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# Research on Treatment of Transient Response for Buried Target in Large Forest

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***Abstract:***

Buried forests have complex meteorological conditions and carbon storage functions. Deep analysis on time transient backscatter response is beneficial to obtain the target feature information. In this paper, the theoretical deduction shows that the energy of surface reflection at different polarization are equal in GPR early-time response stage. Utilizing the relationship of maximum singular value and transient response, the suddenly drops of maximum singular value time is the start of the late-time response stage. With the numerically simulated backscattered response of the slender cylinder buried dry sand environment, the results prove that this processing method can separate the late-time response effectively.

***Keywords**: Large forest, Ground Penetrating Radar;the early-time response;the late-time response;polarization;singular value*

## I. INTRODUCTION

Ground penetrating radar (GPR) is an effective method to detect underground targets by using the discontinuity of underground media. Because of its wide detection range, continuous detection process, convenient operation process, non-destructive and other characteristics, it is widely used in highway and railway, bridge and tunnel, national defense and public security, archaeological investigation and so on [1] .GPR uses Gaussian narrow width pulse signal as incident signal to irradiate the target, and obtains the transient response of the target by receiving backscattering signal.

According to the theory of singularity expansion method (SEM), the time-domain transient response of the target can be divided into two parts: early-time response and late-time response [2]. The early-time response is the response signal generated when the incident wave arrives at the target and starts to interact with the target until the incident signal completely interacts with the target, including the optical scattering from different scattering centers and the modulation

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signal generated by bypassing the target. The late-time response is the signal that the target retains the induced current generated by the incident signal and radiates outward after the incident signal completely passes through the target. Among them, the induced current is related to the natural resonance frequency of the target and can be expressed as the superposition of a series of damped oscillation curves [3]. Research on the treatment of target transient response can effectively analyze the target information contained in early-time response and late-time response.

Many scholars have studied the processing methods of the transient early-time response and late-time response. L.B.Felsen et al. [4] take the cylinder as an example, theoretically elaborated the composition of the transient response, the early-time response in the form of diffraction wave and the late-time response in the form of resonance state, which is very meaningful. On this basis, P. Ilavarasan et al. [5] specifically explained the start of late-time response, which is based on the prior knowledge of the target, but it is not realistic in practical application. In reference [6], the impulse response of half space dielectric target is modeled by time-domain deconvolution, and the late-time response extraction method including the special information of the target is analyzed. In reference [7], the method of moment is used to calculate the frequency domain scattering data of the target. After the inverse Fourier transform and the corresponding signal processing means, the target late- time response data of multiple directions are obtained. In reference [8] ,it estimates a group of poles corresponding to the late-time response in each time window by setting a continuous time window, and uses the convergence of the poles to deduce the boundary point between the early-time response and the late-time response of a cylinder in free space. There is no reasonable explanation for the selection of the starting point, the size of the window and the determination of the step size in the calculation process. With the rapid development of electromagnetic field, the application of polarization is very common [9-10]. In reference [11], by measuring the early and late polarization characteristics of the target and using polarization difference to suppress the early-time response, the early-time response suppression performance can be optimized, but it is required that the late polarization characteristics should be significantly different from the early polarization characteristics. In reference [12], the early-time response and late-time response of a slender cylinder are successfully separated by using different polarization information. The method is simple, but it is only limited to free space.

For the target in the medium environment, there are few researches on the treament of early-time response and late-time response. In this paper, a method is proposed to deal with the time-domain transient response of shallow buried target based on the equal energy of surface reflection wave in early-time response under different polarizations. Based on the relationship between the maximum singular value of Hankel matrix and the transient response, the time

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when the maximum singular value suddenly drops is determined as the start of the late-time response. The method is simple and efficient, which can effectively determine the position of the target and accurately separate the late-time response. It is helpful to realize the purpose of medium characteristics inversion and target orientation recognition.

