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공간통계학을 이용한 3차원 지하영상화

3-Dimensional Subsurface Imaging Using Geostatistics

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Abstract

Forward modelling of ground penetrating radar (GPR) data is implemented using a new finite element ray tracing technique. The method is different from conventional ray tracing techniques in that the radar cross section of buried targets, the effective area of the receiving antenna, and the attenuation along the raypath are computed. The forward models are used to understand radar signatures measured across various ground structures which are important in detecting engineering hazards at construction sites, void spaces beneath simulated road beds, as well as a learning tool to avoid pitfalls in radargram interpretation. Forward modelling of radar data also can be used in predicting possible structures present at cultural property sites.

1. Introduction

The ground penetrating radar (GPR) equation in a lossy medium describes the received power from a buried target (Carcione, 1996; Skolnik, 1990):

$$P_r = \frac{G_t \, P_t \, A_e \, \sigma}{(4\pi)^2 \, R_t^2 \, R_r^2} \exp[-2a\,(R_t + R_r)]$$

where G_r : transmitter gain; P_t : transmitted power; R_t : transmitter -target distance; R_r : receiver-target distance; a : attenuation coefficient; A_e : effective area of receiving antenna; σ : target radar cross section

The purpose of forward modelling is to accurately estimate the return power of GPR microwaves that propagate into lossy media, are reflected from targets having a specified cross section, return from the target after undergoing reflection/transmission, and transect some effective area of the receiving antenna. In forward modelling the transmitter-target and receiver-target distances are specified according to the model structure along with transmitted power and gains.

To estimate the retuned power from GPR, the following radargram modelling is useful:

$$S(t) = I(t) * \sum_{\Theta} D(\Theta) \sum_{k} (A(\Phi)Q(t))_{k}$$

where S : synthetic radargram; I =instrument + receiver + transmitter + impulse responses; D : directional response of the antenna; A : attenuation along the k-th wave type; Q : return amplitude response of the reflected-transmitted-refracted k-th wave type

The synthetic radargram is represented by a summation over the entire directional response of the antenna, and summed for every wave type. Different wave types are traced through the structure which has been digitized into a finite element grid. The grid cells contain a total of 4 parameters; 3 material parameters (ε: dielectric, σ: conductivity, μ: permeability) and 1 identifier containing the coefficients of a spline or polynomial describing structural interfaces through the grid cells. The polynomials allow for infinite number of possible slope determinations in a single grid cell. For this reason, this finite element method is referred to as the Infinite Slope Method (ISM) in this paper (Goodman and Nishimura, 1992; Goodman, 1994).

The advantages of describing structural slopes in terms of shape functions are that small scale structures can be digitized into a relatively coarse grid, but still preserving the entire structural/slope information. In addition, the method is independent of the cell shape, since the grid cells are only used to identify the location of structural boundaries. The antenna aperture is simulated by the presence of the antenna "receiver" existing across several grid cells.

The propagation of electromagnetic waves used in the ISM can easily incorporate varying propagation models; currently a conductive- dissipative wave theory is incorporated (Jackson, 1977). The use of general optic theory to describe the reflection and transmission of electromagnetic radiation is assumed to be valid in the ISM radargram modeling. In this case the structures considered are larger than the wavelength of the microwave. In addition, the microwave properties of the surrounding medium and the structure to be surveyed must have properties close to those of an isolator. The reflection and transmission of parallel polarized microwaves is respectively

$$R = \frac{Z_2 \cos\Theta_1 - Z_1 \cos\Theta_2}{Z_2 \cos\Theta_1 + Z_1 \cos\Theta_2}, \qquad T = \frac{2Z_2 \cos\Theta_1}{Z_2 \cos\Theta_1 + Z_1 \cos}$$

where the impedance for an angular frequency ω, is given by

$$Z = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}}$$

For those antennas which may have mixed polarization transmission properties, the perpendicular polarized wave components can also be included.

