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FDTD MODELING OF A RESISTIVELY LOADED MONOPOLE FOR NARROW BOREHOLE GROUND PENETRATING RADAR

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Abstract—The geometry of a broadband (0.7–2 GHz) monopole antenna intended to be inserted in a narrow borehole for ground penetrating crosshole application is proposed. The monopole antenna is supposed to be designed on a printed circuit board (PCB) using the low-cost microstrip technology. Based on the FDTD approach, the modeling of the antenna surrounded by its environment has been made, and the influence of several parameters on the radiated waveforms has been studied in details. The modeling of a transmission link has also been considered. Such a study aims at the realization of a narrow broadband antenna.

1. INTRODUCTION

Ground Penetrating Radar (GPR) is a geophysical method that allows to characterize the shallow subsurface using short electromagnetic pulses traveling through the earth for several configurations of transmitting and receiving antennas. GPR surveying can be divided into two main modes of operation: surface-based reflection surveying, and crosshole surveying [1–3]. In particular, crosshole radar tomography is being used for high-resolution electromagnetic characterization of the shallow subsurface between boreholes. It relies on the transmission of a short electromagnetic pulse (with duration of a few ns) which is radiated from a transmitting antenna located in one borehole, transmitted through the subsurface, and recorded at a receiving antenna located in an adjacent borehole. The data set acquired using several positions of the transmitting and the receiving antennas as a function of the depth from the soil surface gives a tomographic imaging. The travel times and amplitudes of the

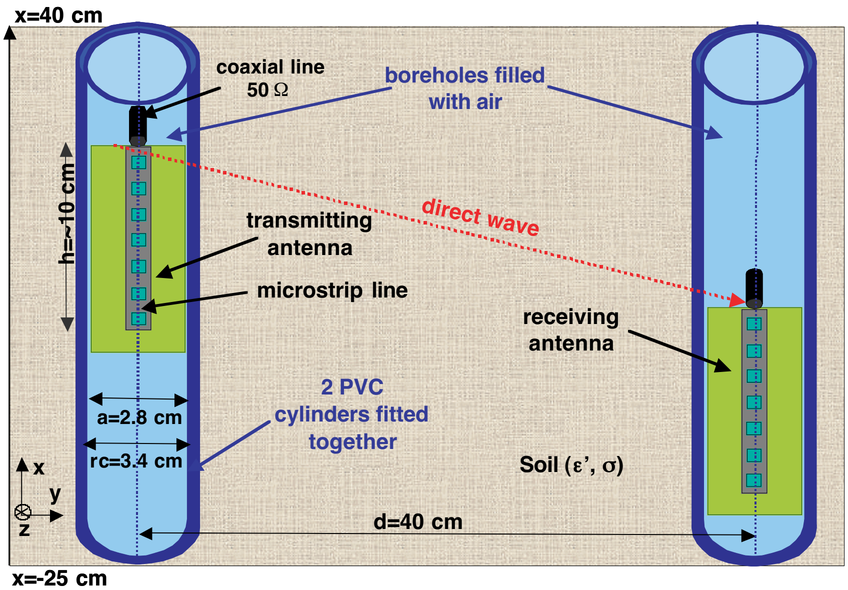


Figure 1. Geometry of a crosshole radar involving 2 loaded monopole antennas in parallel.

electromagnetic waves transmitted through the soil are analyzed to determine the variation of the dielectric properties of the soil (complex permittivities) as a function of depth [3–6]. In our application, we are particularly interested in obtaining a profile in depth of the volumetric moisture content of the soil [3, 4].

