Survey report

Ground Penetrating Radar and Magnetometer Archaeological Prospection at Zaltbommel 2007

Methodology, data acquisition, results, interpretation

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*Magnetometer survey at Zaltbommel (The Netherlands).*

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1 Introduction

During three days in January 2007 the Archaeological Excavation Department of the Swedish National Heritage Board conducted Ground Penetrating Radar (GPR / georadar) and magnetometer measurements for archaeological prospection near the town of Zaltbommel in The Netherlands. The survey was commissioned by Archeologisch Dienstencentrum (ADC) in Amersfoort in order to probe the presence and location of historic and archaeological structures in the subsurface of the development site “De Wildeman”. Figure 1.1 shows the location of the survey sites on fields east of Zaltbommel.

In 2005 and 2006 ADC had excavated a grave field dating to Roman times in the area. The chosen archaeological prospection survey areas are located immediately to the east of the already excavated areas (Figure 1.2).

![Figure 1.1 Overview map of Zaltbommel with the survey sites marked. Map source: ADC.](image)

1.1 Site conditions

The survey sites are located in flat, grass covered fields that are interspersed with drainage channels (Figures 1.2 and 1.3). The groundwater level is at approximately 1.5m depth below surface level. The soil at the survey site consists of heavy clay. Due to earlier rain the soil had been water saturated, causing up to 10cm deep standing water on parts of the georadar area A (Figure 1.4). Due to the cold temperature the water puddles were covered with ice. During the course of the first day of the survey the temperature increased from about 0°C to 5°C causing the ice to melt. A field track in the eastern part of the magnetometer survey area had been planked with heavy metal plates, giving rise to very large magnetic anomalies in its vicinity.
Figure 1.2 High-resolution satellite image (Google Earth) showing the survey areas, drainage channels and field paths. Crop marks indicate older trenches or formerly elevated fields.

Figure 1.3 Map of the proposed georadar survey areas, the actually surveyed georadar areas A and B, the magnetic survey area and the structures excavated by ADC. Drainage channels and a field track are indicated with black lines.
1.2 Description of the field work

The georadar surveys were conducted using a Sensors & Software NogginPlus system mounted in a SmartCart (Figure 1.4). After having tested both 500 MHz and 1000 MHz georadar antennas it was decided to use the 500 MHz antenna since the 1000 MHz antenna showed close to zero signal penetration depth. Even the signal of the 500 MHz antenna appeared to consist mainly of the direct wave when visually inspected on the monitor of the data logger. On georadar survey site A no reflections from within the subsurface were visible. The low penetration depth was attributed to the assumed high soil conductivity due to a heavy clay matrix saturated with water. Because of the possibility of weak reflections being hidden under the strong direct wave, nevertheless the survey of a 50m by 50m area was attempted. The georadar system was moved in zig-zag mode along 50m long survey lines with a cross-line spacing of 25cm for the parallel georadar profiles. The inline georadar trace spacing was 5cm. Maximum recording time was set to 62ns.

Having surveyed an area of 30.75m by 50m the measurements were abandoned by reason that standing surface water was putting the georadar system at risk. An initial analysis of the georadar data did not show any significant anomalies besides the water covered areas.

Due to the unfavourable site conditions for georadar measurements it was decided to test magnetic archaeological prospection for the detection of subsurface structures. An area slightly larger than one hectare (1 hectare = 100m by 100m) was covered with dense magnetometer measurements (Figure 1.2) using a Förster Fluxgate gradiometer (65cm vertical gradient) system with four parallel mounted gradiometer probes (Figure 1.5). The inline sample spacing was 10cm while the cross-line sample spacing was 50cm. The survey area crossed the field track that had been plated with metal slabs, giving rise to large magnetic anomalies in the eastern part of the survey area.
Since the weather during the first two survey days remained relatively dry and because the field containing survey area B had no standing surface water it was decided to attempt another georadar survey at site B on the third day. Survey area B appeared to be slightly more elevated than survey area A. An area of 50m by 50.5m was covered using 25cm cross-line and 5cm inline trace spacing.

All survey areas were geo-referenced using a robotic total station and fix-points with known coordinates in the vicinity of the survey areas. The coordinate information for the fix-points had been provided by ADC. Maximum absolute positioning error (assuming correct fix-point coordinates) is 2.5cm.

The final processing of the GPR and magnetometer data was performed by Alois Eder-Hinterleitner (Central Institute for Meteorology and Geodynamics, Vienna) using purpose written software for special processing of archaeological prospection data. The analysis and interpretation of the geo-referenced prospection data was conducted within the Geographical Information System (GIS) ArcMap. Time-to-depth conversion of the GPR data was performed with a constant velocity of 10cm/ns for the entire subsurface. Since no absolute velocity values were determined the depth information of the depth-slices can vary up to 50%.

Sections 2 and 3 of this report contain a brief introduction to the georadar and magnetic prospection methods respectively. In Section 4 the georadar data and its archaeological interpretation for areas A and B are presented. A description of the magnetic prospection data and its archaeological interpretation is contained in Section 5. Section 6 summarizes the results of the archaeological prospection survey. The Appendix (Section 7) contains images of the georadar and magnetic data. A technical summary of the survey is provided in Section 8.
2 Brief description of the Ground Penetrating Radar method

Ground Penetrating Radar, Ground Probing Radar (GPR) or Georadar is a geophysical measurement method that allows the investigation of the shallow subsurface. A GPR antenna is used to send electro-magnetic waves into the subsurface. These waves are reflected from structures such as large stones, old foundations of buildings, pits, ditches or interfaces of geological layers. The reflected radar waves that are returning to the surface like an echo are recorded with the GPR antenna and used to generate an image of the subsurface.

