Preparing for the Future:
A reappraisal of archaeo-geophysical surveying on Irish National Road Schemes 2001-2010

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Executive Summary

This document reviews Legacy Data generated from 10 years' worth of road scheme activity in Ireland to determine how archaeological geophysical surveys could be carried out on national roads in the future. The geophysical surveys were carried out by several different contractors across a range of challenging field conditions, geologies, weather and seasons. The research is based upon the results of linear schemes but also has validity for wider approaches. The findings of this research are based upon the compilation of all terrestrial archaeological geophysical surveys carried out on behalf of the National Roads Authority (NRA), a review of the success or otherwise of those surveys in comparison with ground-observed excavations and in combination with experimental surveys that tested previously held assumptions or knowledge to determine best practice methods for the future.

The use and success of geophysical surveys in Ireland differ quite significantly from those in the UK, from where many of the methods of assessment were derived or adapted. Many of these differences can be attributed to geology. Ireland has a very high percentage of Carboniferous limestone geology, overlain mostly by tills and frequent occurrences of peat. These soils can reduce, to some extent, the effectiveness of magnetometer surveys; the most frequently used geophysical technique in Ireland. However, magnetometer data can be maximised in these cases by increasing the spatial resolution to produce effective results. An increase in spatial resolution is also effective generally, for enhancing the chances of identifying archaeological features by discriminating between archaeological and geological anomalies as well as increasing anomaly definition and visualisation of small and subtle archaeological features.

Seasonal tests have determined that Irish soils are generally suitable for year round earth resistance assessments although some counties in the southeast of the country may experience very dry soils at the surface during some periods of the year.

A variety of sampling strategies were used in the past, however it is now apparent that detailed assessments across the full length and width of a proposed road corridor are the most appropriate form of geophysical investigation. Magnetometer surveys are generally suitable for most Irish soils and geologies, although exceptions apply in areas of near-surface igneous deposits, deep peat and alluvial soils; however magnetometer surveys are not capable of identifying all types of archaeological features and other methods will be required for a full evaluation.

Analysis of the Legacy Data has determined that in general the NRA archaeological geophysical surveys were historically used in a very positive way on road schemes. The range of features assessed or identified account for most types of archaeological sites in Ireland. These have provided a significant archive of case studies that will be of benefit to future archaeological geophysical research and will help to protect the globally dwindling archaeological resource that is threatened by development-led or commercially driven projects.

1. National Roads Authority Fellowship Research

1.1 Research Purpose

This monograph will investigate the effectiveness of archaeological geophysical surveys on Irish road schemes. Archaeological geophysics is one of many techniques that are used by the National Roads Authority (NRA) to assess the impact of a road scheme upon archaeological deposits.

The aim of this document is to provide the NRA, their consultants and other users of geophysical data with a general grounding of modern archaeological geophysical survey practices, basic theory of techniques, methods used and the variables that impact upon them. The document will provide an in-sight into archaeological geophysics and will assist end-users in their understanding and assessment of reports written by geophysical consultants. The document makes a number of recommendations to the NRA Archaeologists which are neither prescriptive nor universally applicable; the document reviews what has happened in the past and how improvements could be made in the future based on those experiences. Specific advice on how to commission an appropriate geophysical survey for a given area has been summarised in Table 16 and Figure 41, which must be read in conjunction with the relevant sections in this document (Sections 4 Uncontrolled Variables and 5 Controlled Variables). Discussions with NRA Archaeologists have revealed that they intend to use these recommendations to inform them as procurers of archaeological geophysics in best practice, based on the empirical research presented here.

This research assesses legacy data from geophysical surveys accrued during commercial NRA projects and draws conclusions regarding how these could be implemented in future Irish road scheme assessments in a more archaeologically productive way.

The findings of this document are based on a critical review of the demonstrable outputs from 10 years of 'linear' survey undertaken using geophysical methods in national road projects. This research reconsiders the balance between the initial impact and long term success of geophysical work upon NRA schemes and will reflect upon a decade of data collection to establish the significance of and prospects for geophysical survey.

1.2 Justification for the Research

In Ireland, geophysical investigations are generally carried out at the start of a road scheme project. Geophysical consultants often complain that the importance of their surveys in driving subsequent (mostly intrusive) assessments is rarely acknowledged at the publishing stage and that feedback in the form of excavation reports is rare to non-existent. Conversely, those excavating previously surveyed sites often give only negative and anecdotal feedback when features have been 'missed' by the geophysicist. In some cases, due to financial or planning restraints, road schemes fail to progress beyond a preliminary assessment, in which case the geophysical data can be the only significant archaeological investigation, often taking in an undisturbed transect across the landscape. Consequently, there is an uneven acceptance of the suitability of geophysical survey on commercial projects.

1.3 Legacy Data

Between 2001 and 2010, the NRA funded 170 geophysical surveys across Ireland (Bonsall and Sparrow 2013), incorporating just over 1,750 hectares of assessments. Each geophysical survey, ranging in area from less than a hectare to hundreds of hectares spread along several linear kilometres of road scheme (Figure 1), generated an individual report. All but 10 of the 170 geophysical survey events were made available to the Research Fellowship in the form of grey literature reports. The 10 missing reports could not be obtained by the NRA and the relevant consultants were unavailable for contact or comment.

In some cases, elements were missing from the reports e.g. one or more illustrations, administration details such as Detection Licence Number or County, or variables such as geology, survey dates, soil conditions, weather etc. Where possible, e.g. geology or Detection Licence Numbers, the missing elements were obtained from accurate and dependable resources (DAHG 2008; GSI 2012), in other cases, the missing elements remain unknown.

The survey reports form an archive of 'Legacy Data' that are available on the internet via an online geophysical survey database (http://www.field2archive.org/nra/). The geophysical survey results were previously available to the public in the form of grey literature reports held by the NRA, the National Monument Service and the National Museum of Ireland whilst some were available on county council websites.

The NRA geophysical surveys are data rich, extensive in size and often very highly specified. 76% of the geophysical surveys were followed by intrusive excavations; 66% of which were available as grey literature commercial archaeological reports and the remaining 10% are, at the time of writing, in the post-excavation stage. The results of these reports have provided a considerable opportunity to assess the suitability of geophysical methods to map and interpret data that are often the product of subtle features.

As a result of the digital delivery of archaeological and geophysical investigations, the NRA road schemes are an excellent resource to study the parameters that contribute to the successful identification of a range of features and site types. This archive of legacy data represents the most complete geophysical data set assembled for analysis.

1.4 International Context and Significance

Reappraising commercial geophysical data on linear schemes has major ramifications in Ireland and internationally by challenging the agenda under which such work is completed. In a commercial situation the aim of each geophysical survey is to identify - or enhance the existing knowledge of - archaeological deposits, as part of a larger strategy of mitigation and to generally avoid where possible the subsequent (development led) destruction of archaeological features (Dawson and Gaffney 1995; O'Sullivan 2003; Gaffney 2009; Campana and Dabas 2011).

The legacy data generated by the work of the National Roads Authority is not only important for Irish archaeological geophysical research, but internationally as well. Globally, there have been very few studies incorporating large geophysical datasets from variable landscapes and geologies. One large review of geophysical surveys linked together a variety of techniques and methods used across several Mediterranean countries (Sarris and Jones 2000). Three independent reviews of legacy data in England examined less than sixty surveys between them, which encountered a variety of geologies and monument types and were very diverse in specifications and outputs (Gaffney 1997; Hey and Lacey 2001; Jordan 2009). An assessment of similarly diverse surveys from the Trent Valley, England, examined the performance of over 1,000 geophysical projects on sands and gravels but was hampered by a lack of digital data (Knight *et al.* 2007).

There have been considerable expressions of interest in the research across Europe, provoked by preliminary reports at international conferences (Bonsall *et al.* 2011, 2012a, 2014a, 2014b and see Appendix E). Validating the outcomes of ground based remote sensing of archaeological deposits and the reappraisal of road scheme data can play a major part via this research.

International projects that have been investigated by ‘linear’ sampling have utilised geophysical methods sporadically through the last thirty or so years. An early example was the 220 mile long British Gas Southern Feeder Pipeline in the UK (Catherall *et al.* 1984). In that instance, and many that followed, the technology was used to create a context for trial excavations on previously known sites; essentially there was an assumption that *all sites were known in advance* and there was no concept of prospecting for new sites using geophysical techniques.

The investigations carried out by the NRA in the last decade have been significantly different from the British Gas experience and reflect more recent experiences of developer led evaluation style investigations. Embedded within the NRA is a belief that archaeological geophysics can and will add value to the process of discovery that is required for mitigation and cost effective preservation by record. This has been achieved by rigorous specifications issued by the NRA for road scheme investigations. The use of extensive specifications has increased the research potential in that choices made by individual surveyors or consultants are insignificant in comparison to the standard professional response to a work scheme. Additionally, the use of the specification allows the individual surveyor to be ‘removed’ from the equation when one considers the *technical* success of a survey and this is a significant research priority.

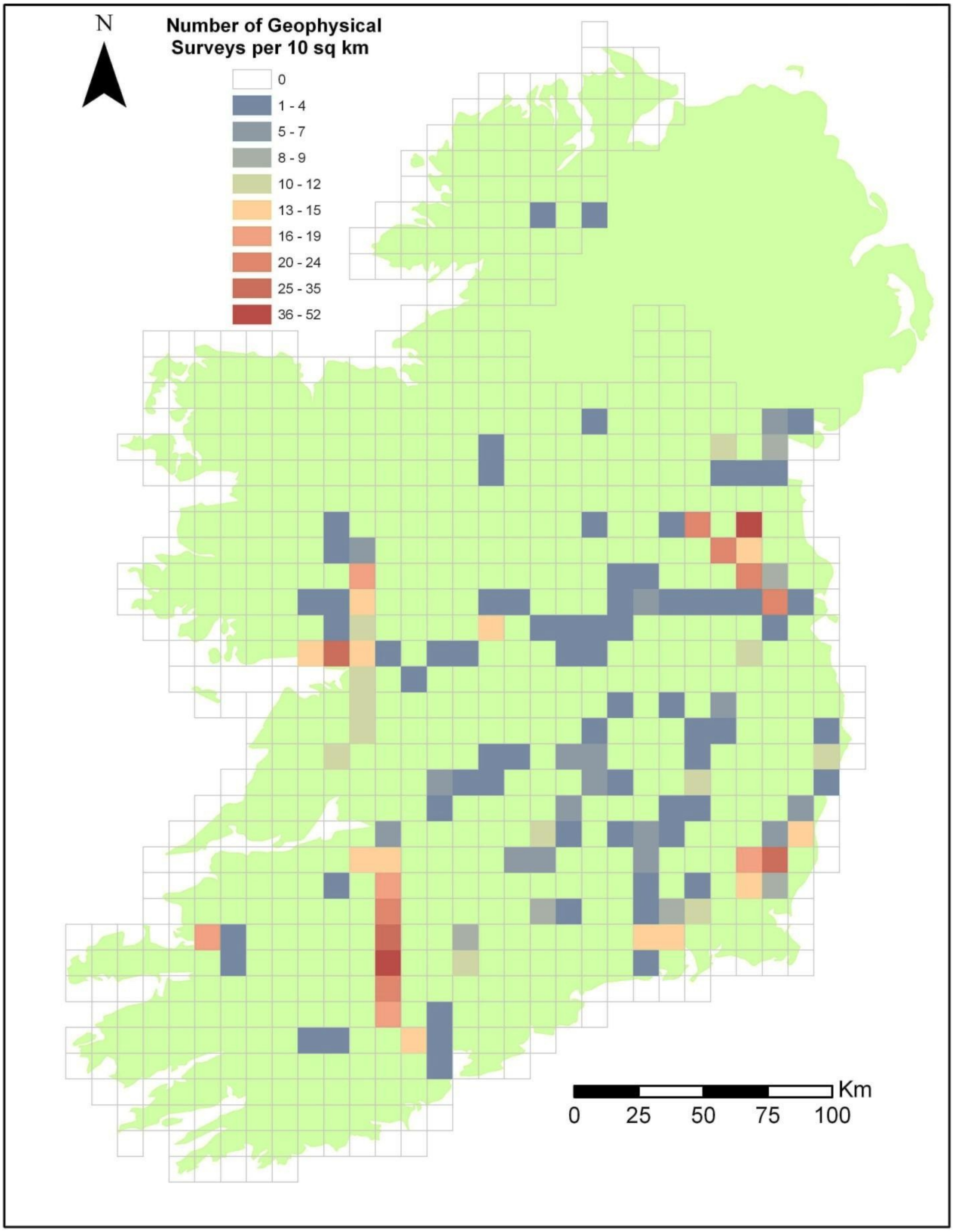


Figure 1. Frequency of geophysical surveys per 10 sq. km on NRA Road Schemes.

2. Review of Geophysical Surveys on Road Schemes

The NRA has, over the course of 10 years used all of the principal geophysical survey techniques that are commonly available for terrestrial assessments of sub-surface archaeological features (Table 1). Magnetometer surveys have been used more frequently than all other techniques combined, mirroring to some extent the experience in the UK (Knight *et al.* 2007; David *et al.* 2008; Jordan 2009). This is not a universal commitment to magnetometry; in the Mediterranean earth resistance was the most commonly used geophysical survey noted in Sarris and Jones (2000); earth resistance, and recently ground penetrating radar (GPR) are most commonly used in the Netherlands, followed almost equally by electromagnetics and magnetometry (Visser *et al.* 2011); in Norway magnetometry and GPR are most commonly, on an almost equal basis (Stamnes and Gustavsen 2013) and GPR has dominated the most recent studies in Sweden (Viberg *et al.* 2011).

Geophysical Technique	Survey Area Coverage (Hectares)	Percentage
Magnetometer	1,442	82%
Magnetic Susceptibility	237	13%
Earth Resistance	50	3%
Electromagnetism	25	<2%
Metal Detection*	1.5	<0.1%
Ground Penetrating Radar	0.3	<0.1%
Total Coverage	1755.8	

Table 1. Geophysical survey techniques used on National Roads Authority schemes.
The majority of geophysical surveys used magnetic techniques such as magnetometer and magnetic susceptibility which are limited to mapping only those archaeological features that exhibit magnetic contrasts. *Metal Detection refers to individual survey reports. A further 44 systematic metal detection surveys are known from archaeological excavation reports.

Geophysical surveys are used to map magnetic, electrical or electromagnetic contrasts within a soil. The contrasts identify anomalies from the general background; these anomalies are the result of archaeological, geological, pedological or modern sources. Soils are dynamic and capable of change via environmental and human action, which impact upon the ability to detect archaeological features. To identify archaeological features in geophysical data a contrast must be observed between the archaeological deposits (e.g. ditches, pits, kilns) and the background soils. If an area is assessed with a particular technique e.g. a magnetometer, and no contrasting anomalies are found, that does not necessarily imply that an archaeological feature does not exist; 'hidden' features may exist within the survey area but may be unmapped because either the given feature type cannot be detected by that particular technique or the individual feature does not differ sufficiently from the local background.

2.1 Geophysical Techniques

The following section provides a simplified explanation of geophysical survey techniques commonly used on road schemes (in Ireland), what they are capable of identifying and their basic principles of operation. Information concerning the choice of instruments that geophysicists can make for a particular survey technique can be found in Section 2.2.

A detailed discussion of the geophysical techniques discussed below can be found in Clark (1996), Scollar *et al.* (1990) and Gaffney and Gater (2003); a thorough review of the recent history and application of geophysical techniques used for archaeological prospection can be found elsewhere (Linford 2006; Gaffney 2008). Geophysical techniques are often described as either passive or active. Passive techniques such as magnetometer surveys, measure naturally occurring phenomena, whereas active techniques, such as earth resistance, electromagnetic, magnetic susceptibility and GPR, measure the response to energy introduced in to the ground.

2.1.1 Magnetometry

The magnetometer technique is the most frequently used instrument on NRA surveys and has been used to cover more than 1,440 hectares, accounting for 82% of all geophysical surveys on road schemes.

- Capabilities

Magnetometers are capable of rapidly identifying a wide range of archaeological features (Figure 2). Burnt soils, in particular *in-situ* burnt deposits such as kilns, furnaces, hearths and burnt mounds of stone can usually be identified with confidence.

Cut or in-filled features such as ditches, pits and post-holes can also be identified if a sufficient magnetic contrast exists between the in-filled feature and the background soils. The role of geology (discussed below, in Section 4.1) is probably the largest limiting factor for a magnetometer survey. Crucially, magnetometers cannot usually identify stone remains (although structures comprised of strongly magnetic rocks e.g. granite and basalt, could potentially be identified if they contrast with the background).

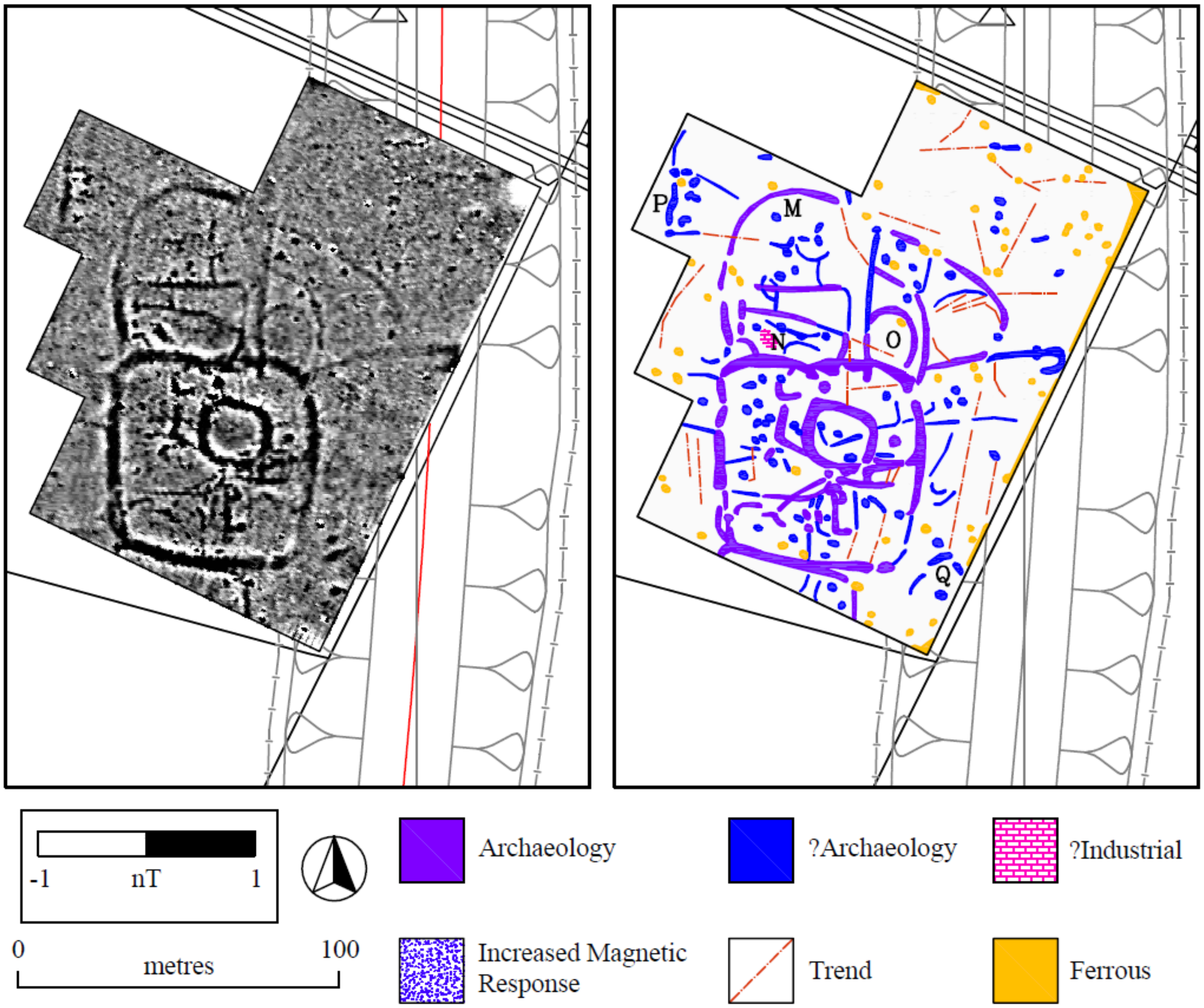


Figure 2. Example of a magnetometer survey.

This survey of the N3 Navan to Dunshaughlin Road, Co. Meath (GSB 2001b) identified a significant amount of archaeological features that were found to represent a series of interlinking enclosures, pits and hearths.

- Principles

The magnetometer is a passive survey instrument; it measures very small variations in the naturally occurring magnetic field of the Earth. Magnetism, for archaeological geophysical applications, is measured in nanoTesla (expressed as nT or 10^{-9} Tesla). Archaeological features create subtle magnetic anomalies (Table 2): ditches and pits create typically weak responses usually induced by the Earth's magnetic field whilst stronger responses from hearths, kilns or industrial deposits often exhibit permanent or thermoremanent magnetisation. Deviations in the magnetic field created by modern sources of interference (fence lines, passing vehicles) and some geologies can obscure anomalies derived from archaeological features.

	Modern Source			Archaeological Source			
	Dublin City	**Car**	**Metal Fence**	**Kiln**	**Hearth**	**Ditch**	**Post-hole**
Magnitude of Anomaly	49,100 nT	49,100 nT + >1,000 nT	49,100 nT + >200 nT	49,100 nT + >100 nT	49,100 nT + >6 nT	49,100 nT + 1-3 nT	49,100 nT + <1 nT

Table 2. Varying magnitudes of different magnetometer anomaly sources, with reference to the local field of approximately 49,100 nT in Dublin.

Ditches or pits filled with magnetically enhanced soil will produce a measurable magnetic field, providing that they contrast with the surrounding sub-soil. In some cases no measurable contrast exists despite the presence of extensive archaeological deposits. It has been suggested that in these instances either a magnetic contrast never existed, or subsequent processes have altered the iron mineralogy of the soil and changed its magnetic susceptibility (Aspinall *et al.* 2008).

2.1.2 Magnetic Susceptibility

Magnetic Susceptibility (MS) is the second most frequently used technique, accounting for 13% of geophysical surveys on road schemes. Its versatility has seen it used both as a reconnaissance tool (identifying areas of archaeological potential and/or unsuitable geology) and as a detailed method of assessment (to supplement magnetometer and/or earth resistance surveys).

Despite being the second most used technique, the success of MS has been limited on NRA road schemes due to variable background changes within and between individual modern fields and strongly variable geological influences. Nonetheless, the MS Legacy Data have provided a significant archive of material that has assessed the ‘usefulness’ of magnetic prospection techniques across the country.

- Capabilities

Magnetic Susceptibility is capable of identifying areas or zones of increased magnetic enhancement resulting from anthropogenic activity. MS tends to be used over broad areas at low sample resolutions (e.g. 5m x 5m or 10m x 10m) in order to identify settlement, occupation and industrial zones, although it can be used at a high resolution (< 2m x 2m) to identify discrete archaeological features.

The technique maps areas of magnetically enhanced soils; it is often difficult to distinguish archaeological sources from modern, environmental and geological magnetism and interpretations are therefore restricted.

- Principles

Human habitation activities are capable of converting the natural iron oxides of the soil into more magnetic forms (e.g. magnetite and maghemite), which can be mapped as zones of magnetic 'enhancement' compared to the background soils (Aspinall *et al.* 2008).

If there is a low level of iron oxides in the background soil then no significant magnetic enhancement will occur, despite the presence of even large and complex archaeological sites. Similarly, if the level of human impact upon soils is relatively low, then no significant anomalous zones will be produced.

On the other hand, a strongly magnetic background response can easily mask the presence of archaeological sites; therefore the technique is strongly dependent on background soils, geology and the level of human impact, whether ancient or modern.

2.1.3 Earth Resistance & Resistivity

Earth resistance data measures electrical resistivity contrasts of soil moisture. The spatial variation in soil resistivity is most commonly collected in Ireland by earth resistance surveys. The electrical properties of soil can also be studied by electromagnetic instruments which measure the same electrical contrast but termed 'apparent conductivity'. Apparent conductivity data collected by electromagnetic instruments are also known as quadrature data.

2.1.3.1 Earth Resistance

Earth resistance has been used across 50 hectares (3%) of NRA road scheme assessments. Resistance surveys can be measured via a variety of 'probe arrays', including the Twin-probe, Wenner, Square and Schlumberger. The NRA have previously specified the exclusive use of the Twin-probe array; however 9.5% of earth resistance surveys successfully employed the use of a Square array on road schemes.

Earth resistance has been required by specifications as a second (16%) or third (6%) investigation technique, after reconnaissance and/or detailed magnetometer and magnetic susceptibility surveys.

Earth resistance has only ever been used in isolation once (0.5%), and yet it has produced very reliable results for the detection of cut earth and stone/masonry features.

- Capabilities

Earth resistance meters are capable of identifying a variety of archaeological features that have the ability to pass an electric charge (Schmidt 2013). Cut or in-filled features e.g. ditches and pits, can be identified if a sufficient moisture contrast exists between the in-filled feature and the background soils. Usually masonry and stone-based features can also be identified by earth resistance, which is a significant advantage over magnetometer surveys. Earth resistance surveys can be carried out rapidly across areas or to obtain depth data along specific profiles using Electrical Resistivity Tomography (ERT). ERT is not particularly suited for large area coverage (due to set-out and probe movement time) but it is useful in selected areas to map the depth and extent of large and deep archaeological features (Tsokas *et al.* 2009), such as souterrains, tombs and moats.

Earth resistance surveys are incapable of measuring magnetic contrasts and cannot directly identify areas of burning and other thermoremanent anomalies (which exhibit a strong magnetic contrast). This may be advantageous for archaeological prospecting on areas of magnetically strong geology.

Earth resistance surveys can be affected by topography, ground surface, vegetation, geology, organic content and soil moisture content (Al Chalabi and Rees 1962; Clark 1996) as well as ground temperature. Background trends of very high or very low soil resistance can mask the presence of stone/masonry features and cut earth features, respectively, variations in the depth of topsoil can also mask the signal from buried features. A discussion of seasonal variations and its affect upon earth resistance data can be found in Section 5.3.2.

- Principles

Earth resistance is an active survey technique that relies upon the injection of a small electrical current into the ground via probes and measures the resistance of the soil. Active techniques are slower than passive magnetic methods of archaeological geophysics, which may have influenced decisions to favour the comparatively faster magnetometer technique in the past.

The presence of a moisture contrast between an archaeological feature and the background soil is critical to the success of the technique. Natural variations in the soil and geology will influence the moisture contrast. Under idealised circumstances, a cut-earth feature retains more moisture than the surrounding soils, whilst a wall or foundation will retain less moisture. The moisture contrasts are measured by earth resistance surveys as anomalies of low and high resistance with respect to the surrounding soil background.

The arrangement of probes (e.g. the Twin-probe, Wenner, Square, Schlumberger arrays) and the distance between the probes alter the penetration depth, sensitivity and spatial resolution. These are properties that influence the earth resistance response and the ability to detect archaeological features. The majority of earth resistance surveys in Ireland have used the Twin-probe array.

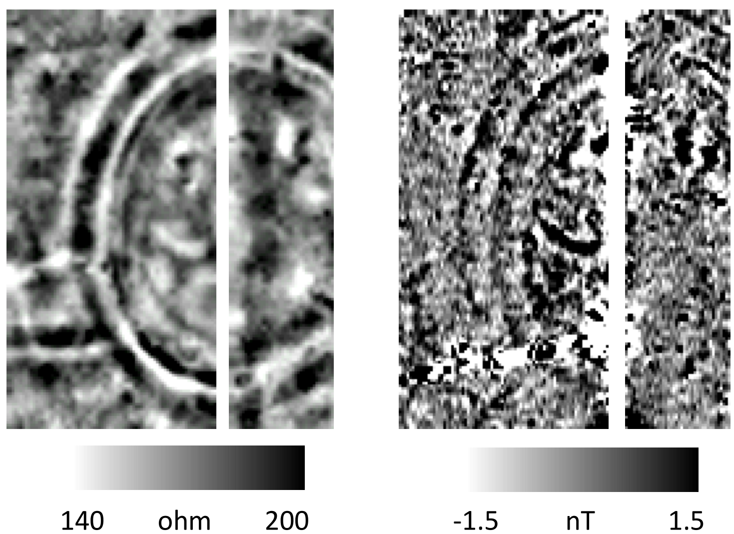


Figure 3. Comparison of earth resistance and magnetometer survey.
A 40m x 64m area at Monanny ringfort (MO031:013), Carrickmacross, Co. Monaghan (GSB 2001a). Left: An earth resistance survey indicated clear and coherent anomalies of low and high resistance indicative of ditches and banks. Right: The magnetometer survey of the same area found that the ditches contrasted weakly against the background soils. Ferrous responses either side of a central 4m wide hedge and across the bottom left of the magnetometer plot have impacted upon the data.

2.1.3.2 Electromagnetism

Very few electromagnetic (EM) surveys have occurred on NRA road schemes, accounting for 1.4% of all geophysical assessments.

This active technique transmits low frequency EM energy into the ground and the returned signal is usually analysed via two properties: a quadrature response (or 'apparent conductivity') and an in-phase response (or 'apparent magnetic susceptibility'). In older instruments (as used on NRA road schemes between 2001-2010) these two properties are measured separately; this is time consuming and may have influenced the use of this technique over the period of study. 25 hectares of EM surveys were carried out on NRA schemes; 98% of those obtained only the in-phase (apparent magnetic susceptibility) response. The remaining 2% obtained the quadrature response (apparent conductivity) only.

The latest generation of EM instruments, developed in the last few years, return *both* the quadrature & in-phase responses *simultaneously*. Despite this, globally, EM instruments are primarily used for their soil conductivity measurements, as a proxy for soil moisture measurements. The instruments do not require ground contact and as such they are favoured in the Middle East and the USA where dry soil conditions are prevalent and often prevent the use of earth resistance meters (Clark 1996; Witten *et al.* 2000; Berle Clay 2006).

- Capabilities

By obtaining *both* apparent magnetic susceptibility and apparent conductivity data simultaneously (Figure 4), EM instruments are capable of identifying a wide range of archaeological deposits, including burnt features (e.g. kilns, furnaces, hearths and burnt mounds of stone), cut-earth or in-filled features (e.g. ditches and pits) and resistive features (e.g. stone structures and earthen embankments).

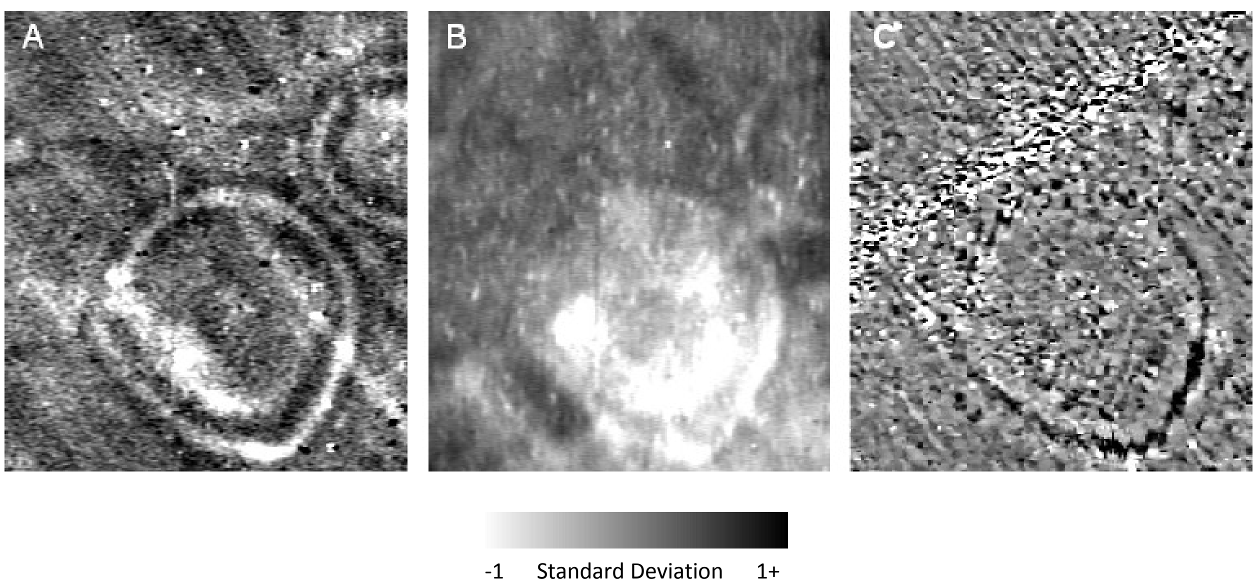


Figure 4. A Comparison of electromagnetic and magnetometer survey data.
A: Electromagnetic (in-phase) apparent magnetic susceptibility survey, clearly indicating a large enclosure and half of a second smaller enclosure. The remaining half of the smaller enclosure was excavated as part of the N17 Tuam Bypass investigations (McKinstry 2010).
B: Electromagnetic (quadrature) apparent conductivity survey, indicating low contrast anomalies for the enclosures.
C: Magnetometer survey, indicating that the largest enclosure contrasts strongly with the background soils, however the remains of the smaller enclosure can barely be seen. Earth-cut ditches often appear as low contrast or no-contrast magnetometer anomalies on Carboniferous limestone soils in the west of Ireland.

The latest EM instruments are also capable of simultaneously returning multiple depth profiles (Simpson *et al.* 2009). These can, theoretically, allow for 3-dimensional surveys. The most significant advantage they offer is the chance to map apparent magnetic susceptibility and apparent conductivity data at multiple depths, for the same area, which greatly increases the chances of identifying archaeological features across the various data sets (Bonsall *et al.* 2012c; 2013a; Simpson *et al.* 2009). A disadvantage of EM surveys is that they tend to identify some archaeological features as broad and amorphous anomalies, rather than the often crisp and coherent anomalies that end-users are familiar with from magnetometer surveys. EM instruments also tend to be used as single sensors, as opposed to some multi-sensor magnetometer systems.

- Principles

The EM instrument passes an alternating current through a transmitter coil, inducing a primary EM field through the ground. A secondary field is produced with the magnetic or conductivity properties of the soil body. As most soils exhibit both of these properties, a quadrature (conducting) and/or in-phase (magnetic) response is detected by a receiver coil. As such, EM surveys can be very useful for the assessment of underlying archaeological deposits that exhibit either a conductivity/resistivity contrast or a magnetic contrast. Given this, EM surveys carried out with the latest instruments are very useful for prospecting a range of archaeological features that are commonly identified via magnetometer and earth resistance surveys.

2.1.4 Metal Detection

One systematic metal detection survey was presented as an isolated report on an NRA road scheme, accounting for 0.58% of all geophysical assessments. The survey was used to specifically assess part of the 1691 battlefield at Aughrim, Luttrell's Pass (Sabin and Donaldson 2005), on the N6 Galway East to Ballinasloe scheme. At least 44 metal detection surveys are known from a number of individual archaeological excavation reports and there may be more examples in the excavation archives.

- Capabilities

Metal detectors are capable of identifying surface and shallow sub-surface metals, but cannot distinguish between modern and ancient metal finds. Some instruments can discriminate between different types of metals.

When combined with a GPS for spot locations, metal detecting can be a very useful tool for mapping the distribution of buried metal finds (Figure 5). Metal detection surveys do not necessarily have to be followed by immediate intrusive finds retrieval: a rapid survey could produce a distribution plot of metal finds (including metal type) for subsequent detailed (and context secure) excavations.

- Principles

Metal detectors use the same principles as electromagnetic devices; they induce a small electromagnetic field (EMF) in to the ground. As the EMF passes over a metal object, a phase shift occurs within the EMF indicating the presence of that object. Different metals cause different phase shifts which can allow for discrimination between certain metals.

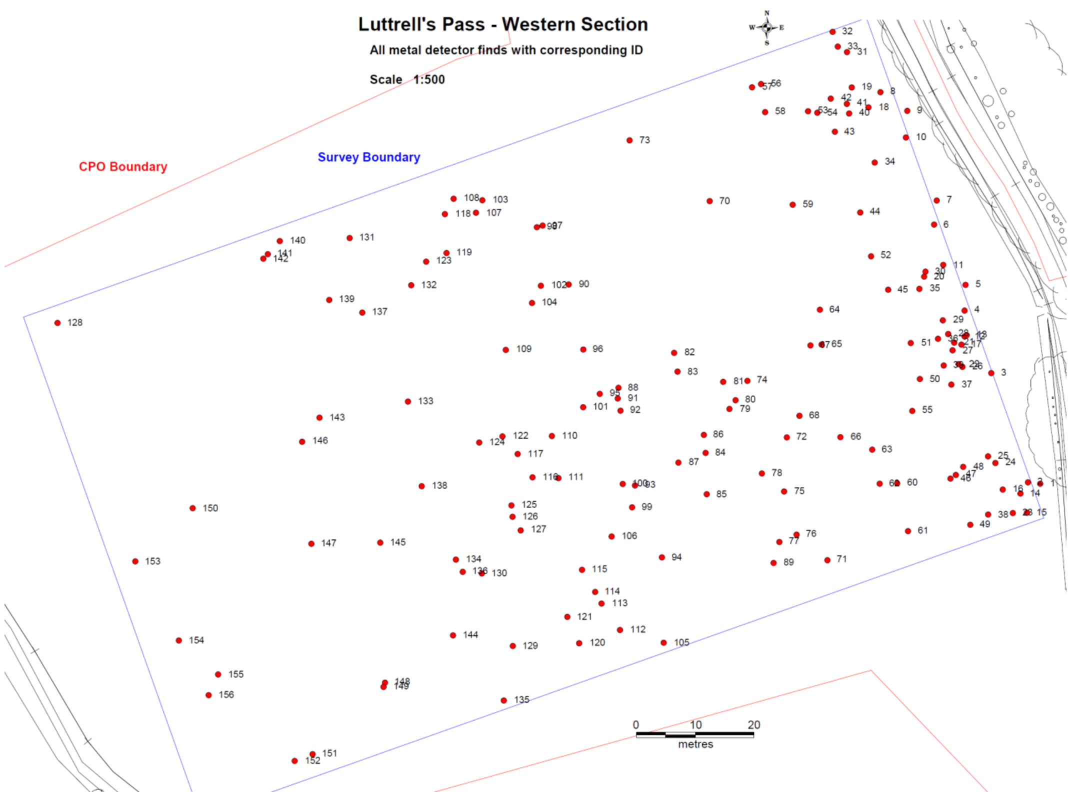


Figure 5. Distribution map of metal finds at Luttell's Pass, County Galway.
Finds were recovered following a detailed metal detection survey along transects spaced 1.5m apart. All finds were logged in on a database and geo-referenced using a sub-metre Differential GPS. After Sabin and Donaldson (2005).

2.1.5 Ground Penetrating Radar

Only one Ground Penetrating Radar (GPR) survey occurred on an NRA road scheme, accounting for 0.58% of all geophysical assessments. The GPR survey was used to collect data along a series of widely spaced lines, in the manner of a geological exploration survey, to identify a souterrain (Whiteford and Calvert 2009). This method is not adequate for the archaeological prospection of discrete features, but could form part of a staged approach for assessing large linear features known to cross a survey area; detailed area surveys are the most suitable GPR method of identifying sub-surface archaeological remains.

- Capabilities

GPR has two major advantages over the traditional geophysical methods: 1) it can be calibrated to give reasonably reliable depth information to produce three-dimensional maps and 2) it can be used over asphalt, concrete and inside buildings (which are often unsuitable for magnetometer and earth resistance surveys.

GPR can be used over a variety of soil types. The Relative Dielectric Permittivity (RDP) of a soil changes depending on the moisture content of the soil (Table 3). RDP is inversely proportional to the speed or velocity at which a radar wave passes through the soil. Soil moisture changes, surface conditions and vegetation can each influence the outcome of a GPR survey. Wet and conductive clay-rich soils can attenuate (or absorb) the radar wave very quickly which leads to reduced penetration depth. The ability to resolve archaeological features is dependent on a combination of the RDP and the selection of a particular GPR antenna frequency.

- Principles

The GPR instrument uses an antenna to emit an EM wave down in to the ground from a transmitter. As the wave intercepts soils or layers of different properties (natural and archaeological), part of the wave is reflected back upwards to a receiver on the antenna, whilst at the same time a portion of the original wave continues down to successive layers in the ground. Each time a contrasting interface is encountered part of the wave is reflected upwards until the wave has been attenuated by the soil. The time, in nanoseconds (nS), taken for the wave to travel down to a given layer from the antenna transmitter and return back to the receiver, is broadly proportional to the depth of the soil (Conyers 2004).

Material	RDP
Dry Sand	3-5
Dry Silt	3-30
Asphalt	3-5
Limestone	4-8
Granite	4-6
Shale	5-15
Clay	5-40
Concrete	6
Saturated Silt	10-40
Dry Sandy Coastal Land	10
Average organic-rich surface soil	12
Organic-rich agricultural land	15
Saturated Sand	20-30

Table 3. Typical Relative Dielectric Permittivity's (RDPs) of materials commonly found in Ireland.
After Conyers (2004). Local soils can vary substantially over reasonably small areas. Pilot studies using different antenna frequencies are often required to determine the most suitable approach.

