Wave Propagation Model and Simulations for Landmine Detection

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1. Introduction

Recently there has been interest in developing new equipment and models for the detection and removal of landmines from field using Ground Penetrating Radar. In this project landmines with and without airgap are modeled using conventional electrical simulation tools. Our approach is to use the time and frequency domain behaviors to support the development of equations for newly developed inverse mathematical solutions. The equations for the voltage in the transmission line models of this paper are identical to Maxwell's equations in one dimension for the Ground Penetrating Radar problem. Therefore, the results of this paper for solutions to the transmission line voltage are equivalent to the predicted E field for this problem.

An Electromagnetic wave propagated from a GPR sees different media of different electrical properties. Assuming that transmitted wave looks directly into different intervening layers and based on the analogy between uniform plane wave and transmission line models discussed above, a transmission line model can be described that matches the same scenario as seen by the transmitted EM wave as shown by figure 1.

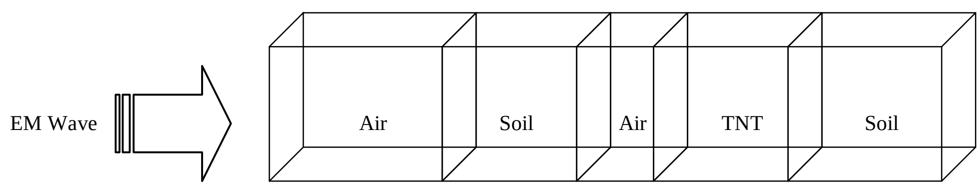


Figure 1: Multi layer Transmission model seen by transmitted EM wave

When a travelling EM wave propagates through one medium and enters the other with different electrical parameters than the first one, it experiences reflection. At all inter-medium junctures transmitted wave has a reflection. Therefore at every such junction part of the wave reflects back and the rest moves forward. Each reflected pulse will be subjected to inter-medium sub-reflections as it travels back to Radar. The pulse of interest is the one that reflects back from the landmine. Its final magnitude will be the product of initial pulse magnitude and transmission & reflection coefficients of each intervening material. Also it is attenuated depending on the attenuation constant and length of each material. In section 2, we describe the relationship between the Electromagnetic wave models and transmission line models. In section 3 we provide results of the transmission line simulations.

2. Modeling Equations

First, let us consider the equations that define wave motion in lossy dielectrics. If a wave propagates in the +z direction, the x component of E field is given by [1]:

$$E_{xs} = E_{x0} e^{-az} e^{-jbz} \tag{1}$$

Where α and β are attenuation and phase constants respectively. These constants when combined give us propagation constant (γ) which is a complex quantity:

$$g = a + jb \qquad (2)$$

In a lossy dielectric having permitivity ε, conductivity σ and permeability μ, propagation constant is given by:

$$g = \pm\sqrt{jwm\,(s + jwe\,)} \qquad (3)$$

Where μ is magnetic permeability in Henry/m, σ is conductivity of the material in Siemens/meter, ω is frequency in radians/m and ε in Farads/m.

The complex intrinsic impedance η of the medium (lossy dielectric) is given by:

$$h = \frac{E_{xs}}{H_{xs}} = \sqrt{\frac{jwm}{s + jwe}} \qquad (4)$$

For a dielectric material loss phasor termed as Loss Tangent δ is defined as:

$$\tan d = \frac{s}{we} \qquad (5)$$

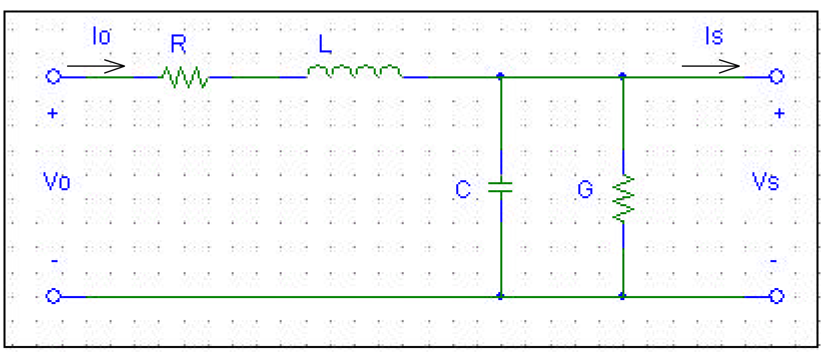


Figure 2: Equivalent circuit for a transmission line.

An equivalent circuit for a transmission line is shown in figure 2. For each equation listed above there is a similar Transmission line equation. For example, voltage wave equation is given by:

$$V_s = V_0 e^{-g} \qquad (6)$$

The Propagation constant becomes:

$$g = \sqrt{(R + jwL)(G + jwC)} \qquad (7)$$

Where R is resistance per unit length in Ohm/m, L is inductance per unit length in Henry/m, G is conductance per unit length in Siemens/m and C is capacitance per unit length in Farads/m.

Finally intrinsic impedance in a Transmission line is defined as:

$$Z_0 = \frac{V_s}{I_s} = \sqrt{\frac{R + jwL}{G + jwC}} \qquad (8)$$

On comparing equations 1 and 6 for both the cases we find that they are identical. So the terms E and V can be used interchangeably as can the terms H and I. By comparing equation pairs 1, 6; 3, 7; and 4, 8; it is clear that if in a transmission line we let V = E, I = H, R = 0, L = μ, G = σ and C = ε, and $\eta = Z_0$ then a transmission line model is identical to the uniform plane wave propagation model.

The values of electrical properties [2] used for simultaions are given in table 1.

$\mu_0 = 4\pi \times 10^{-7}$
$\mu_r = 1$
R = 0
$Z_0 = 377.3\ \Omega$
$\varepsilon_0 = 8.85 \times 10^{-12}$
f = 1 GHz

	ε_r	α nepers/m	β radian/m	tanδ	$\lvert Z_0\rvert=\lvert\eta\rvert$ ohms	$\angle Z_0$ Degrees	G = σ Siemens	L = μ micro henry	C = $\varepsilon_0\varepsilon_r$ Pico Farads
Air	1	0	20.98	0	376.6	0	0	1.26	8.85
Dry Soil	2.5	.417	33.17	.025	238.6	.72	.0035	1.26	22.12
Wet Soil 13% moisture	10	16.23	68.27	0.5	112.82	13.38	.28	1.26	88.4
TNT	2.86	.0319	35.48	.0018	223.14	.052	.286m	1.26	25.3

Table 1: Electrical Properties & calculated parameters

For one meter propagation distance, amplitude of the transmitted pulse in dry soil falls ($e^{-(.417)}$ = 0.659) 0.659 or 20log(.659) = 3.62 dB below its value at z = 0, while in case of wet soil it falls ($e^{-(16.32)}$ = 8.94×10^{-8}) nearly 141 dB below its value at z = 0.

3. Simulation Results

We did simulations using transmission line models in the Pspice 8.0 software package. A 1ns sinusoidal current pulse was applied at the input with a shunt resistance. Shunt resistance is used in some simulations to eliminate back and forth reflections through the transmission line model. For example, if a wave is reflected back from the termination and travels to the source end, it would be reflected again if source does not offer proper termination. Therefore a current pulse with a shunt resistor are used at the souce end of transmission line model.

In the first experiment, an air model is simulated to check impedance $Z_0 = \eta$ of air. The circuit used for simulation is shown in figure 3, where air transmission line has a length of 3 m and is properly terminated with a matched resistance of 377.3 Ω. As EM wave propagates through the transmission line (air) and reaches the termination resistor R, it is not reflected since load end is matched with the transmission line. This is shown in figure 4 where voltage wave at the sending end (Antenna) is shown. In figure 4 only the incident pulse is visible at time t = 1ns with no reflected pulses observed. Finally figure 5 shows how close is the termination matched with transmission line impedance, that the impedance varies in a small conservative circle on smith chart, i.e., from 375.881 to 375.929 ohms. When transmission line is not properly terminated as shown in figure 6 where it is terminated with 100000 ohm resistor, reflected pulses are also visible as the first incident pulse as shown in figure 7. Figure 8 shows the extreme impedance variations with respect to frequency.