## II. THEORETICAL ANALYSIS OF EARLY-TIME RESPONSE AND LATE-TIME RESPONSE

2.1 Polarization analysis of early-time response

GPR transmit high-frequency electromagnetic wave to underground using the transmitting antenna. In the process of electromagnetic wave propagation in underground media, when it meets the target with different electrical properties, it will reflect and refract. The receiving antenna receives the backscattered signal to obtain the time-domain transient response of the target. The system model is shown in Figure 1, including radar transceiver antenna, lossy medium and target (slender cylinder).

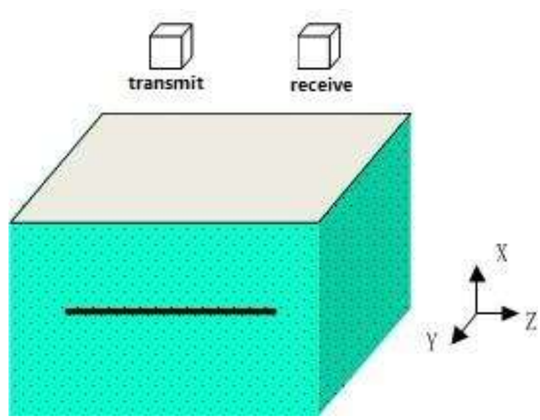


Fig 1: The model of GPR

According to the direction of the electric field intensity in the electromagnetic wave emitted by the transmitting antenna, the electromagnetic wave can be divided into different polarization modes. In spherical coordinates, when the direction of electric field is the same as that of pitch angle theta, it is called theta polarization; when the direction of electric field is the same as that of azimuth angle phi, it is called phi polarization. In two cases, the time domain transient response of the target can be expressed as:

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$$\vec{E}^{bs}(t) = \vec{E}_{po}^{bs}(t)\left[u(t) - u(t - t_L)\right] + \sum_n \vec{E}_n^{bs} e^{s_n t} u(t - t_L) \tag{1}$$

Among them, the first term represents the early-time response, $\vec{E}_{po}^{bs}(t)$ is composed of the initial scattering component and physical optical scattering of the target, concentrating most of the energy and high frequency part of the transient response; the second term represents the late-time response, which is the superposition of a series of damped oscillation curves. $s_n = \sigma_n + j2\pi f_n$ represents the natural resonance frequency of the target, $\sigma_n$ is the attenuation factor, $f_n$ is the resonance frequency. $u(t)$ is a step function and $t_L$ is the theoretical dividing point between early-time response and late-time response.

The rectangular coordinate system as shown in the figure 1,suppose that the transmitting antenna is perpendicular to the target and the incident wave is Gaussian pulse of unit amplitude.In theta polarization, the direction of electric field is along - Z direction and the direction of magnetic field is along - Y direction; in phi polarization, the direction of electric field is along Y direction and the direction of magnetic field is along - Z direction.

$$\vec{E}_\theta = \vec{e}_\theta E_\theta = -\vec{e}_z E_\theta \tag{2}$$

$$\vec{E}_\varphi = \vec{e}_\varphi E_\varphi = \vec{e}_y E_\varphi \tag{3}$$

Poynting vector is also called energy density vector which direction represents the direction of energy flow and modulus represents the energy passing through the unit area perpendicular to the direction of energy flow in unit time. Because the backscattered signal is received in the far field, the average Poynting vectors of the surface reflected wave in the early-time response of the target under theta polarization and phi polarization are as follows:

$$\begin{aligned}\vec{S}_\theta &= \frac{1}{2}\mathrm{Re}(\vec{E} \times \vec{H}^*) = \frac{1}{2}\mathrm{Re}(-\vec{e}_z \Gamma E_\theta \times \vec{e}_y H_\theta^*) \\ &= \frac{1}{2}\mathrm{Re}(-\vec{e}_z \Gamma E_\theta \times \vec{e}_y \frac{\Gamma E_\theta^*}{\eta}) = \vec{e}_x \frac{\Gamma^2}{2\eta}\left|E_\theta\right|^2\end{aligned} \tag{4}$$

