A SMALL SCALE, HIGH RESOLUTION MAGNETIC SURVEY AT THE ARCHAEOLOGICAL SITE OF BIRKA, SWEDEN

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Abstract

A high resolution magnetic survey was carried out at the archaeological site of Birka, situated approximately 20 km west of Stockholm. A new-generation optically pumped cesium magnetometer, G-858 from Geometrics, with a maximum sensitivity of 0.01 nT was used in the survey. An area of totally 504 m² was covered in three windy days in September 1997 with the cesium magnetometer working in vertical-gradient mode. Remnants of the old houses, some of the oldest ditches and an earlier excavation could be seen in the gradient data after processing. Also a total-field measurement was carried out to search for the oldest defence wall at Birka. The bad positioning that followed with the continuous-scan mode made the data very difficult to process efficiently. Some processing was done in Matlab to eliminate effects that might be caused by the geology, but no substantial archaeological results emerged. This work shows that high resolution magnetic surveys can be efficient in detecting archaeological remains even in a very heterogeneous soil, provided very sensitive equipment and correct choice of method. It also emphasized the importance of good positioning in a survey.
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Introduction

In the work for this thesis was a small scale, high resolution magnetic survey carried out at the archaeological site of Birka on the island of Björkö in lake Mälaren, Sweden. The primary target for the survey was to decide whether or not the magnetic method can be used to detect the ditches that were dug as building site boundaries during the Viking age. If it is possible to do so, a large scale magnetic survey could map the original city-plan of Birka. The soil conditions at the site are, however, far from good in a geophysical point of view. Heavily mixed cultural layers and expected weak anomalies from the ditches makes the site a difficult and challenging task.

An earlier geophysical survey was done in Birka by Dr Stümpel before the 1990 excavation started, without giving any substantial archaeological information. The reasons for this is the fact that the instrument (proton precision magnetometer) and method (total-field survey) used not were suited for the complex subsurface present at Birka. A lot has happened technically since 1990, so the conditions for a magnetic survey are better today. New, more sensitive magnetometers and higher resolution, made possible by more powerful data storage and faster magnetometers, might be the aid for a successful survey.

In the end, the only way to find out if a method truly would be successful is to actually carry out a survey.
Part I

Theory
Chapter 1

Magnetic fields

In this chapter I will give some general theory behind magnetic fields and specially define some fundamental concepts behind the geomagnetic field.

1.1 Theory

The magnetic field strength $H$ [A/m], gives rise to a magnetic flux density, $B$ [Vs/m²] or [T] (Tesla), as:

$$B = \mu H$$  \hspace{1cm} (1.1)

where $\mu$ is the absolute permeability of the material. The absolute permeability can also be written as the product:

$$\mu = \mu_0 \mu_r$$  \hspace{1cm} (1.2)

where $\mu_0$ is the permeability of vacuum, which is a fundamental physical constant ($4\pi \times 10^{-7}$ $\Omega$ s/m). The second term, $\mu_r$, is a dimensionless property of the material called the relative permeability. Putting this into equation (1.1) gives:

$$B = \mu_0 \mu_r H = \mu_0 H(1 + \kappa) = \mu_0 H + \mu_0 \kappa H$$  \hspace{1cm} (1.3)

Where we have put $\mu_r = 1 + \kappa$. The dimensionless parameter $\kappa$ is called the susceptibility of the material and is an important quantity since it states the degree to which a material can be magnetised by an external field.

The last part of the second term in equation (1.3), $\kappa H$, is called the intensity of magnetisation in a body and is denoted $M$. Which finally gives that:
\[ \mathbf{B} = \mu_0(H + \mathbf{M}). \tag{1.4} \]

From equation (1.3) and (1.2) it is realized that, for vacuum, \( \mu_r = 1 \) and \( \kappa = 0 \).

### 1.2 The earth's magnetic field

The earth's magnetic field can by a first approximation be described as a magnetic dipole with a magnetic moment of \( \mathbf{m} = 7.94 \times 10^{22} \text{ Am}^2 \) located at the center of the earth. The magnetic potential from a dipole is given by:

\[ W(r) = \frac{\mathbf{m} \cdot \mathbf{r}}{4\pi r^3} \tag{1.5} \]

where \( \mathbf{m} \) is the magnetic dipole moment and \( r \) the distance from the dipole. Working with spherical polar coordinates allows for \( \mathbf{m} \cdot \mathbf{r} \) to be substituted with \( \mathbf{m} r \cos \theta \), where \( \theta \) is the angle between distance vector \( \mathbf{r} \) and the dipole \( \mathbf{m} \). By taking the gradient of the magnetic potential, one can get the theoretical value of \( \mathbf{B} \) at any point outside the dipole:

\[ \mathbf{B}(r) = -\mu \nabla W(r) \tag{1.6} \]

The only two components of the magnetic field \( \mathbf{B} \) will be the radial part, \( B_r \), and the angular part, \( B_\phi \). \( B_\phi \) will fall out due to the symmetry. Carrying out the cylindrical differentiation of equation (1.6) gives:

\[ B_r = -Z = -\mu_0 \frac{\partial W}{\partial \theta} = \frac{\mu_0}{4\pi r^3} 2m \cos \theta \tag{1.7} \]

\[ B_\theta = H = -\mu_0 \frac{1}{r} \frac{\partial W}{\partial \theta} = \frac{\mu_0}{4\pi r^3} m \sin \theta \tag{1.8} \]

The angle between these two components at a point on the Earth's surface is the dip of the Earth's magnetic field and is called the inclination, \( I \) (figure 1.1).

