Some Advances in UWB GPR

Gennadiy Pochanin

Abstract A principle of operation and arrangement of UWB antenna systems with frequency independent electromagnetic decoupling is discussed. The peculiar design of the antenna makes it possible to use it in two different modes: horizontal scanning mode and accurate definition of local object location mode. The technique for automatic local objects detection on GPR images is considered. It is based on the Hough transform for detection of hyperbolic curves. Estimation of the accuracy of the objects′ measured coordinates and evaluation of the detection probability have been performed for the case of automatic interpretation of GPR sounding results.

Key words: Ground penetrating radar, GPR, impulse signal, transmitting-receiving antennas, decoupling, Hough transform, detection probability, false alarm probability.

1 Introduction

A wide variety of ground penetrating radars (GPR) is considered as possible equipment for mine and UXO detection. There are many reports and scientific papers discussing different achievement in this area (e.g. [10], [11], [12] and others).

However, in practice, the power budget of GPR leaves much to be desired when experiments on GPR sounding are carried out. The large power budget of GPR means deeper sounding, higher resolution, higher detection probability and lower false alarm probability. Taking into account characteristics of an existing short pulse

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generator, there is no problem driving a radiating antenna by a power pulse. However, GPR is a short range radar and it demands that the receiving antenna be close to the transmitting antenna. Widely known antennas, like “bow-ties”, wideband dipoles and TEM horns when used as transmitting–receiving GPR antennas are electromagnetically coupled. This means that power pulses are induced in the receiving antenna when the transmitting antenna is excited. It is this coupling phenomena that limits the power budget of GPR. Quite good GPR antenna systems provide decoupling which is about -30 dB.

To overcome this problem the author with his colleagues suggested a way to achieve full frequency independent electromagnetic decoupling, as described in [9]. Details of the transmitting–receiving (TR) antenna design and operational principles are given in Section 2.

Usually UXO and land mines are quite small objects. Under these conditions it is possible to analyze them as local objects. Section 3 considers an approach providing automatic detection of local objects.

It is well known that the local objects with small dimensions form hyperbolic curves in a GPR image. The Hough transform is an effective technique for automatically searching for curves in binary images [2]. This technique is applied to detection of hyperbolic curves in the GPR images as described in [8], [1]. The theory of the Hough transform for fast and precise detection of local objects and for determination of soil properties has been stated in the papers [6] [4]. This method is tested using simulated and experimental data. Relations between the object detection probability and the false alarm probability, and the accuracy of determination of the objects’ coordinates are obtained [5].

2 High Decoupled Antenna for UWB Pulse GPR

2.1 Principle of operation and arrangement

2.1.1 Principle of operation

Two dipoles which are placed symmetrically with respect to the YZ plane and antiphased excited by $G1$ and $G2$ (Fig. 1) generate an electromagnetic field with only Ex and Hy components in the YZ plane. This means that if we place a plane conductor there, the pair of radiating dipoles does not induce any current in this conductor. Thus, receiving antenna in the YZ plane does not receive the electromagnetic field generated by the two dipoles of the transmitting antenna. There is an absolute mutual compensation of electromagnetic fields Ey, Ez, Hx and Hz generated by the transmitting dipoles. Moreover, this holds independently of the exciting signal waveform.

Very high frequency independent electromagnetic decoupling between the TR modules is possible if a single dipole is the radiating antenna and the receiving

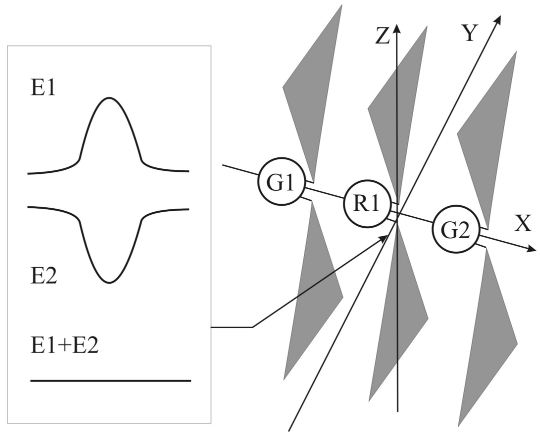

Fig. 1 Electric fields compensation.

antenna is a pair of dipoles placed symmetrically with respect to the YOZ plane. It is only necessary to connect the outputs of the receiving dipoles in an appropriate way (Fig. 2).

