Efficient, Large-scale Archaeological Prospection using a True Three-dimensional Ground-penetrating Radar Array System

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ABSTRACT The Swedish UNESCO World Cultural Heritage site of the Birka and Hovgården Iron Age settlements is well suited for the testing of high-resolution archaeological prospection methods. In May 2006 ground-penetrating radar (GPR) and magnetometer test measurements were conducted at Birka, resulting in data of outstanding quality and new archaeological discoveries, but also demonstrating the need for increased spatial sampling regarding GPR prospection at complex Scandinavian sites. Therefore Birka was selected as a testing ground for a pilot study investigating the suitability of the novel multichannel GPR array system MIRA (MALÅ Imaging Radar Array) for efficient, large-scale GPR surveys with very dense spatial sampling. The study was conducted in May 2008 by MALÅ Geoscience AB in collaboration with the archaeological prospection unit of the Swedish National Heritage Board. The very high-resolution three-dimensional GPR pilot survey demonstrated that it is possible to survey 1 ha and more per day with 8 cm cross-line spacing, mapping archaeological structures in unprecedented resolution, such as postholes of only 25 cm diameter. This paper describes the tested technology and methodology as well as the fieldwork and the results of the study. Copyright © 2010 John Wiley & Sons, Ltd.

Key words: Ground-penetrating radar; multichannel array; high-resolution prospection; Birka and Hovgården; Sweden

Introduction

Over the past three decades numerous archaeological prospection surveys conducted in central Europe, the UK, Mediterranean countries and further afield have demonstrated that non-destructive geophysical near-surface prospection methods can be used successfully and efficiently to map archaeological structures hidden in the subsurface (e.g. Becker, 1995, 2008; Conyers and Goodman, 1997; Neubauer, 2001; Gaffney and Gater, 2003; Kwame, 2003; Leckebusch, 2003). In the same period only a few geophysical archaeological prospec-
Prospections® group in Vienna and the Vienna Institute for Archaeological Science. Initial test measurements conducted by the Austrian specialists in 2003 and 2004 at several locations in Sweden had demonstrated a great potential of both ground-penetrating radar (GPR) and magnetometer prospection methods at different archaeological sites, including the medieval St Olof’s convent in Skänninge, and an Early Iron Age Viking settlement site near Gamla Uppsala (Larsson, 2004).

Regarding efficiency, resolution and quantity of data generated, GPR and magnetometer are considered to be the most suited geophysical archaeological prospection methods in Scandinavia. With the intention of gathering survey experience and representative sample data from different archaeological sites the new archaeological prospection unit conducted a number of magnetometer and GPR test surveys in central and southern Sweden as well as in Norway (Trinks and Larsson, 2007a). In May 2006 over the course of three days an archaeological prospection test survey was conducted at the site of the Viking age settlement Birka, resulting in high-quality data and numerous new archaeological discoveries (Trinks et al., 2007; Trinks and Larsson, 2007b). When in 2008 the new MALA Imaging Radar Array (MIRA), a novel multichannel GPR system, became available, the instrument’s manufacturer conducted, in collaboration with the Swedish National Heritage Board, a large-scale pilot study at Birka covering approximately 3 ha of survey area with very high sample spacing (Trinks et al. 2009). This study and its results are presented in this paper.

The Viking town Birka

The Viking Age settlement Birka located on the island of Björkö in Lake Mälaren some 30 km west of Stockholm constitutes together with the archaeological site Hovgården on the neighbouring island of Adelsö a UNESCO World Cultural Heritage Site (UNESCO, 1994). The measurement conditions at Birka render it an excellent geophysical testing ground with ideal surface conditions and documented complex cultural layers of up to 2 m total thickness containing a wide range of different archaeological structures, which since the Viking Age have to a large extent been left undisturbed by modern construction activities or intensive farming.

During Viking times Lake Mälaren was an inlet of the Baltic Sea. Due to the postglacial rebounce of the Scandinavian landmass the shoreline of Lake Mälaren has sunk since the year AD 800 by approximately 6 m, resulting in ancient harbour constructions nowadays being found on land. In the second half of the ninth century AD Birka, which is assumed to have been established around AD 790, had been largely abandoned for reasons that are yet unknown. Possibly the waterways leading to Birka for travel by boat from the Baltic Sea had become obstructed due to the land rise. Another hypothesis is that the town had been destroyed and that limited availability of wood on the island for reconstruction, heating, firing and cooking may have led to the abandonment of the settlement and trading place, or that political shifts occurred in the region. From the time that the Viking town had been deserted until today the site has remained unsettled. Agricultural activity has disturbed the topsoil only to a depth of about 35 cm.

