Electrical earth-resistance data – in Archaeological Prospection

[NB – a geophysical technique distinct from the physical measurement of soil resistance using a penetrometer]

*Guidance on '**Archaeology to Precision Agriculture (PA)**' data exchange via API platforms and Ecosystem Services (online GIS platforms)*

Part one: Descriptions

Data from earth resistance methods in archaeology are acquired with field-based, electrical systems which record restive contrasts encountered as electrical currents are passed through the soil between sets of consistently spaced probes (electrodes). 'Resistance' measurements relate to the geometry of the electrode configuration as well as to the amount and shape of material present, whilst derived 'resistivity' values (computed from resistance measurements) relate directly to the material properties of the soil, unaffected by neither electrode geometry nor material quantity (Gaffney and Gater, 2003, 28; Schmidt, 2013). Measurement systems may be configured using one or multiple standard electrode-arrays, where the (assumed) depth of investigations is determined by the distance between electrodes (i.e. approximately 1 to 1.5 times the horizontal probe spacing).

Common measurement systems used in archaeology are:

- ***Ground resistance meters*** which measure (electrical) earth resistance (R) in units of Ohms (Ω). Systems are typically mounted on mobile frames in twin-electrode configuration to cover larger areas of open ground systematically (area survey). Resistance meters are also sometimes mounted on specially adapted cart systems configured as 'square' arrays. Resistance area-surveys map the horizontal extent of resistive and non-resistive features at one or more (assumed) depths, usually between 0.5m – 1.5m below the ground surface.

- ***Electrical imaging (EI) systems*** which derive earth resistivity (ρ) in ohm-metres (Ω-m). Systems use static, two-dimensional (2D) linear (expanded) arrays of between 25 – 64 electrodes, to record and generate vertical soil resistivity profiles (pseudo-sections), to (assumed) depths of *c*. 5m or more. Vertical profiling aims to target and explore the depth and stratigraphic relationships of subsoil features. A series of vertical profiles collected in parallel over an area can be stacked side-by-side and interpolated between, to form the approximation of a three-dimensional (2.5D) volume.

Data Types – common to archaeological prospection

Resistance Data (maps)

Resistance area-survey including square array

Resistance data types relate to three workflow stages: collection, processing, interpretation:

- ASCII Text file – as collected raw (unprocessed) in the field or exported post-processed: tabular format delimited text file either fixed-width or with comma-, tab- or space-separated values; sometimes accompanied by a header file recording instrument specific survey parameters
- Grid data – 2D raster format file derived from field data where a matrix of cells visualize the numeric data using a colour legend, typically greyscale; the attribute represented by each cell can be either the unprocessed resistance data (raw) in original collection pattern (un-

interpolated e.g. 0.5m x 1m or 1m x 1m), or the processed resistance value, usually interpolated in an even and/or finer resolution (e.g. 0.25m x 0.25m)

  - Grid data are sometimes supplemented with image format files (e.g. jpeg, tiff, etc.) after processing. Image enhancements include clipping or stretching the range of values on a different scale to enhance contrast and make features of interest more visible. Supplementary image format files are often georeferenced (e.g. geotiff, etc.)

Common Resistance Data Derivatives

Resistance area-survey including square array

- Archaeological interpretation – 2D vector format file of individual features, or sets of features, overlaid and interpreted from the processed grid data as represented geometrically by points, lines or outline polygons
  - Interpreted features are typically classified according to set categories relating to some, or all, of the following:
    - Geophysical signal response (higher/lower resistance value)
    - Archaeology – feature type (wall, ditch, etc.)
    - Archaeology – potential (probable, possible etc.)
    - Geology and/or pedology
    - Modern land use or activity (agriculture, utility, infrastructure, military, disturbance, sporting, leisure, etc.)
- Other classed/clustered data (e.g. management zones, etc.)
- Vectorised interpretation classifications and features might be alternatively represented either individually or collectively, as image format files (e.g. jpeg, tiff, etc.) usually georeferenced (e.g. geotif, etc.)

