Use of 2D FDTD Simulation and the Determination of the GPR Travel Path Angle for Oblique B-Scans of 2D Geometries

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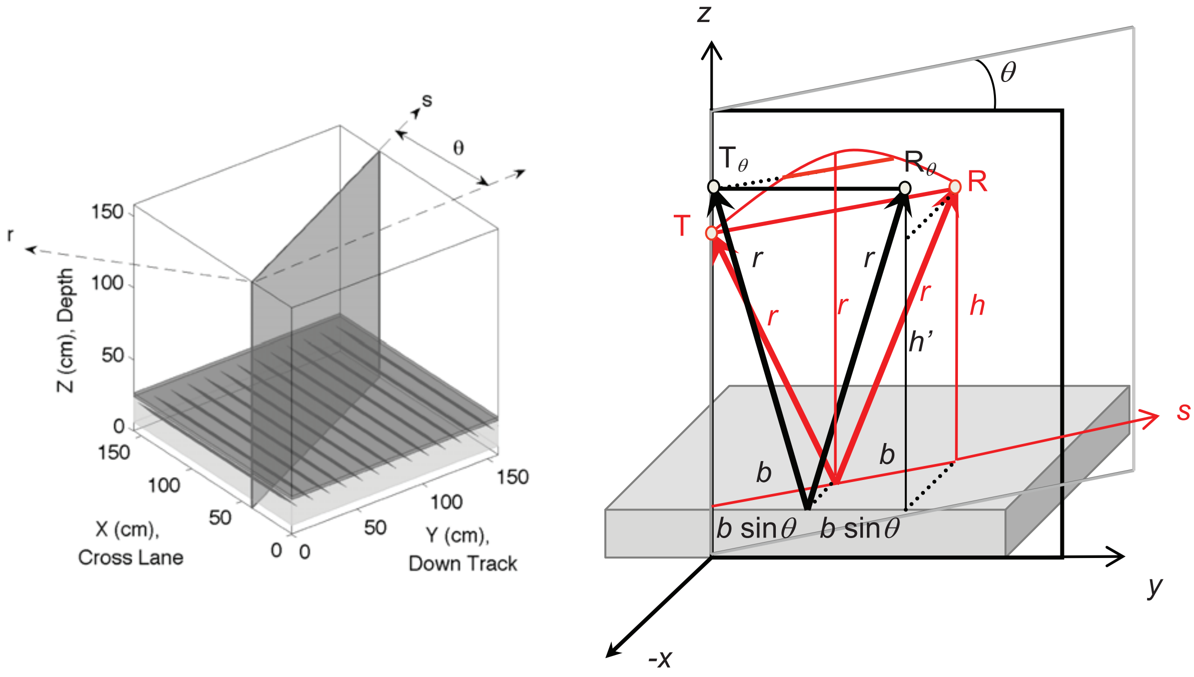
Abstract

The geometry of subsurface features such as tunnels and reinforcing steel buried in a layered media is typically considered invariant in the third dimension. The simulation of electromagnetic wave scattering can therefore be simplified into a 2D problem that accurately represents geometric features and adequately captures scattering when compared to the 3D simulation. As illustrated in Figure 1(a), while the geometry is 2-dimensional in the *y-z* plane, the path that the ground penetrating radar (GPR) travels, along the *s-z* plane, does not necessarily coincide with this cross-sectional plane. The scattering from a subsurface feature, and subsequent interactions, will be different if the GPR is travelling across a tunnel perpendicularly ($\hat{s} = \hat{y}$, $\theta = 0^{\circ}$), than if it is travelling across the tunnel out-of-plane at an arbitrary angle ($\hat{s} \neq \hat{y}$, $\theta \neq 0^{\circ}$).