In second experiment, dry soil model is simulated to check impedance $Z_0 = \eta$ of dry soil. The circuit used for simulation is shown in figure 9, where transmission line has a length of 3 m and is terminated with a resistance of 100000 Ω. As EM wave propagates through the transmission line (Dry soil) and reaches the termination resistor R, it is reflected since load end is not matched with the transmission line. This is shown in figure 10. The incident pulse reaches a peak voltage of 238.91 volts indicating an impedance $Z0 = \eta = 238.91$ ohms for dry soil. This corresponds to the predicted impedance of 238.6 in table 1, varifying our model. The amplitude of next pulse (36.49 V) corresponds to predicted attenuation of 3.62 dB/m. Finally figure 11 shows that impedance varies from 202 ohms to 280 ohms on x-axis of smith chart.

Third experiment is done on wet soil model. The circuit used for simulation is shown in figure 12, where transmission line has a length of 0.1 m and is terminated with a resistance of 100000 Ω. As EM wave propagates through the transmission line and reaches the termination resistor R, it is reflected. In figure 13 incident pulse is shown at 1ns with a +ve peak amplitude of 118.3V. Again this corresponds to the predicted impedance of $Z0 = \eta = 112.8$ ohms in table 1. In middle plot reflected pulse is seen at 3ns. Finally figure 14 shows impedance variations with respect to frequency.

Next series of experiments are done on a combination of transmission lines and for these experiments air impedance value is taken as source and load impedances. First model is shown in figure 15, which drysoil model is tested for air-gap in a mine in the model without TNT. The results are shown in figures 16 & 17. As expected EM wave experiences reflections. The first reflection of 43.13V at 21ns represents the first air soil interface, the second reflection of 12.5V at 23.6ns is the mine air gap reflection. Since the 1cm gap is so narrow as compared to the pulse width, two reflections arn't observed. This is the reason for the unusual shape of this reflection.

Second model is shown in figure 18, which replaces drysoil model with wet soil model. The results are shown in figures 19 & 20. Again EM wave experiences reflections. The first reflection of 113.4V at 21ns represents the first air soil interface, the second reflection of -295.4mV at 23.6ns is the mine air gap reflection. The wet soil pulse (2^{nd} pulse) is nearly obsecured by the air/ground pulse, may be due to simulation tool setup.

Sixth experiment simulates the landmine buried in drysoil without any airgap above the surface of TNT. The circuit used for simulation is shown in figures 21. In figure 22, the incident pulse is seen at ins with a +ve peak amplitude of 188V. The reflection of 43.35V at 21ns represents the first air soil interface, then reflection at 23.6ns is from Soil-TNT interface. As compared to pulse width the 10cm length of TNT is a narrow width, therefore we see an unusual shape of reflected pulse. In figure 23, impedance variations with respect to frequency are shown.

Seventh experiment simulates landmine buried in drysoil with an airgap of 1cm present above the surface of TNT. The model used for simulation is shown in figures 24. In figure 25, the incident pulse is seen at ins with a +ve peak amplitude of 188.15V. The reflection of 43.13V at 21ns represents the first air soil interface, then reflection at 23.6ns is from the air/soil interface and from TNT. In figure 26, impedance variations with respect to frequency are shown.

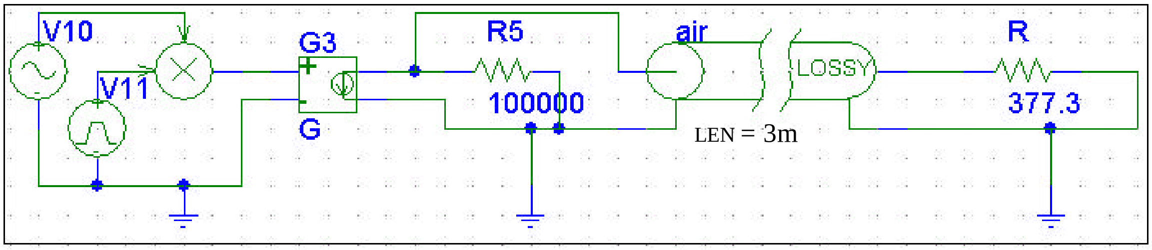


Figure 3: Circuit to check impedance for air model

Figure 4: Voltage at the antenna for circuit of fig3 (no reflections)

