Advances in GPR Imaging with Multi-channel Radar Systems

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***Abstract*- Advances in ground penetrating radar imaging with multi-channel systems have greatly improved the speed and areal coverage of the ground. Along with improved imaging software, datasets recorded with multi-channel systems can be processed at similar speeds to coarsely spaced single channel data that would normally require additional time for interpolation processes to fill in the gaps between lines. With the cross-line spacing approaching a quarter of the wavelength of the transmitted microwaves into the ground, multi-channel systems have the advantage of complete coverage of a site with no need for interpolation in most cases except to fill in the gaps between adjacent tracks if so desired. Multi-channel systems do require additional RSP (radargram signal processes) in order to balance the channels and to condition the data prior to imaging. Spectral whitening and several other RSP methods are shown with their application to imaging of sites from bridge decks for deterioration to the discovery of subsurface archaeological remains. Data processed from several different multi-channel GPR systems are shown.**

Keywords- Ground-penetrating Radar; Three-dimensional Visualization; Array System

I. INTRODUCTION

The advantages of multi-channel systems are that the full-resolution of GPR recording on the ground can be adequately handled by systems in which the antenna channel separation approaches distances less than the transmitted wavelength of central antenna frequency (Grasmueck et al., 2004; Novo et al., 2008). These design characteristics have been accomplished by many of the current GPR manufacturers of multi-channel systems. Even though the first introduction of multi-channel GPR systems dates back to more than 15 years ago (Warhus et al., 1993), the complete acceptance of multi-channel recording was limited by the quality of the data and complex data processing (Francese et al., 2009). Wildly different frequency responses of the multi-channel antenna prevented useful amalgamation of the individual profiles into useful images. However, in the last few years, most of the multi-channel manufacturers have provided GPR systems where the antenna responses of the individual elements are much closer (Linford et al., 2010; Trinks et al., 2010; Simi et al., 2010).

Another important matter is data positioning. The position of multi-channel systems is recorded during the surveys using a RTK-GNSS or a tracking total station with high precision. It is therefore no longer necessary to follow a recording procedure using parallel lines as it was necessary previously without these positioning systems. As a consequence, the array of antennae can theoretically have any arbitrary orientation while surveying an area. However, this can make data processing more challenging.

Typical radargram signal processes (RSP) can be applied to the data to compensate for small differences in the frequency responses of the antennae and balance the signal between the different elements before image construction. In addition, because the density of lines provided by the multi-channel recording is high enough, the necessity to interpolate between the channels is less important (although it remains an option). Initial densities within the 3D volume can be configured to roughly match the in-line spacing, or to propagate the volume grid cell sizes to densities higher than recorded in-line space. In the case when higher densities than the in-line spacing are desired, gap filling between empty binary cells can be applied using a simple nearest neighbor averaging or a weighted average. Before 3D volume compilation is done, the radargrams must go through a variety of RSP.

The typical RSP required to balance the individual channel antenna are:

- removal of DC drift

- 0ns editing
- gaining
- spectral whitening
- background removal
- migration/Hilbert transform (optional)

In our DC drift removal, a simple time domain pulse moving average is used preferably over bandpass filtering. The moving average window approaching about 1/10 the scan length is commonly used. Editing of the radargram signal for the 0ns employs a user defined threshold on the initial pulse or a search for the peak of the first pulse for each trace. The threshold or peak sample detected is then backed up a set number of samples to indicate the rise of the initial pulse. Each trace is then shifted individually by the determined amount of time. Spectral whitening has several important effects on the GPR data. It enhances the vertical resolution of the trace and helps balancing the different characteristics of the antennas of an array. It also enhances the S/N ratio and therefore makes deeper structures better visible (Leckebusch, 2005). Spectral whitening with a sharp cutoff on the high and low frequencies is used. In our examples, un-tapered spectral curves are used. The background removal filter is essentially a process where the average scan across a radargram is subtracted from each individual trace. The background filter is used to remove banding noises that are seen across the radargrams. In the case of multi-channel systems, the average scan over each individual channel is calculated over the entire grid and subtracted from the individual track radargram for each channel.