2.2 Choice of Geophysical Instruments

Once a geophysical technique has been selected, the choice of a particular instrument is, in general, decided by the consultant. Geophysical instruments currently in common use (and could be expected to be used in the future) are given in Table 4. The list is by no means exhaustive; other manufacturers and products are available, the list should not be used to specify a particular type of instrument and listing carries no endorsement of the said products. There are certain advantages and disadvantages to each instrument type. Survey speed is certainly an important, but not necessarily the most important factor and largely depends on the sample resolution used (see 5.2.4).

2.2.1 Magnetometer Instruments

There are two principle methods of measuring magnetic anomalies: the fluxgate gradiometer and the optically pumped magnetometer (Aspinall *et al.* 2008). Of the optically pumped magnetometers, caesium is the most widely used, although potassium (Boschi 2012) has also been used successfully. The overwhelming majority (92%) of magnetometer surveys carried out for the NRA between 2001-2010 used Fluxgate Gradiometers; 8% used a caesium magnetometer system.

- Fluxgate Gradiometers

Fluxgate sensors can rapidly acquire magnetometer data at a sensitivity of about 0.1 nT (Linford *et al.* 2007), which is usually sufficient to resolve most archaeological features. Historically these were hand-held instruments however fluxgates have recently been mounted upon carts for both pedestrian (Gaffney *et al.* 2008) and vehicular-powered surveys (Campana and Dabas 2011; Gaffney *et al.* 2012).

Survey Type	Manufacturer	Instrument	Notes
Magnetometer	Bartington Instruments	Grad601-1 / Grad601-2 Dual	Fluxgate Gradiometer
	Geoscan Research	FM36 / FM256 Dual System	Fluxgate Gradiometer
	Foerster	FEREX	Fluxgate Gradiometer
	Foerster	MULTICAT*	Fluxgate Gradiometer
	Geocarta	AMP*	Fluxgate Gradiometer
	Geometrics	G858 MagMapper	Caesium Vapour
	Scintrex	CS-L	Caesium Vapour
	Scintrex	CS-3	Caesium Vapour
	Scintrex	SM-4 Smartmag	Caesium Vapour
Magnetic Susceptibility	Bartington Instruments	MS-2 / MS-3*	
	SatisGeo	KT-6 Kappameter	
Earth Resistance	Geoscan Research	RM15-D / RM85*	Multiple arrays
	Geoscan Research	MSP40	Mobile Sensor Platform
	Geocarta	ARP	
Electrical Resistivity Tomography	ABEM	Terrameter LS	
	Allied	Tigre	
	Allied	Ohmega	
	ZZ Resistivity Imaging	FlashRES-64*	
Ground Penetrating Radar	MALÅ	MIRA*	Multi-Frequency / Multi-Channel
	MALÅ	GPR Easy Locator*	Single Channel
	GSSI	SIR-3000	Single Channel
	GSSI	SIR-20*	Dual-Channel
	3d-Radar	GeoScope	Multi-Frequency / Multi-Channel
	IDS	STREAM-X*	Multi-Channel
	IDS	RIS MF Hi-MOD*	Multi-Frequency / Multi-Channel
	Sensors & Software	Noggin	Single Channel
	Sensors & Software	PulseEKKO Pro	Single Channel
	Sensors & Software	SPIDAR*	Multi-Frequency / Multi-Channel
Electromagnetic	GF Instruments	CMD Mini-Explorer*	Multi-Depth, In-Phase & Quadrature
	DUALEM	21-S*	Multi-Depth, In-Phase & Quadrature
	Geonics	EM38-MK2	Dual-Depth, In-Phase & Quadrature

Table 4. Geophysical instruments that might be used in Ireland.
Instrumentation is constantly updated and will continue to change substantially in the future. This list is not a recommendation or endorsement of the above instruments. * Denotes instruments developed during or after 2010, since the Legacy Data study period.

- Caesium Magnetometers

Caesium magnetometers have an increased sensitivity by comparison with fluxgate gradiometers and an ability to measure weak magnetic responses in picoTesla (pT or 10^{-12} Tesla). Although they can be hand-held (Becker 2009; Boschi 2012), they are commonly used on carts (Linford *et al.* 2007; Bescoby *et al.* 2009; Gaffney *et al.* 2012) to reduce the effect of operator-induced ‘walker bounce’.

Caesium magnetometers can be used with a static base-station (to which all data are compared and processed against), or as a gradiometer. Both types have featured on NRA schemes in the past and satisfactory results have been obtained by archaeological geophysicists.

Caesium surveys can, under favourable soil conditions, identify subtle and weakly contrasting magnetic anomalies; they have been used successfully across the magnetically quiet chalkland geologies of southeast England and southern Germany to identify discrete prehistoric features (Linford *et al.* 2007; Fassbinder 2010; Gaffney *et al.* 2012).

- Other instruments

Proton precession (Aitken 1960) and optically pumped Rubidium magnetometers (Ralph 1964) were used in the early history of archaeological geophysics, but were slower instruments compared to the fluxgate gradiometer and later, caesium technology.

- Magnetometer Considerations

In general terms, the choice of a magnetometer instrument is decided in advance by the geophysical consultant in relation to personal choice and instrument availability.

Magnetometer surveys should be capable of achieving a sensitivity of 0.1 nT. Although caesium systems are capable of much greater sensitivity, it is impractical and unnecessary to demand this given the anticipated level of background noise on most Irish soils, which are greater than 0.1nT.

Magnetometer instruments suffer from both noise and drift. There are various sources of noise, the most significant is created naturally within the soil but noise levels can be magnified by 'walker bounce' as an instrument is carried across a survey area. Drift is inherent in both the instrument and natural variations but can be compensated for in the field if necessary by the correct alignment of the magnetometer sensors and by basic data processing steps.

Multiple magnetometer sensors mounted on to fixed arrays or carts improve rapid data collection over large areas and help reduce walker induced noise (see Section 5.2.1 for a discussion on cart-acquired data).

It is advantageous to collect data along lines oriented to magnetic north (Aspinall *et al.* 2008). Whilst this should be encouraged wherever possible, the directional constraints of linear corridor surveys mean that it is not always practical. There is rarely a significant loss of archaeological information due to alignment.

- Magnetometer Suitability

Caesium magnetometers can be used as well as, or instead of, fluxgate gradiometer instruments. They should not necessarily be *expected* to work better than fluxgate gradiometers on most Irish soils, simply due to the prevailing magnetically variable soils. Indeed, Irish soils might preclude any of the significant advantages offered by the use of high sensitivity systems. The increased sensitivity offered by caesium magnetometer surveys cannot overcome the absence (or near absence) of magnetic contrasts for some archaeological features; previous surveys using caesium were unable to identify low contrast ditched enclosure monuments, including large hillfort ditches (Bonsall *et al.* 2011).

However, the increased sensitivity of caesium instruments to deep deposits is advantageous for the assessment of deeply buried soils e.g. beneath layers of alluvium (Linford *et al.* 2007). These instruments clearly have a specific role in certain locations.

2.2.2 Earth Resistance & Resistivity Instruments

Geophysical surveys in Ireland and Britain have favoured the use of the Twin-probe resistance array (Gaffney 2008), however other probe arrays have been recently re-evaluated (Aspinall and Gaffney 2001; Aspinall and Saunders 2005). The development of articulated wheeled arrays (Walker *et al.* 2005; Dabas 2009) have been popular in recent years principally due to increases in survey speed and sample resolution (Figure 6).

- Twin-probe Array

The Twin-probe array generally gives a superior horizontal resolution to an underlying archaeological feature, compared to most arrays. Typically Twin-probe arrays are used for archaeological purposes and have a maximum penetration depth of approximately 0.5-1.0m.

The Twin-probe array is adaptable and can, with additional probes and multiplexers, be used to assess soils at multiple depth readings ‘simultaneously’, although this increases the survey time.

Figure 6. Commonly used earth resistance arrays.

Top: MSP40 Mobile Sensor Platform incorporating a wheeled Square array. Bottom Left: Wenner array. Bottom Right: Twin-probe array. Each array is manufactured by Geoscan Research (Photo Credits: H. Gimson, Earthsound Archaeological Geophysics).

Multiplexed Twin-probe arrays are most frequently used to collect data from two adjacent lines (or transects) of data at once, allowing survey times to effectively halve. Despite this, Twin-probe surveys are slower than magnetometer surveys.

The Twin-probe array is connected to a pair of static probes located 30-60m from the array, via a trailing cable (which can impede survey progress, particularly when conducted across tall or thick vegetation such as pasture fields). Survey progress can be interrupted by the need to frequently relocate (and calibrate in the field) the static probes, as the survey progresses across a large area (Clark 1996).

The Twin-probe array has a directional sensitivity; it has been suggested that data should be collected at 90° to the presumed alignment of archaeological features, wherever this is practical (Clark 1996; Walker *et al.* 2005; Schmidt 2013).

- Wenner Array

The Wenner array has poorer horizontal resolution than the Twin-probe, but a superior depth resolution.

All four probes are located upon the Wenner array frame, so there are no trailing cables or interruptions due to probe relocation.

The Wenner array is a slower technique compared to the multiplexed Twin-probe.

Like the Twin-probe, the Wenner array is also sensitive to directionality; data should be collected at 90° to the presumed alignment of archaeological features.

- Square Array

The Square array has a reasonable horizontal resolution and a depth resolution for archaeological surveys.

Like the Wenner, all four probes are located upon a single frame, so there are no trailing cables or interruptions due to probe relocation.

The Square array reduces orientation dependence by simultaneously acquiring a second dataset at 90° to the direction of traverse; a third dataset can be measured directly or calculated from the original two.

This allows for a survey to occur along any axis and does not require traverses at 90° to the presumed alignment of archaeological features (Aspinall and Saunders 2005).

The Square array can be mounted upon (or incorporated on to) a wheeled articulated platform which increases survey speed and sample resolution significantly (Hesse *et al.* 1986; Walker *et al.* 2005). This makes articulated arrays quite suitable for long linear surveys, in areas of smooth terrain and short vegetation.

- Electromagnetic Instruments (measuring soil conductivity and magnetic susceptibility)

For most commercial instruments the depth of penetration is dependent on the spacing and geometry of the transmitting and receiving coils. Most instruments are capable of penetrating to a depth of at least 1-1.5m.

Conductivity data are usually collected at timed intervals in seconds, with high acquisition rates of 0.1s. This allows conductivity data to be sampled at a higher resolution than Twin-probe and Wenner arrays, and is approximately equal to, if not slightly better than the sample rate of articulated Square arrays.

The main advantage of EM conductivity surveys over earth resistance surveys is that probe contact with the ground is not required, therefore it can be used on both very dry soils and wet or waterlogged soils. It can essentially be used upon any surface that a pedestrian can walk. EM instruments are also capable of acquiring magnetic susceptibility data which can also be very beneficial.

- Earth Resistance & Resistivity Suitability

A wide variety of geology, topography, climate, vegetation and monument types will be encountered within a single road scheme. It is sensible to allow the contractor to choose a suitable and appropriate instrument(s) for the collection of earth resistance data that meets the needs of a given area.

Data collection does not need to be restricted to the Twin-probe array. Surveys by the Research Fellowship found that the Wenner, Square and Twin-probe arrays are all capable of identifying 1-2m wide ditched enclosure features at various sites across Ireland. The Research Fellowship also found that apparent conductivity (quadrature) data collected with EM instruments were also capable of identifying the same features. If EM instruments are selected, additional data (in-phase apparent magnetic susceptibility; multi-depth profiles) are likely to be obtained that could also be useful for the assessment of archaeological features.

Monthly reproducible tests demonstrated that the Wenner, Square and Twin-probe array were capable of identifying the same archaeological features throughout the course of a year and that EM conductivity (quadrature) data were also suitable for year round assessments see (Section 5.3.2).

2.2.3 Ground Penetrating Radar

The most important choice to make when commissioning a GPR survey is the selection of an appropriate antenna frequency, which can vary from instrument to instrument or may be comprised of modular or interchangeable frequencies.

- Frequency Selection

GPR instruments traditionally use one antenna at a fixed centre frequency, e.g. 400 MHz – the frequency used dictates the likely depth of penetration to a certain distance (Table 5). Low frequency antenna e.g. 200 MHz can be used to obtain responses from deep layers but have a poor horizontal resolution, whereas higher frequency antenna e.g. 900 MHz can be used at very shallow depths and with a very good horizontal resolution. Archaeological prospection in Ireland typically uses GPR at centre frequencies of approximately 200 MHz and 400 MHz (approximately 1.5m and 3m depth, respectively), however preliminary pilot surveys are usually required to determine which antenna is most appropriate at a given site.

In some cases, more than one antenna may be needed. By using a variety of frequencies, different depths can be examined. For most projects, the depth of an archaeological feature will be unknown; therefore it is advantageous to carry out a GPR survey using more than one antenna frequency.

Centre Frequency (MHz)	Approximate Depth Penetration for Typical Soils (m)	Approximate Horizontal Resolution (m)	Approximate Vertical Resolution (m)
1,000	~1.0	0.2	0.02
500	~2.0	0.4	0.04
200	~3.0	0.8	0.10
100	~5.0	1.4	0.19
50	~7.0	2.4	0.39

Table 5. Approximate capabilities of GPR antenna for depth penetration and resolution.
After David *et al.* (2008).

- Recent Developments

GPR technology has developed at a rapid pace since 2001. Current and developing systems include multi-channel GPR arrays that use several antenna stacked together, sometimes collecting data at a variety of frequencies (Figure 7). These ‘multi-channel’ simultaneously acquire large amounts of densely (and rapidly) sampled data from various depths (Linford *et al.* 2010; Trinks *et al.* 2010; Novo *et al.* 2012).

Figure 7. Examples of GPR equipment.

Top Left: A single channel antenna GPR (human-propelled). Top Right and Bottom: Two single-frequency and multi-channel GPS-enabled GPR units (vehicle-propelled).

A number of recent case studies have used high-resolution GPR at internationally significant archaeological sites such as Silchester (Linford *et al.* 2010) and Stonehenge (Linford *et al.* 2011; Gaffney *et al.* 2012) in the UK, Evreux in France (Novo *et al.* 2012), Birka (Trinks *et al.* 2010) and Uppåkra (Biwall *et al.* 2011) in Sweden and Stubersheim Alb in Germany (Doneus *et al.* 2011).

- GPR Suitability

Although GPR is often perceived as a slow technique, the speed of survey is currently comparable to that of an earth resistance survey. Vehicle-powered multi-channel surveys collect several hectares worth of data acquisition in a single day under favourable conditions. This volume of data inevitably leads to very complex and large datasets, typically of the order of 1 GB of data per hectare, which can require a substantial amount of processing and interpretation time.

In the near future, as technology becomes less expensive, more productive and widely published, multi-channel GPR is likely to be used increasingly on commercially driven projects.

3. Review of Geophysical Survey Procurement

The success or otherwise of a geophysical survey is dependent on many factors. One of these is the manner in which a very large and narrow survey area is sampled. The average *road scheme* assessed via geophysical surveys in Ireland is 118 hectares in area and 18.4 km in length; the average *geophysical survey* covered 25 hectares per road scheme (approximately 21% of the road corridor). Thus, 'full coverage' has not been regularly achieved in the past, despite the fact that rapid sub-surface mapping is possible. Geophysical surveys commissioned between 2001-2010 (Figure 8), fall into one of three assessment types:

1) Area(s) of Archaeological Potential

2) Site or Monument Assessments

3) End-to-End coverage of road schemes

Area(s) of Archaeological Potential (Mitigation)

Accounting for the majority (46%) of the Legacy Data, an "Area of Archaeological Potential" (AAP) refers to a zone within a road corridor that has been subjected to site visits, walkover surveys, desk-top analysis and/or aerial photo surveys. The following criteria (O'Sullivan 2003) generally need to be met in order to qualify as an AAP:

a) presence or proximity of known or suspected archaeological monuments
b) presence or proximity of find-spots of archaeological objects
c) absence of scrub, soft ground, quarrying or other circumstances likely to significantly impede the proposed geophysical survey

Items a) & b) are archaeological criteria and c) directly addresses the suitability of ground conditions for geophysical prospection.

Each AAP survey relied upon a magnetic method of assessment in the first instance, 75% used a magnetometer (in either scanning or detailed mode) and the remainder was assessed via magnetic susceptibility. Non-magnetic archaeological features (stone structures, masonry and some in-filled ditches on certain geologies) cannot be identified if preference is given to magnetic methods of assessment.

On average, AAP account for 10% of the entire road corridor by area. AAP assessments range in size between 0.2 to 183 hectares spread along the length of the road corridor (an average of 10.3 hectares per road scheme). In the majority of cases, no further geophysical surveys were commissioned on a scheme after the AAP assessment occurred. Surveying 10% of a road corridor assesses only the 'known knowns' (*known* sites *etc.*) and the 'known unknowns' (*suspected* sites *etc.*). The remaining 90% of a road corridor is ignored - these are areas that represent the 'unknown unknowns' (*undiscovered* or unrecorded sites) which remain unidentified until intrusive test trenching occurs.

Site or Monument Assessments (Avoidance, Mitigation & Research)

Site or Monument Assessments account for 38% of the Legacy Data. These include known archaeological sites that appear on the Record of Monuments and Places as well as sites identified from test trenching or other investigations. The assessments tend to be reasonably small, ranging between 1 and 9 hectares spread along the length of the road corridor (averaging at 3.7 hectares per road scheme), reflecting a focused investigation of well-defined areas.

The assessment of known sites and monuments allows for the appropriate selection of a particular geophysical technique(s), because many of the variables are already known: geology, local soils, landscape, topography, ground conditions and most importantly, the type of archaeological features present.

Despite this, the Legacy Data indicates a large reliance upon magnetometer surveys (at the expense of all other techniques) and a lack of multiple technique assessments which would be more appropriate for many known archaeological sites.

End–to–End Coverage (General Prospection)

The assessment of road schemes from End-to-End (EEC) accounts for 16% of the Legacy Data. These surveys are used along the entire length of a road scheme via various methodologies (Table 6), but are often limited to a narrow 30% survey ribbon or swathe within the road corridor.

Narrow survey areas should be avoided as linear road schemes are themselves already quite narrow. A geophysical survey should occur over a minimum area of 40m x 40m, in order to visualise contrasts that might be indicative of archaeological deposits. English Heritage Guidelines on geophysical survey suggest that the maximum width of a road corridor (normally between 40m and 100m), should always be completely covered, rather than sampled (David *et al.* 2008).

Phase 1 Method of Assessment	Frequency
Magnetometer Scanning	21%
Recorded Magnetometer Scanning	17%
Detailed Magnetometer Survey (Sample Strip)	7%
Detailed Magnetometer Survey (Sample Strip flanked by 2 Magnetic Susceptibility transects)	14%
Detailed Magnetometer Survey	14%
Centreline Magnetic Susceptibility	7%
Detailed Magnetic Susceptibility	20%

Table 6. Methods of preliminary assessment for End-to-End coverage of road schemes.

The frequency at which the three assessment types were used (Figure 9) is uneven between the various National Road Design Offices (NRDOs) that are responsible for commissioning geophysical surveys. Some NRDOs have seen large amounts of road construction within their geographical remit (e.g. Tramore House, representing the SE), whilst others have had very little road construction (e.g. Donegal in the NW and Kerry in the SW). Road construction is a reflection of population and infrastructure demand, therefore these figures should not be used to assess the use of geophysics at each NRDO, but simply the variation between procuring different assessment types. The variations between NRDOs may be based on a) financial constraints; b) the needs of the archaeological project (e.g. mitigation, investigation, avoidance, research); c) experiential learning; and/or d) previous success/satisfaction with earlier geophysical surveys.

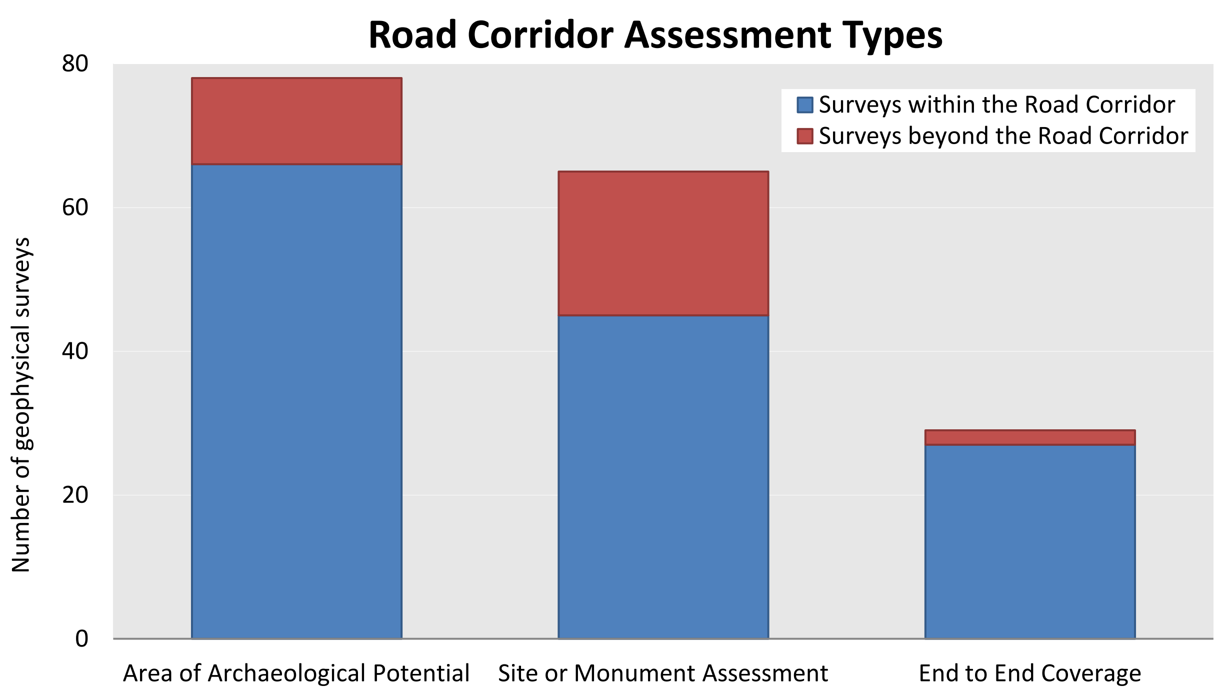


Figure 8. Road corridor assessments using geophysical surveys based on the 2001-2010 Legacy Data. Some geophysical surveys occurred beyond the road corridor, often to give a wider context to known archaeological remains.

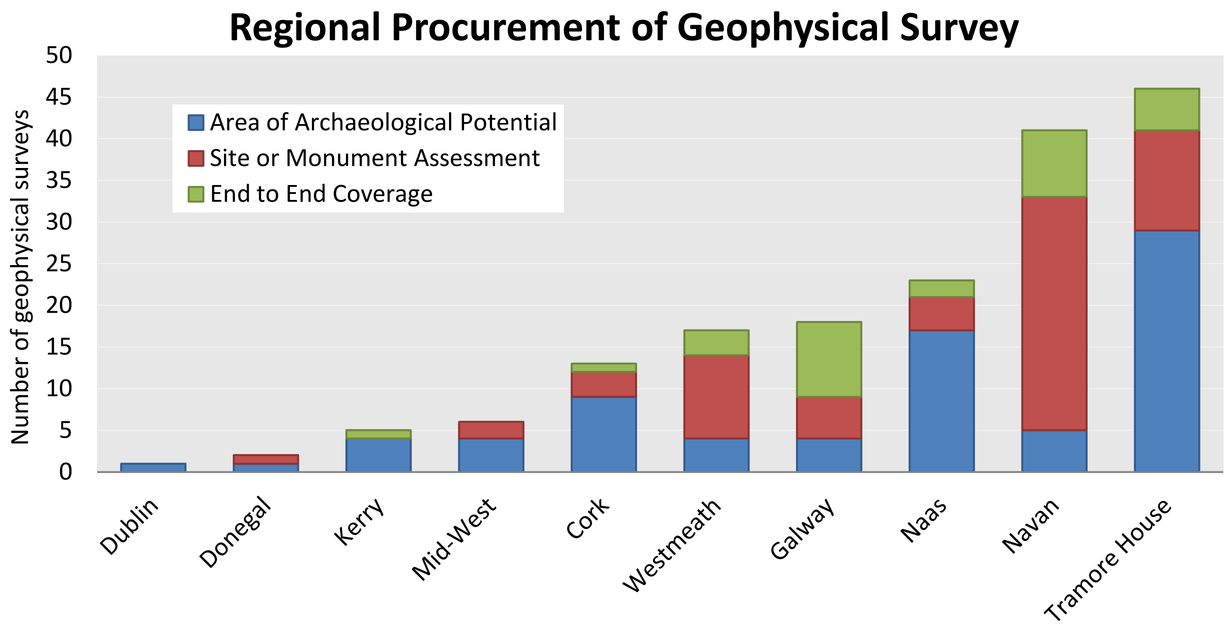


Figure 9. Regional procurement of geophysical surveys per National Road Design Office (NRDO).
Frequency of geophysical surveys mostly reflects the number of road schemes at a given NRDO. Exceptions include high instances of Site or Monument Assessments along the M3 Clonee-Kells Motorway (Navan NRDO) and Areas of Archaeological Potential on the N25 Waterford Bypass (Tramore House NRDO).

3.1 Lessons learnt from Historic Geophysical Survey Specifications

Advice issued by English Heritage (EH) guides curators through the specification process via a simple to use 'Choice of Geophysical Survey' key (David *et al.* 2008: Table 2, p13). The EH advice is cited by various NRA specifications as one of the key documents to which consultants should adhere to. It is apparent however, that this document was not used to its full extent in the past to select appropriate techniques for sites where archaeological features were known or suspected. 77% of available NRA specification documents for Area of Archaeological Potential (AAP) assessments required the exclusive use of a magnetometer survey.

The EH criteria were retrospectively applied by the Research Fellowship to 33% of the 'magnetometer only' AAP specifications (issued between 2003-2010); each of these historic surveys occurred upon sedimentary geologies and for 76 individual AAP locations spread across 7 road schemes[1]. The retrospective application of the EH criteria found that 14% of the AAP surveys inappropriately used

[1] N6 Galway–Ballinasloe, N6 Kilbeggan-Athlone, N17 Tuam-Claremorris, N21 Adare Bypass, N24 Pallasgreen-Cahir, N25 New Ross Bypass, N52 Carrickbridge-Clonfad.

magnetometer survey where other techniques should have been used (e.g. earth resistance / GPR / electromagnetic surveys for areas near to - or upon - the site of castles, tower houses, souterrains and ecclesiastical buildings). One site met the criteria for a GPR / caesium magnetometer survey in an area of deep alluvium.

AAP geophysical survey assessments are, ultimately, a relevance paradox. These assessments were historically carried out to determine the *minimum* amount of knowledge required for a short term goal: determining the presence/absence of archaeological features at *known/prospective* archaeological sites only, based on pre-existing knowledge/assumptions. In these cases, the benefits of commissioning a geophysical assessment beyond those areas of known (or suspected) archaeological features were not fully realised. A detailed analysis of five road schemes[2] found that 79% of *excavated* archaeological sites were both previously unrecorded and unidentified as AAP during the early stages of assessment. Consequently, the *majority of subsequently discovered archaeological sites were not investigated via geophysical survey prior to intrusive test trenching*. These included site types known to exhibit thermoremanent magnetism that were *likely* to have been identified by a detailed magnetometer assessment, e.g. burnt mounds of stone (Bermingham 2009a, 2009b) and kilns (O'Carroll and Petervary 2009). There were also archaeological sites that contained features that *might* have been identified via a magnetometer survey (and/or earth resistance surveys depending on geology, *etc.*) e.g. ring-ditches (Wilkins *et al.* 2007; Wilkins 2009), a ringfort (Conran and O'Carroll 2009) and areas of settlement (Seaver and Conran 2009). These suggest that whilst the identification of AAP at an early stage is useful, *the majority of archaeological sites lie in areas that are considered 'blank' or 'sterile'*.

[2] N6 Galway-East to Ballinasloe; N6 Athlone to Kinnegad; N25 Waterford Bypass; N52 Tullamore Bypass and N11 Gorey to Arklow.

4. Uncontrolled Variables

Geophysical surveys will always be affected by variables, some of which can be controlled and some which cannot. This section examines those that cannot be controlled, the most significant of these being geology and archaeological site types. Linear corridors that traverse large areas will inevitably encounter soils and monuments that provide unknown or uncontrollable factors. However, we can mitigate these variables by selecting the appropriate technique(s) for a given location or site.

4.1 Review of Geological Influences on Geophysical Surveys

It is likely that geology is the largest influence on the success or otherwise of a geophysical survey. The geology of Ireland is varied and often complex. An online data viewer (GSI 2012) can be very useful to determine the geology (both bedrock and surface) of a particular site or road scheme. A geological map (Figure 10) and a simplified description of geologies encountered in the Legacy Data (Figure 11) are provided to illustrate the following discussion.

General Advice on Geology

The range of bedrock and surface geology in Ireland presents some challenges to geophysical surveys. However, the Legacy Data has demonstrated that good results are achievable across many geological formations (Table 7). A discussion of the geological challenges (and relevant advice) can be found in the following pages.

In contrast to England, the chalk soils that offer ideal conditions for a magnetometer survey are absent in the Republic of Ireland which is dominated by Carboniferous limestone bedrock, frequent tills across the near surface and the third highest peat coverage in Europe. Some of the successful experiences on UK soils are not reflected in the NRA Legacy Data for Ireland. *The strategic response of surveys on these challenging Irish soils should not necessarily follow the English (or UK) model.* Similarly there is no reason to translate the following Irish recommendations to the UK or anywhere else.

Important Considerations:
It is clear that on some geologies, more than one technique is required to successfully identify archaeological sites.

However, it is also clear that a detailed magnetometer survey is suitable for the identification of a range of archaeological sites on a favourable geology.

When used upon a *favourable* geology, magnetometer surveys will rapidly acquire data and produce good results.

When used upon *unfavourable* geologies, a magnetometer survey may return, at worst, only geological anomalies, and at best, a lower frequency of monument recognition. In these cases, the use of another technique, such as electromagnetic, earth resistance or GPR should be used, either as a second complimentary survey or as an alternative to magnetometer survey.

A new generation of electromagnetic devices has also shown promise for use on a range of geological types, including those that are traditionally problematic for magnetometer surveys.

4.1.1 Bedrock Geology

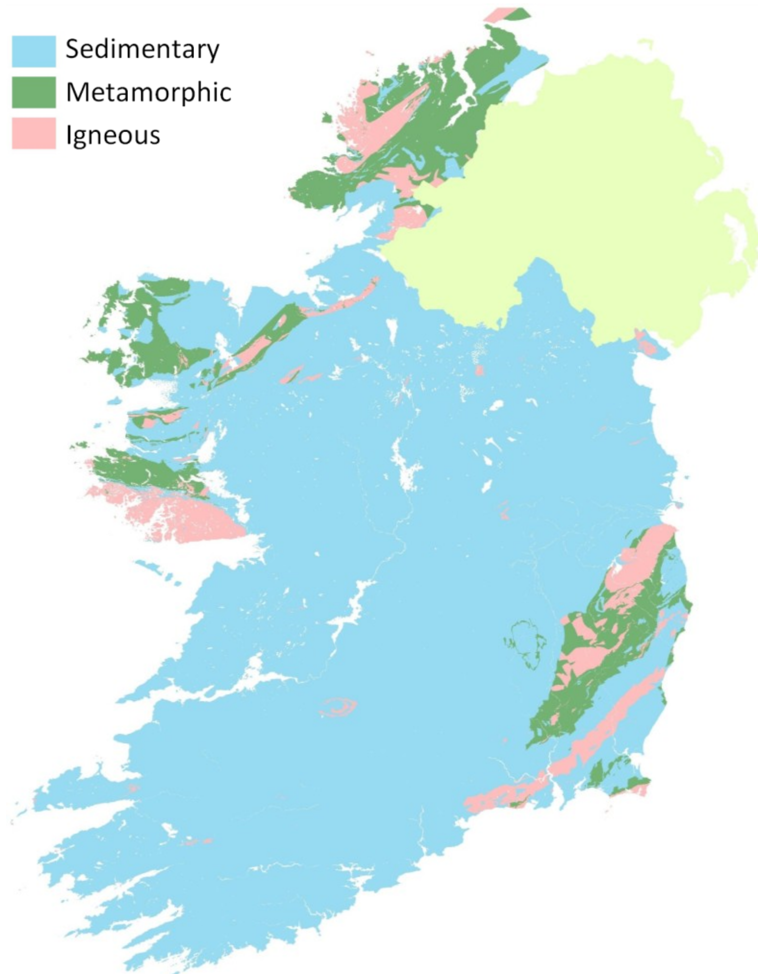


Figure 10. Basic geological formations in the Republic of Ireland.

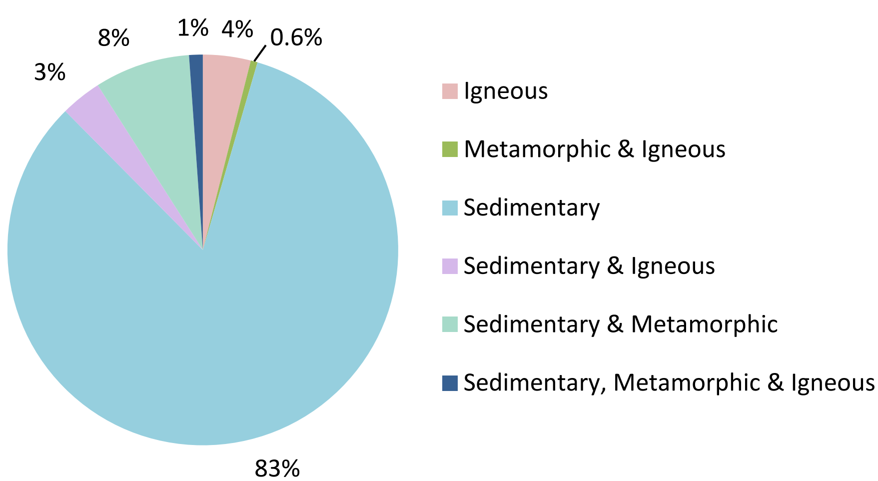


Figure 11. Basic geological rock types encountered in the 2001-2010 NRA Legacy Data.

	Magnetometer	***Resistance***	***Electromagnetic***
Poor	Granite Basalt Dolerite Gabbro		
Moderate to Poor	Greywacke Sandstone		
Moderate	Siltstone Rhyolite Limestone	Sandstone Siltstone	Granite Rhyolite Basalt Gabbro Dolerite
Moderate to Good	Mudstones	Siltstone	Siltstone
Good	Shale Slate	Slate Granite Rhyolite Limestone Shale Basalt Gabbro Dolerite	Slate Limestone Shale Sandstone

Table 7. Idealised performance of geophysical techniques upon principle Irish geologies.

The response to different geologies for a particular technique can be better or worse depending on the type and depth of the overlying surface geology, e.g. near surface basalts can be poor for a magnetometer, but may be improved if basalts are covered by a sufficiently deep layer of surface geology.

4.1.1.1 Igneous

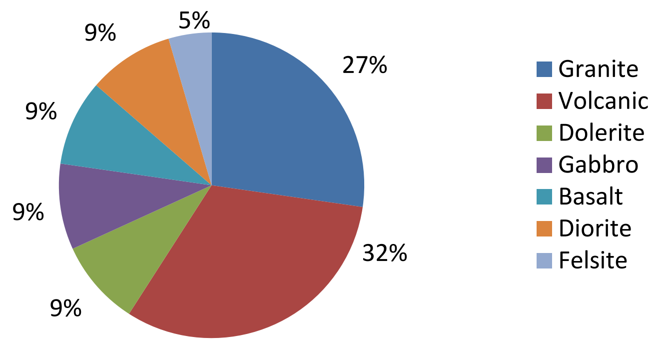


Figure 12. Igneous rocks encountered in the 2001-2010 NRA Legacy Data.

Advice for Archaeological Prospection on Igneous Geology

Areas with a *sufficiently deep layer of surface geology* (or overburden) above the igneous bedrock:

Use a magnetometer. The strong magnetic response of igneous bedrock is reduced by a sufficiently deep overlying surface geology, producing suitable data for archaeological prospection.

Areas of Near-Surface igneous geology:

Avoid the use of magnetometer survey. Areas of insufficiently deep/thick surface geology will respond poorly, producing unsuitable data for archaeological prospection.

Use an Electromagnetic survey in the first instance (to collect both in-phase and quadrature data). Pilot studies for this research have found that igneous geology does not significantly impact upon in-phase (magnetic susceptibility) data derived from modern low frequency electromagnetic devices. The influence of igneous geology (and igneous intrusions on Carboniferous limestone) was not apparent in these studies and useful archaeological information was gained.

Areas of variable depth to igneous geology (e.g. as might be expected along the length of a road corridor):

A preliminary geological geophysical assessment could use magnetometer scanning transects to identify areas unaffected by igneous geology, on the following basis:

a) Such a survey must be regarded as *SCANNING FOR GEOLOGICAL PURPOSES ONLY* and should not be used for the identification of archaeological zones or areas.
b) A geological scan could determine magnetically quiet soils within a road scheme that are suitable for subsequent archaeological assessment with detailed magnetometer surveys.
c) Gradiometers should be used rather than total field (caesium) instruments in order to assess the impact of geology, as small but significant variations in the local magnetic field can be observed easier when using a gradiometer.
d) Areas identified as unsuitable for magnetometer surveys could be investigated with electromagnetic, earth resistance or GPR surveys.

Igneous geology does not influence the quality of data collected using:

Earth resistance, electromagnetic quadrature (conductivity) or GPR surveys.

- Importance

Igneous geologies (Figure 12) are derived from volcanic activity which creates magnetically strong thermoremanent anomalies as a result of very high temperatures in the molten rock formation process. In some cases, thermoremanence can prevent the use of magnetometer surveys at certain locations, whilst at others there are no noticeable effects.

- Location

Igneous rocks are mostly found in Counties Wicklow, Wexford, Carlow, SW Co. Galway, central Co. Mayo and NW Co. Donegal. Intrusions of igneous dykes are often found in the sedimentary geology of Counties Louth and Monaghan. Glacial erratic rocks of igneous origin can, potentially, appear anywhere across the country.

- Previous work on NRA Road Schemes

4% of the 2001-2010 NRA geophysical surveys occurred over igneous geologies.

- Examples of work featured in the 2001-2010 archive

M1 Dundalk Western Bypass, N11 Arklow to Rathnew, N11 Gorey to Enniscorthy, N11 Gorey to Arklow, N9/N10 Kilcullen to Waterford, N30 Clonroche to Enniscorthy, N6 Galway City Outer Bypass, N22 Macroom to Ballyvourney.

- Issues that come from experience

The effect of igneous rock is often dictated by the thickness of the overlying surface geology. The suitability of magnetometer surveys (Figure 13) can sometimes be determined in advance if data from geological investigations are available.

Magnetometer data were severely impacted by strong geological anomalies from granites on the N11 Arklow to Rathnew and M11 Gorey to Enniscorthy schemes (Counties Wicklow & Wexford). Conversely, the impacts of occasional near surface granite outcrops were minimal on magnetometer and magnetic susceptibility investigations along the N30 Clonroche to Enniscorthy scheme (Co. Wexford).

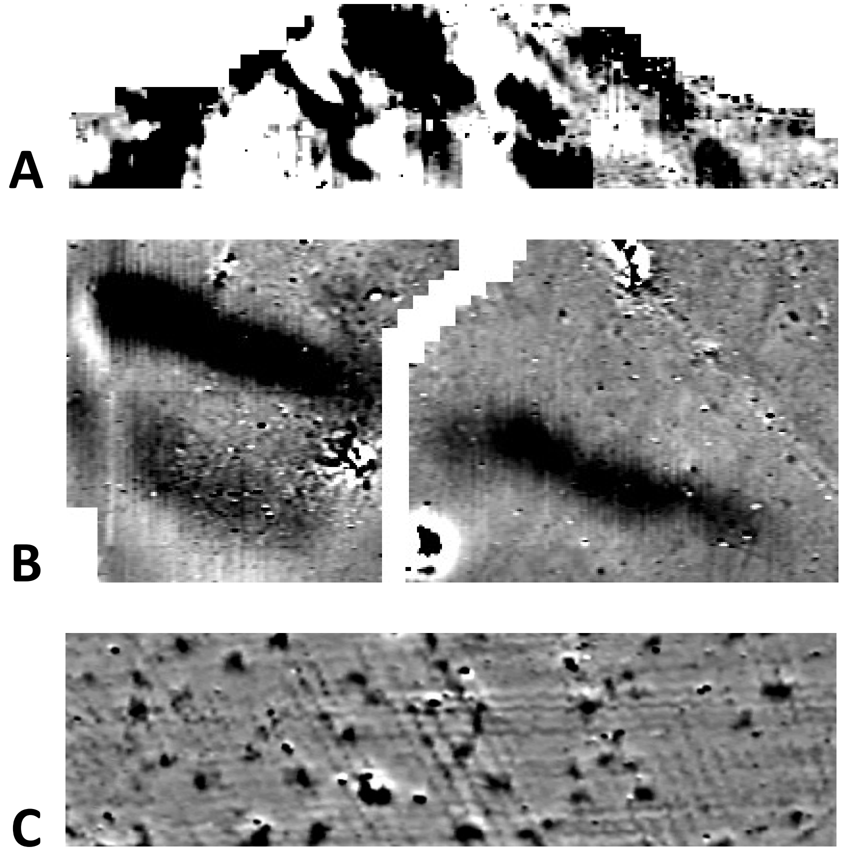


Figure 13. Common types of magnetometer responses derived from igneous rocks.

