Calibration of Interface Induced Polarization for Full Polarimetric Ground Penetrating Radar

Zejun Dong\textsuperscript{1,3}, Xuan Feng\textsuperscript{1,2,3,4,*}, Cai Liu\textsuperscript{1,4}, Wenjing Liang\textsuperscript{1,3}, Haoqiu Zhou\textsuperscript{1,3}

\textsuperscript{1} College of Geo-Exploration Science and Technology, Jilin University, No.938 Xi MinZhu Street, Changchun, China
\textsuperscript{2} Institute of National Development and Security Studies, Jilin University, No.2699 Qianjin Street, Changchun, China
\textsuperscript{3} Science and Technology on Near-Surface Detection Laboratory, Wuxi, China
\textsuperscript{4} Key Laboratory of Geophysical Exploration Equipment, Ministry of Education (Jilin University), No.938 Xi MinZhu Street, Changchun, China

* E-mail: fengxuan@jlu.edu.cn.

Abstract. The traditional ground penetrating radar (GPR) uses only one type of antenna for data acquisition, and only obtains single polarization data of targets. It cannot fully describe the various properties of the target. Full polarimetric GPR is a new technology that uses four different polarization antennas to measure the target and can receive electromagnetic waves of different polarized directions to describe the polarization effect of targets. However, when the plane electromagnetic wave propagates through the ground surface, the polarization direction will rotate, namely interface induced polarization (IIP), which results in the complex interference embedded in the full polarimetric GPR data. In this research, firstly we discuss the generation of the IIP; subsequently how the IIP affect the full polarimetric GPR data is derived; finally the calibration formula is proposed and is applied to the GPR data processing.

1. Introduction

Ground penetrating radar (GPR) is a geophysical method that uses antennas to transmit and receive high-frequency electromagnetic waves to detect the characteristics and distribution of substances in a medium \cite{8,9}. However, for a long time, the utilization of the information acquired from GPR are mostly limited to the amplitude, phase and frequency characteristics \cite{5,2}. The polarization information contained in target scattering wave is not fully used. In recent years, the polarimetric GPR, including polarimetric borehole radar \cite{10,7}, has been developed, and polarization signal analysis has been applied to identify subsurface fractures \cite{14,13}, pipes \cite{1}, and unexploded ordnance \cite{3,11,12}.

The polarization data contains many information of the targets \cite{6,4}, but there are many factors that can cause the distortion of polarization mode. When the plane electromagnetic wave propagate through the ground surface and the soil, the received signal contains not only the information from subsurface targets, but also the information from the ground surface and the soil. In order to obtain more accurate scattering information of the subsurface targets, we have to reduce or eliminate the effects of the surface, namely interface induced polarization (IIP). In this paper, we discuss the reason why the polarization direction of the electromagnetic wave rotate when the wave propagate through the media interface. Subsequently, the effects of IIP are presented in mathematical form, which leads to the calibration formula. Finally, the calibration formula is applied to the GPR data processing.
2. **The Reflection and Transmission of Plane Wave**

When a plane electromagnetic wave is obliquely incident on a plane dielectric interface \((z = 0)\), the reflected wave and the transmitted wave will generate as shown in figure 1:

![Figure 1. Surface reflection and transmission](image)

We define an incident plane formed by the propagating direction of the incident wave and the normal vector of the interface. An obliquely incident plane electromagnetic wave, no matter what kind of polarization modes it is, can be decomposed into two orthogonal linearly polarized waves: one is vertical to the incident plane, known as vertically polarized wave; the other is parallel with the incident plane, called horizontal polarized wave, as shown in equation (1):

\[
E = E_{\perp} + E_{\parallel}
\]  

(1)

Where \(E\) represents the incident plane electromagnetic wave, \(E_{\perp}\) represents vertically polarized wave, and \(E_{\parallel}\) represents horizontal polarized wave.

Therefore, as long as the reflected waves and the transmitted waves of the two components are obtained respectively, the reflected wave and the transmitted wave of the obliquely incident wave can be obtained by recomposition, regardless of the orientation of the electromagnetic field intensity vector.