The central area of the town of Birka is called Black Earth due to the presence of a distinctive dark soil (Figure 1). Today the traces of the settlement and trading place Birka are covered by a meadow, which is used as a sheep-run and for the making of hay (Figure 2). A field track crosses the Black Earth area providing the inhabitants of Björkö village with access to a boat pier in the north. Along the slightly elevated western and eastern rim of the Black Earth several terraces are visible in the topography. The extensive large grave field Hemlanden (‘Homeland’) is located to the east and southeast of the central Black Earth area, containing over 2500 individual burial mounds. An earthen town wall still separates the grave field from the settlement area. A rocky elevation in the northwestern part of the island of Björkö accommodates the remains of a hill fort dating to the Viking age (Holmquist Olausson and Kitzler Ahfeldt, 2002). Today a rampart still surrounds a large part of the hill fort.

Despite the fact that every year between the months of May and September about 43 000 visitors from Sweden and abroad come to Björkö to see the remains of the Viking town Birka, very little is actually known about this place and its history. Johan Hadorph, the then director-general of the Central Board of National Antiquities undertook the first archaeological excavation in Sweden on the island of Björkö in 1680. More extensive scientific archaeological investigations were undertaken by Hjalmar Stolpe in the 1870s and 1880s. He excavated over 800 graves and about 4000 m² in the Black Earth area. However, the exact location and number of his excavation trenches are unknown. In the years 1969–1971 Björn Ambrosiani excavated on Björkö (Ambrosiani, 1973). Between 1990 and 1995 Ambrosiani was leading the comprehensive archae-
Figure 1. Map of the northwestern part of Björkö island. The survey site is located in the Black Earth area between the hill fort in the south and the farm track in the north.

Figure 2. View across the Black Earth area of Birka with the hill fort in the background. In the Viking Age the meadow in the centre would have been the scene of a town consisting of huts, houses and hall buildings, a rampart, tracks and harbour constructions, teaming with traders, craftsmen, sailors, warriors and priests.
ological contextual layers, is underlain by a clay/silt cultural layer, which consists of numerous archaeological structures. The depth of the Black Earth area of Birka varies between 0.2 and 2.2 m. This overall thickness of the cultural layer in the Black Earth area has to a large extent remained undisturbed by modern interferences or disturbances. In an area covering approximately 15 ha remains of an important Viking Age settlement and trading place are to be found just below the plough layer of approximately 30 cm thickness.

The first GPR and magnetometer surveys at Birka were conducted on behalf of Björn Ambrosiani by Harald Stümpel, Susanne Lorra, Birger Lühr and Remmer Kruse from Kiel University, Germany, in preparation of the 1990–1995 Birka Project (Personal communication to Björn Ambrosiani from S. Lorra, 1990). A square measuring 50 m × 50 m was surveyed with 1-m profile spacing in both X and Y directions using an analogue bistatic 120 MHz GPR antenna system with data recording and output on heat sensitive carbon paper strips. A three-dimensional paper model of the paper strips showing the parallel GPR profiles in both survey directions was constructed for data analysis and an interpolated single depth-slice interpretation image was drawn by hand. While the profiles showed good energy penetration of approximately 80 ns for the 120 MHz antenna, as well as reflections from subsurface structures and layering, the possibility for an archaeological identification and interpretation of the data was very much limited.

A shallow seismic survey conducted in 1992 by Andrén and Lindeberg (1997) indicated that the overall thickness of the cultural layer in the Black Earth area of Birka varies between 0.2 and 2.2 m. This cultural layer, which consists of numerous archaeological contextual layers, is underlain by a clay/silt layer.

**Multichannel GPR pilot study 2008**

Over the past years attempts for increased efficiency and resolution of GPR measurements through the use of parallel two-dimensional measurements have been observed (Pipan et al., 1999; Whiting et al., 2001; Neubauer et al., 2002; Seren et al., 2004; Leckebusch, 2005). The collection of two-dimensional GPR sections with dense cross-line spacing and their exact positioning is time-consuming (Leckebusch and Peikert, 2001; Slob et al., 2003). To overcome this several antennae can be used precisely positioned in multichannel antenna arrays, as demonstrated by both operators (Leckebusch, 2005, 2009; Francese et al., 2009; Linford et al., 2009, 2010) and GPR system manufacturers (Gustafsson and Alkarp, 2007). To achieve full-resolution three-dimensional imaging (without aliasing the data) the individual channel spacing should, however, not exceed 0.25 of the wavelength of the antennae centre frequency (Grasmueck et al., 2005; Booth et al., 2008; Novo et al., 2008).