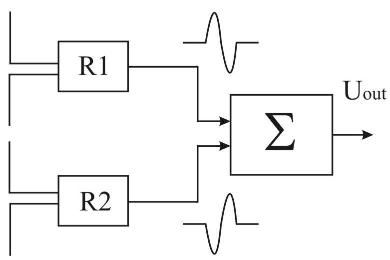

Fig. 2 Summation of signal from the outputs of the receiving module.

EMFs with the same waveform and amplitude are induced in the receiving dipoles under the influence of the radiated electromagnetic field. Subtracting the signals from the outputs of the receiving dipoles, in the summing unit, we achieve a minimal signal at the antenna output. As a result, we have TR antennas decoupling.

Since the signal at the receiving antenna output is the difference of signals received by its two elements; the receiving module is a low-cut filter. The lowest working frequency depends on the relative delay between the signals received by the elements of the receiving module.

2.1.2 Arrangement

The antenna system (Fig. 3) consists of a bow-tie transmitting antenna on the middle plate and a pair of receiving bow-ties, one above and one below the middle plate. The distance between the antenna elements of the receiving module is 160 mm. Thus, it effectively receives the electromagnetic field which arrives from the direction of the X axis, and the typical rise time is less than 0.5 ns. A high voltage short pulse generator is used to drive the radiating antenna. The principle of pulse forming by a drift step-recovery diode [7] provides generation of 450 V in amplitude, 0.5 ns in rise time, and 25 kHz in repetition rate pulses.

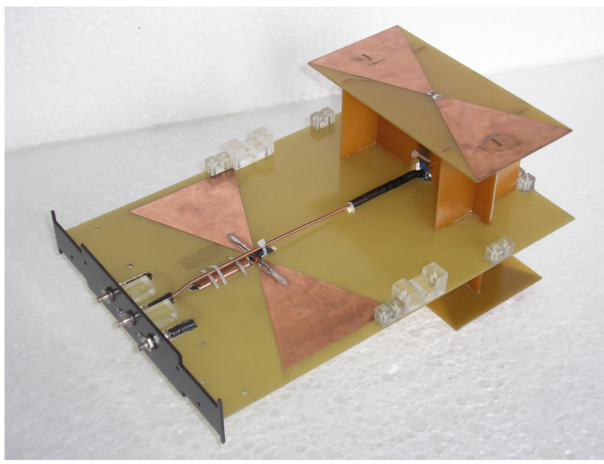

Fig. 3 The antenna system arrangement.

Under these driving signal parameters and absent reflecting objects near the antenna system (Fig. 3) the pulse amplitude at the output of the receiving antenna is less than 3 mV. This implies that the decoupling value is better than -103 dB.

2.2 Modes of operation

There is one more advantage of the antenna system. Its radiation pattern is the product of those of the transmitting and receiving modules. Thus it has only two peaks along the perpendicular to the main plate (in Fig. 3). The pattern has nulls in the bow-ties' plane in any direction. It is unresponsive to clutter coming from objects and other sources of electromagnetic radiation situated in the antenna symmetry plane.

GPR with the described antenna system is able to work in two modes:

1. Horizontal scanning mode.

2. Accurate definition of local object location mode.

Mode 1 is commonly used when the antenna system moves on the ground. The antenna pattern has two peaks in both the nadir and zenith directions, and a null in the horizontal plane. In fact, using this GPR system in horizontal scanning mode is similar to the usualGPR technique. The only advantage is in the power budget, owing to higher decoupling in comparison with conventional bow-tie GPR antenna systems.

In order to provide accurate definition of local object location mode it is necessary to rotate the antenna system around the Z axis (Fig. 1) and to perform sounding moving the antenna along the X axis in Fig. 1.

If the antenna system moves over a local object (Fig. 4), the received signal changes its waveform (Fig. 5).

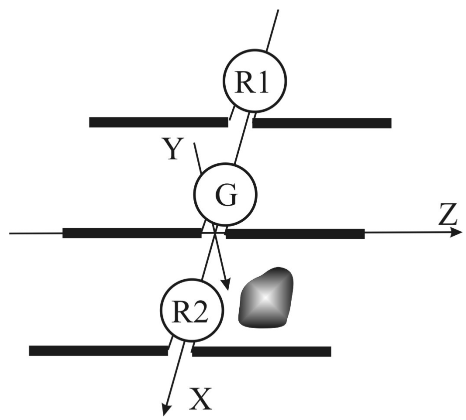

Fig. 4 Accurate definition of local object location.