The GPR technique

GPR antennas used for archaeological prospection typically emit an electro-magnetic signal with an average frequency between 100 and 1000 Megahertz (MHz), similar to radio stations. In general, it can be said that the higher the frequency, the shorter the wave-length of the electro-magnetic wave. The wave-length is defining how well we can resolve structures in the subsurface: a shorter wave-length of higher frequency is able to “see” smaller objects. On the other hand, high frequency electro-magnetic waves suffer more from damping of the signal, compared to electro-magnetic waves with longer-wave lengths and lower frequency.

The frequency dependent damping has the effect that the amplitude of the electro-magnetic signal decreases, the further the signal travels through the ground. Low frequency signals are better suited to look deeper into the ground than high frequency signals. Thus, for the selection of the antenna with the right frequency for our survey we need to make a compromise between penetration depth and desired resolution. Antennas with different frequencies are available (e.g. 100, 200, 250, 300, 500, 800, 900, 1000 MHz), and a 500 MHz antenna is often a good choice for archaeological investigations down to a depth of about 2 to 3 metres with 15cm to 20cm resolution.

The penetration depth and resolution of the georadar method does not only depend on the frequency of the antenna used, but as well on the soil properties at the measurement location. The physical properties of the ground determine the velocity and attenuation of the electro-magnetic waves. In particular, the electrical conductivity of the soil can have a great effect on the radar waves.

Soils with high clay content, or soils that contain a large amount of conductive water, are difficult to investigate with georadar. The uppermost layers of such soils soak up the energy of the electro-magnetic waves and prevent the energy to travel deeper. Sandy soils allow much better depth penetration. Fresh-water in itself poses no problem to GPR investigations. It is possible to conduct a radar survey from a boat, by suspending the antennas into the water of a lake or by placing them on the floor of a rubber-boat. In that case the electro-magnetic waves penetrate through the water into the sediment underneath. Similarly, it would be possible to...
measure on the frozen surface of lakes in winter time, for example to search for harbour constructions or wrecks in shallow water regions, that are inaccessible during summer due to reeds or other seasonal plants.

**How is a GPR survey conducted?**

Before a georadar survey is undertaken it is important to determine the specific conditions of the measurements site. Each project is different and requires the use of an antenna of suitable frequency and a carefully designed measurement grid. If linear structures, such as walls or ditches, are the target, it is best to measure perpendicular to the expected structure. Regular survey areas with equally long profiles allow faster, cheaper measurements, while survey areas that contain obstacles, such as trees, bushes, walls or fences, cause delays.

While the GPR antenna is pulled over the surface an electromagnetic source signal is emitted into the ground. The antenna will then “listen” for fractions of a second and record the returning signal which has been reflected or refracted in the subsurface. For each measurement position along the profile line a time-series of amplitude values ("GPR trace") is recorded. It is important that the data is measured with very dense trace spacing (5cm in profile direction; 25 cm profile spacing).

**How does GPR data look like?**

Each GPR trace is a time-series of amplitude values of the reflections of the electromagnetic GPR signal, recorded with the receiver antenna, some time after emittance of the source signal from the source antenna, at a specific antenna location.

Each GPR profile consists of a large number of GPR traces. These traces can be plotted as an image with the profile distance as horizontal axis and the recording (“listening”) time as vertical axis (Figures 2.3, 2.4). Such an image is called a “GPR section” or “GPR profile”.

![Figure 2.2: Pär Karlsson operating the Sensors & Software Noggin Plus 500 MHz antenna mounted in the SmartCart. The data logger with integrated monitor is fastened in a carrier frame in front of the operator. Profile lines with 1m separation distance are visible on the ground. The antenna is pushed along these lines and in between them with a GPR profile spacing of 25cm. Every 5cm along the profile a GPR trace is recorded.](image)

![Figure 2.3: A GPR section consisting of many GPR traces. The vertical axis is showing the two-way travel time of the GPR signal, and the horizontal axis denotes the distance along the profile.](image)
It is common to record many parallel GPR sections by measuring with the GPR antenna in zig-zag mode along parallel profiles across the survey area. The cross-line distance between the sections should be 25cm. The inline distance of traces in direction of the profile should be 3cm.

The individual GPR sections are merged into a three-dimensional (3D) data volume (Figure 2.5). Data values between the profile sections are interpolated in order to obtain a comparable sample density in inline and cross-line directions.

Such a 3D data volume can be cut like a cake in all directions. Slices of equal recording time, so called time-slices, can be generated by cutting the 3D data volume horizontally (Figures 2.6, 2.7).

**Figure 2.4:** The same data as in Fig.2.3 displayed using grey-scale colour values between negative, minimum amplitude (white) and positive, maximum amplitude values (black).

**Figure 2.5:** Set of parallel GPR sections. This set of two-dimensional (2D) GPR sections can be merged into a three-dimensional (3D) data volume through interpolation between the sections. Normally, the sections are measured in zig-zag mode by pulling or pushing a GPR antenna back and forth over the survey area along parallel, equally long profile lines.