The present experimental configuration appears specific as narrow boreholes are considered for the characterization of test sites of civil engineering earthworks. Usually, a double probe gamma is pushed into boreholes drilled in the soil for measuring precisely its volumetric density along a depth profile between 2 boreholes with diameter 34 mm and separated by a distance of 40 cm (see Fig. 1) [7]. Researches are currently performed in our laboratory to study the possibility of replacing the probe gamma by a crosshole radar which will be able to characterize the soil properties in a depth ranging from 2 to 6 m in the frequency band 0.7–2 GHz. Planar antennas present attractive features such as low-profile, low-cost, and low-weight and can be used in wireless [8–12], sensor [13] or GPR [14] applications; various geometries have been proposed by several authors. In the present context, we have studied the modeling of a realistic loaded monopole whose geometry appears particularly adapted to a narrow borehole; it can be designed on a printed circuit board (PCB). Using FDTD modeling, the influence the influence of several parameters associated with the antenna of several parameters associated with the antenna and borehole geometries, and the surrounding medium on the radiated waveforms has been analyzed in details [15, 16] Afterwards, a transmission link between identical transmitting and receiving loaded antennas has been modeled, and the detected waveforms have been compared to those issued from a punctual probe.

2. ANTENNA DESIGN

The motivation of borehole antenna design is to make a low-cost and simple broadband antenna (0.7–2 GHz) which can be inserted into a narrow borehole of interior diameter 34 mm. In such a case, an antenna formed of a monopole loaded with a resistive profile (according to the Wu-King (WK) increasing resistive profile from the feed-point to the open end of the antenna) appears the best compromise to obtain broadband characteristics in a narrow geometry [17–20]. To insert easily the antenna in the centre of the borehole, we have positioned the antenna in a PVC ($\varepsilon' = 3.5$) borehole with interior diameter $a = 28$ mm and exterior diameter $rc = 34$ mm as shown in Fig. 1; the antennas can be positioned in parallel or facing each other. The antenna is supposed to be fabricated on a 1.5 mm-thick FR4 substrate ($\varepsilon' = 4.4$) with a ground plane on the backside, and it is fed by a 50 Ohms coaxial line. Parameter studies have led to the definition of an antenna made of a microstrip line (with conductor thickness 35 μm) with width of 3 mm and with length of 96 mm. In such a case, the real impedance of the antenna in the considered band is close to 50 Ω, and the first resonant frequency is 1.05 GHz. To lower the reflection at the feed-point and to minimize the reflection at the open end, a modified WK profile has been considered. Thus, the resistance distribution per unit length is expressed by [19, 20]:

$$R(z) = \left\{ \frac{1 - |z/h|}{R_0} + \frac{(1 - |z/h|)^2}{R_0} \right\}^{-1} \tag{1}$$

where:

$$R_0 = \frac{\eta_0 \psi_0}{2\pi h} \tag{2}$$

is the resistance per unit length at the feed point $z = 0$, z is the distance from the feed point along the arms, η_0 is the wave impedance of free space, and h is the length of each arm.

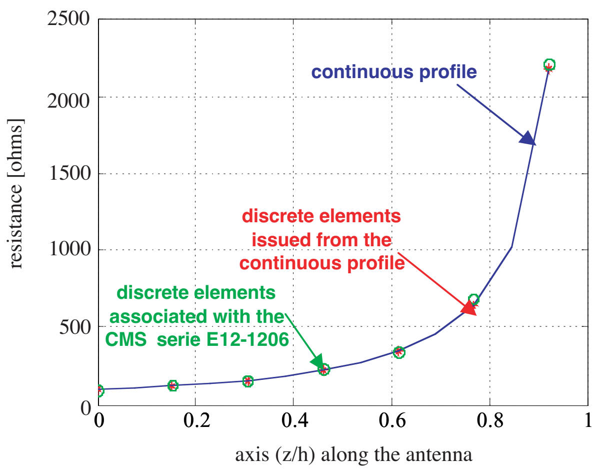


Figure 2. Distribution of the resistive loading along the antenna arm considering 7 discrete elements.