Additionally:

- Conversion to resistivity values: preceding interpretation, resistance area-survey measurements are sometimes first converted to resistivity values to correct for measurement differences arising between surveys of different electrode geometries and then mapped; this might be done for a more realistic comparison of resistive values from multiple surveys over one survey area, as resistivity is more representative of the bulk properties of the ground than resistance (Walker, 2009, Appendix H)

Resistivity Data (profiles)

Vertical resistivity profiles derived from electrical imaging

Resistivity data types relate to three workflow stages: collection, processing, interpretation:

- Ascii text file – as collected in the field (unprocessed or minimally processed) resistance (and/or converted resistivity) values with associated electrodes line-positions or numbers: non-standard tabular format delimited text file either fixed-width or with comma-, tab- or space-separated values; sometimes accompanied by a related file recording instrument specific survey-parameters, and/or a related file containing the (real-world) co-ordinate values of electrode number locations (or survey line start-end points)

Specialist software are needed to convert (reduce) the initial resistance values as measured into ‘apparent’ (i.e. estimated) resistivity values before ‘inverting’ the data – a series of mathematical corrections – to construct a resistivity model section (geo-electrical pseudo-section) for geological/archaeological interpretation.

- Grid data – 2D raster format file derived from the apparent resistivity values where a matrix of cells visualize the processed numeric data measured in the field using a colour legend; the attribute represented by each cell can be either the measured apparent resistivity value, the calculated apparent resistivity value, or the inverse model resistivity value (grid file format)
  - Grid data are sometimes supplemented with image format files (e.g. jpeg, tiff, etc.) after processing. Image enhancements include clipping or stretching the range of values on a different scale to enhance contrast and make features of interest more visible. Supplementary image format files are sometimes georeferenced (e.g. geotiff, etc.).

Common Resistivity Data Derivatives

Vertical resistivity profiles derived from electrical imaging

- Geological/archaeological interpretation – 2D image format files of pseudo-sections are presented typically as stand-alone colour images with depth scales and colour legend; geological and archaeological strata and features are generally identified and interpreted in an accompanying text description. To aid interpretation, pseudo-section images (or copies) are sometimes annotated with text and/or marked geometrically with arrows, points, lines or polygons (e.g. jpegs, png, etc)
  - Interpreted features are typically described according to set categories relating to some, or all, of the following:
    - Geophysical response (higher/lower resistivity value)
    - Geology and/or pedology (strata, thickness, depth, moisture content, compaction etc.)
    - Archaeology – feature type (wall, ditch, bank, compacted surface, etc.)
    - Modern disturbance (relating to agriculture, utility, infrastructure, military, disturbance, sporting, leisure, etc.)

Vocabulary – common to archaeological prospection

(Thematic tags, term lists, thesauri)

Basic description or interpretation of geophysical anomaly

- Earth resistance or resistivity anomaly: high/strong; low/weak; background; geological; etc.

Classification of soil characteristics

- Customized descriptions: layers or strata (geological/archaeological), fills (geological/archaeological/modern disturbance/use), compacted subsoil surfaces (geological/archaeological)

Archaeological interpretation by response and form

- General classification: archaeology (feature type); geological (soil/layer type); modern disturbance/use (structure/utility type etc.)
- Detailed classification (wall (possible/probable), ditch (possible/probable), pit (possible/probable), surface (possible/probable) etc.)

Event description

- FISH Event Types Thesaurus (non-intrusive/geophysical/insert type)
  - http://purl.org/heritagedata/schemes/agl_et/concepts/145134

Part Two: Recommendations to increase interoperability

Identifiers – recommended

Unique identifier for published dataset (e.g. as provided by an open access digital repository)

Data structure – recommended

Core attributes of data types (see above)

Critical information for inclusion

Resistance data (maps)

Resistance area-survey including square array

- Raw data – minimum required attribute fields in order: X, Y, Z, V, TS, H-DOP, V-DOP, where:
  - attribute one is X the first locational co-ordinate (Latitude/Easting)
  - attribute two is Y the second locational co-ordinate (Longitude/Northing)
  - attribute three is V the measured resistance value (Ohms)
  - attribute four is TS the GNSS time stamp
  - attribute five is H-DOP the horizontal quality of the locational GPS measurement
  - attribute six is V-DOP the vertical quality of the locational GPS measurement

  Note: In non-GPS integrated surveys, the minimum required attributes are one, two and four (X, Y, V)

  Note: Where square-array survey results in three measurements (alpha, beta, gamma), V can be divided into V1, V2, V3

- Raster data. Processed grid or image data – a grid matrix of cell (pixel) rows and columns where each cell contains the numeric resistance value; the extent is defined by a bounding box
  - A supplementary, georeferenced version of this grid file, in an image file format where each resistance value is represented by a colour value (e.g. geotiff, etc.), might be useful for non-specialists.
- Vector data. Vector interpretation – geophysical or archaeological features or areas of interest as represented by line or polygons each of which is linked to a database element or row which describes its essential attributes such as line start, line length, line bearing, polygonal area, as well as any additional data; extent is defined by a bounding box

Resistivity data (profiles)

