A theoretical note on scattering and diffraction of radar waves from a seismic disturbance propagating in the near-surface

Kris Innanen

ABSTRACT

A seismic disturbance alters the electrical properties of the Earth. This means, in principle, that within Earth volumes supporting both types of wave propagation, a radar wave field will tend to scatter from a seismic wave field. Given seismic disturbances with length-scales on the order of that of the radar pulse, such interaction may be detectable as back-scattering phenomena. Given seismic disturbances with length-scales much larger than that of the radar pulse, the interaction may be detectable as forward-scattering (e.g., anomalous traveltime) phenomena. Radar data with these characteristics would lend themselves readily to techniques of imaging-inversion, migration, and tomography, and would present the potential for providing "snapshot" images of a seismic wavefield during important stages of its evolution, e.g., as it propagates in poorly characterized and unconsolidated near surface structures. The relative magnitude of these effects as compared to other components of a GPR data set are likely very small. This work remains highly theoretical in that it is not clear whether they could be expected to rise above the noise level in realistic data sets.

INTRODUCTION

A seismic wave field generates small, transient alterations of the electrical properties in the medium through which it propagates. Given the time scales of typical seismic experiments as compared to typical radar experiments (the latter being virtually instantaneous with respect to the former), this in principle suggests that a radar experiment, arranged such that the electric field scatters from these perturbations, could be used to characterize or even form snapshot images of a seismic wave field during propagation. In this paper we provide some simple theoretical descriptions of such scattering.

The investigation of mechanical waves with electromagnetic fields (for instance, the acousto-optic effect, in which Brillouin scattering of light occurs as the consequence of, e.g., an ultrasonic wave), has been extensively described (e.g., Born and Wolf, 1999). Here we consider what is essentially a specific geophysical application of this idea. Advocating practical use of such radar interaction, should it prove measureable, means constraining ourselves to geophysical problems in which both electromagnetic and mechanical waves are supported, the former within a wide enough range of frequencies that imaging is possible. We take this to mean applications will be restricted to GPR/geo-radar, although controlled-source electromagnetic experiments have also been treated extensively as tools for subsurface imaging (see, e.g., the special section in the March-April 2007 edition of Geophysics). Geo-radar in turn implies shallow investigation (depths of 10^0–10^2m), or Earth volumes contained between wells. Nevertheless, within that near-surface range, several applications suggest themselves. For instance, although exploration-scale seismic data involve wave fields that propagate much further than we may investigate with radar, in early and late stages of propagation these fields often undergo complex interactions in the unconsolidated near-surface environment, which radar scattering might render and help characterize.

Geo-radar and seismology are already closely linked, with related wave equations and similar phases detected in their respective data (Bohidar and Hermance, 2002; Nobes et al., 2005). And indeed, most geo-radar imaging methods (Fisher et al., 1992b; Nemeth et al., 1996; Wang and Oristaglio, 2000; Kruk et al., 2003; Grasmueck et al., 2005; Sena et al., 2006; Streich et al., 2007; Irving et al., 2007), inversion methods (Saintenoy and Tarantola, 2001; Day-Lewis et al., 2006; Bradford, 2006; Clement and Knoll, 2006; Di et al., 2006; Ernst et al., 2007; Johnson et al., 2007), and other processing methods such as dispersion removal (Irving and Knight, 2003) have been derived similarly to existing reflection or cross-well seismic techniques. Most importantly for our purposes, however, radar and seismic experiments also often co-exist, and are used to independently investigate the same volume of Earth (Baker and Schmeisser, 1999; Cardimona et al., 1998; Majer et al., 2002; Sloan et al., 2005; Miller and Liner, 2007). It is to these volumes of the subsurface that we focus our attention.

