaced 0.5 m apart, is of the order of 1 m (Clark 1996).

Magnetic susceptibility

Another magnetic method, largely used on reconnaissance or prospecting surveys, is soil magnetic susceptibility. Here magnetic susceptibility is measured directly by a magnetic susceptibility meter at grid points spaced 5 m or 10 m apart. The method, when used in prospecting mode, can be used to map variation in magnetic susceptibility in the landscape that may be due to natural and/or anthropogenic processes. Anthropogenic activities related to settlement, agriculture and industry can all enhance the local magnetic susceptibility of soils (Oxford Archaeotechnics 2003). The magnetic susceptibility method can be effective in detecting and defining burnt mounds and spreads (Slater *et al*. 1996). The nominal depth of investigation is about 10 cm when using an instrument with a 20 cm diameter sensor (Clark 1996). The effective depth of investigation can be greater if the area under investigation has been ploughed and/or if there is good biogenic activity such that material from buried archaeological features is dispersed upwards into the topsoil.

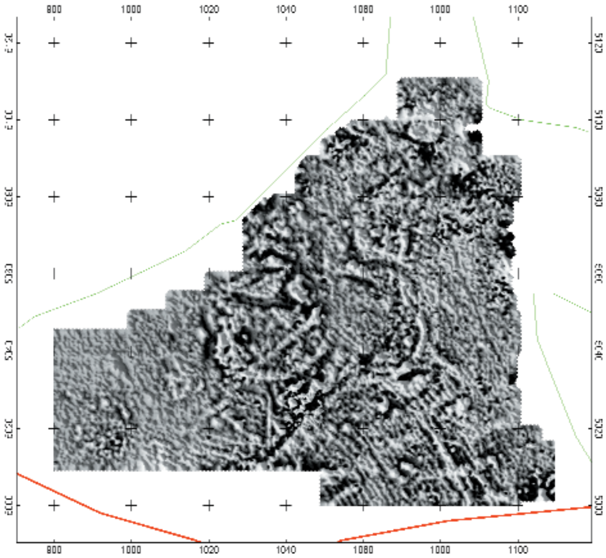
Use of the magnetic susceptibility technique for reconnaissance surveys may be preferable to using unrecorded scanning with a magnetic gradiometer. The results can be plotted on maps that can be interpreted, with supplementary aerial photographic, topographic, geological and archaeological data, to provide an overview of potential zones of anthropogenic activity in the landscape.

Electrical resistance mapping

Electrical resistance survey can be used as a complementary or, depending on the mineral composition of the local bedrock and soils, an alternative to magnetic methods. The method largely relies on mapping the contrast in moisture content and drainage effect of buried objects and features with the soils that contain them. The moisture content of a material is largely affected by its porosity and permeability. In general, low porosity and permeability stone and rock, with associated low moisture content, will have a higher resistance than higher porosity and permeable soils that are moist. Accordingly, buried walls and foundations can show up as higher resistance areas in comparison to lower resistance soils in which they lie. Where a ditch has been cut into the natural soil, and possibly has been silted and/or buried, the ditch fill can have a higher porosity and permeability than the surrounding natural, more compacted soil. In this case the ditch will have a higher moisture content and hence lower resistance when compared with the natural soil.