**Figure 2.6:** A horizontal slice cut through the 3D data volume with travel-time as vertical axis is called a time-slice, since all data values have the same two-way travel-time value.
If the velocity of the electromagnetic waves in the subsurface is known, the 3D data volume can be converted into a 3D block with depth as the vertical axis. Then it is possible to generate depth-slices, which show the reflecting structures at a certain depth or within a certain depth range. Often an average velocity is used for the time-to-depth-conversion (e.g. 10cm/ns). It should be noted that in the case of an average velocity used, depth variations of up to 50%, compared to the real depth, can remain present in the data.

Structures in depth are best recognizable by analyzing a series of depth-slices. From a series of depth-slice images an animation (simple movie) can be generated. Then the viewer can observe the emergence and change of different structures with increasing, or decreasing depth.

Other common GPR data processing steps are the removal of the average trace, or background removal. This process removes signal-ringing in the data and allows to image the uppermost region of the data, which otherwise would be hidden by the high amplitudes of the direct-wave. The direct-wave is the wave that travels directly from the source antenna to the receiver antenna, which are often located both inside the same GPR antenna box. The direct-wave is the first signal that is recorded by the receiver antenna. Since the direct-wave is of several ns length, it covers the reflections that occur in the uppermost layers of the subsurface.
What objects can GPR detect?
Under the right conditions georadar can be used to detect the foundations of buildings, canalisation pipes, pits, ditches, graves, cavities and geological structures such as layer interfaces and faults.

It is important to realize that the GPR method cannot guarantee the detection of objects or structures, particularly if they are small in size (relative to the wave-length used), if their physical properties do not differentiate them from the surrounding material or if the soil conditions are adverse (e.g. in case of limited signal penetration depth caused by a highly conductive soil).

GPR measurements can allow the archaeologist to obtain an image of structures that are hidden in the subsurface without digging. GPR surveying, similar to magnetic prospection, is a non-destructive method.

GPR measurements provide information about the relative depth of structures. If the velocity of the radar waves in the subsurface is known, the absolute depth of structures seen in the GPR data can be determined.

The results of georadar measurements can be used to plan excavation activities efficiently in regard of costs and time. GPR measurements make it possible to target interesting structures and to excavate selectively with the benefit of prior knowledge.

Suggested reading


3 Brief description of the magnetic prospection method

Geomagnetic archaeological prospection is based on the measurement of the Earth’s magnetic field. The detection of archaeological structures is possible when material with some magnetic properties is embedded in a host material with different magnetic properties. The strength of the Earth’s magnetic field in northern Europe is about 50.000 nano Tesla (nT). This field strength varies, depending on the geographical latitude (with respect to the magnetic poles) and depending on solar activity, which can cause variations over short time ranges (minutes, hours, days) and so called magnetic storms. The magnetic field strength that is observed locally at the Earth’s surface depends on the magnetic properties of materials close to the magnetic sensor, the so called magnetometer.

Objects with a different magnetization to the surrounding material will be detectable if the magnetometer is close enough to the object, if the magnetometer is sufficiently sensitive and if the magnetic effect of the object is not overshadowed by a larger magnetic effect of another object nearby. A magnetometer will register the total magnetic field at the measurement location, including the Earth’s magnetic field. In order to detect the very weak magnetic anomalies caused by archaeological structures (typically in the range of 0.01nT – 5nT) in the much stronger global magnetic field (~50,000nT in Sweden), it is common to make two measurements: one measurement with a sensor close to the archaeological object (close to the ground) and one with a sensor that is located further away. The more distant sensor can be located beside the survey area (Variometer setup), or at some distance (normally between 60cm and 2m) above the first sensor (Gradiometer setup) (Figure 3.1). Since the strength of the magnetic field decays with the square of the distance, in many cases only the sensor close to the ground will be able to measure the magnetic effect caused by the archaeological structure. The computation of the difference between the data measured with the two sensors in Gradiometer or Variometer setup will enhance the visibility of weak anomalies in a strong global field. Furthermore, this process will remove the temporal variations of the Earth’s magnetic field from the data.

Another method is to survey in uncompensated mode without a second magnetometer for the difference measurements, and to subtract a mean-value for each profile, as well as a mean value for the survey quadrant. This method is sometimes referred to as “Bavarian Style” since it was introduced by Helmut Becker at Munich (Becker 1999).

Other effects that play a role in archaeological prospection are thermo-remanent magnetization and bio-magnetism. Thermo-remanent magnetization causes burned objects, such as for example fire places, burned bricks and pottery, to acquire an inherent magnetization. Heating of a material above its Curie-temperature causes iron oxides contained in the material to be converted to a more
magnetic form. If cooling takes place in presence of an external magnetic field, a permanent magnetization will be retained by the object through alignment of the magnetic minerals along the direction of the external field. Thus, a burned brick or piece of burned pottery can cause a magnetic anomaly. Not all magnetic anomalies observed in archaeological prospection are attributed to the use of fire or metallic objects. Small bacteria were discovered to contain pure Magnetit crystals (Fassbinder et al. 1990) (Figure 3.2). Such magnetotactic bacteria were observed to cause magnetic anomalies associated with decomposed pre-historic palisades and wooden posts. Another group of magnetotactic sulfur-iron bacteria is credited with causing magnetic anomalies associated with grave fields and body burials (Linford 2004).

