Journal of Applied Geophysics 154 (2018) 108–115

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Significant improvement of detection of underground rectilinear objects based on anisotropy measurements

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ARTICLE INFO

Article history:
Received 13 September 2017
Received in revised form 28 April 2018
Accepted 1 May 2018
Available online 7 May 2018

Keywords:
GPR
Orthogonal scan
Soil anisotropy
Object reflectivity
Underground object
Horizontal resolution

ABSTRACT

Orthogonal scanning is a ground penetrating radar (GPR) method recently developed for underground inspection. Orthogonal scanning GPR is based on measuring the anisotropy of soil layers. When applied to detection of underground narrow rectilinear objects, this method allows for improving the signal-to-noise ratio (*SNR*) and selectivity of GPRs. (Noise refers to signals reflected from large voids, debris of construction materials, etc.).

In this work, we further develop the orthogonal scanning method and show that this method can increase the *SNR* also when the reflected signal is very small, and also significantly improve the horizontal resolution. We show that the *SNR* improving factor can reach several tens of dB. To improve selectivity we have developed a method of dual orthogonal scanning (the so-called differential method) which can significantly improve the selectivity in the horizontal plane. It is shown that for an object depth of 20 m, it is possible to achieve a selectivity of 0.55 m, which is much smaller than that of commercial GPR (5 m).

1. Introduction

Ground-penetrating radar (GPR) is a non-invasive geophysical technique widely used for monitoring underground structures and processes (Finkelshtein, 1994; Bristow & Jol, 2003; Jol 2009; Alfouzan et al., 2016). However, detection of underground rectilinear narrow objects by means of GPR in the presence of high noise levels is still a complicated technical challenge. The noise stems from unwanted signals reflected by various anomalies along the soil depth: voids, remnants of building materials, metal pieces, etc. Therefore, it is a cognitive noise (desired signal and undesired signals are at the frequency). The signals reflected from such anomalies can have a significant amplitude, sometimes exceeding the signal reflected from the object to be detected. In this case, the Signal-to-Noise Ratio (*SNR*) can drop to 1(0 dB) and even lower. Under such conditions GPRs using traditional progressive scanning are not effective. This problem is not considered in known classical works (Finkelshtein, 1994; Bristow & Jol, 2003; Jol, 2009; Alfouzan et al., 2016).

In (Cabrera, 2007), the resolution of commercial GPRs has been experimentally investigated. The empirical formulas derived in (Cabrera, 2007) show that the GPR resolution in the horizontal plane is significantly worse than that the vertical resolution. Among other methods, it seems that the orthogonal electromagnetic (EM) field (or orthogonal scan) methods (Lorenzi et al., 1970; Astafiev et al., 1973; Astafiev, 1974; Bilik, 1982; Bilik & Astafiev, 1983; Benoit Lepage, 2012; Rautio, 2009; Sugak et al., 2014) are most promising for improving the detectability of rectilinear objects in the presence of high noise levels (Lorenzi et al., 1970; Astafiev et al., 1973; Astafiev, 1974; Bilik, 1982; Bilik & Astafiev, 1983).

In (Bilik et al., 2017), the authors proposed a new method (the orthogonal scanning method) for improving the *SNR* and the selectivity of GPRs when used for detection of underground rectilinear narrow objects. In (Bilik et al., 2017), we addressed the problem of detecting underground rectilinear objects with a width of the order of 1.5–2 m (e.g. tunnel, pipe) and a length of 100 m, in the presence of a large number of small (short) reflectors randomly distributed in the soil layers surrounding the object. In this approach, an object of the expected shape (rectilinear), in the presence randomly distributed unwanted signals (background noise), is recognized according to the pattern recognition theory (Fomin, 2012). The operating wavelength in the soil must be smaller than the minimal expected width of the object and the dimensions of the interfering elements in order to avoid diffraction, and Fresnel losses. In general, when the expected object has a simple rectilinear shape, it can be recognized by either of the two following ways:

1. Using an antenna whose radiation pattern has an elongated cross-section, similar to the object shape. In this case, the signal reflected from the object will have the maximum possible amplitude and maximum SNR even at "point" sounding of the soil without scanning. We considered this method in (Bilik et al., 2017), using a "cruciform"

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https://doi.org/10.1016/j.jappgeo.2018.05.002
0926-9851/

diagram in the form of two orthogonal "fan" diagrams. However, it is possible to form such patterns of appropriate sizes only in the range of centimeter or decimeter waves.

2. Using a conventional conic GPR diagram with a special type of scanning, such as orthogonal scanning. In this case, the pattern detected along one of the axes (X or Y) can be similar to the shape of the object. This is a key feature of our method, used in both the previous (Bilik et al., 2017) and present works.

Another key feature of the proposed method is the range of SNR values determined by the extreme values of two sets of random numbers x_i, and y_i (representing the amplitudes of reflected signals, as defined in Section 2), obtained by scanning along the X, Y axes (Kleinberg, 1981). For a "clean" site, the upper and lower limits are presumably equal, that is, $x_{min} = y_{min}$ and $x_{max} = y_{max}$, just as the number of measurement points and the distances between them are equal.

It should be noted that although the signals measured along the X, Y axes in a "clean" area have identical probability distribution, the sums of the signals along these axes may differ to some extent. If a rectilinear object is laid along one of the axes, for instance the Y axis, the lowest amplitude of the reflected signal in that axis y_{min}, will be higher than the lowest random number along the X axis, that is, $y_{min} > x_{min}$.