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$$\vec{S}_{\varphi}=\frac{1}{2}\mathrm{Re}(\vec{E}\times\vec{H}^{*})=\frac{1}{2}\mathrm{Re}(\vec{e}_{y}\Gamma E_{\varphi}\times\vec{e}_{z}H_{\varphi}^{*})$$
$$=\frac{1}{2}\mathrm{Re}(\vec{e}_{y}\Gamma E_{\varphi}\times\vec{e}_{z}\frac{\Gamma E_{\varphi}^{*}}{\eta})=\vec{e}_{x}\frac{\Gamma^{2}}{2\eta}\left|E_{\varphi}\right|^{2} \quad (5)$$

Where, $\Gamma$ is the ratio of the amplitude of electric field of reflected wave to that of incident wave,which is called reflection coefficient. $\eta$ is the wave impedance.

It can be seen from equations (2) and (3), $\left|E_{\theta}\right|=\left|E_{\varphi}\right|$ .Therefore, the energy of the surface reflected wave in the early-time response process is the same under the two polarization modes.

2.2 Convergence analysis of late-time response

Equation (1) is expressed in Laplace transform domain as:

$$\vec{E}^{bs}(s)=\vec{E}_{po}^{bs}(s)e^{-st_{L}}+e^{-st_{L}}\sum_{n}\frac{\vec{E}_{n}^{bs}}{s-s_{n}}e^{s_{n}t_{L}} \quad (6)$$

In the formula,the Laplace transform of the early-time response is an entire function, and the Laplace transform of the late-time response is a series expansion of the poles. The distribution of poles only depends on the shape, size, target attribute of the scatterer, but has nothing to do with the size of incident wave and scattering direction, that is to say, the change of target attitude will not affect the distribution characteristics of poles.

In the time-domain echo model based on SEM theory, in order to more accurately estimate the start of the late-time response, we must select a time point as far ahead as possible in the time dimension. On the basis of equal energy of reflected wave of early-time response, the starting point of windowing is determined, and the time window of transient response data after the starting point is sampled. The Hankel matrix is constructed according to the windowed data, and the singular value of each matrix is calculated. The maximum singular value under each window is selected for comparison, and the time point when the maximum singular value suddenly drops is determined as the start of the late-time response.

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According to the definition of the early-time and late-time response, for a single target in free space, the early-time and late-time response in time domain have definite demarcation points, while in the the medium environment,the early-time and late-time response will be overlapped in time domain. Due to the different position of the target and the medium environment, when the external medium is still in the stage of reflection, refraction and diffraction, the late-time response of the shallow buried target has begun.Therefore, the time-domain transient response of the system model shown in Figure 1 can be divided into three stages according to the time sequence: early-time response stage; early-time and late-time mixing stage; late-time response stage. Based on the fact that the reflected wave energy of the early response surface is equal under theta polarization and phi polarization, the end time of the early-time response surface can be determined, and the position information of the target can also be determined,the start of the late-time response can be determined by using the pole convergence.

## III. SIMULATION RESULT

According to the system model shown in Figure 1, the electromagnetic simulation software XFDTD based on FDTD algorithm is used for modeling and simulation analysis. In the simulation, incident wave is ultra wideband Gaussian pulse with half width of 1ns and bandwidth of 1GHz.Assuming that the medium environment is dry sand, the length a, width b and height c are 800mm, 800mm and 400mm respectively, the relative permittivity is 4, and the conductivity is 0.001s/m. Taking the slender cylinder with high conductivity as an example, the buried depth h is 50 mm, the length L is 700 mm, and the radius R is 5 mm, which ensures that the R/L is small enough to produce the obvious late-time response. The time domain transient responses of the model under theta polarization and phi polarization are shown in Figure 2 and Figure 3 when the incident direction is along -X direction

