Antenna placement for sensing buried objects by radio frequency lateral waves

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Abstract—In this paper, we investigate radio wave propagation in proximity to a planar air-ground interface for the purpose of analyzing and improving the sensing of objects buried in the ground. We consider non-resonant electrically small electric dipole antennas as well as moderately directional resonant electric dipole antennas, both of which are analyzed in a variety of configurations. The ground is modeled as a uniform dielectric of finite conductivity. Our findings suggest that transmitting from beneath the ground plane can introduce significantly more complex wave propagation in contrast to transmitting from above the ground plane, by allowing the lateral and ground wave to mix. We also find that a directional sensor located just above the ground with the beam steered parallel to the ground interface is a good choice for sensing buried objects at a lateral distance due to the low loss of the lateral wave near the interface.

I. INTRODUCTION

Interest in underground sensing continues to grow as does the challenge to increase detection depth, resolution, and standoff distance. In particular, we focus on new radio frequency (RF) sensing ideas designed as possible improvements to conventional ground penetrating radar. In this paper, we evaluate antenna configurations designed to advance two different radar detection challenges, yet are related by the underlying physics. The first challenge is the detection of ever more deeply buried objects and accordingly we explore how to improve the concept of the ground contacting sensor by locating it some distance into the ground. The second challenge is the detection of buried objects, shallow or deep, from a lateral distance along the surface as far away as possible. To address this challenge we investigate using a laterally aimed directional sensor to excite wave propagation along the air-ground interface. This is in contrast to laterally projecting a downward looking sensor from some kind of mechanical platform. This part of our study was motivated by extensive research done by The Ohio State University under the funding support of Raytheon [1], and in turn helped our understanding of lateral waves presented throughout this paper.

We use full-wave solutions to Maxwell’s Equations for the electric field as our primary method to evaluate the various antenna configurations. In particular we have chosen to use the finite difference time domain (FDTD) numerical method to perform our simulations. The method is a good choice for problems with spatially varying material properties and feature rich commercial implementations are widely available. We used one of the leading commercial FDTD software packages for the simulations presented in this paper. One drawback of finite difference discretization is the inability to go beyond cartesian-coordinate aligned planar boundaries and interfaces to accurately conform to slanted and arbitrarily shaped boundaries. Additionally as with other volume-based discretizations, problem sizes grow computationally large for electrically large problems, in contrast to other methods. These drawbacks limit our evaluation to using intermediate sized electrical domains with planar boundaries/interfaces aligned with a cartesian-coordinate system.

II. LATERAL WAVES

Wave propagation near an interface between different media has certain characteristics as governed by the boundary conditions applied to Maxwell’s Equations. We are interested in a high-velocity medium of low conductivity (the air) interfacing with a lower velocity medium of moderate conductivity (the ground). We first consider the well known case of locating the transmitter (in our scenario an electric dipole wire antenna) in the high velocity medium such as the air. The wave emitted from the transmitter refracts at the interface according to Snell’s Law and its phase front distorts from a nearly spherical shape as it enters the ground. This is shown in Fig. 1 where the magnitude of the electric field is plotted. Notice the phase front just below the ground is somewhat flattened and wave propagation just below and along the interface has a linear phase front; this is known as a lateral wave [2]. The lateral wave’s phase front is at an angle given by Snell’s Law and it approaches the critical angle as the originating air-wave’s propagation direction approaches 90° from normal. The wave front smoothly transitions from linear to curved as the propagation direction becomes more normal to the surface.

III. DEEP SENSING VIA A BURIED TRANSMITTER

The concept of burying a transmitter for sensing deep below ground has been previously investigated and been shown to more efficiently deliver signal onto a buried object than the
Fig. 1. The graphic represents a snapshot in time of the magnitude of the electric field 0.289 µs (300 time steps at 962.9 ps/step) after the initial excitation of an electric dipole wire antenna. The dipole is a 2.5 m long center-fed wire embedded in freespace 10 m above a ground plane. The waveform is a sinusoid of frequency 25 MHz and therefore has a freespace wavelength of 12 m. The ground has a conductivity, $\sigma$, of 0.001 S/m and a relative permittivity, $\epsilon_r$, of 4. A cube shaped void with a side length 5 m is shown in the lower left. The color range is 126 dB.