Mathematically the inclination is given by:

\[ \tan I = \frac{B_r}{B_\theta} = -2 \cot \theta = 2 \tan \lambda \tag{1.9} \]
Figure 1.1 Figure showing a) the inclination I and b) the declination D of the earth's magnetic field

where $\lambda$ is the magnetic latitude. By inspection of eq. (1.9) one can see that I varies from $0^\circ$ at the magnetic equator to $\pm90^\circ$ at the magnetic poles. The geographical and magnetic latitude will not be the same since the earth's axis of rotation and the magnetic dipole axis do not coincide.

The other important angle concerning the geomagnetic field is the declination D which states how much the local magnetic north deviates from the true geographic north.

The earth's magnetic field is by no means constant. The geographical location of the north and south magnetic poles changes slowly over the years and is known as the polar wandering. Magnetic fluctuations also occur due to cosmic changes as diurnal changes in the solar wind, local magnetic fields produced by our civilization, like high-voltage wires, radio and TV transmitters. These short-term fluctuations are always a problem when a magnetic measurement is carried out since they tend to disturb the measurements. There are however ways to reduce the influence of the disturbances. The most important ones are:

1. To use a base station.
2. Tie-point measurements. (Measure the same location at different times).
3. Perform gradient surveys.
Chapter 2

Geophysical methods in archaeology

Archaeological excavations are very time consuming and therefore very expensive. Especially in high latitudes where the only time practical to excavate is during the (often short) summer. One semester of excavation at Birka, for example, costs about five million Swedish crowns. It is therefore desired to have a faster and cheaper method to gain information about the subsurface. One way to achieve this is to study the change of the physical properties in the soil due to abnormal concentration of chemical substances and solid objects that often is associated with human occupation. These changes are often very small, so the instruments and methods used have to be very sensitive. This way of using physical methods to examine the subsurface is often called remote sensing or - if made in connection to archaeology - archaeophysics.

In the late 19th century, English archaeologists discovered that the sound when pounding on the ground with a hammer was deeper over a disturbed, archaeologically interesting place, than otherwise. This seismically related method was the first attempt of remote sensing in archaeological prospecting. Fifty years later, Atkinson (1946) conducted the first archaeophysical survey by adapting resistivity surveys to shallow depths. In 1958 Aitken and Hull managed to localize kilns and soil-filled features by studying the small variations in the earth's magnetic field arising from them with a magnetometer. The proton magnetometer, which had a sensitivity down to one gamma, was developed for field use by Waters and Francis (1958). The ground penetrating radar (GPR) was developed by the US army and have been used in archaeology since the 1970:s. Physical methods have now been used for over a century to locate archaeological remains and is today a powerful tool in an archaeological context. Almost all geophysical exploration techniques have been tested for this purpose. The magnetic, electric and electromagnetic method are the most successful so far and are widely used. Gravity and seismic methods have also been tested, but with moderate success.
Geophysical investigations in connection to archaeological excavations are relatively rare in Sweden. One reason for this is the heavily mixed till-soil that cover large areas of Sweden (as well as all other post-glacial areas) which often applies a considerable amount of noise to the data. Among the Swedish archaeophysical surveys are the one in the Vendel area in northern Uppland (Persson, 1993) where low (VLF), intermediate (EM-38) and high frequency (GPR) electromagnetic techniques as well as phosphate analysis and magnetometry were evaluated. A total-field and vertical-gradient magnetic survey detected the remains of a fort in Lindholmen, southern Sweden (Sträng, 1995).

2.1 The magnetic method

Some archaeological objects - such as fire-hearths, kilns and objects made out of burnt clay - are favourable to detect with the magnetic method since they possess a relatively strong permanent magnetisation. Also pits and ditches can often, due to induced magnetisation, be detected. The diversity and speed of the magnetic method has made it one of the most frequently used techniques in archaeogeophysical surveys.

There are principally two techniques that are used when deviations in the earth's magnetic field are to be measured; total-field and gradient. The most conventional of these is the total-field measurement where the earth's total magnetic field is measured with one sensor at one height in each point. Background magnetic field and cultural noise can then be corrected for with a base-station, which is a second, stationary magnetometer situated some distance away from the site. The total-field anomaly, $\Delta T$, is therefore given by

$$\Delta T = |T| - |R|$$

where $T$ is the measured total magnetic field which consists of both the regional magnetic field and anomalies from magnetized bodies. $R$ is the Earth's regional magnetic field given by the base-station. The unit of $\Delta T$ is nT, but the unit "gamma" ($\gamma$) is often used. The relation between them is that $1\text{nT}=1\gamma$.

In gradient measurements, the spatial change either in the vertical or the horizontal direction of the geomagnetic field is measured. By measuring the horizontal gradient one will get an extreme value at the center of the anomaly which improves visual interpretation of the data. The vertical-gradient, on the other hand, has the ability to enhance shallow structures because of the effective band-pass filtering you get with such a set-up.

