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Processing of images recorded by the radar method, aimed at construction of metric 3D models of subsurface objects and structures

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Abstract: The radar method, executed with the use of ground penetrating radars – the georadars, belongs to non-intrusive methods of positioning subsurface structures and objects. The direct result of the survey is the so-called radargram – a radar image, that is a vertical cross-section of the penetrated medium. It brings an information on the existence and mutual position of ground layers and subsurface structures and objects. The radargram, as the direct result of measurement, demands further processing for its interpretation and use.

The consecutive steps leading from a non-metric radargram to the metric 3D model, based on corresponding surveying and georadar data are presented. The paper concentrates on the problem of broadening the scope of interpretation and applications of georadar surveys thanks to proper integration of advanced filtering programs, graphical software and programs from the CAD and SIT environment. The aim of the integration is a metric 3D model of subsurface objects and structures located with the georadar method. The ways and stages of generation of the spatial subsurface models, presented in the paper, complement surveying sources of data for thematic maps.

Keywords: Georadar, radargram, 3D models of subsurface objects and structures

1. Introduction

Numerous papers published, including those in proceedings of international conferences on applications of the georadar method, present possibilities of the use of 3D models, created on the base of georadar images, in interpretation of subsurface objects and phenomena. Those models are most often used in geology of shallow strata, archaeology and analysis of road beds. Examples of application of such 3D models to detection, dimensioning and orientation of sediment layers can be found in (Pringle et al., 2004; Szerbiak et al., 2001). For proper positioning of registered profiles and proper dimensioning and orientation of penetrated layers, local terrain topography should be accounted for, together with the precise location of the examined area. Data necessary for metrization of these models are often supplied by geodetic measurements, for example using GPS (Xu et al., 2000; Kim et al., 2005), automatic tacheometers (Lehmann and Green, 1999) or photogrammetry (Pringle et al., 2004). The georadar method finds also important applications in location of underground utilities (Annan et al., 1984; Nawrocki and Piasek, 2005a; 2005b), where the crucial issues pertain to proper selection of infrastructure detection methods, influence of georadar data filtering (Tjora and Eide, 2004) and properties of the penetrated medium (Nawrocki and Piasek, 2005a; 2005b). Authors of the last paper do not consider applications of the georadar method to completion of utility maps. In general, papers pertaining to applications of the georadar method usually do not account in detail for procedures leading from non-metric radargrams to metric spatial models, and ignore its surveying applications.

The essence of this paper consists in presentation of methodology of radargram processing, resulting in creation of a metric 3D model of a penetrated object or a subsurface region, and in presentation of procedures transferring non-metric radargrams into environments of software used in preparation of electronic maps. Presented results show in detail certain steps of procedures leading from georadar survey of details to their presentation on those maps.

The paper presents methodology of a broadened radargram processing, aimed at compatibility with digital maps. Possibilities and limitations of the existing software are discussed. Special attention paid to surveying applications resulted in a deeper insight into metrization and vectorization of radargram data. The basic steps of processing include import, filtering and interpretation of radargrams, then export of the data into a CAD software for conversion into a metric raster, followed by vectorization and incorporation into digital map database, with final analysis and eventual complement. As an example illustrating that problem, results of test measurements and data processing aimed at recognition of subsurface structures at a closed down and already filled up shaft, are presented.

2. Characteristics of advanced software for processing of results of georadar measurements

Manufacturers of the georadar equipment supply with it specialized software of various application scope and level of advancement. In general these are programs for radargram filtering and creation of non-metric 3D models of penetrated areas. Specialized software conformable with georadars of one manufacturer does not warrant compatibility with instruments of other brands. The list of software of different manufacturers, used recently in processing of radargrams, is given in Table 1. Programs listed in one row are more or less equivalent. Three groups of programs can be distinguished. The first group contains programs for collection and basic filtering of georadar data. Programs for 3D visualization of measurement results belong to the second group. The third group contains software designed for special applications, like investigation of road pavement, bridge construction or tunnel lining.

