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Electromagnetic Imaging of Rough Dielectric Surface Profiles using a Single-Frequency Reverse Time Migration Method

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Abstract

An electromagnetic imaging scheme, which makes use of a single-frequency reverse time migration (RTM) technique to reconstruct two-dimensional (2D) rough surface profiles from the scattered field data, is formulated and implemented. The unknown surface profile, which is expressed as a one-dimensional height function, is the interface between two dielectric media. It is assumed that the profile is illuminated from one side and the scattered fields are "measured" along a line on this same side. RTM is used to construct a cross-correlation imaging functional that is numerically evaluated to yield an image of the investigation domain. The maxima of this functional yields an accurate reconstruction of the rough dielectric surface profile.

Index Terms

Inverse electromagnetic scattering, electromagnetic imaging, rough surface, reverse time migration

I. INTRODUCTION

Electromagnetic imaging methods that are capable of accurately reconstructing rough surface profiles are highly sought after in various areas of engineering such as remote sensing, geophysics, materials and surface science, optics, and underwater communications. Such electromagnetic imaging problems call for the reconstruction of an inaccessible surface profile using the scattered field data often measured away from the profile itself. This reconstruction process is challenging since it is inherently ill-posed (the scattered field data is mapped onto an unknown surface profile) and nonlinear (the scattered field is a nonlinear function of the dielectric/profile function) [1], [2]. Approaches proposed to overcome these challenges often rely on using (iterative) linearization and/or regularization techniques [3]–[5] or semi-analytical methods like small perturbation or Kirchhoff Approximation that are valid only under certain assumptions [6]–[8]. Besides the iterative numerical imaging methods, the reverse time migration (RTM) has recently been formulated as a non-iterative direct approach to electromagnetic imaging, and it has been successfully used in the reconstruction of two-dimensional (2D) objects as described in [9].

In this work, building upon the framework formulated in [9], an electromagnetic imaging scheme, which makes use of a single-frequency RTM technique to reconstruct 2D rough surface profiles from the scattered field data, is developed. It is assumed that the rough surface is the interface between two penetrable dielectric media and it is expressed as a one-dimensional (1D) height function. The profile is illuminated by line sources from one side and the scattered fields along a line on this same side, which should ideally be collected by real measurements, are generated synthetically from the numerical solution of surface integral equations [10], [11]. RTM is used to construct a cross-correlation imaging functional that is numerically evaluated to yield an image of the investigation domain. Identifying the maxima of this functional leads to the direct reconstruction of the 1D height function representing the dielectric surface profile.

II. METHODOLOGY

Let $x := (x_1, x_2)$ denote the position vector in the 2D domain of interest. The rough surface profile, characterized by a height function $x_2 = f(x_1)$ is the interface between two non-magnetic and lossy dielectric media. The permittivity and the conductivity in these two media are denoted by ε_p and σ_p, $p \in \{1, 2\}$. It is assumed that the surface profile has local roughness such that $f(x_1)$ is nonzero over a finite interval.

The profile is illuminated using N_t number of transmitter antennas that are located in the first medium ($p = 1$) at a height of $x_2 = \beta$, $\beta > \max f(x_1)$. The positions of these transmitters are denoted as $x_t := (x_{1t}, \beta)$, $t = 1, 2, \ldots N_t$. It is assumed that all transmitters are line sources. Then, the incident field is represented as $\hat{x}_3 u^i(x; x_t)$, where $u^i(x; x_t)$ is given by

$$u^i(x; x_t) = \frac{i}{4} H_0^{(1)} \left(k_1 \sqrt{(x_1 - x_{1t})^2 + (x_2 - \beta)^2} \right).$$

Here, $H_0^{(1)}(.)$ is the zeroth order Hankel function of the first kind, $k_1 = \omega\sqrt{\mu_0 \varepsilon_1 + i\mu_0 \sigma_1/\omega}$ is the wavenumber in the first medium, and μ_0 is the permeability in free space.

Since it is assumed that there is no variation along $\hat{x}_3$ direction (i.e., assumption of 2D problem), all the fields in the domain interest have only x_3 component just like the incident field $\hat{x}_3 u^i(x; x_t)$. Thus, the field generated in the first medium due to the transmitter located at x_t is expressed as $u_1(x; x_t) = u^i(x; x_t) + u^s(x; x_t)$, where $u^s(x; x_t)$ represents the field scattered/reflected from the discontinuity between the two media, i.e., the rough dielectric surface profile. It is assumed that the scattered fields are "measured" using N_r number of receiver antennas that are located in the first medium at a height of $x_2 = \alpha$, ($\alpha > \max f(x_1)$). The positions of these receivers are denoted as $x_r := (x_{1r}, \alpha)$, $r = 1, 2, \ldots N_r$. Ideally, $u^s(x_r; x_t)$ should be collected by measurements, but, here, they are generated synthetically from the numerical solution of surface integral equations [10], [11].