A: Near surface igneous geology can create a background of strong magnetic anomalies, such as this section of the M11 Gorey to Enniscorthy Scheme (Leigh 2011). Archaeological features are rarely visible under these conditions when using a magnetometer. White -2 nT; Black +3 nT; Plot: 40m x 170m; 1m x 0.25m.

B: Intrusions of igneous dykes appear as long linear thermoremanent anomalies, typically 15m - 20m in width and up to several hundred metres in length. A 7 nT to 40 nT igneous dyke can be seen running across the centre of a survey area on the N11 Gorey to Arklow Scheme (Bonsall and Gimson 2005). A shorter, 1 nT to 10 nT dyke, runs parallel and to the bottom left of the larger dyke. These strongly magnetic intrusive dykes mask the presence of weaker anomalies that might be archaeologically significant that typically range between 1 nT to 6 nT. White -10 nT; Black +10 nT; Plot: 90m x 200m; 1m x 0.125m.

C: Multiple glacial erratics derived from igneous material across the N6 Galway East to Ballinasloe Scheme (Roseveare and Roseveare 2004). Erratics appear as isolated thermoremanent anomalies which contrast strongly against the magnetically quiet Carboniferous limestone bedrock. These anomalies can easily be confused with other sources of thermoremanence that may have an archaeological origin such as hearths or strongly magnetic in-filled pits. White -3 nT; Black +3 nT; Plot: 40m x 140m; 1m x 0.15m.

Igneous dykes tend to be approximately 15-20m in width and can extend for several hundreds of metres. They are strongly magnetic and prevent magnetometer surveys from detecting weaker archaeological features within a narrow corridor. Igneous dyke intrusions limited the effectiveness of narrow corridor magnetometer surveys on the M1 Dundalk Western Bypass (Co. Louth) and the N2 Carrickmacross to Aclint Realignment (Co. Monaghan).

The location of glacial erratic rocks can sometimes be deduced if substantial boulders appear above the soil surface; however when they are buried, magnetometer surveys may identify them as thermoremanent anomalies. A wide area of erratic boulders can be identified fairly easily as randomly deposited anomalies across a survey area; however isolated rocks can easily be mistaken for other sources of the thermoremanence, such as hearths.

- Potential Future Advances

Detailed GPR assessments might be suitable for large, isolated and significant archaeological sites on igneous geology where costs are not prohibitive.

Large scale motorised-GPR surveys could become commercially viable in the next few years. At present speed and efficiency is limited to large area surveys rather than narrow corridors or small fields.

4.1.1.2 Metamorphic

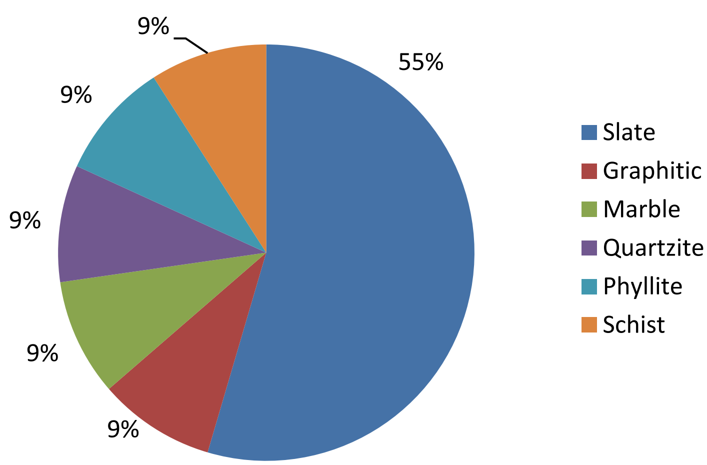


Figure 14. Metamorphic rocks encountered in the 2001-2010 NRA Legacy Data.

Advice for Archaeological Prospection on Metamorphic Geology

Magnetometer surveys:

Will benefit from a 0.5m traverse spacing, to increase the resolution of archaeological features and to help discriminate against geological trends.

Metamorphic geology does not influence the quality of data collected using:

Earth resistance, electromagnetic quadrature (conductivity) or GPR surveys.

- Importance

Metamorphic geologies (Figure 14) are formed by a major alteration of existing rocks due to high temperature and pressure. Metamorphic geologies can potentially create similar problems to igneous geologies, however it has been found that magnetometer surveys are largely unaffected by metamorphic rocks.

- Location

Metamorphic geologies are largely isolated and mostly located in Counties Wexford, Waterford, Wicklow, Donegal, NW Co. Mayo and NW Co. Galway.

- Previous work on NRA Road Schemes

None of the 2001-2010 NRA geophysical surveys occurred over exclusively metamorphic geologies; however 10% were surveyed over a mixture of metamorphic and igneous and/or sedimentary rocks.

- Examples of work featured in the 2001-2010 archive

N25 Waterford Bypass, N25 Waterford to Glenmore, N15 Lifford to Stranorlar, M50 Dublin Motorway, N2 Finglas to Ashbourne, N11 Arklow to Rathnew.

- Issues that come from experience

In general detailed magnetometer assessments on metamorphic rocks have been mostly effective. Magnetometer scanning was less useful, due to poor levels of discrimination between natural and archaeological responses.

- Potential Future Advances

The assessment of metamorphic geologies is generally quite satisfactory. Detailed GPR surveys could be used in those areas unsuitable for magnetometer assessments, however a variety of other techniques, see above, are already available.

4.1.1.3 Sedimentary

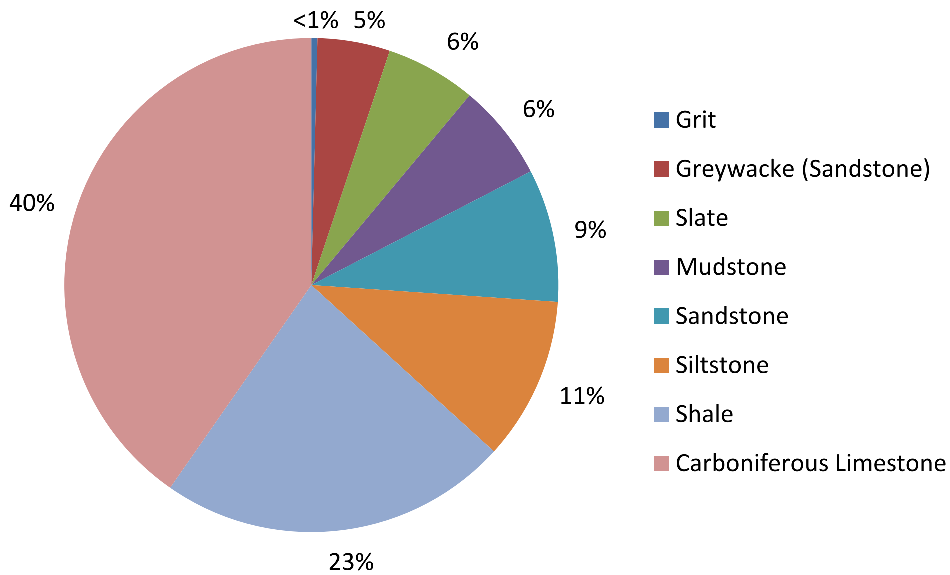


Figure 15. Sedimentary rocks encountered in the 2001-2010 NRA Legacy Data.

Advice for Archaeological Prospection on Sedimentary Geology

In the east of the country:

Particularly Counties Dublin, Meath, Kildare, Laois, Carlow and south Co. Louth:

Detailed magnetometer surveys at a spatial resolution of 1m x 0.25m are *generally* very good at identifying archaeological features.

Pilot studies carried out for the Research Fellowship have found that magnetometer surveys, (even in the areas above), *will benefit from a 0.5m traverse spacing* in order to visualize subtle archaeological responses and to help discriminate against geological trends.

In the west and southwest of Ireland:

Pilot studies should be carried out to determine a suitable technique and sample resolution.

These could include magnetometer, earth resistance or electromagnetic surveys.

If magnetometer surveys are required:

A traverse spacing of 0.5m is highly recommended.

Magnetometer surveys *may be less useful in areas of peats:*

Where the magnetism of both cut-earth and thermoremanent features have been weakened or suppressed by the contribution of waterlogging and organic matter (see discussions on peat, Section 4.1.2.1).

Sedimentary geology does not influence the quality of data collected using:

Earth resistance, electromagnetic (both conductivity & magnetic susceptibility) or GPR surveys.

- Importance

Sedimentary rocks (Figure 15) are the most frequent rock type in Ireland. The rocks have a low magnetic contrast that provides a reasonably low and uniform background for the identification of magnetic anomalies; however this has both advantages and disadvantages for archaeological prospection.

Carboniferous limestone was the most frequent rock type and the only type of limestone encountered in the Legacy Data. Magnetometer surveys in the UK and Europe often benefit from the prevalence of chalk limestone which provides one of the best backgrounds for identifying archaeological features (Payne 1996; Knight *et al.* 2007; Linford *et al.* 2007). In Ireland, chalk is only found at three locations (all around the townland of Ballydeenlea, Farranfore, Co. Kerry, amounting to no more than 9 hectares in area) and in the north east of Northern Ireland. Studies in the Trent Valley, UK (Knight *et al.* 2007), found that ground-observed geophysical surveys on Carboniferous limestone were approximately 70% less successful than those on chalk.

- Location

Sedimentary rocks dominate Ireland and are essentially located over the entire country (Figure 10), with exceptions in the NW and SE. Igneous intrusions (dykes) and glacial erratics are also commonly found within or upon otherwise sedimentary rocks.

- Previous work on NRA Road Schemes

The vast majority of the 2001-2010 NRA geophysical surveys occurred on sedimentary rock. Most (83%) were carried out over exclusively sedimentary rock, mixtures of sedimentary with igneous (3%) and/or metamorphic rocks (9%). 40% of the geophysical surveys on sedimentary rock occurred on Carboniferous limestone, a rock type that accounts for 50% of the Republic of Ireland's geology.

- Examples of work featured in the 2001-2010 archive

Some examples include: M3 Clonee to North of Kells, N2 Slane Bypass, N6 Galway to East Ballinasloe, N52 Tullamore Bypass, N17 Tuam Bypass, N8 Fermoy to Mitchelstown, N22 Tralee Bypass.

- Issues that come from experience

Sedimentary geology has been problematic for magnetometer scanning; 71% of sites excavated by the NRA on this geology were not identified, including sites that contained substantial enclosure features. This reflects problems both with the scanning method (biased towards large archaeological features) and the often low contrast between archaeological features and the background soils.

Detailed magnetometer assessments vary in success on sedimentary rocks. In general, sedimentary geology is suitable for detailed magnetometer surveys across most of the country, although there are some exceptions:

- Shales return particularly good responses and some of the clearest data have been returned on the Carboniferous limestone and shales in the vicinity of the M3 Clonee-North of Kells scheme.

- Some Carboniferous limestones (in the west of Ireland and Co. Kerry), can respond less well when covered by peats or waterlogged soils. These issues can be overcome by implementing pilot studies (to test one or two techniques and spatial resolution), to determine an appropriate strategy.

- Some CUT-EARTH FEATURES can respond quite poorly to a magnetometer survey, creating either a very weak magnetic contrast or no contrast at all (Figure 16). In some cases, there are broad indications of archaeological sites, but poor definition of individual anomalies. The overlying surface geology (see Section 4.1.2 Surface Geology) is an important influence on the outcome of surveys on sedimentary geology. In particular the presence of peat or tills can reduce the effectiveness of a magnetometer survey for the detection of cut-earth features.

- BURNT FEATURES normally respond very well to magnetometer surveys on sedimentary rocks, contrasting strongly with the background soils. However, some of these can be small (<1m), and are often overlooked when interpreting large linear corridors in favour of more substantial anomalies.

- Sandstone can return some particularly poor responses for magnetometer surveys of cut-earth features. The N8 Fermoy to Mitchelstown Scheme, Co. Cork, returned a very low success rate for the identification of archaeological sites. The same scheme had a high rate of false negatives in the magnetometer data, where misleading natural trends were interpreted as archaeological features.

- Potential Future Advances

In general, the use of magnetometer, electromagnetic and earth resistance surveys where required, will provide adequate assessments of sedimentary geologies. Large scale motorised-GPR surveys could become commercially viable for archaeological purposes in the next few years which will increase the speed of collecting high-resolution data.

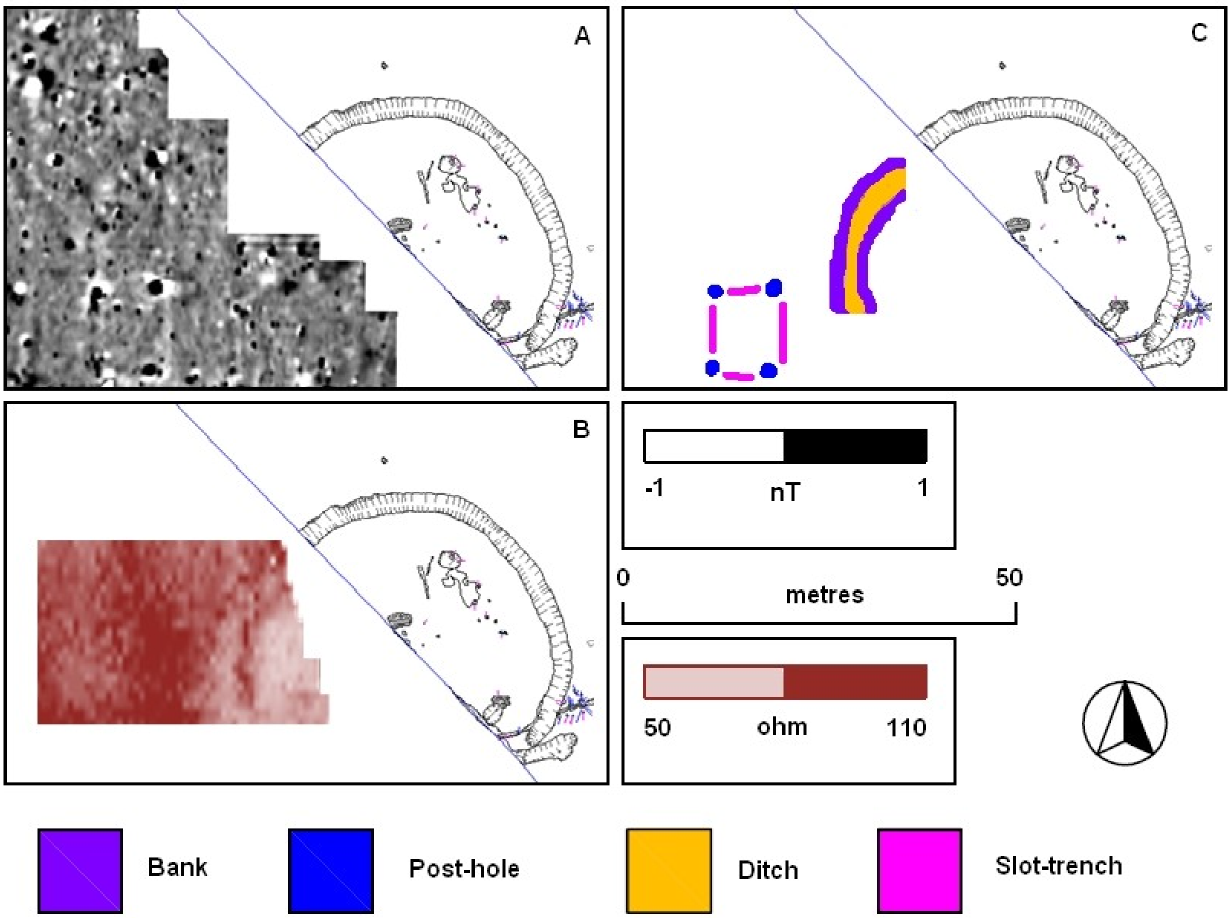


Figure 16. Limitations of magnetometer surveys on Carboniferous limestone.
The ringfort enclosure at Magheraboy on the N4 Sligo Inner Relief Road (Danaher 2007) illustrates some of the problems encountered on Carboniferous limestone geology and the benefit of using multiple methods to identify archaeological features.

A: A pilot survey carried out by the Research Fellowship used high-resolution (0.5m x 0.1m) cart-mounted magnetometers. There were no indications of the known substantial medieval ringfort enclosure ditch (2.7m width 1-1.5m depth) in the magnetometer data due to an absence of measurable contrasts between the ditch fill and the bedrock.

B: A low resolution earth resistance survey (1m x 1m) carried out at the time of the original road scheme excavation (Bonsall and Gimson 2003b), clearly identified a portion of the ringfort ditch.

C: The post-pits and stone-packed slot trenches of a previously unrecorded Neolithic structure were clearly interpreted from the magnetometer data, just a few metres from the ringfort.

4.1.2 Surface Geology

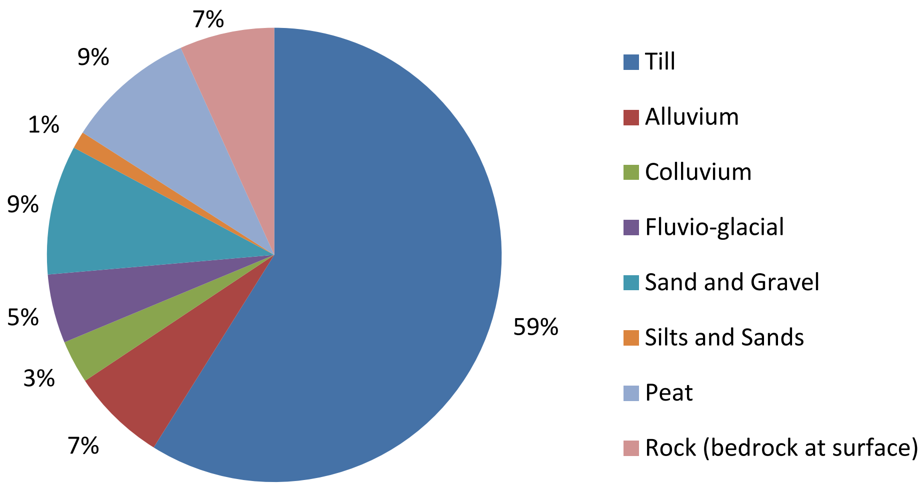


Figure 17. Surface geology encountered in the 2001-2010 NRA Legacy Data.

4.1.2.1 Peat

Advice for surveying Known Sites on Peat

Trackways:

Prospection at *known/suspected* trackway sites:

Induced Polarisation was used successfully by the Fellowship to detect a *known wooden trackway* and trace it for several metres at Edercloon (see Potential Future Advances, below, and Appendix B).

GPR surveys have detected *known wooden trackways* in waterlogged peat at the Sweet Track on the Somerset Levels, UK (Armstrong 2010), although mixed results were reported due to changeable hydrology.

GPR and ERT surveys have been successfully used over a *known paved or causewayed* trackway at Leamonaghan, Co. Offaly (Gibson 2012).

General prospection for an *unrecorded* trackway (or over sites of unknown potential) is problematic:

The potential for using Induced Polarisation, GPR and/or ERT over *entire road schemes* is at present limited.

Pre-bog field walls:

At Slievemore on Achill Island, Co. Mayo, the Fellowship (Bonsall *et al.* 2012c) identified pre-bog field-walls via:

Earth resistance survey (using a Wenner array).

Electromagnetic quadrature and in-phase (conductivity and magnetic susceptibility) survey.

Advice for Archaeological Prospection on Peat

Where peat depth is known:
Specific techniques can be selected (Table 16) and targeted as required if intrusive investigations have revealed an indication of soil profiles, depth and archaeological feature type. This requires prior knowledge that might be gained from geological investigations along a road corridor.

Where peat depth is unknown:
Auger surveys should be used to obtain meaningful interpretations. Archaeological prospection strategies often require an element of testing or trialling of a particular technique(s) or method(s) as part of a pilot study before committing to a larger geophysical survey. This is preferable especially when evaluating a particularly large area, or in regions of irregular geologies/soils, where prior knowledge of the expected responses is poor.

Augering
Prior to geophysical assessment
Is a simple and efficient means of assessing an area.
Determines the depth of soil horizons & bedrock.
Soil samples can be analysed e.g. mass specific magnetic susceptibility.
Can be used to inform subsequent geophysical surveys.

In conjunction with geophysical assessment
Has long been used as part of a wider strategy of assessment in Europe.
In the Netherlands, where field conditions permit it, augering is always used to supplement geophysics.
Aids the interpretation of specific geophysical anomalies.

Methodologies similar to those established to study Dutch Holocene deposits (Simpson *et al.* 2009; Orbons 2011) could be applied equally to Ireland; EM surveys could be used to identify gravel ridges within peatland, which are subsequently checked by geophysicists via core-augering. The auger survey determines their depth below ground and the palaeo-height-differences. This assessment method is not designed to identify discrete archaeological features such as enclosure ditches or hearths, but to identify archaeologically prospective areas where further assessment e.g. intrusive testing, may be required at an early stage.

- Importance

Peatlands cover 11,392 km^2 of Ireland, approximately 16.5% of the country, the third highest occurrence in Europe, after Finland and Estonia (Montanarella *et al.* 2006). The prevalence of peat in Ireland is a serious issue for the geophysical surveyor and its frequent occurrence will impact the outcome of geophysical surveys much more than most European countries.

Peatlands are a highly valued resource for archaeologists as they are capable of preserving a wide range of organic objects. The location of high-profile archaeological finds such as bog butter, psalters and bog bodies cannot be detected by archaeological geophysical surveys. However, structural features comprised of organic materials, such as wooden trackways and crannogs, can potentially be mapped by geophysical techniques, as can pre-bog/peat elements such as field walls and burnt mounds of stone.

- Location

Peat coverage by county is highest in Counties Mayo, Donegal and Galway, followed by Sligo, Kerry and Wicklow (Hammond 1981; Conaghan *et al.* 2000).

- Previous work on NRA Road Schemes

9% of the 2001-2010 NRA geophysical surveys occurred on peat, with the majority in Co. Galway.

- Examples of work featured in the 2001-2010 archive

N18 Ennis Bypass, N6 Ballinasloe to Athlone, N6 Galway to East Ballinasloe, N6 Galway City Outer Bypass, N6 Loughrea Bypass, N4 McNeads Bridge to Kinnegad, N4 The Downs, N17 Galway to Tuam.

- Issues that come from experience

Peat, like all soils, is an ever changing media. Variations in the physical and chemical properties of peat have a strong influence on geophysical assessments even in the short term, such that some anomalies representing archaeological deposits may appear or disappear from year to year.

Magnetometer and magnetic susceptibility surveys on NRA road schemes have been of limited use on peatland. These observations are consistent with the latest research in the use of geophysical surveys on peat and waterlogged sediments (Weston 2004; Armstrong 2010). Magnetic susceptibility surveys from different schemes have produced a useful archive of data: along almost 80km of linear road corridors in the west of Ireland, 11.8% of the MS data values were negative, a strong indicator of wet and/or organic material.

Waterlogging can impede and/or prevent magnetic susceptibility enhancement. This effect was observed in a 5m x 5m magnetic susceptibility assessment of peaty soils on the N4 McNeads Bridge scheme (Co. Westmeath), where no significant anomalies were identified over burnt mounds of stone (Hayes 2005), features known to exhibit a strong magnetic susceptibility (Hunter and Dockrill 1990; Slater *et al.* 1996). While this may seem counterintuitive, it has been reported that in waterlogged environments soils that are *heated* rather than *burnt*, actually suppress the magnetic susceptibility of a soil (Weston 2004), hence heating need not always lead to enhancement, or as much enhancement as one might expect.

Recent research (Armstrong 2010) has suggested that large structural elements, such as trackways, can themselves influence hydrology within the peat, acting as a proxy to alter the mineral composition, the contrasts of which can be detected by geophysical methods.

- Potential Future Advances

Induced Polarisation (IP) exploits the polarisable properties of wood that make it contrast against the surrounding peat material. Schleifer *et al.* (2002) demonstrated that spectral Induced Polarisation is capable of identifying wooden planks in a waterlogged environment, however spectral IP is not widely available. Fieldwork carried out for the Research Fellowship (Bonsall *et al.* 2013b) demonstrated that Time-domain IP was also capable of identifying wooden trackways in the peat and bogs at Edercloon on the N4 Dromod to Roosky scheme (see Appendix B). The survey was able to map the extent of the trackways and trace them beyond the road scheme. Time-domain IP will be particularly useful for the mapping of trackway extent and direction, in cases where a trackway(s) has been identified; however it is felt that the method is not suited for use as a 'blind' prospection technique in areas of unknown archaeological potential.

4.1.2.2 Alluvium / Colluvium

Advice for Archaeological Prospection on Alluvium & Colluvium

Alluvium:
Complimentary augering surveys are especially useful for estimating the depth of alluvial cover prior to geophysical survey technique selection (Weston 2001) and could be used to determine an appropriate survey technique.

Best practice suggests that a pilot study should be undertaken in areas of alluvium in order to determine an appropriate survey methodology.

Pilot studies at the 4 hectare Bronze Age and Medieval site of Moneytucker (N30 Clonroche to Enniscorthy scheme, Co. Wexford), assessed four 0.16 hectare areas with high resolution magnetometer and earth resistance surveys to develop a suitable methodology for the remaining area of the site. Multi-method magnetometer, magnetic susceptibility and earth resistance surveys at high resolution enhanced the visualisation of archaeological features compared to standard resolution surveys (Bonsall and Gimson 2007) and similar strategies could be considered.

<u>Use of magnetometer surveys:</u>
Gradiometers can respond very poorly to alluviated soils.
Total field magnetometers can respond better than fluxgate instruments.
A 0.5m traverse spacing is highly recommended for magnetometer surveys of alluvial environments.
Magnetometers should not be relied upon as the sole method of investigation

Colluvium:
Magnetometer surveys over colluvium have been improved by resurveying areas after the mechanical removal of the plough soil (Lyall and Powlesland 1996). This approach might be useful for the assessment of small isolated patches of colluvium that occur on or near significant archaeological sites; however it is not a logistically viable method for archaeological prospection along a linear corridor and assumes the presence of widespread archaeological deposits.

- Importance

Whilst the deposition of alluvial (river deposits) and colluvial (deposits at the base of slopes) sediments is quite different, their affect upon magnetometer surveys are similar and they are discussed together. The deposition of these sediments can reduce the expected geophysical response of an archaeological feature.

- Location

The long and linear nature of road schemes means that alluvial and/or colluvial sediments will be traversed regularly by the route of a corridor. River and hilltop environments are both favourable for a number of archaeological monument types, therefore it is important to assess these sediments appropriately. This may require particular alterations to a methodology to account for alluvial/colluvial locations.

- Previous work on NRA Road Schemes

7% of the 2001-2010 NRA geophysical surveys occurred on alluvium and 3% on colluvium.

- Examples of work featured in the 2001-2010 archive

Alluvium: Moneytucker (N30 Clonroche to Enniscorthy), Bealick (N22 Oven to Ballyvourney), Woodstown (N25 Waterford Bypass).

Colluvium: N11 Gorey to Enniscorthy, Bustyhill (N7 Rathcoole to Kildare County Boundary), N25 New Ross Bypass, N15 Lifford to Stranorlar.

- Issues that come from experience

Alluvium can create a low magnetic background for magnetometer surveys, however this is deceptive as alluvial soils strongly affect the ability to detect archaeological features due to an increased distance between the target and the sensor. Alluvial cover can mask responses, misrepresent the extent of archaeological features and create anomalies or trends that are often misinterpreted as archaeological (Weston 2001).

On a positive note, magnetometer surveys are particularly good at identifying palaeochannels (e.g. on the N15 Lifford to Stranorlar, Co. Donegal; N22 Macroom to Ballyvourney Bypass, Co. Cork). Palaeochannels are often associated with prehistoric archaeological sites and are important features that help understand the wider palaeolandscape.

- Potential Future Advances

Research in the UK has suggested that cart-mounted total field caesium magnetometers (non-gradiometric) could be useful for identifying features buried beneath alluvium (Linford *et al.* 2007).

A new generation of low frequency electromagnetic devices have shown promise for the study of archaeological features buried beneath alluvium (Simpson *et al.* 2009). However they have yet to conclusively demonstrate an ability to identify the range of material and at a depth such as might be expected under alluvium and colluvium in Ireland.

The use of GPR could also be useful at alluvial / colluvial sites. GPR can estimate the depth of alluvial cover, which may assist the planning of intrusive investigations (Carey *et al.* 2006).

Earth resistance surveys can face similar problems to magnetometer surveys depending on the thickness of the alluvium / colluvium; the use of wider probe spacings for Twin-probe or Wenner arrays may be required in order to assess deeper sediments, but at a loss in feature resolution.

4.1.2.3 Surface or Near Surface Geology

Advice for Archaeological Prospection on Surface or Near-surface rock

Aerial photography and mapping can be used to help identify areas of outcropping or near-surface bedrock prior to the use of geophysical surveys.

Areas of exposed Carboniferous limestone paving should be excluded from geophysical surveys:

No buried archaeological features will be apparent.

Use of geophysics may be required over gradually increasing soil horizons.

- Importance

A geophysical survey is of limited use on patches of thin soils (although a magnetometer could be used to identify areas of surface burning). Depending on the type of bedrock (as discussed above), these outcroppings can influence geophysical data.

- Location

The nature of road schemes means that they will traverse areas of near-surface or outcropping geology with exposed bedrock features. Rock outcropping can occur anywhere in the country. In a few areas of Ireland a distinctive Carboniferous limestone karstic landscape has developed where soil cover is thin or non-existent such as Co. Clare (e.g. the Burren) and parts of Counties Cavan, Galway, Sligo and Leitrim.

- Previous work on NRA Road Schemes

7% of the 2001-2010 NRA geophysical surveys occurred in areas of near surface bedrock or outcropping. Most of these were along road schemes where outcropping was frequent or where Carboniferous limestone paving was occasionally encountered (mostly, but not exclusively, in Co. Galway).

- Examples of work featured in the 2001-2010 archive

N6 Galway City Outer Bypass, N28 Bloomfield to Ringaskiddy, N2 Slane Bypass, N25 Waterford to Glenmore, N11 Arklow to Rathnew.

- Issues that come from experience

Outcrops within a road scheme act as obstacles that can reduce the survey area of a geophysical assessment.

Depending on the rock type (see 4.1.1 Bedrock Geology), magnetometer surveys may identify high contrast geological anomalies (e.g. igneous) that make archaeological features difficult or impossible to identify, whilst resistance surveys will map very high resistance anomalies near outcrops, again, reducing the measurable contrast of archaeological features.

4.1.2.4 Tills (Boulder Clay)

Advice for Archaeological Prospection on Tills (Boulder Clays)

Magnetometer surveys:

Detailed magnetometer surveys ***should always*** be the preferred option.

The use of 0.5m traverse separations will increase the chances of successfully identifying archaeological features for detailed magnetometer surveys.

Unrecorded magnetometer scanning surveys ***should not*** occur on tills.

GPR surveys:

GPR surveys are often affected by signal attenuation when used on clays, essentially failing to obtain a good response from the underlying archaeological features and therefore should be trialled prior to large surveys.

Tills do not generally affect the quality of data collected using:

Earth resistance and electromagnetic (both conductivity & magnetic susceptibility) surveys.

- Importance

Tills are very important due to their frequent occurrence across the country; the majority of Irish soils are tills. Experience from England showed that tills (boulder clays) gave a generally poor response to a magnetometer survey (Knight *et al.* 2007; David *et al.* 2008). It is very important to develop the use of multi-method assessments in Ireland on these soils, rather than rely on a single (magnetometer) method.

- Location

Tills account for the majority of soil types across the country and can be found in almost every part of Ireland.

- Previous work on NRA Road Schemes

The overwhelming majority (59%) of the 2001-2010 NRA geophysical surveys occurred on tills or boulder clays, mostly in Counties Meath and Kilkenny (reflecting the high number of assessments on the M3 and M9/M10 motorways), followed by Counties Laois, Cork, Kildare, Waterford and Westmeath.

- Examples of work featured in the 2001-2010 archive

N9/N10 Carlow Outer Relief Road, M20 Cork to Limerick, N77 Ballynaslee Realignment, M7 Portlaoise to Castletown, M3 Clonee to North of Kells, M9/M10 Kilcullen to Waterford, N2 Carrickmacross to Aclint, N4 Sligo Inner Relief Road.

- Issues that come from experience

The success rate upon tills has been variable. The majority of unrecorded magnetometer scanning surveys were undertaken on tills and this, combined with the influence of sedimentary geology, explain why the technique has failed to identify some large and significant archaeological features in the past.

Detailed magnetometer surveys in Counties Meath and Kilkenny have been reasonable for the recognition of large ditched enclosure sites, but not particularly good for internal features or small and discrete elements.

- Potential Future Advances

Signal attenuation in clay is currently a significant issue preventing the widespread use of GPR on such soils. Multi-sensor / multi-depth EM surveys may offer a better outlook.

4.1.2.5 Fluvio-glacial / Glacial Sand and Gravel

Advice for Archaeological Prospection on Fluvio-glacial Sand and Gravel

Magnetometer surveys:

The use of 0.5m traverse separations will increase the chances of successfully identifying archaeological features for detailed magnetometer surveys.

A magnetometer should not be relied upon to 'guide' the location of other surveys. In general, a multi-method approach (using magnetometers and at least one other instrument), will be best.

Glacial sand and gravel does not generally affect the quality of data collected using:

Electromagnetic in-phase (magnetic susceptibility) and GPR surveys; an increase in their use should be considered.

- Importance

Glacial action has introduced sand and gravel across the landscape as well as deposits of 'exotic' boulders that may be significantly different from the bedrock. The depth of glacial deposits can vary greatly, which can both improve a successful magnetometer survey (e.g. thick glacial material overlying igneous geology) or impede it (e.g. reducing the contrast of sedimentary geology).

- Location

Glaciation affected large swathes of Ireland during the retreat of the last Ice Age. The west and southwest of Ireland were particularly affected, although examples can be seen nationwide.

- Previous work on NRA Road Schemes

9% of the 2001-2010 NRA geophysical surveys occurred on fluvio-glacial or glacial sand and gravels, mostly in County Galway.

- Examples of work featured in the 2001-2010 archive

M9/M10 Carlow Outer Relief Road, N6 Galway to East Ballinalsoe, N17 Tuam to Claremorris.

- Issues that come from experience

The responses have been variable across the country but are generally favourable.

Gravel eskers can produce a variable background in magnetometer data that may obscure subtle features.

A significant issue on the N52 Tullamore to Kilbeggan scheme were the frequent appearances of natural trends that *resemble* the characteristics of circular ring-ditch enclosure-type and pit-type anomalies. On the other hand, some *actual* archaeological features could be equally dismissed as natural variations. Long sections of linear ditches and modern drains are often easily identified by magnetometer surveys within these conditions.

- Potential Future Advances

GPR surveys could be used more frequently in future archaeological geophysical assessments on road corridors, although generally other techniques are already available that work satisfactorily. Pilot schemes that include elements of magnetometer and EM surveys may be useful before committing or relying upon one method of survey.

4.2 The Identification of Archaeological Features in Geophysical Data

The ease at which an archaeological feature can be identified is *generally* proportional to its size, which increases the contrast with the background. Large features such as enclosure ditches, can be identified relatively easy from detailed geophysical surveys, whereas small-scale features, such as post-holes and inhumations can be difficult to identify. The importance of spatial resolution in regards to detecting archaeological features is discussed in Section 5.2.4.

Archaeological features vary in shape, size, magnetism, resistivity, conductivity and magnetic susceptibility. The geophysical properties of an archaeological feature (Table 8) are largely dictated by the creation of the feature, whether it cuts the earth (and has been backfilled), has been burnt or is constructed from stone or brick. The feature must contrast with the background in some way that can be measured in order to be identified as anomalous.

Thermoremanent Features (Burnt Deposits)	**Cut and In-Filled Features (Ditches/Pits)**	**Structural Features (Wall-footings/Stone)**
Magnetometer	Magnetometer	Earth Resistance
Electromagnetic	Electromagnetic	Electromagnetic
Magnetic Susceptibility	Earth Resistance	GPR
	GPR	

Table 8. Geophysical techniques used to identify common types of archaeological features.

Appropriate use of Geophysical Techniques by Period

Geophysical prospection techniques cannot be used to date anomalies but there are some general conclusions that can be drawn by period McCarthy (2010) assessed almost 2,300 sites excavated between 2002-2009 on NRA road schemes, based on data obtained from the NRA Archaeological Database (NRA 2012). The frequency of periods represented were the Bronze Age (35%), medieval (10%), post-medieval (8%), Iron Age (8%), Neolithic (7%), early modern (7%), Early Medieval (6%) and Mesolithic (1%). These results are encouraging as the majority of periods feature monument types that are readily identifiable from geophysical data.

Mesolithic features are likely to be represented by hearths and stake-hole type structures. Hearths can be identified by magnetometer surveys. Stake-hole features are not likely to be identified by even the highest resolution geophysical surveys.

Features from the ***Neolithic***, mostly represented by small and narrow timber structures, palisades, post-pits and post-holes, tend to be small in scale compared to features from subsequent periods. These can be challenging to identify in magnetometer data as they are often rapidly backfilled (creating poor- or low-contrast features) and are too narrow to identify by standard earth resistance survey. Burnt soils or deposits can be identified by a magnetometer, whilst surrounding structures or enclosures may not. Post-pits and post-holes require a high resolution assessment; generally, they cannot be identified in general prospection surveys, however weak trends can be interpreted if complimentary *a priori* knowledge is available (e.g. the size or trajectory of a feature). Stone cairns, megaliths, tombs and pre-bog field walls should be assessed by earth resistance, EM conductivity or GPR surveys.

The majority of features associated with the ***Bronze Age***, ***Iron Age*** and the ***Early Medieval*** periods (enclosure complexes, ring-ditches, occupation activity, burnt mounds of stone, industrial furnaces / kilns) tend to respond well to detailed magnetometer surveys on favourable geology. As discussed above, timber structures dating from these periods can be difficult to identify.

The ***medieval*** sites often comprise stone built structures that do not respond well to magnetometer surveys and require assessment via earth resistance, EM conductivity or GPR surveys. Ditched enclosures, ring-ditches, burnt and industrial features tend to respond well to magnetometer surveys on favourable geology.

The ***post-medieval*** period, in addition to already mentioned feature types, introduced further industrial deposits that can be identified by magnetometer surveys. Walls made of brick (a fired material), are strongly magnetic and can be identified in magnetometer data; brick walls are also visible in earth resistance, EM conductivity or GPR survey data.

The ***early modern*** period frequently encounters ferrous materials that create strong contrasts upon a magnetometer survey, often at the expense or earlier features that are likely to be of a comparatively lower magnetic contrast. Alternative techniques, earth resistance, EM conductivity or GPR surveys, may be required.

4.2.1 Appropriate use of Geophysical Techniques by Monument Type

It is rarely acceptable to place dates on to geophysical interpretations. Geophysics can, in some instances, interpret archaeological *features* by period, based on the morphology of the anomaly and known monument typology, the presence/absence of ferrous material and knowledge from other investigation methods (see for example Johnston *et al.* 2009). In general however, 'a ditch is a ditch', and monuments can only be interpreted in those terms. A linear ditch crossing a narrow road corridor could represent a Neolithic territorial boundary or a post-medieval field division. Similarly, a thermoremanent anomaly will be created from both a recent bonfire and a Mesolithic hearth. A modern cattle burial may create the same anomaly as a large Neolithic pit *etc.*. Ferrous materials are equally ambiguous; a Viking sword in a burial cut will create a similar anomaly as a modern crowbar. Nevertheless, the identification of a range of site types is possible.

4.2.1.1 Thermoremanent (Burnt) Features

McCarthy (2010) assessed the NRA Archaeological Database and recorded categories for different site types (Table 10) and their frequency of excavation. 73% of McCarthy's site type categories include features that a geophysicist would potentially describe as thermoremanent *viz.* features that contain burnt deposits that can be clearly identified by detailed magnetometer surveys on most Irish soils. The site type categories used by McCarthy are *archaeological* and did not envisage a *geophysical* comparison (e.g. the category for 'isolated pits or hearths', would, from a geophysical perspective only count 'hearths' as a thermoremanent feature). Sampling strategies that do not cover the full extent of a road corridor will not identify many of these thermoremanent features as they are often small and isolated.