In addition to the above linkages between radar methods and seismic methods, it is also clear that the mechanical behavior of the Earth and the electrical behavior of the Earth are fundamentally coupled, giving rise to seismoelectric phenomena (e.g., Zhu and Toksöz, 2005), which have been used for exploration purposes (e.g., Dupuis et al., 2007). Butler et al. (1996) and Russell et al. (1997) list four seismoelectric effects of interest to exploration, one of which is the alteration of the local medium resistivity due to a propagating seismic wave, which was originally attributed to a likely "loose-contact phenomenon between the particles of the earth" (Thompson, 1936). More recent investigations have tended to confirm the existence of a relationship between stress/strain and resistivity (e.g., Morat and Mouel, 1987). Alterations of the conductivity (or the dielectric permittivity) of a medium amount to alterations of the index of refraction appropriate to a radar experiment*. For our current purposes, then, the most important consequence of the observation of Statham, Blau and Thompson (Thompson, 1936) is that a geo-radar field within the Earth will, in principle, tend to scatter from a seismic disturbance at many or all points during the latters' propagation.

RADAR REFLECTION FROM A RAPIDLY-VARYING SEISMIC DISTURBANCE

Given seismic disturbances with length-scales on the order of that of the radar pulse, the radar-seismic interaction may be detectable as back-scattering phenomena (Figure 1). In this section we investigate this possibility analytically and numerically.

A mathematical model of radar reflection from seismic disturbances

To arrive at a simple mathematical model of such scattering, we begin by describing the radar response in a seismically quiescent environment. The electric field in such an experiment is assumed to satisfy a three parameter model involving the conductivity σ, the

*In fact, a patent exists (Peterson, 1983) for the use of seismic waves to enhance static spatial variations in electrical properties being investigated with airborne and spaceborne radar.

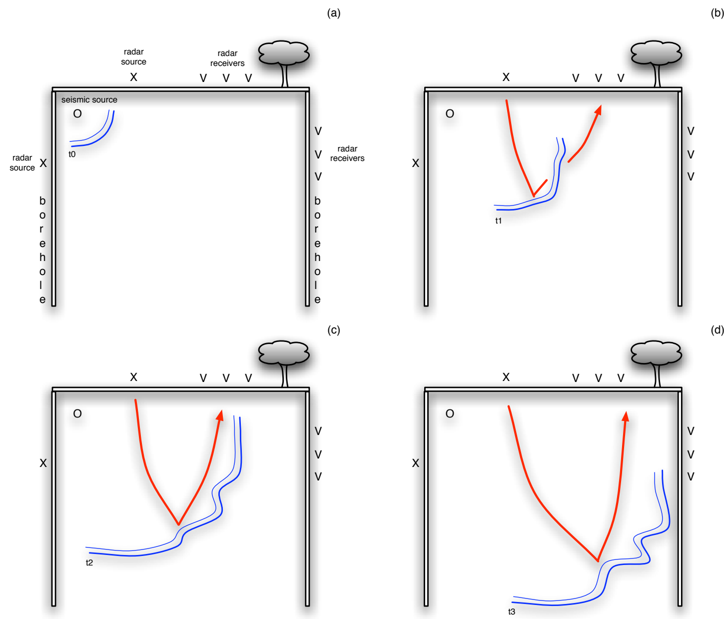

FIG. 1. Schematic diagram of radar reflecting from a seismic wavefield at four times during its propagation. (a)–(d) Times t_0–t_3 respectively. With a (relatively) rapidly varying seismic waveform assumed to induce a perturbation in medium electrical properties, an incident radar field is illustrated undergoing a backscattering process. In the following section we numerically treat the cases of seismic alteration of both conductivity and permittivity.