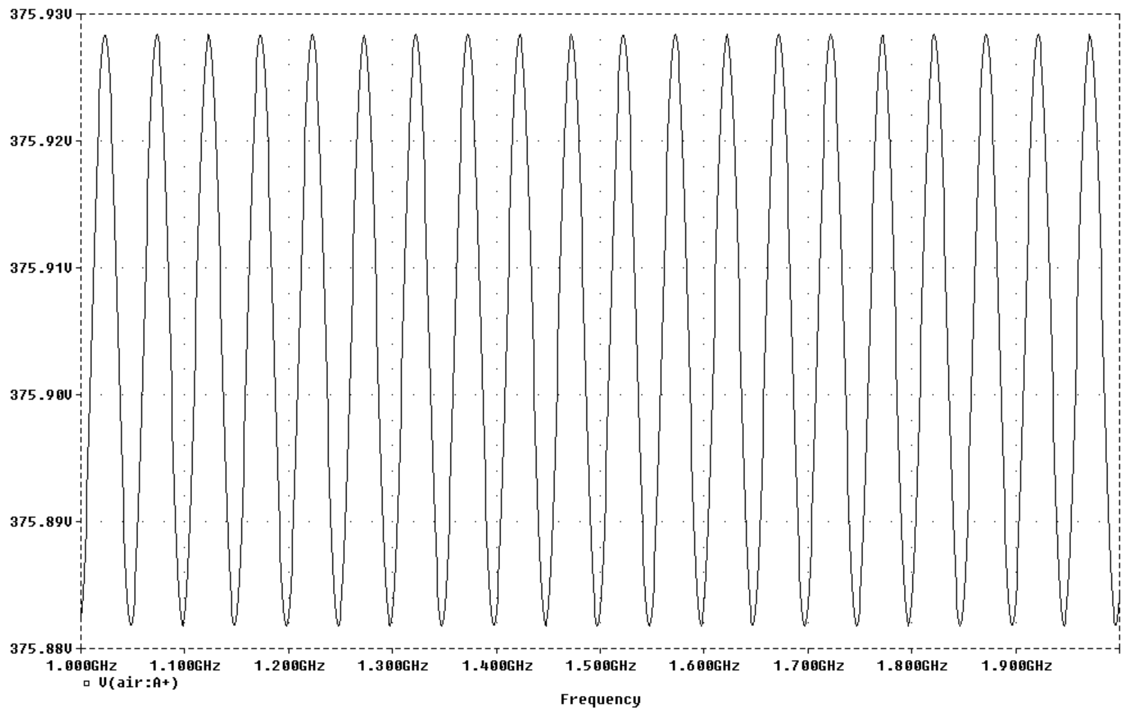


Figure 5: Votage at the antenna, Frequency sweep plot from 1 GHz to 2 GHz

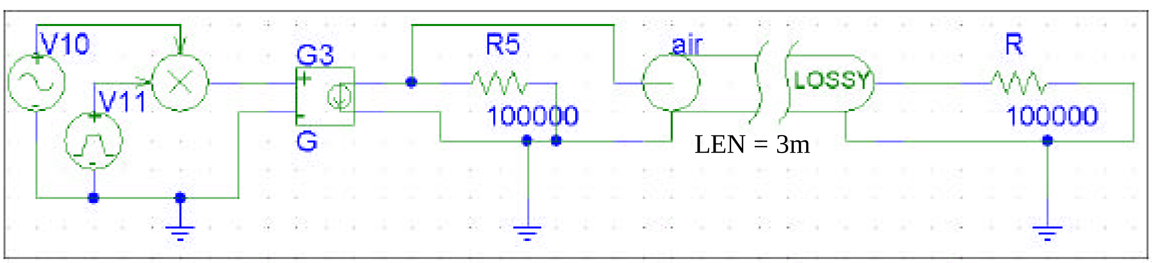


Figure 6: Air transmission line model terminated with 100KΩ

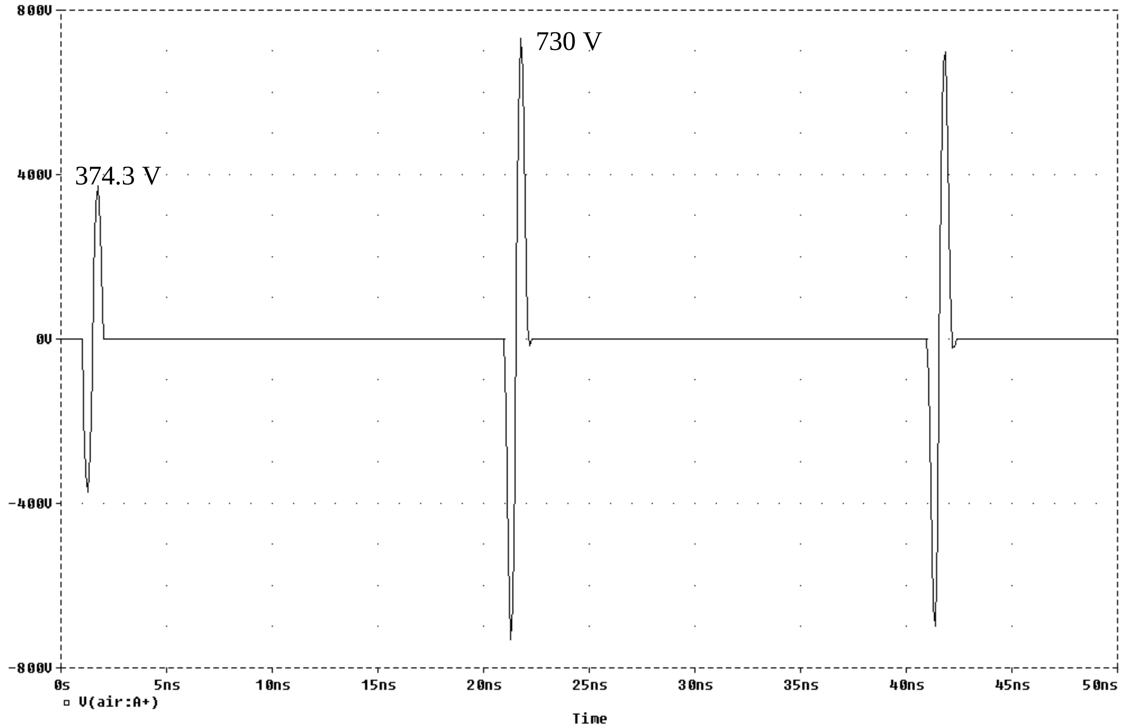


Figure 7: Voltage at the antenna for 100K termination.