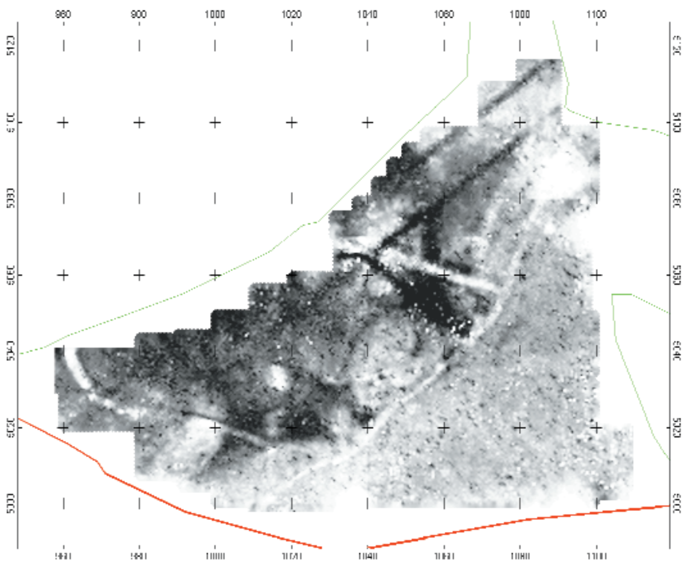
A resistance survey is carried out using a resistance meter and associated electrode array that passes current into the ground and measures the resulting voltage. A calculated resistance value is displayed and digitally logged on the resistance meter. Resistance surveys by their nature are much slower to carry out than magnetic gradiometer surveys since electrodes have to be pushed into the ground. Surveys are carried out on grids with readings normally taken at 0.5 m and 1 m intervals along lines spaced 1 m apart. The depth of investigation of the resistance method largely depends on the array type and electrode spacing used. For the commonly used twin array, with a 0.5 m electrode separation, the depth of investigation is about 1 m (David 1995). Resistance values measured on a particular survey area cannot be compared directly with those of a survey carried out in a different location. In practice, this does not present a problem since we are only interested in mapping relative contrasts in resistance on a particular site.

In a survey area where the bedrock is shallow and it is composed of igneous and/or metamorphic rock, there is a possibility that these rocks will either be magnetic or contain minerals that have a high magnetic susceptibility. In this case it may be necessary to use a resistance survey as the primary survey method, as magnetic gradiometer readings may be affected by the response to the bedrock geology or soils derived from it.