In May 2008 the GPR manufacturer MALÅ Geoscience AB in collaboration with the archaeological prospection unit of the Swedish National Heritage Board conducted a large-scale archaeological prospection study at Birka using the new MALÅ Imaging Radar Array (MIRA). This array system is defined by (i) closely spaced channels, (ii) free combination of transmitter and receiver antennas, (iii) near-identical antenna responses and (iv) precise positioning. The purpose of this pilot study was to test the performance of this array GPR system in practice at a site where well expressed archaeological structures are known to exist in the ground.

**The MALÅ Imaging Radar Array**

The MIRA standard system consists of 17 GPR antennae (400 MHz) positioned in two overlapping rows of nine transmitter and eight receiver antennae (Figure 3). The MIRA system can be equipped with up to 16 transmitters and 15 receiver antennae. Aside from the 400 MHz system, alternative arrays with 200 MHz or 1.3 GHz antennae are available. Each receiver antenna records signals of two adjacent transmitter antennae, resulting in the case of the 400 MHz antenna system in 16 channels with a cross-line trace spacing of 8 cm, corresponding to 0.25 of the wavelength.

The 16-channel system covers a 128 cm wide swath for each driven track. In-line GPR trace sampling was set to 8 cm with a trace stacking factor of 4. The antenna array was placed in a box mounted ahead of a motorized front mower with hydraulic lift (Figure 3). Power supply and a field computer for data collection were provided on the vehicle.

Accurate positioning of the GPR measurements is crucial. For this purpose either a robotic total station or a RealTimeKinematic-GPS (RTK-GPS) can be used. The position information from the total station, respectively RTK-GPS, is transferred via radio link to the measurement vehicle where the information is recorded together with the GPR data. The total station prism or GPS rover antenna is mounted on the GPR antenna array (Figure 4). Additionally, a calibratable odometer is attached to a wheel of the carrier vehicle.
providing exact in-line distance information. For orientation of the individual swaths a spray paint maker device (Figure 4) is used to mark the start- and end-points as well as the course of individual profiles. While spray paint navigation works well on short, dry grass, an independent navigation or guidance system may be better suited for efficient large-scale surveys on, for example, harrowed fields. In any case, it is

Figure 3. Left: the novel MALÅ Imaging Radar Array (MIRA) consisting of 16 channels (400 MHz) with 8 cm cross-line channel spacing in a box hydraulically mounted in front of a lawn mower. The data logger in the form of a tough-book is fastened in front of the operator. Right: this MIRA antenna box contains an array of 17 antennae (8 receiver and 9 transmitter antennae). Dashed lines indicate transmitter–receiver antenna combinations and the arrows symbolize the 16 GPR channels with 8 cm cross-line spacing, resulting in 128 cm total swath width.

Figure 4. The prism mounted above the MIRA system (left) for positioning using a robotic total station (right). In the latest set-up the prism, respectively RTK-GPS antenna, can be mounted on top of the survey vehicle, permitting reliable, constant tracking and minimizing GPS multipath effects. The spray paint marker for colour marking of survey tracks can be seen next to the prism mount (left).
Figure 5. View of the survey area. The extent of the GPR survey area covering 3 ha is marked with a white line. The first two MIRA survey tracks are indicated with arrows.

Figure 6. Left: overview showing almost the entire surveyed area. The grey band marked with letter A indicates the base of an older, inner town rampart that underground still has the shape of a wall. Right: data detail showing a building located at the foot of the hill fort in the outer town area (see Figure 7).
recommended that grass-covered areas are mowed prior to the survey for improved data quality. Start and stop positions for individual survey swaths can be chosen freely. The definition of a virtual baseline may help to achieve full area coverage by collecting data along parallel swaths oriented approximately perpendicular to the baseline.

The GPR and positioning data from the MIRA system is directly handled in the rSlicer software avoiding complicated and time-consuming import routines. This software allows the pre-processing, interpolation, coordinate system transformation and three-dimensional migration of the GPR data, followed by interactive interpretation of the observed features.

The results can be printed and exported as georeferenced TIFF- or DXF-files for use and further analysis in GIS environments.