When the object is located far from the antenna system, the output signal amplitude is very small. As the distance between the antenna and object decreases the output amplitude increases. It reaches its maximum when one of the elements of the receiving antenna is over the object (Fig. 5).

The amplitude goes to zero when the object is in the antenna symmetry (YZ) plane. At further antenna displacement the signal amplitude increase again. It changes its polarity and reaches its maximum when the other element of the receiving antenna goes directly over the object. Thus, if during movement the signal amplitude at the output of the antenna system goes through zero and changes polarity, it means that a local object is in the ground and the location of the object corresponds to the location of the antenna symmetry plane where the output signal was minimal.

Figure 6 shows results of a test of the antenna working in accurate definition of local object location mode. The initial GPR profile, without applying any data pro-

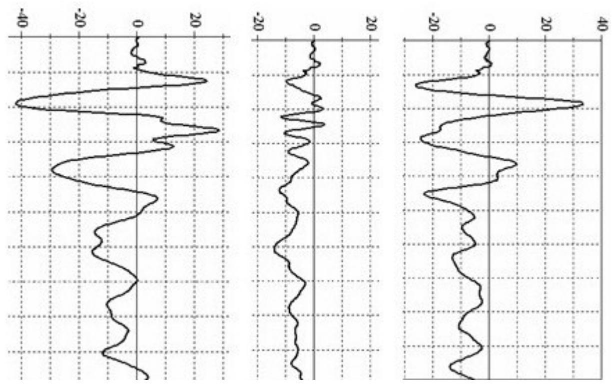

Fig. 5 Output signals.

cessing procedures, is shown on the left. It corresponds to a section of the sounded path 1 m in length.

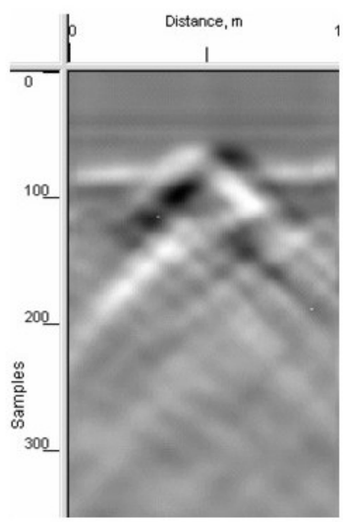

Fig. 6 Experimental profile.

Accuracy of the object's horizontal coordinate measurement is about 2 cm. It should be noted that, in contrast to horizontal scanning mode, the accurate definition of local object location mode provides high horizontal resolution at shallow depth.

3 Automatic Object Detection with GPR Images Containing a Response from a Local Object

3.1 Use of the Hough transform for detection of GPR hyperbolic curves

The Hough transform associates the original binary image of the profile (the so-called "space of signals") with another image (the Hough space) where a set of hyperbolic curves that cross at one point with coordinates x_0', y_0' (position of a local object in the Hough space) corresponds to one hyperbola in the space of signals. In other words, one pixel that is a component of the source hyperbola drawn in Figure 7 as a dashed curve is the vertex of the hyperbola in the Hough space.

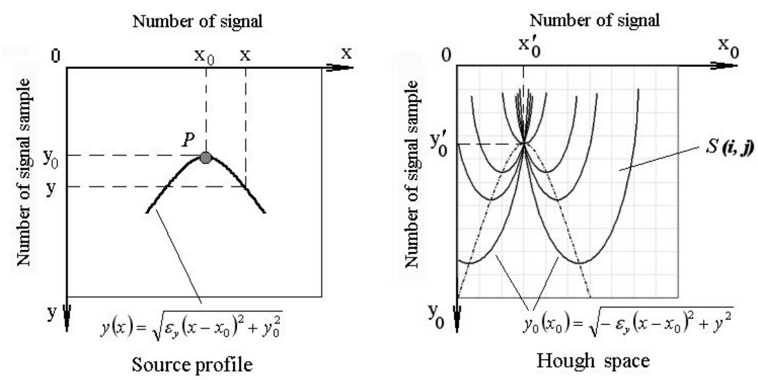

Fig. 7 The hyperbolic curve in the binary image of the profile and the Hough space.