The most frequently excavated sites on NRA Road Schemes were **fulachta fiadh*/burnt mounds of stone*** and ***burnt spreads*** (accounting for 35% of all excavated site types). *Burnt* mounds of stone can be easily identified by detailed magnetometer and EM magnetic susceptibility surveys (enhanced magnetic properties due to burning). Mounds may not be identified by a magnetometer if the stones were only *heated* rather than *burnt*. However a mound of *stones* (either burnt or not) will respond well to earth resistance and EM conductivity surveys. *Burnt* spreads of typically thin material are less likely to be identified by magnetometer and EM methods due to poor contrasts with the background soils and potentially not at all by earth resistance or GPR.

	Magnetometer	***Resistance***	***Electromagnetic***	***GPR***
Not Applicable	Paving / Floor	Hearth Kiln / Furnace Timber Structure Cremation	Timber Structure	Occupation Activity Timber Structure Cremation
Poor	Masonry Foundation	Occupation Activity Gully Post-hole Ditch <1m wide	Small Pit <2m Gully Robber trench Stone-packed trench Cremation	Gully Ditch <1m wide Robber trench Stone-packed trench
Moderate to Poor	Gully Ditch <1m wide Inhumation	Small Pit <2m Ditch <2m wide Inhumation	Post-hole Ditch <1m wide Inhumation	Hearth Kiln / Furnace Ditch <2m wide Inhumation
Moderate	Post-hole Ditch <2m wide Palaeochannel Road / Track Robber trench Stone-packed trench Timber Structure Cremation	Large Pit >2m Palaeochannel Road / Track	Occupation Activity Ditch <2m wide Palaeochannel Road / Track	Post-hole Road / Track
Moderate to Good	Large Pit >2m Small Pit <2m Ditch >2m wide Occupation Activity Brick Foundation		Large Pit >2m Hearth Kiln / Furnace Brick Foundation Paving / Floor	Small Pit <2m Burnt Mound of Stones
Good	Hearth Kiln / Furnace Burnt Mound of Stones	Ditch >2m wide Robber trench Stone-packed trench Masonry Foundation Burnt Mound of Stones Brick Foundation Paving / Floor	Ditch >2m wide Masonry Foundation Burnt Mound of Stones	Large Pit >2m Ditch >2m wide Palaeochannel Masonry Foundation Brick Foundation Paving / Floor
Technique Score:	**66/105 (63%)**	**54/105 (51%)**	**58/105 (55%)**	**56/105 (53%)**

Table 9. Theoretical capability scores for idealised responses of archaeological features.
Geology and sample resolution must be taken in to account. Scores are based on points for each of the 21 archaeological feature categories: Good = 5 points, Moderate to Good = 4, Moderate = 3, Moderate to Poor = 2, Poor = 1, Not Applicable = 0. Highest possible score is 105 (percentage rates are given in parentheses).

		Suitability (dependent on geology and appropriate sample resolution)			
Excavated Site Types	**Frequency of Excavation**	*Magnetometer*	*Earth Resistance*	*Electromagnetic*	*GPR*
***Fulachta fiadh* / burnt mound**	35%	Good	Good	Good	Good
Burnt spread		Moderate	N/A	Moderate	N/A
Industrial	19%	Good	N/A	Moderate	Poor
Isolated pit	19%	Good	Moderate	Moderate	Moderate
Hearth		Good	N/A	Good	Poor
Permanent Structures (stone / masonry)	12%	Poor	Good	Good	Good
Temporary Structures (timber / turf)		Poor	Poor	Poor	Moderate
Burial	6%	Poor	Poor	Poor	Moderate
Agricultural (ditch / gully / farm track)	4%	Good	Moderate	Moderate	Moderate
Ringfort / enclosure	3%	Good	Good	Good	Good

Table 10. Theoretical geophysical responses to common archaeological site types.
The site types refer to the top 98% that occur in the NRA Archaeological Database, 1992-2009, as defined by McCarthy (2010). Sub-categories have been defined where appropriate e.g. an earth resistance survey is 'Good' at identifying a burnt mound of stones but not suited at all to identifying a burnt spread.

Industrial features, including ***metal-working sites***, ***kilns*** and ***charcoal-production pits***, accounted for 19% of excavated sites, as did sites of ***isolated pits*** and ***hearths***. In total, these account for another 38% of all excavated site types that can be identified by detailed magnetometer survey (these site types can also be found by EM magnetic susceptibility survey). Earth resistance surveys are really only suited to the detection of an in-filled pit for this category of site type. ***Slag heaps*** can be mapped using Induced Polarisation as well as magnetometer and EM magnetic susceptibility survey.

4.2.1.2 Structures

12% of excavations occurred at ***settlement sites***, defined as temporary or permanent structures. ***Timber structures***, as discussed above, can sometimes be identified using a high resolution (0.5m x 0.25m) magnetometer survey. In many cases the response from a hearth may be the only anomaly generated from a timber structure, although burnt post-pits in the corners of a structure and stone-packed slot-trenches were identified at the Magheraboy Neolithic complex (Figure 16).

The Research Fellowship has experimented on the site of known 19th century ***turf structures*** using magnetometer and EM surveys, without any meaningful results, although associated enclosing features and trackways were identified by both methods. Turf does not have any significant properties that contrast for geophysical instruments, although those structures with a stone or imported surface might be identified by earth resistance, EM conductivity or GPR surveys.

Stone structures, including ***cashels***, are best identified by earth resistance, EM conductivity or GPR surveys. They will not usually be identified by magnetometer survey although exceptions occur for structures built from weakly magnetic sandstone such as cashels on the M20 Cork-Limerick motorway (Bonsall and Gimson 2009; Harrison 2012) or igneous rocks that sufficiently contrast with the geological background). As discussed above, ***brick structures*** can be identified in magnetometer data (due to the firing process), as well as earth resistance, EM conductivity or GPR survey.

Palisade and narrow ***causewayed enclosures*** can be very difficult to identify in even high resolution magnetometer data; GPR may be the most appropriate choice for the identification of these features, again at a high resolution (0.25m x 0.05m). As discussed above, *a priori* knowledge is useful for the interpretation of magnetometer data in a case such as this.

4.2.1.3 Cut-Earth Features

McCarthy (2010) analysis of the NRA Archaeological Database recorded up to 13% of site types that could be described broadly as 'cut-earth' features ('farm tracks', which are not cut-earth features, were included by McCarthy's original 'agricultural' site type category).

Ringforts and ***enclosures*** accounted for 3% of site types excavated (for cashels, see stone structures, above). These can be identified easily by magnetometer surveys on favourable geologies. Carboniferous limestone soils are sometimes poor for the detection of ringfort and enclosure sites; in these areas high resolution (0.5m x 0.25m) magnetometer surveys or an alternative/additional technique, such as earth resistance, EM (conductivity and magnetic susceptibility) or GPR surveys should be used.

Burials accounted for 6% of site types. ***Inhumations*** and ***cremations*** are particularly difficult to identify in geophysical data and there is no set methodology (the matter is discussed in detail in Appendix A). There may be a need to use an 'ultra' high resolution survey following methodologies used by forensic geophysical investigations. Burial complexes, enclosed by a ring-ditch are however much easier to identify (see ‘enclosures’, above), even if the individual burials are difficult to image.

Agricultural sites, including ***ditches***, ***field boundaries***, ***farm tracks*** and ***gullies*** accounted for 4% of excavated site types. Tracks are likely to be identified by earth resistance, EM conductivity or GPR surveys. The remaining site types tend to appear regularly in magnetometer data. ***Field walls*** can be identified in earth resistance, EM conductivity or GPR surveys. They will not usually be identified by magnetometer survey although exceptions occur for field walls built from weakly magnetic sandstone such as those on the M20 Cork-Limerick motorway (Bonsall and Gimson 2009; Harrison 2012). Pre-bog field walls at Slievemore, Achill Island, Co. Mayo were identified by the Research Fellowship via earth resistance (Wenner array) and EM conductivity survey (Bonsall *et al.* 2012c).

4.3 Landscape

Geophysical surveys across entire road corridors need to be adaptable to the wide range of landscapes encountered when assessing linear corridors. The Legacy Data contain surveys from 24 of the 26 counties in the Republic of Ireland and have a reasonable spatial distribution focused upon national routes between the major cities of Dublin, Cork, Limerick, Galway, Kilkenny and Waterford.

The most frequently surveyed counties were Meath (20%), Waterford (10%), Galway (9%) and Cork (8%), the remaining surveys accounted for less than 7% per county (Figure 18). Dublin, as a county, has very few surveys, reflecting the road scheme activity that occurs beyond both its borders and the M50 motorway that surrounds it.

Surveys were most frequent in the province of Leinster (57%), reflecting the number of motorways that converge upon Dublin, followed by Munster (29%) and Connacht (11%). The Legacy Data from Ulster (3%) account for the three counties (Cavan, Monaghan and Donegal) in the Republic of Ireland.

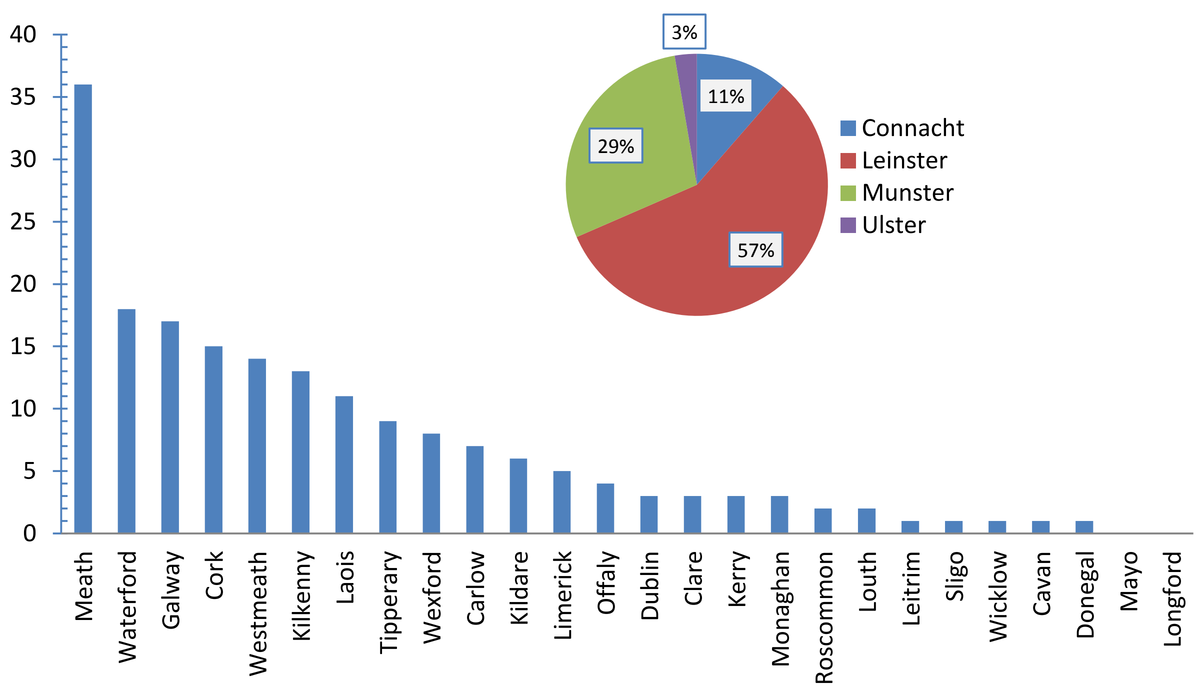


Figure 18. Distribution of NRA geophysical surveys by county and province.

The terrain traversed by road schemes varies across the country. In general, geophysical data are best acquired on reasonably flat surfaces. When surveying on sloping ground (hills, drumlins) the positional accuracy of data can be difficult to maintain, hand-held magnetometers are often tilted (inducing errors), survey speed is impeded and grid-layout can often be difficult – these problems increase proportionally with the angle of slope. Walking downhill is no better than walking uphill; if possible surveys should ideally follow the contours along a slope to maintain an even surface, although this is not always possible with linear route corridors.

Surveys at Areas of Archaeological Potential are restricted to 'reasonably flat terrain without scrub, soft ground or quarrying', specifically to expedite a geophysical assessment (O'Sullivan 2003), whereas End-to-End coverage of a route corridor may routinely encounter such unfavourable ground. Upland areas need not be excluded from geophysical assessments as it has been noted that the uplands of Ireland are not particularly high (O' Brien 2009) and were suitable for a range of occupation sites (Rathbone 2013).

4.3.1 Land Use

Crops, vegetation, ploughed soils and livestock alter the quality of geophysical data and significantly impede survey progress. The majority of land encountered in the NRA Legacy Data were grassland pasture (52%), followed by arable and pasture (28%), undifferentiated grassland (9%) and arable (6%). Bog / Reclaimed Bog / Wetland / Marsh accounted for 2% of land.

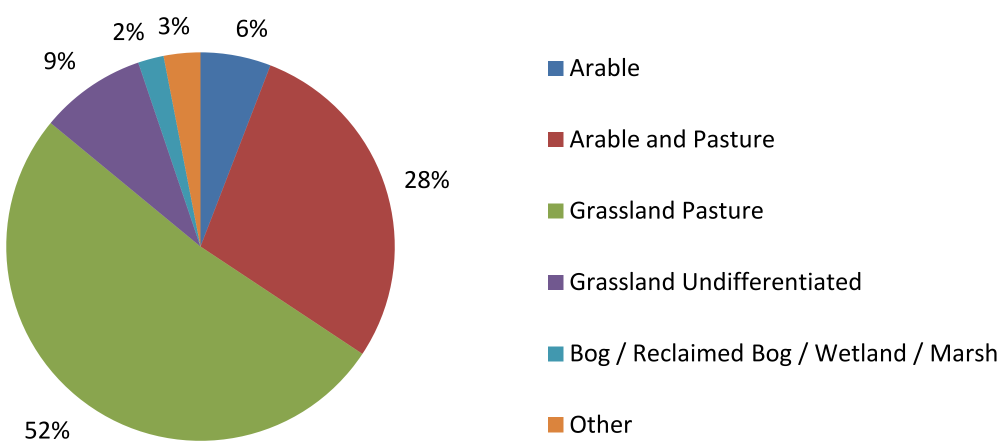


Figure 19. Land Use encountered in the 2001-2010 NRA Legacy Data.

4.3.1.1 Grassland Pasture and Arable (including vegetable, cereal and silage crops)

Recently harvested crops are ideal for unhindered survey progress.

Young crops of silage <0.2m in height are suited to the progress of magnetometer, electromagnetic and GPR surveys. Earth resistance surveys using the twin-probe array may be slightly impeded by trailing cables caught amongst clumps of grass / weeds.

Tall, thick and dense crops (including silage) >0.2m in height:

- Positional accuracy decreases with crop height. It is best to wait until harvest rather than proceed through high crops. Crops buffer instruments from side to side as they are 'forced' through the crop, reducing data quality in magnetometer, earth resistance, electromagnetic and GPR surveys.

- Ground contact is poor or impossible for earth resistance arrays and magnetic susceptibility probes.

- *Consideration should be given to crop damage*. Geophysical data are typically collected along lines spaced 0.5–1m apart covering every square metre of an available survey area. Mature silage, vegetable and cereal crops (both young and mature), could be flattened by walker trails and/or geophysical equipment. Motorised geophysical equipment will have increased potential for damaging a mature crop.

- Once silage is cut, it is typically left on the ground for a few days to dry. Cut silage is slippery to walk upon, produces an uneven surface (resulting in poor data quality) and prevents ground contact for earth resistance and magnetic susceptibility probes. Fieldwork upon cut silage should be delayed until the silage has been collected and/or baled.

- Most geophysical instruments allow for the insertion of dummy or blank readings and can accommodate the presence of small isolated obstacles such as silage bales in a survey area, if required.

4.3.1.2 Undifferentiated or unmanaged grassland

Unmanaged grasses clump together forming hummocks and depressions (Figure 20). These produce an uneven surface that can affect the quality of collected data and reduce positional accuracy, although geophysical survey data can still be useful in these areas. Unmanaged wet soils can lead to thick vegetation e.g. bog grass or rushes that are as difficult to survey as a mature arable crop.

Figure 20. Unmanaged grassland.
In the background, short grass has provided a uniform surface. In the foreground, unmanaged grassland can be seen to have created hummocks of bog grass and depressions which can lead to poor data collection for a variety of instruments.

4.3.1.3 Bog / Reclaimed Bog / Wetland / Marsh

See general discussions on Peat (Section 4.1.2.1) regarding methods of geophysical prospection. The main consideration is that walking across wet and saturated soils reduces positional accuracy and impedes survey progress.

Reclaimed bog may contain imported materials. At the site of drained loughs, such as Clonkeen Lough, Co. Galway (Bonsall and Gimson 2006), magnetometer surveys are of little use, instead these could benefit from a metal detection survey (if votive deposits are envisaged) or an EM survey to define the lake shore, which may be archaeologically prospective. If wooden remains, such as a trackway or a crannog need investigation, an induced polarization survey would be suitable.

4.3.1.4 Woodland

Woodland is not generally appropriate for geophysical prospection surveys (Kulessa *et al.* 2004). However, if a known monument needs to be assessed within woodland, electrical resistivity tomography (ERT) and metal detection surveys could be considered.

4.3.1.5 Ploughing

Surveys on ploughed land should be avoided. Ploughed soil is uneven, reduces positional accuracy, impedes survey progress, prevents ground contact (for earth resistance and magnetic susceptibility probes) and generally results in poor quality - and often noisy - data.

Ploughed *and* harrowed soils are much more suitable for working on as the surface is generally smooth. Recently harrowed wet soils can result in very soft and sinking ground, which reduces positional accuracy and impedes survey progress.

Recently seeded soils are generally very good for survey progress, the land is usually firm and seeds are not damaged by surveyors.

4.3.1.6 Livestock

Cattle and horses should be moved out of a survey area. They are curious animals that tend to follow surveyors. Sheep are also disruptive, but timid. Given the speed at which a typical prospection survey moves through a field, sheep generally tend to stay away from survey activity. However, *any* stampeding livestock have a tendency to pull up survey ropes, tie-lines and survey markers, as well as endangering the safety of the equipment, surveyors and themselves. Passing livestock can potentially create anomalies in magnetometer data due to the presence of metal (e.g. ID tags for most livestock or horseshoes).

4.3.2 Vehicle-Powered Surveys

Articulated methods of assessment towed by all-terrain vehicles (ATVs) have recently been developed for magnetometer (Doneus *et al.* 2011; Gaffney *et al.* 2011), earth resistance (Dabas 2009) and GPR surveys (Linford *et al.* 2010; Trinks *et al.* 2010; Biwall *et al.* 2011; Linford *et al.* 2011; Verdonck and Vermeulen 2011); some of these technologies have already been applied to large scale commercial assessments such as the 120km motorway BREBEMI project in northern Italy (Campana and Dabas 2011) but are not necessarily suited to all landscapes.

Articulated magnetometers provide a smooth and uniform method of data collection. These will still be strongly affected by uneven terrain, however if an ATV is capable of safely traversing a site then data can be collected. The Foerster MULTICAT system encloses a series of magnetometer probes in a cylindrical drum which would be suitable in areas of scrub as the protective drum would prevent excessive probe movement. The MULTICAT system has yet to be validated as an archaeological prospection tool, although the FEREX magnetometer probes which it uses are suitable (Gaffney *et al.* 2008; Ullrich *et al.* 2011). This suggests that this sort of system may be a useful device on soft ground and areas of undifferentiated or unmanaged grassland.

Uneven terrain is difficult to assess with a ground-coupled GPR antenna due to the need for permanent ground contact which can be broken by earthworks, pockmarks and vegetation. It has been suggested (Linford *et al.* 2010) that an air-launched antenna could be of value in this instance. Notable drawbacks to the air-launched system are strong responses derived from the air-ground interface, unexpected responses from point reflectors caused by contrasts between the air and subsurface (Linford *et al.* 2010) and potentially, a limited frequency range (Leckebusch 2011). Despite these drawbacks, an air-launched system towed by an ATV could provide a very high resolution assessment of the underlying archaeological features that compares favourably with ground-coupled data over even ground and produces much better quality data over uneven ground (Linford *et al.* 2010).

4.3.2.1 Damage to the Environment

Most geophysical surveys occur before a compulsory purchase order (CPO) is issued, often several years in advance of construction activity. Consideration should be given to the environment and the landowners when commissioning a survey that may utilise an ATV; there is a considerable difference between a farmer’s use of an ATV to access land (along mostly pre-existing routes), and a high resolution geophysical survey (systematically covering an entire road corridor). Comparative evidence suggests that ATVs *might* be capable of traversing uneven and soft ground, but their use can cause soil compaction/erosion, damage to vegetation, soil and animals, as well as noise disturbance to birds and other wildlife. The pressure exerted by ATV tyres when the vehicle is turning or braking is typically greater than a pedestrian boot or shoe and has an increased potential to damage vegetation (Cater 2008). Undoubtedly on dry flat grassland, the use of an ATV would be acceptable but not all ground conditions may be suitable for it.

Precautions are required to mitigate excessive speeds as the likelihood of ATV 'rollover' is a distinct possibility on uneven ground. Agricultural investigations (Moore 2008) have found that 'haste' and 'unpredicted surface changes' accounted for 44.5% of ATV 'loss of control events'. 'Secondary visual tasks' accounted for a further 15.1%, which is significant for geophysical assessments given the level of concentration required for the tasks of driving in the variable environment encountered on linear corridors, the navigation of closely sampled data and in-field data viewing.

The NRA should advise geophysicists (within a specification or briefing document), if the use of ATVs is acceptable or not for a particular scheme. There are clear benefits when appropriate conditions allow for ATV use.

4.4 Sources of Interference

Geophysical surveys rely on magnetic, electrical and electromagnetic contrasts to map archaeological features. These properties are susceptible to various sources of interference in the landscape that are commonly encountered in geophysical surveys.

4.4.1 Diurnal Variations

Magnetometers can be impacted by natural diurnal variations in the Earth's magnetic field, due to solar winds. Strong coronal mass ejections from the Sun strongly increase the background magnetism of the Earth. Caesium instruments usually compensate for diurnal variations by using a second, stand-alone, magnetometer base station, by configuring in the gradient formation or by removing long wavelengths of diurnal variations by using a time-based high-pass filter (Roseveare 2013). Diurnal variations are usually removed automatically by the gradient set-up of fluxgate magnetometer instruments.

4.4.2 Services and Utilities

Magnetometer surveys are impacted by pipes which, constructed from ferrous material, can create very large and easily recognizable anomalies several times wider than the actual pipe diameter (5-20m either side of the pipe, high pressure gas pipes can create even larger anomalies). These strong anomalies mask the presence of archaeological responses in the vicinity of the pipe. The effect of pipes on particularly narrow linear corridors can be substantial; if their presence is known it is advised that an alternative technique is used to assess the presence/absence of archaeological features in that area.

Overhead and underground electrical cables can create substantial magnetometer and earth resistance interference. Overhead cables are usually high enough to reduce any interference to magnetometer surveys, although highly sensitive caesium magnetometers can sometimes be affected to a small degree by some cables.

Underground electrical cables are not buried to an equivalent depth below the soil as their overhead counterparts are above the soil; these cables will create very strong interference on magnetometer, earth resistance, GPR and electromagnetic surveys and will mask the presence of archaeological features.

In many cases, utility companies are unaware of the precise location of their buried services, in which case a geophysical survey can provide some useful information if invasive excavations are likely.

4.4.3 Pylons

The steel frames of pylon bases are set in concrete and create magnetic anomalies of several hundred nanoTesla; wooden telegraph poles are usually supported by steel tendons which also create strong anomalies.

4.4.4 Passing Traffic

Passing traffic will create strong anomalies in magnetometer, magnetic susceptibility, EM and GPR surveys; earth resistance surveys are unaffected by traffic. The metal content of stationary cars are likely to produce anomalies of several hundred nanoTesla in magnetometer data and can be detected 10-20m away (Aspinall *et al.* 2008); the larger the vehicle, the stronger the anomaly. A moving vehicle will create an elongated version of the same anomaly until it has passed beyond the range of the magnetometer. EM and GPR responses will be disturbed by the electromagnetic field of a working engine. Magnetic susceptibility may map exhaust particulates as strong zones of magnetic enhancement, that can be distributed several metres from a road.

Geophysical surveys along road corridors will inevitably pass alongside or across existing road schemes. Surveyors should preferably wait for vehicles to pass before collecting data near existing roads, but in some cases this will not be possible; interference must either be tolerated, traverses repeated or a practical decision must be made to terminate the survey before approaching the road.

4.4.5 Fences and Gates

Fences produce strong anomalies in magnetometer data. Single strands of wire (such as those found on electric fences that sub-divide large fields, as well as strands of barbed wire above stone walls), produce a measurable anomaly. The average Irish agricultural fence will generate an anomaly that can be detected 3-5m away.

Ideally fields should be surveyed in such a way that the fence line is located on the edges of a rectangular survey area; in practice this rarely happens on road corridors. The alignment of fences can significantly reduce a survey area, particularly narrow corridors. The effect is compounded when surveying across several small irregular shaped fields. Alternative techniques should be sought if fence lines pass near or over known or suspected archaeological features requiring investigation.

Ferrous gates create very strong anomalies in magnetometer data, usually several hundred nanoTesla, about 10m x 5m in size, elongated along its axis.

4.4.6 Boreholes

Boreholes are essentially very deep metal cylinders, sometimes in-filled with concrete. These produce strong magnetic anomalies in magnetometer data, typically 10m in diameter, which mask the presence of archaeological features in that area. Boreholes are frequently encountered along the centerline of road scheme assessments, as geological investigations tend to occur just before an archaeological geophysical investigation. The benefit of boreholes of course is a wealth of geological and pedological information that can be used to inform the geophysical survey strategy.

4.4.7 Radio Waves

Radio waves broadcast on commonly used frequencies can interfere with earth resistance, GPR and EM surveys. Many GPR antennas are described as ‘shielded’ from external broadcasts although it is best to ensure that sources of radio interference that can be controlled are reduced to a minimum. Local sources of interference (mobile phones, radios, pagers, Bluetooth devices *etc.*) can be turned off or kept away from the survey area but broadcasts from large transmitters, passing traffic, airport radar, military and emergency services cannot. The interference from large transmitters, antenna and airport radar can extend to several kilometres. In some cases, the effect on GPR antenna will be so great that the instrument cannot be used at all. The probe geometry of earth resistance meters can be altered in the field to reduce or remove the effect of external broadcasts, if they are noticed.

4.4.8 Modern Structures

Houses and farm buildings of post-19th century date are ferrous- and concrete-heavy; these materials create strong magnetic anomalies several tens of meters in size, capable of masking the presence of archaeological features in magnetometer data. GPR data can be affected by localised electrical transmissions and other radio waves. Earth resistance data are not generally affected by proximity to modern structures.

4.4.9 Cultivation Furrows

Many of the 18th and 19th century cultivation furrows found across Ireland are a source of archaeological information. Furrows are rarely corroborated by excavations as they are difficult to see with the human eye or are located in the topsoil. Magnetometer surveys identify them easily as many have imported magnetic materials that act as fertiliser, or previous growth that is burnt *in situ* that create strong and narrow thermoremanent anomalies. The presence of furrows (and their apparent termination) can also help infer the presence of field boundaries that again may not relate to discernible archaeological feature in the excavation.

From a geophysical perspective however, cultivation furrows can often be a source of frustration and prevent monument recognition. Strongly magnetic parallel lines can easily obscure both small and sometimes large features in magnetometer data. Traverses aligned along the furrows could be advantageous; however the absence of a topographic expression for the furrows means that their alignment is unknown prior to a survey. When conducting surveys on narrow corridors it is often impractical to orientate the traverse to an optimum direction.

5. Controlled Variables

The variables that can be controlled, some of which are location specific, need to be addressed for geophysical surveys. These will enhance the effectiveness of future surveys, the strategies used, their procurement, execution and reporting.

5.1 Procurement

5.1.1 Procurement Agencies and End-Users

The NRA are end-users of geophysical data and most surveys are commissioned by them, some however are requested on behalf of the NRA by a third party agent, typically an archaeological consultancy or an engineer. In these instances NRA specification documents are not issued and the third party agent initiates a competitive procurement process by requesting proposals or research designs from geophysical contractors.

These projects can be awarded to the lowest-priced quotation, sometimes without regard for how appropriate a geophysical technique and method may be for site specific variables. Given the discussions above, in the long run, the lowest-priced quotation is not necessarily the most economically advantageous quotation. This method of procurement differs significantly from the NRA method; whilst both the agent and the NRA require a competitive procurement process, the latter tend to issue highly prescribed specifications and a Bill of Quantities (BoQ) to assess proposals in a directly comparative manner, while the former simply requests a 'geophysical survey' and chooses the lowest-priced proposal. In such a procurement strategy it is often difficult to distinguish between an *appropriate* and an *inappropriate* research design. It seems beneficial that geophysical surveys on road schemes requested by non-NRA agents should employ the same standards of procurement, where possible, to ensure consistent and appropriate methods of assessment.

For example, an archaeological consultancy sought quotations for a geophysical survey to form part of an environmental impact statement. Geophysical research designs were judged on price rather than a relevant methodology; the successful proposal commissioned by the archaeological consultancy was a magnetometer survey. The geology at the site was unfavourable for the magnetometer survey – it was dominated by the igneous thermoremanent effect of granite outcropping, appearing as large linear and amorphous zones of strongly magnetic anomalies that obscured the majority of archaeological features. Had a specification been incorporated into the procurement stage, an alternative method of survey would have occurred over at least a sample of the survey area, based on similar assessments specified in the past.

5.1.2 Competence of Surveyors

The most recent specifications issued by the NRA during the Legacy Data study period (Westmeath 2010) require certain levels of competence for geophysical consultants. Unfortunately some issues have been noted in the Legacy Data that indicate some levels of inexperience in the collection and interpretation of *archaeological* geophysical data. In some cases, *geological* geophysicists have had limited experience in the collection, interpretation and presentation of *archaeological* data. In other cases, archaeological companies have employed *inexperienced archaeologists* to collect, interpret and present *geophysical* data. Consultants should demonstrate that they employ professional and experienced *archaeological geophysicists*, rather than an archaeologist or a geophysicist.

The criteria below (Table 11) are not meant to be restrictive and are suggested requirements of competence that represent a combination of current NRA requirements and those desired by English Heritage (David *et al.* 2008). Evidence of previous licence eligibility, as currently required by the NRA, has been removed as a criteria, as it is not an effective means of vetting the ability or competence of a *professional archaeological geophysicist* (any archaeologist or geophysicist can obtain a Detection Licence from the government).

5.1.3 Recommendations

- Third-party agents (archaeological consultancies, engineers) procuring geophysical surveys for road schemes should adhere to the same standards of procurement as the NRA.
- Third-party agents should adopt NRA practice of seeking Quotations submitted in response to a Specification (of appropriate techniques and methods to be used) and a Bill of Quantities, rather than a generic request for a 'geophysical survey'.
- All procurement of geophysical surveys on road schemes should take note of the variables discussed in this document regarding a suitable and appropriate survey methodology.
- Ensure that the geophysical services (including fieldwork, data treatment, report and archive) are undertaken by competent and professional archaeological geophysicists.
- The project manager (and the available field assistants) should be named at the procurement stage and their relevant experience submitted for review. The project manager (lead geophysicist) should

be on site to ensure the quality of data collection. Suggested criteria for the suitability of an archaeological geophysicist can be found in Table 11.

- Membership of professional institutions or relevant associations and societies should be desired and encouraged. These include: Institute of Archaeologists of Ireland (IAI), Institute for Archaeologists (IfA), International Society for Archaeological Prospection (ISAP), European Association of Geoscientists & Engineers (EAGE), European GPR Association (EuroGPR) and the Geophysical Association of Ireland (GAI).

Project Manager: Experienced Geophysicist - Responsible for collection, processing, & interpretation of data is likely to fulfil the following:	
Requirement	*Demonstrates*
Curricula Vitae	Career in ***archaeological geophysics***, to date. Competence in environmental, engineering or geological geophysics *is not an acceptable proxy*.
A post-graduate degree in an appropriate ***archaeological science*** (e.g. MSc in Archaeological Prospection, MSc in Archaeological Science). A degree in ***archaeology*** is also highly desirable.	An ability to understand the varied morphology of *archaeological* features that might generate *geophysical* anomalies; an ability to collect, interpret and present complex geophysical data.
Experience in *a supervised capacity of a large number of different* ***archaeological site surveys***, or a *minimum of three full years'* ***supervised experience*** of archaeological geophysics.	Strong background and experience of collecting geophysical data.
Five full years experience of leading, and reporting on archaeological geophysical projects of a similar scale.	An ability to manage a project, collect and interpret archaeological information from complex geophysical data and present findings to a non-specialist audience.
If such techniques are required by the contract: Experience in the collection, interpretation and reporting of non-standard or 'novel' geophysical data (e.g. electromagnetic, ground penetrating radar, electrical resistivity tomography, induced polarisation).	Competence of the required geophysical survey technique beyond 'standard' magnetometer and earth resistance surveys.
Competence in basic metric survey procedure.	Ability to collect spatial data.

Survey Personnel: To assist the Project Geophysicist in the collection of data	
Requirement	*Demonstrates*
Curricula Vitae	Career in archaeological geophysics, to date.
Experience, preferably in a supervised capacity, of at least 10 different site surveys, or a post-graduate degree in an appropriate science.	Experience of collecting geophysical data.
Competence in basic metric survey procedure.	Ability to collect spatial data.

Table 11. Suggested criteria for professional archaeological geophysicists working on road schemes.

5.2 Data Acquisition

5.2.1 Methods of Data Acquisition

Geophysical data are typically collected using hand-held instruments or human-propelled cart-mounted arrays. Large landscape assessments have recently used vehicle-propelled arrays to cover very large survey areas over a short period of time by acquiring data in a 'gridless' fashion with a GPS (Campana and Dabas 2011; Gaffney *et al.* 2012). Calculating field work time is problematic: real world examples of survey speed and coverage over uninterrupted landscapes (Table 12) are not typical of NRA road schemes, due to multiple set-outs which impact upon the timing.

General Advice on Methods of Data Acquisition

There are a number of methods of acquiring geophysical data, each of which are valid and appropriate for a range of different landscapes and area sizes likely to be encountered on road corridor assessments. The choice of acquisition method (hand-held, cart, gridded, gridless) should be determined by the individual consultant.

Constraints on fieldwork time:

Large survey areas can be assessed rapidly with multiple sensors.

However the set-up time may be prohibitive in small areas due to a need to dismantle and reassemble equipment per land holding, particularly if the set-up involves an ATV.

On average there are 3.96 land holdings per linear kilometre along NRA road schemes (or 1 land holding per 0.46 hectares of survey area).

Human-propelled or Vehicle-propelled Arrays?

The frequency of land owners across an NRA road scheme, the remote location of some survey areas and the often wet and boggy soil encountered could suggest an argument for hand-held / human-propelled arrays on many Irish road corridors rather than vehicle-propelled arrays. However, vehicle-propelled arrays will save significant time and costs in open areas and their use should be encouraged.

Cart Mounted Arrays:

Geophysical surveys in Ireland are heading towards cart based systems (but not necessarily vehicle-propelled systems).

Gridless Data Acquisition:

Gridless (GPS derived) data are becoming more commonplace. Gridless data offers the benefits of a grid-free strategy and precise data location, which increases the data quality and reduces processing.

Areas susceptible to poor GPS coverage (e.g. tree canopies adjacent to woodland or some field boundaries) will be unsuitable for gridless data collection.

A discussion of acquisition methods can be found in the following pages.

Method	*Survey Time*
Handheld (traditional method)	6 hours
Human-propelled cart	1 hour 40 minutes
Vehicle-propelled cart	45 minutes

Table 12. Expected survey times using modern methods of magnetometer data collection.
The timings refer to a detailed 0.5m x 0.25m magnetometer survey over an idealized uninterrupted 1 hectare landscape. It is evident that increasing the number of sensors in an array will reduce these survey times.

5.2.1.1 Notes on Gridless Data Acquisition

Most NRA Legacy Data were collected in a regular gridded format (i.e. along regularly spaced parallel lines across one of several grids that make up a given survey area), however a small number of gridless GPS-acquired data were recently collected on road schemes. Gridless data typically use an RTK GPS to record the location of geophysical data and map the local topography at a very high resolution.

74% of magnetic susceptibility surveys used a DGPS to gridlessly acquire data; each survey station was accurately located upon the presented data plots by a cookie trail or as geo-rectified dot-proportional plots. The data gathered were widely spaced (5m x 5m or 10m x 10m) and achieved an acceptable and appropriate positional accuracy of 0.5m.

Only 1.8% of magnetometer surveys used GPS-acquisition and all of these dated to 2010, reflecting the relatively recent availability of magnetometer-GPS interfaces. Magnetometer data are collected on a much denser grid than a magnetic susceptibility survey (e.g. 1m x 0.25m), at a rapid pace, typically 10 readings per second, which requires very high positional accuracy (≤0.1m) in order to avoid the displacement of anomalies.

Unlike regular gridded surveys, gridless data does not have to be collected along straight lines; a typical field procedure may involve collecting data along the perimeter of a survey area and continuing inwardly along the line of a spiral to the centre. The data can be considered 'pseudo-random' in terms of their spatial location rather than following a strict traverse and sample spacing. Randomly collected data can be gridded to a prescribed spatial resolution (e.g. 1m x 0.25m), by interpolating between the data. In some cases, where data collection is too sparse to be interpolated it is vital that gridless data are presented as ‘empty’ with gaps clearly illustrated on the survey plots to avoid misleading interpretations.

Some of the 2010 gridless magnetometer data were sparsely collected and processed in such a way that data were shifted and interpolated between ‘blank’ areas where no data collection occurred - this created false anomalies or artefacts in the data and should be avoided at all costs. Sparsely collected data can be easily illustrated by including cookie trails or point clouds of acquired data (Schultze *et al.* 2008), which could be submitted as digital pdf documents with the final report archive.

5.2.2.2 Hand-held instruments

These are small, portable and refer to most single and dual-system magnetometers that were used on NRA road schemes in the past, as well as earth resistance meters, magnetic susceptibility, GPR and electromagnetic instruments. The vast majority of the 2001-2010 NRA Legacy Data were collected using hand-held instruments.

The main advantages of these instruments are that they can mostly be used in any area that a human can access (including tight corners and small fields), they can be passed easily across field walls and fences (aiding the speed of set-up times for multi-field surveys) and they allow the operator to instantly gauge the geophysical response of the underlying soil without resorting to recalibration of the instrument.

Data are collected in a series of grids which are laid out on the ground using markers. Some hand-held instruments, particularly magnetic susceptibility meters, can be used with a GPS to collect gridless data, as described above.

Hand-held magnetometers using non-GPS strategies often suffer from positional errors that need to be accounted for by post survey processing.

A disadvantage of hand-held instruments is motion-induced noise created by walker gait, which varies between individual surveyors.

Whilst hand-held instruments may be considered slower than cart mounted arrays, they offer a considerable advantage when used on heavily ploughed or uneven terrain or in areas of dense vegetation (Linford *et al.* 2007).

5.2.2.3 Cart Mounted arrays

Recent trends in data collection have seen the use of arrays of different geophysical instruments mounted upon wheeled carts (Becker 2001). Active techniques that inject a signal into the ground (earth resistance, electromagnetic, magnetic susceptibility, GPR) are generally slower than passive techniques that measure naturally occurring phenomena (magnetometer surveys). Some types of magnetometers rapidly collect data to take advantage of the technological changes offered by cart mounted arrays.

The benefits of cart-based prospection are the rapid and high density of acquired data largely free from periodic errors and sensors that are kept at a constant height above the ground (Gaffney 2008), increasing the amount of detail offered by magnetometer surveys (Figure 21). High density data acquisition enables the collection of data at 0.5m traverse intervals, increasing the detection of subtle low contrast anomalies such as post-pits (Linford *et al.* 2007). Carts reduce motion-induced noise by mounting instruments upon a stable platform and allowing smooth movement over uneven surfaces when using a large wheel diameter. Cart or sledge mounted instruments can however show pronounced topographical effects (earthworks, ridges, unstable ground) more than a handheld fluxgate magnetometer (Linford *et al.* 2007).

- Human-propelled cart arrays

Human-propelled carts usually incorporate three or more magnetometer probes upon a wheeled array. As well as the advantages discussed above, carts make it much easier to control a bank or array of multiple sensors than by hand.

Carts can be awkward to use in tight corners or irregular shaped fields, as the width of the array dictates the space required. Carts can collect data from ground-marked grids or can output data to a GPS for gridless data collection. GPS-acquired data also eliminates the presence of 'staggered' data and high positional accuracy which results in less processing. If carts are used in favourable areas of a suitable size and shape then they can be an efficient way of surveying.