T a b l e 1. The list of selected software for radargram processing

Group	Mala GeoScience	Sensors&Software	GSSI	IDS
1	GPR.EXE GroundVision RedExplorer	SpiView EKKOView	RADAN	IDS K2 IDSGRED/S
2	Easy 3D ReflexW	EKKO3D Conquest 3D	QuickDraw Super 3D module	IDSGRED/S 3D IDSGEOMAP TOOLS
3			Structure Identification Module Advanced Road Structure Assessment Module Bridge Assessment Module	IDSGRED/IN/SubReM IDSGRED/IN/Tunnel IDSGRED/IN/Layer

In the investigations presented in this paper the programs ReflexW and Easy 3D, supplied by the Swedish company Mala Geoscience (Mala GeoScience, 2000a, 2000b), the manufacturer of the RAMAC/GPR georadars, were used first of all. The ReflexW program was prepared by the Sandmeier Software (Sandmeier, 2004). It is destined for processing, interpretation and transmission of data. The program contains functional modules for radar, seismic and ultrasonic investigations. The 2D data analysis module allows easy import of data in several formats, including RAMAC, conversion of the data into a single cross-section or a series of cross-sections, application of vertical and horizontal filters and other processing possibilities. The module for processing of three-dimensional data shows sections of x, y, and z axes created in a manually scaled window and presents data in form of a rectangular parallelepiped. The modelling module allows interactive presentation of a two-dimensional, layered model and simulation of electromagnetic or seismic wave propagation on this model.

3. Basic stages of radargram processing in the process of filtering and 3D model creation

The basic stages in radargram processing are:
- selection of proper colour scale for the radargram,
- determination of horizontal and vertical scale of the radargram,
- filtering of the radargram image,
- interpretation of filtering results,
- processing of radargrams aimed at creation of 3D models of the located object,
- interpretation of obtained models.

Proper selection of colours and their scale, spanning usually a dozen or so dyes of different level of intensity, allows successful visualization of elements recorded on the radargram.

The horizontal scale (upper and lower) of the radargram, usually given in metres, represents length of the profile, along which the antenna moved during measurement. The vertical scale (left and right) allows for determination of depth of the located object and is marked in units of distance or travel time of the electromagnetic wave in the medium.

The filtering process is aimed at enhancement of the detected object with respect to the background of the surrounding medium. It consists in application of available filters in proper sequence, within the accepted colour scale.

Some programs or program modules used in postprocessing allow creation of a complex composition and presentation of results in form of a 3D solid. The creation of a 3D model of an object is superseded by postprocessing of separate radargrams. The spatial model is then a result of composition and interpolation of the separate radargrams. Such a model facilitates interpretation concerning position of the object, and to a certain extent its shape, but also informs about some other phenomena in the penetrated medium. An example of a spatial model of subsurface structures, prepared using the Easy 3D software of Mala Geoscience, is shown in Figure 1. On the right-hand side of the picture there are: a view of the front plane of the 3D model (the upper image) and a view of the upper plane of the 3D model (the left side of the figure). The 3D model determined in that manner facilitates determination of relations between mutually perpendicular profiles and interpretation of content of the radargrams.

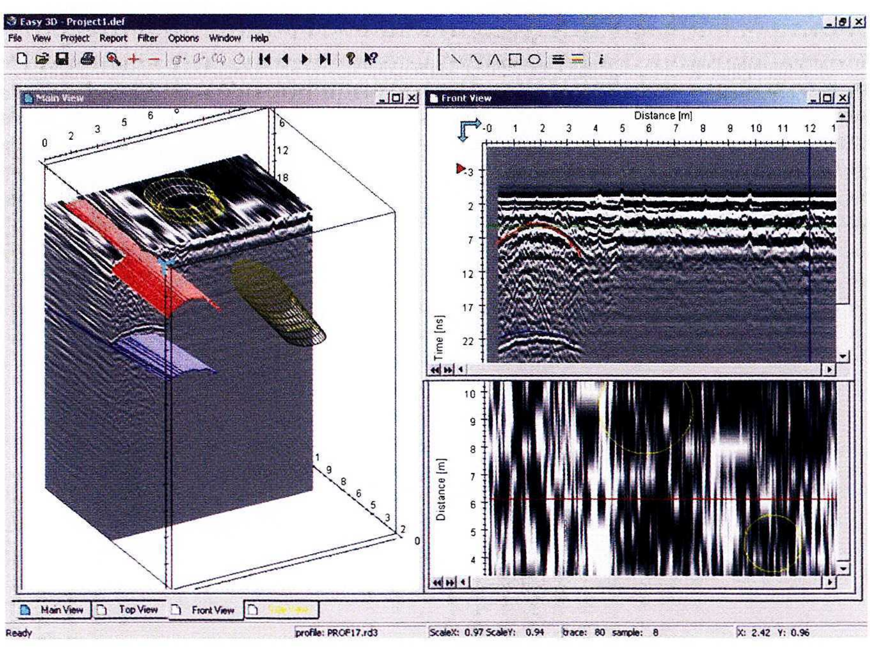

Fig. 1. The three-dimensional radar model created with the Easy 3D program

4. Capabilities and limitations of the radargram processing software for collection of spatial information

Using the example of the ReflexW and Easy 3D software, preferred by the Swedish manufacturer of georadars – company Mala Geoscience, in Table 2 there are listed capabilities and limitations of the radargram processing software, as applied to acquisition of 3D data, especially that oriented towards the needs of surveying.