Refraction along the raypath is given by Snell's law;

$$K_1 \sin\Theta_1 = K_2 \sin\Theta_2$$

where

$$K=\omega\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}+1\right)}$$

The return amplitude response computed in the ISM radargram modeling for a wave which undergoes reflections R1 , R2 ⋯ Ri and transmissions T1 , T2 ⋯ Tj for the k-th wave type, is given by

$$Q_k(t)=(R_1R_2\cdots R_i)_k\ (T_1T_2\cdots T_j)_k\ \delta(t-t_k)$$

The 1...i and 1...j refer to the two media encountered along the raypath. The delay time of the k-th ray is t_k. The delay time is the integral of the wave slowness over the path of the ray. With the use of the delta function, the return amplitude response from simple reflection/transmission contains a series of spikes. The magnitudes of the spikes correspond to the combinations of reflection and transmission coefficients for the k-th wave type, with locations at time t_k.

The attenuation along the raypath is also monitored in the ISM radargram modeling and can be described as

$$A=\int e^{-a(\Psi)\Psi}\,d\Psi$$

where ψ signifies the path of the wave, and a is the attenuation coefficient;

$$a=\omega\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right)}$$

The final process in creating the synthetic radargram involves the convolution with the instrumentation responses including the receiving and transmitting antenna. The impulse response wavelet is normally assumed to represent a far-field response of the antenna, although near field responses can also be used if they are known and reflected waves are recorded within the near-field time window. Most GPR antenna impulses approach far field antenna responses within a half wavelength in the ground (Duke, 1990).

To run the ISM radargram modeling rays are sent into the grid having a direction and starting amplitude specified by the directional response. The ray also has a wave type specification telling whether reflection or transmission should occur at the boundary. If the waves return to the starting grid location or within grids representing the horizontal aperture of the antenna, and have completed their reflection/transmission itinerary, then they are recorded. If the wave exceeds the time window designated, the wave is not recorded and the next wave type is started. If the wave encounters more interfaces than is written into it's travel itinerary it is also discarded.

The ISM radargram modeling incorporates and properly predicts the effects of geometrical spreading in refractive media. The relative amplitudes of features in the model can be statistically sampled and radar cross sections estimated for buried targets/structures. To successively implement and predict geometrical spreading requires however, a proper digitization interval used to simulate the directional response of the radar antenna. For structural models in which small objects at great depth are observed, a very fine digitization interval for the response is necessary to insure that the target is recorded.

2. Modeling

An ISM radargram modeling is applied to several engineering situations which commonly occur. Modeling is a structure containing a low microwave velocity zone. In this case, the low velocity zone is modelled as a water zone in three layers. The important wave types which traverse the modelled structure are shown in the lower right hand diagram along with their predicted travel times and spatial distribution. The travel time plot allows for additional interpretation. of what is commonly referred to as radar echoes. Interlayer multiples are specified by wave types - TRRRT and TTRRRTT. The ISM radargram modeling is for a 300MHz radar antenna having a simple sinusoidal response.

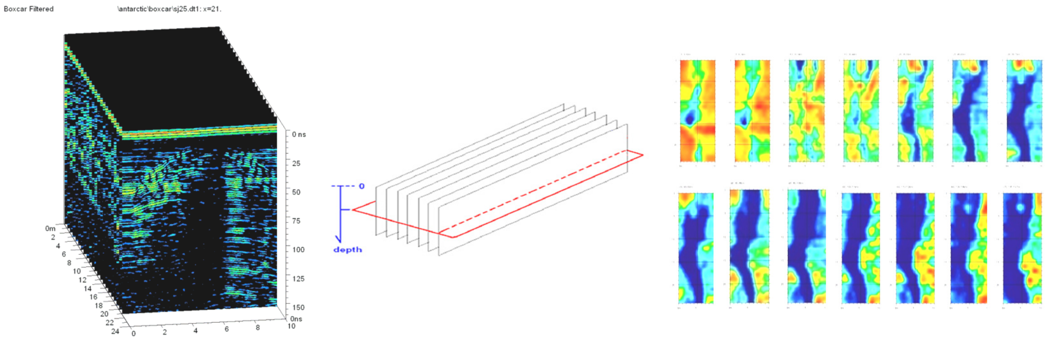
The synthetic radargrams shows a lensing effect whereby the rays are refracted downward into the low velocity zone and arrive later in the radar scan. The low velocity zone is found to be narrower than the actual structure when imaged with radar. The low velocity zone causes shadow zone off to their side, in which little or no wave energy is transmitted. The other important information in the interpretation of radar at low velocity zones are the possibility of measuring bright reflection events at the top of the zone. The lensing effect simulated is quite found at sites where ruptured water mains and pipes have created water ducts beneath solid/cohesive ground. The ISM radar modeling can help discover those pipes areas which may been ruptured. Radargram modelings are also estimated beneath modelled road bed structures in which void spaces are found. Typical road bed dielectric and conductivity values are used (Ulriksen, 1982); the void space floor is identified with additional material caved in from a upper road layer. The modeling shows several important features which are indicative of void spaces (high velocity zones) beneath the road bed. At the top of the void space a phase reversal is observed. In addition, the waves traversing the void space are found to warp upward since microwave velocities are highest in the void region and require the least amount of travel time to return to the receiving antenna. Using forward modelling, as is done with the ISM radar- gram modeling, it should be possible to estimate the sizes of void spaces which is crucial to road rehabilitation programs.