dielectric permittivity ϵ, and the magnetic permeability μ (Fisher et al., 1992a; Oldenborger and Routh, 2006). Assuming that $\mu = \mu_0$ is spatially constant but σ and ϵ within the Earth are permitted arbitrary spatial variation, the electric field E to be measured satisfies

$$\left[\nabla^2 + K^2\right] E(\mathbf{x}, \mathbf{x}_s, \omega) = \delta(\mathbf{x} - \mathbf{x}_s), \tag{1}$$

where

$$K^2 = -i\omega\mu_0\sigma(\mathbf{x}) + \omega^2\mu_0\epsilon(\mathbf{x}), \tag{2}$$

and where ω is angular frequency, and $\mathbf{x}$ and $\mathbf{x_s}$ are the spatial locations of the observation and source points respectively. To conveniently describe conductivity perturbations, we further consider a reference medium in which $\sigma = \sigma_0$ and $\epsilon = \epsilon_0$ are also spatially constant, and in which the electric field E_0 satisfies

$$\left[\nabla^2 + K_0^2\right] E_0(\mathbf{x}, \mathbf{x}_s, \omega) = \delta(\mathbf{x} - \mathbf{x}_s), \tag{3}$$

where

$$K_0^2 = -i\omega\mu_0\sigma_0 + \omega^2\mu_0\epsilon_0. \tag{4}$$

Routh and Johnson (2005) and Innanen et al. (2007) posed this as a forward scattering problem, the latter of whom defined dimensionless perturbations accounting for the difference between $\sigma(\mathbf{x})$ and σ_0 and $\epsilon(\mathbf{x})$ and ϵ_0:

$$\begin{aligned}\gamma(\mathbf{x}) &\equiv 1 - \frac{\sigma_0}{\sigma(\mathbf{x})},\\ \xi(\mathbf{x}) &\equiv 1 - \frac{\epsilon_0}{\epsilon(\mathbf{x})}.\end{aligned} \tag{5}$$

The actual field and the reference field are related by the Born series[†]:

$$\begin{aligned}&E(\mathbf{x}, \mathbf{x}_s, \omega) = E_0(\mathbf{x}, \mathbf{x}_s, \omega)\\ &- \frac{i\omega\mu_0}{\sigma_0}\int E_0(\mathbf{x}, \mathbf{x}', \omega)\left[\gamma(\mathbf{x}') + \frac{i\omega\sigma_0}{\epsilon_0}\xi(\mathbf{x}')\right] E_0(\mathbf{x}', \mathbf{x_s}, \omega)\\ &- \dots \ .\end{aligned}$$

For simplicity in this paper we will make the Born approximation for the reflected electric field, which is accurate for small, spatially un-extended perturbations:

$$\begin{aligned}E(\mathbf{x}, \mathbf{x}_s, \omega) \approx &E_0(\mathbf{x}, \mathbf{x}_s, \omega) - \frac{i\omega\mu_0}{\sigma_0}\int E_0(\mathbf{x}, \mathbf{x}', \omega)\\ &\times \left[\gamma(\mathbf{x}') + \frac{i\omega\sigma_0}{\epsilon_0}\xi(\mathbf{x}')\right] E_0(\mathbf{x}', \mathbf{x_s}, \omega).\end{aligned} \tag{6}$$

The electric field in a seismically quiescent volume of the Earth, then, is assumed to satisfy equation (6).

When a seismic wave field propagates through this Earth volume, causing a displacement $\mathbf{u}(\mathbf{x}, t)$, all relevant seismoelectric phenomena, including Thompson's, are activated. Let us assume that the local medium conductivity and dielectric permittivity will each be locally, linearly, and instantaneously perturbed by small changes in some set of scalar variables ϑ_i associated with the wave motion. For instance, the simplest scalar variable that directly measures the transient elastic "squeezing" of the medium is the dilatation, or volume strain,

$$\vartheta_1(\mathbf{x}, t) = \nabla_x \cdot \mathbf{u}. \tag{7}$$

Since a radar signal has propagated several hundred kilometres (and attenuated beyond measurement) during the course of a single seismic Δt, let us further consider the seismic time variable to be fixed at some t_0 during the entire radar scattering process. We have

$$\begin{aligned}\gamma_e(\mathbf{x}) &= \sum_i a_i\, \vartheta_i(\mathbf{x}, t_0),\\ \xi_e(\mathbf{x}) &= \sum_i b_i\, \vartheta_i(\mathbf{x}, t_0),\end{aligned} \tag{8}$$