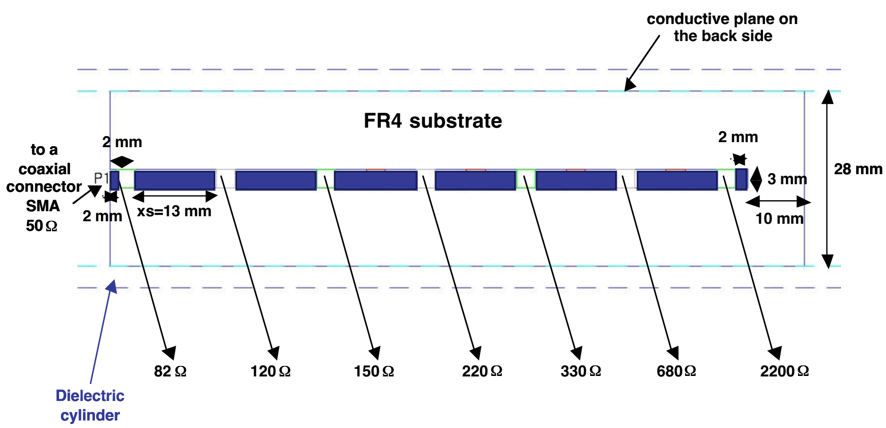
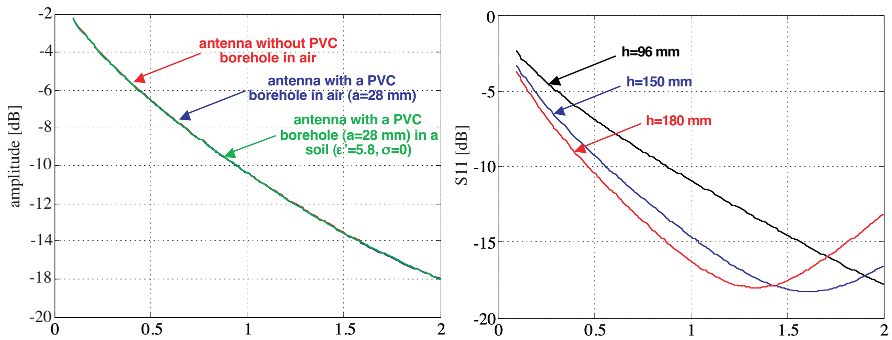


Figure 3. Geometry of the resistively loaded monopole with 7 CMS resistances.

ψ_0 is in general a complex-valued function of the frequency and of the dimension of the dipole or monopole antenna, but in practice several authors design a resistive profile by taking the parameter ψ_0 at its zero frequency such as [17, 18]:

$$\psi_0 = 2\left[\ln\left(\frac{2h}{r}\right) - 1\right] \tag{3}$$

The value of ψ_0 has an influence on the absorption of the current



(a) S11 (dB) of the loaded monopole with length h=96 mm

(b) S11 (dB) of the loaded monopole (with a PVC borehole, in air) with lengths h=96 mm (xs =13 mm), 150 mm (xs=22 mm), and 180 mm (xs=27 mm)

Figure 4. Amplitude of S_{11} (dB) of the loaded monopole in the presence or not of a PVC borehole filled with air in soil ($\varepsilon' = 1$ and $\varepsilon' = 5.8$).