II. MULTI-CHANNEL IMAGING

Multi-channel imaging of a site at the Consiglio Nazionale delle Ricerche, in Rome was made at a workshop in December, 2010 with the IDS STREAM multi-channel system. The GPR configuration used a 15 channel setup where the antenna separation was 12cm (Figure 1). This system also has additional flexibility to use two linear arrays that are offset to provide a 6cm element separation as well. Shown in Figure 2 is a 3D fence plot showing multi-channel imaging with this equipment over a survey site at CNR. The image shows dipping stratigraphic layers. The advantages of high density lines afforded by multi-channel imaging, are that effective radargrams can be mapped in any direction other than just in the in-line direction. The antenna separation is sufficient to map and show stratigraphic 2D sections in any direction across the site. The data was collected by GeoStudi Astier in Italy, and processed using GPR-SLICE v7.0 Ground Penetrating Radar Imaging Software (www.gpr-survey.com).

Fig. 1 The STREAM X system. White boxes (back of the car) contain an array of 15 antennae. A hydraulic mechanical system allows lifting the antenna boxes up and down in order to assure good ground-coupling and to avoid obstacles.

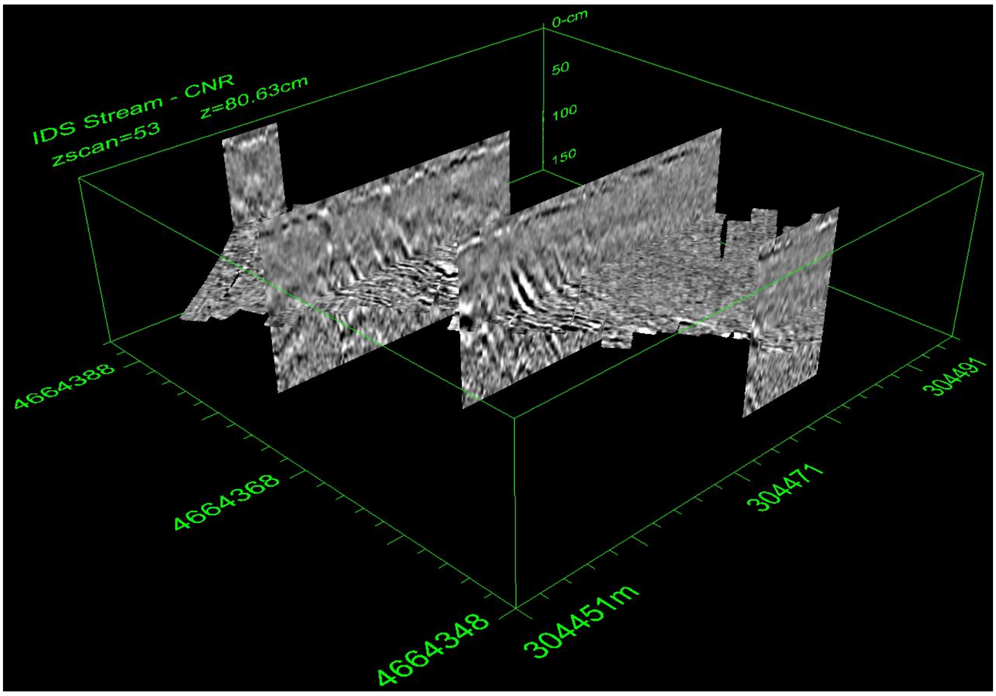

Fig. 2 Multi-channel imaging at the CNR site as part of ITABC archaeological geophysics workshop was made with an IDS STREAM-X system. The image shows closely sampled dipping stratigraphic layers.

The application of multi-channel imaging for bridge deck assessments is becoming a highly sought thing after application of GPR multi-channel systems because of the quick and thorough areal coverage of these systems. The science to exactly determine deterioration is still being researched but some promising approaches have been recently published (Simi et al., 2012). The quality of imaging however that can be achieved with today multi-channel systems is shown for the high frequency multi-channel system from IDS of Italy. This system supports 8 transmitters and 8 receivers at 2GHz central frequency. Shown in Figure 3 is a subsurface image of a bridge deck test area where two known densities of rebar were used in the construction. The high quality image within this system suggests that the high frequency channels are well balanced and can greatly assist in the research of empirical and theoretical assessment of bridge deck deterioration.