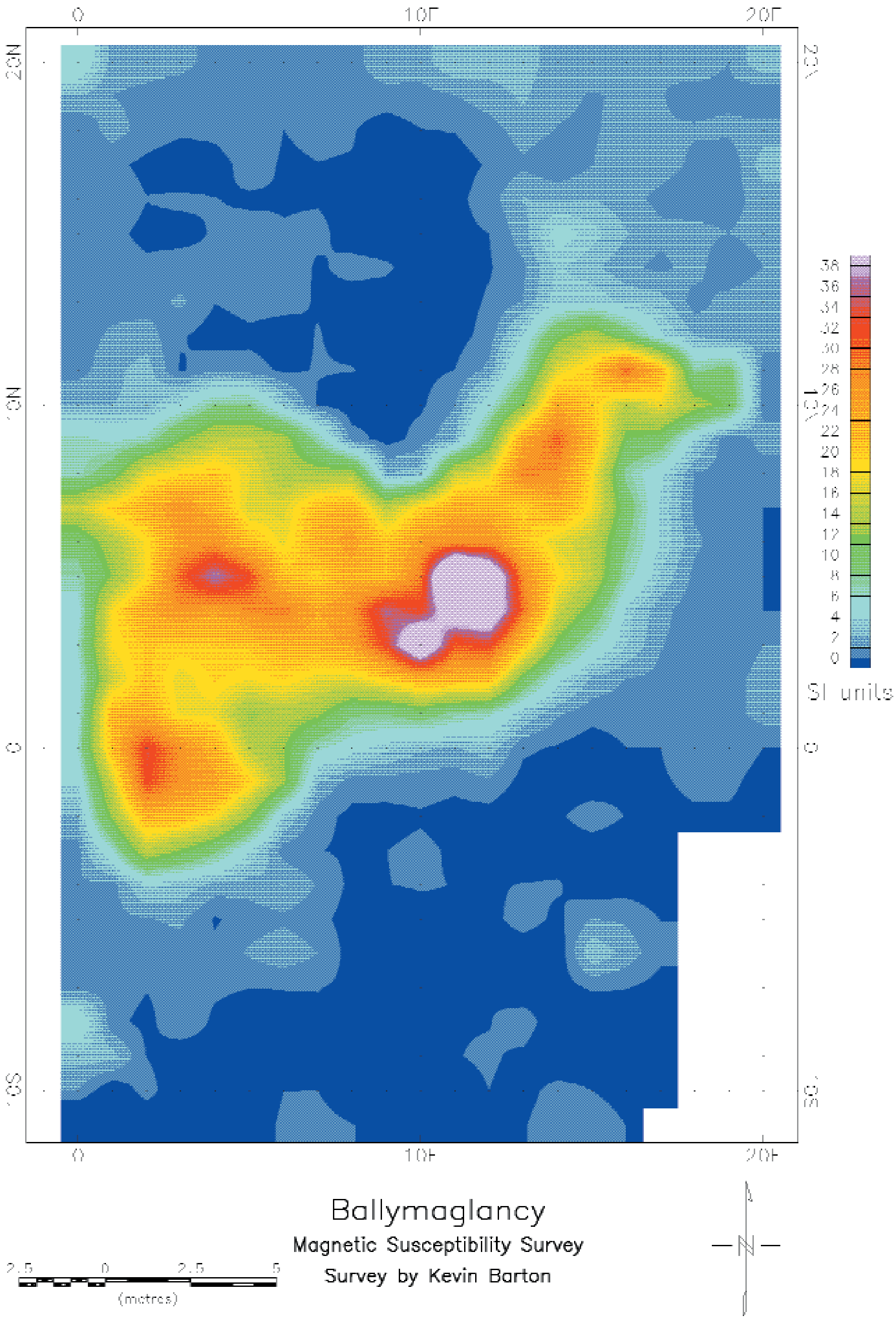


Magnetic gradiometer results from an early church site show circular enclosures overprinted by later ridge & furrow cultivation marks (after Madden 1999)

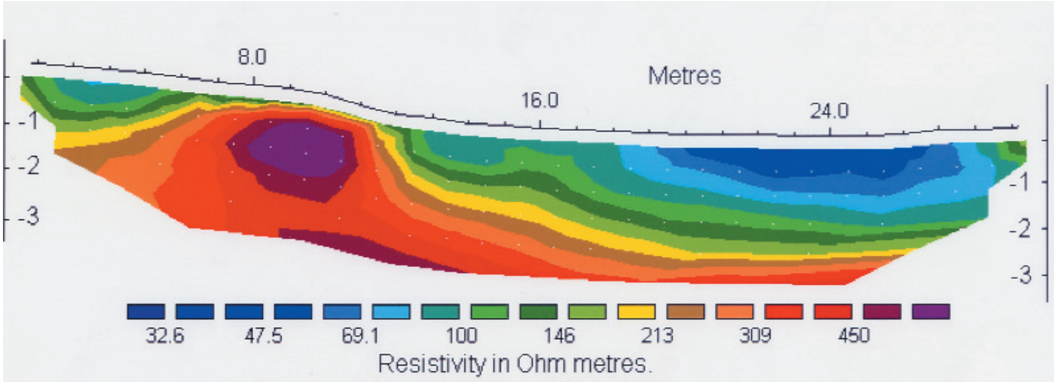
Magnetic susceptibility equipment including measurement console, 20 cm fieldloop and datalogger (Shane Rooney)



Electrical resistance results showing buried walls (white) and a set of parallel ditches (black) (after Madden 1999)



Magnetic susceptibility results showing a strong response (in red) to a burnt mound or 'fulacht fiadh' (Kevin Barton)



Electrical tomography depth section across a buried souterrain. The stone-lined, air-filled souterrain is the high resistivity zone shown in red (after Madden 1999)

Electrical tomography

Unlike the methods described above, the results of tomography are plotted in profile, as depth sections, rather than in plan, as maps. The method is especially useful in providing sections across buried/silted ditches and for investigating souterrains or underground chambers.

Depth sections are surveyed by exploiting the principle that by progressively expanding the electrode spacing for a given array type, the current will flow progressively deeper in the ground and hence the resistance measured will reflect progressively deeper levels. In order to compare resistances measured at different levels, or depths, it is necessary to convert each resistance value to a resistivity value. This enables resistances measured to be compared in a standardised way which takes into account the different electrode spacing needed to collect data for each level or depth. In archaeological work electrode spacings are expanded from 1 m to 6 m, in a series of 1 m steps, giving an approximate depth of investigation of 3 m. Using special cables connected to a resistivity meter controlled by a laptop computer, sections of lengths 25 m and upwards can be surveyed. If a topographic profile is surveyed along the line of the section, then it can be draped on the electrical tomography section.