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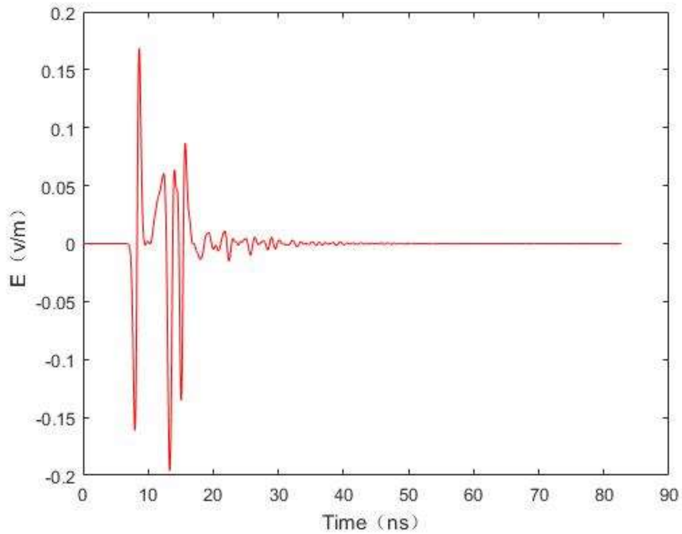


Fig 2: The transient response in Phi

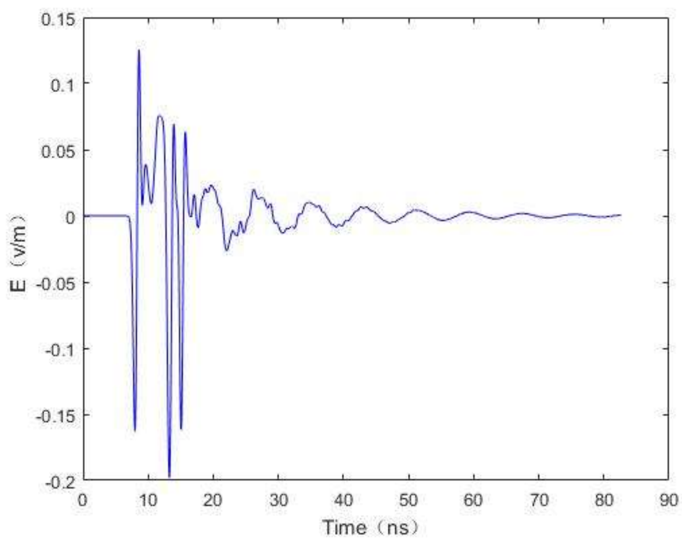


Fig 3: The transient response in Theta

It can be seen from Figure 2 and Figure 3 that the time of surface reflection wave under the two polarizations is about 8.61ns.The time domain transient response is very different after 9.18ns in theta and phi polarization cases, which can be used to determine the location of the target.As time goes on, the incident wave reflects through the medium environment (at 13.27ns) and diffracts along the surface (at 18.29ns), and the transient response under both polarizations appears pulse like waveform. It is assumed that in the system model, the medium environment is replaced by a cuboid, which increases the number of diffraction along the surface. Therefore, in a short period of time after 13.27ns, it also shows some pulse like characteristics.

The time-domain transient response is segmented, and each segmentation signal is processed by short-time Fourier transform, which can effectively track the change of spectrum energy with time. The step size of adjacent signal segments is half of the length of each segment.According to the simulation conditions,the time-domain transient response of the two polarizations is 82ns, the number of sampling points is 3600, and the sampling interval is about 0.023ns. The length of each signal segment is 100 points, and the corresponding number of segments is 71. The spectrum energy of each signal segment is calculated and normalized, and the result is shown in Figure 4. It can be seen that after 9.18ns, there is a significant difference in the energy of the two polarization, which is used as the end point of the surface reflection wave in the early-time response stage.