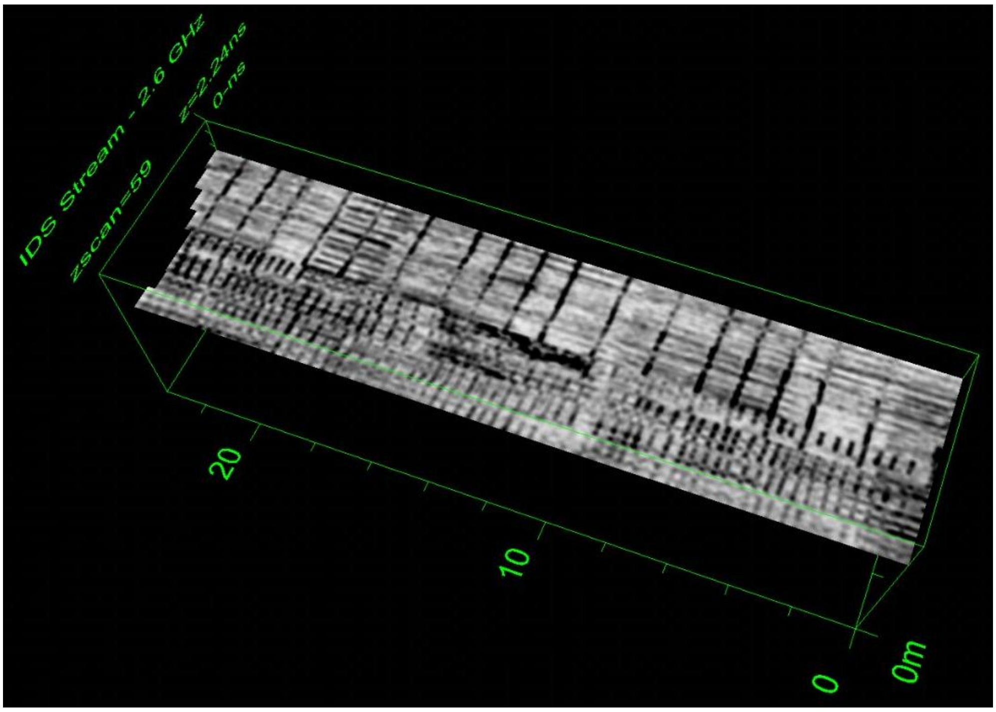

Fig. 3 Multi-channel imaging of a bridge deck was done with an IDS multi-channel system that used 16 channels of 2 GHz separated by 10cm. Two areas of different rebar densities can be clearly seen in the time-slice image at 2.24 ns below the ground surface. (Data Courtesy of IDS of Italy).

III. DISCUSSION

As mentioned earlier, the balancing of the antennae is an important processing step. Until now this is often done using an FK-filter on the time- or depth-slices (Leckebusch 2005). But as the profiles are not necessarily straight it becomes difficult to use an FK-filter with a specific orientation. In the future, it will be necessary to develop more advanced footprint filters that try to characterize the differences by only comparing the antennae of the array. The adjustments for each antenna found could then be applied to the complete dataset. This is a similar approach as the standard background removal that is routinely applied during data processing.

When the slices are interpolated, it is possible to retain the high resolution in the inline direction by only interpolating perpendicular to the survey direction. Hence if we want to fill the gaps among empty cells we need to know the local direction of the survey. This could be determined from the recorded positions or one might also expect some new ways of extracting this information directly from the data itself. Multi-channel systems allow recording large areas in great detail (Figure 4). The amount of data recorded is getting larger and heavier. Therefore, it becomes very difficult to visually analyze all data either in the form of radargrams or slices. Modern software technology helps to extract the relevant information in an automatic or semi-automatic way. Recently, we have seen different approaches to extract the wanted information (targets) from a data cube. One way of doing it is to use iso-surfaces. If these are combined with some advanced logic, the geometry of the buried remains of archaeological sites can be extracted (Schmidt and Tsetskhladze 2013, Leckebusch et al. 2008). The future will see more advanced systems and also a routine application of such pattern recognition techniques. As the interpretation of the data is the most time consuming task, these techniques could revolutionize the application of GPR in general by reducing the time needed to interpret the data which would reduce the overall costs.