- Vehicle-propelled cart arrays

New research has led to the development of high speed data acquisition for most geophysical techniques. Vehicles such as quad-bikes, other ATVs and tractors can be used to tow or push large arrays of geophysical equipment, including magnetometers, resistance arrays, GPR antenna and/or combinations of these (Dabas 2009; Campana and Dabas 2011; Gaffney *et al.* 2012). Such arrays collect data in a gridless fashion and require high-speed GPS measurements in order to correctly locate each data point. This method of data collection has been used successfully on parts of the Italian BREBEMI Motorway Project (Campana and Dabas 2011).

Whilst high speed data acquisition is very useful for covering wide areas, the morphology of fields in Ireland may limit the speed of data collection. The impact of ATVs on fragile surfaces might be detrimental to the sub-surface archaeological features on culturally or environmentally sensitive sites.

Figure 21. Cart mounted magnetometer arrays.

Cart mounted arrays tend to be modular and can increase in size to accommodate additional sensors. Top: Vehicle-propelled array of 10 magnetometers spaced 0.5m apart at Stonehenge, Wiltshire, UK. Bottom: Human-propelled array of 4 magnetometers spaced 0.5m apart at Carrowmore Megalithic Cemetery, Co. Sligo.

5.2.3 Survey Direction and Orientation

The recommendations below should be followed where possible, although in reality the orientation of most geophysical assessments will be determined by the direction of the road corridor, survey area size and the orientation of adjacent field boundaries / obstacles within a survey area.

1. Magnetometer surveys should preferably be carried out along lines oriented to magnetic north, where possible, in order to increase the magnetic resolution of features (Scollar *et al.* 1990).

2. Geophysical surveys, regardless of technique, should preferably be carried out at 90° to the presumed alignment of archaeological features (or 45° over rectilinear structures). This should be taken advantage of in cases where known archaeological features are being assessed, where possible, whilst also giving consideration to (1).

5.2.4 Spatial Resolution

General Advice on Spatial Resolution

Magnetometer surveys across Europe – including commercial motorway assessments (Campana and Dabas 2011) - are typically carried out at 0.5m traverse intervals. Ireland has fallen in with the UK system of mostly using 1m traverses, however geophysicists and curators in the UK are increasingly using 0.5m intervals (see Appendix E).

As we now appreciate, Irish archaeological features are generally comprised of magnetically low contrasting anomalies upon often noisy or magnetically variable backgrounds. Traverse intervals of 1m were historically considered preferable as they halved the survey time of a 0.5m assessment. Even under ideal conditions, not all types of archaeological features will be visible at a 1m traverse separation (Table 13). The narrow nature of linear corridors also hampers the successful interpretation of low contrasting anomalies captured at 1m traverse intervals.

Modern multi-sensor magnetometer surveys can quickly assess sites at 0.5m traverse intervals. 0.5m traverse intervals are required in some areas in order to find “the site” upon certain geologies, as discussed in Section 4.1.

When surveying on linear corridors, the use of 0.5m traverse intervals will benefit the visualization and interpretation of weak anomalies.

		Magnetometer Spatial Resolution (m)				Earth Resistance Spatial Resolution (m)			
Scale	**Feature Type**	**1 x 0.25**	**0.5 x 0.25**	**0.5 x 0.125**	**0.25 x 0.25**	**1 x 1**	**1 x 0.5**	**0.5 x 0.5**	**0.25 x 0.25**
Large	Ditch	✓	✓	✓	✓ (overkill)	✓	✓	✓	✓ (overkill)
↓	Burnt Mound of Stone	✓	✓	✓ (overkill)	✓ (overkill)	✓	✓	✓ (overkill)	✓ (overkill)
	Wall					✓	✓	✓	✓ (overkill)
	Gully		✓	✓	✓ (overkill)		✓	✓	✓ (overkill)
	Pit >1m	✓	✓	✓	✓ (overkill)	✓	✓	✓	✓ (overkill)
	Pit <1m		✓	✓	✓			✓	✓
	Hearth	✓	✓	✓ (overkill)	✓ (overkill)				
	Kiln	✓	✓	✓ (overkill)	✓ (overkill)				
	Inhumation				✓			✓	✓
	Post-hole				✓				
	Cremation Burial		✓	✓	✓				✓
	Ferrous: Sword	✓	✓	✓	✓ (overkill)				
Small	Ferrous: Nail		✓	✓	✓				

Table 13. Different spatial resolutions for geophysical surveys upon favourable soils.
These will alter depending on the geology (see Section 4.1) e.g. low contrast magnetic geologies such as Carboniferous limestone will greatly benefit from a 0.5m x 0.25m magnetometer survey to identify ditches, however a 1m x 0.25m survey will be acceptable for the identification of most burnt features on the same geology.

Data are collected at a spatial resolution which is comprised of the traverse (or 'line') interval and the sample interval, e.g. magnetometer data are commonly collected at a spatial resolution of 1m x 0.25m. The spatial resolution influences how well an archaeological feature can be visualised (Figure 22) and usually affects the fieldwork time and costs (Figure 23).

- Sample Interval

The data collected at regular distances along each traverse are referred to as the sample interval. An increase in the sample interval improves the spatial resolution of the survey and helps to reduce the influence of random noise within the dataset (Schmidt and Marshall 1995; Linford *et al.* 2007). For instruments that automatically trigger data collection (magnetometer, EM, GPR instruments and some earth resistance meters), the sample interval can be high as it does not significantly impact upon the survey time. Some instruments sample along a line in time, rather than by distance e.g. data are collected every 0.1 second. Processing software is used to grid time-sampled data to an acceptable distance interval.

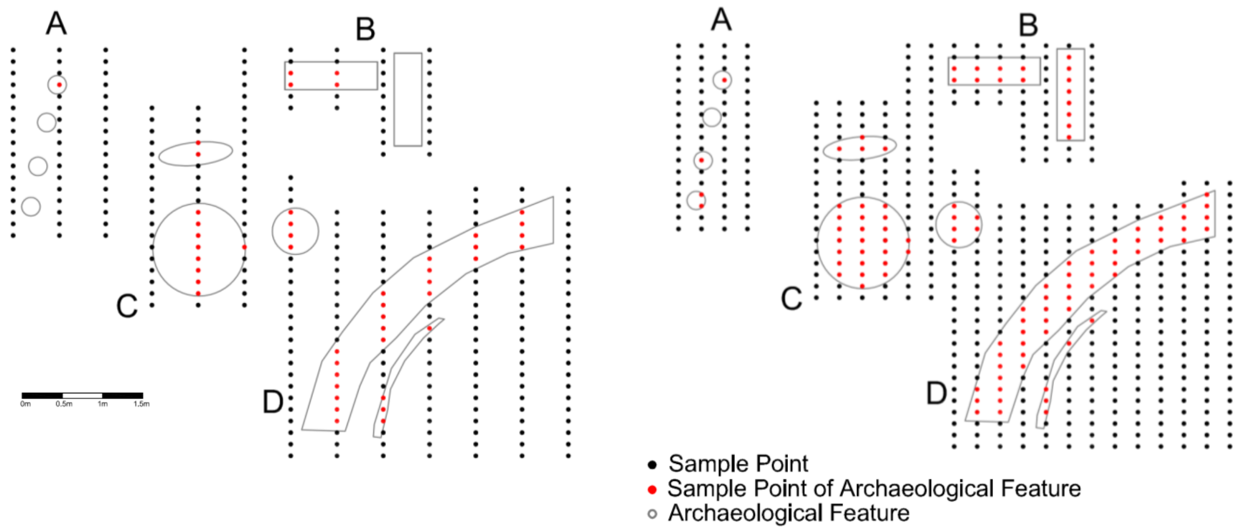


Figure 22. Spatial resolution of magnetometer surveys over archaeological features.
A: 50cm post-holes; B: 2m x 0.6m grave cuts; C: pits measuring 2m & 1m in diameter and an elongated 0.5m x 1.6m pit; D: a 1m wide ditch and a 0.2m wide gully.

Left: A 1m x 0.25m spatial resolution is useful for identifying large scale features in magnetometer data.
Right: A 0.5m x 0.25m spatial resolution gives a better definition of large scale features and can identify smaller scale features.

Some very small scale features, such as post-holes may or may not be identified at a 0.5m x 0.25m spatial resolution. The ability to identify archaeological features is also dependent on the geology and the magnetic content of the feature. Isolated anomalies of 1 sample point are likely to be disregarded unless a coherent pattern e.g. a circle of isolated points can be seen.

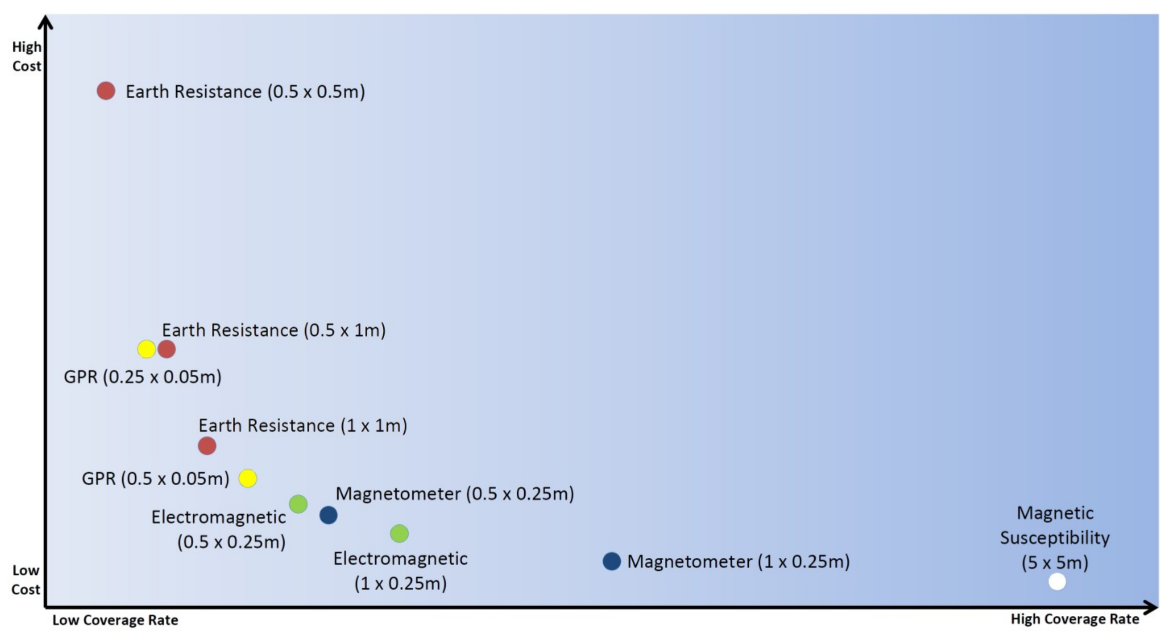


Figure 23. Sample resolution and relative fieldwork costs for daily area coverage rates.
Costs are normally dictated by fieldwork time. High volume data, e.g. from GPR, will require significant processing time & costs.

- Traverse Interval

The traverse interval dictates how often a surveyor must traverse a survey area, which ultimately dictates the survey time and most fieldwork costs. An increase in the traverse interval greatly improves the visibility of small and weakly contrasting anomalies (Schmidt and Marshall 1995).

5.2.5 Survey Grid Accuracy

Geophysical survey grids are co-registered (tied-in) to the National Grid and are subsequently used to display geophysical data upon a digital basemap. Surveys from the 2001-2010 Legacy Data were mostly (84%) recorded using a Differential GPS to sub-metre accuracy; RTK GPS were used to sub-centimetre accuracy in 6% of cases (Figure 24).

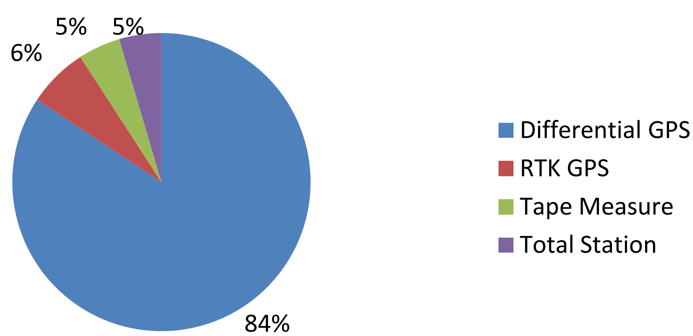


Figure 24. Methods of co-registration used from the 2001-2010 NRA Legacy Data.

The NRA currently specify that geophysical grid locations must be accurate to within 0.1m using an RTK GPS or similar; this is not particularly suitable for the collection of geophysical data. Geophysical survey grids need to be *sub-metre accurate*, but do not require 0.1m accuracy due to issues of spatial accuracy:

1) Most gridded magnetometer data are collected along a line at timed intervals; ideally the timing should coincide with a prescribed sample interval e.g. every 0.25m, however fluctuations in ground height, slope, vegetation, surface cover and individual surveyors gait will induce errors and compromise spatial accuracy. The data are subsequently spread out equally along a line or between fiducial markers.
2) Data displayed in an OSi digital basemap is only as accurate as the basemap itself, which is derived from aerial photographs.
3) Digitising anomalies in CAD or GIS introduces errors. Normally when interpreting data, positive magnetometer anomalies are digitised however these are not always the *source* of the anomaly.
4) The centre of a magnetometer anomaly does not represent the centre of the underlying archaeological feature or other magnetic source. The distance of displacement depends on the type of magnetometer used and the traverse direction; generally anomalies are shifted 0.17-0.33m to the south for the optimum north-south traverse (Aspinall *et al.* 2008).

General Advice on Sampling Strategies and Survey Coverage

Sampling strategies have been used in the past to assess very large survey areas. The modern speed of survey coverage is much higher than 10 years ago, as a result *less sampling is required for modern geophysical surveys* and *full coverage is preferable and affordable* for most road corridor assessments.

<u>Ideally, the NRA should be working towards:</u>

Sampling:
Full coverage (100%) of road corridors should occur *using the most appropriate technique* for a given area.

- Multi-sensor platforms make 100% surveys a feasible method of assessment.
- Using an *inappropriate technique* over 100% of a road corridor <u>adds no value at all to an investigation</u>.

Sampling at a rate of 50% is *reasonable* in terms of a *statistical representation* of a road corridor; however *the strategy of exclusively sampling the centreline is poor*. If a 50% threshold is used then *the sample needs to be spread out across the width of the road corridor*.

- This could be achieved via evenly spaced strips of equal size across the width of the road corridor.
- The amount of *meaningful* data contained in each strip could however be very poor
- Consideration should be given to how much *archaeological information is lost within the non-surveyed areas* (Figure 25).
- Although a sampling strategy such as this will collect 50% less data than a full coverage survey, the time required to set-out grids *etc.* is similar to the 100% coverage option; *fieldwork time - and costs – should not be expected to be halved* compared to a full coverage assessment.

Magnetometer:
Use magnetometer surveys in areas of *favourable* geology.

Magnetometer surveys *should be used at 0.5m traverse spacing* and 0.25m sample intervals (or better) to provide increased definition and a better interpretation of archaeological features.

Other Techniques:
Use *more than one technique at some locations* to identify more archaeological feature types.

Alternative techniques should be sought *where geological conditions are unfavourable for magnetometer survey*, or where specific archaeological sites (masonry structures, *etc.*) are suspected.

Avoid prescribed rates of survey techniques. Specifications have previously allowed for a sample of earth resistance survey (typically around 20% of the area from an earlier magnetometer survey). Historically, these surveys were only actually *used* or *taken-up* 63% of the time.

- The use of earth resistance and/or other techniques needs to be enhanced by *requiring* it when specified.
- This is especially important in the *absence* of magnetometer anomalies to introduce a 'control' element.

Earth resistance and/or electromagnetic surveys should be used to supplement magnetometer surveys, where necessary.

Surveying more than required:
The minimum survey area required to visualize geophysical contrasts should be 40m x 40m. The effect of *future* sources of magnetic interference (traffic, fence lines, *etc.*), should also be considered. 20% of the Legacy Data included magnetometer surveys located *beyond* the road scheme. These surveys were partially impacted by magnetic interference generated by the new road itself, anomalies that extend several metres in width on either side of the road.

Consideration must given to how much information will be lost when sampling. The examples below illustrate different methods of sampling the same survey area. Method (A) indicates a pair of enclosures and associated occupation activity. The top left of the plot contains interference from a strong magnetic source.

A: Full coverage magnetometer data at Chapelstown, Co. Carlow.

B: 50% coverage using 20m chequerboard grids. This method will miss features less than 20m in size, but creates a very good background for spotting discrete linear / curvilinear features that cross a survey area.

C: 50% coverage using 20m swathes. This method will miss features less than 20m in size, but creates a good background for spotting discrete features.

D: The same method as (C), with the swathes shifted in to the previously 'blank' areas. For prospection there is no way of telling in advance if the survey will 'hit' archaeological deposits; the 'sample' is systematic.

E: 50% coverage using 10m swathes. This method will miss features less than 10m in size and creates a reasonable background for spotting discrete features.

F: 50% coverage using 5m swathes. This method will miss features less than 5m in size (hearths, kilns, furnaces, *etc.*) and creates a poor background for spotting discrete features.

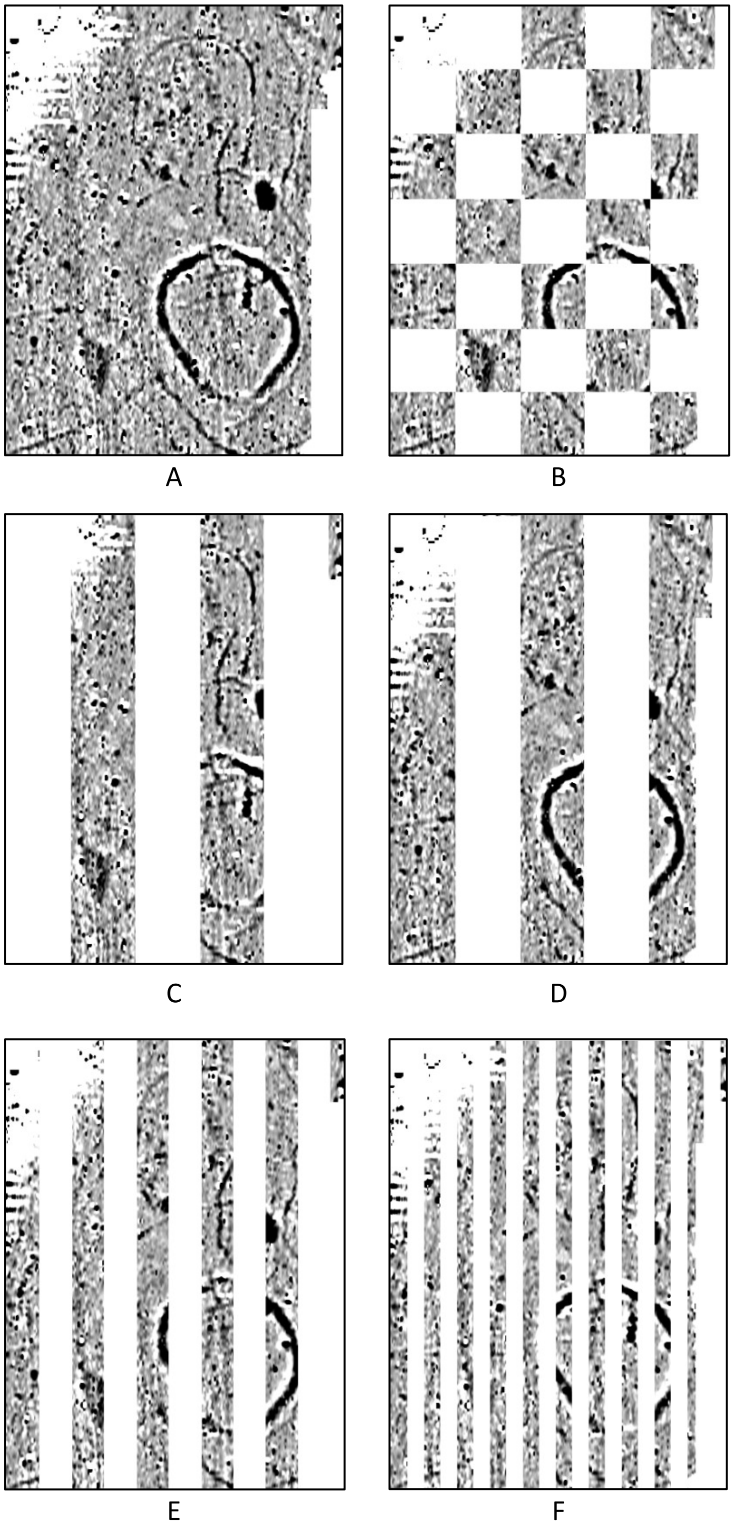


Figure 25. Example of sampling strategies for very large survey areas.

Plot: 100m x 140m -1 nT (White) to 2 nT (Black). North at top. Original images after GSB (2004), with additions.

Recent observations (CAGS 2014) suggest that sampling strategies are beginning to fall out of favour in deference to 'full' or 'reduced' coverage surveys ('reduced' survey confined to regular shaped rectangular blocks, avoiding irregular areas with respect to field boundaries).

5.2.6 Historic Sampling Strategies used along the length of a road corridor 2001-2010

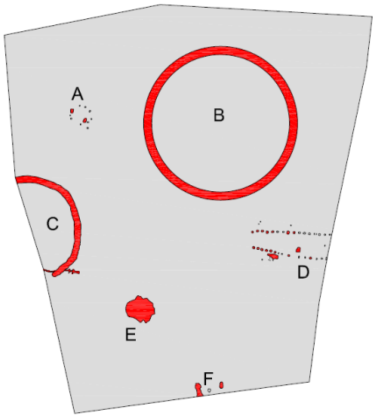
100% coverage of a corridor is the most preferable form of assessment as all areas are covered evenly, albeit through a sampling strategy - from a geophysical perspective the survey area is still 'sampled' as a magnetometer cannot identify *all* archaeological features and the spatial resolution is not great enough to identify *all* subtle features such as small pits, post-holes and inhumations. From a 'sampling strategy' perspective, a 100% detailed approach is the highest achievable form of investigating a landscape; however a 100% survey could still be inadequate if the spatial resolution is too great.

Areas of Archaeological Potential (AAP) and Site and Monument surveys are typically assessed with detailed magnetometer surveys. Road schemes that require End-to-End Coverage (EEC) represent the least frequent type of assessment commissioned by the NRA between 2001-2010, but account for the largest area.

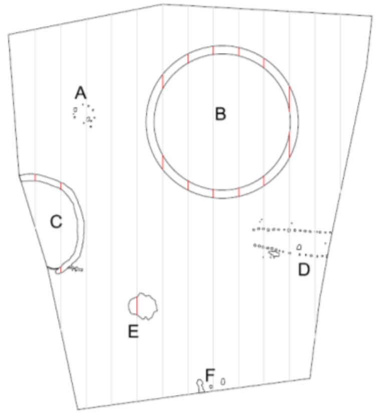
EEC assessments occurred in two or more phases of work, the first being a form of reconnaissance, the second a sample of detailed survey. All EEC assessments used magnetic or electromagnetic prospection methods in the first instance (Table 14). Phase 1 techniques varied, Phase 2 is always comprised of a detailed magnetometer survey. Occasionally a third phase of assessment occurred, using earth resistance surveys. EEC surveys investigate a wide range of geologies, soils, landscapes and topography via a variety of methodologies. The sampling strategies historically used to assess EEC road schemes by the NRA (Figure 26) are briefly discussed below.

Phase 1 Method of Assessment	Area Coverage of the Road Corridor	Frequency
Magnetometer Surveys		***Total: 21***
Detailed Magnetometer Survey 1m x 0.25 m	100%	4
Detailed Magnetometer Survey 1m x 0.25 m (Sample Strip)	30%	2
Detailed Magnetometer Survey 1m x 0.25 m (Sample Strip) flanked by two Magnetic Susceptibility transects	32%	4
Unrecorded Magnetometer Scanning	7-10%	6
Recorded Magnetometer Scanning & Magnetic Susceptibility	45%	5
Magnetic Susceptibility Surveys		***Total: 8***
Centreline Magnetic Susceptibility	1%	2
Magnetic Susceptibility 10m x 10 m	100%	4
Magnetic Susceptibility 5m x 5 m	100%	2
Total Number of road schemes that were assessed with End-to-End Coverage:		***29***

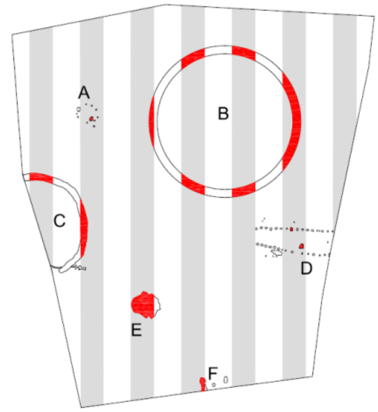
Table 14. Methods of Phase 1 End-to-End assessments from the 2001-2010 NRA Legacy Data.



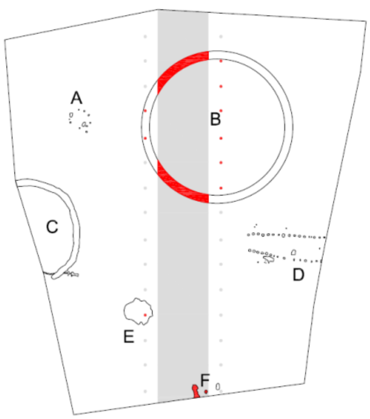
Detailed Magnetometer Survey
(1m x 0.25m)



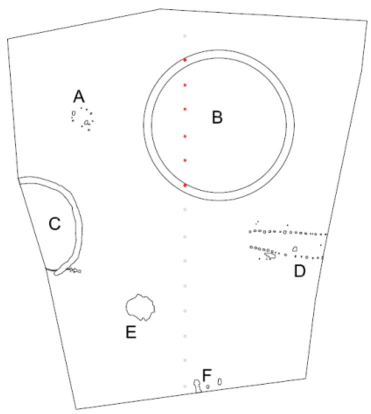
Unrecorded Magnetic Scanning
(10m transect spacing)



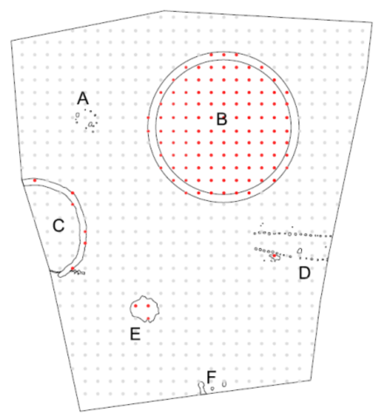
Recorded Magnetic Scanning
(1m x 0.25m; 9m swathes, 11m gaps)



Sample Strip: Detailed Magnetometer Survey (1m x 0.25m) flanked by two Magnetic Susceptibility transects (sampled 10m along the line)



Centreline Magnetic Susceptibility
(sampled 10m along the line)



Detailed Magnetic Susceptibility
(5m x 5m)

Figure 26. Historic Phase 1 End-to-End methods from the 2001-2010 NRA Legacy Data.

Sampling strategies are compared over a fictional area comprised of real and idealized archaeological features to illustrate the potential coverage for each method (in grey) and for each individual site (in red). The detection (and subsequent interpretation) of the archaeological features depends on soil type, feature contrast and sample resolution.

A: Circular post structure at Derryvorrigan 2 (Lennon 2008).

B: Idealized circular enclosure ditch, 30m diameter.

C: Ringfort enclosure at Magheraboy (Danaher 2007).

D: Post-pit alignment at Ballingowan 4 (Bartlett *et al.* 2010).

E: Burnt mound of stones at Ballyclogh South (Whitty 2009).

F: Cereal-drying kiln, bowl furnace and oval pit at Derrinsallagh 3 (Lennon 2009).

- Detailed Magnetometer Survey – Full Coverage (100% Area Coverage of the Road Corridor)

Detailed magnetometer surveys were used in 14% of road corridor assessments.

An entire road corridor is covered with a 100% detailed survey (where practical). The detailed magnetometer survey was typically carried out at a spatial resolution of 1m x 0.25m.

A detailed survey will ensure that all soils within a road scheme are assessed; a wide range of archaeological features that create measurable magnetic anomalies will be identified by this method. As such, a detailed assessment is the most comprehensive form of magnetometer survey. Research undertaken by the NRA Fellowship found that detailed magnetometer surveys over exclusively sedimentary rocks have a highly effective success rate on NRA road schemes (88%) and are particularly well suited to the identification of large archaeological site types (Bonsall *et al.* 2014a, 2014b).

- Detailed Magnetometer Survey - Sample Strip (30% Area Coverage of the Road Corridor)

Detailed sample strips of magnetometer survey were used in 7% of road corridor assessments (a further 14% were supplemented by magnetic susceptibility surveys).

Any road corridor represents a narrow area, a geophysical survey requires wide areas of background data to discriminate between natural and archaeological responses. The sample strip method investigates an area of the road corridor which is narrower still. For this method, 30% of the road corridor width was sampled using a central strip or ribbon of detailed magnetometer survey, typically 20m wide, collecting data at a 1m x 0.25m spatial resolution.

Most magnetometer sample strip surveys (80%) also included magnetic susceptibility survey transects to assist the interpretation of the magnetometer data and to inform a strategy for additional targeted magnetometer surveys (see for example Cork 2004).

Large linear and curvilinear anomalies that pass through the strip were difficult to identify due to the narrow survey area and poor contrasts. Strongly magnetic cultivation furrows also reduced the effectiveness of this method. 20m wide survey strips were largely ineffective; particularly where multiple small and irregular shaped fields impacted upon the length of each strip. Geophysicists were unable to make informed statements regarding the remaining soils beyond the sample strip. The minimum survey area required to visualize geophysical contrasts should be 40m x 40m.

- Magnetometer Scanning
    - Unrecorded Magnetometer Scanning (7-10% Area Coverage of the Road Corridor)

Unrecorded magnetometer scanning accounted for 21% of assessments.

The NRA applied what was considered a 'standard' scanning methodology such as that noted by the English Heritage (David 1995) and IFA guidelines (Gaffney *et al.* 2002). Scanning is less intensive than a detailed magnetometer survey, allowing for a rapid assessment of very large areas, by walking along transects spaced 10m-15m apart.

The origin of unrecorded scanning at 10m transect intervals was noted by Clark (1996) for being highly effective for rapidly assessing the density of occupation within Iron Age hillforts in England, rather than prospecting across large areas or narrow corridors. The present research found that scanning failed to identify 71% of subsequently excavated archaeological sites on NRA road schemes (Bonsall *et al.* 2014b).

Unrecorded scanning does not collect data and no paper or digital records are created. Scanning is typically followed up by a sample of detailed magnetometer survey. The rate of subsequent detailed surveys varied between projects (from 14% to 78% of the scanned area) but was, on average, 30% of the total scanned area. The minimum survey area required in the subsequent detailed work to visualize geophysical contrasts should be 40m x 40m.

Natural variations in the bedrock and near surface geology can often exceed the background response. Individual anomalies are difficult to interpret and archaeological features cannot be distinguished from modern features. The scanning method is biased to moderate or strong magnetic anomalies (areas of burning, industry, large ditches, occupation activity) and is unlikely to identify weakly magnetic ephemeral features (such as those created by pits, post-holes, smaller ditches, gullies). Unrecorded scanning is strongly dependent on the geophysicist's experience of interpreting field data, rather than reflecting upon the subtleties of a digital dataset in an office environment.

English Heritage guidelines note that magnetometer scanning "may be used at the discretion of surveyors who are experienced in its application...[the] technique should not otherwise be included in briefs or specifications" and that it "should not be relied upon as the sole geophysical method used to evaluate an area" (David *et al.* 2008). Scanning was historically popular in the UK since the earliest commercial surveys of the 1980s. There is now a general consensus among UK curators and practitioners that scanning has been recently relegated in favour of detailed magnetometer surveys (see Appendix E and CAGS 2014), which, thanks to the latest multi-sensor instruments, make full / detailed coverage an affordable option. Scanning does not tend to be used in continental Europe. Additionally, Irish soils have a variable magnetic background that is rarely conducive to unrecorded scanning.

- Recorded Magnetometer Scanning (45% Area Coverage of the Road Corridor)

Recorded magnetometer surveys were used in 17% of road corridor assessments (a further 14% were supplemented by magnetic susceptibility surveys).

Bartlett (2003) proposed and subsequently used the recorded magnetometer scanning method on a small number of road corridors, some of which were supplemented by magnetic susceptibility surveys. In those cases, recorded scanning collected some magnetometer data although the technical details of the survey (sample resolution used, traverse direction) were unavailable for review.

The Bartlett method sampled 45% of the road corridor by collecting magnetometer data across 9m wide strips or swathes, alternating with 11m wide gaps. It is often difficult to visualise and recognise archaeological features within narrow swathes of data; large enclosure ditches might be appreciable across several equally spaced swathes but small and subtle anomalies are unlikely to be seen, as will archaeological features that only exist within the non-surveyed areas.

- Magnetic Susceptibility Surveys

  - Centreline Magnetic Susceptibility (1% Area Coverage of the Road Corridor)

The centreline magnetic susceptibility method was used in 7% of all EEC assessments. The methodology was used as a reconnaissance to determine suitable areas for subsequent detailed magnetometer and/or resistance surveys (O'Sullivan 2004).

The magnetic susceptibility survey sampled the road corridor at a rate of 1% area coverage by collecting a single traverse of data at 10m intervals along the centreline of a road corridor. The data varied considerably between and within adjacent fields and was of very limited archaeological use (Bonsall and Gimson 2004; Krahn 2005). The method only characterised the general magnetic susceptibility response of each individual field. It is wholly biased to soils on the centreline and it is difficult to understand the significance of each value in relation to potential underlying archaeological deposits. The surveys were typically followed by limited samples of detailed magnetometer (1.1-1.4% area coverage of the road corridor) and earth resistance (0.3-1.2% coverage) surveys, neither of which were large enough to adequately assess the archaeological potential of a road scheme.

Best practice (David *et al.* 2008) recommends that single long traverses of magnetic susceptibility measurements should be avoided. This method should not be used to prospect for archaeological remains and should be avoided in future.

- Detailed Magnetic Susceptibility (100% Area Coverage of the Road Corridor)

A detailed magnetic susceptibility survey occurred on 21% of EEC assessments. An even coverage was achieved via a symmetrical spatial resolution across the entire corridor (60% were carried out at 10m x 10m and the remaining 40% at 5m x 5m).

Magnetic susceptibility covered the entire road corridor for 100% area coverage. The method can be useful in some circumstances, particularly if used to supplement detailed magnetometer data. However, as a reconnaissance technique, magnetic susceptibility surveys were hampered by strong variations in the local geology and within individual fields.

The speed of modern detailed magnetometer surveys has, to some extent, removed some of the benefits offered by a preliminary magnetic susceptibility survey e.g. in 2003 a magnetic susceptibility survey at 5m x 5m resolution assessed 4.28 ha per day (Bonsall and Gimson 2003a), whilst in 2010 a magnetometer survey using hand-held instruments at a 1m x 0.25m resolution assessed 5 ha per day (Bonsall and Gimson 2010).

5.3 Seasonality

The time of year at which data are collected can influence the outcome of a geophysical survey. Infrastructure assessments occur throughout the year; some road scheme schedules can be flexible whilst others must accommodate fixed deadlines. It is assumed however, that the time of year at which a survey is carried out *can* be chosen in advance, therefore it is important to be aware of the seasonal influences and limitations that impact upon the success or otherwise of geophysical surveys.

General Advice on Seasonality

Ireland has very little 'seasonal' variation due to a *reasonably* stable climate.

Monthly *earth resistance surveys found that ditched enclosures could be identified* throughout a 15 month seasonality study period (and in each of the datasets from three earth resistance probe arrays).

From these results we know that:
There is *some variation* at certain points of the year:

The *optimum* time for data collection was found to be in spring.

The *least optimum* time was found to be June and December.

During very dry periods it can be expected that in some parts of the country (particularly the southeast, where rainfall is lower than the rest of the country) *earth resistance data may not be collected* due to the effect of evapotranspiration preventing the insertion of probes into the ground.

However, *the contrasts that we wish to measure exist at depth*, beneath the dry surface, therefore *methods that do not require ground contact, such as electromagnetic conductivity surveys*, can act as a suitable alternative.

5.3.1 Review of geophysical surveys through the year

5.3.1.1 Legacy Data Archive

The NRA Legacy Data contains a great deal of information regarding the weather, soil conditions and time of year encountered during the collection of geophysical data. However, weather and soil conditions are difficult to assess for large road scheme surveys that occurred over several weeks and across several kilometres; the conditions are likely to be quite changeable and are probably generalised in the grey literature e.g. the weather was mild during the 8 weeks of survey.

- Weather

Weather conditions were recorded in 41% of the geophysical reports (Figure 27). In terms of rainfall, wet weather occurred during 44% of the surveys (5% of those being 'very wet'), dry weather in 26% (2% being 'very dry'), 'changeable or variable' conditions in 25%, and 5% were 'fine or mild', all of which gives a reasonable insight in to the nature of Irish weather.

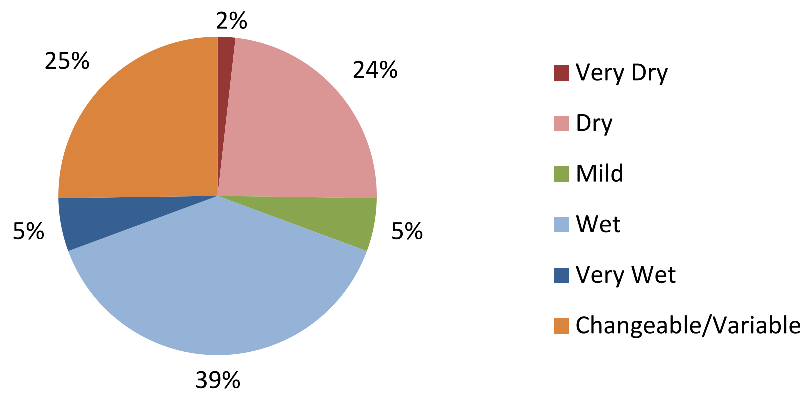


Figure 27. Weather conditions encountered in the 2001-2010 NRA Legacy Data.

- Soil Conditions

Soil conditions were recorded in 49% of the geophysical reports (Figure 28). 33% of soils were moist, 30% were dry (3% being very dry), 23% were wet, 11% were water-logged, 2% were boggy, and the rest were variable.

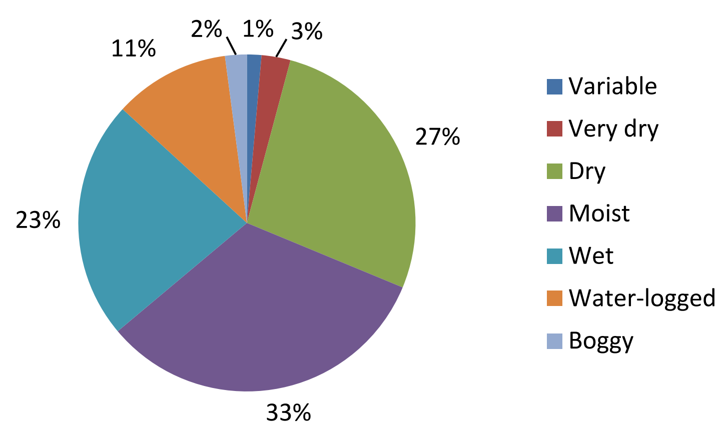


Figure 28. Soil conditions encountered in the 2001-2010 NRA Legacy Data.

- Survey Duration and Periods

The time of year during which geophysical survey fieldwork occurred was recorded in 92% of the reports (Figure 29). The vast majority of surveys (81%) were carried out in less than 2 months and 6% of surveys took longer than 5 months. The surveys were carried out at all times of the year and are reasonably distributed by both month (Figure 30) and season (Figure 31). Surveys occurred most frequently in November (11.4%) and April (11.1%) and least often in March (4.6%). Slightly more surveys were carried out in summer (27%) and autumn (25%) than winter and spring (24% each).

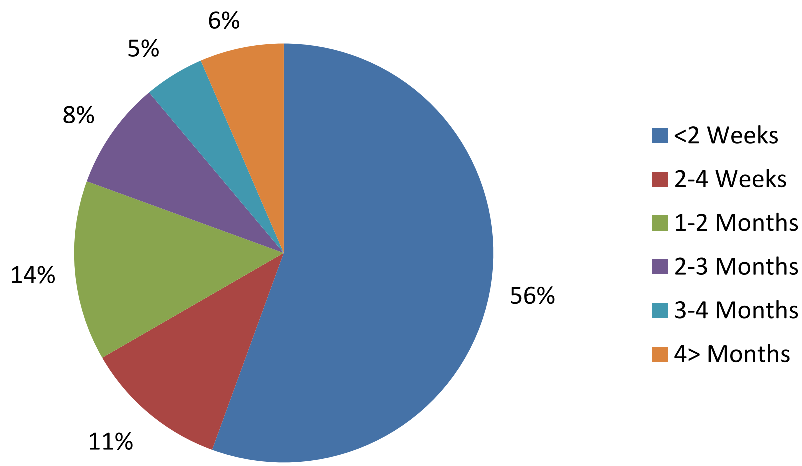


Figure 29. Duration of geophysical surveys in the 2001-2010 NRA Legacy Data.