**Description of the fieldwork**

During the pilot study parallel swaths of up to 170 m length were measured in one direction at a speed of approximately 4 km/h. Survey speeds of up to 19 km/h are possible with the same settings, that is time window, number of samples, trace spacing and trace stacking factor. Generally, it is the site conditions (surface roughness, obstacles preventing straight lines,
crossing traffic, etc.) that practically limit the survey speed. Possible set-ups with towed antenna arrays instead of front-mounted systems may be better suited in more uneven terrain or for high-speed mapping.

In grass the vehicle tracks were clearly visible and permitted, in combination with degradable colour spray-paint markers, a good guidance to achieve complete area coverage. Successive profiles were measured with a small overlap in order to avoid gaps in the data.

In order to generate a base map over the survey area, point and line features in the surroundings were directly mapped in the data acquisition software and subsequently used during data processing. In order to geo-reference the survey area a number of control points were measured every time the total station was moved (e.g. at the beginning of each day of fieldwork or when the survey progress demanded a relocation of the total station). Both total station and RTK-GPS positioning systems were successfully tested. Efficient fieldwork can be conducted by two people taking turns between the operation of the MIRA system and checking the positioning system (e.g. manual adjustments of the total station).

Within five continuous hours 56 survey swaths covering 150 m by 62 m (9300 m²) were recorded with an in-line and cross-line trace spacing of 8 cm, corresponding to a total of 134.4 line kilometres. In comparison, two surveyors using a manually operated single antenna with 25 cm cross-line and 5 cm in-line trace spacing would in the same time cover an area of 50 m by 50 m (2500 m²; in total 10 line kilometres).

Over the course of three days an interconnected area covering approximately 3 ha (Figure 5) was surveyed in the Black Earth area of Birka. The processing of this amount of data was done during two days, resulting in geo-referenced times-slices.

**Results**

The novel GPR array system used in this investigation permitted the discovery and mapping of a considerable number of new features of archaeological interest in the Black Earth of Birka in unprecedented resolution (Figures 6 and 7). For the first time it was possible to image GPR anomalies that were interpreted to be caused by postholes, or stones contained in postholes, of only 25 cm diameter (Figure 7). Björn Ambrosiani had in 1998 suspected the existence of an older, inner town rampart due to larger stones found by the waterside and through analysis of the terrain. While the first GPR survey in 2006 had already mapped parts of this older, inner town rampart including a gate, the new measurements contributed with a much improved resolution of the subsurface structures. A row of assumed postholes is visible on the inside of this rampart, as well as a gate leading into the inner, central town area, which presumably contains remains of the oldest buildings and greatest thickness of the cultural layer (Figure 6). In the central area remains of buildings and constructions are visible in great detail. However, the presence of several building phases renders the archaeological interpretation of the observed anomalies complex. Outside the inner town rampart the archaeological interpretation is easier due to a lower number of overlapping structures and corresponding anomalies. The boundaries of property plots, buildings (Figure 7), wells and trenches are some of the structures that can be interpreted easily by taking advantage of the possibility of the data processing and visualization software rSlicer to analyse vertical GPR sections along freely chosen polygon paths selected interactively across anomalies visible in horizontal GPR time-slices. Thus, small trenches or the buried wall of the rampart and for instance wells were quickly analysed and identified.

Several straight trenches are visible in the data. One trench is, for example, crossing diagonally the building

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![Figure 8. A GPR trace with positive and negative amplitudes (1). Corresponding trace of absolute data values (2) and trace envelope (3). If GPR time-slices or depth-slices are calculated over a certain time-window or depth range it is common to first compute the envelope trace of the data in order to avoid cancellation of positive and negative data values.](image-url)
shown in Figure 7. Hjalmar Stolpe’s excavations in the Black Earth in the 1870s comprised approximately 2500 m² mostly located to the south of the field track. In 1874 Stolpe dug five ca. 120 m long, 1.2 m wide and up to 1.8 m deep trenches with 4.5 m interspacing oriented perpendicular to the farm track (Ambrosiani, 1990). In 1878 Stolpe additionally investigated the space between the two most westerly trenches. The localization of Stolpe’s excavation trenches in combination with detailed studies of the excavation reports and find catalogue prepared by Erik Sörling in the first part of the 20th century (Ambrosiani, 1990) may offer the possibility to determine the origin of some of the artefacts found by Stolpe.