The visibility of magnetic anomalies depends on the magnetic properties of the surrounding environment. If the magnetization of the background medium is low and homogeneous, artifacts generating a sufficiently strong magnetic field disturbance will clearly stand out. If however the area of investigation is magnetically inhomogeneous and contains objects of high magnetic susceptibility, then it will be difficult or impossible to see the weak magnetic anomalies produced by some archaeological structures, such as wooden post holes, thin walls, single stone settings.

It is possible, that the lack of magnetic susceptibility in a material produces a negative magnetic anomaly, for example limestone blocks embedded in a sandy soil with clay content. The limestone, a product of biological shells and skeletons, contains no, or only very little magnetisable material, while the iron minerals contained in the surrounding soil cause it to be positively magnetized.

Pre-historic settlements and the use of fire caused an artificial increase in magnetization in soils within and surrounding the inhabited areas (Le Borgne 1955, 1960, 1965). Therefore, such areas may stand out in the result of a magnetic survey (in the so called magnetogram), due to the contamination of the soil containing burned material. Furthermore, ditches, pits and post holes filled with artificially magnetically enriched soils due to human activity may appear as positive anomalies. It may be possible to identify fire places within houses, or to determine whether a structure seen in the magnetogram was destroyed by fire. In the most cases the amplitude of magnetic anomalies observed in archaeological prospection is in the range of few nT to some pico Tesla (1 pico Tesla = 0.001 nT).

The magnetic prospection method is very sensitive to any magnetisable material in the vicinity of the sensors. Therefore it is important, that as little as possible magnetisable material is present during measurements. Instrument carts are usually made of plastic, wood and other non-magnetic materials (Figure 3.3). Rivets in the shoes of the instrument operator or metallic frames of spectacles may cause sufficient disturbance to render entire measurements useless.

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1 magnetic susceptibility is the magnetization of a material per unit applied field
3.1 Description of different magnetometer types

The hardware needed for magnetic measurements involves one or more magnetometers. If gradient measurements shall be conducted at least two magnetometer sensors are required. A non-magnetic cart or carrier frame is generally used to mount the magnetometers. The data is recorded with a data logger. Power supplies in form of batteries are required. A survey grid defined with measuring lines on the ground and an electronic distance marker attached to the data logger, or a highly accurate GPS system (RTK-GPS) for the recording of positioning information are needed.

Several different types of sensors exist for the measurement of magnetic fields: Proton precession magnetometers, Fluxgate and Förster magnetometers, Overhauser-effect magnetometers, optically pumped Cesium magnetometers, and SQUID magnetometers.

Proton-precession magnetometers

Proton-precession magnetometers measure the free-precession frequency of protons that have been polarized in a direction approximately normal to the direction of the Earth’s magnetic field. When the polarizing field is suddenly removed, the protons spin about the axis of the Earth’s field. The protons precess at the Lamour precession frequency, which is proportional to the magnetic field. In general, a bottle of fluid rich in hydrogen atoms, e.g. distilled water or a hydrocarbon such as kerosene or alcohol, is surrounded by a coil of wire which can be energized by a direct current to produce a strong magnetic field. When the current is shut off, the precessing protons in the fluid induce a very weak signal into the same coil, which is now connected to a suitable output device. Proton precession magnetometers measure only the total magnetic field. The advantage of this magnetometer type is that it is cheaper than all other types of magnetometers. Their disadvantages are that they have a slow sampling interval and a low sensitivity. Even though Proton magnetometers have been used successfully for archaeological prospection surveys, this type of instruments is not useful for large-scale, high resolution surveys of archaeological structures with weak corresponding anomalies.

Overhauser-effect magnetometers

Overhauser-effect magnetometers are in principle proton precession devices, with an order of magnitude greater sensitivity than proton magnetometers. A radio-frequency signal is used to excite electrons of a special chemical which is dissolved in a hydrogen-rich liquid. The electrons then pass their excited state on to the hydrogen nuclei, whereby they alter their spin state.
populations and polarize the liquid. This happens with much less power and to greater extend than in standard proton precession magnetometers. Overhauser-effect magnetometers have a higher cycling, and therefore sampling speed, than proton precession magnetometers, since the liquid can be polarized while the signal is being measured. This type of magnetometer is very energy efficient. The sensitivity of Overhauser-effect magnetometers is smaller than 0.015 nT / \sqrt{Hz} . However, maximum sampling rates are still just 10Hz, rendering Overhauser-effect magnetometers too slow for fast, high-resolution archaeological surveys.

**Fluxgate magnetometers**

The Fluxgate magnetometer is a purely electronic magnetometer. A Fluxgate sensor contains a highly permeable nickel-iron alloy core in ring shape. A current is applied to a coil (the primary coil) that is wound around the core in order to saturate the magnetization of the atoms in the core. Saturation magnetization is reached when the magnetic axes of the atoms in the core are aligned. In the presence of an external magnetic field and by using an alternating current to drive the primary coil, an asymmetry in the magnetic field that is induced in a second coil can be measured. This asymmetry is proportional to the external magnetic field and depends on the orientation of the sensor. In archaeological prospection Fluxgate magnetometers are generally used to measure the vertical component of the magnetic field. The orientation dependency of Fluxgate magnetometers requires that Gradiometer setups are carefully adjusted. Fluxgate gradiometers have a relatively high sensitivity and the sample rate is sufficiently fast.

