Electromagnetic induction (EMI) data – in Archaeological Prospection

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

Part one: Descriptions

Electromagnetic induction data in archaeology are generally derived from frequency domain electromagnetic instruments which comprise at least one pair of transmitter-receiver coils. An oscillating primary magnetic field is generated around the transmitter, which induces a secondary magnetic field by interacting with conductive materials in the soil. The receiver then picks up the secondary field, which allows evaluating the difference in amplitude and phase shift of the secondary versus the primary field. The separation distance of the coils influences the size of the measured soil volume, whilst the orientation of the coils influences the shape of the measured soil volume. Both the in-phase (IP) and out-of-phase (OP) or (QP, quadrature phase) signal response can be evaluated. This provides the potential to, under certain (generally low conductivity) conditions, evaluate variations in two geophysical properties:

- electrical conductivity (via the QP component)
- magnetic susceptibility (via the IP component)

Data Type – common to archaeological prospection

EMI data types relating 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 conductivity or magnetic data (raw) in original collection pattern (un-interpolated e.g. 0.25m x 1m), or the processed conductivity or magnetic value, usually interpolated in an even and/or finer resolution (e.g. 0.25m x 0.25m or 0.125m x 0.125m)

    - Grid data are sometimes supplemented with image format files (e.g. jpeg, tiff, etc.) after processing such as clipping of the range of values 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 Data Derivatives

- Archaeological interpretation – 2D vector format files of individual features, or sets of features, overlaid and interpreted from 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 (high/low conductivity or magnetic susceptibility)
        - Archaeology – feature type (wall, ditch, etc.)
        - Archaeology – potential (probable, possible etc.)

        - Geology and/or pedology
        - Modern activity (agriculture, utility, infrastructure, military, disturbance, sporting, leisure, etc.)
- Other classed/clustered data (e.g. management zones, etc.)
- Subsurface electrical conductivity models
- 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.)

Vocabulary – common to archaeological prospection

(Thematic tags, term lists, thesauri)

Basic description or interpretation of geophysical anomaly

- Electrical conductivity: high / low; strong / enhanced
- In-phase magnetic susceptibility: high / low; strong / weak; enhanced / decreased; ferrous, overwhelming disturbance, etc.

Classification of soil characteristics

- Customized descriptions: fills (possible / probable, linear / discrete), areas (texture, highlights), cultivation (trends), drains (possible / probable), boundaries (former / modern), trackways (former / modern), etc.

Archaeological interpretation by response and form

- General classification (archaeology (possible / probable), modern structure, etc.)
- Detailed classification (wall (possible / probable), ditch (possible / probable), pit (possible / probable), kiln (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 (for example as provided by an open access digital repository)

Data structure – recommended

Core attributes of data types (see above)

Critical information for inclusion

- Raw – minimum required attribute fields in order: X, Y, 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 conductivity or magnetic value (ppt or dimensionless unit SI)
    - attribute four is TS the GNSS time stamp
    - attribute five is H-DOP the horizontal quality of the locational GNSS measurement

- attribute six is V-DOP the vertical quality of the locational GNSS measurement

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

- Raster data. Processed grid or image data – a grid matrix of cell (pixel) rows and columns where each cell contains the numeric conductivity or magnetic value; extent is defined by a bounding box
  - A supplementary, georeferenced version of this grid file, in an image file format where each amplitude value is represented by a colour value (e.g. geotiff, etc.), might be useful for non-specialists
- Vector data. Vector interpretation – geophysical / 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

Data processing – recommended

Ground conductivity meter (frequency domain) – apparent electrical conductivity (ECa)

- Raw – edit tabular file to X,Y,V where V is the apparent electrical conductivity value in mS/m
- Processing required to make it useful
  - Recommended minimum: calibration/drift/temperature correction followed by inversion procedure(s)
  - Re-sampling: interpolation between inline and crossline sampling to even appearance

Ground conductivity meter (frequency domain) – apparent magnetic susceptibility (MSa or Ka)

- Raw – edit tabular file to X,Y,V where V is the apparent magnetic susceptibility value in ppt or dimensionless unit SI
- Processing required to make it useful
  - Recommended minimum: calibration/drift correction followed by inversion procedure(s)
  - Re-sampling: interpolation between inline and crossline sampling to even appearance (as above), followed by low pass filter for smoothing

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 with additions) 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	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	Mandatory	Character String (Free text)