![Figure 2. Surface reflection and transmission of vertically and horizontal polarized wave.](image)

We start by defining the values of the field components at the interface \((z = 0)\) by subscripts ‘\(r\)’ for reflected, ‘\(i\)’ for incident, and ‘\(t\)’ for transmitted. The reflection coefficient and the transmission coefficient of vertically polarized wave can be represented using Snell’s law:

\[
\Gamma_{\perp} = \frac{E_{r\perp}}{E_{i\perp}} = \frac{\eta_2 \cos \theta_i - \eta_1 \cos \theta_i}{\eta_2 \cos \theta_i + \eta_1 \cos \theta_i}
\]  

(2)

\[
T_{\perp} = \frac{E_{t\perp}}{E_{i\perp}} = \frac{2 \eta_2 \cos \theta_i}{\eta_2 \cos \theta_i + \eta_1 \cos \theta_i}
\]  

(3)
Similarly, for the horizontal polarized wave, when the E field is polarized in the plane of incidence, the reflection coefficient and the transmission coefficient is shown as follows:

\[
\Gamma_{||} = \frac{E_{r||}}{E_{i||}} = \frac{\eta_1 \cos \theta_t - \eta_2 \cos \theta_i}{\eta_1 \cos \theta_t + \eta_2 \cos \theta_i} \tag{4}
\]

\[
T_{||} = \frac{E_{t||}}{E_{i||}} = \frac{2\eta_2 \cos \theta_t}{\eta_1 \cos \theta_t + \eta_2 \cos \theta_i} \tag{5}
\]

In conclusion, the obliquely incident plane electromagnetic wave can be decomposed into vertically polarized wave and horizontal polarized wave. As the reflection coefficient of these two kinds of waves are different, the polarization direction rotates when we use the reflected waves of vertically polarized wave and horizontal polarized wave to recompose the virtual reflected wave.

3. **Interface induced polarization**

For full polarimetric GPR, the Sinclair matrix S is used to represent the scattering of electromagnetic wave.

\[
S = \begin{bmatrix}
S_{HH} & S_{HV} \\
S_{VH} & S_{VV}
\end{bmatrix}
\tag{6}
\]

\(S_{VV}, S_{HH}, S_{VH}, \) and \(S_{HV}\) are the data obtained by using the four types of antennas in figure 3, respectively.

**Figure 3.** Four types of antenna combinations

Considering the model in figure 4. The electromagnetic wave propagates through the interface between medium 1 and 2 twice before and after being scattered by the targets.

**Figure 4.** Electromagnetic wave propagation model.

Subsequently, the final data obtain with Y polarized transmitting antenna and X polarized receiving antenna can be represented by the formula below:
where \( E_r = [E_{rH}, E_{rV}]^T \), \( E_t = [E_{tH}, E_{tV}]^T \) represent the types of antenna combinations shown in figure 3. TH1 and TV1 are the transmission coefficient of two types of waves when the waves propagate from medium 1 to medium 2. TH2 and TV2 are the transmission coefficient of two types of waves when the waves propagate from medium 2 to medium 1. In fact, the matrix \( T_1 \) and \( T_2 \) represents the Sinclair matrix of the interface. The four components of the measuring Sinclair matrix can be computed:

\[
\begin{bmatrix}
S_{1H1} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} T_{H2} & 0 \\ 0 & T_{V2} \end{bmatrix} \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \begin{bmatrix} T_{H1} & 0 \\ 0 & T_{V1} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = T_{H1}T_{H2}S_{HH} \\
S_{1HV} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} T_{H2} & 0 \\ 0 & T_{V2} \end{bmatrix} \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \begin{bmatrix} T_{H1} & 0 \\ 0 & T_{V1} \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = T_{H1}T_{V2}S_{HV} \\
S_{2VH} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} T_{H2} & 0 \\ 0 & T_{V2} \end{bmatrix} \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \begin{bmatrix} T_{H1} & 0 \\ 0 & T_{V1} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = T_{V1}T_{V2}S_{VV} \\
S_{2V2} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} T_{H2} & 0 \\ 0 & T_{V2} \end{bmatrix} \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \begin{bmatrix} T_{H1} & 0 \\ 0 & T_{V1} \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = T_{V1}T_{V2}S_{VV}
\end{bmatrix}
\]