In the "classical" case [2] for HT calculation the Hough space should be divided by a rectangular mesh into collecting elements $S(i,j)$ of fixed size. The number of black points in the original binary image that lie on the curve $y_0(x_0)$ is calculated for every collecting element. Thus the spatial accuracy depends on the size of a collecting element. Then maximal values of S are calculated as a function of three variables y_0, x_0 and ε, and a collecting element with the highest value corresponds to three parameters defining the detected hyperbola in the original binary image.

The standard HT requires long-term computations. The authors have suggested a way to reduce computation time using the following algorithm:

- the Hough space should be divided into collecting elements - 1x1 pixels in size,
- one hyperbola $y_0(x_0)$ in the Hough space should be plotted for every black point of the whole original image,
- coordinates of each point of this hyperbola should be calculated, and the accumulator corresponding to these coordinates should be increased by one.

So, if several hyperbolas fall within one element, the accumulator grows according to the number of hyperbolas.

It is obvious that the Hough space should be calculated and plotted only once. All points in the original image are already taken into consideration. Thus, this reduces the calculation time considerably. Moreover, this technique precisely determines coordinates of the hyperbola vertices because the element size is originally 1x1 pixels.

3.2 Hough space at different permittivity values

Consider the Hough space of a single hyperbola when the value of ε used in calculations differs from the correct value. The Hough space has been imaged for a test hyperbola similar to those shown in Figure 7 when x_0 and y_0 are fixed and ε takes several different values. The correct value of ε is 12.

The simulation results are shown in Figure 8. Histograms of collecting elements along the coordinate y_0, i.e., vertical profiles of the accumulator in collecting elements (VPACE), form a cross-section of the Hough space with the plane along the straight line $x_0 = x_0'$. It is perpendicular to the plane $x_0 y_0$.

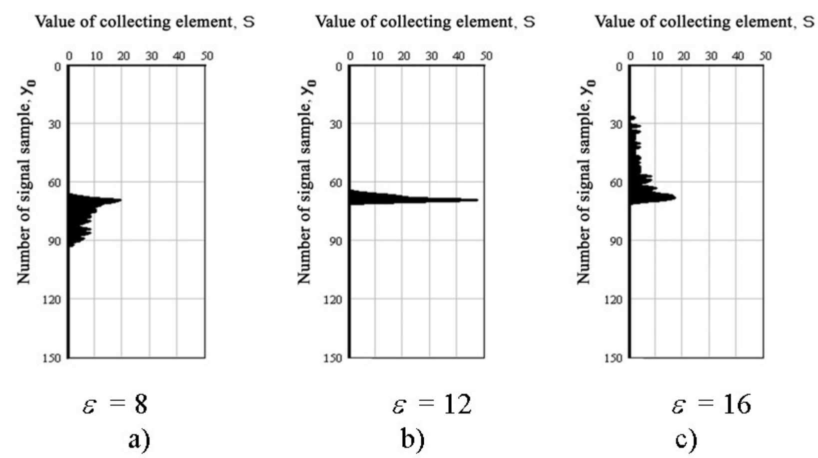

Fig. 8 Histograms of collecting elements along the coordinate y_0.

One can see that at the exact matching of the actual value ε the VPACE looks like a peak at y_0' (Figure 8 b). Depending on the value of mismatch and its sign (greater or less than the actual ε) it shows changes with depth either from zero to fast growing and then slow drop, or slow growing then peak and the fast drop to zero.

Thus, when ε changes there are phenomena typical for focusing. Therefore, when a specified value of permittivity does not correspond to its actual value, there is a defocusing in the Hough space. The defocusing pattern depends on the difference between the calculated and actual values of ε.

An algorithm for adaptive selection of ε (Figure 9 b) has been developed based on the behavior of $S(\varepsilon)$.