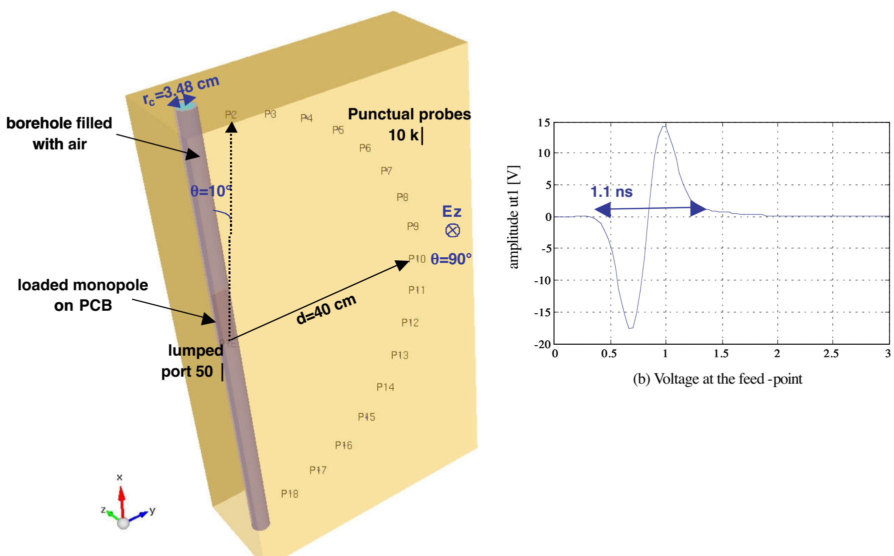
along each arm; its choice appears as a compromise since the distributed absorption must not reduce too heavily the antenna radiation efficiency; so, its value is usually chosen between 3 and 11. Choosing $\psi_0 = 3$, the continuous resistive loading along the antenna has been appropriately discretized in a number of sections; as shown in Fig. 2 and Fig. 3, 7 sections have been currently defined. In the FDTD numerical model, each resistance is modeled by a square with sides of 2 mm. The source is a lumped source with a characteristic impedance of 50 Ω. The overall antenna geometry has been optimized in order to obtain a reflection coefficient S_{11} (see Fig. 4) at the feed-point less than -6 dB in the frequency band [0.7; 2 GHz] with a reduced number of resistive elements in order to reduce dissipation along the antenna [17–21].

3. PARAMETER STUDY

A detailed parameter study has been performed in order to analyze the influence of the surrounding environment on the waveforms radiated by the loaded monopole inserted in a borehole made of PVC (see Fig. 5) and filled with air. We have first studied the waveforms radiated in air using 17 probes regularly positioned in the half right plane $[10°; 170°]$ as a function of the observation angle at a distance $d = 40$ cm (assumed to be the separation distance between boreholes). Afterwards, the waveforms detected by probes in an adjacent borehole have been analyzed in the presence of a surrounding medium made of air or soil ($\varepsilon' = 5.8$, $\sigma = 0$, $\mu = 1$). Finally, the waveforms issued from a complete transmission link including identical transmission and receiving antennas have been studied.

3.1. Radiated Waveforms Detected by Probes as a Function of the Observation Angle

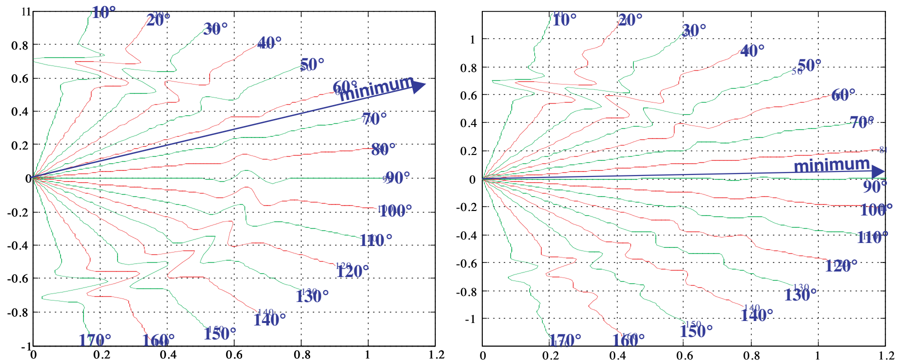
As shown in Fig. 5, punctual probes (with a 1 mm height in the 3 directions) have been positioned at a distance $d = 40\,\mathrm{cm}$ from the antenna feed-point in a plane (xOy) parallel, and in a plane (xOz) perpendicular to the antenna. Several probe orientations have been considered in order to detect the components $(Ex, Ey$, and $Ez)$ of the electric field radiated by the antenna for a range of observation angles $[10°; 170°]$ with a step of $10°$. On Fig. 6a and Fig. 6b the radiated waveforms of Ez in both planes xOy and xOz are presented respectively. The amplitudes of Ez in both planes are amplitudes of the same order with a minimum amplitude corresponding to angles close to 65° and 90°, respectively. In the plane xOz a phase variation of 180° in the waveforms is observed on both sets of angles $[10°; 90°]$ and $[90°; 170°]$. Moreover, we have observed that in both planes the



(b) Voltage at the feed -point

(a) Geometry of the radiating loaded monopole

Figure 5. Modeling of the borehole monopole with the FDTD approach (EMPIRE software) using surrounding probes; (a) the geometry, and (b) the voltage at the feed point.