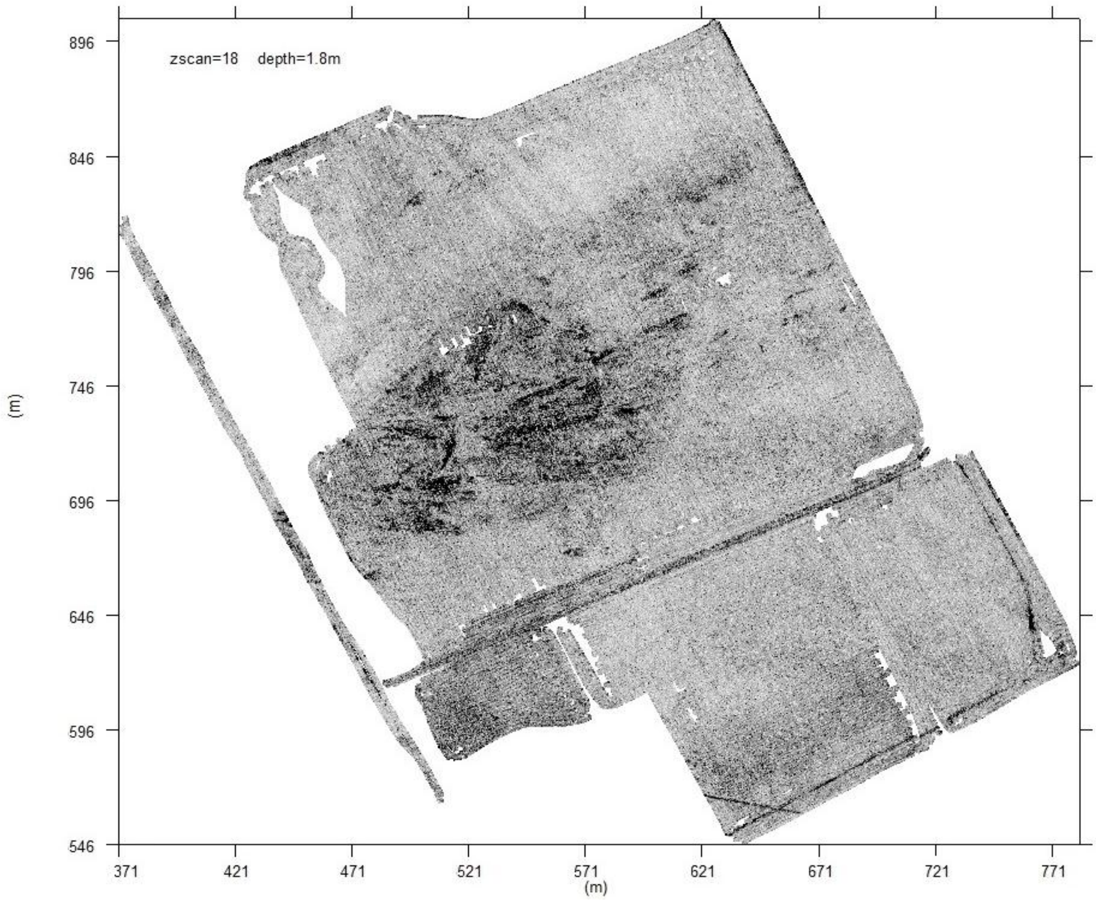

Fig. 4 Hilbert transform horizontal slice at 1.8m depth. The 12 hectare site was surveyed using a STREAM X multi-channel system Apart from different utilities at the bottom right part of the slice, reflections from geological layers can be seen in the middle of the slice.

In civil engineering it is required to map buried pipes, utilities, rebars and tension cables and to extract their width and type. All these objects are represented as hyperbolas in the GPR data. Fortunately the signals of the hyperbolas include much more information about the structures than is used today. Some algorithms try to extract the dielectric constant of the overlying material, position and diameter of structures from the hyperbolas (Shihab and Al-Nuaimy 2005). One big advantage of this approach is the ability to apply them an almost raw data with no time-consuming migration or other processing steps required (Figure 5). The individual hyperbolas have then to be connected to a representation of the complete underground utility network, rebar system or archaeological remains. Figure 6 shows an example of semi-automatic feature extraction performed over an archaeological site.