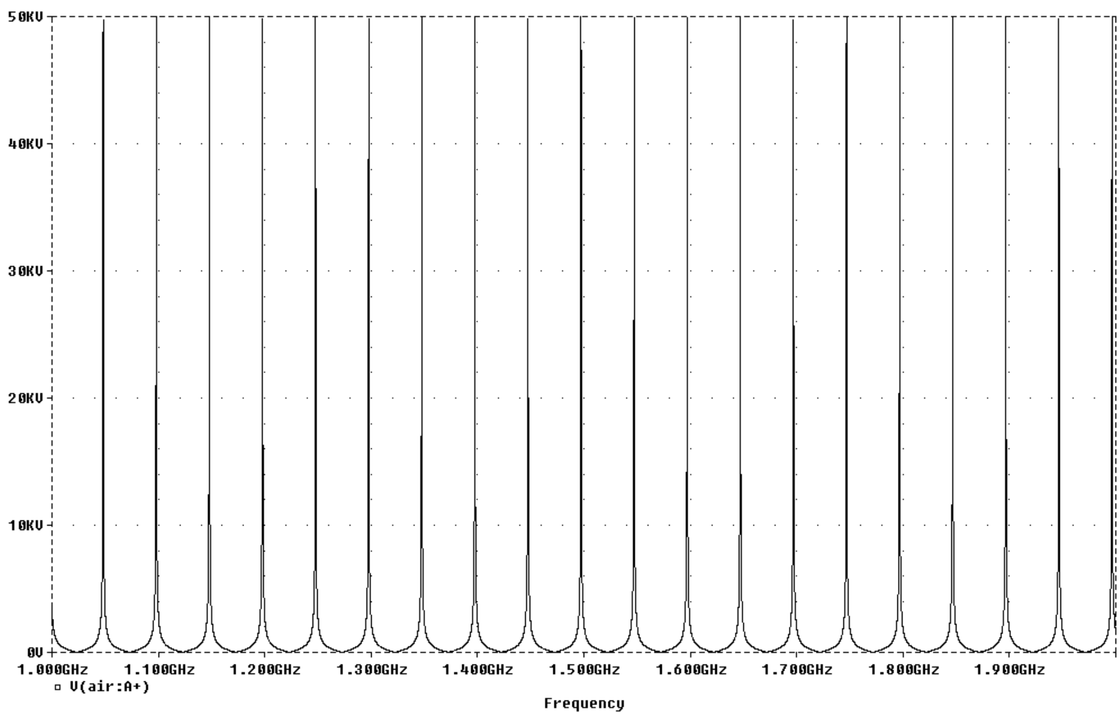


Figure 8: Voltage at the antenna, Frequency Sweep plot from 1GHz to 2GHz

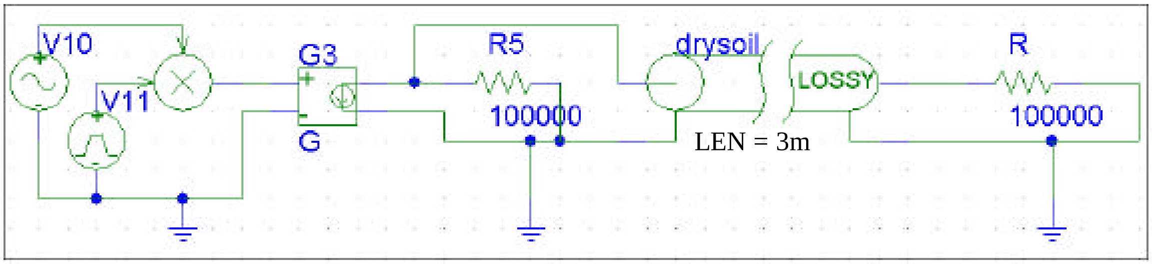


Figure 9: Dry soil model to check dry soil transmission line impedance

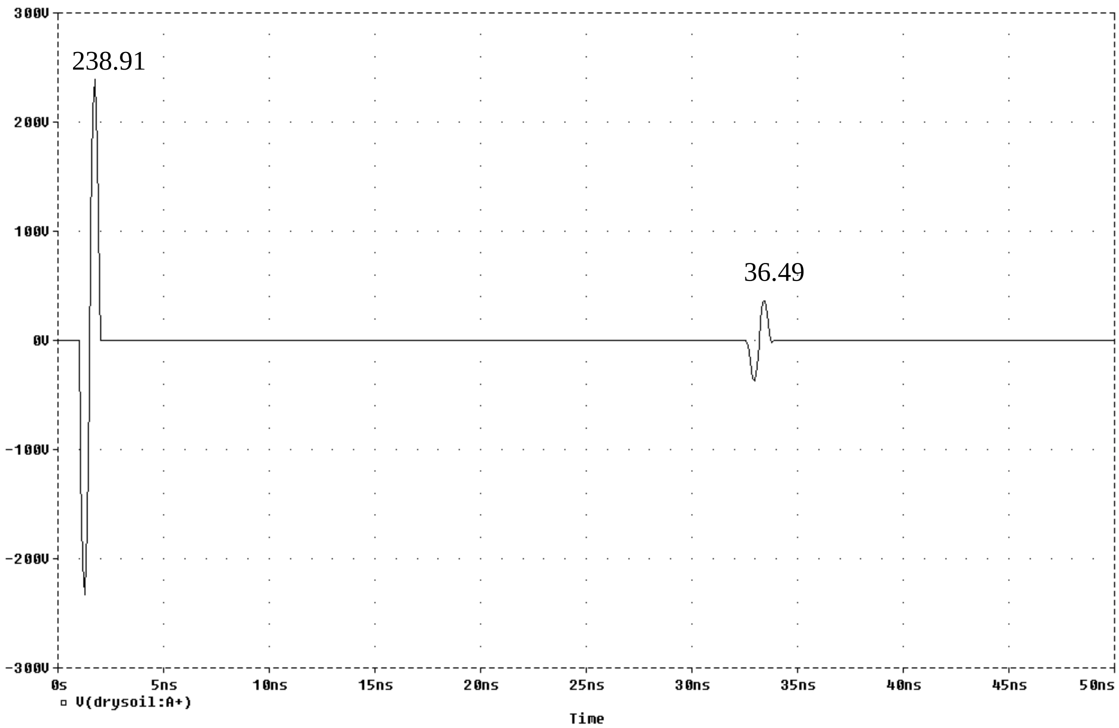


Figure 10: Voltage at the antenna for Dry-Soil Model

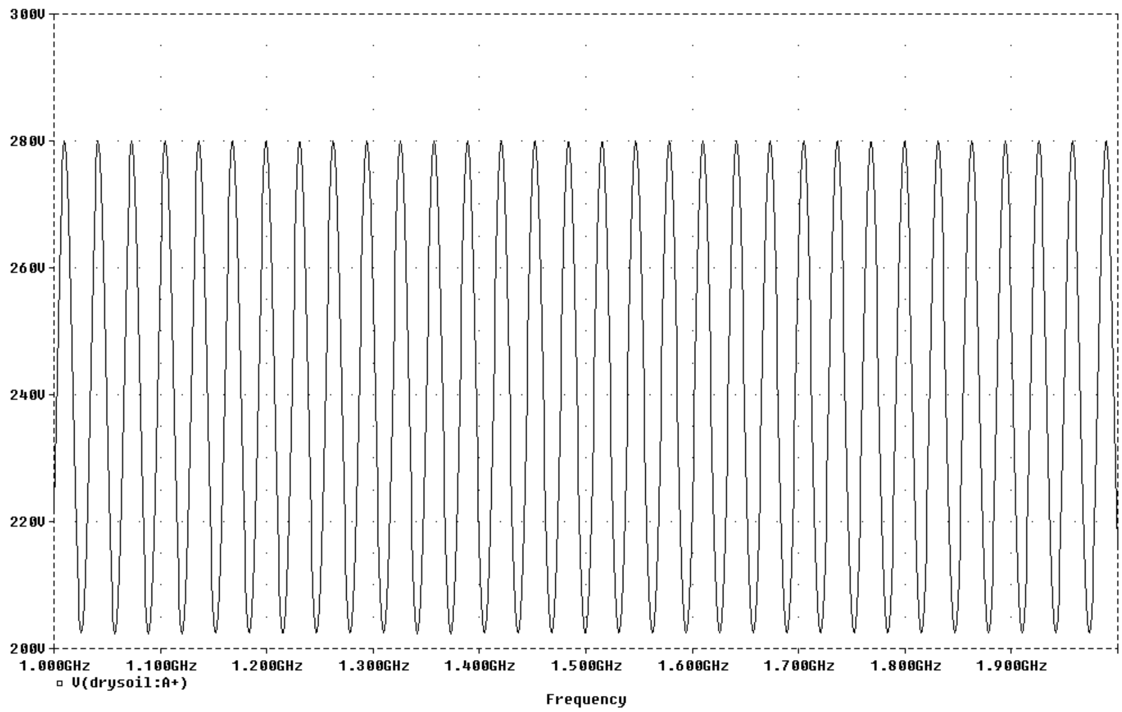


Figure 11: Voltage at the antenna for dry soil, Frequency Sweep plot from 1GHz to 2GHz

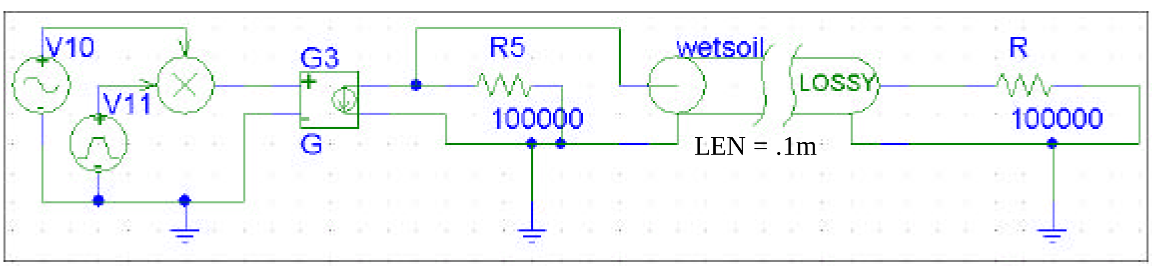


Figure 12: Wet soil model to check wet soil transmission line impedance

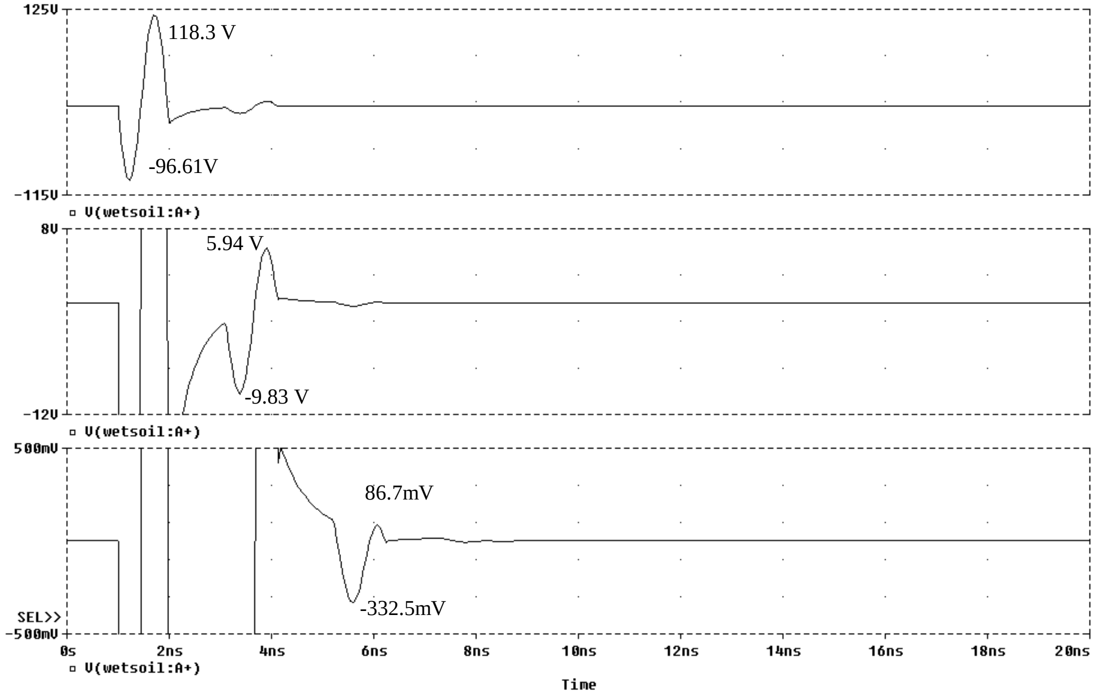


Figure 13: Voltage at the antenna for Wet-Soil Model with transmission line length = 0.1m. Top: Incident pulse occurs at 1ns; Middle: 0.2m round trip reflection pulse occurs at 3ns Bottom: 2^{nd} reflection at 5ns.