The RTM technique relies on the Claerbout's imaging principle [12] which states that the the backward- and forward-propagating fields coincide in time and space along a discontinuity between two media. Once $u^s(x_r; x_t)$ is acquired, its complex conjugate $\overline{u^s}(x_r; x_t)$ can be treated as a backward-propagating (or time-reversed) field [13]. The next step is to determine the cross-correlation between $u^i(x; x_t)$ (as forward propagating field) and $\overline{u^s}(x_r; x_t)$ (as backward propagating field) as a way to generate an image of discontinuities in the domain of interest. To this end, a cross-correlation imaging functional $I(x)$ is defined as described in [9]:

$$I(x) = -\frac{k_1^2}{N_t N_r} \Im \left\{ \sum_{t=1}^{N_t} \sum_{r=1}^{N_r} u^i(x; x_t) u^i(x; x_r) \overline{u^s}(x_r; x_t) \right\}.$$

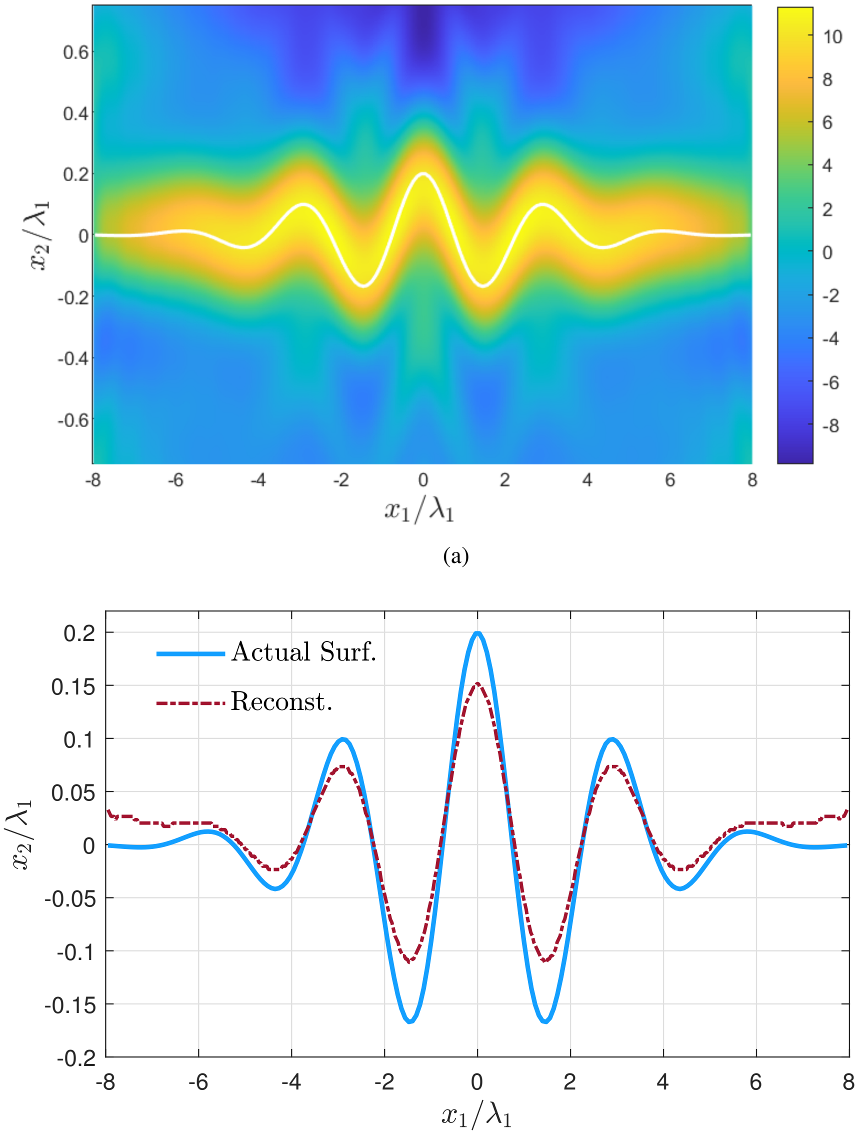
III. NUMERICAL RESULTS

In this example, $\varepsilon_1 = \varepsilon_0$, $\sigma_1 = 0$, $\varepsilon_2 = 3.6\varepsilon_0$, and $\sigma_2 = 10^{-5}$, corresponding to a scenario where the rough surface is the interface between free space and dry soil. The height function of this surface is given by

$$f(x_1) = 0.2 \cos(x_1 2\pi/3) e^{-0.08 x_1^2}. \tag{1}$$

The free-space wavelength corresponding to the operation frequency of the transmitters is $\lambda_1 = 1\,\mathrm{m}$. The other transmitter parameters are $N_t = 150$, $\beta = 2\lambda_1$, and the distance between two adjacent transmitters are $\Delta = 0.2\lambda_1$ such that and $x_{1t} = -15\lambda_1 + \Delta(t - 1)$. The receivers are located along the same line, precisely the parameters are $N_r = 150$, $\alpha = 2\lambda_1$, and $x_{1r} = -15\lambda_1 + \Delta(r - 1)$.

Fig. 1(a) shows $I(x)$ computed in the domain of interest. Clearly, maxima of $I(x)$ correspond to the rough surface profile. Indeed, the profile reconstructed from the numerically computed maxima of $I(x)$ for samples of x_1 (via search) matches well with the actual profile described by $f(x_1)$ in (1) as shown in Fig. 1(b).



(a)

(b)

Fig. 1. (a) $I(x)$ computed in the domain of interest. (b) Actual surface profile described by $f(x_1)$ in (1) and the reconstruction obtained using the numerically computed maxima of $I(x)$ for samples of x_1.

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