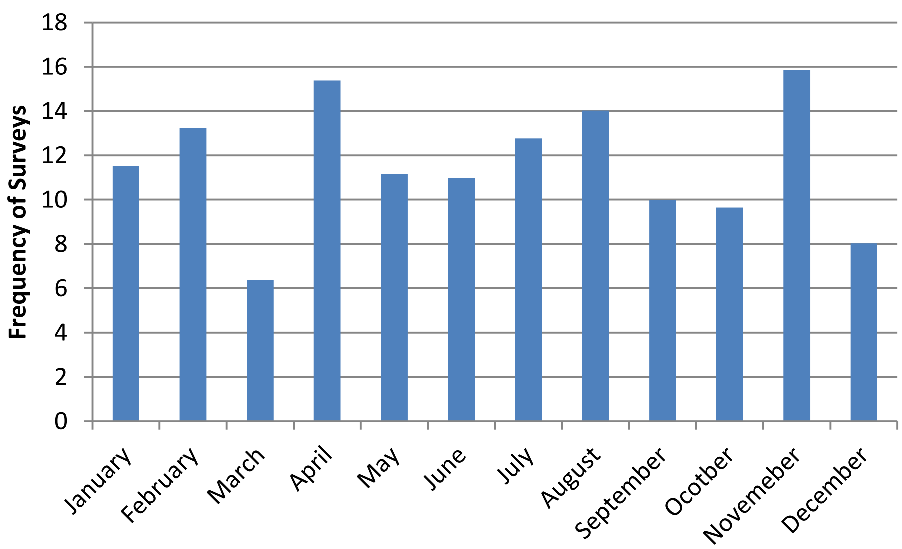


Figure 30. Frequency of geophysical surveys throughout the year in the 2001-2010 NRA Legacy Data.

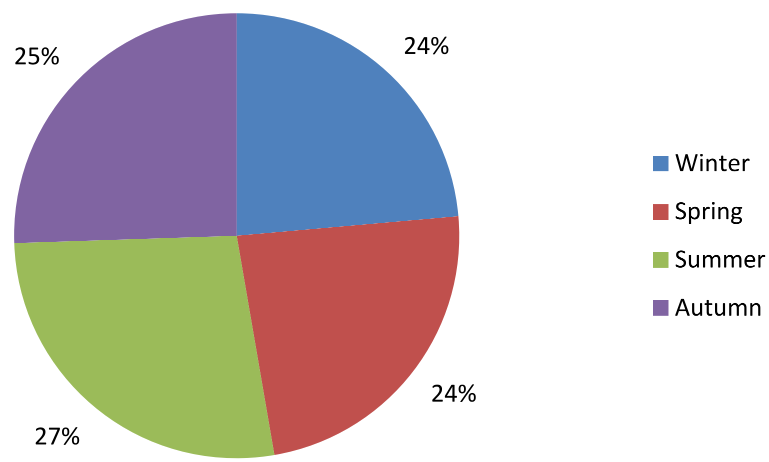


Figure 31. Seasonal frequency of geophysical surveys in the 2001-2010 NRA Legacy Data.

5.3.1.2 Practical Considerations

The Legacy Data suggest that between 2001-2010, most geophysical surveys were carried out during wet weather conditions, with only 2% being carried out in very dry weather. The soil conditions were mostly moist, dry or wet and this did not appear to vary strongly between seasons.

Rainfall does not generally effect the *collection* of geophysical data, although very heavy rainfall may cause erroneous earth resistance data due to water collecting upon the exposed probe terminals. The main concern for rainfall is health and safety, as fieldwork occurs on slippery and uneven surfaces. Rainfall can also result in poor data collection, reduced positional accuracy and slow or impeded progress across wet ploughed fields.

Water-logged or boggy soil conditions (accounting for 13% of cases), were mostly encountered on peaty ground during autumn and winter, although some encounters occurred during the summer. These soils can impede the smooth and uniform collection of detailed geophysical data and/or prevent survey progress. Geophysical surveys should try to avoid areas of water-logging and poaching where possible due to water-ingress in the instruments, to avoid poor data collection and for health and safety reasons. In many cases, this simply means carrying out a geophysical survey during favourable weather rather than the depths of winter, possibly allowing for re-mobilisation where required.

Extremely dry soil conditions were recorded in 3% of cases (mostly in the summer). Compaction made in very moist or boggy ground (e.g. from cattle hoof-prints or tractor wheel ruts *etc.*) can cause depressions (>0.1m) that bake hard during dry summer conditions to create a very unstable surface upon which to walk. There have been instances where detailed geophysical surveys were abandoned on such ground due to the collection of poor quality magnetometer data, uneven earth resistance probe contact and health and safety concerns.

5.3.2 Seasonal Variations in Moisture Change

Seasonal changes in rainfall alter the moisture content in the ground, which in turn affects the ease an electrical charge can be passed through the soil. Earth resistance data are strongly influenced by the moisture content in the ground (Al Chalabi and Rees 1962; Hesse 1966; Clark 1980), as are conductivity, electrical resistivity tomography and ground penetrating radar data. There are variations in climate for individual countries and regions, however the weather can generally be expected to influence earth resistance data in the following ways (Schmidt 2009):

- In idealised circumstances
  - a moisture retaining ditch creates a low resistance contrast with the background soils
  - a stone wall will create a strong high resistance contrast.

- During very wet weather
  - excess water can saturate soils and reduce the contrast of a ditch compared to the background soils
  - water can pool upon the surface of a stone wall, allowing an electrical charge to pass through easily, creating a low resistance anomaly and inverting the expected high resistance response

- During very dry and hot weather
  - evapotranspiration may cause vegetation to take out all the moisture in a ditch, which may bake hard and create a high resistance anomaly, rather than a typical low resistance anomaly
  - the contrast is reduced so that a stone wall may be difficult to distinguish from the surrounding dry soils.

- Earth Resistance Seasonality Study

The Research Fellowship carried out seasonality surveys over a 15 month period (January 2011 to June 2012) to determine the effect of weather upon earth resistance surveys on Irish soils. The surveys obtained earth resistance data at monthly intervals over a 40m x 40m area that encompassed ditches from two Early Medieval enclosure monuments at Kilcloghans, Co. Galway.

- Probe Geometry

The underlying earth resistance response to an electrical charge can be altered by changing the 'probe geometry' on the array in a number of ways. Changing the probe geometry influences the depth of penetration and the resolution of the archaeological feature being examined, as well as practical issues such as survey speed and set-out time (see Section 2.2.2 Earth Resistance & Resistivity Instruments). The assessment used the three common earth resistance arrays for each survey (Twin-probe, Wenner and Square arrays).

- Results

The surveys identified a time-lag delay (of approximately one month) between rainfall and a measurable moisture change in earth resistance data e.g. high rainfall in April has a measurable effect on earth resistance data gathered in May (Figure 32). Seasonality surveys in the UK (Parkyn 2012) carried out at more frequent intervals, have charted time-lags of between one and four weeks depending on the overall weather history of a site.

In the Irish context, resistance over the ditches were on average 67% of the background soil response i.e. the ditches contrasted by 33% from the background. The contrasts between the ditches and the background soils were strongest between March-May (on average a 44% contrast occurred during these months that corresponded to periods of reasonably low rainfall and gradually increasing temperature). Data collected in April afforded the highest contrast factor at 50%. The poorest contrast factors were observed in the months of June (a 26% contrast due to low rainfall and high temperature) and December (a 26% contrast due to low temperature and high rainfall).

- Circumstances preventing the collection of data

Extremely dry soil conditions were recorded in 3% of the Legacy Data. During these conditions it is sometimes impossible to *collect* earth resistance data. During periods of low rainfall and warm weather, very dry soils can actually *prevent* the use of an earth resistance survey due to an *inability to insert the probes in to the ground*. This example of seasonality (due to evapotranspiration) occurs at the near surface and not within the archaeological features themselves.

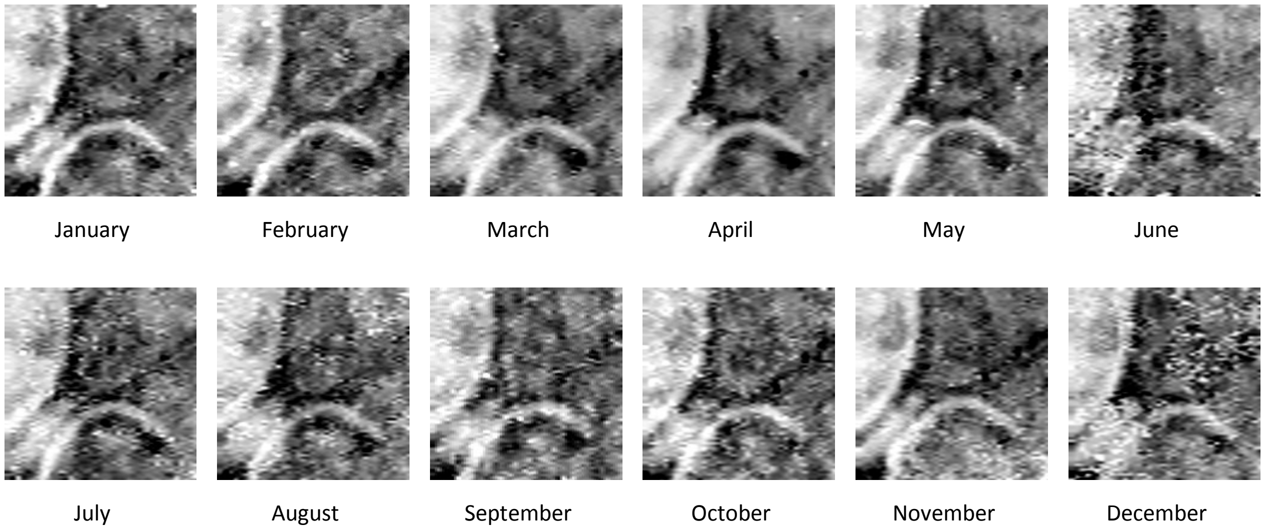


Figure 32. Earth resistance seasonality data gathered at monthly intervals in 2011.
Data were collected over a 40m x 40m area using a Wenner array. The area encompassed arcing ditches from two Early Medieval enclosure monuments at Kilcloghans, Co. Galway. Data are displayed at +/- 2 standard deviations from the mean (black=high resistance, white=low resistance). Data collected and displayed at 0.5m x 1m.

A clear example of this type of seasonal problem occurred in the southeast of the country during the summer of 2011, at an enclosure in Davidstown, Co. Kilkenny (Bonsall *et al.* 2013a). An electromagnetic survey, which did not require ground contact, returned very clear and coherent apparent conductivity data which was used as a proxy for the unobtainable earth resistance data (Figure 33). The conductivity survey indicated the presence of ditches and banks at the enclosure site.

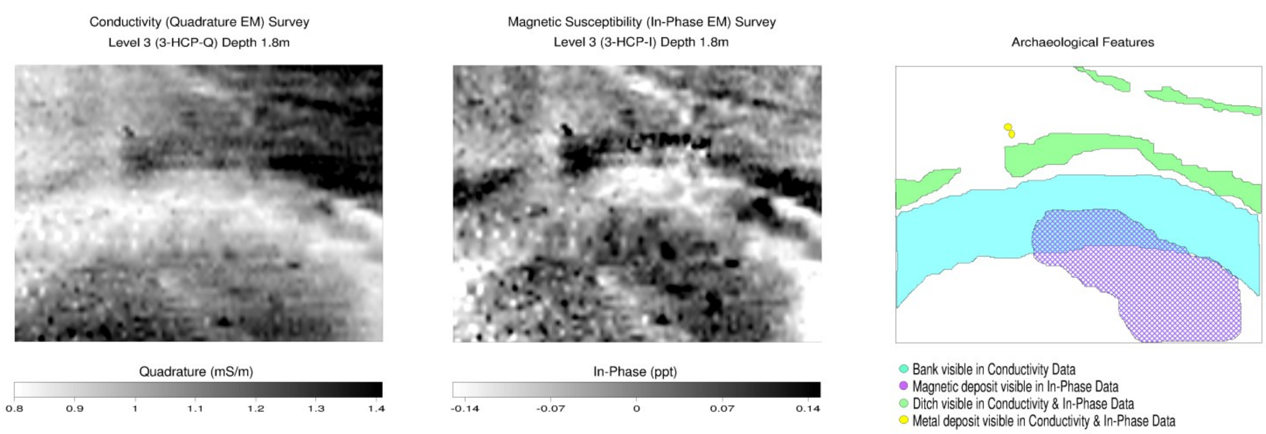


Figure 33. Electromagnetic apparent electrical conductivity data as an alternative to earth resistance data.
Data reproduced from Bonsall *et al.* (2013a). In June 2011, a dry early summer prevented the insertion of earth resistance probes into the very dry surface soils at Davidstown, Co. Kilkenny. An electromagnetic instrument was used to collect apparent electrical conductivity data as a suitable alternative to the earth resistance survey, which had to be abandoned. The electromagnetic instrument also simultaneously collected apparent magnetic susceptibility data. Both of the electromagnetic datasets identified an enclosure ditch.

5.4 Data Presentation and Visualization

The following section briefly discusses the steps used to take field data and synthesize the results into a report. This is particularly important as there have been some instances in the past where non-archaeological geophysicists have applied erroneous methods of processing and visualization – the NRA should be in position to recognize 'bad data' or visualization and request alterations or further data collection as an alternative.

- Downloading Data

Geophysical data are stored in data loggers associated with the geophysical instrument; data are typically downloaded via dedicated geophysical software to a field computer once or more each day and are referred to as 'raw' data. The download software varies for each manufacturer of geophysical instruments, but generally outputs the raw data to a common type of file(s) that can be used by other geophysicists.

- Processing Data

The raw data are processed by a variety of methods using one or more geophysical software packages (Figure 34). Processing 2D data (such as magnetometer and earth resistance data) can be relatively straight forward, whilst 3D data (such as that derived from GPR) can require complex and time consuming processing steps.

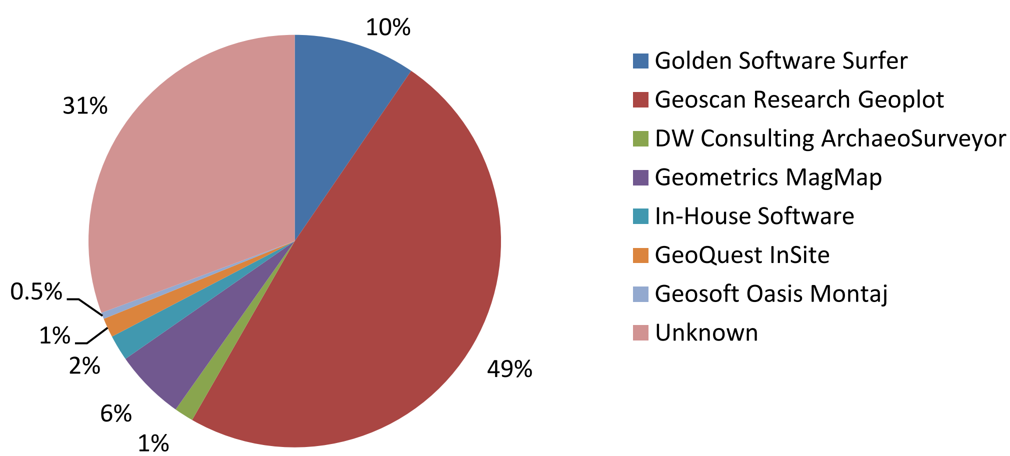


Figure 34. Software used to process geophysical data gathered in the 2001-2010 NRA Legacy Data.

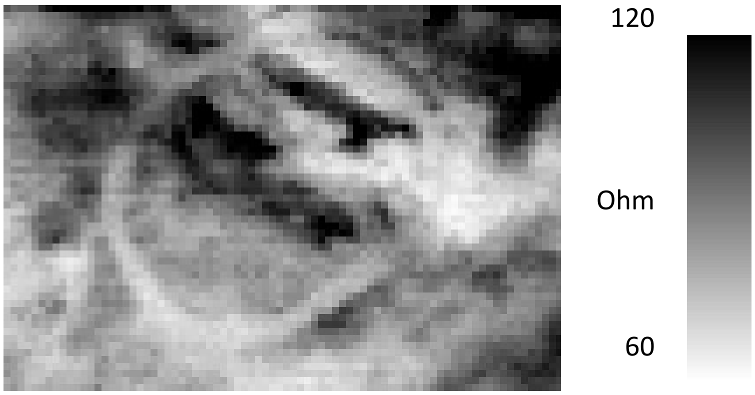
Pre-processed data improvement steps (e.g. despiking, data equalization around zero, destagger) are required to fix common minor flaws in the collection of 2D data. The pre-processed data are reinstated to their correct values and position and are not fundamentally altered.

Further processing steps (e.g. filtering, interpolation) are used to improve the overall appearance of data and/or emphasize specific anomalies (Figure 35).

Filtering smoothes data and can be used to remove the impact of near surface geology or improve the response of subtle archaeological features. Low Pass Filters (LPF) are commonly used to reduce the background noise of magnetometer data. High Pass Filters (HPF) are used to emphasize weak contrasts and subtle responses by removing broad background changes; these are commonly used to improve earth resistance data. LPF does not significantly alter the statistical properties of data, whereas HPF flattens data and equalizes it (changing the range of resistance data from a purely positive measurement greater than zero e.g. 60 to 120 ohms, to both positive and negative measurements centered around zero e.g. changed to -10 to +10 ohms).

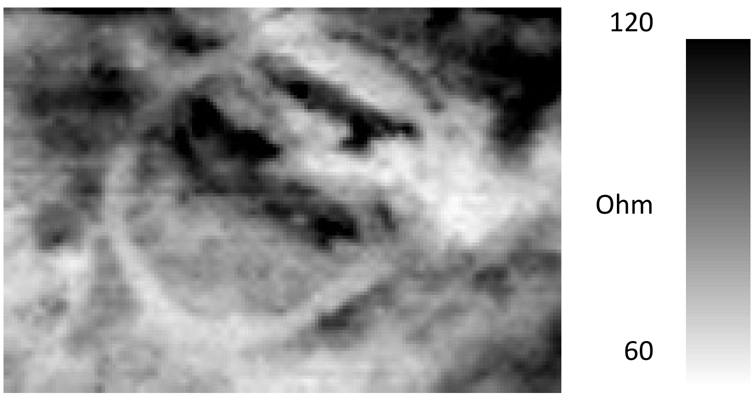
Interpolation is used to 'fill in the gaps' between collected data (Figure 36). For hand-held collected data, the spatial resolution of a magnetometer survey is typically 1m x 0.25m - the image of the data is visually improved if the points are interpolated to 0.5m x 0.25m or to a symmetrical spacing of 0.25m x 0.25m. The interpolation function fills in the gaps by taking the surrounding values into account. Interpolation does not alter the statistical properties of the data but it can increase the 'size' of small scale, high contrast and potentially erroneous data. Generally the process of interpolation smoothes the data and is usually the last processing step.

Filtering alters the data and can in some instances remove archaeological features. Archaeological geophysicists must understand these processing functions and compare the raw, the pre-processed data and the processed data to ensure archaeological features removed via processing are accounted for and interpreted, even if they cannot be seen in the presented data plots. In some cases, new 'anomalies' can also be created by the processing steps applied, and these are normally referred to in the report to avoid subsequent end-users placing undue relevance upon artefacts of processing. Processing, particularly image processing should occur as and when required and should not be applied universally to all data in a prescribed manner.



Raw earth resistance data

The data were collected (and are displayed) at a spatial resolution of 1m x 1m.



De-spiked and interpolated earth resistance data

The data collected at 1m x 1m have been interpolated to (and are displayed) at 0.5m x 0.5m, to give a smoother appearance.

High pass filtered earth resistance data

The data are still displayed at the (original) spatial resolution of 1m x 1m, but have been high pass filtered (to remove broad natural and geological changes and to emphasize smaller scale changes).

High pass filtering alters the statistical properties of the data and equalizes them around zero.

Figure 35. Some common processing steps applied to 2D geophysical data.
Data are from Chapelstown enclosure, N9 Carlow Outer Relief Road (GSB 2004)

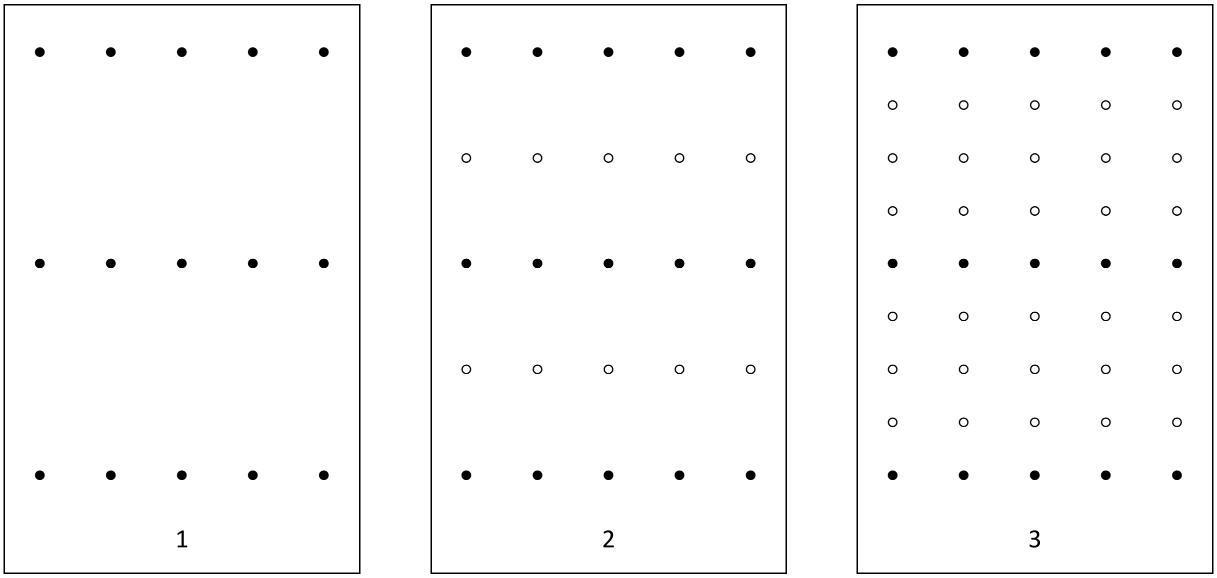


Figure 36. Interpolation of data points.

Interpolation fills in the gaps between collected data points in order to improve the image. 1) Solid circles represent data collected at a spatial resolution of 1m x 0.25m. 2) Hollow circles represent points that have been interpolated between the collected data to create a smoother appearance at a spatial resolution of 0.5m x 0.25m. 3) Hollow circles have been interpolated further to give a symmetrical spatial resolution of 0.25m x 0.25m.

- Archiving Geophysical Data

There has, in the past, been some confusion regarding the archiving of geophysical ‘data’. Most geophysical reports are submitted to the NRA as pdf documents, often supplemented by georectified images and interpretations in CAD or GIS format, to inform the location of subsequent investigations. Whilst those files are important end-products, they do not represent the entire corpus of geophysical ‘data’. The ‘data’ represents each and every measured reading or response obtained in the field and is commonly archived as ASCII ‘xyz format’ files – these files are not archived in the written report itself but as a number of digital files (typically supplied on CD-ROM). These files can be opened in text editors or spreadsheets and may be imported into most geophysical software packages. Outputs may typically be expected as one file, per technique, per survey area (or per field).

The majority of NRA specifications have previously requested that consultants follow the best practice archiving guidelines (Schmidt *et al.* 2002; Schmidt and Ernenwein 2011) issued by the Archaeology Data Service (ADS). Only 42% of the 2001-2010 Legacy Data had associated digital ‘data’ (in the format required by the ADS guidelines) archived with the NRA. It is important for digital data to be archived so that it can be revisited in the future and can be used to validate how a geophysical survey was carried out.

Pre-processed ***data improvements*** *should be archived* with the NRA in 'xyz format' ASCII data, following the most recent best practice guidelines (Schmidt and Ernenwein 2011). This ensures that subsequent users can review, recreate or reprocess the archived data.

Processed data (e.g. filtered or interpolated data) may *also* be archived *at the discretion of the contractor* as the plots presented in a report best illustrate the accompanying interpretation rather than the full range of data; the requirement for archiving therefore, should always be pre-processed data rather than processed data.

General Advice on Visualizing Geophysical Data

All geophysical techniques:
Data derived from large road schemes will have a variable background.

The clipping values should show the *most appropriate range* for a given data set
These need not be the same throughout a report

Colourscale plots, introducing a range of dynamic colours, can be useful to highlight certain anomalies e.g. areas of burning, ferrous responses, geology, strong (modern) interference.

Unnecessarily large clipping values that show all or most of the data:
Tend to 'wash-out' anomalies of archaeological interest (Figure 38).
Can be used to mask poorly collected/processed data.

- Visualizing Data

A 1m x 0.25m magnetometer survey will collect 40,000 data points per hectare, a 1m x 0.5m earth resistance survey will collect 20,000 data points; geophysical software typically presents these data as a greyscale plot, where individual data points are assigned a shade of grey depending on their value.

The range of magnetometer data could be as large as +/-1,000 nT or smaller than +/-10 nT. Earth resistance data could be as large as several hundred ohms or smaller than 10 ohm, depending on the geology and the array used.

The entire range of data is unlikely to be reproduced in a report, but will be 'clipped' to show the most relevant archaeological data (Table 15 and Figure 38). The range of the clip size is entirely dependent on the data collected. Most of the archaeological information is typically found within +/-1 standard deviation from the mean of magnetometer data and +/-2 standard deviations from the mean of earth resistance data. Not all of the interpreted geophysical anomalies will be visible on the final data plots. In some cases, the clip values selected will blur or shrink the response of weakly contrasting anomalies, and in other cases the processing steps applied to the data may have removed some anomalies entirely.

Soil type	Potential clipping range (to visualize archaeological features)
Weak contrast soils e.g. some areas of Carboniferous limestone and sandstone	-0.5 to +0.5 nT (may require a very narrow data range)
Average soils	Variable e.g. -1 to +2 nT, -2 to +2 nT, -3 to +3 nT
High contrast soils	-12 to +12 nT (may require a large data range)

Table 15. Examples of typical magnetometer clipping ranges for different soil contrasts.

- Presentation of Data

Images created in processing software can be exported as graphic files (jpeg, bmp, png, tiff *etc.*). The graphics files are 'frozen' or captured images of the geophysical data – data cannot be altered at this stage. Images can be inserted into a digital basemap or third party programs. Geophysical graphics are traditionally required by the NRA in Computer Aided Design (CAD) outputs for the benefit of subsequent phases of archaeological investigation (Figure 37).

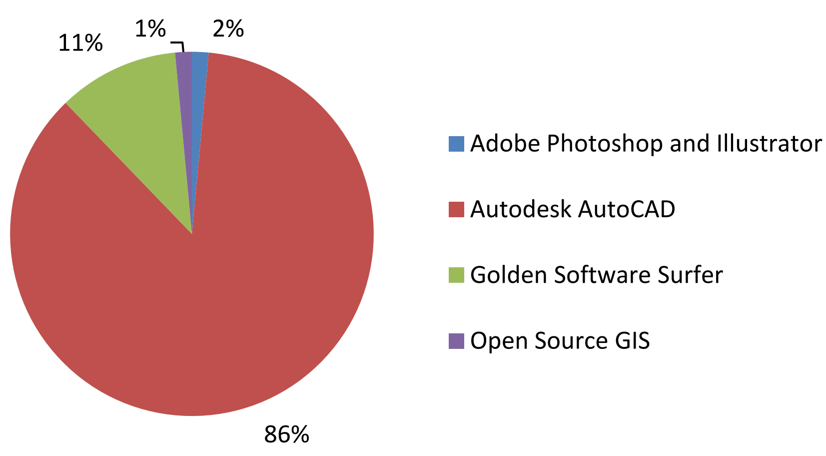
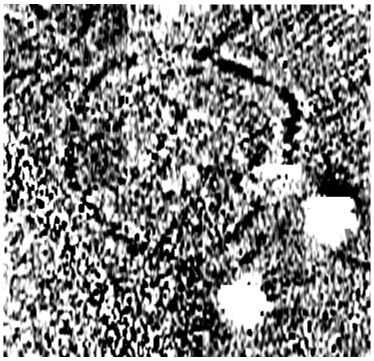
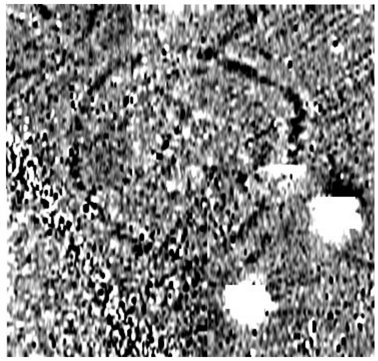
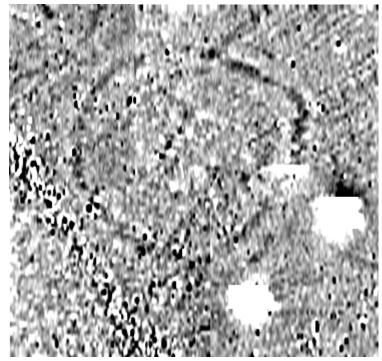
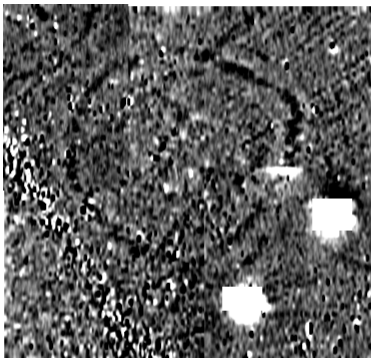
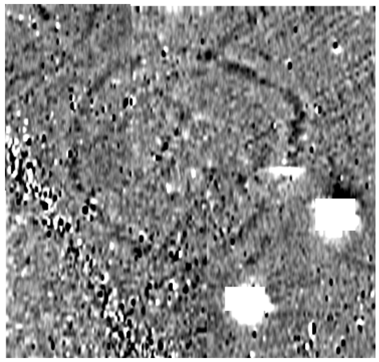
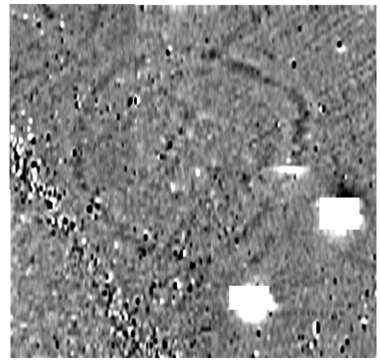


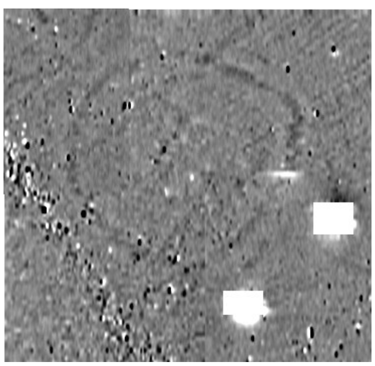
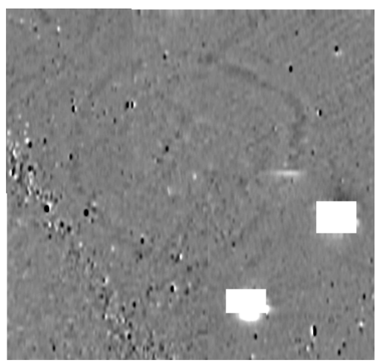
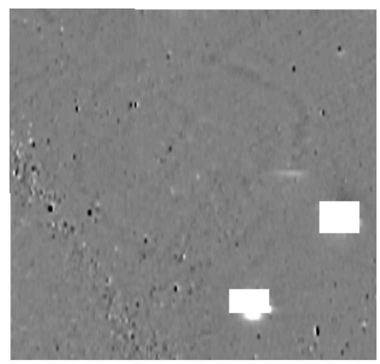
Figure 37. Software used by consultants in the 2001-2010 NRA Legacy Data to present their survey results.

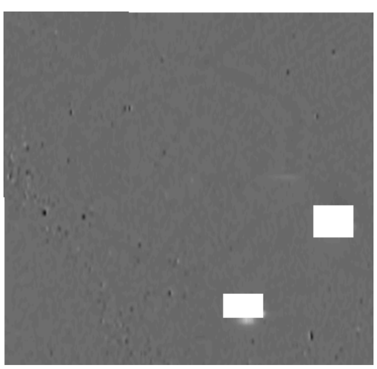
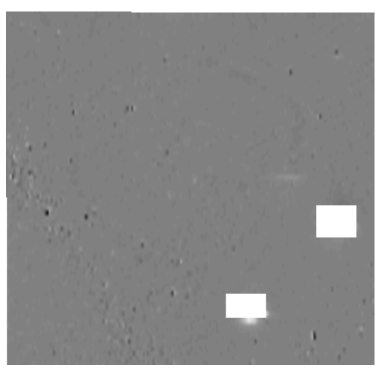
A: White-Black: -0.5 to 0.5 nT | B: White-Black: -1 to 1 nT | C: White-Black: -1 to 2 nT

D: White-Black: -2 to 1 nT | E: White-Black: -2 to 2 nT | F: White-Black: -3 to 3 nT

G: White-Black: -5 to 5 nT | H: White-Black: -10 to 10 nT | I: White-Black: -20 to 20 nT


90m x 90m Area.

Data collected at 1m x 0.125m, interpolated to 0.25m x 0.25m

J: White-Black: -50 to 50 nT

K: White-Black: -70 to 50 nT (this is the full range of data)

Figure 38. Various clipping ranges for magnetometer data.

Data from Kilcloghans enclosure, N17 Tuam Bypass. Blank areas represent strongly magnetic obstacles in the field.

Beyond the NRA Legacy Data archive, geophysical data are increasingly being incorporated into a Geographical Information Systems (GIS) which can be exported to CAD format (as a dxf file) if required. In a GIS, the *data*, not just the captured *images*, can be inserted and the clip value of the data can be altered as required. GIS data are increasingly used in archaeological geophysics as they can be integrated with a variety of other digital datasets (Neubauer 2004). GIS is highly suited to solving problems and answering research questions due to an ability to query and assess spatial information, rather than just display it.

Interpretation drawings should be drawn or digitized into CAD or GIS software. Geophysical data are not isolated sources of information; they must be presented and interpreted in relation to accurate and relevant mapping. Modern maps should be used as a basemap and reference should also be made to historic mapping, LiDAR data and aerial photography, where available in order to consider the source of geophysical anomalies.

'Floating' data are not an acceptable style of presentation in a report - these are instances of presenting geophysical data in isolation without any form of background CAD or GIS mapping, usually as an image file (Figure 39). Floating data reduces the usefulness of the geophysical survey, fails to tie the data into the real world and loses important information regarding the geographical context of the survey. Most geophysicists do not present floating data, however some have presented data in this manner in previous NRA reports. This practice is not encouraged.

In the past, another form of data display, XY Traceplots, were requested by the NRA as part of a geophysical report. These show the magnitude of the data along a line and represent an almost 'pure' way of visualizing the data. Geophysicists use XY Traceplots to make their interpretation, however it is usually sufficient to archive these on a CD-ROM, along with the pre-processed digital data.

Gridless GPS-acquired data should be presented as collected, i.e. with gaps (due to signal loss, obstacles or field boundaries) clearly illustrated within the survey plots, to avoid misleading interpretations.

Despite the presence of NGRs, a north arrow, chainage and the survey area, this style of display is poor as the data are not referenced to a digital basemap (although a digital basemap was provided on CD-ROM, but not in the report). Geophysical data should always be referenced to a digital basemap and 'floating' data such as this is not useful.

The clipped range of the data (+/-15 nT) is also too large. The data are derived from a caesium magnetometer and have been equalized around zero. The values displayed here have a range of 30 nT; archaeological anomalies are unlikely to exceed a range of 12 nT. The range featured in this plot is broadly comparable to images H and I in Figure 38, where the archaeological response has been mostly 'washed-out'.

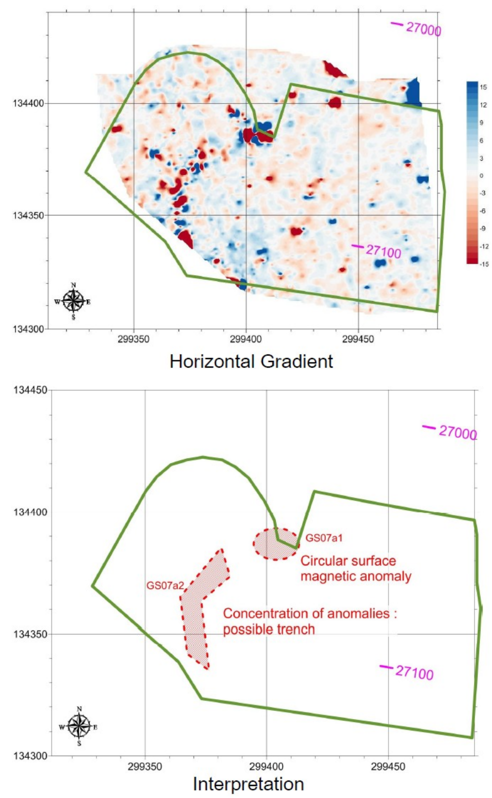


Figure 39. An example of 'floating' geophysical data.

General Advice on Methods of Geophysical Data Interpretation

Interpretation classes or categories vary wildly between geophysical consultants, dependent on experience, expertise, confidence and in-house terminology or styles. Some terms merely describe geophysical anomalies in simple terms e.g. 'archaeology' or 'natural/geology' whilst others will place a more archaeological interpretation upon the anomalies e.g. 'ditch', 'pit', 'industrial' or 'ferrous'.

Geophysical anomalies should be interpreted to distinguish between archaeological or geological features where possible. The Legacy Data demonstrated that some natural geological anomalies can appear very similar to archaeological-type responses which may account for the cautious interpretations applied by some geophysical consultants.

There is no single way in which to interpret data. Recent trends have categorized geophysical responses in terms of their archaeological components i.e. at Wroxeter (Shropshire, UK) and elsewhere, terms such as barrow, building, burning, ditch, enclosure, hearth, kiln, palisade, pit, post-hole, timber-frame, wall, *etc.* were used (Buteux *et al.* 2000; Neubauer 2004) and interpretations of structural components including surface area, entrances and use of buildings (Benech 2007). These terms are much easier to apply on research sites where *a priori* archaeological knowledge can provide a significant framework for the interpretation of features that may be encountered, as opposed to the 'blind' prospection surveys carried out across road corridors.

Each geophysical report should *use consistent terminology* throughout. The strength of the Wroxeter interpretation is that for the first time a true classification was agreed and described, so that there were no misunderstandings about what the interpretation classes actually meant. Nearly all geophysical evaluation work follows this form. Gaffney and Gater (2003) extended this to illustrate the commercial challenges by using decreasing levels of confidence that may be supported (or unsupported) by other sources - road corridor prospection data *might* be expected to incorporate such interpretative terminology:

- 'ditch' (coherent anomaly *supported* by other data e.g. excavation, aerial photo)
- 'archaeology' (coherent anomaly *unsupported* by other data)
- '? archaeology' (less coherent anomaly that *may* represent archaeological features).

These terms could be accompanied by descriptive terms for non-archaeological anomalies:

- 'natural' (geological features)
- 'interference' (modern sources of interference e.g. fences, traffic).
- 'ferrous' (responses from iron – some of which could be *either* archaeological or modern)

In general *a prescribed or approved list of NRA-style interpretation categories should be avoided* as it will limit the creativity and critical thinking of a geophysicist. However, each category must be described so that the meanings are clearly understood by the general reader.

6. Strategy for Commissioning Geophysical Surveys

6.1 Economic use of Geophysical Techniques

When specifying a particular technique, the cost should not be considered first; more important factors to consider are the appropriateness of a given technique to the geology and archaeological features (if known), as well as landscape, land use, seasonality and a techniques susceptibility to local sources of interference. However, the capability score generated in Section 0 (Table 9) of each geophysical technique can be used to suggest which is the most economical by comparing the survey speed, which dictates costs (Figure 40). The comparison (Figure 40) indicates that a (dual-sensor) magnetometer survey is the most economically advantageous technique, capable of rapidly assessing a wide range of features (multi-sensor systems increase survey speed further). Electromagnetic surveys (commonly used as a single sensor instrument) are the next most economic (half as fast and capable of identifying c. 8% less feature types than a magnetometer survey), followed by GPR (dual-channel) and earth resistance which are broadly similar. Modern GPR systems are slightly faster than twin-probe earth resistance arrays; although GPR data require significantly higher processing time which will increase costs. It must be remembered from Table 9 that while earth resistance has a lower capability score than a magnetometer, it is able to identify certain features e.g. stone buildings, that a magnetometer cannot, thus consideration must always be given to the specific needs of the survey.