Metadata for specific techniques		
Low Frequency Electromagnetic Surveys		
Coil configuration	Mandatory	Character String (Free text or Controlled List Value):
Instrument height above ground	Mandatory	Decimal / Numerical
Recorded component	Mandatory	Character String (Free text or Controlled List Value):
Output unit (QP)	Mandatory	Character String (Controlled List Value): ,, h field intensity ratio [ppt],, h low induction number ECa [mS/m] (general standard instrument output),, h modelled ECa [mS/m] (e.g. robust ECa value)
Output unit (IP):	Mandatory	Character String (Controlled List Value): ,, h field intensity ratio [ppt] (general standard instrument output),, h modelled MSa [mS/m) (e.g. robust MSa value)
Data String	Mandatory	Character String (Controlled List Value): Instrument specific standard, extended
Data Rate in Hertz	Mandatory	Decimal / Numerical
Instrument Frequency in Hertz	Mandatory	Decimal / Numerical
Trolly Model	Mandatory	Character String (Controlled List Value): tbd
Drift correction method	Mandatory	Character String (Controlled List Value): none, tie line, line zeroing, etc.
Distance front of instrument to transmitter in metres	Mandatory	Decimal / Numerical
Instrument orientation/orientation Tx-Rx axis with respect to moving direction	Mandatory	Character String (Controlled List Value): parallel, orthogonal in horizontal plane, orthogonal in vertical plane, etc.

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 EMI data in precision agricultural management decisions

Electrical conductivity data

EMI survey is already an established method of soil investigation in precision agriculture where, in non-saline environments, apparent electrical conductivity (ECa) data can identify areas of changing soil texture (clay, sand, silt) both laterally and vertically, and help inform on soil salinity, soil organic matter and soil water content, as well as other soil parameters such CEC and mineralisation. ECa data are furthermore used to design soil sampling surveys often with a view to reducing sample points (Heil and Schmidhalter, 2017).

When applied in archaeological surveys, ECa measurements are collected generally at higher resolution (Schmidt *et al*. 2015) than in agriculture (*cf*. King *et al*. 2003, 9–10 and 78–80) and can detect:

- the fill of cut features such as ditches and larger pits which might indicate increased water retention / organic matter / nutrient levels (also increased clay content, CEC, Salts)

- buried stone structures or rubble such as stone walls which might indicate decreased moisture levels / organic matter / nutrient levels
- the remains of banks or mounds which might represent areas of compaction and decreased moisture levels / organic matter / nutrient levels
- contextual information on soil extents and geomorphology which, when coupled with elevation data might give insight into erosion patterns and drainage

The higher resolution of the archaeological ECa data might also assist in refining:

- targeted soil sampling strategies (thereby reducing costs)
- the identification of soil management zones
- yield prediction (when used in combination with existing yield maps)
- variable rate including variable seed maps across large areas
- gauging and monitoring carbon stock (in combination with soil carbon sampling analysis)

Limitations
The linear relationship between the QP response and the low-induction ECa value outputted by most instruments (see McNeill 1980), becomes invalid in high conductivity (*c*. >100 mS/m) environments (Beamish, 2011; Callegary et al., 2007). Here, the low-induction ECa value generally leads to an underestimation of true ECa values, warranting adaptive modelling to obtain accurate ECa values (Hanssens et al., 2019).
ECa surveys do not produce good results in areas of poor conductance such as in high acidity environments.

Magnetic susceptibility data

Through the in-phase signal component, EMI instruments offer the potential to evaluate variations in soil magnetic susceptibility (MS). This provides a complimentary dataset informing on soil mineralogy (presence of magnetic iron oxides), as well as giving potential insights into complex interactions such as soil genesis, weathering, soil erosion/redistribution, and under certain conditions nutrient balance (see also ipaast guidance for magnetic data for details).

However, in contrast to archaeology, MSa datasets are not currently exploited to their full potential in soil and agricultural sciences despite the capability to provide diverse, high resolution and complementary data to ECa surveys (De Smedt 2021).

For example, MSa data collected with EMI instruments provide useful soil information:

- in areas of poor conductance (high acidity environments) which are challenging for ECa measurements
- in discerning lateral development of soil along hillslope, as opposed to its vertical movement (related to drainage and soil saturation)
- on topsoil thickness (for example in discerning an additional soil horizon over shallow geology which is the result of plough-enhanced erosion of shallow geology mixing with the more magnetically susceptible topsoil)
- on the identification of low-lying soil zones in palaeo-channels (for example over chalk geologies where accumulations of hill wash are equally enhanced by more moderate magnetic solifluction deposits)
- which is useful in guiding P sampling surveys (on account of the importance of iron oxides in P fixation esp. in acidic, dry sandy areas)
- in delimiting soil management zones

For further discussion of magnetic anomalies identified in MSa surveys (see also ipaast guidance for magnetic data).

