Journal of Applied Geophysics 67 (2009) 288–295

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

A strategy for the determination of the dielectric permittivity of a lossy soil exploiting GPR surface measurements and a cooperative target

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ARTICLE INFO

Article history:
Received 10 December 2007
Accepted 10 September 2008

Keywords:
Ground Penetrating Radar
Microwave tomography
Soil dielectric permittivity determination

ABSTRACT

In this paper we deal with an indirect measure of the dielectric permittivity of the soil starting from GPR surface data collected on a buried "cooperative" target, meant as an object buried on purpose and whose extent is known a-priori. This target is exploited in order to achieve, from its image obtained from a suitable GPR data processing, an indirect measure of the dielectric permittivity of the embedding soil. GPR data processing is based on a linear microwave tomographic approach funded on the Born Approximation. Using this Born approach on two-dimensional inversion tests, we investigate the effect of the soil's electrical conductivity and permittivity on this indirect measure and demonstrate that the electrical field scattered by a spot-like buried object permits an accurate estimation of the soil permittivity even when no information of the soil conductivity is available.

1. Introduction

An accurate measure of the dielectric permittivity of the soil is of interest for several hydrological applications, as optimal irrigation and pollution monitoring, only to quote few examples (Binley et al., 2001; Daniels et al., 1995; Galagedara et al., 2003; Huisman et al., 2003; Lambot et al., 2004a,b). In addition, an accurate knowledge of the dielectric properties of the soil is of interest in the framework of inverse scattering approaches applied to GPR data in order to detect and image properly the buried targets of interest (Persico and Soldovieri, 2004).

In a previous paper by Soldovieri et al. (2008a), we have presented a strategy to retrieve the dielectric permittivity of the soil starting from GPR measurements at the air/soil interface. This method is funded on a microwave tomography approach (Persico et al., 2005; Cui and Chew, 2002; Hansen and Johansen, 2000; Meincke 2001; Soldovieri et al., 2008b), and exploits Ground Penetrating Radar (GPR) data over a buried target with a transverse section that is electrically small.

The method introduced by Soldovieri et al. (2008a) has been tested even in an inhomogeneous scenario (half-space geometry with the air/soil interface) but only in the lossless case or in cases where the conductivity of the soil was accurately known.

The method is suitable also in the case of non homogeneous soil due to the presence of spurious buried targets, on condition that the mutual interactions between the different objects are negligible. When this does not happen, we have a more complicated problem to be solved since the inverse scattering problem becomes non-linear (Colton and Kress, 1992).

If the non homogeneity is given by a layered structure of the soil we can have two cases. If the target of interest is in put in the shallower layer, the rationale of the method still holds because, approximately, we can see all the further layers as a further spurious targets. In this case the permittivity retrieved is that of the layer that contains the target of interest. Differently, if the target of interest is embedded in one of the deeper layers, the problem becomes more complicated and is beyond the purposes of this paper.

Here, we aim to overcome some limitations of the approach presented by Soldovieri et al. (2008a) and in this paper we face the case of a homogeneous lossy soil with unknown conductivity. This is often the case of applicative interest, because usually the conductivity of the soil is harder to be retrieved with respect to the permittivity. The extension of the method presented by Soldovieri et al. (2008a) to this more challenging case has required some modifications to the solution algorithm, as it will be shown.

The paper is organized as follows. In Section 2, we briefly sketch the inverse scattering algorithm at the basis of the strategy of determination of the soil permittivity. In Section 3 the strategy based on the inverse scattering algorithm is summarized and the effect of the inaccuracy in the knowledge of the soil conductivity is analysed. In Section 4, the updated solution strategy is presented and the numerical analysis is shown. Conclusions follow in Section 5.

2. The inverse scattering algorithm

In this section we present briefly the inverse scattering algorithm, that underlies the proposed method for the permittivity retrieving.

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doi:10.1016/j.jappgeo.2008.09.007

We consider the two dimensional geometry given in Fig. 1. The background inhomogeneous medium is built up of two half-spaces separated by a planar interface at $z=0$. The upper half-space is constituted by free space, the lower one schematises the (homogeneous) soil, and shows a relative dielectric permittivity ε_b and an electrical conductivity σ_b. The source is a time-harmonic (time dependence *exp(j2πft)*) filamentary *y*-directed electric current, invariant along the *y*-axis. The above assumptions make scalar the problem at hand (Leone and Soldovieri, 2003). The data are multi-frequency in the band $[f_{min}, f_{max}]$ and a multi-monostatic measurement configuration B-scan (Daniels, 2004) is assumed, where the source and observation points coincide. The targets are invariant along the *y*-axis and their cross-section is enclosed in the rectangular investigation domain $D=[-a,a]X[z_{\min},z_{\min}+2b]$ that represents a domain in the soil whose extent along the *x*-axis ranges from $-a$ to a and in depth (*z*-axis) from $z_{\min}$ to $z_{\min}+2b$. The unknowns of the inverse scattering problem are the relative dielectric permittivity distribution $\varepsilon_r(x,z)$ and the conductivity distribution $\sigma(x,z)$ inside *D*, whereas the data are the scattered field measurements gathered in the observation domain at the air/soil interface with extent $[-x_M,x_M]$. The problem is customarily recast in terms of the contrast function (Persico et al., 2005; Cui and Chew, 2002; Meincke 2001; Leone and Soldovieri, 2003), defined as

$$\chi(x,z)=\frac{\varepsilon_{eq}(x,z)-\varepsilon_{eqb}}{\varepsilon_{eqb}} \tag{1}$$

where

$$\varepsilon_{eq}(x,z)=\varepsilon_0\varepsilon_r(x,z)-j\frac{\sigma(x,z)}{2\pi f} \tag{2}$$

and

$$\varepsilon_{eqb}=\varepsilon_0\varepsilon_b-j\sigma_b\,/\,2\pi f \tag{3}$$

are the equivalent complex dielectric permittivity of the targets and of the soil, respectively. In the previous expressions ε_0 is the dielectric permittivity of the free space, ε_b and σ_b are the above defined relative dielectric permittivity and the electrical conductivity of the soil, respectively. Since the relevant targets are included in the investigation domain *D*, the contrast function vanishes outside *D*.