The high fidelity of the data, due to well balanced signals of the individual channels, as well as the very high spatial resolution offered by the system, demands careful data processing. Standard single-channel GPR data acquired with comparatively coarse profile spacing of for example 25 or 50 cm are commonly sliced into GPR time- or depth-slice images showing the average data value over a certain time or depth range (e.g. 10 cm thick slices) after computation of the GPR trace envelopes, which are computed in order to avoid cancellation of negative and positive amplitudes (Figure 8). In the case of the high-resolution MIRA data single sample slices were generated without vertical averaging, preserving the polarity of the positive and negative amplitude values (256 greyscale values evenly mapped with white representing minimum and black maximum signal amplitude). Making use of the entire amplitude spectrum of the GPR traces, both negative and positive amplitudes, single sample slices with greatest spatial resolution of the anomalies can be
obtained. Subtle features are better defined in full polarity, single-sample slices compared with vertically averaged, thick time- or depth-slices. While the latter may be used to obtain an overview impression of the more massive structures contained in the subsurface, the former is most suited to image in detail the smallest structures. For a comprehensive analysis of the data a combination of both ways of visualizing the data appears best, that is thick-slice visualization followed by detailed analysis of thin slices, ending up with single sample slices. Under the assumption of a reasonable constant velocity used for depth-conversion, slices of 50, 40, 30, 20, 10 and 5 cm thickness and single sample slices should be generated for the entire data volume. These slices as well as corresponding slice animations should be used for thorough data analysis. Figure 9 shows a single sample slice with full amplitude spectrum (equivalent to trace 1 in Figure 8) next to a single sample slice with absolute amplitude values (equivalent to trace 2 in Figure 8). The computation of envelope traces would decrease the vertical and horizontal resolution of the data and blur the anomalies. Single sample full amplitude slices depict boundaries, such as for example the interface between the town rampart and the soil on top, with greatest clarity. It should be noted that the visualization of single-sample slices through animation is crucial for the understanding of the information contained in these high-resolution images.

Since large excavations in this specific area are prohibitively expensive and in their nature destructive to the archaeological site, the pilot survey has resulted in valuable new archaeological information of hitherto unseen quality, which otherwise would not have been obtainable. The large amount of data poses challenges in regard to data handling and interpretation (Adcock, 2009).

A considerable increase in both GPR survey speed and sampling density (16-fold and more) compared to single-channel measurements has been demonstrated. The laborious set-up of survey grids and placement of profile lines on the ground is superseded by the use of a total station or RTK-GPS.

It is not unrealistic to assume daily area coverage of up to 1.5 ha with the MIRA system for a trained team of two operators in flat, open terrain. The comparison in Table 1 illustrates the efficiency of the multichannel GPR system over traditional single channel measurements in the case of a four-day project. In both cases it would be possible to half the in-line trace spacing. In the case of a single-channel survey this would lead to a factor of 10 between in-line and cross-line trace spacing, while for the MIRA system a factor of two would still permit a sensible interpolation of the data to pixels of 4 cm size.

### Conclusions and outlook

The pilot study at Birka has demonstrated that:

(i) very efficient high-definition (8 cm \( \times \) 8 cm trace spacing) GPR surveys for archaeological prospection are possible;

(ii) the MIRA system and integrated positioning solutions are mechanically and in terms of data quality, robust, reliable and field-worthy for large-scale applications;

(iii) the 400 MHz antenna array results in data of good vertical and horizontal resolution;

(iv) the large amount of data and data handling will become major issues when areas larger than 1 ha are surveyed.

Since the pilot study in May 2008 the MIRA system has been improved, further permitting increased survey efficiency and fieldwork to be conducted by a single person.

Third party navigation and guidance solutions may be integrated and increase survey efficiency further. At the time of writing it is possible to survey with the MIRA system even in zigzag mode. This has been a new development since the pilot study at Birka where only parallel swaths in one direction were measured. The mounting of the reflector prism on top of the survey vehicle allows for unobstructed, constant tracking.

Professional archaeological prospection will before long switch to the use of multichannel GPR array systems for large-scale applications, achieving spatial coverage rates that today are common for magnetometer surveys (Gaffney, 2008). Systems such as the one presented here will permit the efficient mapping and imaging of large-scale archaeological sites in three dimensions and thereby considerably contribute to the protection of endangered cultural heritage.

### Table 1. Comparison of the single-channel system and the MAL Imaging Radar Array (MIRA) system

| Manual single channel system | MIRA system               |
|------------------------------|----------------------------|
| 4 days of fieldwork          | 4 days of fieldwork        |
| Trace spacing 5 cm \( \times \) 25 cm | Trace spacing 8 cm \( \times \) 8 cm |
| 40 km total profile length   | 750 km total profile length|
| 10 000 m² coverage           | 60 000 m² coverage         |
| 0.8 million traces recorded  | 9.36 million traces recorded|
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