Vertical resistivity profiles derived from electrical imaging

- Base data (text). Minimum required attribute fields in order: X, Y, Z, V1, V2, V3, TS, H-DOP, V-DOP, where:
  - attribute one is X the first locational co-ordinate of a measurement centre point (Latitude)
  - attribute two is Y the second locational co-ordinate of a measurement centre point (Longitude)
  - attribute three is Z the third locational co-ordinate of a measurement centre point (height above ellipsoid/ODN)
  - attribute four is V1 the measured ground resistance (Ω) in Ohms
  - attribute five is V2 the apparent (estimated) ground resistivity (ρ) in Ohm-metres

- attribute six is V3 the inverted (calculated) ground resistivity (ρ) in Ohm-metres
- attribute seven is TS the GPS time stamp
- attribute eight is H-DOP the horizontal quality of the locational GPS measurement
- attribute nine is V-DOP the vertical quality of the locational GPS measurement

Note: In non-GPS integrated surveys: the minimum required attributes are A, M, N, B, V1, V2, V3 where:

- attribute one is the line position of current electrode A
- attribute two is the line position of potential electrode M
- attribute three is the line position of potential electrode N
- attribute four is the line position of current electrode B
- attribute five is V1 the measured ground resistance (Ω) in Ohms
- attribute six is V2 the apparent (estimated) ground resistivity (ρ) in Ohm-metres
- attribute seven is V3 the inverted (calculated) ground resistivity (ρ) in Ohm-metres

Note: Alternatively, each electrode position could be specified as the number along an electrode array with the (real-world) position of each electrode number recorded in a separate file which is useful for 3D surveys (Schmidt and Ernenwein, 2011, Appendix 1)..

- Raster data. Processed grid or image data – a grid matrix of cell (pixel) rows and columns where each cell contains the numeric resistivity (apparent or inverted) value; the extent is defined by a start and end points in real world co-ordinates
    - A supplementary, georeferenced version of this grid file, in an image file format where each resistivity (apparent or inverted) value is represented by a colour value (e.g. geotiff, etc.), might be useful for non-specialists

- Interpretative files. Interpretive text descriptions in text-file format, and/or image files annotated with text and/or marked geometrically with arrows, points, lines or polygons (e.g. jpegs, png, etc)

Data processing – recommended

Relating to instruments typically used to collect resistive data in archaeology (see above)

Ground resistance meter (resistance area-survey inc. square array)

- Raw file – tabular with X, Y, V where V is the earth resistance value in Ohm (Ω) units
  Note: For multiplexed surveys generating multiple grids at depth, separate files can be combined into one overall file with X, Y, V1, V2, V3, etc. Similarly, for square array surveys alpha, beta, gamma measurements can be represented by V1,V2,V3.
- Processing required to make it useful (resistance data):
    - Defect removal where necessary (e.g. despiking, grid-edge matching, etc.), suppress broad geological responses (e.g. high pass filter) to enhance weaker responses of potential archaeological interest
    - Additional enhancements – smoothing (e.g. low pass)
    - Re-sampling: interpolation between inline and crossline sampling to even appearance

Resistivity profiler (resistivity – single profiles)

- Base file – tabular, typically with A_pos, M_pos, N_pos, B_pos, V, where V is initially the resistance value in Ohm (Ω) units
- Processing required to make it useful (resistivity data):

- Reduction (conversion) of resistance values to apparent resistivity values in Ohm-metres (Ω-m) units; also required for further inverse modelling
- Pseudo-section modelling: inversion – the apparent resistivity values converted into a resistivity model section through an iterative process of corrective calculations

Metadata standard – recommended

For minimum metadata requirements, the BonaRes Metadata Schema for soil surveys is recommended (see Appendix 1 metadata ipaast template for a list of mandatory metadata elements). In addition, IPAAST-CZO recommends the following core elements (Schmidt and Ernenwein, 2011, Section 5.3) for inclusion with geophysical datasets:

Geophysics Metadata		See Appendix 1 metadata ipaast template for full definition
(All survey techniques and data types)		
Duration/Collection date	Mandatory	Date (ISO 8601)
Survey type	Mandatory	Character String (Controlled List Value): tbd
Instrumentation	Mandatory	Character String (Free text)
Area surveyed in hectares	Mandatory	Character String (Free text)
Method of coverage	Mandatory	Character String (Controlled List Value): gridded/line/non-gridded/scanning/etc.
Line separation (cross-line) in metres	Mandatory	Decimal / Numerical
Reading interval (in-line) in metres	Mandatory	Decimal / Numerical
Additional remarks/notes e.g. weather	Optional	Character String (Free text)