**Optically pumped magnetometers**

Optically pumped magnetometers are as well referred to as Alkali-vapor, or Absorption-cell magnetometers. The most common optically pumped magnetometers are Cesium magnetometers. Other magnetometers of similar type are Rubidium and Potassium magnetometers. Cesium magnetometers are currently the most sensitive professionally and commercially used magnetometers. The functioning of these magnetometers is based on the Zeeman Effect, which is the splitting of a single atomic energy level into two or more energy levels, due to the presence of a magnetic field. Cesium, Potassium and Rubidium atoms posses single valence electrons that are sitting in the ground state (lowest energy level), unless they are excited by an external force. In the presence of a magnetic field this ground state splits into two levels, G1 and G2. Optically pumped magnetometers contain a glass vapor cell in which a gaseous metal (Cesium, Rubidium or Potassium) is exposed to polarized light of a specific wave-length. This light causes the electrons of the alkali atoms to be excited from the G1 ground state into a higher excited energy level, G3, which is energetically higher than G2. The higher energy level G3 is not stable and the electrons fall back into level G2, since the level G1 is unavailable. The light is filtered in such way that the electrons will not jump from G2 state into the excited state G3. Energy level G1 is depleted of electrons by optically pumping them into energy level G2. When energy level G2 is full no more energy can be absorbed and the vapor cell becomes transparent. At this stage a radio frequency (RF) signal is applied, which causes the electrons to drop back into energy level G1, and the cell to become opaque again. Then the pumping cycle begins again. The frequency required to repopulate level G1 varies with the ambient magnetic field and is called Lamour frequency. The Lamour frequency is a measure for the total magnetic field strength. The main advantage of Cesium magnetometers is their high sensitivity, between 0.002 and 0.05 nT (0.002 nT = 2 picoTesla), depending on sample rate (slower sample rate, higher accuracy). Cesium magnetometers are able to sample at up to 100Hz (100 samples per second). Cesium magnetometers have a very wide operational range.

**SQUID magnetometers**

SQUID (Superconducting Quantum Interference Device) magnetometers are the most sensitive magnetometers in use. SQUIDs are able to measure tiny magnetic fields as small as 1 femto-Tesla (1 fT = 10^-15 nT). They are used to measure biomagnetic effects, such as the magnetic field of the brain (few fT) or the magnetic field of the heart (50,000 fT). SQUID magnetometers consist of two superconductors separated by thin isolating layers to form two Josephson junctions.
Their sensitivity is associated with the measurement of magnetic field changes that are associated with one flux quantum. The gradient of a SQUID magnetometer is just a few centimeters.

A comparison between Cesium gradiometer (Geometrics G-858) and SQUID gradiometer measurements for archaeological prospection has been described by Chwala et al. (2003). One advantage of SQUID magnetometers is the high sampling rate of 100Hz (100 samples per second), allowing for high survey speed. Even much higher sampling rates are possible. The second advantage is the very high dynamic range of SQUID magnetometers. The requirement to cool the sensor down to 77K with liquid nitrogen or helium in order to achieve superconductivity may be seen as disadvantage. For each gradiometer about one liter of liquid helium is needed every two days.

**Magnetic susceptibility meters**

The magnetic susceptibility describes the degree of magnetization of a material in response to an applied magnetic field. Different soils and rocks have different magnetic susceptibilities, depending on the amount of magnetizable minerals contained. Magnetic susceptibility measurements in themselves can be used for archaeological prospection. In contrast to passive magnet field measurements with a magnetometer require measurements of the magnetic susceptibility the active application of a magnetic field. Therefore, magnetic susceptibility measurements are much slower to conduct than magnetic field measurements. The ability to measure the magnetic susceptibility of a material is important in order to determine the potential for magnetic prospection on a specific site. Furthermore, magnetic susceptibility measurements can be used to understand and determine the origin of magnetic anomalies on archaeological sites, for example by measuring samples taken from an archaeological cross-section or by taking soil samples from various regions of an excavation.

### 3.2 Geomagnetic data processing and visualization

The most common steps for geomagnetic data processing involve geometric corrections to adjust line-shifts in the direction of the profile, the calculation of the magnetic gradient using data obtained from a second magnetometer, band-pass frequency filtering for the removal of high frequency noise or long-wavelength background variations, smoothing filter, trace-equalization, down-ward and up-ward field corrections, and pole-corrections. While the last two mentioned filter types are special geophysical data processing techniques, belong the other methods to standard image processing algorithms.

Geo-magnetic data is commonly visualized as a grey-scale or colour-scale map. Experts tend to prefer grey-scale images over colour images since the measured data (magnetic field intensity) corresponds best to the smoothly varying intensity changes of a grey-scale image. Colour-scale images display magnetic field variations with different colour values and varying colour intensity, therefore assigning two attributes to a single variable. Therefore, colour images can be more difficult to understand and interpret than simple grey-scale images.

**Suggested reading**

4 Presentation of the georadar data

In this section the georadar data and its interpretation for the survey sites A and B are presented and the results discussed.

4.1 Presentation of the results from the georadar survey of area A

The location of the georadar survey area A is shown in Figures 1.2 and 1.3. The data contains almost no interpretable structures due to the very limited signal penetration caused by the high soil conductivity. The most obvious anomaly is caused by the standing water on the surface (Figure 4.1.1). In several depth-slices faint anomalies in form of linear and curvilinear structures are visible. An example depth-slice is shown in Figure 4.1.2. In Figure 4.1.3 several visible anomalies are drawn. An archaeological interpretation of the cause for these structures is difficult. The long linear anomalies may be related to trenches, ditches or paths. Anomalies that appear to enclose an area may be related to pits or buildings. In the south-west corner of the data a dark region can be seen, which appears to be related to the excavation that had been conducted nearby.