Subsequently, the scattering matrix effected by the interface is derived:

\[
\hat{S} = \begin{bmatrix}
\hat{S}_{1HH} & \hat{S}_{1HV} \\
\hat{S}_{2VH} & \hat{S}_{2V2}
\end{bmatrix} = \begin{bmatrix}
T_{H1}T_{H2}S_{HH} & T_{V1}T_{H2}S_{HV} \\
T_{H1}T_{V2}S_{VH} & T_{V1}T_{V2}S_{VV}
\end{bmatrix}
\]

Based on formula (9), we can easily derived the IIP calibration formula:

\[
S = \begin{bmatrix}
S_{1HH} & S_{1HV} \\
S_{2VH} & S_{2V2}
\end{bmatrix} = \frac{\hat{S}_{1HH}}{T_{H1}T_{H2}} \frac{\hat{S}_{1HV}}{T_{V1}T_{H2}} = \begin{bmatrix}
\hat{S}_{1HH} & \hat{S}_{1HV} \\
\hat{S}_{2VH} & \hat{S}_{2V2}
\end{bmatrix}
\]

4. Calibration of typical targets

In order to verify the calibration formula, we measured polarimetric data of two typical targets in laboratory (Figure 5), the measuring line was right on the targets, the measuring points was 101, the distance of every two points was 1 cm, the frequency was from 800MHz to 4000MHz, the sampling points was 1024. The two typical targets are metallic plane and 45° metallic dihedral. The theoretical Sinclair matrix of these two targets are shown in formula 11 and 12.

\[
S_{\text{plane}} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}
\]

\[
S_{45^\circ\text{dihedral}} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}
\]
In the measurement, a vector network analyzer and a Cartesian coordinate robot (Figure 6) with different antenna combinations (Figure 7) were used for data collection, the interval between feeding points of transmitting and receiving antennas is 8 cm for all three polarimetric modes with the same axis direction. The data of the plane and 45° dihedral are shown in Figure 8-9, respectively.

Figure 5. Four types of targets in the dry sand trough. (a) metallic plane. (b) 45° metallic dihedral.

In the measurement, a vector network analyzer and a Cartesian coordinate robot (Figure 6) with different antenna combinations (Figure 7) were used for data collection, the interval between feeding points of transmitting and receiving antennas is 8 cm for all three polarimetric modes with the same axis direction. The data of the plane and 45° dihedral are shown in Figure 8-9, respectively.

Figure 6. Full polarimetric GPR measurement system.

Figure 7. Three types of antenna combinations. (a) HH polarization. (b) HV polarization. (c) VV polarization.

Subsequently, we calculate the Incident angle $\theta_i$ and transmission angle $\theta_t$ based on figure 10. The results are shown in table 2. Subsequently, the transmission coefficients can be derived, which are shown in table 2 as well. Finally the transmission coefficients are applied to formula (10) for the calibration. The average Sinclair matrix comparisons between the matrix before and after calibration are shown in table 3.
Figure 8. Full polarimetric GPR data of plane. (a) HH polarization; (b) HV polarization; (c) VV polarization.

Figure 9. Full polarimetric GPR data of 45° dihedral. (a) HH polarization (b) HV polarization (c) VV polarization.

Figure 10. Incident angle and transmission angle calculation. (a) Plane; (b) 45° dihedral.

Table 2. Transmission coefficients

| Target   | Incident angle(°) | Transmission angle(°) | TH1    | TH2    | TV1    | TV2    |
|----------|-------------------|-----------------------|--------|--------|--------|--------|
| Plane    | 11.97             | 7.69                  | 0.7806 | 1.2250 | 0.7784 | 1.2216 |
| 45° dihedral | 10.94             | 7.04                  | 0.7812 | 1.2234 | 0.7794 | 1.2206 |

From table 3, we can find that for both plane and 45° dihedral, the calibrated matrix are closer to the theoretical matrix; this means our proposed calibration method can suppress the interface induced polarization to some extent. However, the calibration results are not perfect. The reasons contain the interface undulations and roughness as well as the effect of the soil. Thus, we need to take the rough interface and soil influence into account in the future.
Table 3. Average Sinclair matrix comparisons between the the matrix before and after calibration

| Target  | Theoretical Sinclair matrix | Average measured Sinclair matrix | Average calibrated Sinclair matrix |
|---------|-----------------------------|----------------------------------|-----------------------------------|
| Plane   | $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ | $\begin{bmatrix} 1 & -0.0230 \\ -0.0230 & 0.9849 \end{bmatrix}$ | $\begin{bmatrix} 1 & -0.0231 \\ -0.0231 & 0.9882 \end{bmatrix}$ |
| 45° dihedral | $\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$ | $\begin{bmatrix} 0.0162 & 1 \\ 1 & 0.0016 \end{bmatrix}$ | $\begin{bmatrix} 0.0161 & 1 \\ 1 & 0.0016 \end{bmatrix}$ |