Ground penetrating radar

Ground penetrating radar (GPR) is another method that collects data to produce a depth section. Some archaeological applications of ground penetrating radar are found in providing sections across buried walls, silted ditches and sections across souterrains. The basic principle is that a pulse of electromagnetic energy is directed into the ground from a transmitter. Where there is a suitable contrast in resistivity, such as at a stratigraphic interface or at the boundary of a buried archaeological feature, there will be a reflection of the energy back to the surface, where it is captured by a receiver. The return time of the reflections provides information on the depth to stratigraphic horizons and geological and archaeological features that may be found within them (Conyers & Goodman 1997).

In electromagnetic/GPR methods a soil property called electrical conductivity is important. Electrical conductivity is simply the reciprocal, or inverse, of resistivity. Soil generally has a high conductivity, which equates with low resistivity, and stone has a low conductivity, which equates with high resistivity.

A GPR survey is carried out by moving a transmitter and receiver along a survey line. The transmitter is fired at fixed time or distance intervals and the received reflections are displayed in real time on a laptop computer which plots a section of travel time (Y axis) against distance (X axis) along the survey line. The depth of investigation depends largely on the electrical conductivity of the soil and the frequency of the transmitted energy. Low electrical conductivity, as with clays, will rapidly attenuate the transmitted pulse and give a shallow depth of investigation, while higher conductivity, as with sandy soils, will give greater depth. Some compensation for the influence of the electrical properties of the soil can be made by the choice of transmitter frequency. Typical depths of investigation are 5 m to 20 m for a 100 MHz system and 1 m to 2 m for a 450 MHz system. The choice of transmitter frequency is always a compromise between low frequency (100 MHz), deeper investigation with lower resolution of features, and higher frequency (450 MHz), shallower investigation with higher resolution of features.

GPR typically has the highest station or sampling rate along a survey line with data being collected, depending on transmitter frequency, at 0.05 m to 0.5 m intervals. A relatively new application of GPR in archaeology is the 3-D survey. Here lines are surveyed very close together (0.25 m to 1 m) and all the resulting sections merged to form a depth cube. This cube can be viewed from different angles or cut open to reveal buried features. The 3-D technique provides a very useful data visualisation tool (Madden 1999).

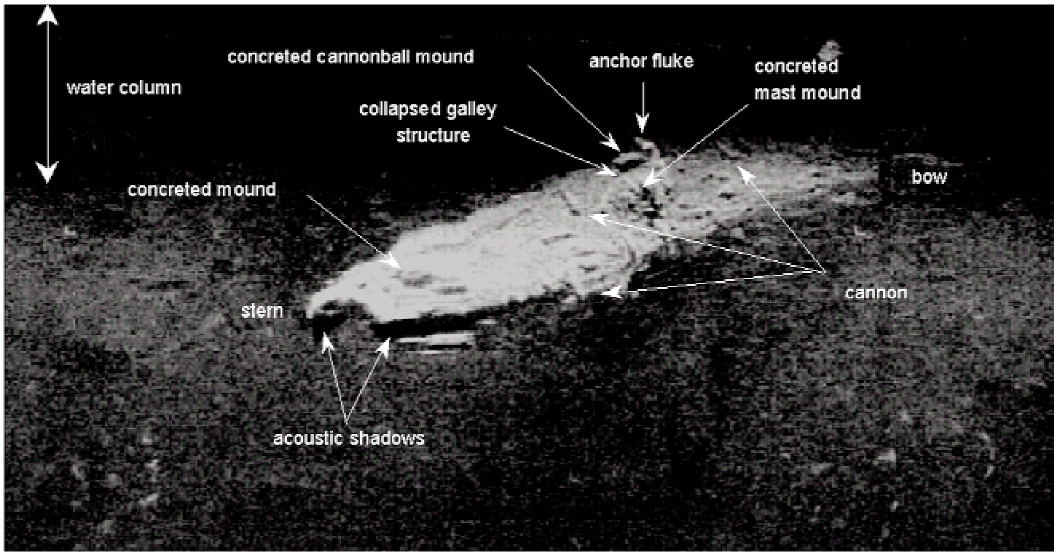
It is good practice to carry out GPR and electrical tomography surveys in tandem in order to assist with the interpretation of GPR sections (Waddell & Barton 1995).