There are no standard techniques in measuring the magnetic gradient, but a widely used method to get the vertical gradient is to measure the total-field at two different
heights, subtract the readings and divide with the distance between the sensors. By doing this one will get an average gradient over a distance rather than the true gradient.

The mathematical expression for this operation is:

$$\frac{\partial T}{\partial z} = \frac{T_2 - T_1}{h_2 - h_1}$$  \hspace{1cm} (2.2)

where:
- $T_{\partial z}$ is the finite-difference approximation of the vertical gradient
- $T_1$ and $T_2$ are the readings from sensor 1 and 2 respectively
- $h_2 - h_1$ is the distance between the sensors.

Using two probes instead of one, efficiently eliminates diurnal and other large scale effects since they will influence both of the probes to approximately the same amount. The upper sensor will serve as a base station and it will also filter away long wavelength anomalies. It is however always recommended to use a base station to monitor the noise.

Vertical-gradient surveys are especially well suited for archaeological surveys since it tends to enhance shallowly located objects. The relative enhancement can be seen if the Fourier-spectrum of the two methods is studied. The relation between the two spectra is:

$$F\left( \frac{\partial T}{\partial z} \right) = F(\Delta T)|k|$$  \hspace{1cm} (2.3)

Where:
- $F\left( \frac{\partial T}{\partial z} \right)$ is the Fourier-spectrum of the vertical gradient.
- $F(\Delta T)$ is the Fourier-spectrum of the total-field anomaly.
- $|k|$ is the absolute value of the wave-number.

What equation (2.3) says is that the spectrum of the gradient data is equal to the spectrum of the total-field data multiplied with the respective wave-number. Since shallow objects are richer in high wavenumber energy they will be selectively enhanced in the gradient data. It also implies that if the total-field anomaly is known, the gradient can be calculated analytically and vice-versa.
Conclusively, the two main advantages of using a vertical gradient survey in archaeology are:

1) The effective elimination of diurnal variations.
2) The selective enhancement of near-surface objects compared to deeper ones.
Chapter 3

Physical properties of soils

The basis of all geophysical prospecting is the fact that the object - or feature - that is prospected for possesses different physical properties than the surrounding material. A contrasting content of magnetic minerals will cause an anomaly in the magnetic field around the object, allowing for the anomalous feature to be detected and located. The same goes for density in gravity-surveys and resistivity in resistivity-surveys.

One problem when prospecting for archaeological features is the low-magnitude of the anomalies that most archaeological objects produce. A kiln of burnt clay can produce an anomaly of up to 500 nT, but most other features, such as ditches and pits, only give rise to anomalies of typically a few, or even fractions, of nano-Teslas. The reason for this is, of course, the small dimensions and low magnetisation often associated with archaeological remains. The way to overcome this problem is careful planning of the survey and to use very sensitive instruments.

Physically, a soil is an aggregate of grains from eroded bedrock, air and water. The content of magnetic minerals in a soil is therefore dependent on the magnetic content of the rock from it was eroded - which in most cases is the parent. This makes soils in vulcanic areas more likely to have high magnetisation. Soils in earlier agricultured areas might - of reasons treated in chapter 3.1.2 - also have a somewhat increased magnetic susceptibility. The water- and air content, which governs for the electric and electromagnetic properties, is mainly dependent on the pore size and hence the grain size of the soil. A soil is characterised by its grain size by the definitions given in table 3.1 [Loberg 1993].
<table>
<thead>
<tr>
<th>Soil class</th>
<th>Grain-size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>&lt;2 µm</td>
</tr>
<tr>
<td>Silt</td>
<td>&gt;2 and &lt;20 µm</td>
</tr>
<tr>
<td>Sand</td>
<td>Fine &gt;20 and &lt;200 µm</td>
</tr>
<tr>
<td></td>
<td>Coarse &gt;200 µm and &lt;2 m m</td>
</tr>
<tr>
<td>Gravel</td>
<td>&gt;2 and &lt;20 m m</td>
</tr>
</tbody>
</table>

Table 3.1 Relation between soil-type and grain-size.

3.1 Magnetic properties

3.1.1 Magnetic minerals in soils

The magnetism of a soil is principally dependent on its iron content. The most magnetic iron oxide is magnetite which consists of both Fe²⁺ and Fe³⁺ ions. A constant net magnetic moment - or permanent magnetisation - arises in magnetite since the magnetic moment from the Fe²⁺ ions are not completely cancelled in the lattice. Magnetite, however, have not been found in any larger quantities in areas of former human occupation, which makes it of moderate interest in an archaeological point of view. Maghaemite, on the other hand, has. It is supposed to be the most important mineral for soil magnetism in earlier agricultured areas of human occupation (Aitken 1974).

Haematite appears in almost all soils and is the most common iron-oxide in soils. Almost all Fe³⁺ ions in the lattice are arranged in a way that their net magnetic moment is cancelled, which makes it only weakly magnetic. Despite its weak magnetisation, haematite is important in soil-magnetism since there are mechanisms that convolves it into more magnetic minerals.