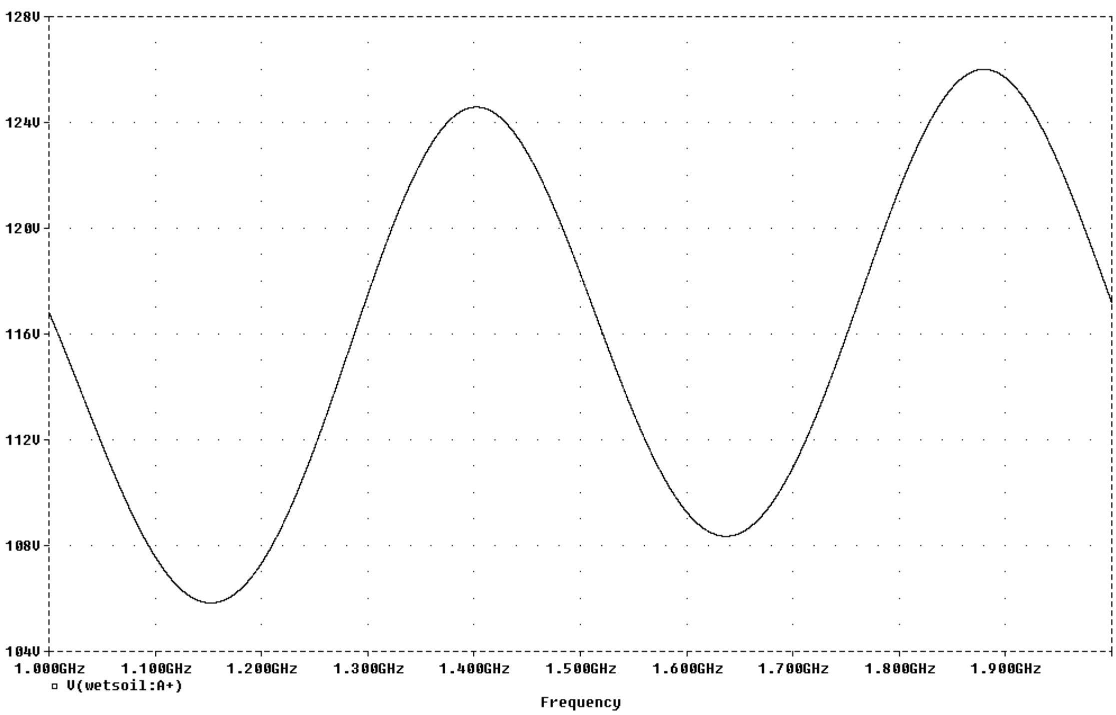


Figure 14: Voltage at the antenna for Wet-Soil Model, Frequency Sweep plot from 1GHz to 2GHz

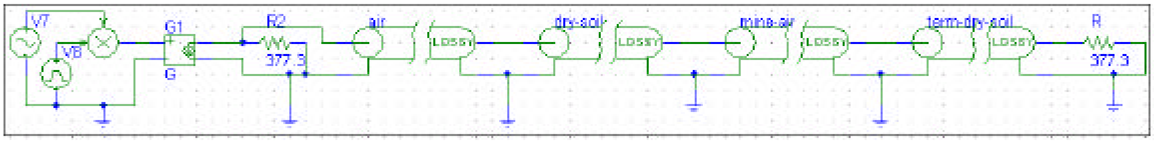


Figure 15: Air-drysoil-air-drysoil model. With lengths as air = 3m, drysoil = 0.25m, airgap = 1cm and drysoil = 100m.

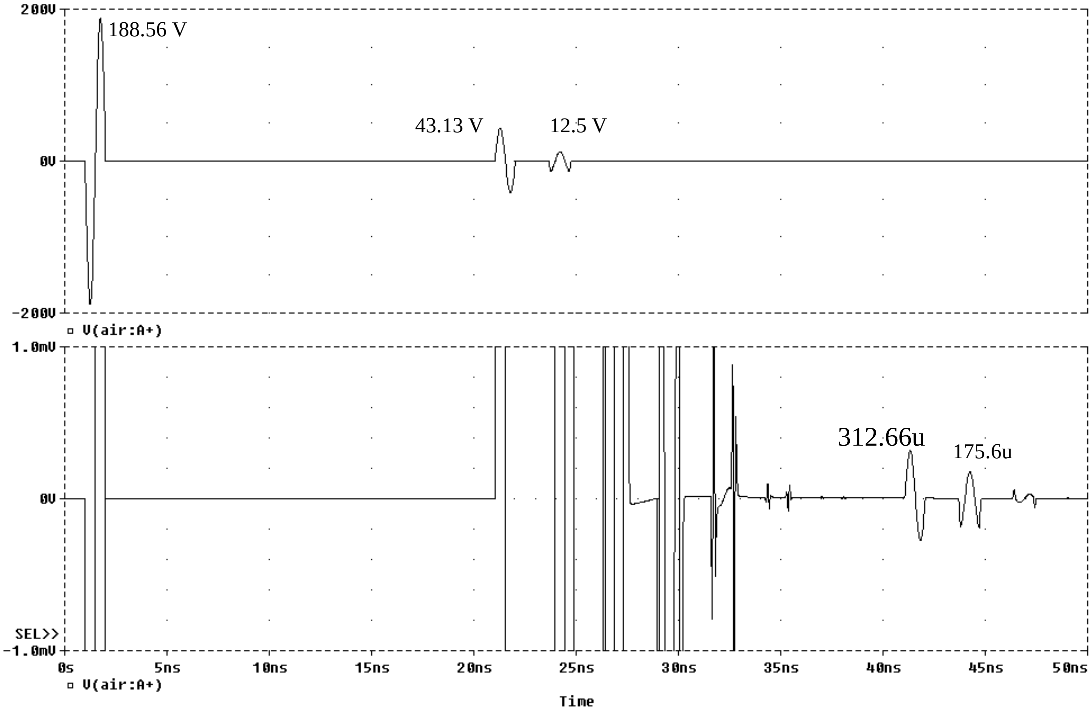


Figure 16: Voltage at the antenna for Air-drysoil-air-drysoil model. With lengths as air = 3m, drysoil = 0.25m, airgap = 1cm and drysoil = 100m. Top: Normal view. First reflection occurs at 21ns. Bottom: Magnified view.