[†]See the topical review by Weglein et al. (2003) for a detailed description of forward and inverse scattering in the seismic exploration problem.

where γ_e and ξ_e are the perturbations associated with the wave. To account for this in the model of the radar experiment, we include γ_e and ξ_e in equation (6), such that, using equation (8), the scattered field $E_s = E - E_0$ becomes

$$\begin{aligned} E_s(\mathbf{x}, \mathbf{x}_s, \omega, t_0) &\approx -\frac{i\omega\mu_0}{\sigma_0} \int E_0(\mathbf{x}, \mathbf{x}', \omega) \\ &\times \left[\gamma(\mathbf{x}') + \sum_i a_i\, \vartheta_i(\mathbf{x}', t_0) + \frac{i\omega\sigma_0}{\epsilon_0}\xi(\mathbf{x}')\right. \\ &+ \left.\frac{i\omega\sigma_0}{\epsilon_0}\sum_i b_i\, \vartheta_i(\mathbf{x}', t_0)\right] E_0(\mathbf{x}', \mathbf{x_s}, \omega). \end{aligned} \tag{9}$$

Hence, within a scattering framework, and assuming a particular linear relationship between the electrical and mechanical properties of the medium, we find in equation (9) a model for radar scattering from the seismic wave field. The magnitudes of the constants a_i and b_i (assuming the validity of this relationship) are of course a practically important issue: given the observations discussed by Thompson (1936) we expect that they not be nil, however, they may be small enough to make straightforward measurement difficult.

In equation (9) the electric field is seen to scatter both from static variations in the medium electrical properties and any perturbations due to seismic disturbances (e.g., γ as well as γ_e). In modeling (or indeed, examining) data associated with a seismic disturbance only, we may wish to treat the latter in isolation. We separate the two by modeling (or acquiring) a "flat", the radar response prior to the activation of any seismic sources. From equation (6), we model the scattered flat response as E_f, where

$$\begin{aligned} E_f(\mathbf{x}, \mathbf{x}_s, \omega) &\approx -\frac{i\omega\mu_0}{\sigma_0} \int E_0(\mathbf{x}, \mathbf{x}', \omega) \\ &\times \left[\gamma(\mathbf{x}') + \frac{i\omega\sigma_0}{\epsilon_0}\xi(\mathbf{x}')\right] E_0(\mathbf{x}', \mathbf{x_s}, \omega). \end{aligned} \tag{10}$$

The scattered field at time t_0 of a seismic experiment may be pre-processed by subtracting the flat to obtain

$$\begin{aligned} E_s^e(\mathbf{x}, \mathbf{x}_s, \omega, t_0) &= E_s - E_f \\ &\approx \frac{i\omega\mu_0}{\sigma_0} \int E_0(\mathbf{x}, \mathbf{x}', \omega) \left[\sum_i a_i\, \vartheta_i(\mathbf{x}', t_0)\right. \\ &+ \left.\frac{i\omega\sigma_0}{\epsilon_0}\sum_i b_i\, \vartheta_i(\mathbf{x}', t_0)\right] E_0(\mathbf{x}', \mathbf{x_s}, \omega), \end{aligned} \tag{11}$$

suppressing[‡] scattering from fixed variations in the electrical properties of the medium and leaving intact scattering particular to the seismically disturbed environment. Having done this, let us define E_s^e to be the modelled data D.

[‡]To the same level of accuracy as the linear, Born approximation.