A visual inspection can sometimes be enough to approximate the magnetic characteristics of a soil since the iron oxides in the soil tends to make it somewhat red.

3.1.2 Enhancement of magnetic susceptibility in areas of former occupation

Heating is proposed to be one of the major factors that increases the susceptibility of the top-soil. When haematite is heated above 500 degrees Celsius in presence of organic material it turns into the highly magnetic mineral magnetite. Parts of this magnetite reduces back into haematite but other ions, maybe sodium or water, stabilise the crystal lattice and results in the intermediate magnetic mineral maghaemite [Scollar 1990].
Burn-beating have been practised by man for thousands of years to make the soil more fertile. In this way large areas of land gets burnt and hence its soil more susceptible. Since soils are bad heat conductors, only the topmost centimeters of the soil get affected by the burn-beating. Fire-hearths and kilns, on the other hand can enhance the susceptibility down to about 10 cm below surface level. Through time, this more susceptible soil travels downwards due to lateral mixing of the soil by earth worms, ploughing etc. This enhanced susceptibility value is therefore an indicator of human activity and can - with the aid of a susceptibility meter - be used to locate areas of former human occupation. Examples of susceptibilities associated with archaeological features is given in table 3.2.

The fact that fire enhances the magnetism of soils has been proved in many laboratory experiments over the years.

Another mechanism that also is proposed to enhance top-soil susceptibility is fermentation. Alternating dry and humid periods are assumed to convolve the weakly magnetic mineral haematite to maghaemite through reduction-oxidation processes [Aitken 1974]. Because the fermentation is supposed to be a very long-term effect, it has yet not been successfully proved in a laboratory.

<table>
<thead>
<tr>
<th>Sub-stratum</th>
<th>Archeological feature</th>
<th>Susceptibility (SI/kg * 10^4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chalk</td>
<td>Barrow ditch</td>
<td>0.17-02</td>
</tr>
<tr>
<td>Chalk</td>
<td>Pits</td>
<td>0.7-2.6</td>
</tr>
<tr>
<td>Clay</td>
<td>Ditch</td>
<td>1.5</td>
</tr>
<tr>
<td>Gravel</td>
<td>Pits</td>
<td>2-12</td>
</tr>
<tr>
<td>Limestone</td>
<td>Ditch</td>
<td>1-1.5</td>
</tr>
</tbody>
</table>

Table 3.2 Approximate susceptibility values (specific) for archaeological features with different substrata.
Part II

Field-work
Chapter 4

Birka study

4.1 Introduction

Birka was from the year 750 to about 950 AC a flourishing town on the island of Björkö in the lake Mälaren in Sweden (figure 4.1). With its position in the waters between the Baltic Sea and Gamla Uppsala, which was the religious centre of Sweden at this time, Björkö was a natural place for the king to found a city. Findings of jewellry, spices and especially coins from all over the world has proved that Birka was one of the most important trading centres in the Viking age Sweden, but suddenly everything changed. Birka for about 200 years a successful town, lost its importance. The reasons for this can be found in the light of the post-glacial rebound that occurs due to the latest glaciation of Sweden that ended about 10 000 years ago. As the waters in Mälaren were getting shallower, the ships were getting larger and therefore demanding greater depth. The already stony passages around Björkö got even more difficult to pass. In the end of the Viking-age it had become too risky and difficult to get to Birka, so the settlement disappeared and was for hundreds of years known only by its name.

Many theories about where the lost city of Birka once was situated started to circulate and almost as many unsuccessful excavations were carried out to find it. Eventually a Swedish zoologist named Hjalmar Stolpe came to Björkö in the late 19:th century to search for amber-imbedded insects. Digging in the black soil, Stolpe found extensive occupation layers. Being an amateur archaeologist, he realized that he had found something extraordinary and started to organize an excavation. This was the start of the first systematic and scientific excavation ever of Birka.

The archaeological excavation of Birka made by Riksantikvarieämbetet between 1990 and 1996 has given an insight in how everyday life was like in a late Viking-age
settlement in northern Europe. However, many secrets still remain that a continued excavation or perhaps an extensive high-resolution geophysical survey could reveal.

Figure 4.1 Location of Björkö.

4.2 Site description and targets

Birka is situated on the western shore of Björkö and the area of the former settlement is today relatively flat farming land (figure 4.2). Outside the main settlement follows a burial field with approximately 5,000 Viking-age graves of which a majority have been excavated or plundered. The former Viking-age shoreline has now been uplifted to approximately 5 meters above sea-level, so no remains of the settlement is expected to be found below that level.

The top-soil contains rocks no larger than 3 cm in diameter due to hundreds of years of heavy ploughing. The cultural layers, nowhere thicker than 2.5 m, consists of very unsorted material with rocks between 15 and 80 cm in size. Under this follows a thin layer of sand and gravel upon a massive clay-layer.

Two different features, building-sites and passages, can be distinguished despite the heavy mixing of the cultural-layers.
Figure 4.2 Map over the black earth on Björkö. The square marks the centremost parts of Birka.