The 2D Finite Difference Time Domain (FDTD) simulation of wave propagation well approximates the true 3D propagation in a cross sectional plane for geometries invariant in the third dimension [1]. The 3D FDTD simulates realistic wave propagation and scattering between elements even when the cross-sectional plane geometry is two-dimensional. For the same geometric invariance, when the GPR is moving out-of-plane, a 2D simulation can still be used to generate reasonably accurate B-scans. This is accomplished by projecting the physical geometry and antenna configuration back into the *y-z* plane. However, inaccuracies arise when the antenna is bi-static because the delay from transmitter to scatterer to receiver is underestimated in the 2D projected geometry. For 2D simulation, assuming an air-launched GPR with a given bi-static phase center separation 2*b* and height above the surface *h*, the transmitter (*T*) and receiver (*R*) can be approximated by translation into the *y-z* plane. A circle centered on the surface directly under the mid-point of the line segment between the transmitter and receiver has a radius *r* of $\sqrt{b^2 + h^2}$. If the transmitter and receiver are located in the *s-z* plane and translated to the *y-z* plane, their separation is reduced by cos θ, but their height *h'* must increased so that they are the

same distance r from the point on the surface directly under the mid-point of the line segment between the 2D transmitter (T_θ) and the 2D receiver (R_θ) or $h' = \sqrt{r^2 - b^2 \cos^2 \theta}$ above the surface of the deck as shown in Figure 1(b). With this mapping, the total path length to the closest ground point is the same for 2D and 3D, as are the horizontal distances from each transmitter and from each receiver to a cross sectional feature at a given y-coordinate. It will be shown that results using this reconfigured excitation are well-matched to the 3D results.



(a) (b)

Figure 1. (a) Example geometry for antenna movement in the *s*-direction and polarization in the *r*-direction (b) Translation of bi-static transmitter (T) and receiver (R) from the *s*-*z* plane to the *y*-*z* plane.

Waves propagating from an air-launched Ground Penetrating Radar (GPR) are essentially spherical in air. Once the waves pass into a dielectric material such as soil or concrete, the wavefront shape and B-scan contours for scattering by a point object at a fixed depth are essentially hyperbolic. The exact shape can be well approximated by a hyperbola with parameters that depend on the dielectric constant of the surface media, the height of the source, the depth of the point object [2], and the separation between the transmitter and receiver. Figure 2 shows a comparison of hyperbolas extracted from the B-scan of scattering from a rebar buried 4.8cm under concrete generated by 3D and 2D FDTD simulation. The sensor configuration has a bi-static separation of 51.0cm, and a height above the concrete surface of 30.0cm. Even at large out-of-plane GPR travel path angles, such as θ ≈ 66°, the hyperbolas generated using the 2D configuration translated to the *y-z* plane, described in Figure 1(b), match extremely well with the 3D generated hyperbolas. There is a slight time discrepancy between the hyperbolas. This is due to the differential distance that the wave travels through the concrete between the 3D out-of-plane bi-static and 2D translated bi-static cases. This differential distance will be derived and implemented into the analysis.