Metadata for specific techniques		
Earth Resistance or Resistivity Surveys		
Electrode configuration	Mandatory	Character String (Controlled List Value): twin/wenner/square/vertical profile/etc.
Electrode spacing	Mandatory	Decimal / Numerical
Multiple configurations	Mandatory	Character String (Free text)
Instrument gain	Optional	Character String (Controlled List Value): „h x10 „h x100 „ etc.
Current range in mA	Optional	Decimal / Numerical

Additional Metadata for specific data type (See above)		
Survey Methodology (for raw datasets)		
Data grid layout	Mandatory	Character String (Free text)
Data grid size	Mandatory	Character String (Free text)
Resolution	Mandatory	Character String (Free text)
Survey direction	Mandatory	Character String (Free text)
Line sequence	Mandatory	Character String (Free text)
Sampling position (if applicable)	Mandatory	Character String (Free text)
Data processing (for processed datasets)		
Processing history list	Mandatory	Character String (Free text)
Archaeology (for Interpretation datasets)		
Monument type	Mandatory	Character String (Controlled List Value): tbd
Monument period	Mandatory	Character String (Controlled List Value): tbd
SM /Heritage List number	Mandatory	Decimal / Numerical

Part Three: Scope Notes and Schema (to encourage exchange)

Scope Note 1

Applications of earth resistance or resistivity data in precision agricultural management decisions

Earth resistance or resistivity measurements are related chiefly to soil water content, amongst other soil properties. Depending on method, they effectively map horizontal and vertical variation in soil moisture and compaction, two soil properties of primary interest to plant and soil health in agriculture.

Resistance area-survey data map spatial variation horizontally over a larger area at an assumed depth. Typically, resistance area-surveys target the first 1m below ground level potentially providing information on moisture/compaction in root zones of many standard crops (*c*. 0.6m). Multiplexed resistance area-surveys (with two or more electrode configurations) can provide horizontal variation at multiple depths, potentially of interest for crops/plants with deeper root growth (> 0.6m). Moisture/compaction maps derived from resistance data over larger areas could potentially be incorporated into farm-management plans and/or help delineate farm-management zones; these data could also assist in guiding soil sampling strategies.

Electrical imaging profile data map spatial variation vertically and are typically used in archaeology to complement area surveys by providing additional depth estimates of larger buried features, as well as geomorphological information/context across larger areas (Schmidt et al., 2015, 74–75). Information at depth on sub-soil depth and overburden thickness could be of potential value in relation to assessing drainage patterns, tracking soil movement/erosion, or identifying sub-soil compaction which could impact on root growth.

Environmental aspects: moisture and compaction data can potentially inform and monitor environments aspects of soil health. For example, low-levels of moisture can indicate carbon loss in organic soils (carbon stability over time), conversely high-levels of moisture can indicate reduced soil strength (leading to soil failure) (Neilson *et al*., 2021). Top-soil depth is also important in monitoring carbon storage potential and erosion, whilst high-levels of compaction can impact on biodiversity (Neilson et al., 2020). Consequently, resistive data could potentially be incorporated into soil carbon-stability maps, and/or soil risk maps.

Limitations

Earth resistance measurements (and derived resistivity values) are affected by seasonal variation resulting in differing contrasts over time; this could equate to a complete lack of moisture contrast in saturated or extremely dry conditions.

In archaeology, resistance area survey is usually employed as a targeted application over specific targets (i.e. smaller areas) such as structural remains on account of its slow rate of collection and slightly courser resolution (relative to magnetic gradiometer surveys).

Archaeological application of earth resistance methods is typically once-off; repeat measurements might be of greater value to agricultural (and environmental) applications to monitor and assess changes in moisture over season/time.

Resistive anomalies:

- the fill of interpreted ditch and pit features will most likely retain moisture, as potentially reflected in increased plant growth; this also applies to the fill of any cut drainage features identified
- interpreted wall, surface and area of compaction features will most likely retain less moisture, as potentially reflected in decreased plant growth
- interpreted wall, surface and area of compaction features could potentially signal an increase in calcium levels which could be potentially related to plant health
- larger, linear cut features identified, such as former field boundaries where a hedgerow has been removed, could potentially point to surviving carbon stock, because of potential associations with vanished hedgerows (Collier, 2021; cf. Van Den Berge *et al*., 2021)
- depth estimations from resistivity profiles (or multiplexed resistance) measurements of subsoil depth/thickness could potentially indicate constraints on root depths of crops, especially if overlying certain archaeological remains or other abrupt changes in the subsoil resulting from the presence of concrete or rubble intrusions
- precise horizontal extent of pedological/geological soil variations (dependant on processing)