Guidelines for terrestrial geophysical surveys

Currently there are no published guidelines and standards in Ireland and survey designs often refer instead to guidelines published by English Heritage (David 1995). A second publication (Schmidt 2002) provides a framework for documenting, reporting and archiving geophysical data. Some County Councils in England have published an archaeological code of practice (e.g. Lincolnshire County Council 1997) containing, among other things, guidelines on geophysical survey. The Institute of Field Archaeologists has published professional standards and guidances for methods of archaeological field evaluation and these include non-destructive field techniques such as geophysics (IFA 2001).

Integrating geophysical survey with archaeological assessment

Geophysical survey is a tool that should be considered at an early stage in an archaeological appraisal. Non-invasive, non-destructive survey means that reconnaissance geophysical survey could be carried out in parallel with a walkover survey to inform the initial assessment of the archaeological potential of a road corridor. The interpretation of the reconnaissance survey should be guided by available information from aerial photography, known archaeological sites and monuments, other observations from the walkover survey, and the topography and geology of the study area. At a later stage, the reconnaissance survey may in turn inform the design of a detailed geophysical survey and testing strategy. Again, information from the walkover, aerial photography, topography and geology should all be considered at this stage.



Interpreted 500 kHz sonograph. This example from a research and conservation project in Bantry Bay, County Cork, shows the wreck-site of La Surveillante, a relic of the French Armada of 1796 (after Quinn et al.*, 2002b)*

Waterborne geophysical survey methods

There has been increasing attention to underwater cultural heritage in recent years with resources being devoted to its management, protection and investigation (e.g. Oxley & O'Regan 2001; UAU 2000a & 2000b). In the context of road schemes it is likely to be at significant bridge crossings or perhaps on port access roads that waterborne survey may be necessary. In contrast to terrestrial geophysical methods, which largely rely on magnetic methods, waterborne surveys use a number of acoustic methods complemented by magnetometer survey.

Acoustic methods largely rely on the ability of stratigraphic horizons and/or geological and archaeological features within them to either reflect, refract or absorb acoustic energy. The frequency of the acoustic energy and the angle at which it strikes the interfaces is a key factor in determining the nature of the response. The choice of acoustic method, order and mode of deployment are governed by the archaeological objectives, the available archaeological and geological/morphological information, and the nature of potential targets and area under investigation. Surveys can be carried out in salt, brackish or fresh water, in the sea, estuaries, rivers or lakes. A minimum navigable water depth of 1 m to 2 m is required, depending on the method used.

Archaeological targets and survey layout

Targets can be wooden posts or timbers, and ceramic, stone or metal features, in sizes varying from tens of centimetres to tens of metres, either lying on the sediment/water interface or buried in sediment. High resolution geophysical methods, used in marine hydrocarbon and engineering surveys, have been adapted for use in surveying for

Multibeam echo sounder transducers mounted on the bow of a shallow-draft survey vessel (Shane Rooney)

underwater archaeological features.

As with terrestrial surveys, surveying accuracy is crucial in waterborne surveys. Survey vessels use single or multiple differential global positioning systems (DGPS) to achieve up to 5 m or sub-metre positional accuracy, respectively. This accuracy is necessary if one considers that a survey vessel may need to reposition itself over an anomaly in order for divers to carry out a subsequent inspection.

Side scan sonar

This is the main method used for underwater survey. It uses a beam of acoustic pulses transmitted from either side of a towfish. These pulses reflect or backscatter from the river or lake bottom. There is negligible penetration of the acoustic pulse into the river bottom. The resolution of features largely depends on their attitude and position with respect to the river bed, the transmitted pulse, proximity to the towfish and the transmitter frequency. Frequencies of 500 kHz to 1 MHz give the best resolution but have a relatively poor range in the water column. Lower frequencies in the range 50 kHz to 100 kHz give lower resolution but greater range. Simultaneous dual frequency 100 kHz/500 kHz systems are available and give high resolution and long range.

