

# Determination of Parameters of Subsurface Layers Using GPR Spectral Inversion Method

Zhong-lai Huang and Jianzhong Zhang

**Abstract**—A step-by-step spectral inversion algorithm is proposed in this paper to estimate the thickness, depth, permittivity, and conductivity of layered media from ground-penetrating radar (GPR) signals. Due to the distinct GPR spectral responses to media parameters, different attributes of the spectra are used to estimate, separately, one or several parameters within each step. Such estimated parameters are then used as starting values in a nonlinear optimization problem for the inversion of all parameters simultaneously from the whole GPR spectral data. The cost function of the optimization problem is defined as the difference between the modeled generalized reflection coefficient spectrum of subsurface layers and the actual one. The optimization problem is solved by using a modified stochastic hill-climbing (SHC) algorithm. The method is applied on synthetic data of a wedge model and real data from two highway GPR detections. The results show that the step-by-step spectral inversion method can reduce the ambiguity of the inversion and improve its accuracy and efficiency.

**Index Terms**—Generalized reflection coefficient, ground-penetrating radar (GPR), layered media, spectral inversion.

## I. INTRODUCTION

THE ground-penetrating radar (GPR) has been widely applied in civil engineering and geophysics for the characterization of subsurface structures [1], [2], buried objects [3]–[5], and medium dielectric properties [6]–[8]. In this paper, we focus on layered media concerning which a lot of works have been done so far. Kao *et al.* created a new multilayer model and used the common-middle-point method of seismic exploration to estimate the thickness and dielectric constants of highway pavements [9]. However, the echoes of reflective layers need to be distinguishable in the time domain. Huang and Yi used a parameter calibration method to estimate the permittivity and thickness of pavements, but a drilled core must be provided for *a priori* information [10]. Patriarca *et al.* established an objective function in the frequency domain with Green's function to invert layer thicknesses and dielectric parameters [11]; however, when too many parameters are involved, *a priori* information of the target layers must be given to make accurate estimation.

For GPR detection in a lossy medium, with increasing antenna frequency, the vertical resolution of the GPR data will

increase, but the penetration depth will decrease because of the attenuation of the GPR wave. In some applications of GPR, such as contaminant mapping [12] and fluvial sedimentology [13], the antenna frequency must be sacrificed to reach the penetration depth required, and the vertical resolution of the GPR data will be limited. In addition, since the target region is usually unknown, the antenna frequency chosen in the field measurement may be too low to identify potential thin layers involved in the region. In these situations, when thin layers are encountered, signal processing methods and algorithms should be necessary to improve the resolution of GPR imaging and to estimate thin layers.

Spectral inversion is a seismic method that uses *a priori* information and spectral decomposition to improve images of thin layers whose thicknesses are below tuning thickness, which is defined as a quarter of a wavelength. Puryear and Castagna formulated the method to invert frequency spectrum for layer thicknesses [14]. The method has strong adaptability for thin layers. In this paper, we present an improved spectral inversion method for GPR data. Based on the characteristics of electromagnetic (EM) wave propagation in layered media, we define a generalized reflection coefficient at each interface between two electric layers and use the coefficients to establish a cost function for spectral inversion, which includes parameters of layer depth, thickness, and dielectric properties. Through analysis of the relationship between the parameters and the reflection coefficient spectrum, a new step-by-step method of GPR spectral inversion has been proposed, which greatly helps improve inversion accuracy and convergence speed.

Problem formulation, including derivation of the generalized reflection coefficient and the establishment of the cost function, is given in Section II. The details of the new spectral inversion method are explained in Section III. The method is applied on synthetic data from a wedge model first and then on two real GPR data of highway pavements. The results are presented in Section IV.

## II. PROBLEM FORMULATION

### A. Generalized Reflection Coefficients

Consider an  $L$ -layer model as shown in Fig. 1, where  $\epsilon$ ,  $\sigma$ , and  $\mu$  are the permittivity, conductivity, and magnetic permeability of the medium, respectively. Each layer is linear, homogeneous, and isotropic. The propagation constant  $\tilde{\gamma}$  can be written as [15]

$$\tilde{\gamma} = \alpha + j\beta \quad (1)$$

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## **Table of Contents Determination Of Macro Subsurface Models By Generalized Inversion**

1. Understanding the eBook **Determination Of Macro Subsurface Models By Generalized Inversion**
  - The Rise of Digital Reading **Determination Of Macro Subsurface Models By Generalized Inversion**
  - Advantages of eBooks Over Traditional Books
2. Identifying **Determination Of Macro Subsurface Models By Generalized Inversion**
  - Exploring Different Genres
  - Considering Fiction vs. Non-Fiction
  - Determining Your Reading Goals
3. Choosing the Right eBook Platform
  - Popular eBook Platforms
  - Features to Look for in an **Determination Of Macro Subsurface Models By Generalized Inversion**
  - User-Friendly Interface
4. Exploring eBook Recommendations from **Determination Of Macro Subsurface Models By Generalized Inversion**
  - Personalized Recommendations
  - **Determination Of Macro Subsurface Models By Generalized Inversion** User Reviews and Ratings

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---

- Determination Of Macro Subsurface Models By Generalized Inversion and Bestseller Lists
- 5. Accessing Determination Of Macro Subsurface Models By Generalized Inversion Free and Paid eBooks
  - Determination Of Macro Subsurface Models By Generalized Inversion Public Domain eBooks
  - Determination Of Macro Subsurface Models By Generalized Inversion eBook Subscription Services
  - Determination Of Macro Subsurface Models By Generalized Inversion Budget-Friendly Options
- 6. Navigating Determination Of Macro Subsurface Models By Generalized Inversion eBook Formats
  - ePub, PDF, MOBI, and More
  - Determination Of Macro Subsurface Models By Generalized Inversion Compatibility with Devices
  - Determination Of Macro Subsurface Models By Generalized Inversion Enhanced eBook Features
- 7. Enhancing Your Reading Experience
  - Adjustable Fonts and Text Sizes of Determination Of Macro Subsurface Models By Generalized Inversion
  - Highlighting and Note-Taking Determination Of Macro Subsurface Models By Generalized Inversion
  - Interactive Elements Determination Of Macro Subsurface Models By Generalized Inversion
- 8. Staying Engaged with Determination Of Macro Subsurface Models By Generalized Inversion
  - Joining Online Reading Communities
  - Participating in Virtual Book Clubs
  - Following Authors and Publishers Determination Of Macro Subsurface Models By Generalized Inversion
- 9. Balancing eBooks and Physical Books Determination Of Macro Subsurface Models By Generalized Inversion
  - Benefits of a Digital Library
  - Creating a Diverse Reading Collection Determination Of Macro Subsurface Models By Generalized Inversion
- 10. Overcoming Reading Challenges
  - Dealing with Digital Eye Strain
  - Minimizing Distractions
  - Managing Screen Time
- 11. Cultivating a Reading Routine Determination Of Macro Subsurface Models By Generalized Inversion
  - Setting Reading Goals Determination Of Macro Subsurface Models By Generalized Inversion
  - Carving Out Dedicated Reading Time
- 12. Sourcing Reliable Information of Determination Of Macro Subsurface Models By Generalized Inversion
  - Fact-Checking eBook Content of Determination Of Macro Subsurface Models By Generalized Inversion
  - Distinguishing Credible Sources

13. Promoting Lifelong Learning
  - Utilizing eBooks for Skill Development
  - Exploring Educational eBooks
14. Embracing eBook Trends
  - Integration of Multimedia Elements
  - Interactive and Gamified eBooks

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