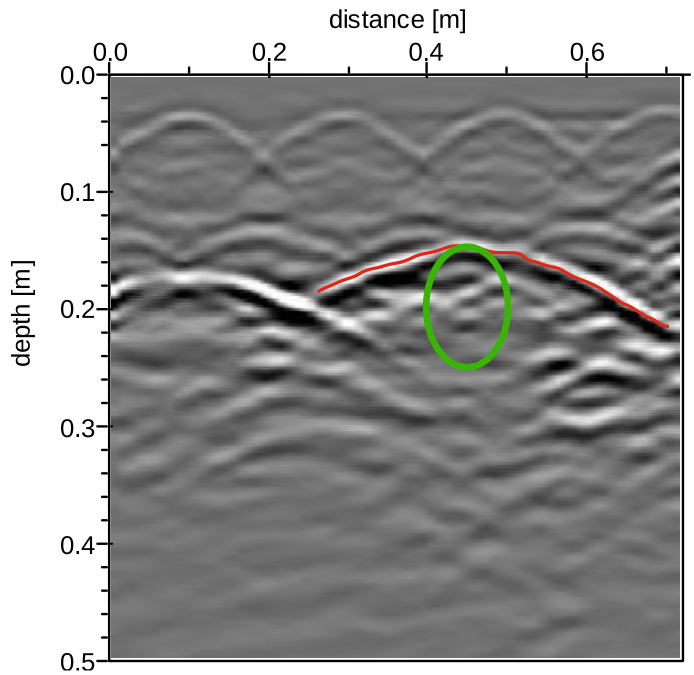

Fig. 5 GPR profile collected on a concrete bridge, recorded with a 2GHz antenna. This survey was done prior to a redevelopment and the aim was to locate the tension cables because any damage to these would severely reduce the stability of the bridge. In the top, four hyperbolas represent four rebars. Below, the two strong hyperbolas are searched tensions cables. In red colour automatic hyperbola detection and proper fitting provides information about the dielectric constant for correct depth estimation. As well, the position and diameter of the target are automatically detected (in green colour). Information about the diameter is important as it is required to calculate the stability of the bridge and dimension the additional reinforcement.

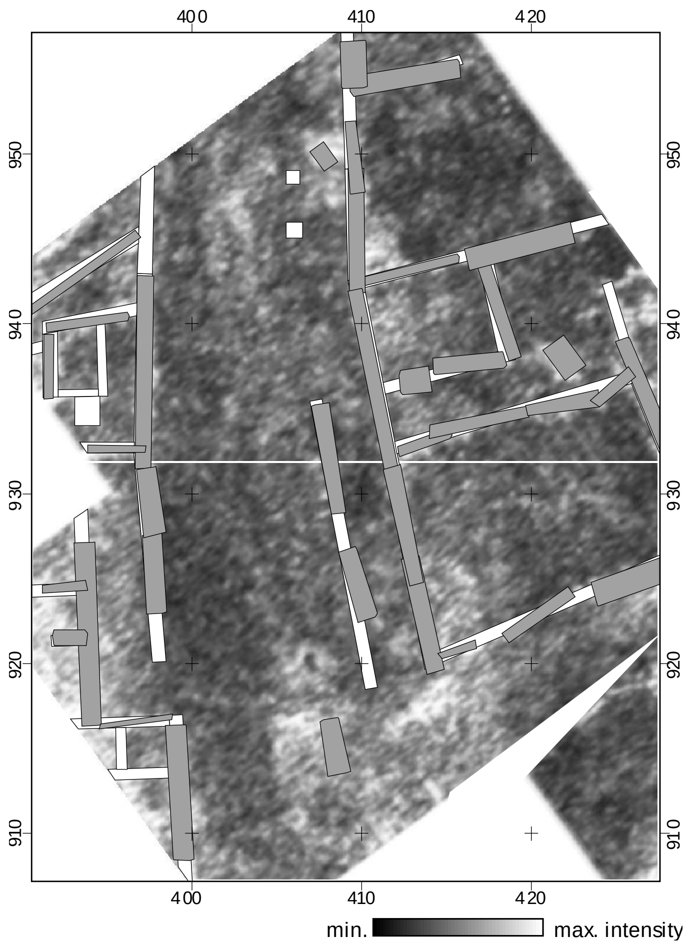

Fig. 6 This small part of a depth-slice at a depth of 0.9 - 1.0 m was recorded in a Roman town to map all archaeological structures. The density of anomalies is very high making the interpretation a time-consuming task. The anomalies are first interpreted manually shown in white and then for comparison a semi-automatic technique is used to extract the geometry in 3D shown in gray. The slice shows a Roman street running north-south with buildings and their interior subdivision to each side.