4.2.1 Building-sites

These are the areas that contain the remnants of the houses and workshops of Birka. Some houses in the late Viking-age had a foundation of stone while others did not. The walls were most certainly made of wood and clay with stone-filling. Bones, ash, coal and remains of fire-hearts are common in these layers (figure 4.3).

The primary targets in these areas are fire-hearths and stone foundations. A fire hearth should, if present, give a clear, positive anomaly in vertical-gradient data if it had been used long enough to produce sufficient susceptibility. Depending on the construction and the material, just one firing may be enough to provide a clear anomaly in a magnetic survey [Gibson, 1986]. A foundation of burnt stone could in the same way give a positive anomaly.
4.2.2 Passages

It is known that ditches were dug a couple of dm's into the clay when Birka was founded to mark the first building site boundaries (figure 4.4). As the town grew, they eventually had to serve as deposits for domestic waste. They therefore contain excrement, ash, remains of planks that was laid out on and around the ditches and huge amounts of bone. These oldest ditches extend through the whole cultural layer with a width of about 1.5 m [Ambrosiani 1995]. There are also more recent ditches that were dug out as the town expanded. They are smaller than the oldest ones, about 1 m wide and a few dm's deep.

If the pattern of these ditches could be mapped, something could be said about the original city plan of Birka which would be of great archaeological interest.

A ditch will give different anomalies all depending the magnetic characteristic of the filling and the surrounding material. Normally a positive anomaly is expected, but there are also examples of negative ones. For example was a negative anomaly of 200 nT recorded over a ditch at the Balfurg henge monument in Fife [Tsokas, Rocca, 1986].
Figure 4.3 Remnants of one of the building sites. A fireplace (1m in diam.) is situated in the middle of the room and one of the subsidiary ditches passes along the right wall. The ditch is darker than the surrounding soil due to the organic material that was deposited in it during the Viking age.

Figure 4.4 One of the oldest ditches (1.5-2m wide). They were dug perpendicular to the shoreline and served as building site boundaries when the settlement was first founded. Subsequently they became deposits for domestic waste.
4.3 Previous geophysical survey

In 1990, a team geophysicists from Kiel made a magnetic and GPR survey on the site to be excavated to evaluate the archaeological prospecting potential of the different methods and to give additional information about the archaeological remains in the area.

A summation of the results of the two methods is given below and in table 4.1.

4.3.1 Magnetic survey

The magnetic survey at Birka was carried out using a proton magnetometer with an accuracy of 0.1 nT. Measurements were made every 0.5 m in a 50x50 m grid with a line separation of 1 m.

Two persons handled the equipment; one placed the sensor stick on the measuring point while the other handled the electronics at some distance away to minimize the user made noise. A sensor height of 0.8 m was initially used, but was later changed to 0.5 m when it proved to give a too poor resolution.

After filtering away the long wavelength anomalies caused by the geology, three almost parallel anomalies could be seen in the SW-NE direction. After excavation these anomalies proved to arise from medieval draining ditches and therefore younger than Birka. The measurement also gave some positive anomalies, interpreted as fire hearts.

4.3.2 GPR

Using a 120 MHz transmitter with a transmitter - reciever separation of 0.5 m and a time window of 100 ns, the area was investigated with the GPR. The equipment was mounted on a sled and pulled along the survey lines. The measurements were made in continuous-scan mode.

From the GPR data it was possible to deduce the distance to the underlying clay-layer and hence the thickness of the cultural layer. Areas of former excavations was discovered since the mixing of the soil in these areas contrasted with the stratification in the undisturbed parts.

4.3.3 Conclusions

The instruments used in the 1990 survey did not have a sufficient resolution and the grid was too sparse to be able to detect any of the small-scale archaeological features at the site.
From these early measurements it is obvious that more sensitive methods must be applied. However, the survey shows that the magnetic and electromagnetic surveys work complementary to each other (table 4.1).

<table>
<thead>
<tr>
<th>Target</th>
<th>Detected with method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medieval ditch</td>
<td>Magnetic yes, GPR yes</td>
</tr>
<tr>
<td>Earlier excavated areas</td>
<td>Magnetic no, GPR yes</td>
</tr>
<tr>
<td>Fire heart’s</td>
<td>Magnetic yes, GPR no</td>
</tr>
<tr>
<td>Thickness of cultural layer</td>
<td>Magnetic no, GPR yes</td>
</tr>
</tbody>
</table>

Table 4.1 The methods used in 1990 and the features detected with respective method.

4.4 Preparing the field-work

After studying the work by Dr Stümpel in 1990 (see section 4.3) the planning of the field-work began. A cesium gradiometer with base station were kindly lent us by Dr Alan Green at the university of Zürich. Because no GPR with high enough resolution was at hand, the initially intended electromagnetic survey was cancelled.

4.4.1 Choice of site

The area was chosen close to the former excavation with help by Dr Ambrosiani (figure 4.5, 4.6). This would give a chance to correlate our results with the results from the excavations. An electric fence (not in use during the time of the measurements) around the area forced us to place the survey-grid a few meters away to prevent noise.
Figure 4.5 Photo of Birka and the survey areas chosen.