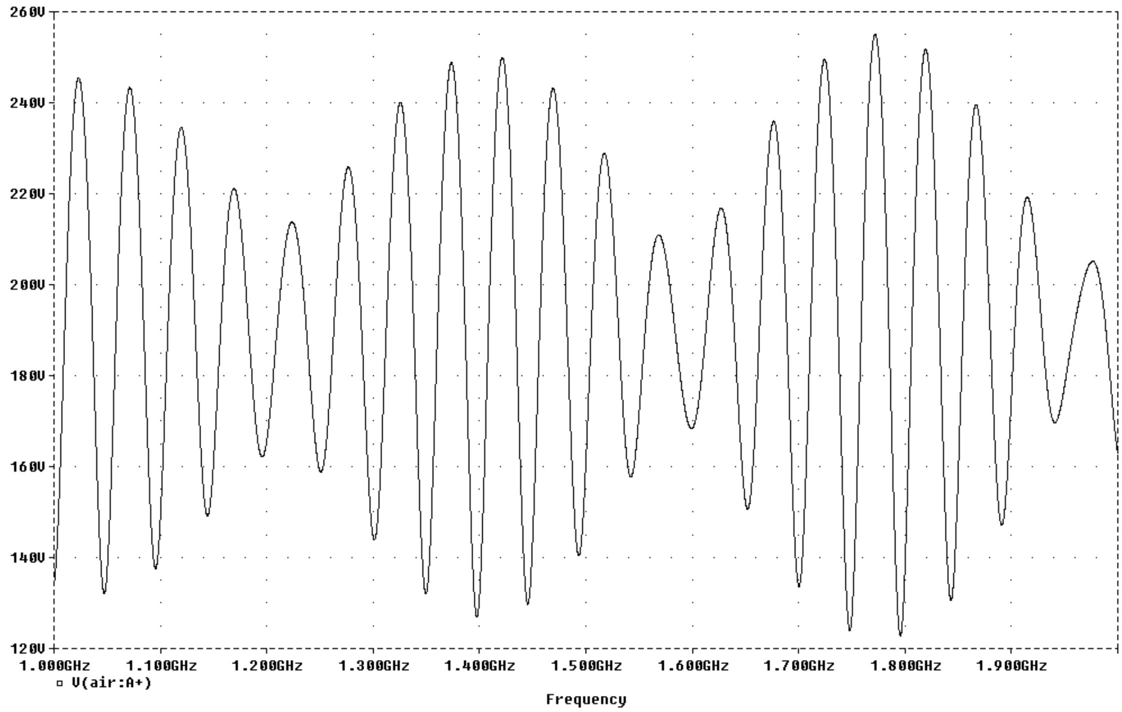
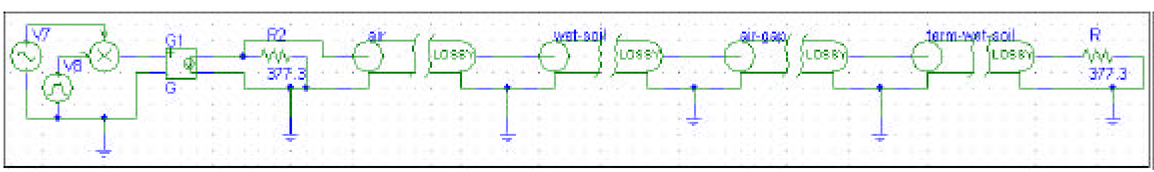


Figure 17: Voltage at the antenna for Air-drysoil-air-drysoil model. With lengths as air = 3m, drysoil = 0.25m, airgap = 1cm and drysoil = 100m. Frequency Sweep plot from 1GHz to 2GHz



Firure 18: Air-wetsoil-air-wetsoil model. With lengths as air = 3m, wetsoil = 0.1m, airgap = 1cm and wetsoil = 10m.

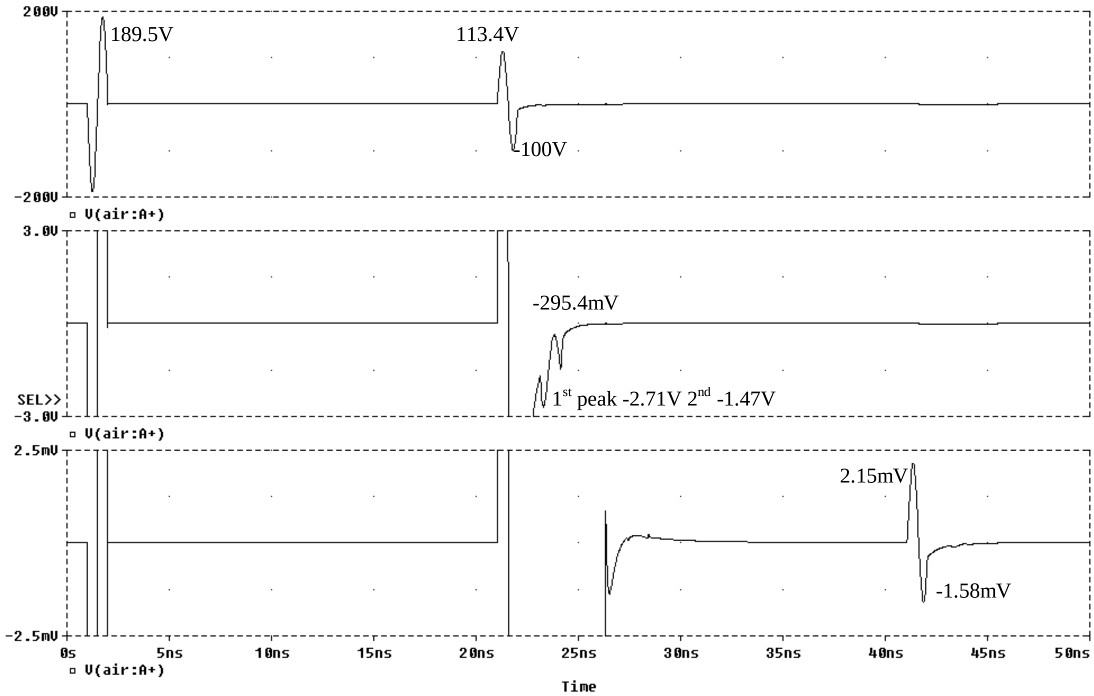


Figure 19: Voltage at the antenna for Air-wetsoil-air-wetsoil model, With lengths as air = 3m, wetsoil = 0.1m, airgap = 1cm and wetsoil = 10m. Top: Normal view. First reflection occurs at 21ns. Bottom: Magnified view.