All depth-slices are listed in the Appendices 7.1 and 7.2 with and without filter applied.

Figure 4.1.1 Georadar depth-slice showing the extent of the water puddle as dark reflection in survey area A.
Figure 4.1.2 Georadar depth-slice showing some faint structures that may be attributed to archaeology in survey area A. See interpretation in Figure 4.1.3.

Figure 4.1.3 Interpretation of faint structures visible in the georadar data of survey area A.
4.2 Presentation of the results from the georadar survey of area B

This section describes the results of the GPR survey conducted at area B. The location of the survey area B is shown in Figures 1.2, 1.3 and 4.2.1.

![Map showing georadar survey area B relative to the structures excavated by ADC.](image)

The GPR data is presented as filtered and unfiltered depth-slice images of 10cm thickness. Figure 4.2.2 provides an overview of all structures interpreted in the GPR data of area B.

A large number of linear structures that are running in NNW-SSO direction and that are visible in the uppermost part of the data are interpreted as recent agricultural traces, presumably caused by ploughing. A possible trench in the same orientation is indicated. Further recent structures are curvilinear and straight vehicle/tractor tracks in the upper part and alongside the southern edge of the survey area.

Other linear structures that do not coincide with those running NNW-SSO are marked. Some of those that are visible in the eastern and southern part of the survey area may be caused by animal tunnels (e.g. rabbits).

In the SW region of the survey area a large dark anomaly can be observed (see Figures 4.2.4 & 4.2.6) which is indicating an increased absorption of the GPR signal. Here the GPR survey area borders at a previously excavated area. A possible explanation for this clearly visible structure in the GPR data could be that possibly at this location the excavated earth had been temporarily deposited during the duration of the excavation. Such an earth deposit could cause changes in the local soil conditions that could explain the anomaly observed, such as compaction of the ground with an effect on soil density, soil humidity and soil water permeability. Another effect could be a locally increased deposition of clay minerals in the soil vacuoles due to the deposited earth.
Archaeologically the most interesting GPR data anomalies are a number of dark blotches best visible in Figures 4.2.4 and 4.2.6. Compare these depth-slice images with the interpretations shown in Figures 4.2.2, 4.2.3 and 4.2.5. Compare as well with the additional depth-slice images listed in the Appendix 7.3 and 7.4.

The anomalies marked “Possible_archaeological_structures” in Figures 4.2.2, 4.2.3 and 4.2.5 possibly correspond to pits, graves or other structures related to the grave field excavated in the vicinity. In particular the four darker anomalies centrally located in the southern half of the survey area (see Figures 4.2.4 and 4.2.6 as well as Figures 7.3.2 to 7.3.5 and 7.4.2 to 7.4.5.) appear due to their rectangular shape as man-made structures. Their dimension of approximately 2m to 3m side length would agree with the interpretation as pits or graves.

Due to the very adverse soil conditions which caused strong absorption of the GPR signal the data and image quality is poor. It is reasonable to assume that the same survey conducted under more favourable conditions in regard to soil humidity (e.g. after a period of warm, windy and dry days) would have resulted in data of higher quality due to increased signal penetration depth, greater signal-to-noise ratio and therefore higher resolution.
Figure 4.2.2 Interpreted structures in GPR survey area B.
Figure 4.2.3 Interpreted structures and depth-slice 30-40 cm, filtered.
Figure 4.2.4 Depth-slice 30-40 cm, filtered.
Figure 4.2.5 Interpreted structures and depth-slice 30–40 cm.
Figure 4.2.6 Depth-slice 30–40 cm.
5 Presentation of the magnetic prospection data

In this section the magnetometer prospection data and its interpretation are presented. The magnetic prospection data shown here represents the variations of the vertical component of the local magnetic field. Each magnetometer probe of the Förster Ferex gradiometer system contains two magnetometer sensors, one close to the ground (approximately 20cm above ground surface) and a second 65cm above the lower sensor. Both sensors measure the vertical component of the global Earth magnetic field (contains as well other far field disturbances such as effects of the regional geology). Structures in the near surface causing a local change of the Earth magnetic field due to their higher or lower magnetization compared to the surrounding subsoil have a larger effect on the magnetometer sensor that is closest to the ground compared to the more distant sensor. By calculating the difference between the two sensors the large, time-variant far field component (global magnetic field) is removed and only the small variations due to near surface structures remain in the data.

The magnetic field data is visualized using greyscale images that vary in 256 discrete steps linearly between white (minimum) and black (maximum). By displaying the data for various amplitude ranges (different clip-off values for minimum and maximum amplitudes) it is possible to visualize the different structures in the data, similar to chaining the contrast of an image. The smaller the clip-off range the stronger the contrast.

Strong magnetic anomalies are often caused by ferromagnetic objects (e.g. iron objects) which appear as a black spot with a surrounding white halo. Many such anomalies can be observed in the data displayed in Figures 5.1 to 5.4.