equivalent transmitter located above the ground [3]. This is primarily due to avoiding the partial reflection of the signal off the air-ground interface. Additionally the transmitter may also be closer to the buried object, thereby reducing the strong signal attenuation within the ground on route to the object. In Fig. 2 the magnitude of the electric field is plotted for a buried dipole transmitter. It is shown that the buried transmitter emits a nearly spherical wave that is similar to it being surrounded by air, but scaled by the surrounding permittivity. It is also shown that this ground wave refracts into the air and creates an airwave. This refracted air-wave then induces a lateral wave in the ground just as if the transmitter was located above ground. A major difference between locating a transmitter above or below ground is the presence of the nearly spherical ground wave and its interference with the lateral wave. Examination of Fig. 2 suggests that whether an object is first illuminated by a ground wave, lateral wave, or a wave characterized by their interference - depends on the locations of the buried object and transmitter. Objects further away from the transmitter are more likely to be first illuminated by the lateral wave since its velocity is higher than the ground wave. Shallow objects are also more likely to be first illuminated by the lateral wave for the same reason. Deeper objects and those closer to the transmitter are more likely to be illuminated by the nearly spherical ground wave. Fig. 3 shows the effects of higher ground conductivity in which the magnitude of the electric field is plotted for ground conductivities of (a) 0.01 S/m and (b) 0.1 S/m. As expected, increased conductivity reduces the attenuation length scale (i.e. skin depth) and the fields are more strongly attenuated. Additionally, higher ground conductivity leads to proportionally more propagation through the air and stronger confinement of the lateral wave to the surface.

Fig. 2. The graphic represents a snapshot in time of the magnitude of the electric field 0.356 µs (370 time steps at 962.9 ps/step) after the initial excitation of an electric dipole wire antenna. The dipole is a 2.5 m long center-fed wire embedded in the ground 10 m below the surface. The waveform is a sinusoid of frequency 25 MHz and therefore has a freespace wavelength of 12 m. The ground has a conductivity, $\sigma$, of 0.001 S/m and a relative permittivity, $\epsilon_r$, of 4. A cube shaped void with a side length 5 m is shown in the lower left. The color range is 126 dB.

(a) $\sigma = 0.01$ S/m (b) $\sigma = 0.1$ S/m

Fig. 3. The graphic represents a snapshot in time of the magnitude of the electric field 0.356 µs (370 time steps at 962.9 ps/step) after the initial excitation of an electric dipole antenna. The dipole is a 2.5 m long center-fed wire embedded in the ground 10 m below the surface. The waveform is a sinusoid of frequency 25 MHz and therefore has a freespace wavelength of 12 m. A cube shaped void with a side length 5 m is shown in the lower left. The ground has a relative permittivity, $\epsilon_r$, of 4 and a conductivity (a) $\sigma$, of 0.01 S/m and (b) $\sigma$, of 0.1 S/m. The color range is 210 dB.
antenna patterns calculated by the modified method of images to those computed by full-wave FDTD method for a short electric dipole antenna over a ground plane of various electrical conductivities. Typical ground electrical conductivities are in the range of 0.001-1.0 S/m [5]. As shown in the figure, both methods predict a shift upward and away from the ground with the shift decreasing as the conductivity increases. However the full-wave solution correctly shows that there is transmission along the ground (at angles $\theta = 90^\circ$) and $270^\circ$ as well as propagation into the ground (for angles in the range $90^\circ < \theta < 270^\circ$).

In order to study how to strongly illuminate a buried object from a far-off lateral distance, we choose a scenario where the antenna location (i.e. height) is varied, but not its orientation. This choice yields a series of FDTD simulations, one for each height. The heights are relative from the dipole’s lowest point to the ground surface, and range from 0.5 m to 40.5 m at a spacing of 5 m (i.e. 0.5 m, 5.5 m, 10.5 m, \ldots, 35.5 m, 40.5 m). We choose to vertically orient the electric dipole antenna in part to take advantage of the polarizing angle, in part to take advantage of aiming the beam center close to the direction of interest, and in part due to the loss of accuracy of the FDTD method for surfaces nonaligned with the cartesian grid. The vertically oriented dipole takes advantage of that fact that an ideal plane wave with an electric vector in the plane of incidence has a reflection coefficient of zero at the polarizing angle. Vertical orientation is therefore a good choice to help minimize surface reflection due to polarization considerations. However, further refinement in orientation to direct the beam center onto the object (refraction included) will in general occur at a different orientation than minimizing the surface reflection. Additionally such refinement may be difficult to precisely quantify due to unknown and potentially