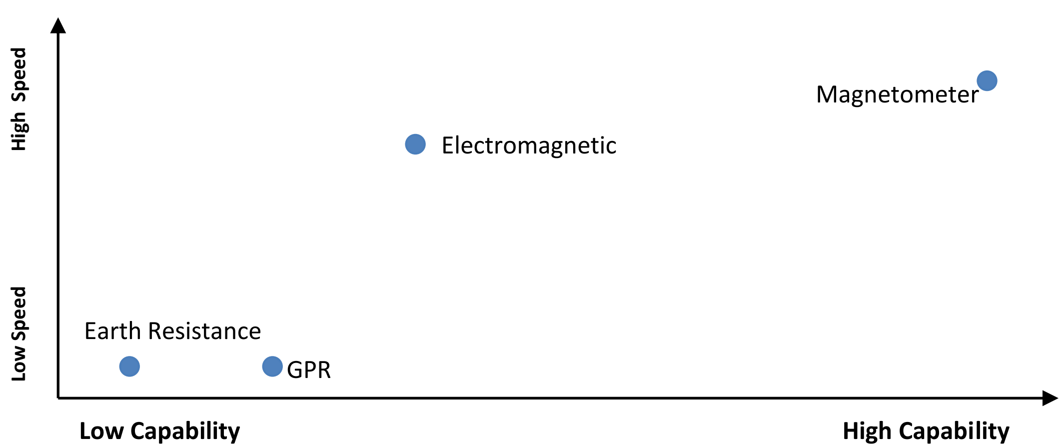


Figure 40. Capability of detecting archaeological features vs. survey speed.
For the purposes of this assessment, 'survey speed' reflects the approximate time taken to survey (not set-out) a one hectare area at industry standard spatial resolutions: magnetometer (1m x 0.25m, using a dual system), earth resistance (1m x 1m, with a twin-probe), electromagnetic (1m x 0.25m, acquiring simultaneous conductivity and magnetic susceptibility data) and GPR (0.5m x 0.05m, using a dual-channel system).

6.2 Specifying Geophysical Survey Methods in the Future

In order to assist the specifications of the future, the English Heritage 'Choice of Geophysical Survey Key' have been updated and adapted for the exclusive benefit of surveys carried out on Irish road corridors as Table 16 and in graphical form as Figure 41. Road schemes covering larger areas may require alternative methods of selection and very narrow corridors (such as those used for pipeline or rail), will require a rectilinear survey area with a suggested minimum width of 40m. Table 16 and Figure 41 have been designed to identify the most *appropriate* techniques for *each environment* under investigation, for example:

- A 3km roadway beginning on *Carboniferous limestone plateau*, descending a valley side with *deep colluvium*, crossing a large *raised bog* and entering a *brownfield site* at the edge of an *urban area*, would require the chart to be used several times.
- A 300m link road crossing an area of *raised bog* would only require the chart to be used once.
- The chart should be consulted for *each* AAP survey or Site/ Monument survey.

We know from the Legacy Data that statistically, the *majority* of geophysical surveys assessing road corridors in Ireland will:

- *encounter unknown archaeological deposits* (i.e. previously unrecorded features)
- occur in a *rural area*
- contain *little or no peat*
- overly a *sedimentary* geology

These variables will result in a recommendation for a detailed magnetometer survey at 0.5m x 0.25m spatial resolution, to be followed up by a sample of earth resistance or electromagnetic survey to investigate features and act as a control.

	Criteria to be applied to each survey environment	Go to
1	What sort of location is the Survey Area in?	
	Rural, semi-urban or	3
	Urban (built up)	2
2	Try GPR. Electromagnetic, earth resistance and/or magnetometer survey may also be appropriate, if conditions permit.	
3	What is the depth of the overlying peat deposits?	
	There is no peat present or the peat deposit is less than 0.5m deep	4
	The peat deposit is 0.5-1.0m deep or	7
	The peat deposit is greater than 1.0m deep	14
4	Are the archaeological features	
	shallow (less than 1.0m depth) or unknown	5
	deep (e.g. a very large ditch, greater than 1.0m depth) or	2, 11
	very magnetic (e.g. a kiln, furnace, or other industrial deposits) or	13
	weakly magnetic?	7, 11
5	What is the geology?	
	metamorphic / sedimentary or	6
	igneous or	12
	Surface geology with magnetic pebble components	7
6	Are the expected features mostly	
	masonry / stonework or	7
	cavities or	9
	large earth-cut features (e.g. channels, moats) or	7, 9, 10
	industrial features (including hearths, furnaces, kilns, brick built structure *etc.*) or	10
	ordinary earth-cut features (ringfort / enclosures, ditches, pits, *etc.*) or	10
	other burnt feature (e.g. burnt mound of stones, building)	10
	diffuse / small (i.e. post-hole features, palisade features)	11
	unknown?	10
7	Try a detailed (0.5m x 1m) earth resistance area survey (Twin-probe, Wenner or Square arrays) or a detailed (0.5m x 1m) EM area survey (apparent conductivity & apparent magnetic susceptibility) or a detailed (0.25m x 0.05m) GPR area survey or	8
	If you are assessing a wooden trackway	16
8	Is it the possible site of	
	a stone building or	7
	features greater than 1.0m depth, including souterrains?	9
9	Try electrical resistivity tomography (ERT) profiles across the feature or a detailed (0.5m x 0.05m) GPR area survey.	
10	Try a detailed (1m x 0.25m) magnetometer area survey. Strongly consider a 0.5m x 0.25m spatial resolution in areas of sedimentary geology to identify earth-cut features. Other techniques can and should be used to investigate features of interest and/or as a control Predominantly gley soils should be assessed with electromagnetic conductivity / earth resistance and magnetometer surveys Pilot studies using a magnetometer, earth resistance or electromagnetic survey may help determine the most suitable method	
11	Try a detailed magnetometer area survey at a 0.5m x 0.25m spatial resolution. Other techniques can and should be used to investigate features of interest and/or as a control	
12	Use a pilot ***geological*** scan to determine areas suitable for detailed magnetometer area survey or try a detailed (0.5m x 0.25m) EM area survey (apparent conductivity & apparent magnetic susceptibility) or try a detailed (0.5m x 1m) earth resistance area survey (Twin-probe, Wenner or Square arrays) or try a detailed (0.25m x 0.05m) GPR area survey	
13	Try a detailed (1m x 0.25m) magnetometer area survey or	
	if on igneous geology	12
14	Is the purpose of the survey over peat	
	for general prospection of unknown deposits or	15
	to trace the extent of known wooden trackways?	16
15	Try EM transects across the peat at 5m transect intervals, to identify areas of raised ground Consider combining the results with targeted hand-augering or on a regular 10m x 10m grid if mechanical augers are available. Geological Investigations may also provide useful information. Augering could determine the depth below ground and palaeo-height-differences to identify archaeologically prospective areas. Further information could be gained by budgeting for laboratory magnetic susceptibility analysis of the cored soils, in advance of intrusive testing.	
16	Try induced polarization (IP) profiles across the feature to trace its extent.	

Table 16. Choice of geophysical survey methods for use on Irish road schemes.

After David *et al.* (2008), with adaptations. Clearly state in the Briefing Document if the use of ATVs is permitted on the contract. Other variables, such as seasonality, landscape, land use, sources of interference *etc.*, should also be considered, some of which cannot be controlled.

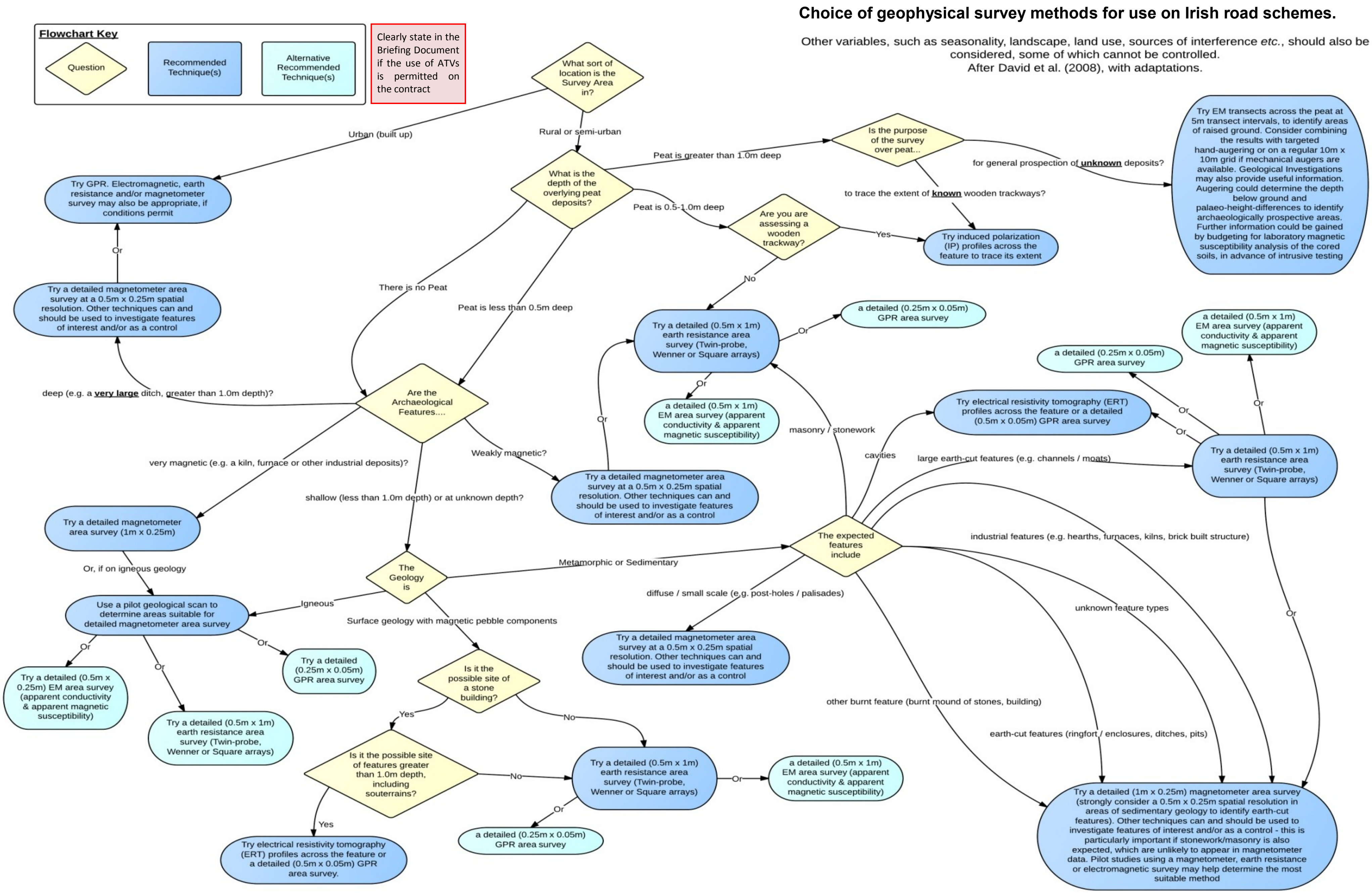


Figure 41. Graphical representation of Table 16.

Advice for surveying Areas of Archaeological Potential

The AAP assessment is designed to act as a form of mitigation for high risk areas of archaeological features, to create baseline data at an early stage of assessment. The AAP method could be applied in the first instance to map the archaeological resource at perceived high risk areas.

Geophysical techniques should be selected (using Table 16 and Figure 41) with *appropriate consideration given to*:

The *type of archaeological feature* likely to be encountered (based on physical properties, shape and size) and the *environment* (including geology, landscape, land use and access).

If a wide variety of archaeological features are suspected at an AAP:

A general prospection strategy for unknown features should be employed

An *appropriate* geophysical technique should be selected at 0.5m traverse intervals.

Low Risk Areas: Argument for Full Prospection of the road corridor (End-to-End Coverage)

Attention must equally be given to the perceived *low risk* areas as part of a broader geophysical assessment. The Legacy Data review found that *79% of excavated archaeological sites were not selected for AAP assessments* – those areas were considered as low risk 'blank' or 'sterile' that *actually contained more archaeological sites than the 'high risk' AAP areas*.

In low risk areas, a general prospection strategy should be employed, using Table 16 and Figure 41as a guide for the appropriate geophysical techniques, as dictated by the local geology.

Advice for surveying Sites and Monuments

Geophysical techniques should be selected (using Table 16 Figure 41) with *appropriate consideration given to*:

The *type of archaeological feature* likely to be encountered (based on physical properties, shape and size)

The *environment* (including geology, landscape, landuse and access).

If a variety of archaeological features of different physical properties are likely (e.g. a cut-earth ringfort ditch and a masonry/stone souterrain), more than one survey technique will be required.

On known monuments, a detailed assessment strategy should be employed, using appropriate geophysical techniques at 0.5m traverse intervals.

Specific advice for surveying challenging archaeological sites such as burials (inhumations and cremations), wooden trackways and souterrains can be found in the Appendices.

Advice for surveying an Entire Road Scheme (End-to-End Coverage)

Consideration *must be given to variations in geology* across a road scheme (use Table 16 and Figure 41 as a guide).

For *most* road schemes *a detailed geophysical assessment would be suitable*.

In cases where road schemes are very large (*hundreds* of hectares), a sampling strategy is required that may alter with varying geologies within the road corridor. These would have to be examined on a case by case basis.

Methods:
The complete dependence upon magnetic methods of prospection is particularly hazardous (as discussed in Section 4.1).

Future assessments should include provisions for a detailed earth resistance or electromagnetic survey at a minimum (and/or other techniques).

These should be used as a standard form of assessment (rather than on a contingency basis, as is currently the practice).

The amount of which other techniques should be used could vary from site to site and from region to region.

Pilot schemes are likely to play a strong role in the future of geophysical data collection on NRA road schemes. Pilot schemes should compare data from at least 2 different instruments at a number of locations along a road scheme to determine the most appropriate method across the remainder of the road scheme. If possible, the tests should occur over the position of known or strongly suspected monuments to help determine instrument suitability. It may be reasonable to expect that one technique may be better suited to a specific area(s) along the road scheme rather than the entire scheme.

7 Outcomes of Survey

The contents of a professional geophysical report have been documented elsewhere (Gaffney *et al.* 2002; David *et al.* 2008) and are widely requested in NRA specifications.

It is apparent from reviewing the 2001-2010 Legacy Data that some of the requirements are not met as frequently as the NRA would suppose and that common omissions occur. The NRA should be in a position to judge the suitability of a report and request amendments or other action as required.

Common Omissions from Geophysical Reports

Some reports omitted to record reasonably basic information, the most common omissions from the Legacy Data archive were: weather (absent from 57% of reports), soil conditions (54%), data processing software used (34%), method of processing data (28%), data presentation software used (23%), townland surveyed (16%), detection licence number (14%), date(s) of fieldwork (14%), method of grid set-out e.g. GPS (12%), land use (6%), spatial resolution (1%) and instrument type used (1%). The NRA requires geophysical consultants to adhere to archiving guidelines (Schmidt *et al.* 2002; Schmidt and Ernenwein 2011). Most of the omitted categories above are required by those guidelines, therefore some reports fall short of the standards required.

With particular reference to the needs of subsequent users of geophysical data (archaeologists, engineers, publishers, researchers), the following issues are also often omitted from geophysical reports, but *should be expected* when presenting geophysical images and interpretative text:

Graphics:
Images of geophysical data *must* be displayed upon (and co-registered with) a digital basemap.
Floating data, isolated from a basemap, is inappropriate.

A north arrow, scalebar and a greyscale for the geophysical data (including clipping range and units of measurement e.g. black = 2nT and white = -2nT *etc.*) should be displayed.

Plots should be presented in CAD or GIS programmes.

Figures derived from CAD or GIS should be archived in pdf and dxf or shp format in the first instance. Other file formats may be submitted alongside these as secondary files.

Text:
There should be a discussion of how the geophysical data were processed and the clipping range used for display.

A record should be kept of known weaknesses or errors in the geophysical data or the data acquisition process.

A description should be made of the interpretative classes used.

Raw Data:
Digital geophysical data should be expected as pre-processed data (i.e. minimal processing), so that it is available for review. Data volume will depend upon the method(s) selected but may be expected as one xyz ASCII format file, per field, per technique used.

- Feedback

The NRA specification document may ask for recommendations in the geophysical report. There should be a feedback loop that obliges the archaeologist to give feedback to the geophysical consultant directly. This could give scope for the geophysical consultant to review their findings at the end stage of an excavation report.

Feedback will also allow the geophysicist to validate their interpretation – test trenching reports have frequently described geophysical anomalies as 'non-archaeological' which is not necessarily true. Archaeological features are not limited to those that cut through the natural or upstanding structural remains, but also include thin laminar features deposited on existing sediments. Geophysical surveys are capable of mapping archaeological features, including those that are not immediately appreciated by the naked eye upon excavation or soil stripping. A questionnaire issued by the Research Fellowship found that 17% of licensed archaeologists in Ireland had to wait several days or more than one week to recognise ditched features in open test trenches. Due to project exigencies (in particular health and safety), the NRA requires test trenches to be opened and closed within one day, which is not conducive to the effect that weathering has on the ability to visualise archaeological features. By assessing final excavation reports (that investigate a larger area than test trenches), the geophysicist will get suitable feedback that could modify subsequent interpretations or strategies in the future.

- NRA Geophysical Survey Database

The 2001-2010 NRA geophysical surveys have created a Legacy Archive of 170 reports. There is no reason why the analysis of geophysical data should stop at this juncture. Archaeological excavation reports are required to include a prescribed pro-forma for the NRA Archaeological Database; a similar requirement should be made for future geophysical reports that can be uploaded to the NRA Geophysical Survey Database. This will allow future geophysical survey events to be entered on to a database (by a non-geophysicist). The Geophysical Survey Database could be used in addition to standard geophysical archiving practice as outlined by the Archaeology Data Service (Schmidt and Ernenwein 2011) and not as a replacement for it.

8 Implementation of Geophysical Surveys in the Future

The assessment of the Legacy Data has found that in general the NRA archaeological geophysical surveys have been used in a very positive way on road schemes. The projects have achieved high standards of work that have resulted in significant discoveries between 2001-2010. The geophysical surveys were carried out across a range of challenging field conditions, geologies, weather and seasons. The range of features assessed or identified account for most types of archaeological sites in Ireland and have provided a significant archive of case studies that will be of benefit to future archaeological geophysical research.

The research indicates that there are a number of ways in which geophysical surveys might be improved in the future, based on the information obtained from the Legacy Data. The main points are summarised here and the reader is directed to examine the in-depth discussions for each category within this review.

8.1 Geology

The most important variable in the successful application of geophysical surveys is geology (Section 4.1 Review of Geological Influences on Geophysical Surveys), particularly with reference to magnetometer surveys which have been and are likely to continue as the most frequently used technique. An understanding of the underlying geology (and variations across a road scheme), is *essential* for the selection of an *appropriate* geophysical technique and spatial resolution.

The majority of the country is underlain by Carboniferous limestone geology which creates good contrasts for burnt features but occasionally poor contrasts for cut-earth features. Encouragingly, high resolution magnetometer surveys (at spatial resolutions of 0.5m x 0.25m) not only *improve the detection of cut-earth features* on Carboniferous limestone and other sedimentary geologies, but *are also affordable and viable* thanks to recent advances in data collection methods. Successful application of this by the Research Fellowship has already led to the take-up of high resolution 0.5m x 0.25m magnetometer surveys by the NRA that has led to an improvement in the quality of magnetometer data on Carboniferous limestone and greywacke (sandstone) geologies.

Areas of igneous geology present a different challenge to geophysical surveys. Igneous geology is strongly magnetic and depending on the thickness of the overlying surface geology, can severely impact upon magnetometer data. However, neither earth resistance nor electromagnetic conductivity surveys are affected by the magnetic properties of igneous geology. Another positive aspect is that surveys conducted for the Research Fellowship demonstrated that electromagnetic magnetic susceptibility data are not strongly impacted, if at all, by the magnetic properties of igneous geology.

8.2 Landscape

Rolling hills, drumlins and other instances of sloping ground may induce noise in magnetometer data and strongly contrasting geological responses in earth resistance data (Section 4.1 Review of Geological Influences on Geophysical Surveys and Section 4.3 Landscape). These cannot be avoided; however cart-mounted magnetometers may reduce some of the noise and increases in spatial resolution may help to distinguish between natural and archaeological features.

8.3 Seasonality

Seasonal variations throughout the year can impact upon geophysical techniques that map contrasts in moisture, such as earth resistance, electromagnetic conductivity and GPR. The 15 month study by the Research Fellowship (Section 5.3.2 Seasonal Variations in Moisture Change) found that in general *Irish soils are suitable for the detection of ditched enclosures throughout the year*. Some seasonally dry soils may cause ground contact problems for earth resistance surveys in warmer and drier parts of the country, however moisture mapping techniques that do not require ground contact, such as electromagnetic conductivity can be used instead.

8.4 Instrumentation

Geophysical instruments have evolved substantially since 2001 and at a rapid pace (Table 4). It is clear that the next ten years will also see further improvements in technology and data collection methods, particularly in the GPR and magnetometer markets. It will remain true that there is no single technique that is appropriate for all archaeological sites or all geologies. Economical geophysical surveys will always be better served by using an *appropriate* technique for a given survey area rather than the universal application of an inappropriate but cheaper technique. A *range* of techniques will often be required in order to satisfactorily assess the sub-surface archaeological resource at different areas along a road scheme (see Section 6 Strategy for Commissioning Geophysical Surveys and Table 10).

8.4.1 Vehicle-powered surveys

There are clear benefits in using vehicles in large flat fields. However, ATVs may not be particularly suited to some of the small and irregular shaped field systems found in parts of Ireland. The NRA should advise geophysical consultants (within a specification/briefing document), if the use of ATVs is acceptable or not for a particular scheme. The impact of an ATV on soils, the environment and crops should be considered where appropriate (Section 4.3.2 Vehicle-Powered Surveys).

8.4.2 Magnetometers

Magnetometer data and collection speed is improved if the instruments are mounted on a cart. The use of pedestrian-powered carts can be expected to increase in the future; vehicle-powered carts may be useful in some areas (Section 5.2.2.3 Cart Mounted arrays).

Fluxgate magnetometers are likely to continue as the most frequently used magnetometer (Section 2.2.1 Magnetometer Instruments). Caesium magnetometers can be used as well as (or instead of) fluxgate gradiometer instruments. Caesium should not necessarily be *expected* to work better than fluxgate magnetometers, as Irish soils might preclude any of the significant advantages offered by the use of high sensitivity caesium systems. Either sensor can be used if best practice is observed.

8.4.3 Earth Resistance & Resistivity

Earth resistance or EM conductivity surveys (Section 2.2.2 Earth Resistance & Resistivity Instruments) should be used more frequently than in the past, particularly on Carboniferous limestone soils that cause low or no magnetic contrasts for cut-earth archaeological features. Specifications for earth resistance surveys should not require the exclusive use of a Twin-probe array (as in the past); investigations have demonstrated that Wenner and Square arrays and EM conductivity meters also work very well on Irish soils. Electrical resistivity tomography is useful for mapping the extent of known features at depth (particularly large features such as moat channels, or souterrains), but is not useful for general prospection.

8.4.4 Electromagnetic Instruments

EM conductivity data should be considered as an alternative for earth resistance data; EM conductivity fieldwork tends to be faster than most earth resistance surveys and returns similar soil contrast data. Most EM instruments will additionally return apparent magnetic susceptibility data as well as apparent conductivity data; this makes EM surveys very useful in areas not suited to magnetometer assessment. The latest EM instruments also return multi-depth data, increasing the chance of identifying archaeological features (Section 2.1.3.2 Electromagnetism).

8.4.5 Ground Penetrating Radar

GPR may be suited to archaeological prospection in certain areas along a road scheme. Antenna frequency selection is the most important variable as it, and the local soils, determine the depth of penetration. The depth of archaeological deposits is mostly unknown and the selection of an appropriate antenna frequency at the procurement stage can be difficult – preliminary pilot studies may be required in the first instance with two (or more) antenna frequencies in order to make an informed decision. Modern dual- and multi-frequency GPR instruments offer two or more frequencies that are likely to be very useful for archaeological prospection in the future (Section 2.2.3 Ground Penetrating Radar).

8.5 Area Survey Coverage

It is currently possible to incorporate *large scale prospection strategies* to identify archaeological deposits along the length and width of a road scheme to provide 'full coverage' (Section 6.2 Specifying Geophysical Survey Methods in the Future and Appendix E), which the NRA may wish to employ as necessary, with caveats based on observations made throughout this document. If isolated areas are surveyed, they should cover an area of at least 40m x 40m (0.16 hectare) and should be rectilinear in shape, avoiding circular shaped survey areas (which have been previously required in past).

The majority of geophysical surveys were exclusively used at Areas of Archaeological Potential or for Site and Monument assessments, rather than full prospection (End-to-End Coverage) of a road scheme. The historic use of geophysics at these locations partly echoes the presumptive British Gas experience of the 1980s (Catherall *et al.* 1984) that *sites were known in advance* and with little or no concept of prospecting for new sites using geophysical techniques. Geophysical surveys are economically suited to the prospection of large areas and previously unknown archaeological sites.

73% of the most frequently excavated site types, according to the NRA Archaeological Database (McCarthy 2010), were thermoremanent (burnt) features. The majority of those are small and are not generally visible above ground (industrial deposits, burnt spreads, furnaces, kilns), but can be clearly identified by detailed magnetometer surveys on most Irish soils. Using a detailed geophysical survey across the full extent of a road corridor will ensure that most of these small sites will be identified.

8.6 Sampling Strategies

Best practice guidelines for geophysical surveys suggest that *the maximum width of a road should always be completely covered, rather than sampled* (David *et al.* 2008). Magnetometer surveys have traditionally been the primary technique of archaeological geophysical surveys on road schemes and will probably continue to do so in the future. *Magnetometer surveys are best suited to the collection of detailed data across large areas* (preferably the width of a road scheme or larger) rather than a detailed assessment of narrow strips or preliminary scanning surveys. Standard technology utilising dual system magnetometers can easily assess 2.5 hectares per person per day, using a detailed survey. The latest technology (comprising large arrays of magnetometers) can rapidly assess the same area, at a higher sample resolution, in much less time. Full coverage of road corridors with detailed assessment will always be the most suitable method.

8.6.1 Large Areas

Taking a pragmatic view, very large road schemes (comprising *hundreds* of hectares), may require some degree of sampling. This would have to be on a case by case basis. Initially this could be achieved by sampling at a rate of 50% via a series of evenly spaced strips of equal size across the width of the road corridor. Consideration should under these circumstances be given to how much archaeological information is lost within the non-surveyed areas and the sample may need to be altered due to existing roads / field boundaries and existing archaeological information. However, it has been noted that detailed magnetometer surveys in excess of 100 hectares are now commonplace elsewhere (see Appendix E) and sampling strategies are being used less in favour of 'full coverage assessments'.

8.6.2 Pilot Schemes

Where necessary it is recommended that pilot schemes are adopted on NRA road schemes. Pilot schemes will involve the use of at least 2 different instruments at a number of locations along the length of a road scheme. The data from these instruments should be compared and assessed for the suitable application across the remainder of the road scheme. If possible, the tests should involve work upon known or strongly suspected monuments (e.g. aerial photo or topographic anomalies) to help determine their suitability. It may be reasonable to expect that one technique may be better suited to a specific area(s) along the road scheme rather than the entire scheme.

8.7 Spatial Resolution

Geophysical survey collection methods have advanced significantly in the last ten years and have made the collection of high resolution magnetometer data a feasible and affordable option that will return a significantly improved dataset, allowing for the visualization of small and subtle features that are frequently encountered on Irish soils (5.2.4 Spatial Resolution). The term 'high resolution' refers to an increase in the traverse spacing e.g. from 1m to 0.5m, to allow for the collection of 0.5m x 0.25m data, as opposed to standard resolution data (1m x 0.25m). Increasing the in-line density does not have the same benefit.

8.8 Flexibility of Specifications

Geophysical specifications are historically rigid, but the outcome of the review suggests that there should be more flexibility in order to adapt to often unknown circumstances e.g. erratic and unpredictable geological conditions. This should be balanced by the fixed price contract which the NRA requires for consultants. This can be achieved by specifying the use of a particular technique, spatial resolution and area (the variables that influence cost), whilst also requesting fixed prices for a *range of techniques and spatial resolutions* that can be used *if required*, following consultation with an NRA archaeologist. This will also allow for pilot surveys to be undertaken using an alternative method, to justify its application on a wider scale.

For example, a specified magnetometer survey at 0.5m x 0.25m spatial resolution over a one hectare area may be found to be unsuitable at certain sites where known monuments fail to appear in the data due to low magnetic contrasts. Following a consultation with NRA archaeologists, approval may be sought for the use of an electromagnetic or earth resistance survey that may be better suited to the local conditions (at previously specified fixed prices per hectare). This would allow the geophysical consultant to recommend a course of alternative action whilst data are being collected, rather than wait until the end of the project.

8.9 Outputs

In the future, these are the following outputs that should be required from a geophysical consultant working on an NRA road scheme:

1. The NRA will require the production of *hard copy* reports as per the specifications.

2. Reports provided as *digital soft copies* (pdf) to the NRA. Geophysical data and outputs are entirely digital.

3. Digital data (xyz ASCII pre-processed geophysical files; dxf CAD files; shp GIS files) to accompany geophysical reports.

Both reports and digital data should be archived. At the end of the project a full digital archive (including pre-processed geophysical data) should be submitted to the NRA.

An entry should be prepared for the NRA Geophysical Survey Database, to be submitted with the geophysical report. The NRA Geophysical Survey Database begun by the Research Fellowship should continue as a publicly accessible database of survey coverage and/or digital geophysical reports. Pro-forma templates will be supplied by the NRA.

The NRA is in favour of circulating archaeological excavation reports to the geophysical consultant for an opportunity to review or evaluate their data. Geophysical consultants should take advantage of this.

8.10 Publishing

The NRA have a strong commitment to publishing archaeological investigations on road schemes, having issued (to date) 11 scheme monographs, 9 annual seminar proceedings and 8 annual copies of Seanda Archaeology Magazine, as well as numerous pamphlets. Papers by contractors, consultants and NRA Archaeologists have also appeared frequently in magazines, peer reviewed journals and conferences. Geophysical surveys are however under represented and very few have been published. This can be due to a number of factors, including reluctance and the general tendency of geophysicists to avoid publicising high profile archaeological sites prior to a scientific excavation that might encourage illegal activity.

The NRA are in a position to make a unique contribution to archaeological geophysical research: a state body with access to an archive of over 1,700 hectares of digital geophysical data, derived from a variety of methods and assessing a wide range of archaeological sites, landscapes and geologies. Most importantly, the majority of the data has been ground-observed and can answer important questions regarding the use of geophysics that extend beyond the remit of this review. Ireland has a rich archaeological heritage, complicated geological formations and a large amount of peat coverage; these are important variables that would interest and benefit the international research community.

Geophysical consultants should be encouraged in the future to publish interesting methodological case studies, particularly in relation to challenging environments or monument types, which will require integration with intrusive excavations. Neither the NRA nor geophysical consultants should be afraid to publish false positive results as these help determine the limitations imposed by particular techniques, environments or monuments.

9 Glossary

Burnt features: Features (modern or ancient) that have been subjected to intense heat resulting in burning such as: hearths, kilns, furnaces, burnt mounds of stone. Burning produces clear and strongly contrasting magnetic anomalies that can be identified through their thermoremanence. The effect of *burning* is not the same as *heating*, therefore 'heat-shattered stones' may not create a strong magnetic anomaly, whereas 'burnt stones' will.

Cut-earth features: An archaeological feature that cuts the earth, e.g. a ditch or a pit. The subsequent in-filled material can be mapped via a variety of geophysical techniques.

Drift: Repeat measurements at a static point will naturally 'drift' up and down over time, influenced by temperature and/or the gradual misalignment of some sensors. This drift is noticeable along lines of rapidly acquired data and across grids as a change in the background. Magnetometer and electromagnetic instruments tend to suffer from inherent drift which can be removed easily by processing software.

Fiducial Mark: A digital marker inserted into geophysical data during data collection (via a push button) that relates to a physical reference point on the ground. These markers are used during data processing or visualisation to identify grid edges or zones of interest.

In-filled features: See 'Cut-earth features'.

Interference: Interference sources reduce the quality of geophysical data and can mask the presence of archaeological features. Potential sources might include radio waves (e.g. mobile phones, airport radar, police radio *etc.*) or metal features (fence lines, gates, boreholes, structures).

Method (geophysical): Magnetometer surveys can use a variety of methods to assess a given area. Scanning and detailed surveys are two methods that use a magnetometer in very different ways, the former method will achieve low sample density at high speed and the latter will achieve high rates of coverage at a lower speed.

Noise: Noise, or specifically, soil noise, represent unwanted responses, usually in the background. Noise can be created by changes in the local soils, can be indicative of some archaeological activities and can be induced or magnified by irregular or erroneous walking styles.

Resistive features: An archaeological or natural feature that has a higher earth resistance than the surrounding soil. Typical examples would include a wall, a stone structure or near surface geology.

Sampling Strategy: A method of systematically sampling a survey area. Sampling can begin at 100% (e.g. full coverage of a road scheme) and reduce accordingly.

Spatial Resolution: The rate at which data are collected across a survey area. These are normally cited in the format of 'traverse interval x sample interval' e.g. 1m x 0.25m for a magnetometer survey.

Technique (geophysical): Techniques refer to the type of data collected in a geophysical survey. These include, but are not limited to: magnetometer, earth resistance, electromagnetic, magnetic susceptibility and ground penetrating radar surveys.

Thermoremanence: When materials are heated above a certain temperature and subsequently cool, they acquire a permanent thermoremanent magnetisation which can be identified by a magnetometer survey. The temperature varies with the minerals present but is about 600° Centigrade. Both geological (e.g. igneous rocks) and archaeological (e.g. hearths, kilns) materials can acquire thermoremanent magnetisation. This prevents the identification of archaeological features on near-surface igneous geology.

Walker Bounce: Refers to the slight rising and dipping motion of a surveyor walking across the land. This can induce unwanted soil noise within data and varies between individual surveyors.

10 Contributors

This document has been produced by James Bonsall, Dr. Christopher Gaffney and Professor Ian Armit of Archaeological Sciences, Division of Archaeological, Geographical and Environmental Sciences at the University of Bradford.

Earthsound Archaeological Geophysics acted as the Industrial Partner in the research and assisted in fieldwork and data collection.

The research was commissioned by the National Roads Authority (NRA) of Ireland and funded by an NRA Research Fellowship. Data from this document have been produced by the Research Fellowship and from an archive of archaeological geophysical survey reports commissioned by the NRA between 2001-2010.

Early drafts or sections of the document were sent to a number of consultants who provided valuable comments and feedback:

Dr. Laureen Buckley (Forensic Anthropologist)
Victor Buckley (National Monuments Service)
Mary Deevy (National Roads Authority)
Rob Fry (University of Bradford)
Heather Gimson (Earthsound Archaeological Geophysics)
Margaret Keane (National Monuments Service)
Paul Logue (Northern Ireland Historic Monuments Unit)
Michael MacDonagh (National Roads Authority)
Paul O’Keeffe (National Roads Authority)
Stuart Rathbone (Field Archaeologist)
Martin Roseveare (ArchaeoPhysica Ltd)
Dr. Armin Schmidt (GeodataWIZ Ltd)
Rónán Swan (National Roads Authority)

11 Acknowledgements

Thanks are due to all of the archaeological staff at the National Roads Authority during the research period for their insights and discussions: Rónán Swan, Michael Stanley, Frantisek Zak Matyasowszky, Lillian Butler, Mary Deevy, Noel Dunne, Niall Roycroft, Róisín Barton-Murray, Sébastien Joubert, Richard O'Brien, Ken Hanley, Paul O'Keeffe, Sheelagh Conran, James Eogan, Edward Danaher, Bernice Kelly, Mairead McLaughlin, Michael MacDonagh, Jerry O'Sullivan, Orlaith Egan, Gráinne Leamy, Deirdre McCarthy and Martin Jones.

Staff and researchers at the University of Bradford are also thanked for their assistance with aspects of the research, in particular Tom Sparrow, Rob Fry, Finn Pope-Carter, Andy Parkyn, Rob Legg, Stuart Fox and Cathy Batt. A number of geophysical consultants have also taken the time and trouble to provide insights in to their experiences of geophysical data collection and these are due thanks: Armin Schmidt, Heather Gimson, Martin Roseveare, Ann Roseveare, John Gater, John Nicholls, Cornelius Meyer, Alastair Bartlett, Joe Fenwick, Michel Dabas, Steve Sheriff, Arne Anderson Stamnes, Joerg Fassbinder, Kayt Armstrong, Paul Linford, Neil Linford and Andy Payne.

Finally thanks are due to the staff of Earthsound Archaeological Geophysics, especially to Heather Gimson and Darren Ó Riagáin for invaluable assistance in fieldwork, data collection and support for the Research Fellowship.

12 References

Aitken MJ (1960) Magnetic Prospecting: The Proton Gradiometer. *Archaeometry* 3(1): 38-40.

Al Chalabi MM and Rees AI (1962) An experiment on the effect of rainfall on electrical resistivity anomalies in the near surface. *Bonner Jahrbucher* 162: 266-271.

Armstrong K (2010) *Archaeological geophysical prospection in peatland environments* PhD Thesis. Archaeology. Bournemouth University.

Aspinall A and Gaffney C (2001) The Schlumberger array—potential and pitfalls in archaeological prospection. *Archaeological Prospection* 8: 199–209.

Aspinall A, Gaffney C and Schmidt S (2008) *Magnetometry for Archaeologists* Geophysical Methods for Archaeology.

Aspinall A and Saunders MK (2005) Experiments with the Square Array. *Archaeological Prospection* 12: 115-129.

Bartlett ADH (2003) *M3 Clonee to North of Kells, Report on Archaeogeophysical Survey 2002, Section 3: Navan to Kells and Kells Bypass.* Bartlett-Clark Consultancy. Unpublished Report. March 2003.

Bartlett T, Hession J and Long P (2010) *N22 Tralee Bypass/Tralee to Bealagrellagh, Co. Kerry. Archaeological Services Contract, Stage (i) and Stage (ii) – Standard Test Excavation and Pre-excavation Services (including Townland Boundary Survey and Architectural/Built Heritage Survey). Final Test Excavation Report, under Ministerial Directions Number A056 (E4149)* Headland Archaeology (Ireland), unpublished report, Project code TBTS10, November 2010.

Becker H (2009) Caesium-magnetometry for landscape-archaeology. In Campana S and Piro S (eds) *Seeing the Unseen. Geophysics and Landscape Archaeology.* London. Taylor & Francis: 129-165

Becker H (ed.) (2001) *Duo- and quadro-sensor configuration for high speed/high resolution magnetic prospecting with caesium magnetometer* Magnetic prospecting in archaeological sites. ICOMOS, Munich.

Benech C (2007) New approach to the study of city planning and domestic dwellings in the ancient Near East. *Archaeological Prospection* 14: 87–103.

Berle Clay R (ed) (2006) *Conductivity Survey: A Survival Guide* In Johnson JK (ed) *Remote Sensing in Archaeology: An Explicitly North American Perspective*. Alabama: University of Alabama Press, 79-108.

Bermingham N (2009a) *N6 Galway to East Ballinasloe PPP Scheme, Archaeological Contract 3, Phase 2, Final Report, Killescragh 2: Co. Galway, Trackway and Burnt Mound*. CRDS Limited.

Bermingham N (2009b) *N6 Galway to East Ballinasloe PPP Scheme, Archaeological Contract 3, Phase 2, Final Report, Killescragh, Co. Galway, Burnt Mound (Killescragh 1).* CRDS Limited.

Bescoby D, Bowden W and Chroston PN (2009) Magnetic survey at *Venta Icenorum*, Caistor St Edmund: Survey strategies and initial results. *Archaeological Prospection* 16: 287–291.

Biwall A, Gabler M, Hinterleitner A, Karlsson P, Kucera M, Larsson L, Löcker K, Nau E, Neubauer W, Scherzer D, Thorén H, Trinks I, Wallner M and Zitz T (2011) *Large-scale archaeological prospection of the Iron and Viking Age site Uppåkra in Sweden.* In Drahor MG and Berge MA (eds) *9th International Conference on Archaeological Prospection*: 218-222. Izmir, Turkey.

Bonsall J and Sparrow, T (2013) *NRA Archaeological Geophysical Survey Database*. http://www.field2archive.org/nra/

Bonsall J, Fry R, Gaffney C, Armit I, Beck A and Gaffney V (2013a) Assessment of the CMD Mini-Explorer, a new Low-frequency Multi-Coil Electromagnetic Device, for Archaeological Investigations. *Archaeological Prospection* 20: 219-231.