Figure 4.6 The excavated areas and the 1997 geophysical survey area. 1) 1969-71 excavations 2) 1990 excavation area 3) The main 1997 survey area 4) The 1997 corridor. This location of our survey allows us to correlate our results with the area excavated in 1990 (2).
4.4.2 Survey parameters

To theoretically optimize the survey results (i.e. resolution and area coverage), the requirements in table 4.2 should be met.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station spacing</td>
<td>As dense as possible</td>
</tr>
<tr>
<td>Line spacing</td>
<td>As dense as possible</td>
</tr>
<tr>
<td>Bottom sensor elevation</td>
<td>As close to the ground as possible</td>
</tr>
<tr>
<td>Sensor separation</td>
<td>As close to each-other as possible</td>
</tr>
<tr>
<td>Grid area</td>
<td>As large as possible</td>
</tr>
</tbody>
</table>

Table 4.2, Requirements on the survey parameters.

These criteria are easily fulfilled with infinite time and patience. However, in real life, there is always a trade-off between resolution and area coverage.

After careful consideration the above parameters were chosen as follows:

Station-spacing
The material in the cultural layer is very heterogeneous and the archaeological targets relatively small. This makes a very dense station-spacing needed to be able to tell random boulders from archaeological remains. A spacing of 0.2 m was considered reasonable.

Line-spacing
The line-spacing should if possible, as mentioned earlier, be chosen equal to the station-spacing. With a calculated total time of about 4 seconds for measuring and moving (given by trial measurements) this would mean that a very small area could be covered as the time to complete the survey was very limited (figure 4.7). Since we knew the direction of the oldest ditches (normal to the Viking-age shoreline) a less dense line-spacing was needed as they were laid out to run at normal angle to the ditches. A line spacing of 0.4 m was chosen to favor area-coverage.
Figure 4.7 The relation between total measuring time, line separation, sample time (dt) and resolution (line spacing = station spacing) indicating a great loss in area coverage with a small increase in sample time.

**Bottom sensor elevation**
Since the magnetic dipole field decreases with the inverse cube of distance (see section 1.2), it is important to get as close to the target as possible. This is very important in an archaeological survey where the targets often are very weakly magnetic. Unfortunately the ground does not consist only of pure archaeological remains in a homogenous soil, also randomly distributed highly magnetic stones and modern rubbish occur in the topmost layers. A too low sensor elevation would take up too much of this surface clutter. To avoid surface influence and brushing against the vegetation an elevation of 0.2 m was chosen.

**Sensor separation**
To get the true vertical gradient, the distance between the sensors will have to be infinitesimal small. This means that the sensors themselves should be infinitesimal small, which of course is not the case. Another problem is the noise due to coupling between the sensors that will occur if they are too close (in-depth study has been made by Herwanger 1997). To prevent coupling and to increase the dynamic range of the signal, a separation of 0.8 m was used.
4.4.3 Gradiometer setup

After deciding the survey parameters (see section 4.4.2) the gradiometer had to be mounted in such a way that it fulfilled these parameters and in the same time was rapid and easy to handle. A solution that in that stage was considered reasonable is shown in figure 4.8.

Two persons handled the equipment. One carried the setup around the site and placed it on the spots to be measured checking that the sensors were vertical with a leveller mounted on the horizontal rod. The second person handled the data-storage at some distance behind to avoid disturbances. All wires were firmly tied to the frame to reduce induction noise.

A faster solution to the setup problem would be to mount a small wheel with an odiometer at the end of the sensor stick. The setup could then be pushed along the survey-line and each measurement would be trigged by the odiometer. This would save some valuable time in the measuring process and allow for large areas to be covered in short time.

![Figure 4.8 The gradiometer set up used.](image)

4.5 Field-work procedure

The measurements were carried out between the 17:th and 19:th of September 1997. Strong wind, especially at the first two days, made positioning the gradiometer somewhat difficult and slowed down the procedure.

Two persons laid out the survey lines while the other two handled the gradiometer. Care had to be taken so that the persons placing the measuring-lines did not influence the gradiometer. In this way the measurements could proceed continuously.
Initial problems with the batteries resulted in that only a small area was covered the first day. The total survey-area (figure 4.9) consists of two separate areas measured with two different techniques in two different modes.

**Main area**  This area was covered in vertical gradient mode with parameters and sensor setup as chosen in section 4.4.2 and 4.4.3.

**Corridor**  In an attempt to detect the oldest defence-wall, a corridor of about 130 m length and 5 m width was constructed. The base station cesium sensor was then used to make a total-field measurement in continuous scan mode over 5 lines along the corridor. The sensor was mounted on the end of a stick and carried along at as constant height as possible (30 cm). A sample interval of 0.2 s was chosen because it would give a measuring point separation of about 20 cm at a walking speed of 1 m/s.
Figure 4.9 The survey grid (dotted) and topography at the site.
4.6 Instrumentation

The instrument used was an optically pumped cesium magnetometer, G-858, from Geometrics with a sample-rate of up to 10 Hz and a maximum sensitivity of 0.01 nT (figure 4.10). This is about one order of magnitude better than the common proton-precision magnetometers and is needed to satisfy the demands of speed and sensitivity in archaeological investigations.