IV. LATERAL SENSING BY A DIRECTIONAL TRANSMITTER

The lateral sensing concept is that of a transmitter located above the ground surface that is designed to illuminate just below the surface from a far-off lateral distance. In order to strongly illuminate an object (or search volume) above ground, typically a transmitter can be oriented such that it is “aimed” at the object by knowing the antenna’s far-field radiation pattern. It is more challenging to maximize the signal on a buried object or volume beneath the ground surface at a lateral distance by similarly adjusting the antenna’s position and orientation. This is due to several factors, among them are (a) directing the antenna pattern (e.g. beam center) onto the object involves refraction across an interface, (b) the loss due to partial reflection at the interface being angle dependent, and (c) the pattern’s shift up and away from the ground due to its proximity to a ground plane of finite electrical conductivity.

We first address the shift up and away from the ground of the antenna pattern caused by its proximity to a ground plane of finite electrical conductivity [4]. A common method to evaluate an antenna located above a ground plane is the method of images. For ground planes of finite electrical conductivity, this method is modified such that the image contribution is weighted by the Fresnel reflection coefficient. However, this analysis disregards the lateral wave and therefore produces an erroneous result in that the pattern goes to zero as the grazing angle goes to zero. In Fig. 4 we compare far-field

![Fig. 4. The graphic represents the far-field antenna pattern normalized to one for a range of electric conductivities of the ground. The antenna is assumed to be an electrically short wire dipole and for the FDTD simulation is a 0.6 m long center-fed wire whose center is 2 m (a quarter wave) above the surface. The excitation waveform is a sinusoid of frequency 37.5 MHz and therefore has a freespace wavelength of 8 m. The ground has a relative permittivity, $\epsilon_r$, of 4. The angle zero corresponds to vertical whereas the angles $90^\circ$ and $270^\circ$ correspond to propagation along the surface.](image1)

![Fig. 5. The magnitude of the electric field versus time inside a 5 m cubic void. The void’s leading edge is located a lateral distance of 55 m from the dipole axis and is 10 m deep. The antenna is a full-wave electric wire dipole 6.5 m long, center-fed, with a sinusoid waveform of frequency 46.2 MHz and a corresponding freespace wavelength of 6.5 m. The ground has a conductivity, $\sigma$, of 0.001 S/m and a relative permittivity, $\epsilon_r$, of 4. The three curves correspond to the antenna’s height above the ground as measured from its lowest endpoint and take the values of 0.5 m (see Fig. 6a), 15.5 m (see Fig. 7a), and 40.5 m above the ground.](image2)
spatially varying material properties. Limiting the dipole to vertical orientation is a recognition, that for illuminating buried objects from a far-off lateral distance, it directs the beam center near to the search volume while helping to minimize surface reflection.

We consider a resonant full-wave wire dipole antenna instead of the electrically small dipole antennas that have been previously considered. This choice offers a narrower beamwidth in the plane parallel with the ground and may potentially couple more strongly to the lateral wave. The results of the simulations are shown in Fig. 5, which shows the magnitude of the electric field versus time inside a 5 m cubic void. Only results corresponding to three of the nine different antenna heights are shown to make the figure more readable. At convergence, the void is illuminated the strongest at a height of 15.5 m. The illumination increases monotonically with height until reaching a maximum (at a height of 15.5 m) and then monotonically decreases as the height increases further. It is not surprising that the strongest illumination occurs at an intermediate height. The vertical polarization’s reflection coefficient has a minimum at a corresponding intermediate height. It is interesting to note that the maximum steady-state field strength in the void differs by approximately a factor of two between the weakest and strongest configurations. This supports the idea that a directional antenna positioned near to the ground and steered parallel to the ground while not being optimal, may actually be useful, in that it is a relatively simple orientation and the illumination remains strong. Fig. 6 shows the field snapshot and far-field pattern for the antenna configuration closest to the surface (height of 0.5 m). Fig. 7 shows the field snapshot and far-field pattern for the antenna configuration that most strongly illuminates the void (height of 15.5 m).

V. CONCLUSION

We investigate the use of a buried transmitter for deep sensing as well as the use of a directional above-ground transmitter for far-off lateral sensing. We find that both share the underlying physics of lateral wave propagation. Our findings suggest that transmitting from beneath the ground plane can introduce significantly more complex wave propagation in contrast to transmitting from above the ground plane, by allowing the lateral and ground wave to mix. We also find that a directional sensor located just above the ground with the beam steered parallel to the ground interface is a good choice for sensing buried objects at a far-off lateral distance due to the low loss of the lateral wave near the interface.

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