Radio Frequency Electromagnetic Wave Communication in Deep Oil Wells

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Effective communication in oil wells is challenging because of partially-conductive soil and rock, and inhomogeneities in the ground. An alternative approach to communicating with the drill head, or electronics associated with it, is to use the drilled hole itself as a path for communication. The typical well hole is cased with a steel lining and surrounded by air or cement. The electrically-conductive casing, along with a second conductor consisting of the earth itself, acts like a dielectric waveguide used in fiber optics to guide light. The earth is not very conductive, but as long as it has a different dielectric constant than air, it can act to guide waves axially through the gap between the steel and the ground.

An analysis of typical oil well geometry (axi-symmetric about the drill center with metal for $\rho < R_1 = 7.5$ cm and slightly lossy soil with $\varepsilon_2 = 5 + i\,0.07$ at 1 MHz for $\rho > R_2 = 9.5$ cm where the 2 cm annular gap between the two radii is filled with air) requires numerical searching across the complex plane for wavenumber solutions to the appropriate guidance relation given by:

$$\varepsilon_1 k_{\rho 2} J_1(k_{\rho 1}R_2) K_0(k_{\rho 2}R_2) Y_0(k_{\rho 1}R_1) + \varepsilon_2 k_{\rho 1} J_0(k_{\rho 1}R_2) K_1(k_{\rho 2}R_2) Y_0(k_{\rho 1}R_1) = \varepsilon_1 k_{\rho 2} J_0(k_{\rho 1}R_1) K_0(k_{\rho 2}R_2) Y_1(k_{\rho 1}R_2) + \varepsilon_2 k_{\rho 1} J_0(k_{\rho 1}R_1) K_1(k_{\rho 2}R_2) Y_0(k_{\rho 1}R_2)$$

where the dispersion relations for air and ground are $k_{\rho 1}^2 + k_z^2 = \omega^2 \mu_0 \varepsilon_1$ and $-k_{\rho 2}^2 + k_z^2 = \omega^2 \mu_0 \varepsilon_2$, respectively, and *J, K*, and *Y* are standard Bessel functions. This equation results from satisfying the transverse field boundary conditions at the two interfaces. For these parameters at 1 MHz, the solution is $k_z = 0.0440 + i\,0.000882$ m^{-1}.

Axi-symmetric (2D) Finite Difference Frequency Domain (FDFD) computations for the given geometry at 1 MHz are shown in the figures for a 392 x 2025 point computational grid in the ρ and z directions which includes a 12-point Perfectly Matched Layer (PML) on the three open sides of the grid. The FDFD computation matches the analytical solution quite well; the slight ripples that can be observed that are a result of small standing waves created by imperfections in the PML. The circumferential magnetic field H_ϕ and Poynting power S_z are concentrated in the annular gap between the casing and the rock. The corresponding electric fields are mostly radial, dropping by a factor of 5 at the rock interface. Note that the power decreases by only 7.7 dB per 1000 m of depth. At 1 MHz, this would provide sufficient bandwidth to transfer information at any typically-desired rate.