5. Conclusions

In this research, we analyze generation of the interface induced polarization (IIP) for full polarimetric ground penetrating radar (GPR). The polarization direction of electromagnetic wave will rotated when it propagates through an interface because of the different transmission coefficients of vertically polarized wave and horizontally polarized wave. Subsequently, how the IIP affects the full polarimetric GPR data is derived in mathematical form. Finally the calibration formula is proposed. We applied the calibration method to the full polarimetric data of plane and 45° dihedral obtained in laboratory. The calibration results show that the calibrated matrix is closer to the theoretical matrix; this means our proposed calibration method can suppress the interface induced polarization to some extent. However, the calibration results are not perfect. The reasons contain the interface undulations and roughness as well as the effect of the soil. Thus, we need to take the rough interface and soil influence into account in the future.

References

[1] Boniger U and Tronicke J 2012 Subsurface utility extraction and characterization: Combining GPR symmetry and polarization attributes IEEE Transactions on Geoscience and Remote Sensing 50 736–746
[2] Cao B, Gruber S, Zhang T, Li L, Peng X and K Wang, et al 2017 Spatial variability of active layer thickness detected by ground-penetrating radar in the Qilian Mountains Western China Journal of Geophysical Research Earth Surface 122 574-591
[3] Chen C 2001 Fully-polarimetric ground penetrating radar application IEEE Antennas and Propagation Society International Symposium 4 604-607
[4] Chen C, Higgins M B, Neill K O and Detsch R 2001 Ultrawide-bandwidth fully-polarimetric ground penetrating radar classification of subsurface unexploded ordnance IEEE Transactions on Geoscience and Remote Sensing 39 1221–1230
[5] De Pascale G P, Pollard W H and Williams K K 2008 Geophysical mapping of ground ice using a combination of capacitive coupled resistivity and ground-penetrating radar, Northwest Territories, Canada Journal of Geophysical Research Atmospheres 113 F02S90
[6] Feng X, Yu Y, Liu C and Fehler M 2015 Combination of H-Alpha Decomposition and Migration for Enhancing Subsurface Target Classification of GPR IEEE Transactions on Geoscience and Remote Sensing 53 4852-4861
[7] Feng X, Zou L, Lu Q, Liu C, Liang W and Zhou Z 2012 Calibration with high-order terms of polarimetric GPR IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 5 717-722
[8] Feng X, Zou L, Liu C, Lu Q, Liang W and Li L, et al 2011 Forward modeling for full-polarimetric ground penetrating radar Chinese Journal of Geophysics 54 349-357
[9] Kao C, Li J, Wang Y and Liu C 2007 Measurement of Layer Thickness and Permittivity Using a New Multilayer Model From GPR Data IEEE Transactions on Geoscience and Remote Sensing 45 1761-1768
Sensing 45 2463-2470
[10] Miwa T, Sato M and Niitsuma H 1999 Subsurface fracture measurement with polarimetric borehole radar IEEE Transactions on Geoscience and Remote Sensing 37 828–837
[11] Neill K O 2001 Discrimination of UXO in soil using broadband polarimetric GPR backscatter IEEE Transactions on Geoscience and Remote Sensing 39 356–367
[12] Roth F, Genderen P V and Verhaegen M 2003 Processing and analysis of polarimetric ground penetrating radar landmine signatures
[13] Sassen D S and Everett M E 2009 3D polarimetric GPR coherency attributes and full-waveform inversion of transmission data for characterizing fractured rock Geophysics 74 J23
[14] Zhao J and Sato M 2006 Radar polarimetry analysis applied to single-hole fully polarimetric borehole radar IEEE Transactions on Geoscience and Remote Sensing 44 3547-3554.