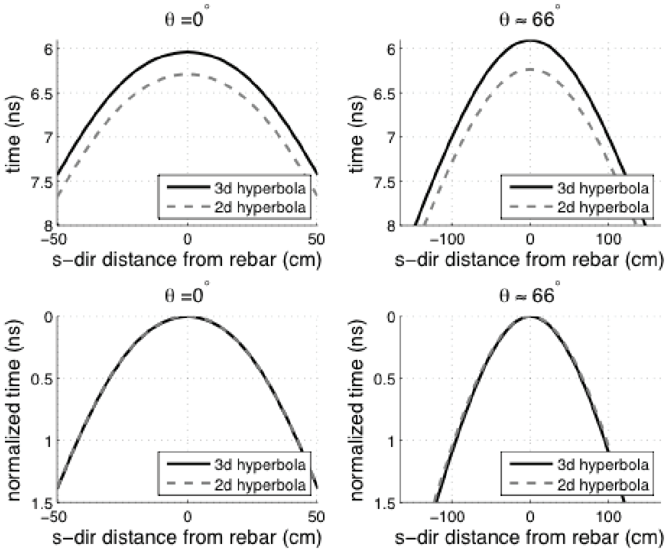
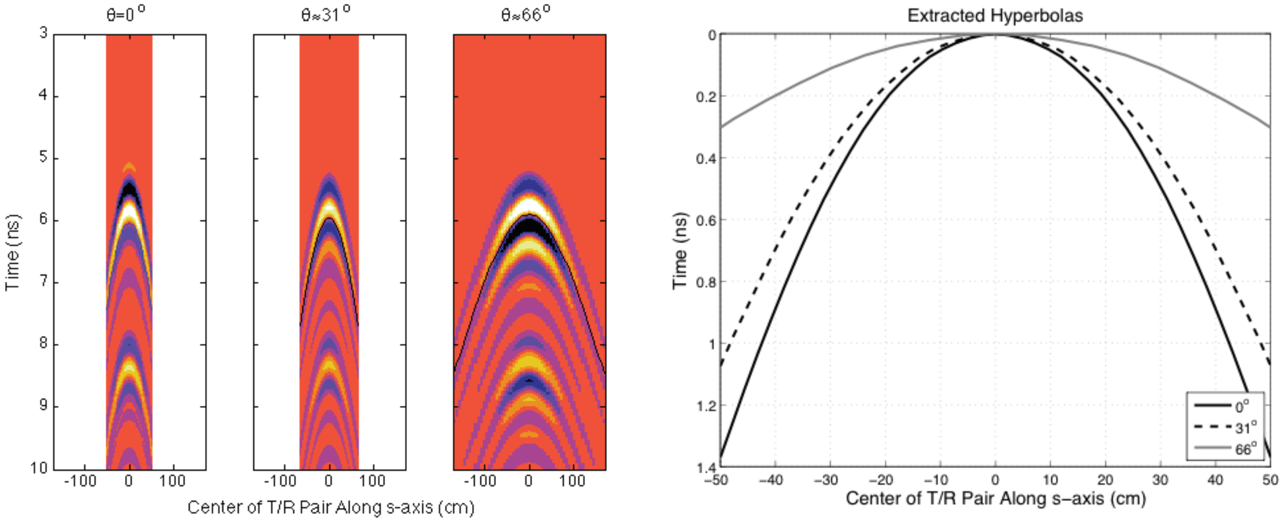


Figure 2. Comparison between the 3D and 2D simulated B-scan contours of scattering from a single rebar buried in concrete. The normalized time plots account for the differential distances the waves travel in the 2D simulation and better indicate matching of the shape.

Figure 3(a) shows B-scan contours from the 3D FDTD for a single 1.8cm diameter rebar buried under approximately 4.8cm of concrete at a variety of angles of GPR travel path. The central excitation frequency and bandwidth were both approximately 1GHz. The background air/concrete interface has been removed to highlight the scattering from the single rebar target. The differences in the hyperbolic shapes of the scattering due to the reinforcing steel is more clearly shown by comparing the hyperbolas plotted in Figure 3(b).

By comparing the 2D computed B-scan contours to 3D measured B-scans it is possible to determine the angle of the GPR travel path. It is evident from Figure 3(b) that changing the out-of-plane GPR travel path has discernable influence on the shapes of the hyperbolas. Since the hyperbolas match well between the 3D bi-static configuration and 2D translated bi-static configurations, a library of 2D FDTD generated B-scan hyperbolas populated from initially estimated point scattering targets (tunnels, arrays of rebar) for various angles of GPR travel path can be used to determine the angle of GPR travel relative to the cross sectional plane.



(a) (b)

Figure 3. (a) 3D FDTD simulated B-scan contours for a reinforcing steel bar buried in concrete with background removed, and (b) comparison of hyperbolas plotting the B-scan scattered signal peaks at various angles.

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References

[1] K. Belli, H. Zhan, S. Wadia-Fascetti, and C. Rappaport, “Comparison of the accuracy of 2D versus 3D FDTD air-coupled GPR modeling of bridge deck deterioration,” *Research in Nondestructive Evaluation*, vol. 20, no. 2, pp. 94—115, Apr. 2009.

[2] C. Rappaport, “Accurate determination of underground GPR wavefront and B-scan shape from above ground point sources,” *IEEE Trans. Geoscience and Remote Sen*sing, vol. 45, no. 8, pp. 2429-2434, Aug. 2007.