To specify further, we consider a 2D seismic wave with a 2D radar experiment (since Fourier methods are used, the 3D extension is immediate). A plausible simplification is that radar scattering is dominated by the effect of one variable ϑ on one electrical parameter. The earlier review of the literature suggests that the volume strain and the conductivity are likely candidates, leading to

$$\begin{aligned} &D(k_g, z_g|k_s, z_s, \omega) \\ &= -\frac{ia_1\omega\mu_0}{\sigma_0}\int\int dx'dz' E_0(k_g, z_g|x', z', \omega)\vartheta_1(x', z', t_0) \\ &\times E_0(x', z'|k_s, z_s, \omega), \end{aligned} \tag{12}$$

where $\vartheta_1(x', z', t_0)$ is defined as in equation (7). A further possibility is that the volume strain and the dielectric permittivity are similarly related:

$$\begin{aligned} &D(k_g, z_g|k_s, z_s, \omega) \\ &= -\frac{b_1\omega^2\mu_0}{\epsilon_0}\int\int dx'dz' E_0(k_g, z_g|x', z', \omega)\vartheta_1(x', z', t_0) \\ &\times E_0(x', z'|k_s, z_s, \omega). \end{aligned} \tag{13}$$

There is currently no abundance of evidence to suggest one, other, or either are the more plausible. We will treat them with equal weight in the following sections.

A numerical model of radar reflection from seismic disturbances

In this section we illustrate the behavior of back scattered radar energy from a seismic disturbance, in which the length scales of the latter are close to those of the former. All seismic wave field snapshots were calculated using 2D acoustic forward modeling code written at M-OSRP by Sam Kaplan. All geo-radar wave fields and reflection and transmission radar data were calculated using 2D GPR forward modeling code written and published by Irving and Knight (2006). We consider a 10 x 20m 2D volume of Earth with homogeneous acoustic properties, and consider a seismic source (either a true source or a diffraction) somewhere below having caused a wavefield to propagate up toward the surface. At the center of this surface we place a radar source.

We next assume that the acoustic wavefield represents a perturbation of either the dielectric permittivity (ϵ) or the conductivity (σ) in the volume; in essence this means that the frozen acoustic wave field is a "model" through which we may propagate the radar field.

Figures 2 and 3 are examples of this propagation for the ϵ only and σ only cases; the latter can be seen to produce weaker reflections, but in both cases a scattered field is seen to have been created. Plotted is the y-component of the electric field.

RADAR TRANSMISSION THROUGH A SLOWLY-VARYING SEISMIC DISTURBANCE

Given seismic disturbances with length-scales much larger than that of the radar pulse, the interaction may be detectable in the phase of transmitted, or forward-scattered, radar signals (Figure 4). In this section we investigate this possibility numerically.