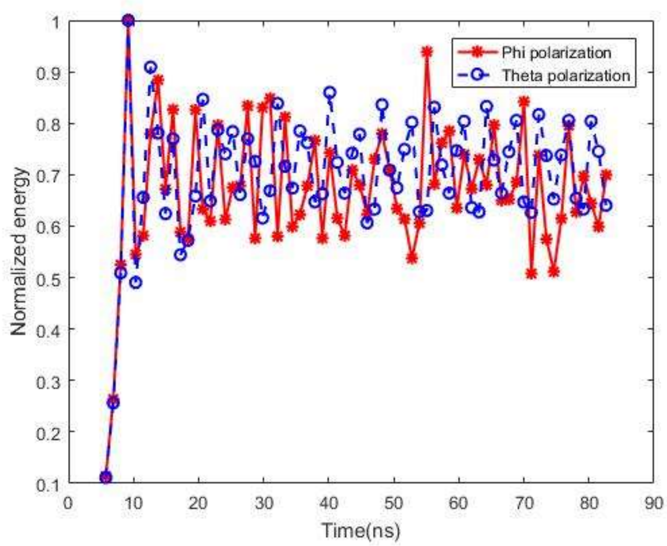


Fig 4: The comparison of normalization power with different polarization

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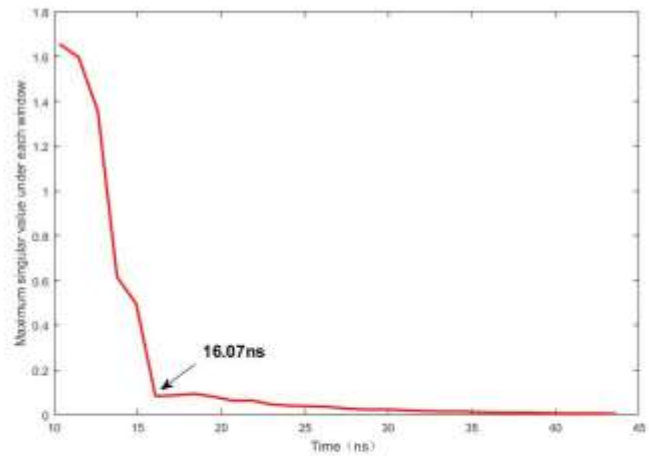


Fig 5: The biggest singular value in different window

The late-time response of the model is more obvious in theta polarization mode.which is further analyzed. The length of the signal is selected as 400 points, about 10ns, to ensure that it contains at least a section of resonance frequency information. According to the pulse width of the incident pulse, 50 sampling points are selected as the step size, which is about 1 ns. Starting from the end point (9.18ns) of the surface reflection wave in the early-time response, 30 groups of signal data are obtained according to the size of the window and step, and the maximum singular value of each group of data is calculated. The analysis results are shown in Figure 5. It can be seen from the figure that with the advance of time, the maximum singular value gradually decreases, and 16.07ns is the time when the maximum singular value suddenly drops, that is to say, this moment is the start of the late-time response phase.

When the incident wave reaches the target position, the surface reflection wave ends, and the difference between the simulation value and the theoretical value is 7.4%. The end of the early-time response of the slender cylinder is the end time of the axial length of the incident wave around the cylinder, and then it overlaps with the diffraction of the external medium environment. The start of the late-time response is the end time of the incident wave passing through the dielectric body. The simulation value is basically consistent with the theoretical value, and the error is only 0.4%.

## IV. CONCLUSION

In this paper, the relationship between the early-time response and the late-time response of the target in the medium environment is analyzed in detail. A method to deal with the early-time response and the late-time response is proposed from the two aspects of energy equality and singular value characteristics under different polarizations.Taking the slender cylinder in the dry sand environment as an example, the XFDTD simulation results show that the time when the singular value suddenly drops is the start of the late-time response phase. In the future research, the algorithm is extended to the target which is more in line with the actual properties of the medium, which has profound significance for the detection of underground water filled fractures.

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