The modelings shown are for transmitter and receiver co-located (zero offset). The modelings can also be adapted to acquisition for wide angle reflection, refraction, and array studies which were recently introduced into GPR data acquisition (Fisher *et al.*, 1992).

CONCLUSIONS

The possibilities of using forward models which have been computed for a variety of conditions, and then searching the models for a best match with field data may be easily facilitated using the ISM modeling. Particularly in road surveys where surface layers may be significantly smaller than the probing wavelengths and deconvolution techniques can work only marginally, a system based on active comparison of stored modelled structures may provide a more reliable interpretation.

The ISM modeling, although it does not currently model diffracted waves or inhomogeneous waves, can accurately provide a close approximation to the full waveforms measured across most simple structures in the ground. Forward modelling is essential to understanding and interpreting raw radar records and should be used in all situations possible to add confidence in the site interpretation.



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References

Carcione, J. M. (1996) Ground-penetrating radar - wave theory and numerical simulation in lossy anisotropic media. Geophysics, 61, 1664-1667.

Duke, S. (1990) Calibration of ground penetrating radar and calculation of attenuation and dielectric permittivity versus depth. Ph.D. thesis, Colorado School of Mines, T-3920.

Goodman, D. and Nishimura, Y. (1992) 2-D synthetic radargrams for archaeological investigation. Finland Geological Survey, special paper 16, 4th International Conference on Ground Penetration Radar, Rovanlemi, Finland, 339-343.

Goodman, D. (1994) Ground-penetrating radar simulation in engineering and archaeology. Geophysics, 224-232.

Fisher, E., McMeham, G. A., Annan, A. P. (1992) Acquisition and processing of wide-aperture ground-penetrating radar data. Geophysics, 57, 494-504.

Hatton, L., Worthingon, M.H., and Makin, J. (1986) Seismic Data Processing. Blackwell Scientific publication, Inc.

Imai, T., Sakyama, T. and Kanemori, T. (1987) Use of ground penetrating radar and resistivity surveys for archaeological investigation. Geophysics, 53, 137-150.

Jackson, J.D. (1977) Classical Electrodynamics. John Wiley & Sons, New York.

Skolnik, M.I., (1989) Radar Handbook. McGraw-Hill Book Co.

Shon, H. (1996) Application of Ground Penetrating Radar for Archaeological Monuments. Econ. Environ. Geol., 29, 745-752.

Shon, H., and Yamamoto, T. (1992) Simple data processing procedures for seismic section noise reduction. Geophysics, 57, 1064-1067.

Ulriksen, C.P.F. (1982) Application of impulse radar to civil engineering. Ph.D. Thesis, Univ. of Technology, Lund, Sweden.

Vaughan, C.J. (1986) Ground penetrating radar surveys used in archaeological investigations. Geophysics, 51, 595-604.

Yamamoto, T., Shon, H., and Goodman, D. (1991) High resolution subbottom imaging using a reflection system: Part I-seismic/radar section interpretation by data transformation. IEEE Oceans, 425-429.