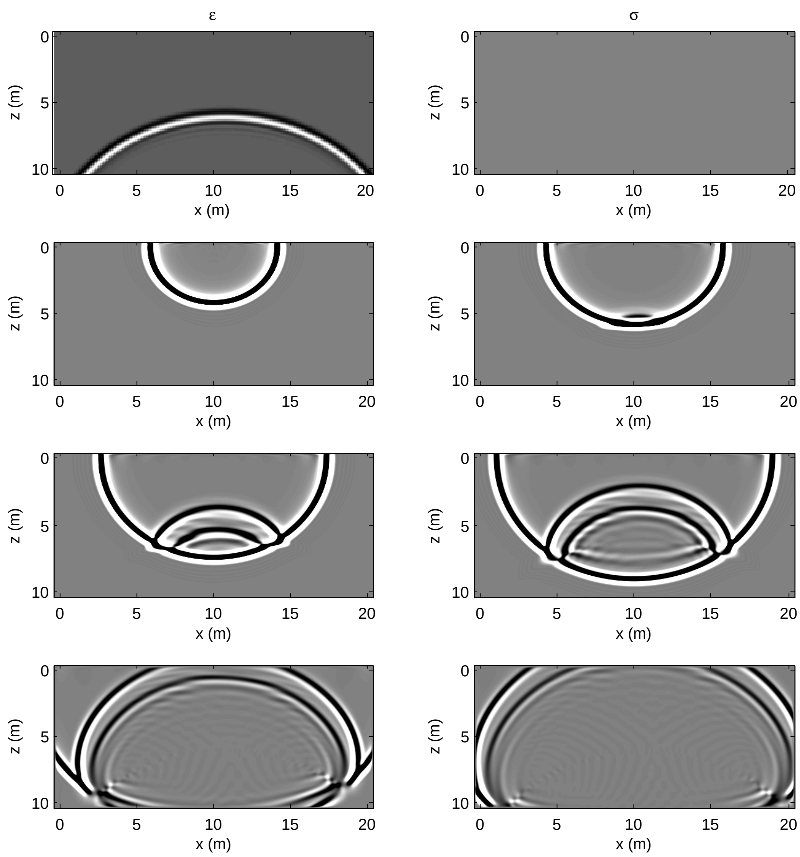

FIG. 2. Numerical model of radar wave field reflecting from a seismic disturbance. In this case we assume a linear instantaneous relationship between (e.g.) seismic volume strain and the dielectric permittivity. The top panels illustrate the spatial distributions of σ and ϵ; here σ is held constant. In the remaining panels the radar wave field is shown at six time points during its propagation.

A numerical model of radar transmission through a seismic disturbance

We illustrate the behavior of forward scattered radar energy propagating through a seismic disturbance, in which the length scales of the latter are large compared to those of the former. All geo-radar wave fields and reflection and transmission radar data were calculated using 2D GPR forward modeling code written and published by Irving and Knight (2006). We again consider a 10 x 20m 2D volume of Earth with homogeneous acoustic properties, and consider a seismic source (either a true source or a diffraction) somewhere below having caused a wavefield to propagate up toward the surface. On the left edge of the volume, halfway down, we place a radar source.

We again assume that the acoustic wavefield represents a perturbation of either the dielectric permittivity (ϵ) or the conductivity (σ) in the volume.

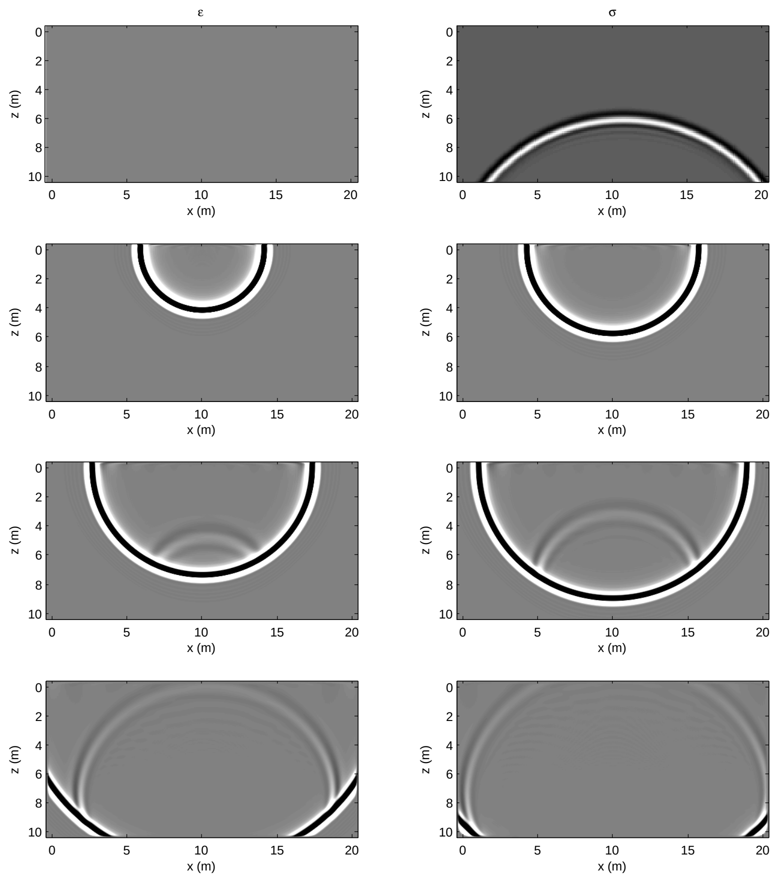

FIG. 3. Numerical model of radar wave field reflecting from a seismic disturbance. In this case we assume a linear instantaneous relationship between (e.g.) seismic volume strain and the conductivity. The top panels illustrate the spatial distributions of σ and ϵ; here ϵ is held constant. In the remaining panels the radar wave field is shown at six time points during its propagation.