Scope Note 2

Data in precision agriculture potentially relevant to interpretating earth resistance or resistivity datasets in archaeology

Earth resistance area-mapping is also applied in agriculture particularly in Europe (Ünal et al., 2020; Lück et al., 2009; Gebbers et al., 2009), often in specialised practices such as viticulture (Rossi et al., 2013). Towed mobile-systems (e.g. Veris 3100 or ARP systems) consisting of multiplexed electrode-arrays with integrated GNSS produce large coverage moisture mapping in two-dimensions at up-to-three depths (between *c*. 0.5m – 2m). Such moisture maps could in theory (depending on sampling strategy) provide information on larger archaeological features, and/or provide additional geomorphological context to previously recorded archaeological features at landscape scale.

Limitations
Sampling strategies for large area electrical earth-resistance survey in agriculture are relatively coarse (in contrast to archaeological prospection) with traverse intervals set routinely to between 10m – 20m. However, where systems and sampling have been adjusted for archaeological purposes, data have proved successful, often proving advantageous in conditions unfavourable to other techniques (Dabas, 2009; Terrón et al., 2015; Piroddi et al., 2020).

Soil sampling is routinely carried out in precision agriculture to analyse the physical, chemical and biological properties of the soil under laboratory conditions. Typical analyses measure soil for texture (clay, sand, silt), individual macro-nutrients (as well as many micro-nutrients), CEC, organic content (carbon) and moisture retention. Results can play a role in validating and refining the interpretation of non-intrusive soil resistance or resistivity data (including depth) which can then be more confidently extrapolated over the wider area. This could help confirm the presence, extent and nature of anthropogenic disturbances in the bedrock (the fill of cut-features). Additionally, it could provide important geomorphology context for known archaeological remains such as topsoil thickness and bedrock depth with the potential to help inform on soil movements due to erosion or drainage.

Limitations
Soil sampling strategies in agriculture are usually undertaken at relatively course resolutions; their usefulness is enhanced for archaeological purposes, when used in conjunction with more detailed non-intrusive soil surveys, as provided by EMI, over larger areas.

Soil analysis using XRF (gamma ray) instruments and ICP-OES sensors on soil core samples is established practice in precision agriculture. As several soil properties (such as texture, moisture, chemical content) are relevant to the resistive response of buried features (Schmidt et al., 2015: 71), identifying these physical, chemical and biological properties of soil could provide additional relevant information for the analysis of resistive datasets and/or features.

Vehicle mounted gamma-ray instruments (Groundhog and Soiloptix) are a recent introduction to agricultural practice, geared towards mapping in-field spatial variations of topsoil properties. Results could complement the interpretation of results of earth resistance area-surveys by providing additional information on physical and chemical properties of the soil.

Limitations
Commercially available Gamma-ray instruments typically target the tillage layer (i.e. top 0.3m of soil, although measurements up 0.5m below surface are viable (Rentschler et al., 2020; Viscarra Rossel et al., 2007)), whereas archaeological resistance area-surveys typically sense at >0.5m depth. An additional limitation might be the courser sampling strategies of both lab- and vehicle-based gamma-ray surveys in agriculture which are considered course in archaeological terms.

Moisture measurements provided by *in-situ* moisture sensors (e.g. Farm21 or Van Walt Pico probes) are becoming increasingly part of agricultural practice (Hardie, 2020) and can record daily/weekly/seasonal changes in soil moisture content; these data could prove useful in planning archaeological resistance or resistivity surveys.

Limitations
Although *in-situ* soil moisture sensors are sometimes arranged in networks (Briciu-Burghina et al., 2022) throughout arable fields, many are situated in field margins for practical purposes; measurements may therefore not relate directly to areas targeted by archaeological prospection.

Schema

(1) Related to – topography, geology, hydrology, complimentary soil mapping (moisture, texture, compaction), modern services, documented archaeological features (historic mapping, aerial photography, earthwork survey, geophysics, excavation)

(2) Recommended further processing / analysis

- Resistance data (area) – translate vector data (resistance anomalies / archaeological interpretation) into agricultural useful terms or soil management zones perhaps relating to erosion, disturbance, drainage, anthropic inclusions in soils, enriched soils, compacted soils, etc.
- Resistivity data (profile) – translate profile interpretations into soil thickness or agricultural useful terms or soil management zones perhaps relating to erosion, disturbance, drainage, anthropic inclusions in soils, enriched soils, compacted soils, etc.

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