(a) Normalized radiated waveforms of Ez in the plane xOy for observation angles in the range [0,180°]

(b) Normalized radiated waveforms of Ez in the plane xOz for observation angles in the range [0,180°]

Figure 6. Waveforms (voltages ut2–ut18) associated with field Ez radiated at angles in the range $[10°; 170°]$ by the resistively loaded monopole in (a) the plane xOy, and (b) in the plane xOz.

amplitude of Ey appears negligible. The waveforms associated with field Ex show more marked undulations and thus more time dispersion; their amplitudes are of the same order as compared to field Ez.

3.2. Radiated Waveforms Detected by Probes in a Adjacent Borehole

The transmitting monopole is assumed to remain at a fixed position ($x = 0$), and the radiated waveforms are detected by a punctual probe which is moved along the Ox direction from $x = 200$ mm to $x = 400$ mm, with a step of 37.2 mm (see Fig. 7). The transmitting monopole and the punctual probe are inserted in a borehole made of PVC and are separated by a distance $d = 40$ cm. The influence of the borehole itself and of the dielectric permittivity of the soil ($\varepsilon' = 1$ and $\varepsilon' = 5.8$) have been studied. The results collected in Fig. 8 highlight the fact that in air the PVC borehole has a weak influence on the waveforms radiated by the monopole; it introduces a weak delay as compared to the case where it is not present. In a soil characterized by a real permittivity $\varepsilon' = 5.8$, it can be observed that the estimated delay of 3.3 ns due to the lower velocity of electromagnetic waves ($v = c/\sqrt{\varepsilon'}$) as compared to the propagation in air is close to the theoretical value of 3.21 ns. Moreover, from Fig. 9 we remark that the amplitudes of the signals in the presence of presence of soil are higher than in the air.

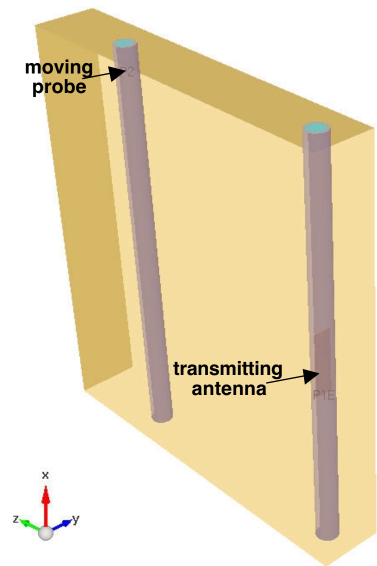


Figure 7. Modeling of the borehole monopole with the FDTD approach (EMPIRE software) with a moving probe along axis Ox in the plane xOz in an adjacent borehole.