Another advantage of multi-channel systems is the capability of extracting a more reliable estimation of the depth of buried targets through rapid common mid-point (CMP or also known as multi-offset) measurements (Davis and Annan, 1989). In the past all surveys recording multi-offset data with GPR suffered from the large amount of time needed to record the data (Booth et al 2008, Pipan et al 1999). Modern multi-channel systems have the ability to freely configure the receiver and transmitter antenna pairs. By moving a properly configured multi-channel instrument a complete profile of CMPs can be recorded at the same time a profile is recorded with a conventional single channel system. This definitely opens new possibilities for advanced and detailed underground mapping.

Although multi-channel systems require different processing steps than conventional instruments, they offer new potentials at the same time as significant progress is expected in near future. Currently, subsurface imaging with multi-channel GPR provides the most efficient method for surveying sites that can accommodate large radar systems. The speed with which data can be collected, the density of sampling of the ground, along with the high quality and similarity of antenna channels bodes for increased usage of multi-channel systems in the future for all subsurface imaging disciplines.

REFERENCES

[1] Booth, A.D., Linford, N.T., Clark, R.A., Murray, T. 2008. Three-dimensional, multi-offset ground penetrating radar imaging of archaeological targets. Archaeological Prospection, 15(2): 93-112.

[2] Davis, J.L., Annan, A.P. 1989. Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy. Geophysical Prospecting, 37(5): 531-551.

[3] Francese, R.G., Finzi, E., Morelli, G., 2009. 3-D high-resolution multi-channel radar investigation of a Roman village in Northern Italy. Journal of Applied Geophysics, Volume 67, Issue 1, Pages 44-51.

[4] Grasmueck, M., Weger, R., Horstmeyer, H., 2004. Full-resolution 3D Imaging for Geoscience and Archeology. Tenth International Conference on Ground Penetrating Radar, 21-24 June, Delft, The Netherlands, 1, 329-332.

[5] Leckebusch, J. 2005. Use of antenna arrays for GPR surveying in archaeology. Near SurfaceGeophysics, 3(2): 111-115.

[6] Leckebusch, J, Weibel, A, Bühler, F. 2008. Semi-automatic feature extraction from GPR data. Near Surface Geophysics, 6(2): 75-84.

[7] Linford, N., Linford, P., Martin, L. and Payne, A. 2010, Stepped frequency ground-penetrating radar survey with a multi-element array antenna: Results from field application on archaeological sites. Archaeological Prospection, 17:187-198. doi: 10.1002/arp.382

[8] Novo, A., Grasmueck, M., Viggiano, D., and Lorenzo, H., 2008. 3D GPR in Archeology: What can be gained from dense data acquisition and processing?, 12th International Conference on Ground Penetrating Radar, June 16-19, 2008, Birmingham, UK.

[9] Pipan, M., Baradello, L., Forte, E., Prizzon, A., Finetti, I. 1999. 2-D and 3-D processing and interpretation of multi-fold ground penetrating radar data: a case history from an archaeological site. Journal of Applied Geophysics, 41(2-3): 271-292.

[10] Schmidt, A., Tsetskhladze, G. 2013. Raster was Yesterday: Using Vector Engines to Process Geophysical Data. Archaeological Prospection, 20(1): 59-65.

[11] Shihab, S., Al-Nuaimy, W. 2005. Radius estimation for cylindrical objects detected by ground penetrating radar. Subsurface Sensing Technologies and Applications, 6(2): 151-166.

[12] Simi, A., Manacorda, G., Miniati, M., Bracciali, S., Buonaccorsi, A. 2010. Underground asset mapping with dual-frequency dual-polarized GPR massive array. 13th International Conference on Ground Penetrating Radar, June 21-25, 2010, Lecce, Italy.

[13] Simi, A., Manacorda, G., Benedetto, A. 2012. "Bridge deck survey with high resolution Ground Penetrating Radar". Proceedings of 14th International Conference on Ground Penetrating Radar, June 4-8, Shanghai, China.

[14] Trinks I., Johansson B., Gustafsson J., Emilsson J., Friborg J., Gustaffsson C., Nissen J., Hinterleitner A. 2010. Efficient, large-scale archaeological prospection using true three-dimensional GPR Array System, Archaeological Prospection, 17, 175-186.

[15] Warhus, J.P., Mast, J.E., Nelson, S.D., Johansson, E.M. 1993. Ground-penetrating imaging radar development for bridge deck and road bed inspection. U.S. Department of Energy by the Lawrence Livermore National Laboratory (Contract W-7405-Eng-48). 16 pp.