In this paper, we adopt a solution approach based on the Born Approximation (BA), because it allows to achieve an effective inversion algorithm and reliable results in terms of localization and size of the targets.

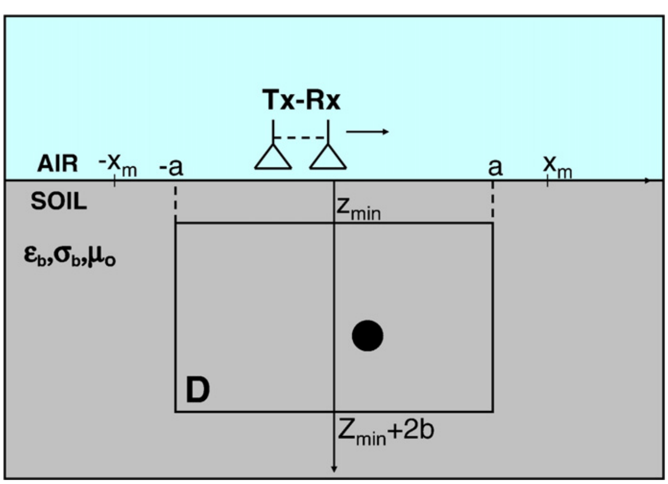

Fig. 1. Geometry of the 2D problem for the microwave inverse scattering approach. The measurement configuration is multi-monostatic, the observation domain is the line $[-x_M, x_M]$ at the air soil interface and the investigation domain D is the rectangle $D=[-a,a]X[z_{\min},z_{\min}+2b]$. The soil is homogeneous and shows a relative dielectric permittivity ε_b and an electrical conductivity σ_b. Its magnetic permeability, instead, is that of the free space free space, μ_o.

Under BA, the relationship between the unknown contrast function and the scalar scattered field data is provided by the following integral equation (Persico et al., 2005; Cui and Chew, 2002; Meincke 2001; Leone and Soldovieri, 2003):

$$E_s(x_s,\omega)=k_s^2\int_D G_e(x_s,\omega,\vec{r}')E_{inc}(x_s,\omega,\vec{r}')\chi(\vec{r}')d\vec{r}' \tag{4}$$

where E_s is the electric scattered field measured at the abscissa x_s along the observation line (that ranges from $-x_M$ to x_M) at the air–soil interface, $\omega=2\pi f$ is the circular frequency; k_s is the wave-number in the soil. G_e is the Green's function of the problem, and E_{inc} is the incident field (i.e., the electric field in absence of buried scattering objects); their expressions are given in (Leone and Soldovieri, 2003).

A discretization of Eq. (4) is achieved by resorting to the method of moments (MoM) (Harrington, 1961). In particular, the contrast function is expanded along basis functions that are Fourier coefficients (harmonics) along the *x*-axis and rectangular pulse-functions along the *z*-axis; the test functions are impulsive, i.e., a point matching is applied in the data space. Since the inversion of Eq. (4) is an ill-posed problem (Colton and Kress, 1992), the inversion of the resultant matrix is customarily ill-conditioned and some regularization is needed. In this paper, we adopt a regularization scheme based on the Truncated Singular Value Decomposition (TSVD) (Bertero and Boccacci, 1998).

3. Retrieving the permittivity of the soil from an inverse scattering algorithm

The possibility to retrieve the dielectric permittivity ε_b (and theoretically also the conductivity σ_b) of the soil by exploiting Eq. (4) arises from the fact that these quantities affect the linear integral relation of Eq. (4). In particular, they play a role in the definition of the wave-number k_s that in its turn enters into the definition of the functions $E_{inc}(x_s,\omega,\vec{r}')$ and $G_e(x_s,\omega,\vec{r}')$. Therefore, when the standard inverse scattering problem is tackled, actually one should know the dielectric permittivity and conductivity of the soil in order to build the correct Born model in Eq. (4).

In this paper, we reverse the point of view and try to determine the dielectric permittivity of the soil as the value that, when introduced in the integral Eq. (4), drives to the "reconstruction" closest to the known buried target, embedded in the soil on the purpose.

Consequently, the problem of how quantifying the quality of the reconstruction arises, i.e. we have to identify a figure of merit that makes us able to characterize the "best" reconstruction.

A possible choice could be based on the least square difference between the dielectric properties of the actual and reconstructed objects. However, this criterion in general does not work since we are making use of a linear inversion algorithm based on BA. As well known, under the BA, it is usually not possible to achieve a quantitative reconstruction, due to the model error and to the filtering properties of the linear scattering operator (Persico et al., 2005; Leone and Soldovieri, 2003).

According to the consideration above, here we adopted a different point of view where the goodness of the reconstruction is evaluated in terms of others features related to the actual distribution of the contrast function. This point of view is exploited in radar and optics literature where the goodness of the reconstruction is evaluated in terms of the sharpness (Ahmad et al., 2007), the compactness (Garder et al., 2004), the entropy (Martorella et al., 2006), the spectral features (Ho et al., 2007), only to quote few examples.

The definition and the exploitation of different sharpness measures are well assessed in the field of the auto-focussing techniques for Synthetic Aperture Radar imaging where one of the general aims is to