The most obvious anomaly visible in the measured data is the very strong anomaly caused by the metal slates that were used to plate the field track. Using a Wallis filter their wide ranging disturbing effect could be suppressed strongly. Besides a large number of presumably metallic objects that cause small point like anomalies (Figures 5.3 & 5.4) several wide, curvilinear structures stand out (Figures 5.1 & 5.2). These structures are interpreted as filled trenches (Figure 5.5). In the central part several linear structures are visible which are difficult to interpret. They are possible related to the former agricultural use of the land. Some structures that may be of specific archaeological interest are marked in the interpretation (Figure 5.5).

The unfiltered magnetic data is shown in the Appendix 7.5. The large effect of the metal-plated field track is very noticeable in the unfiltered magnetometer data. In Appendix 7.6 the interpretation is shown superimposed onto the filtered magnetic data.
Figure 5.1 Magnetic prospection data after Wallis filtering using a white clip-off value of -1nT and black clip-off value of +2nT.

Figure 2.2 Magnetic prospection data after Wallis filtering using a white clip-off value of -2nT and black clip-off value of +3nT.
Figure 5.3 Magnetic prospection data after Wallis filtering using a white clip-off value of $-4\text{nT}$ and black clip-off value of $+6\text{nT}$.

Figure 5.4 Magnetic prospection data after Wallis filtering using a white clip-off value of $-8\text{nT}$ and black clip-off value of $+12\text{nT}$. 
Figure 5.5 Interpretation of the magnetic prospection data.
6 Archaeological analysis and interpretation

Under the right conditions georadar and magnetometer prospection methods are efficient tools to gain information about structures hidden in the subsurface. Geophysical prospection methods make no difference between archaeological, historical or modern structures in the ground. If a contrast between specific physical properties of a structure of interest and the surrounding subsoil exists, if the measuring device is sensible enough to detect this contrast and if the anomaly is not overshadowed by stronger disturbing signals it is possible to detect and map the location and shape of buried objects.

At the survey site Zaltbommel the physical contrast in the subsurface in case of the georadar method was very low due to the high water content of the soil (reaching saturation levels). Furthermore, the high clay content of the soil caused due to its good electrical conductivity a strong absorption of the electro-magnetic georadar signal in the ground, limiting the penetration depth considerably, in particular in case of survey area A. Nevertheless, it was possible to map several structures of possible archaeological interest. The detected anomalies could possibly be caused by pits or graves. Traces of trenches, probably old drainage trenches, have been mapped. It can be seen that the small difference in soil humidity between the slightly more elevated survey area B and the partly water covered area A led to a much better signal and data quality. Thus, it is expectable that a survey conducted under more favourable conditions in regard to soil humidity, e.g. in spring or summer after a period of dry weather, would have resulted in data of considerably higher quality, showing more structures in greater detail.

Several of the anomalies detected with the georadar method may be related to the nearby excavated Roman grave field or a corresponding settlement. Therefore small scale targeted excavations for validation of the geophysical survey data would be suited to gain understanding about the origin of these anomalies. For example, the investigation of one of the presumed pits or graves detected in georadar area B would allow the drawing of conclusions about other anomalies in the vicinity.

The magnetic prospection survey revealed the presence of several filled trenches. The infill material displays an increased magnetic susceptibility compared to the surrounding subsoil, indicating cultural activity, most likely through the use of fire (thermo-remanent magnetization of soil). The distribution of anomalies that are likely to be caused by metallic (ferromagnetic) objects shows increased numbers in the western and eastern parts of the magnetometer survey area. The upper central area, which is bounded by the curvilinear trenches, shows a reduced occurrence of this kind of anomalies. Several weakly expressed magnetic anomalies may be caused by archaeological structures in the ground, such as shallow trenches, graves or remains of buildings.

Due to the disturbing effect of the metal plated field track it is difficult to say whether the number of structured magnetic anomalies significantly decreases towards the east of the survey area.

Neither the georadar nor the magnetometer prospection method have resulted in very clear indications for similar archaeological structures as excavated in the nearby (western) area, such as shallow ring-trenches of up to 12m diameter, which would clearly have been interpretable archaeologically. The lack of such structures in the geophysical prospection data can not be used as negative evidence for the absence of archaeological structures, particularly since the measurement conditions were not ideal. The magnetic prospection data indicates the presence of archaeological structures to the east of the excavated site (marked in the interpretation as “other linear structures”) and the georadar data from area B indicates with great probability several further archaeological structures.
The results of the archaeological prospection survey (Figure 6.1) indicate several structures of possible archaeological interest that appear worth while to be investigated through targeted excavation.

If any parts of the surveyed area have been or are to be excavated it is advisable to always compare the excavation results with the data images and to use the here presented interpretation just as a guide. The data images in printed and digital form contain considerably more detailed information than a simplified, subjective interpretation.

The benefit of the georadar prospection methods is likely to have been greater if the survey would have been conducted in a dryer/warmer period.

Figure 6.1 Summary of the georadar and magnetometer data interpretations.
7 Appendix

7.1 Filtered GPR depth-slices (10cm) of survey area A
**Figure 7.1.1** Georadar depth-slice (filtered) of survey area A (0-10cm depth).

**Figure 7.1.2** Georadar depth-slice (filtered) of survey area A (10-20cm depth).
Figure 7.1.3 Georadar depth-slice (filtered) of survey area A (20-30cm depth).

Figure 7.1.4 Georadar depth-slice (filtered) of survey area A (30-40cm depth).
Figure 7.1.5 Georadar depth-slice (filtered) of survey area A (40-50cm depth).