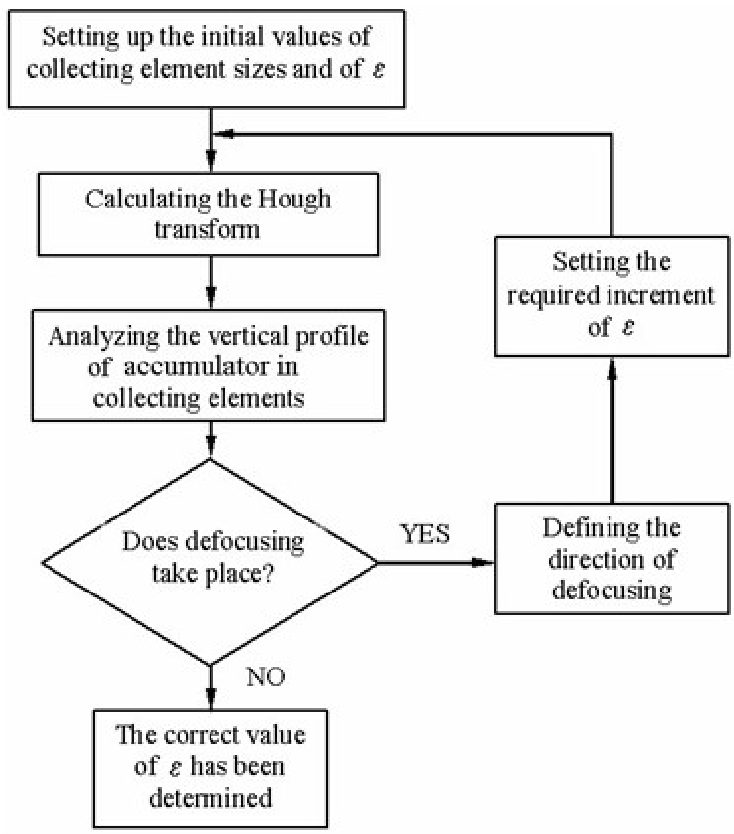

Fig. 9 The algorithm for adaptive selection of ε.

This algorithm has been tested using several simulated and experimental GPR profiles. 2% error for permittivity estimation can be achieved for the geometrically generated curves. The error increases to $5-10\%$ for simulated images and to 12% for experimental data because of the presence of clutter. Error in ε calculation corresponds to error in calculation of coordinates of the local object location.

Thus, the algorithm is applicable for automatic GPR data processing and automatic detection of local objects in GPR profile. It allows minimizing the influence of the human factor on data processing, and calculates the object coordinates with accuracy which is not worse than one pixel in the GPR image.

3.3 Performance of automatic object detection method

Usually object detection cannot be done unambiguously. If we deal with a binary classifier, which divides a set of detected targets into two classes – real (the positive instances) and false alarms (the negative instances), the ensemble of metrics in [3] is used for performance measurement.

The second problem that has to be solved while searching for objects is determination of coordinates of the object's location and estimation of errors in these coordinates. It is possible to simulate the necessary profiles using the finite-difference time domain method (FDTD) software.

The automatic object detection method has been tested with

- geometrically simulated local objects images,
- FDTD simulated local objects images,
- experimental data with several local objects [5].

In the first item the classifier marked all true positive instances correctly while processing the image simulated using hyperbola tracing, though several false alarms appeared. In the FDTD examples some problems with classification occurred due to the presence of clutter and to the non-ideal shape of the hyperbolic curves. Comparison between coordinates of the detected peaks and coordinates of the hyperbola vertices shows that the X coordinates of all the vertices in the first example have been determined with zero error, while the determined coordinates of vertices for the second example have a maximal displacement of 2 pixels from the source values. This means that it is possibile to determine the horizontal coordinates of the object with zero error. The absolute error in the determination of the Y coordinate of the hyperbola vertices did not exceed 3 pixels for all images.

Experimental data analysis shows that if the separation threshold is selected so that it provides detection of all objects, the false alarm probability will be 91.6%. If the threshold is selected so that the false alarm probability equals 0, then only 60% of all objects (three of five) are detected.

Examples of GPR images with only one clearly visible hyperbola in the binary image were analyzed as well. Here, if the threshold yields 100% detection probability then the false alarm probability will be 33.3%. This is less than in the previous example.

Thus, the possibility to detect subsurface objects in a GPR image automatically and to find their coordinates accurately has been shown using examples of simulated and experimental GPR images. The developed method based on the Hough transform allows this. It has been demonstrated that 100% object detection probability is achievable, and at the same time the false alarm probability is minimal. Nevertheless, it is necessary to optimize the criteria for choosing the optimal threshold for separating the Hough space peaks. This requires more complete statistical data and enough simulated and experimental GPR images.

4 Summary

Two ideas regarding an antenna system with high and frequency independent transmitting–receiving antennas decoupling, and the Hough transform for automatic detection of local objects in GPR images, were discussed. Improved GPR performance was shown.

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