Three-dimensional imaging algorithm of multi-layer medium ground penetrating radar

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Introduction

- GPR is mainly based on the refraction and reflection characteristics of electromagnetic waves in different media layers. According to the echo signals obtained by the receiving antenna, the location information of underground targets can be obtained.
- The subsurface media is often multi-layered and the distribution properties of the medium are usually unknown.
- The selection of refraction points on each division surface causes inaccurate imaging results. Therefore, the paper adopts the equivalent medium layer theory for ground-penetrating radar 3D imaging.
- Sparse Bayesian algorithm has become an important class of branches in sparse representation theory. It is flexible and can avoid the overfitting problem, which has been mostly applied to ground penetrating radar imaging research in recent years.

Methods & Results

Signal Model

The target $O(x,y,z)$ is buried in the ground medium $(z>h_0)$. The MIMO radar antennas are scanned in the $z=0$ plane with a total of M. Below the antenna array is the air layer with thickness h_0 and below the air are $l-1$ different planar dielectric layers with thickness $h_1 \cdots h_{l-1}$. Set f_0 as the starting frequency of the system , step frequency Δf , the echo signal transmitted by the m-th antenna received by the n-th antenna by the p-th frequency point is

$$e(t,p)=\rho_i e^{j2\pi f_p (t-\tau_i^{mn})}$$

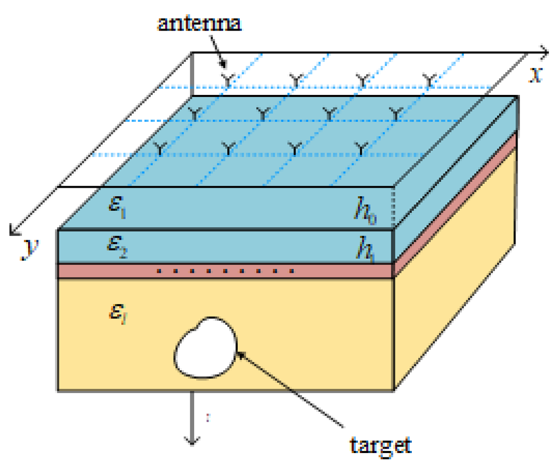

Figure 1. Multi-layer media imaging model

The Equivalent Medium layer Theory

In the multilayer media imaging problem, the multilayer planar media can be transformed into a three-layer media model by introducing an equivalent media layer. As shown in Figure 2, all layers beyond the air layer and the buried target layer are equated as a layer of medium.

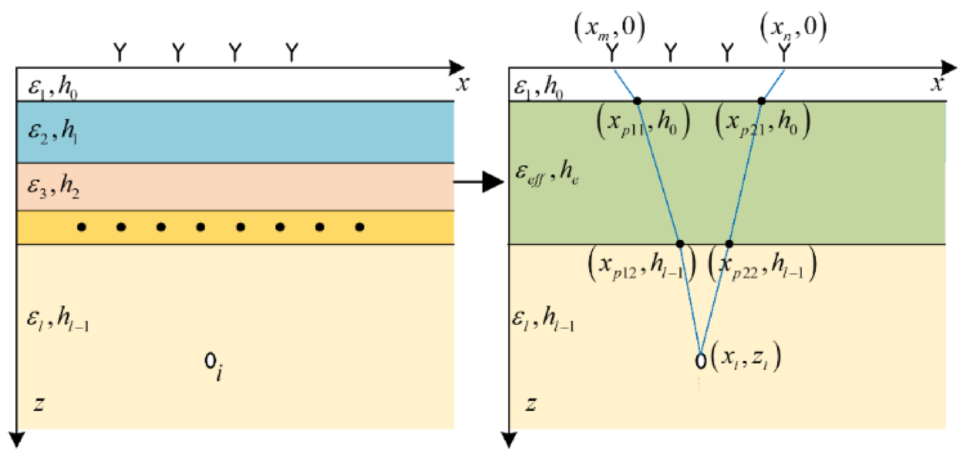

Figure 2 Multi-layer media equivalent schematic

The equivalent dielectric constant and the thickness of the intermediate medium layer is

$$\varepsilon_{eff}=\frac{\bar{D}}{\bar{E}}=\frac{\sum\int_{h_{i-1}}^{h_i}\varepsilon_l E_l dh}{\sum\int_{h_{i-1}}^{h_i}E_l dh}=\frac{\sum\varepsilon_l h_l}{\sum h_l} \qquad h_e=\sum_{i=1}^{l-2}h_i$$

The time delay at grid point can be expressed as

$$\tau_i^{mn}=\frac{\sqrt{(x_m-x_{p11})^2+(y_m-y_{p11})^2+h_0^2}+\sqrt{(x_m-x_{p11})^2+(y_m-y_{p11})^2+h_0^2}}{c}+\frac{\sqrt{(x_{p12}-x_{p11})^2+(y_{p12}-y_{p11})^2+h_e^2}+\sqrt{(x_{p22}-x_{p21})^2+(y_{p22}-y_{p21})^2+h_e^2}}{c/\sqrt{\varepsilon_{eff}}}+\frac{\sqrt{(x_{p12}-x_i)^2+(y_{p12}-y_i)^2+(z_i-h_{l-1})^2}+\sqrt{(x_{p22}-x_i)^2+(y_{p22}-y_i)^2+(z_i-h_{l-1})^2}}{c/\sqrt{\varepsilon_l}}$$