Table 2. The comparison of capabilities and limitations of the Easy 3D and ReflexW software

Easy 3D	ReflexW
Generates the model from mutually parallel profiles: – profiles should be evenly spaced – profiles scanned in reverse directions can be processed	Generates the model in two ways, using parallel profiles: – separated by equal distances, – separated by arbitrary distances, profile position is given in coordinate files
The shortest profile determines dimension of the model, what forces profiles of equal lengths. This demand can make fieldwork diffcult	Profiles of different length can be used
Number of tracks in a single profile is limited, what determines the length of radargrams or forces degradation of measurement data	Number of tracks in a profile is limited
It is not possible to apply an arbitrary coordinate system. Length of profile determines position and orientation of the model	Work in any coordinate system is possible
A simple vectorization on arbitrary profiles is possible	Vectors from the 2D module can be used
Vectors can be joined to form planes	Vectors can be joined to form planes
Other graphic or vector objects cannot be imported	Other graphic or vector objects cannot be imported
Radar data can be filtered	Radar data can be filtered
Model can be navigated	Model can be navigated
Profiles cannot be exported to the graphic BMP format	Profiles can be exported to the graphic BMP format (good quality of image, non-metric distorted scale in different directions)

In the georadar measurements for surveying purposes it is important to acquire and analyze information sufficient for precise determination of position of subsurface objects and structures. It is important to determine geometric relations between those objects and topographic details on the surface of the investigated terrain, and also the influence of the subsurface structures on the investigated area. An analysis of those relations is especially important, when the interpretation results are fed into a general database, containing also a digital map, DTM and/or GIS. But the solutions obtained with the standard software, both 2D and 3D, are only intermediate tools for search for demanded final information.

The discussed software does not allow for importing of other raster or vectorized information (vector map, orthophotomap). Work in a suitable coordinate system is not always possible. Though the radargram can be represented as a graphic image, its scale is distorted in both directions. The above mentioned limitations of standard software, and, on other hand, detailed information present on radargrams and its importance for practical application, make integration of the software with selected graphic and CAD programs indispensable, if a valuable, comprehensive information on the object and its subsurface structure is to be collected.

5. A procedure for extraction of metric information from radar images

As a result of filtering and interpretation of radar data in the postprocessing software one can obtain two groups of essential information:

- a vectorized line in the form of a series of points determining the shape of the object and position of subsurface structures,
- a raster radargram image which, when calibrated, can be vectorized as a metric raster image.

The graphic image of the profile – the result of radargram processing, has the distorted scale along both axes. So it cannot be directly used in the aspect of metric vectorization. A calibration process is necessary before an import of the image into the CAD environment in direct relation to a map, plan or position with respect to existing details. It should be noted that the ReflexW software does not allow a direct export of a vectorized calibrated file into the DXF format, but the information can be stored as an ASCII file, and then the file can be converted and imported into a CAD software. On the other hand the Easy 3D software does not allow any export of a vectorized model.

In the example that completes the discussion, sinkhole measurement data, taken with the RAMAC/GPR were used. The survey was made along profiles, that form an irregular grid of parallel and perpendicular lines. Radargrams obtained were transformed in the ReflexW program into a specified coordinate system and then properly filtered. Characteristic features of the profiles were vectorized and then exported into an ASCII file (Fig. 2). The most important data in the file are coordinates of points marking boundaries of subsurface layers and their depth.

The properly prepared ASCII file was imported to the DXF format using the MicroStation software, what allowed for creation of a spatial vector model of the subsurface layers in a universal format for the CAD and GIS environments. The non-metric image of the radar profile was calibrated using an affine transformation. Common points for the transformation were the points computed from the real length and depth of the recorded profiles. As a result the radar image in the form of a metrized raster was obtained. It should be noted here, that there is a slight difference between the vector obtained from the radargram and the vector from the raster. In the first case the maximum amplitude of the detected layer can be controlled automatically, so the layer detection is done without the operator's inference, while in the second case the vector line depends solely on the operator's interpretation.

