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Application of Freeman decomposition to full polarimetric GPR for improving subsurface target classification

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ABSTRACT

Migration technique can reconstruct the subsurface target imaging from record ground penetrating radar (GPR) data. Depending on the reconstructed imaging, we possibly distinguish subsurface target by the geometrical feature. But some different targets have similar reconstructed imaging, which will confuse us. Freeman decomposition is a technique for fitting a three-component scattering mechanism model to polarimetric synthetic aperture radar observations, which is successfully used in the classification of terrain objects. This paper applies the model-based Freeman decomposition to full polarimetric GPR data to improve the subsurface target classification. We use a full polarimetric GPR, which is constructed in laboratory with three types of antenna combinations, HH, VV and VH combinations, to acquire experiment data sets for testing the method. Metallic plate, ball, dihedral and volume scatter with many branches, are buried in the homogenous dry sand under flat ground surface, and three dimensional data sets are acquired above each buried target. After signal processing, we obtained subsurface target imaging by migration and color-coded polarimetric information by Freeman decomposition. Results showed that it can improve the classification capability of GPR for the subsurface target to use both the geometrical feature and polarimetric information.

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1. Introduction

Migration technique can reconstruct the target imaging from the record data [1,2], has been well developed in seismic data processing. A number of different migration methodologies, for example, reverse time migration [3–5], F-K migration [6], and Kirchhoff migration [7–9], have been applied successfully to a range of different ground penetrating radar (GPR) applications. Depending on the geometrical features of the subsurface reconstructed target imaging, we can possibly distinguish subsurface targets. But it is not always easy to identify the subsurface targets using only the imaging, because different targets may have similar imaging.

GPR data are commonly acquired using a perpendicular broadside antenna configuration, which transmitter and receiver antennas are oriented parallel to each other and perpendicular to the direction of survey line. As most GPR systems employ linearly polarized dipole antennas, the transmitting antenna emits an electromagnetic (EM) wavefield whose electric field is polarized parallel to the long axis of the dipole, and the receiving antenna records only the component parallel to its long axis [10]. However, it has been noted that various targets of GPR surveys, such as buried pipes and fractures, have polarization-dependent scattering characteristics [11,12]. As a consequence, polarization-dependent scattering properties have important implications for target detection, survey design, and data interpretation [10].

Polarimetric technology has been one of the most important advances in microwave remote sensing during recent decades [13,14]. Currently, polarimetric technology is being introduced into GPR to improve the detection capability. A full-polarimetric borehole radar system has been developed with combinations of dipole antennas and axial slot antennas. Because dipole antenna radiates vertical (V) electric field, and axial slot antenna radiates horizontal (H) electrical field, the system can acquire fully polarimetric data sets, which are used to analysis the subsurface fracture characterization, in drilled borehole [15,16]. A commercial pulse EKKO 100 GPR system with two independent dipole

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antennas has been used to perform a multipolarization acquisition surveying to detect the location and azimuth of vertically oriented fractures [11], and three different antenna configuration, VV copolarized, HH copolarized, and VH crosspolarized dipole antenna configurations, have been used to collect full-polarimetric reflection data for characterizing fractured rock [12]. A broadband full-polarimetric GPR system with a horn-feb bowtie (HFB) antenna has been developed for unexploded ordnance (UXO) classification [17]. Another broadband full-polarimetric GPR system with Vivaldi antennas has been developed for improving subsurface imaging and targets classification [18–20].

Polarimetric decomposition methods are a type of polarimetric analysis methods, which can extract polarization characteristics, that have been common in the terrain and land-use classification based on polarimetric synthetic aperture radar (SAR) data [21]. Currently, polarimetric analysis is being applied to polarimetric GPR for extracting subsurface targets properties, which offers a new means of discriminating subsurface target shapes from one another, for example, distinguishing subsurface UXO from other subsurface objects by backscatter characteristics [22], detecting vertical fracture by exploiting the polarization properties [11], and reconstructing subsurface high quality color-coded target image by merging the polarimetric decomposition and migration firstly [18,19].

Freeman decomposition is a type of polarimetric analysis technique, which has the advantage that it is technique for fitting a physically based, three-component scattering mechanism, not a purely mathematical construct [21,23]. The three-component scattering mechanisms are a surface-like scatter from a slightly rough surface, for example, a top surface of a big pipe, a double-bounce scatter from a pair of orthogonal surfaces, for example, one side wall and floor of tunnel, and a volume scatter from a set of randomly oriented scatter. The Freeman decomposition has been applied into a full-polarimetric borehole radar with combination of dipole and axial slot antennas to achieve polarization attributes, which help to interpret the subsurface fractures [24].

In this study, we apply the Freeman decomposition to a full-polarimetric GPR. Four easy metal targets buried in an ideal dry sand medium are chosen to test the potential of polarimetric target decomposition technique. Based on the geometrical and physical properties of these subsurface targets and the physical properties of its surrounding material, strong polarization phenomena will occur. Section 2 will introduce the methodology. Section 3 will apply the method to the experiment data sets acquired by a full polarimetric GPR. Discussion and conclusion will be given in Section 4.