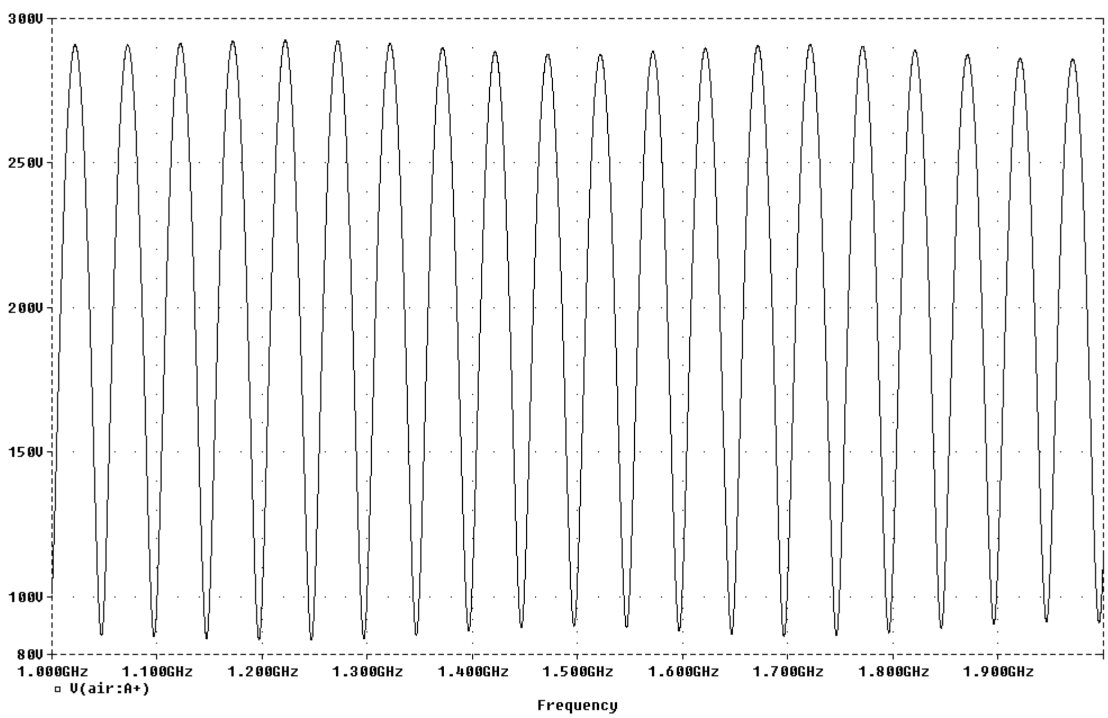


Figure 20: Voltage at the antenna for Air-wetsoil-air-wetsoil model, With lengths as air = 3m, wetsoil = 0.1m, airgap = 1cm and wetsoil = 10m. Frequency Sweep plot from 1GHz to 2GHz

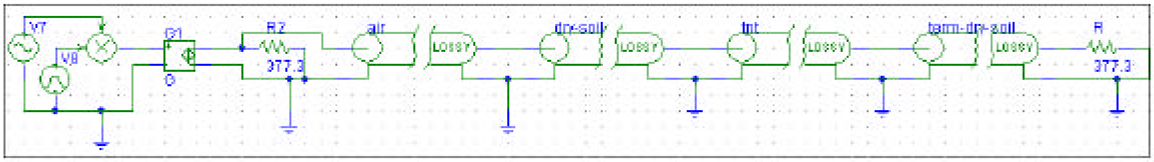


Figure 21: Air-drysoil-TNT-drysoil model. With lengths as air = 3m, drysoil = 0.25m, TNT = 10cm and drysoil = 100m.

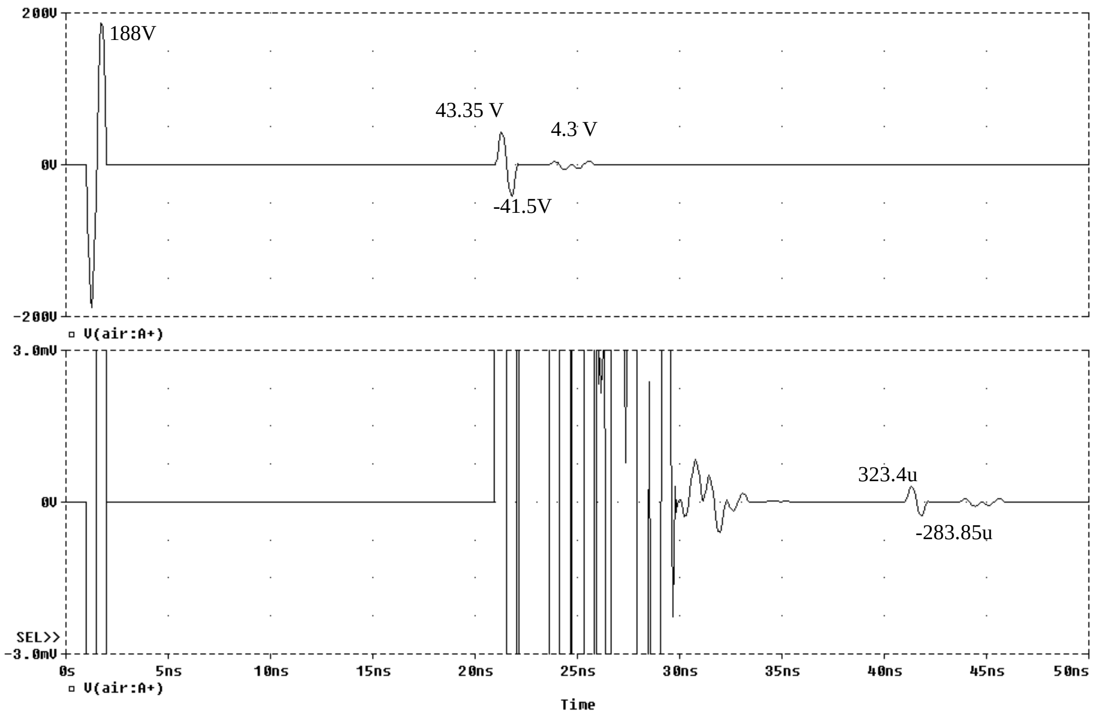


Figure 22: Voltage at the antenna for Air-drysoil-TNT-drysoil model, with lengths as air = 3m, drysoil = 0.25m, TNT = 10cm and drysoil = 100m. Top: Normal view. First reflection occurs at 21ns. Bottom: Magnified view.

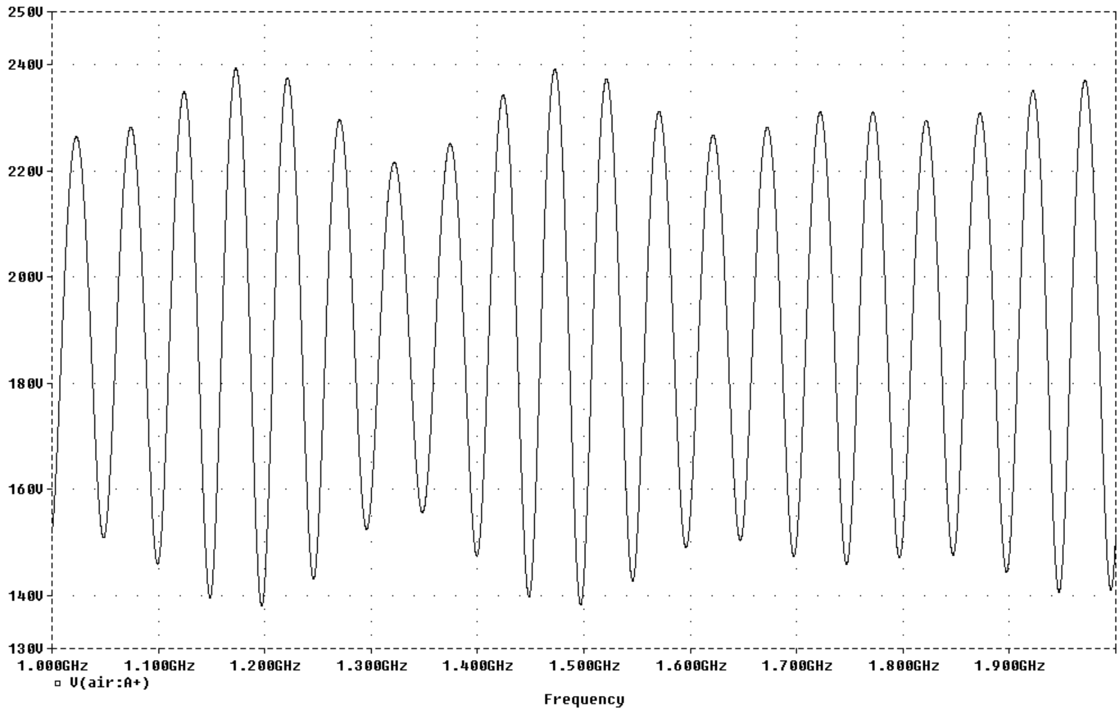


Figure 23: Voltage at the antenna for Air-drysoil-TNT-drysoil model, with lengths as air = 3m, drysoil = 0.25m, TNT = 10cm and drysoil = 100m. Frequency Sweep plot from 1GHz to 2GHz

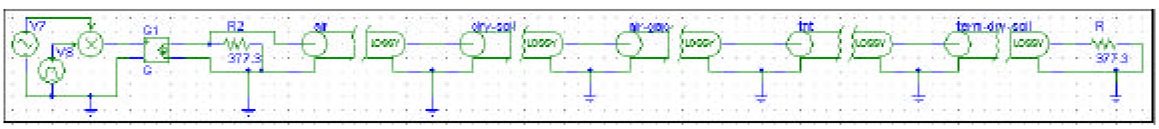


Figure 24: Air-drysoil-airgap-TNT-drysoil model. With lengths as air = 3m, drysoil = 0.25m, airgap = 1cm, TNT = 9cm and drysoil = 100m.