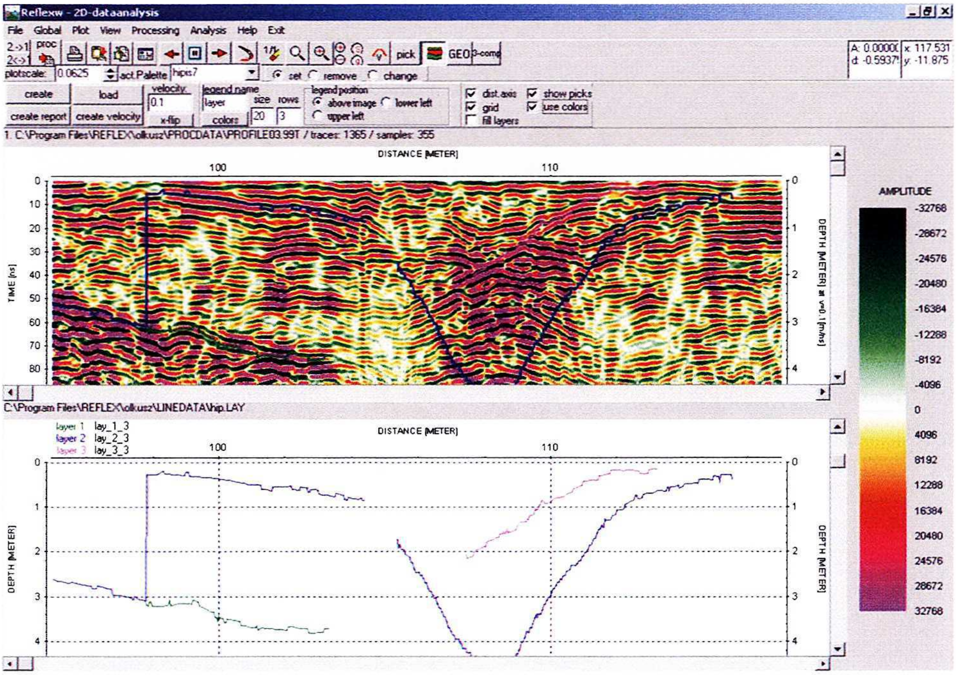

Fig. 2. An example of vectorization on a radargram using the ReflexW software

6. Application of the CAD programs to visualization of radar measurement results

The data comprising vector lines in a DXF file and the metric radar images obtained along the procedure described in the section 5 were used for creation of the sinkhole model shown in Figure 3.

Data prepared in that way offer wider possibilities of application of radar profiling results, as the model can be created from profiles of any length. The model does impose neither direction nor spacing between the profiles, as every radargram can be treated as a separate entity during the elaboration process. It allows a quick change of the coordinate system and allows work within the coordinate system of any radargram as soon as the local system is defined. It is also possible to examine mutual relations at intersections of any radar images, as shown in Figure 4. The processed radargrams shown in Figure 4, mutually correlated, allow a more feasible interpretation of distribution of layers at the intersection points and in their vicinity. Presentation of larger number of intersecting radargrams broadens the scope of interpretation of radar survey results.

Universality of CAD software allows an import of additional data pertaining to given object: results of other investigations or results of other periodic radar soundings. This allows for a comparative analysis.

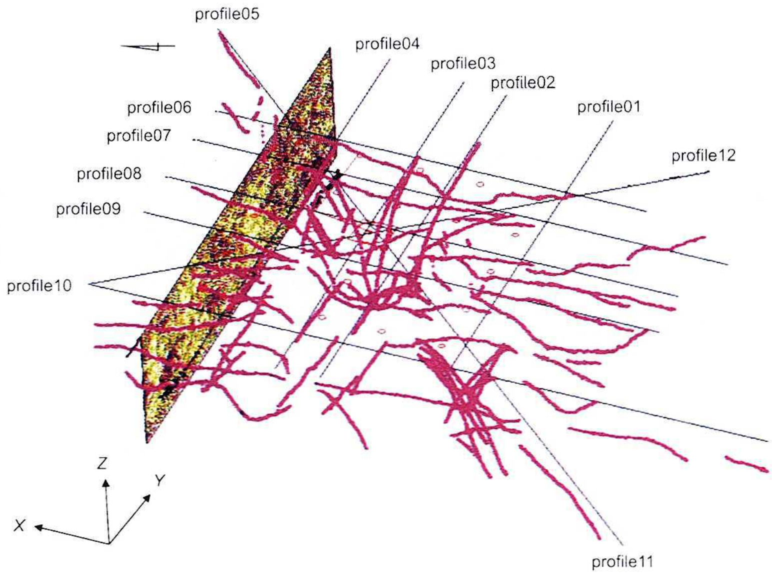

Fig. 3. The spatial model of a sinkhole created from radar data with the AutoCAD program