Limitations
The complex relationship between in-phase response and the subsurface magnetic susceptibility in low and high conductivity environments: at increased conductivities (<100 mS/m), and particularly in saline environments, the in-phase response is generally dominated by the subsurface conductivity. In such cases, it is not possible to obtain extract reliable information on soil magnetic susceptibility from the in-phase response.

Scope Note 2

Data in precision agriculture potentially relevant to the interpretation of EMI datasets in archaeology

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 pivotal role in validating and refining the interpretation of non-intrusive electromagnetic soil data 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 topsoil (such as ferrimagnetic soil enrichment)
- 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, bedrock depth
- Erosion, drainage patterns and soil movement

Both of which can identify surviving palaeotopography, such as preserved soil or bedrock layers (under mounds), eroded [ancient] surfaces or palaeochannels

Environmental data such as soil temperature or rainfall could assist in calibration procedures such as adaptive drift correction and edge matching, necessary to compensate for changing diurnal variables during EMI surveys or seasonal inconsistencies between EMI surveys.

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.

Schema

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

(2) Recommended further processing / analysis

- translate vector data (soil texture classifications; electrical / magnetic anomalies; archaeological interpretation) into agricultural useful terms or soil management zones relating to soil texture, as well as erosion, disturbance, drainage, anthropic inclusions in soils, enriched soils, compacted soils, etc.

- Standard soil sample analyses (e.g. iron content, phosphorus content, etc.), either laboratory based or measure *in situ* could be useful in interpreting EMI datasets

References

Beamish, D., 2011. Low induction number, ground conductivity meters: A correction procedure in the absence of magnetic effects. *Journal of Applied Geophysics* 75, 244–253. https://doi.org/10.1016/j.jappgeo.2011.07.005

Callegary, J.B., Ferré, T.P.A., Groom, R.W., 2007. Vertical Spatial Sensitivity and Exploration Depth of Low-Induction-Number Electromagnetic-Induction Instruments. *Vadose Zone Journal* 6, 158–167. https://doi.org/10.2136/vzj2006.0120

Clark, A. 1990. *Seeing beneath the soil; prospecting methods in Archaeology*. Reprint London: Routledge, 2000.

Crowther, J., Barker, P., 1995. Magnetic susceptibility: Distinguishing anthropogenic effects from the natural. Archaeological Prospection 2, 207–215. https://doi.org/10.1002/1099-0763(199512)2:4<207::AID-ARP6140020404>3.0.CO;2-#

Cuenca-García, C., 2019. Soil geochemical methods in archaeo-geophysics: Exploring a combined approach at sites in Scotland. *Archaeological Prospection* 26, 57–72. https://doi.org/10.1002/arp.1723

De Smedt, P. 2021. *Soil magnetism and proximal soil sensing: a perspective*. EEGS WG-PSS SEG Symposium. Presented virtually 16-19 August 2021

Hanssens, D., Delefortrie, S., Bobe, C., Hermans, T., De Smedt, P., 2019. Improving the reliability of soil EC-mapping: Robust apparent electrical conductivity (rECa) estimation in ground-based frequency domain electromagnetics. Geoderma 337, 1155–1163. https://doi.org/10.1016/j.geoderma.2018.11.030

Heil, K., Schmidhalter, U., 2017. The Application of EM38: Determination of Soil Parameters, Selection of Soil Sampling Points and Use in Agriculture and Archaeology. *Sensors* 17, 2540. https://doi.org/10.3390/s17112540

King, J. A., Dampney, P. M. R.,Lark, R, M.,Wheeler, H. C., Bradley, R. I., Mayr, T., and N Russill, 2003 Evaluation of non-intrusive sensors for measuring soil physical properties, HGCA/AHDB Project Report No. 302, https://ahdb.org.uk/evaluation-of-non-intrusive-sensors-for-measuring-soil-physical-properties

McNeill, J. D. 1980 Electromagnetic Terrain Conductivity Measurement at Low Induction Numbers (Technical Note 6). Technical Notes. Ontario: Geonics Limited.

Schmidt, A., and Ernenwein, E.G., 2011. *Geophysical data in archaeology: a guide to good practice*. ADS, 2nd fully revised edition. https://guides.archaeologydataservice.ac.uk/g2gp/Geophysics_Toc (accessed 11.8.21).

Schmidt A.R., Linford P., Linford N., David A., Gaffney C.F., Sarris A., and Fassbinder J., 2015. *EAC Guidelines for the use of Geophysics in Archaeology: Questions to Ask and Points to Consider*. EAC Guidelines 2. Namur, Belgium: Europae Archaeologia Consilium (EAC), Association Internationale sans But Lucratif (AISBL).