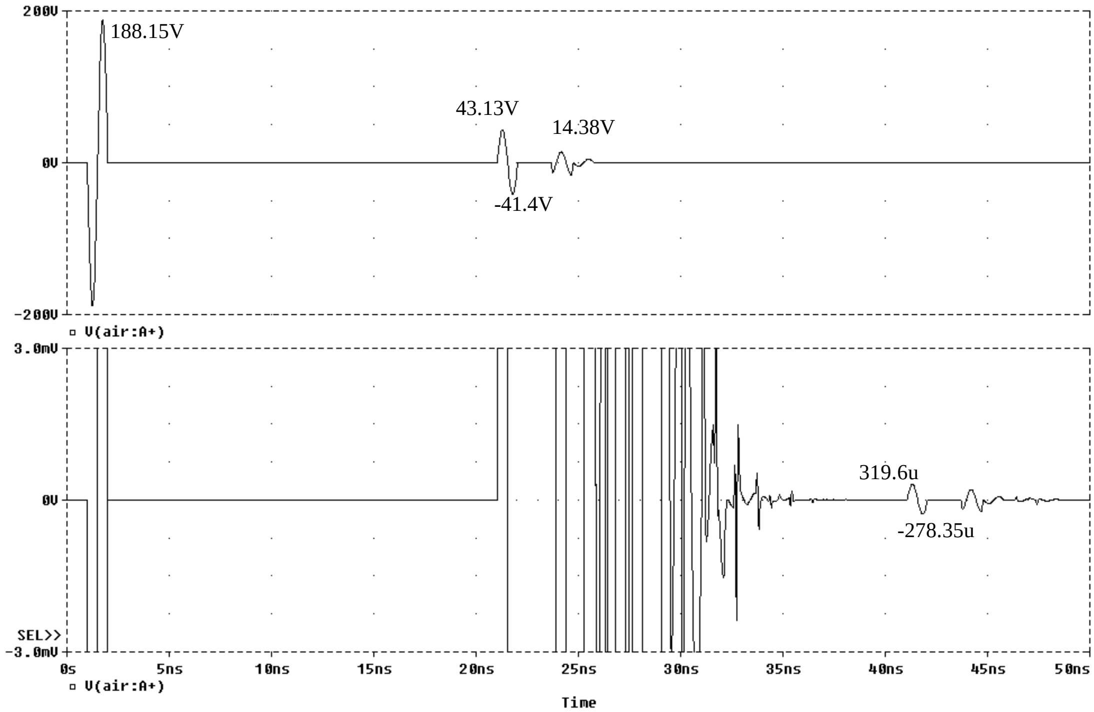


Figure 25: Voltage at the antenna for Air-drysoil-airgap-TNT-drysoil model, with lengths as air = 3m, drysoil = 0.25m, airgap = 1cm, TNT = 9cm and drysoil = 100m. Top: Normal view. First reflection occurs at 21ns. Bottom: Magnified view.

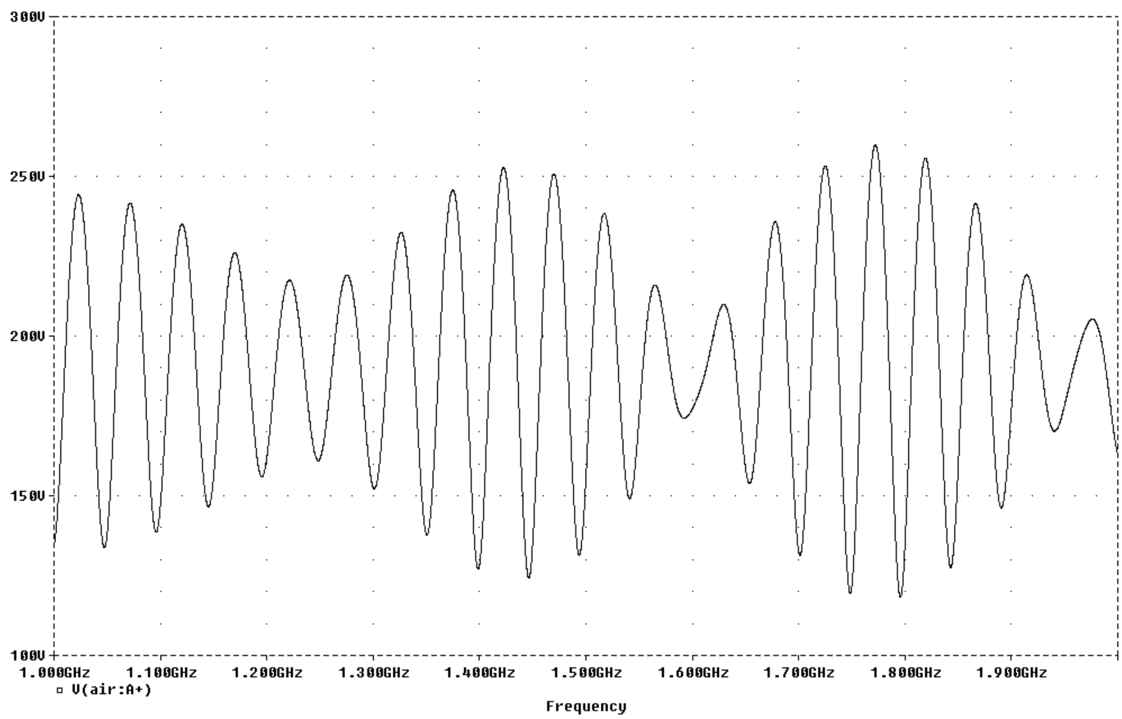


Figure 26: Voltage at the antenna for Air-drysoil-airgap-TNT-drysoil model, with lengths as air = 3m, drysoil = 0.25m, airgap = 1cm, TNT = 9cm and drysoil = 100m. Frequency Sweep plot from 1GHz to 2GHz

4. Comparisons

	Predicted loss	Measured loss	Published Data [3]
Dry soil	3.62 dB/m	3.74 dB/m	2 dB/m
Wet soil 13% moisture	141 dB/m	130 dB/m	100 dB/m

Table 2: Comparison between measured and predicted loss.

Model	V amplitude at Antenna	V amplitude of reflection from ground	V amplitude of reflection from target/ground
Air-drysoil-air-drysoil	188.56 V	43.13 V	12.5 V
Air-wetsoil-air-wetsoil	189.5 V	113.4 V	-295.4mV
Air-drysoil-TNT-drysoil	188 V	43.35 V	4.3 V
Air-drysoil-airgap-TNT-drysoil	188.15 V	43.13 V	14.38 V

Table 3: Amplitude of Voltage wave.

5. References

1. Hayt, William H., "Engineering Electromagnetics".
2. Anh H. Trang, "Simulation of Mine detection over Dry soil, Snow, Ice and Water", SPIE Vol. 2765.
3. US Army Data, Belvoir RD&E Center.