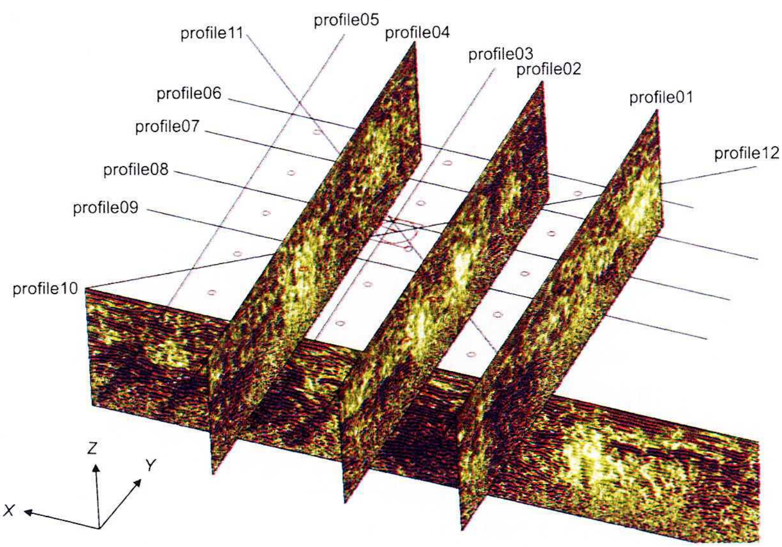

Fig. 4. Correlation of structures on radargram cross-sections

Processing of georadar measurement data with the use of the model prepared in such a way is possible for arbitrarily long profiles, and results of the processing allow computation of areas and volumes of the detected objects and further processing of vector data in space.

The above presented stages of data processing and presentation facilitate wider implementation of results of georadar measurements in surveying milieu. The raw radar data is not a self-contained, closed information, but an information that can be acquired and used as complementary to data from other sources. It can easily be found, that the data can be of great value to surveying applications. The data, properly prepared, can contain geometric information tied to coordinate system, what allows for creation of maps and numerical models of subsurface objects and structures. Also changes of the object with time can be explained through analysis of state of the structure itself. An easy import of maps, orthophotomaps, plans and DTM facilitates determination of mutual relations of terrain topography and subsurface structures.

7. Concluding remarks

Application of the methodology, developed by the authors, for extraction of metric information from subsurface radar images, called radargrams, allows completion of feature maps created in CAD and GIS environments.

The basic steps of radargram data processing into a map are as follows:

- import of data during postprocessing into a proper coordinate system,
- filtering of radargrams,
- interpretation of filtering results,
- vectorization of radar data with software designed for postprocessing of radargrams or export of the radar image and its calibration into metric raster with software for digital processing of images,
- import of vectorized lines into the DXF format or vectorization of metrized radargrams using software of the CAD environment,
- analysis of information gained from the spatial radar data with respect to the content of a digital map,
- eventual update of the digital map using the results of radar measurements.

Proper and skillful use of the georadar method as a surveying tool, and proper processing of the georadar data, enriches the scope of surveying works and broadens the range of available information both for elaboration of electronic maps and for building of Geographic Information Systems.

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Przetwarzanie obrazów rejestrowanych metodą radarową w procesie tworzenia numerycznego modelu 3D obiektów i struktur podpowierzchniowych

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Streszczenie

Metoda radarowa, realizowana poprzez wykorzystanie przyrządów nazywanych georadarami, należy do nieniszczących metod określania położenia struktur i obiektów podpowierzchniowych. Bezpośrednim efektem pomiaru georadarem jest tzw. radargram, który jest radarowym obrazem, czyli zapisem dotyczącym pionowego przekroju penetrowanych warstw, struktur i obiektów podpowierzchniowych. Dostarcza on informacji o istnieniu i wzajemnym usytuowaniu tych warstw i innych elementów. Często przedmiotem badań są struktury i obiekty podziemne. Radargram jako bezpośredni wynik pomiaru wymaga właściwego opracowania w celu jego interpretacji i wykorzystania.

Artykuł skupia uwagę na zagadnieniu rozszerzenia możliwości interpretacji i wykorzystania wyników pomiarów georadarowych poprzez właściwą integrację zaawansowanych programów filtrowania tych wyników, programów graficznych oraz programów środowiska CAD i SIT. Celem takiej integracji jest uzyskanie metrycznego modelu 3D obiektów i struktur podpowierzchniowych lokalizowanych metodą georadarową. Przedstawione w opracowaniu sposoby i etapy generowania przestrzennych modeli podpowierzchniowych uzupełniają metody prac geodezyjnych w zakresie pozyskiwania danych stanowiących treści map tematycznych.