2. Methodology

2.1. Full polarimetric GPR data

Here, we assume that detection area is in 'far field', and polarization is defined as the orientation of the electric field vector in the plane perpendicular to the wave propagation direction. A GPR antenna can be designed to transmit and receive electromagnetic waves with a well-defined polarization. Generally vertical (V) polarization and horizontal (H) polarization are defined to describe the orientation of the electric field vector orthogonal and parallel to the direction from transmit antenna to receive antenna, respectively, shown in Fig. 1. A typical commercial GPR is a type of single polarimetric GPR that would transmit vertically polarized waveforms and receive the same(acquiring VV data). A full polarimetric GPR would alternate between transmitting H-and V-polarized waveforms and receives both H-and V-polarized signals, and consequently acquires VV, HH, VH and HV data. Because the role of the transmit antenna and receive antenna can be interchanged in GPR system, VH data is equal to HV data. Therefore, along a survey line, the full polarimetric GPR can acquire a set of data,

$$\left\{\boldsymbol{D}(\boldsymbol{x},\omega)\right\}=\left\{\boldsymbol{S_{HH}}(\boldsymbol{x},\omega),\boldsymbol{S_{VV}}(\boldsymbol{x},\omega),\boldsymbol{S_{VH}}(\boldsymbol{x},\omega)\right\} \tag{1}$$

where $\boldsymbol{x}$ is the position of survey point, and ω is angular frequency. The members of the set are three matrices,

$$\boldsymbol{S_{HH}}(\boldsymbol{x},\omega)=\left[S_{HH}(\boldsymbol{x},\omega)\right]=\begin{bmatrix} S_{HH}(\boldsymbol{x}_1,\omega_1) & \cdots & S_{HH}(\boldsymbol{x}_n,\omega_1)\\ \vdots & \ddots & \vdots\\ S_{HH}(\boldsymbol{x}_1,\omega_m) & \cdots & S_{HH}(\boldsymbol{x}_n,\omega_m)\end{bmatrix}$$

$$\boldsymbol{S_{VV}}(\boldsymbol{x},\omega)=\left[S_{VV}(\boldsymbol{x},\omega)\right]=\begin{bmatrix} S_{VV}(\boldsymbol{x}_1,\omega_1) & \cdots & S_{VV}(\boldsymbol{x}_n,\omega_1)\\ \vdots & \ddots & \vdots\\ S_{VV}(\boldsymbol{x}_1,\omega_m) & \cdots & S_{VV}(\boldsymbol{x}_n,\omega_m)\end{bmatrix}, \tag{2}$$

and

$$\boldsymbol{S_{VH}}(\boldsymbol{x},\omega)=\left[S_{VH}(\boldsymbol{x},\omega)\right]=\begin{bmatrix} S_{VH}(\boldsymbol{x}_1,\omega_1) & \cdots & S_{VH}(\boldsymbol{x}_n,\omega_1)\\ \vdots & \ddots & \vdots\\ S_{VH}(\boldsymbol{x}_1,\omega_m) & \cdots & S_{VH}(\boldsymbol{x}_n,\omega_m)\end{bmatrix}.$$

where n is the number of survey point, and m is the number of frequency point. $S_{VV}(\boldsymbol{x},\omega)$is a typical 2-D VV data acquired by a common stepped frequency GPR system. $S_{HH}(\boldsymbol{x},\omega)$ and $S_{VH}(\boldsymbol{x},\omega)$ are HH and VH data, respectively. Using these data, we can build a classical coherent Sinclair matrix [21] at each measurement point,

$$\boldsymbol{S}(\boldsymbol{x_i},\omega_j)=\begin{bmatrix} S_{HH}(\boldsymbol{x}_i,\omega_j) & S_{VH}(\boldsymbol{x}_i,\omega_j)\\ S_{VH}(\boldsymbol{x}_i,\omega_j) & S_{VV}(\boldsymbol{x}_i,\omega_j)\end{bmatrix},\ i=1,\ldots,n;j=1,\ldots,m. \tag{3}$$

Consequently, GPR data are also a set of coherent matrices,

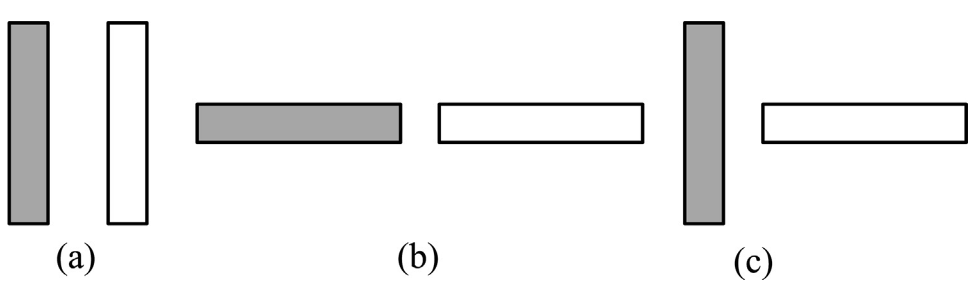

Fig. 1. Antenna configurations used in a full-polarimetric GPR system. (a) VV copolarized. (b) HH copolarized. (c) VH crosspolarized. The gray block represents the transmitting antenna, and the white represents the receiving antenna.

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