The acoustic beam has a width that allows good coverage of the river bottom with each pass of the survey vessel along a series of transects. The beam width, or swath width, depends on the frequency and the water depth. The transmitted pulse is reflected from the river bottom, or objects on the bottom, and is received by a transducer in the towfish. The returned signal passes up the towcable to a processing/display unit and digital recorder situated on the survey vessel. Hard, upstanding features reflect or return more energy and are displayed as high contrast images while softer features, with lower reflectivity, may be seen as low contrast images. Sometimes scour marks in the river bed can be detected using side scan sonar and these may provide indirect evidence for the presence of hard features such as timbers, log boats or canoes. The nature of submerged objects has a bearing on whether they can be imaged by side scan sonar (Quinn *et al.* 2002a).

Sub-bottom profiling

This method uses a lower frequency acoustic pulse, between 1 kHz and 15 kHz. This penetrates the river bottom and is reflected back from structures having contrasting acoustic properties, thus giving a section along the track of the survey vessel. The degree of penetration is dependent on frequency, with high frequency giving poor penetration and high resolution and low frequency giving high penetration but poor resolution.

A typical system such as a Chirp can resolve features between 0.1 m and 0.15 m and penetrate the river bottom in the range 5 m to 50 m. The Chirp system consists of a series of acoustic transmitters housed in a towfish and a receiver system which is towed behind the towfish. The transmitter emits a continuous stream of acoustic waves that pass through the river bottom into the underlying sediments and bedrock. The acoustic properties of the sediment or bedrock-layering control the degree to which the acoustic energy will be reflected back to the receiver system. The reflected signal is passed up the towcable to a processing/display unit, plotter and digital recorder. The image output to the plotter is a section along the track of the towfish and receiver system.

Surveys are carried out along a series of transects spaced according to the objectives of the survey and the likely size of targets being sought. The depth sections provided by sub-bottom profilers enable sub-river bottom features to be resolved that might be due to archaeological and/or geological sources. Again, the nature of the river or sea bottom may have an impact on the preservation potential of archaeological features and objects (Quinn *et al.* 2002b)

Bathymetry survey

This method measures water depth and can also locate wrecks and other features if they stand above the river bed. The use of acoustic methods in measuring water depth is evolving rapidly. Basic systems use single beam echo sounders that measure the travel-time of a single pulse reflected off the river bottom, or features resting on it, and convert this to depth based on the velocity of sound in water. The beam width is narrow. This results in a narrow search path and the survey vessel has to pass over a potential archaeological target in order to map it. Surveys are carried out along transects or grids with a continuous trace, showing the variation in water depth, and are plotted on a recorder on the survey vessel.

Modern surveys use multibeam echo sounders which provide 100% coverage of the river bottom or seabed within the study area. They also provide a second product in the form of a backscatter data set which is analogous to side scan sonar. The survey vessel collects data along a swath width which, in shallow water, is largely dependent on water depth. This method allows the morphology of the river bottom and potential archaeological targets to be rapidly mapped in a limited number of transects with high resolution images being produced. A high resolution image of the river bed is a very valuable tool in prospecting for archaeological features and in establishing their river bed setting.

Magnetometer survey

A magnetometer can be deployed in towfish and used to make magnetic anomaly maps. Anomalies can be caused by geology as well as archaeology. Waterborne magnetometry measures the Earth's total magnetic field which includes localised effects caused by iron objects lying on or in the river bed. The Earth's field is time-varying and drift corrections have to be applied to the data.

A magnetometer survey is carried out along a series of parallel transects or on a survey grid. The choice of line spacing is critical as the coverage of the river bottom is not 100% and small objects/features may be missed. The ideal situation for deployment of a magnetometer is small scale surveys over previously defined targets, or where the archaeological target is likely to contain a large number of iron objects.

Guidelines for waterborne geophysical surveys

To date, there are no published guidelines and standards in Ireland but there are a number of guidelines published in the United States of America (e.g. MMS 2002) relating to archaeological resource assessment on hydrocarbon and pipeline leases.