Figures 2 and 3 are examples of this propagation for the ϵ only and σ only cases; the latter in this case produces very weak alterations of the field, whereas the former produces clear variations. Plotted is the z-component of the electric field.

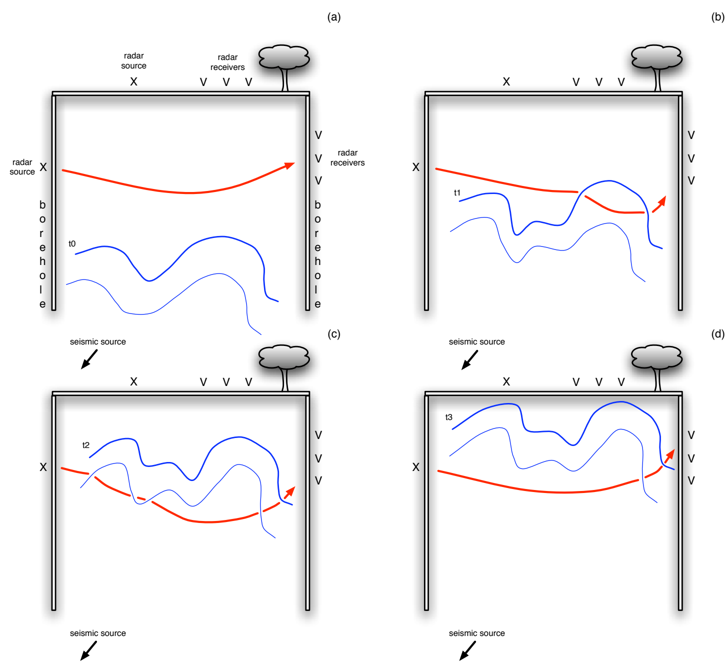

FIG. 4. Schematic diagram of radar transmitting through a seismic wavefield at four times during its propagation. (a)–(d) Times t_0–t_3 respectively. With a (relatively) slowly varying seismic waveform assumed to induce a perturbation in medium electrical properties, an incident radar field is illustrated undergoing a perturbed, forward scattering process. We numerically treat the cases of seismic alteration of both conductivity and permittivity.