Sparse Bayesian Algorithm

The reconstruction expression of the scene reflection coefficient can be expressed as

$$\boldsymbol{e}=\boldsymbol{\Theta s}+\boldsymbol{n}$$

Assuming that s satisfies a Gaussian distribution with mean 0 and variance α^{-1}

$$p(s|\alpha)=\prod_{i=0}^{N}CN(s_i|0,\alpha_i^{-1})$$

According to Bayes' rule, the posterior distribution of S is

$$p(s|\boldsymbol{e},\alpha,\sigma^2)=\frac{p(\boldsymbol{e}|\boldsymbol{s},\sigma^2)p(\boldsymbol{s}|\alpha)}{p(\boldsymbol{e}|\alpha,\sigma^2)}=CN(\boldsymbol{s}|\boldsymbol{\mu},\boldsymbol{\Sigma})$$

$$\boldsymbol{\Sigma}=(\sigma^{-2}\boldsymbol{\Theta}^{\mathrm{T}}\boldsymbol{\Theta}+\boldsymbol{A})^{-1}$$

$$\boldsymbol{\mu}=\sigma^{-2}\boldsymbol{\Sigma\Theta}^{\mathrm{T}}\boldsymbol{e}$$

Experiment

The imaging area size is set to 0.6m*0.6m*0.8m, a total of 4 different layers of media layers. The target is buried at 0.55m. We set up 36 antennas to form a MIMO array, set the starting frequency of the transmitting antenna to 400MHz, step frequency to 60MHz, and each array element is equally spaced at 0.1m intervals in the horizontal and vertical directions.

Table I media layer parameter

Media type	Dielectric constant	Electrical conductivity	Thickness
air	$\varepsilon_1=1$	$\sigma_1=0$	$h_1=0.1m$
sand	$\varepsilon_2=3$	$\sigma_2=0.001$	$h_2=0.1m$
soil	$\varepsilon_3=4$	$\sigma_3=0.001$	$h_3=0.1m$
soil	$\varepsilon_4=6$	$\sigma_4=0.001$	$h_4=0.5m$

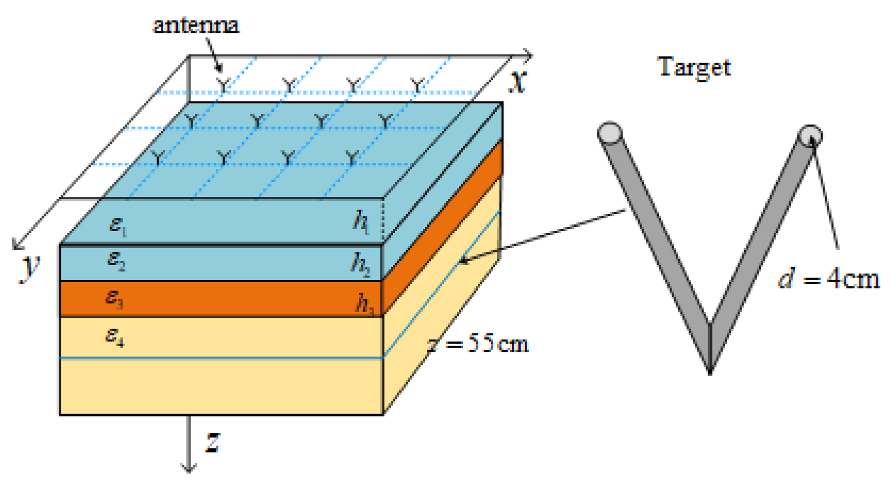

Figure 3 Experiment Scene

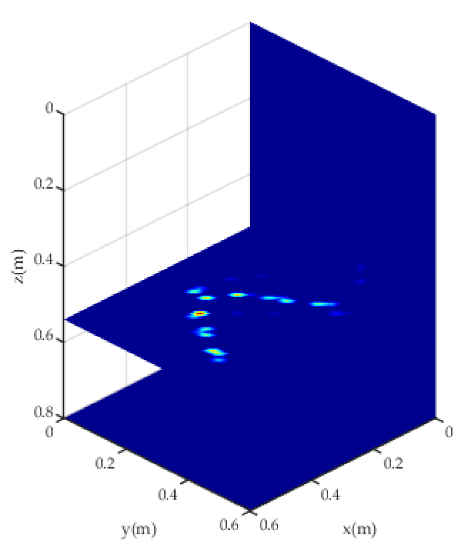

Figure 4 Imaging result of z = 0.54m.

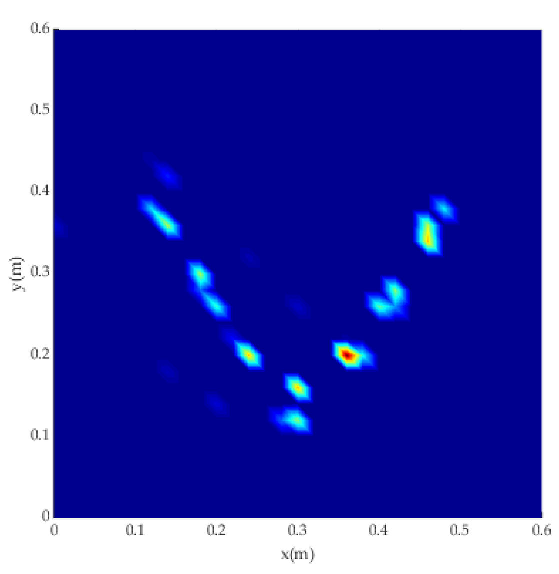

Figure 5 Top view of z = 0.54m

Conclusion

A multilayer media ground-penetrating radar three-dimensional imaging algorithm is presented. By applying equivalent media layer theory and Bayesian compressive perception theory, this method performs three-dimensional imaging of buried targets. The experimental result demonstrates that the position and shape of the target are accurately displayed in the imaging results and have good resolution performance.