Bonsall J, Fry R, Pope-Carter F, Gaffney C and Armit I (2013b) *Mapping Prehistoric Wooden Trackways using Time Domain Induced Polarisation*. In Neubauer W, Trinks I, Salisbury RB and Einwögerer C (eds) Proceedings of the 10th International Conference on Archaeological Prospection. Vienna, Austria.

Bonsall J, Gaffney C and Armit I (2011) *Magnetic Surveys are failing to find Archaeology: Analysis of Legacy Data from the West of Ireland.* In Drahor MG and Berge MA (eds) *9th International Conference on Archaeological Prospection*: 58-64. Izmir, Turkey.

Bonsall J, Gaffney C and Armit I (2012a) *Did we find anything? Feedback and Statistical analysis of Ground Truthed Magnetometer Data*. Recent Work in Archaeological Geophysics. The Geological Society, Burlington House, Piccadilly, London: Near Surface Geophysics Group.

Bonsall J, Gaffney C and Armit I (2014a) A Decade of Ground Truthing: Reappraising Magnetometer Prospection Surveys on Linear Corridors in light of Excavation evidence 2001-2010. In Kamermans H, Gojda M and Posluschny AG (eds) *A Sense of the Past: Studies in current archaeological applications of remote sensing and non-invasive prospection methods*. BAR International Series 2588.

Bonsall J, Gaffney C, Armit I and Swan, R. (2014b) *Tales from Across the Water: Analysing the Irish Experience of Geophysical Surveys*. Commercial Archaeological Geophysics Seminar. Bradford Centre for Archaeological Prospection. The University of Bradford. March 14th 2014.

Bonsall J, Gaffney C, Sparrow T and Armit I (2012c) *Multi Depth Electromagnetic Survey - changing the way we prospect for archaeology?* Recent Work in Archaeological Geophysics. The Geological Society, Burlington House, Piccadilly, London. Near Surface Geophysics Group.

Bonsall J and Gimson H (2003a) *N4 McNeads Bridge to Kinnegad Road Improvement Scheme, County Westmeath: Archaeological Geophysical Survey.* Earthsound Archaeological Geophysics. Unpublished Report No. 16. October 2003.

Bonsall J and Gimson H (2003b) *Sites 2B & 2C, N4 Sligo Inner Relief Road, Magheraboy, County Sligo: Archaeological Geophysical Survey.* Earthsound Archaeological Geophysics. Unpublished Report No. EAG 15.

Bonsall J and Gimson H (2004) *N6 Ballinasloe to Athlone Dual Carriageway, County Roscommon; Archaeological Geophysical Survey.* Earthsound Archaeological Geophysics. Unpublished Report No. EAG 37. November 2004.

Bonsall J and Gimson H (2005) *N11 Gorey Arklow Link, County Wexford: Archaeological Geophysical Survey*. Earthsound Archaeological Geophysics. Unpublished Report No. 40. January 2005.

Bonsall J and Gimson H (2006) *N17 Galway to Tuam National Road Scheme, County Galway: Archaeological Geophysical Survey.* Earthsound Archaeological Geophysics. Unpublished Report No. EAG 84. November 2006.

Bonsall J and Gimson H (2007) *Land Adjacent To Site 1, Moneytucker, N30 Clonroche To Enniscorthy, County Wexford; Archaeological Geophysical Survey* Earthsound Archaeological Geophysics, unpublished report number EAG 101, 5 April 2007.

Bonsall J and Gimson H (2009) *Selected Sites of Potential Archaeological Interest M20 Cork to Limerick Motorway Scheme; Archaeological Geophysical Survey Detection* Earthsound Archaeological Geophysics, unpublished report number EAG 167, 28 September 2009.

Bonsall J and Gimson H (2010) N52 Tullamore Kilbeggan Link Road Archaeological Consultancy Services Contract Stage (i) i Geophysical Survey. Earthsound Archaeological Geophysics, unpublished report number EAG 194, 29 October 2010.

Boschi F (2012) Magnetic Prospecting for the Archaeology of Classe (Ravenna). *Archaeological Prospection* 19: 219-227.

Buteux S, Gaffney V, White R and Van Leusen M (2000) Wroxeter hinterland project and geophysical survey at Wroxeter. *Archaeological Prospection* 7: 69–80.

CAGS (2014) *CAGS 2014*. Archived stream of presentations from the Commercial Archaeological Geophysics Seminar, Bradford Centre for Archaeological Prospection, University of Bradford, 14-15 March 2014. https://www.youtube.com/channel/UCNaiffyqPRWf7vY_OFY27fg, accessed 16th March 2014.

Campana S and Dabas M (2011) Archaeological Impact Assessment: The BREBEMI Project (Italy). *Archaeological Prospection* 18: 139–148.

Carey CJ, Brown TG, Challis KC, Howard AJ and Cooper L (2006) Predictive Modelling of Multiperiod Geoarchaeological Resources at a River Confluence: a Case Study from the Trent Soar, UK. *Archaeological Prospection* 13: 241-250.

Cater C (2008) High Impact Activities in Parks: Best management practice and future research Sustainable Tourism Cooperative Research Centre.

Catherall PD, Barnett M and McClean H (1984) *The Southern Feeder The Archaeology of a Gas Pipeline*. London. The British Gas Corporation.

Clark AJ (1980) *Archaeological Detection by Resistivity.* PhD Thesis. Archaeology. Southampton. University of Southampton.

Clark AJ (1996) *Seeing beneath the soil: prospecting methods in archaeology* (rev. ed). London. Batsford.

Conaghan J, Douglas C, Grogan H, O' Sullivan A, Kelly L, Garvey L, Van Doorslaer L, Scally L, Dunnells D, Wyse Jackson M, Goodwillie R and Mooney E (2000) Distribution, Ecology and Conservation of Blanket Bog in Ireland. Dublin, Ireland: Enviroscope Environmental Consultancy.

Conran S and O'Carroll F (2009) *N6 Galway to East Ballinasloe PPP Scheme, Archaeological Contract 3, Phase 2, Final Report, Newcastle: Co. Galway, Ringfort with Medieval or Post-Medieval Settlement*. CRDS Limited.

Conyers LB (2004) *Ground-Penetrating Radar for Archaeologists* Geophysical Methods for Archaeology. Oxford. AltaMira Press.

Cork (2004) *Archaeological assessment of the N8 Fermoy Mitchelstown Road Scheme: Specification to Tenderers for the contract to conduct a geophysical survey of the route of a proposed road scheme on behalf of Cork County Council.* Cork County Council, Cork National Roads Design Office.

Dabas M (2009) Theory and practice of the new fast electrical imaging system ARP. In Campana S and Piro S (eds) *Seeing the Unseen. Geophysics and Landscape Archaeology.* Proceedings of the XVth International Summer School. London. Taylor & Francis: 105-126.

DAHG (2008) *Detection Spreadsheet*. Department of Arts, Hertitage and the Gaeltacht.

Danaher E (2007) *Monumental Beginnings: The Archaeology of the N4 Sligo Inner Relief Road*NRA Scheme Monographs 1. National Roads Authority, Dublin.

David A (1995) *Geophysical Survey in Archaeological Field Evaluation*. Ancient Monuments Laboratory, English Heritage.

David A, Linford N and Linford P (2008) *Geophysical Survey in Archaeological Field Evaluation* (Second Edition ed). English Heritage.

Dawson M and Gaffney CF (1995) The application of geophysical techniques within a planning application at Norse Road, Bedfordshire (England). *Archaeological Prospection* 2(2): 103-115.

Doneus N, Flöry S, Hinterleitner A, Kastowsky K, Kucera M, Nau E, Neubauer W, Scherzer D, Schreg R, Trinks I, Wallner M and Zitz T (2011) *Integrative archaeological prospection - Case study Stubersheimer Alb.* In Drahor MG and Berge MA (eds) *9th International Conference on Archaeological Prospection*: 166-168. Izmir, Turkey.

Fassbinder J (2010) Geophysical Prospection of the Frontiers of the Roman Empire in Southern Germany, UNESCO World Heritage Site *Archaeological Prosopection* 17: 129-139.

Gaffney C (2008) Detecting Trends in the Prediction of the Buried Past: A Review of Geophysical Techniques in Archaeology. *Archaeometry* 50(2): 313-336.

Gaffney C (2009) The use of geophysical techniques in landscape studies: experience from the commercial sector. In Campana S and Piro S (eds) *Seeing the unseen: geophysics and landscape archaeology*. London. Taylor and Francis Group: 201-204.

Gaffney C, Gaffney V, Cuttler R and Yorston R (2008) Initial Results using GPS Navigation with the Foerster Magnetometer System at the World Heritage Site of Cyrene, Libya. *Archaeological Prospection* 15: 151-156.

Gaffney C, Gaffney V and Neubauer W (2011) *Methodological and archaeological challenges of the Stonehenge Hidden Landscapes Project.* In Drahor MG and Berge MA (eds) *9th International Conference on Archaeological Prospection*: 180-182. Izmir, Turkey.

Gaffney C, Gaffney V, Neubauer W, Baldwin E, Chapman H, Garwood P, Moulden H, Sparrow T, Bates R, Löcker K, Hinterleitner A, Trinks I, Nau E, Zitz T, Floery S, Verhoeven G and Doneus M (2012) The Stonehenge Hidden Landscapes Project. *Archaeological Prospection* 19: 147-155.

Gaffney C and Gater J (2003) *Revealing the Buried Past: Geophysics for Archaeologists*. Stroud. Tempus Publishing.

Gaffney C, Gater J and Ovenden S (2002) *The use of Geophysical Techniques in Archaeological Evaluation.*

Gaffney S (1997) *The use of fluxgate gradiometry in archaeological investigations: an investigation into the most appropriate use.....with particular reference to geology*. MPhil Thesis. Univeristy of Bradford.

Gibson PJ (2012) *Geophysical Imaging of the Leamonaghan Togher*. Archaeology Ireland 26.1: 20-21. Dublin. Wordwell.

GSB (2001a) *N2 Realignment Carrickmacross to Aclint, Co Monaghan: Geophysical Survey.* GSB Prospection. Unpublished Report No. 2001/18.

GSB (2001b) *N3 Navan to Dunshaughlin Road, Co. Meath: Geophysical Survey*. GSB Prospection. Unpublished Report No. 2000/104.

GSB (2004) *Carlow Outer Relief Road: Archaeological Geophysical Survey*. GSB Prospection. Unpublished Report No. 2004/70. October 2004.

GSI (2012) *GSI Datasets Public Viewer*. http://spatial.dcenr.gov.ie/imf/imf.jsp?site=GSI_Simple: Geological Survey of Ireland.

Hammond RF (1981) *Soil Survey Bulletin No. 35: The Peatlands of Ireland*. Dublin: An Foras Taluntais.

Harrison S (2012) *M20 Cork Limerick Motorway Scheme: Archaeological Consultancy Services Contract No 1 of 2010*. Headland Archaeology Ltd. Unpublished Report No. M20G10. January 2012.

Hayes A (2005) *Final Report on Archaeological Excavation of Fulachta Fiadh/Burnt Mounds at Newdown & Heathstown, Co. Westmeath*. Aegis Archaeology Limited, unpublished report ref 2-5, May 2005.

Hesse A (1966) The importance of climatologic observations in archaeological prospecting. *Prospezioni Archaeologiche* 1: 11-13.

Hesse A, Jolivet A and Tabbagh A (1986) New prospects in shallow depth electrical surveying for archaeological and pedological applications. *Geophysics* 51.3: 585-594.

Hey G and Lacey M (2001) *Evaluation of Archaeological Decision-making Processes and Sampling Strategies* European Regional Development Fund Interreg IIC - Planarch Project. Oxford. Oxford Archaeological Unit.

Hunter JR and Dockrill S (1990) Recent research into burnt mounds on Fair Isle, Shetland, and Sanday, Orkney. In Buckley V (ed.) *Burnt Offerings: International Contributions to Burnt Mound Archaeology*. Dublin. Wordwell Limited: 62-68.

Johnston SA, Campana D and Crabtree P (2009) A Geophysical Survey at Dún Ailinne, County Kildare, Ireland *Journal of Field Archaeology* 34: 385-402.

Jordan D (2009) How Effective is Geophysical Survey? A Regional Review *Archaeological Prospection* 16: 77-90.

Knight D, Pearce M and Wilson A (2007) Trent Valley Gravels Geophysics Assessment. York: University of Nottingham, Archaeology Data Service [distributor].

Kulessa, B, Chiarulli, B and Haney, S (2004) Geophysics in support of industrial archaeology in a challenging environment: Shade iron furnace, Pennsylvania, USA. *Archaeological Prospection* 11: 181-187.

Krahn H (2005) *N18 Oranmore to Gort Road Scheme, Co. Galway: Archaeological Geophysical Survey.* Minerex Geophysics Limited. Unpublished Report, MGX Project Number: 5024. February 2005.

Leckebusch J (2011) Comparison of a Stepped-Frequency Continuous Wave and a Pulsed GPR System. *Archaeological Prospection* 18(1): 15-25.

Leigh JM (2011) *Geophysical Survey Report: M11 Gorey Enniscorthy Road Scheme, County Wexford*. J.M. Leigh Surveys. Unpublished Report. April 2011.

Lennon A (2008) *M7 Portlaoise-Castletown/M8 Portlaoise-Cullahill Motorway Scheme - Contract 2 Coolfin - Derrinsallagh & Townparks Phase 2 - Excavation Report on the Archaeological Excavation of Derryvorrigan 2, Co. Laois*. Archaeological Consultancy Services, unpublished report, September 2008.

Lennon A (2009) *M7 Portlaoise-Castletown/M8 Portlaoise-Cullahill Motorway Scheme - Contract 2 Coolfin - Derrinsallagh & Townparks Phase 2 - Excavation Report on the Archaeological Excavation of Derrinsallagh 3, Co. Laois*. Archaeological Consultancy Services, unpublished report, February 2009.

Linford N (2006) The application of geophysical methods to archaeological prospection *Reports on Progress in Physics* 69: 2205–2257.

Linford N, Linford P, Martin L and Payne A (2007) Recent results from the English Heritage caesium magnetometer system in comparison with recent fluxgate gradiometers. *Archaeological Prospection* 14: 151-166.

Linford N, Linford P, Martin L and Payne A (2010) Stepped Frequency Ground-penetrating Radar Survey with a Multi-element Array Antenna: Results from Field Application on Archaeological Sites *Archaeological Prospection* 17(3): 187-198.

Linford N, Linford P, Payne A, David A, Martin L and Sala J (2011) *Stonehenge: Recent results from a ground penetrating radar survey of the monument.* In Drahor MG and Berge MA (eds) *9th International Conference on Archaeological Prospection*: 86-89. Izmir, Turkey.

Lyall J and Powlesland D (1996) The application of high resolution fluxgate gradiometery as an aid to excavation planning and strategy formulation. *Internet Archaeology* 1: http://intarch.ac.uk/journal/issue1/beardah/kdeia1.html

Lynch GL and O'Donnell L (2007) Cremation in the Bronze Age: Practice, process and belief. In Grogan E, O'Donnell L and Johnston P (eds) *The Bronze Age landscapes of the Gas Pipeline to the West: an integrated archaeological and environmental assessment* 105-124. Bray. Wordwell.

McCarthy D (2010) *Digging, data and dissemination*. Seanda NRA Archaeology Magazine 5: 41. Dublin. National Roads Authority.

McKinstry L (2010) The excavations of a ringfort and souterrain at Kilcloghans, Co. Galway. *Journal of the Galway Archaeological and Historical Society.* 62.

Montanarella L, Jones RJA and Hiederer R (2006) The distribution of peatland in Europe. *Mires and Peat* 1: 1-10.

Moore C and O'Connor DJ (2009) *N4 Dromod Roosky Bypass Advance Archaeological Works Contract: Edercloon Final Excavation Report, Ministerial Direction A31 (A31-025 / E3313).* . CRDS Limited, unpublished report, November 2009.

Moore DJ (2008) *A systems analysis of quadbike loss of control events on New Zealand farms*. PhD Thesis. Massey University, Palmerston North.

Neubauer W (2004) GIS in archaeology—the interface between prospection and excavation. *Archaeological Prospection* 11: 159–166.

Novo A, Dabas M and Morelli G (2012) The STREAM X Multichannel GPR System: First Test at Vieil-Evreux (France) and Comparison with Other Geophysical Data *Archaeological Prospection* 19: 179–189.

NRA (2012) *NRA Archaeological Database*. http://archaeology.nra.ie/ Last Accessed: 15/11/2012.

O'Sullivan J (2003) *Specification for the contract to conduct an archaeological geophysical survey on the route of the proposed N6 Galway to Ballinasloe national road scheme, on behalf of Galway County Council* 16. National Roads Design Office, Galway County Council.

Orbons J (2011) *Electromagnetic surveys for palaeo-landscape analyses in sedimentation areas.* In Drahor MG and Berge MA (eds) *9th International Conference on Archaeological Prospection*: 187-190. Izmir, Turkey.

O' Brien W (2009) *Local Worlds. Early Settlement Landscapes and Upland Farming in South West Ireland*. Cork. Collins Press.

O'Carroll F and Petervary T (2009) *N6 Galway to East Ballinasloe PPP Scheme, Archaeological Contract 3, Phase 2, Final Report, Gortnahoon: Co. Galway, Prehistoric Pits, Early Medieval Kilns and Sunken Structures.* CRDS Limited.

O'Sullivan J (2004) *Specification to tenderers for a contract to conduct an archaeological geophysical survey of the route of the proposed N6 Ballinalsoe to Athlone national road scheme*. Galway County Council, May 2004.

Parkyn A (2012) *Multi-sensor platforms for the geophysical evaluation of sensitive archaeological landscapes.* PhD Thesis. Department of Archaeological Sciences. University of Bradford.

Payne A (1996) The Use of Magnetic Prospection in the Exploration of Iron Age Hillfort Interiors in Southern England *Archaeological Prospection* 3: 163-184.

Ralph EK (1964) Comparison of a Proton and a Rubidium Magnetometer for Archaeological Prospecting *Archaeometry* 7: 20-27.

Rathbone S (2013) A Consideration of Villages in Neolithic and Bronze Age Britain and Ireland *Proceedings of the Prehistoric Society* Published online. http://dx.doi.org/10.1017/ppr.2013.2

Roseveare M (2013) *pers. comm*. Discussion of caesium magnetometer surveys.

Roseveare MJ and Roseveare A (2004) *N6 Galway to East Ballinasloe Geophysical Survey Report.* ArchaeoPhysica. Unpublished Report, Project GAL20031. August 2004.

Ruffell A, McCabe A, Donnelly C and Sloan B (2009) Location and Assessment of an Historic (150–160 Years Old) Mass Grave Using Geographic and Ground Penetrating Radar Investigation, NW Ireland *Journal of Forensic Science* 54(2): 382-394.

Ruffell A and McKinley J (2008) *Geoforensics*. Chichester. Wiley-Blackwell.

Sabin D and Donaldson K (2005) *N6 Galway to Ballinasloe National Road Scheme: Luttrell's Pass A024/5.1 and control area A024/5.11, Metal detection survey.* Archaeological Surveys. Unpublished Report Reference No. 110. September 2005.

Sarris A and Jones RE (2000) Geophysical and Related Techniques Applied to Archaeological Survey in the Mediterranean: A Review. *Journal of Mediterranean Archaeology* 13.1: 3-75.

Schleifer N, Weller A, Schneider S and Junge A (2002) Investigation of a Bronze Age Plankway by Spectral Induced Polarization *Archaeological Prospection* 9: 243-253.

Schmidt A (2009) Electrical and magnetic methods in archaeological prospection. In Campana S and Piro S (eds) *Seeing the unseen: geophysics and landscape archaeology*. London. Taylor and Francis Group: 67-82.

Schmidt A (2013) *Earth Resistance for Archaeologists.* Lanham. AltaMira Press.

Schmidt A, Archaeology Data Service. and Arts and Humanities Data Service. (2002) *Geophysical data in archaeology : a guide to good practice* AHDS guides to good practice. Oxford. Oxbow.

Schmidt A and Ernenwein E (2011) *Guide to Good Practice: Geophysical Data in Archaeology*. http://guides.archaeologydataservice.ac.uk/g2gp/Geophysics_Toc: Archaeology Data Service. Available from (Accessed 01/10/2011).

Schmidt A and Marshall A (1995) *Impact of Resolution on the Interpretation of Archaeological Prospection Data*. In Sinclair A, Slater E and Gowlett J (eds) The Application of Scientific Techniques to the study of Archaeology Oxbow Monograph 64.

Schultze V, Linzen S, Schler T, Chwala A, Stolz R, Schulz M and Meyer H (2008) Rapid and Sensitive Magnetometer Surveys of Large Areas using SQUIDs - the Measurement System and its Application to the Niederzimmern Neolithic Double-ring Ditch Exploration *Archaeological Prospection* 15: 113-131.

Scollar I, Tabbagh A, Hesse A and Herzog I (1990) *Topics in Remote Sensing 2: Archaeological Prospecting and Remote Sensing*. Cambridge. Cambridge University Press.

Seaver M and Conran S (2009) *N6 Galway to East Ballinasloe PPP Scheme, Archaeological Contract 3, Phase 2, Final Report, Caraun More: Co. Galway, Bronze Age Pits, Early Medieval Settlement and Watercourses.* CRDS Limited.

Simpson D, Van Meirvenne M, Saey T, Vermeersch H, Bourgeois J, Lehouck A, Cockx L and Vitharana UWA (2009) Evaluating the Multiple Coil Configurations of the EM38DD and DUALEM-21S Sensors to Detect Archaeological Anomalies. *Archaeological Prospection* 16: 91-102.

Slater L, Kulessa B and Barton K (1996) An investigation of the ability of geophysical methods to detect and define Fulachta Fia (Burnt Mounds) on Clare Island, Co. Mayo, Ireland. *Archaeological Prospection* 3(2): 53-69.

Stamnes AA and Gustavsen L (2013) *Archaeological Usage of Geophysical Methods in Norwegian Cultural Heritage Management – a Review*. NTNU Museum of Natural History and Archaeology and the Norwegian Institute for Cultural Heritage Research.

Trinks I, Johansson B, Gustafsson J, Emilsson J, Friborg J, Gustafsson C, Nissen J and Hinterleitner A (2010) Efficient, Large-scale Archaeological Prospection using a True Three-dimensional Ground-penetrating Radar Array System. *Archaeological Prospection* 17(3): 175-186.

Tsokas GN, Tsourlos PI and Papadopoulos N (2009) Electrical resistivity tomography: A flexible technique in solving problems of archaeological research. In Campana S and Piro S (eds) *Seeing the Unseen. Geophysics and Landscape Archaeology.* London. Taylor & Francis.

Ullrich B, Kaufmann G, Kniess R, Zoellner H, Meyer M and Keller L (2011) Geophysical Prospection in the Southern Harz Mountains, Germany: Settlement History and Landscape Archaeology Along the Interface of the Latène and Przeworsk Cultures. *Archaeological Prospection* 18: 95-104.

Verdonck L and Vermeulen F (2011) *3-D Survey with a Modular System: Reducing Positioning Inaccuracies and Linear Noise*. In Drahor MG and Berge MA (eds) *9th International Conference on Archaeological Prospection*: 204-212. Izmir, Turkey.

Viberg A, Trinks I and Lide K (2011) A Review of the Use of Geophysical Archaeological Prospection in Sweden. *Archaeological Prospection* 18: 43-56.

Visser CA, Gaffney C and Hessing WAM (2011) Het gebruik van geofysische prospectietechnieken in de Nederlandse archeologie: Inventarisatie, analyse en evaluatie van uitgevoerde onderzoeken tussen 1996 en 2010. Vestigia BV Archeologie & Cultuurhistorie, Report number V887; Project number V10-1968; 30 June 2011.

Walker R, Gaffney C, Gater J and Wood E (2005) Fluxgate Gradiometry and Square Array Resistance Survey at Drumlanrig, Dumfries and Galloway, Scotland *Archaeological Prospection* 12: 131-136.

Westmeath (2010) *Tender for N52 Tullamore Kilbeggan Link Road, Archaeological Consultancy Services Contract Stage (i) i Geophysical Survey, Part 1 Suitability Assessment Questionnaire* Westmeath and Offaly County Councils.

Weston DG (2001) Alluvium and Geophysical Prospection. *Archaeological Prospection* 8: 265-272.

Weston DG (2004) The Influence of Waterlogging and Variations in Pedologyand Ignition upon Resultant Susceptibilities: a Series of Laboratory Reconstructions. *Archaeological Prospection* 11.2: 107-120.

Whiteford J and Calvert R (2009) *Geophysical Ground Investigation to Locate a Souterrain near Tuam, County Galway.* Whiteford Geoservices Limited.

Whitty Y (2009) *N11 Rathnew to Arklow Road Improvement - Ballyclogh South, County Wicklow: Final report*. Irish Archaeological Consultancy, unpublished Report, June 2009.

Wilkins B (2009) *N6 Galway to Ballinasloe Scheme, Contract 2. Final Report on archaeological investigations at Site E2440, a Late Bronze Age cist and ring-ditch in the townland of Ballykeeran, Co. Galway* Headland Archaeology Limited.

Wilkins B, Bunce A and Lalonde S (2007) *N6 Galway to Ballinasloe Scheme, Contract 2. Final Report on archaeological investigations at Site E2438, a ring-ditch with cremation deposits in the townland of Deerpark, Co. Galway*. Headland Archaeology Limited.

Witten AJ, Levy TE, Adams RB and Won IJ (2000) Geophysical Surveys in the Jebel Hamrat Fidan, Jordan. *Geoarchaeology* 15(2): 135-150.

Appendix A: Notes on Small Scale Funerary Monuments

Inhumations

The geophysical response of an inhumation is unlikely to be identified by a standard archaeological geophysical survey and requires specific attention. Burials are very difficult to identify for a number of reasons. It must be remembered that there are no geophysical techniques capable of identifying skeletal remains – an inhumation can only be identified by the in-filled grave cut.

Physical Properties:

A human burial or grave cut is normally <2m x <1m (much less for an infant).

Grave cuts tend to be excavated and subsequently backfilled within hours or days – the back-filled soil has no measurable magnetic enhancement compared to the surrounding soil.

The grave cut can be measured by the contrast in electrical conductivity – the disturbed fill of the grave retains more moisture than the surrounding soil and tends to appear as an anomalous zone in an earth resistance or conductivity survey. The grave cut is also likely to appear in GPR data.

Grave goods, coffin nails and iron grave markers may give a magnetic response, depending on their size and material composition.

Suggested Methods and Spatial Resolution:

The best practice for identifying an inhumation follows forensic methodologies (Ruffell and McKinley 2008; Ruffell *et al.* 2009).

In order to successfully identify a burial, a combination of earth resistance and magnetometer survey should be used at a high resolution, or a GPR or electromagnetic survey could also be used.

Combined earth resistance and magnetometer survey
An earth resistance survey should be carried out at a sample interval of 0.25m x 0.25m.
A magnetometer survey should be used at a sample interval of 0.25m x 0.25m.

GPR survey
A GPR survey should be used at a sample interval of 0.5m x 0.05m. An appropriate antenna should be selected based on the known or suspected depth of the grave.

Electromagnetic survey
An electromagnetic survey should be trialled at a high sampling density.

Cremations

Cremated skeletal remains are smaller targets than inhumations but are comprised of burnt material that can be identified by a magnetometer.

Physical Properties:

Cremation pits are likely to be small scale features 0.2 – 0.5m in diameter and <0.3m deep (Lynch and O'Donnell 2007).

The soils associated with the cremation deposit are likely to be identified by a magnetometer or electromagnetic (in-phase) survey. An associated urn might also be expected to add to the magnetic response.

The cremation pit may appear as a small isolated anomaly in an earth resistance or conductivity survey and may appear in GPR data.

Suggested Methods and Spatial Resolution:

Although an earth resistance or GPR survey might identify a small pit, a cremation burial is best assessed using magnetic methods; a magnetometer or electromagnetic survey should be used at a high resolution.

Magnetometer or Electromagnetic survey

A magnetometer or electromagnetic (in-phase and conductivity) survey should be used at a sample interval of 0.5m x 0.25m.

Cillín (Children's Burial Ground)

The reuse of prehistoric and medieval enclosure monuments for the extra-mural burial of unbaptised children presents a challenge to archaeological geophysics. The detection of neo-natal and post-natal inhumations is almost impossible, although an enclosing ditch or wall may be identified if present.

The question is largely one of scale: a geophysical survey can be commissioned to rapidly assess the enclosure monument, but in order to assess extra-mural burials a detailed and ultra-high resolution survey is required. Additionally, some adult inhumations (e.g. suicides, shipwrecked sailors, strangers, unrepentant murderers *etc.*) might also be expected in a Cillín, in which case, all of the considerations applied to adult inhumations, discussed above, must be considered.

For the assessment of neo-natal and post-natal burials, the following factors apply:

Physical Properties:

Neo-natal and post-natal inhumations are likely to be less than 0.2m x 0.4m in size, and the depth of burial is typically very shallow.

The size of the grave cut is little bigger than 2-3 spades worth of earth, almost immediately backfilled with no measurable magnetic enhancement compared to the surrounding soil.

The grave cut can be measured by earth resistance or conductivity survey only at ultra-high resolutions (less than 0.25m x 0.25m), or GPR (less than 0.25m x 0.05m).

Grave goods, coffin nails and iron grave markers may give a magnetic response, depending on their size and material composition.

Suggested Methods and Spatial Resolution:

In most cases the most applicable methodology will be to assess the enclosure monument at high-resolution (e.g. a magnetometer survey at 0.5m x 0.25m) and accept the limitations of geophysical methods that cannot positively identify neo-natal or post-natal inhumations, which may be best investigated by hand-dug intrusive excavations.

If the detection of neo-natal or post-natal inhumations is regarded as a priority then ultra-high resolution geophysical methods *should be used in combination* as detailed below. It should be noted that such a survey will identify a large number of anomalies that may represent natural soil noise or disturbance.

Combined earth resistance and magnetometer survey

An earth resistance or electromagnetic conductivity survey should be carried out at a sample interval of 0.125m x 0.125m.

A magnetometer or electromagnetic in-phase survey should be used at a sample interval of 0.125m x 0.125m.

GPR survey

A GPR survey should be used at a sample interval of 0.2m x 0.05m. An appropriate antenna should be selected based on the known or suspected depth of the grave.

Appendix B: Case Study of Wooden Trackways at Edercloon

Some wooden trackways (or *toghers*) can be mapped by geophysical techniques. GPR has returned mixed results on the Sweet Track in the Somerset Levels, UK due to changeable hydrology (Armstrong 2010). The most suitable method for the assessment of large and dense wooden remains is Induced Polarisation (IP) a technique that exploits the polarisable properties of wood to create contrasts with the surrounding peat material. Schleifer *et al.* (2002) demonstrated that frequency-domain spectral induced polarisation (SIP) was capable of identifying wooden planks in a waterlogged environment. SIP measuring instruments however are not widely available whereas time-domain IP measurements can be commonly collected by most resistivity instruments. IP collects data along a single line and produces a depth profile beneath that line (i.e. the resulting data plot is similar in format to an archaeological section drawing).

Fieldwork carried out for the Research Fellowship (Bonsall *et al.* 2013b) at the Edercloon Bog trackway complex (Moore and O'Connor 2009) used time-domain IP to identify and trace trackways beyond the excavation area. The research indicated that time-domain IP is capable of identifying a range of differently sized wooden trackways in peat and able to map the extent of some trackways beyond the road scheme. The method is not suited for use as a 'blind' prospection technique in areas of unknown archaeological potential as it depends upon an assumed knowledge of the trackway orientation and an estimate of likely depth. Time-domain IP will be particularly useful for mapping the extent and direction of a trackway that has been identified by small scale intrusive investigations.

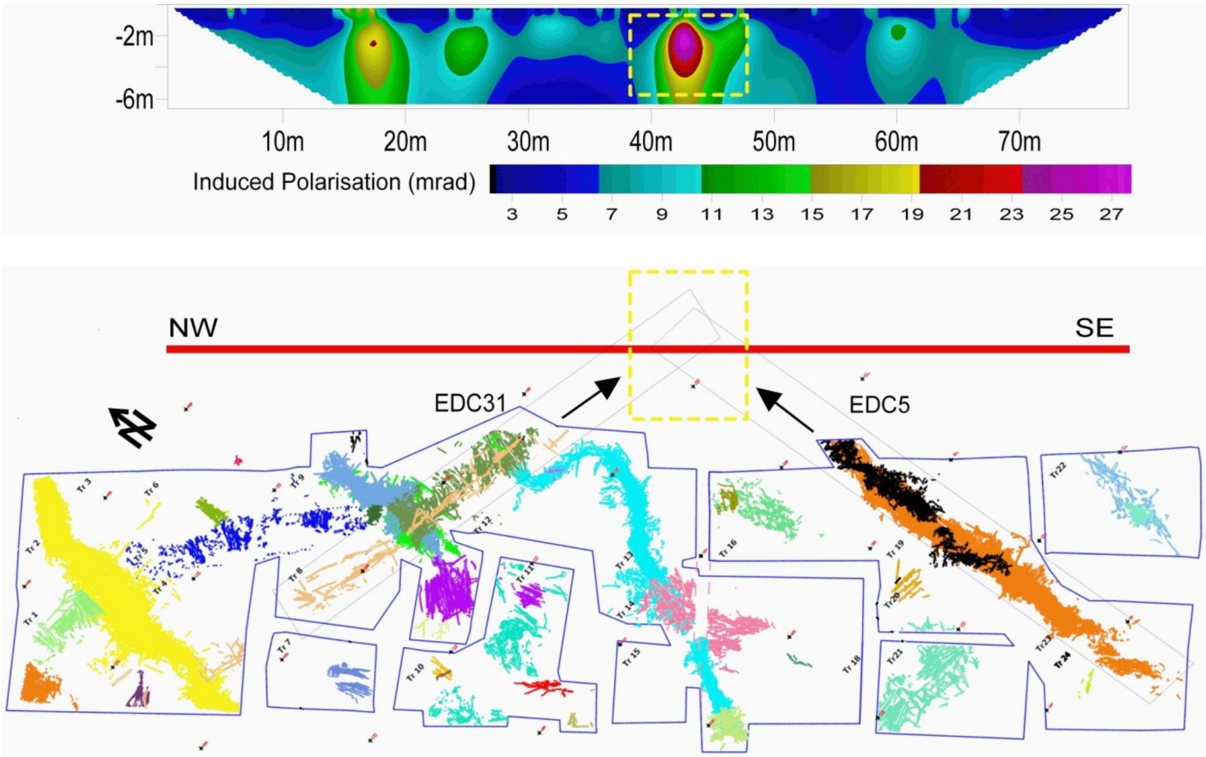
The following methodology was used for the collection of IP data at Edercloon Bog (specific instruments and manufacturers mentioned should not be taken as an endorsement; others are available):

The IP survey profiles were located 10m from the known edge of the Edercloon Bog excavation to avoid anomalous data generated by the disturbed and backfilled soil. The orientation of the profiles should (if possible) be perpendicular to the trackways. At Edercloon, the varied orientation and frequency of trackways (and the surrounding field boundaries) resulted in the collection of profiles at an oblique angle.

The data were collected using a ZZGeo FlashRES64 instrument along profiles 31.5m in length, using 64 electrodes spaced 0.5m along the profile. Data were extracted into pseudo-Wenner, Wennerß, Schlumberger and Double-dipole arrays.

16 parallel profiles of IP data were collected. Each profile was spaced 0.5m apart. The 16 profiles covered an area 8m in width by 31.5m in length. This area was large enough to trace and visualize the trackways. An additional 80m long profile was also collected in order to gain wider information about the adjacent soils.

If the objective of an IP survey were to trace the full extent of the trackways, then further profiles should be collected across an agreed survey area e.g. the full width of the road.



Time-domain Induced Polarisation (IP) data from Edercloon Bog.

Top: The IP data were gathered along an 80m traverse.
Bottom: Plan of the excavated trackways along the N4 Dromod-Roosky scheme (Moore and O'Connor 2009) and the location of an 80m long IP traverse line.

A high contrast anomaly identified 43m along the traverse is believed to be trackway EDC5 or EDC31 (or potentially an amalgam of both trackways abutting or crossing over and beneath one another). The anomaly coincides with the projected trajectory of excavated trackways EDC5 (Middle to Late Bronze Age primary togher) and EDC31 (Late Bronze Age to Iron Age secondary togher). Both of the togher were quite substantial; EDC5 was 1.3m in depth, 3.6m in width and 32.5m in length; EDC31 was 0.6m in depth, 4.8m in width and 12m in length.

A number of moderate contrasting anomalies were also identified in the IP data at 18m, 25m and 60m along the 80m traverse that could potentially correspond to a number of other trackways in the area.

Appendix C: Notes on Souterrains

The extent of souterrains can be mapped by electrical resistivity tomography (ERT), or via ground penetrating radar (GPR).

Electrical Resistivity Tomography Method of Mapping Souterrains

ERT profiles should be located over the known or suspected location of a souterrain.

The orientation of the profiles should, where possible, be perpendicular to the souterrain. The souterrain should be located in the centre of the profile, if possible.

ERT data can be collected along 31.5m long profiles, using 64 electrodes spaced 0.5m along the profile. This should achieve a reasonable depth to the target whilst maintaining suitable spatial resolution for near surface features.

If the objective of the ERT survey is to trace the *full extent* of the souterrain, then further profiles should be collected across an agreed survey area.

Ground Penetrating Radar Method of Mapping Souterrains

A detailed GPR methodology should be used over the souterrain.

As souterrains are very large targets, a sample resolution of 1m x 0.05m could be acceptable, although better information would be gained from a 0.5m x 0.05m resolution.

An appropriate antenna(e) will need to be selected to ensure that the depth of penetration is satisfactory. Antennas in the 200-500MHz range might be expected to return suitable data.

Appendix D: How to assess Igneous Geology

The following text is a suggested methodology to assess the viability of magnetometer surveys in areas of igneous geology at uncertain (or variable) depth. Magnetometer surveys should be avoided in areas of *near-surface* igneous geology. If the depth of igneous rock is uncertain or varies significantly over a long corridor route, a preliminary *geological* geophysical assessment could use magnetometer scanning transects to identify areas *unaffected* by the magnetic response of igneous geology. This should be used for geological purposes only and ***should not be used for the identification of archaeological zones or areas***, however it should be carried out by archaeological geophysicists as they will be able to appreciate the level of geological impact upon archaeological features. The geological scan could form part of a detailed route corridor assessment, or as a preliminary pilot study under a separate contract.

Pilot Study: Geological Scanning Method

Geological scanning should occur along *at least three* parallel transects spaced 30m apart, giving even coverage across the width of the road corridor. Narrow road schemes less than 60m in width should be scanned along both edges of the road corridor *and* down the centreline.

Gradiometers should be used for the scanning survey. Total field instruments may not allow for the instant recognition of 'high' or 'low' contrasts if the background responses are unknown.

Magnetometers should be set to a sensitivity level of 1nT. Scanning will be unrecorded and surveyors should maintain notes assessing the impact of geology on a given field. Observations should be archived in a written report and digital basemap.

Categories of Observations:

Strong Impact

Areas of widely variable magnetic contrasts, or consistently high responses, would *indicate zones that should not be surveyed with a detailed magnetometer survey*. Alternative methods such as electromagnetic, earth resistance or GPR surveys should be considered in these areas.

Low Impact

Zones of reasonably low or consistent contrast would be *appropriate areas for detailed magnetometer surveys*. Some small pockets of geological anomalies may still be expected, between the 30m wide transects, and this can be regarded as an acceptable outcome. Either fluxgate gradiometers or caesium instruments can be used for the detailed survey (which should follow a detailed survey methodology, appropriate to the local conditions).

Appendix E: Current Geophysical Practices in the UK

The first Commercial Archaeological Geophysics Seminar was held in the UK on the 14-15 March 2014, with most of the content archived via a live-stream of the presentations (CAGS 2014). The seminar brought together geophysicists, archaeologists and curators that were concerned with the practicalities of archaeological geophysical specifications, survey and reporting in the UK's commercial arena. Many of the outputs of the conference are relevant to geophysical surveys currently commissioned in Ireland:

- Recognition and agreement that unrecorded magnetometer scanning is no longer sought by UK curators and is no longer offered by most UK geophysical consultants.
- Detailed magnetometry is the predominant method of assessment in the UK.
- Many UK consultants acquire magnetometer data using a cart or sledge system.
- Survey speeds in excess of 5 ha of magnetometry per day are being regularly suggested by consultants and curators.
- Detailed magnetometer surveys in excess of >100 ha are not only viable but are now a regular occurrence for development-led projects in the UK.
- The use of 0.5m line spacing for the collection of magnetometer data is now viable.
- Significant challenges for geophysicists are trying to persuade UK archaeologists and/or curators of the benefits of magnetometer data collected at a 0.5m line spacing and the need for alternative geophysical techniques to counter the reliance upon magnetometry.
- Sampling strategies, such as those outlined in Figure 25, are beginning to fall out of favour in deference to 'full' or 'reduced' coverage surveys ('reduced' survey confined to regular shaped rectangular blocks, avoiding irregular areas with respect to field boundaries).