Figure 7.1.6 Georadar depth-slice (filtered) of survey area A (50-60cm depth).
Figure 7.1.7 Georadar depth-slice (filtered) of survey area A (60-70cm depth).

Figure 7.1.8 Georadar depth-slice (filtered) of survey area A (70-80cm depth).
Figure 7.1.9 Georadar depth-slice (filtered) of survey area A (80-90cm depth).

Figure 7.1.10 Georadar depth-slice (filtered) of survey area A (90-100cm depth).
7.2 Unfiltered GPR depth-slices (10cm) of survey area A
Figure 7.2.1 Georadar depth-slice (unfiltered) of survey area A (0-10cm depth).

Figure 7.2.2 Georadar depth-slice (unfiltered) of survey area A (10-20cm depth).
Figure 7.2.3 Georadar depth-slice (unfiltered) of survey area A (20-30cm depth).

Figure 7.2.4 Georadar depth-slice (unfiltered) of survey area A (30-40cm depth).
Figure 7.2.5 Georadar depth-slice (unfiltered) of survey area A (40-50cm depth).

Figure 7.2.6 Georadar depth-slice (unfiltered) of survey area A (50-60cm depth).
Figure 7.2.7 Georadar depth-slice (unfiltered) of survey area A (60-70cm depth).

Figure 7.2.8 Georadar depth-slice (unfiltered) of survey area A (70-80cm depth).
Figure 7.2.9 Georadar depth-slice (unfiltered) of survey area A (80-90cm depth).

Figure 7.2.10 Georadar depth-slice (unfiltered) of survey area A (90-100cm depth).
7.3 Filtered GPR depth-slices (10cm) of survey area B

Figure 7.3.1 Georadar depth-slice (filtered) of survey area B (0-10cm depth).
Figure 7.3.2 Georadar depth-slice (filtered) of survey area B (10-20cm depth).
Figure 7.3.3 Georadar depth-slice (filtered) of survey area B (20-30cm depth).
Figure 7.3.4 Georadar depth-slice (filtered) of survey area B (30–40cm depth).
Figure 7.3.5 Georadar depth-slice (filtered) of survey area B (40-50cm depth).
Figure 7.3.6 Georadar depth-slice (filtered) of survey area B (50-60cm depth).
Figure 7.3.7 Georadar depth-slice (filtered) of survey area B (60-70cm depth).
Figure 7.3.8 Georadar depth-slice (filtered) of survey area B (70-80cm depth).
Figure 7.3.9 Georadar depth-slice (filtered) of survey area B (80-90cm depth).
Figure 7.3.10 Georadar depth-slice (filtered) of survey area B (90-100cm depth).
7.4 Unfiltered GPR depth-slices (10cm) of survey area B

Figure 7.4.1 Georadar depth-slice (unfiltered) of survey area B (0-10cm depth).
Figure 7.4.2 Georadar depth-slice (unfiltered) of survey area B (10-20cm depth).
Figure 7.4.3 Georadar depth-slice (unfiltered) of survey area B (20-30cm depth).
Figure 7.4.4 Georadar depth-slice (unfiltered) of survey area B (30–40cm depth).
Figure 7.4.5 Georadar depth-slice (unfiltered) of survey area B (40-50cm depth).
Figure 7.4.6 Georadar depth-slice (unfiltered) of survey area B (50-60cm depth).
Figure 7.4.7 Georadar depth-slice (unfiltered) of survey area B (60-70cm depth).
Figure 7.4.8 Georadar depth-slice (unfiltered) of survey area B (70-80cm depth).
Figure 7.4.9 Georadar depth-slice (unfiltered) of survey area B (80-90cm depth).
Figure 7.4.10 Georadar depth-slice (unfiltered) of survey area B (90-100cm depth).
7.5 Unfiltered magnetometer data

Figure 7.5.1 Magnetometer data unfiltered. Minimum (white) = -1 nT; maximum (black) = 2 nT.
Figure 7.5.2 Magnetometer data unfiltered. Minimum (white) = -2 nT; maximum (black) = 3 nT.

Figure 7.5.3 Magnetometer data unfiltered. Minimum (white) = -6 nT; maximum (black) = 6 nT.
Figure 7.5.4 Magnetometer data unfiltered. Minimum (white) = -8 nT; maximum (black) = 12 nT.
7.6 Filtered magnetometer data with interpretation

Figure 7.6.1 Magnetometer data Wallis filtered with interpretation superimposed. Minimum (white) = -1 nT; maximum (black) = 2 nT.
Figure 7.6.2 Magnetometer data Wallis filtered with interpretation superimposed. Minimum (white) = -2 nT; maximum (black) = 3 nT.

Figure 7.6.3 Magnetometer data Wallis filtered with interpretation superimposed. Minimum (white) = -4 nT; maximum (black) = 6 nT.
**Figure 7.6.4** Magnetometer data Wallis filtered with interpretation superimposed. Minimum (white) = -8 nT; maximum (black) = 12 nT.
### 8 Survey Documentation

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<td>Detection of historical and archaeological structures in the ground, in particular of possible traces of a Roman grave field and related settlement traces</td>
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This documentation is based on the guide: Geophysical Data in Archaeology: Guide to Good Practice by Armin Schmidt, Arts and Humanities Data Service (http://ads.ahds.ac.uk/project/goodguides/geophys/).