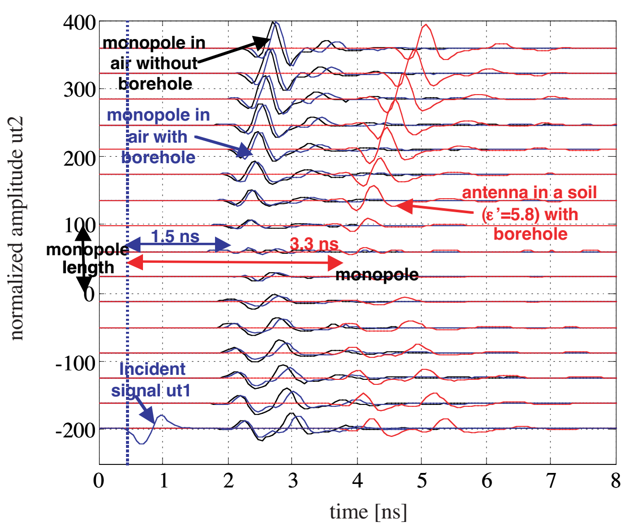
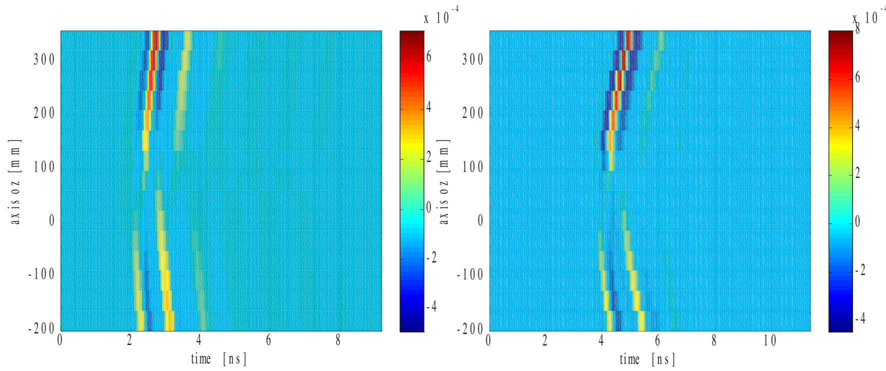


Figure 8. Waveforms Ez radiated by the resistively loaded monopole and detected by a moving punctual probe (voltage ut2) along axis Ox in the plane xOz in the presence or absence of a borehole made of PVC in both transmission and reception.

3.3. Waveforms Detected by a Receiving Antenna

The transmitting monopole is assumed to remain at a fixed position ($x = 0$), and the radiated waveforms are now detected by an identical receiving monopole. In Fig. 10, the comparison of the waveforms detected with a probe and a receiving antenna in air in the plane



(a) Waveforms associated with Ez (voltage ut2) and radiated in air

(b) Waveforms associated with Ez (voltage ut2) and radiated through a soil (ε'=5.8, σ=0)

Figure 9. 2D plots of the waveforms Ez (voltage ut2) radiated (a) in air, and (b) through a soil ($\varepsilon' = 5.8$, $\sigma = 0$) by the resistively loaded monopole in the presence of a borehole made of PVC in both transmission and reception, and detected by a moving punctual probe (voltage ut2) along axis Ox in the plane xOz.

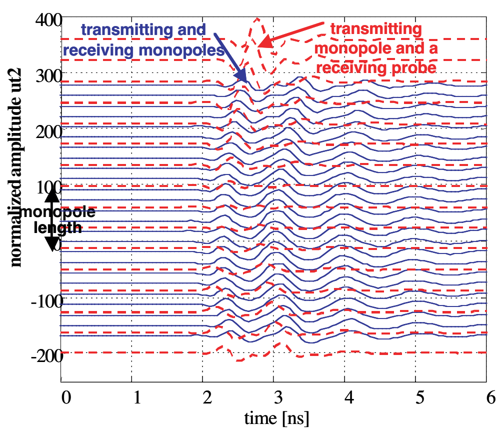


Figure 10. Comparison of waveforms Ez radiated through the air in the plane xOz by the resistively loaded monopole and detected by a moving receiving monopole or a punctual probe (voltage ut2) along axis Ox.

xOz highlights that the receiving antenna introduces time dispersion and smoothing; thus, the waveforms detected for angles ranging in $[10°; 170°]$ show similar shapes. Such an observation is useful for solving the inverse problem [2–5].

4. CONCLUSION

A microstrip loaded monopole for narrow borehole and broadband application has been proposed. The specifications involving a narrow borehole and a broad frequency band suppose a compromise solution. Thus, parameter studies have been performed in details using FDTD modeling of the antenna with its environment to further understand the radiating phenomena in the time and the space domains. These studies will help the design of such an antenna. The next step is the antenna realization and its characterization on the test site of the LRPC Rouen in the presence of different types of soils (sands, silts...).

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