At ETH in Zürich there are three cesium sensors with two control units available. Sensor readings from both the upper and lower sensor, time of reading and position information are digitally stored in the control units. Data is then easily transferred to a PC with the program "Magmap 96" for rapid displaying of the data. The data can be presented in 2D, 3D as well as single profiles. "Magmap 96" also allows correction of erraneous readings and correction in positioning. In combination with a portable PC, an initial check of the data can be done \textit{in situ} which allows for instant re-investigation of areas with damaged or lost data.

The sensitivity of the magnetometer gets higher with longer sample time. A maximum sensitivity is however reached after one second, why sample times longer than that is unnessessary (table 4.3).

<table>
<thead>
<tr>
<th>Sample-time (s)</th>
<th>Sensitivity (nT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>0.01</td>
</tr>
<tr>
<td>0.20</td>
<td>0.03</td>
</tr>
<tr>
<td>0.10</td>
<td>0.05</td>
</tr>
</tbody>
</table>

\textbf{Table 4.3 Instrument specification for the G-858 magnetometer.}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{G-858(console).jpg}
\caption{The G-858 console.}
\end{figure}
Chapter 5

Data processing

To get maximum information from the data it has to be corrected from erraneous readings and filtered from noise. Furthermore it has to be presented in a way that is easy to interpret.

5.1 Processing

Erraneous readings were deleted and the dataset interpolated before any further processing of the data was made. The collected data always contain noise from the surroundings. Magnetic bedrock often give rise to long-wavelength anomalies in the data and small near-surface magnetic objects produce short-wavelength anomalies. There is also often a certain amount of cultural noise. To enhance the signal from the interesting objects and get maximum information from the data a noise-reducing filter can be applied. The noise can be diminished by using either low-pass or high-pass filter. These are spatial filters that acts depending on the wavelength and amplitude of the signal. High-frequency (short wavelength) signals are discarded with the low-pass filter and low-frequency (long wavelength) with the high-pass.

A typical low-pass convolution filter is the 9-point Hanning matrix which is defined by the 3x3 point filter:

\[
\begin{array}{ccc}
0.06 & 0.10 & 0.06 \\
0.10 & 0.36 & 0.10 \\
0.06 & 0.10 & 0.06 \\
\end{array}
\]

Low-pass filtering is a smoothing procedure that tends to smear out spiky features with high frequency and large amplitude. This smoothing can sometimes smear out the shape of data-spikes so that they look like real features [Kanasewitch 1973], but it can be overcome by using a non-linear filter.
A non-linear filter is a kind of low-pass filter that only consider the wavelength of the signal. An amplitude tolerance can then be added so that it only removes spikes with an amplitude bigger than the specified. A non-linear filter checks if the half wavelength of the feature is less than the specified width and its amplitude greater than the specified. If this is the case it simply removes those values and interpolate the dummy values with the surrounding data. It is therefore an efficient way of removing spikes in the dataset.

5.2 Software

The program package OASIS montaj ver. 4.1 for PC was used to process and present the data from the main-area. This is a program for processesing of potential-field data and gives the user access to a number of different filter packages in both the time- and space domain. It also give possibilities to present the results in various ways, for example color-shaded relief. Dynamical linking between spreadsheets, maps and profiles makes the identification of interesting features easier. Interactive modelling of the result is also possible with the program GM-SYS.

5.3 Main area

An initial check of the main-area data shows the distribution of the gradient data. Almost all readings range between -20 and +20 nT/m in a symmetrical distribution around zero. Some peaks in the data-set of several hundred nano-teslas can be identified as iron rubbish in the topmost layers. The frequency distribution is plotted in figure 5.1.

![Radially averaged power spectrum](image)

**Figure 5.1** Radially averaged power spectrum, showing the frequency distribution in the main area data.
The data was read into OASIS, and when it was cleaned from erranus data, it was gridded (interpolated) with bi-directional gridding (figure 5.2). Since this type of gridding is very fast, it is to prefer if the data-set is very large. It also has the ability to enhance trends that cross the line direction [OASIS montaj 1997], which is desirable in this case. After the gridding was a 9-point Hanning filter applied. Shallow anomalies were then suppressed with a 1 c/m low-pass filter (Butterworth). Finally, the data was corrected to the pole to correct for the local direction of the geomagnetic field with a filter in the OASIS package and plotted in color shaded-relief (figure 5.3). Table 5.1 shows the processing steps schematically.

By using greyscale plotting, one often enhance the linear structures. This was done with the filtered main area data (figure 5.4).

<table>
<thead>
<tr>
<th>Processing step</th>
<th>effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual correction</td>
<td>Removal of erraneous data</td>
</tr>
<tr>
<td>Bi-directional gridding</td>
<td>Interpolation</td>
</tr>
<tr>
<td>9-point Hanning filter</td>
<td>Smoothing</td>
</tr>
<tr>
<td>1 c/m low-pass filter</td>
<td>Reduction of surface noise</td>
</tr>
<tr>
<td>Reduction to the pole</td>
<td>Correct for direction of magnetizing-field</td>
</tr>
</tbody>
</table>

Table 5.1 The processing steps used for the main area data.