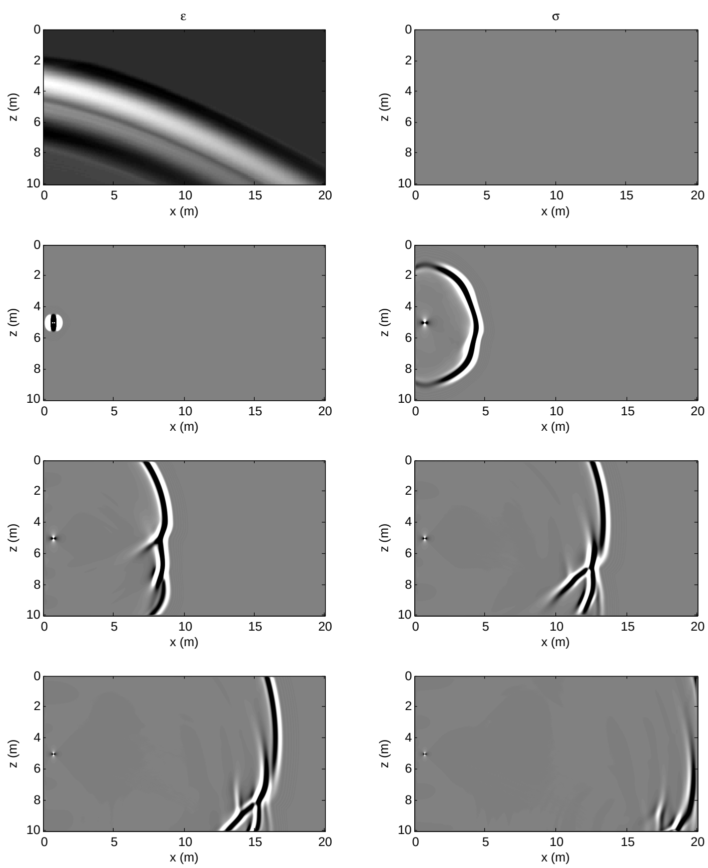

FIG. 5. Numerical model of radar wave field propagating through a seismic disturbance. In this case we assume a linear instantaneous relationship between (e.g.) seismic volume strain and the dielectric permittivity. The top panels illustrate the spatial distributions of σ and ϵ; here σ is held constant. In the remaining panels the radar wave field is shown at six time points during its propagation.

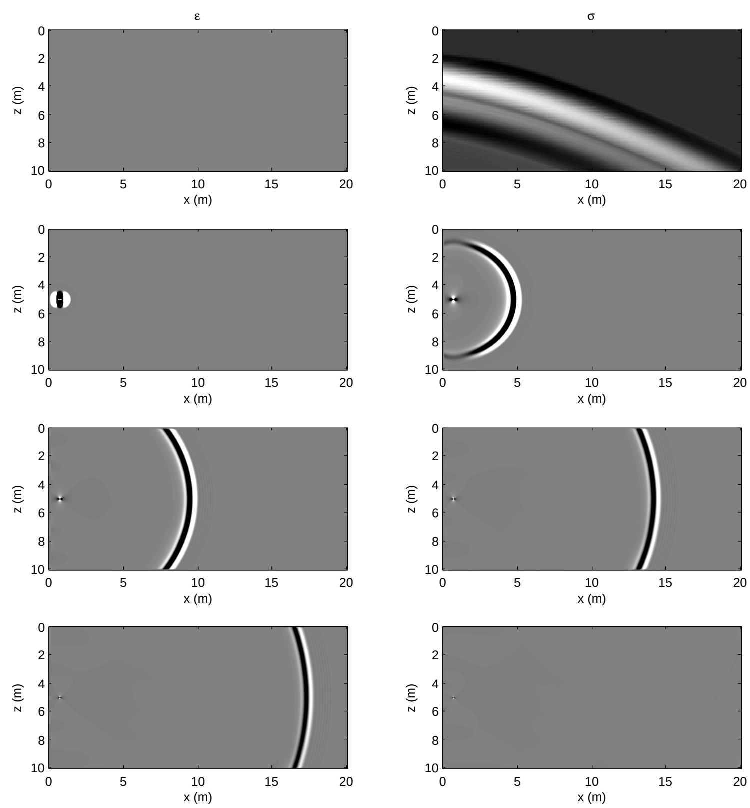

FIG. 6. Numerical model of radar wave field propagating through a seismic disturbance. In this case we assume a linear instantaneous relationship between (e.g.) seismic volume strain and the conductivity. The top panels illustrate the spatial distributions of σ and ϵ; here ϵ is held constant. In the remaining panels the radar wave field is shown at six time points during its propagation.

DISCUSSION

As with the companion paper in this CREWES report on nonlinear seismology, the developments we present pre-suppose that these complex types of wave behaviour, and the data amplitudes that arise from them, are large enough to be measured. That, of course, is not guaranteed. However, our acquisition, instrumentation, and processing technology continue to improve. As they do, we should be prepared to quantify the complicated but potentially informative electromagnetic and seismic phenomena that may be at play in the Earth right now, hidden, though perhaps only temporarily, below a dropping noise level.

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