The definition of the site anisotropy refers to the difference between sums of signals along the X and Y axes. Thus, the anisotropy measured under these conditions is a property of the spatial picture of the reflectivity of interfering elements and the object. Thus, using the proposed method, even when the highest signal amplitudes along the two axes are equal ($x_{max} = y_{max}$), the sum of the amplitudes of the reflected signals along the Y axis will be most probably greater than the sum along the X axis. Moreover, the difference between these sums, and hence the gain in SNR, increase with both y_{min} and N. This is a main novelty of the proposed method, confirmed by digital simulation with a random number generator (Bilik et al., 2017).

It should be especially emphasized that the SNR improvement can be obtained even when y_{max} is somewhat lower than x_{max} ($y_{max} < x_{max}$), corresponding to the most difficult case where the signal is completely "drowning" in the noise. Furthermore, as shown below, the proposed method does not require using antennas of different polarization for scanning along the X, Y axes, and satisfactory results can be achieved with antennas of identical polarization, especially when N is high. However, the power of this method can be further enhanced if antennas of different polarization are used, especially when the difference between the soil and the object permittivity is high.

In this paper, we wish to further investigate the ideas of (Bilik et al., 2017) and find the conditions for significant increase of both the SNR improvement factor and the resolution in horizontal plane, in order to allow for detection of several closely space rectilinear objects. For this purpose, the performance of the proposed method was studied for a wider interval of the GPR reflected signals. We have developed a method of dual orthogonal scanning (the differential method) which can essentially improve the horizontal resolution.

2. The proposed method

The proposed method is based on measuring the soil anisotropy in a horizontal plane at a certain depth.

Diffraction can be avoided if the wavelength in the soil λ_{medium} is smaller than the object width d:

$$\lambda_{medium} = \frac{\lambda_{vac}}{\sqrt{\varepsilon_r \mu_r}} \leq d, \tag{1}$$

where λ_{vac} is the wavelength in vacuum, and ε_r and μ_r (taken as 1) are the soil's relative permittivity and permeability (real parts), respectively. λ_{medium} and λ_{vac} correspond to the central frequency f_0 of the probing

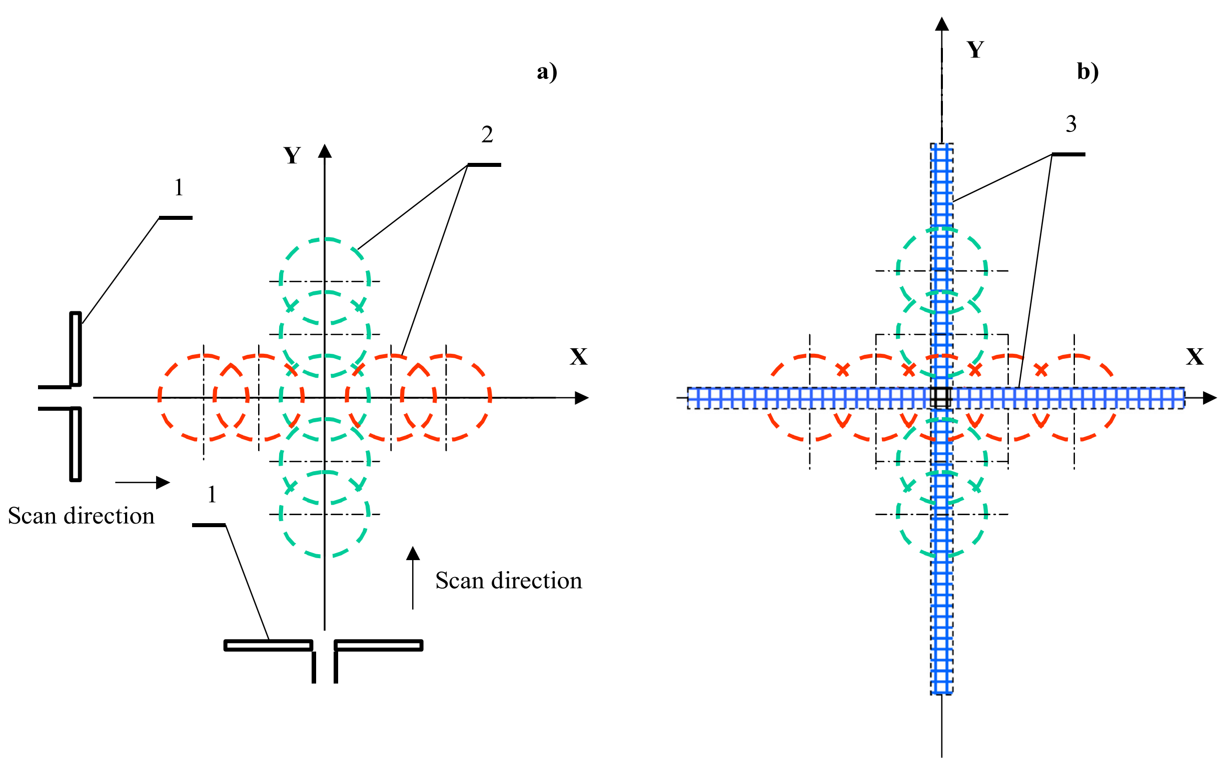

Fig. 1. The "orthogonal" scanning GPR method a) Initial anisotropy measurement on a site of clean soil. b) The best course of scanning upon detection of an underground rectilinear narrow object. 1 - GPR antenna, 2 – beam cross-section diagrams at the studied soil depth, 3 - search of an extended object (tunnel, pipe, etc.).