To even further enhance the linear features in the cross-line direction was a stacking made in Excel. The weighting function that was applied in the convolution was a 5-point triangle filter of the type:

\[
1 \ 3 \ 5 \ 3 \ 1
\]

The convolution was carried out in the space-domain. If the data-set is very large it is desirable to perform the convolution in the time-domain since less mathematical operations are needed and hence will increase the speed of the calculations [Kanasewitch 1973].

The stacked data was then re-read into OASIS, gridded and plotted in color-shaded relief. This process somewhat enhanced the linear features in the cross-line direction (figure 5.5).
Figure 5.2 Raw magnetic data from the main area.
**Figure 5.3** Filtered magnetic data from the main area.
Figure 5.4 A greyscale picture that enhances the linear features in the data.
Figure 5.5 Stacked data from the main area.
5.4 The corridor

The most striking feature in the corridor data is the large and wide anomaly in the middle of the profiles (figure 5.6). The width and an amplitude of more than 700 nT indicates that it is a geological formation causing it. Consultation with the local farmer dismissed the first ideas of an abandoned power line or water drainage.

The bad positioning in the corridor data - due to the continuous scan - made it impossible to process in Oasis without any pre-processing. Instead a Matlab program was written to do the processing. All profiles were read into vectors and filtered with a 3.8 m Hanning filter to extract and remove the large anomaly.

![Magnetic total-field data from the corridor (the two first lines)](image)

**Figure** 5.6 Total field data from the corridor. The large anomaly in the middle is most certainly of geological origin.

The residual data from this filtering (figure 5.7) shows slightly increased values in the middle of the profiles. This could easily be mis-interpreted as a true anomaly, but is rather a filtering effect caused when the Hanning filter moves over the narrow top of the anomaly.
Figure 5.7 Residual total field magnetic data from the corridor. The slightly increased values in the middle of the profile are caused by the filtering.

A rough model of a highly susceptible (0.08 SI) intrusion running perpendicular to the survey lines was created with the gravity- and magnetic modelling program GMM. The result (figure 5.8) shows a good fit to the measured data. The minimum depth of the model also correlates well with the approximate 8 m that the resistivity measurements in 1998 suggested (Masters, 1998). A highly magnetic intrusion would also explain the high susceptibility of the black earth, since the soil would contain grains eroded from the rock underneath.

Figure 5.8 A rough model of a highly magnetic intrusion causing the anomaly.
5.5 Interpretation

After the processing and plotting of the data, a number of interesting features appeared of which some most certainly are of archaeological origin.

**Main area**

The most prominent feature here is the long and narrow NNE-SSW feature that follows the long-side of our survey-grid and extends throughout the whole area. This is most likely one of the late 19th century excavations made by Hjalmar Stolpe. It is known that he dug trenches typically 1 - 1.5 m wide and about 2 m deep. The approximate location and direction of one of these trenches coincide well with our anomaly. It could not be an effect from the measurements since it is not absolutely parallel to the survey lines, but has a slight SW direction (figure 5.9).

The exact position of the Stolpe trenches have not been known before. By locating them, one will also be able to deduce the original position of the artefacts excavated by Stolpe which in turn will add new information about Birka.

Three NW-SE anomalies that are cut-through by the long anomaly can after correlation with the 1990 results be interpreted as three of the oldest ditches that the 1990 survey failed to detect (figure 5.10).

Some quadratic high-anomaly areas can by guidance of their size and shape be interpreted as the remnants of old houses. The high positive anomalies suggests large amounts of burnt clay or stones from a fire-hearth.

A summary of the detected features is given in figure 5.11.

**Corridor**

The for archaeological surveys very large anomaly (700 nT) in the middle of the profiles is most certainly of geological origin. No archaeological object with a maximum depth of 2.5 m could give rise to an anomaly with this amplitude and width. The model made in GMM suggests that an intrusion approaching the surface at the middle of the profiles at a depth of approximately 10 m causes this anomaly (figure 5.12).
Figure 5.9 Interpretation of the linear magnetic anomalies.

Figure 5.10 An extrapolation of the excavated ditch into our survey area gives the expected direction of the anomalies.
Figure 5.11 Interpretation of the main area data plotted with the topography. Note that the anomalies interpreted as ditches run perpendicular to the topography, indicating that they truly are the oldest ditches.
Figure 5.12 Schematic picture of a highly magnetic intrusion causing the large anomaly in the corridor data.
Conclusions

Even though the conditions at Birka are - due to the heavily mixed, heterogeneous soil - very complex in an archaeophysical point of view, this work has showed that a magnetic survey can be succesful in locating archaeological targets even in such conditions. It also gave substantially more detailed information about the subsurface compared to the magnetic survey carried out in 1990. The main reasons for this is the difference in spatial resolution, instrument prestanda and the, for detection of shallow objects, superior vertical-gradient method.

The survey also showed the importance of a rapid and convenient gradiometer set-up. Only an excavation can verify the interpretation of the magnetic maps. An excavation would also give us possibilities to correlate some of the un identified objects and therefore even further deduce the potential of the magnetic method in areas with complex soil conditions. There are, unfortunately, no funds for such an excavation today. Perhaps could the extended geophysical survey, also including a resistivity and GPR survey, in the spring of 1998 give some additional information that confirms our results.
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References


