GROUND PENETRATING RADAR FOR TUNNEL DETECTION

Mustafa Kuloglu and Chi-Chih Chen

ElectroScience Laboratory, Department of Electrical & Computer Engineering,
The Ohio State University,
1320 Kinnear Rd. Columbus, OH 43212 E-mails: kuloglum@ece.osu.edu, chen.118@osu.edu

1. INTRODUCTION

Ground penetrating radar (GPR) is a commonly used technique for surveying subsurface structures [1][2]. GPR system performance depends heavily on soil types and specific targets. GPR systems have important civil and military applications such as detection of buried pipes, bunkers and tunnels [3][4]. However, GPR systems for locating deep tunnels still face many challenges. Therefore this paper will discuss about challenges involving tunnel detection and will provide a systematic procedure to provide these key system parameters. One of the challenges GPR faces for deep tunnel detection is the propagation loss due to spreading and soil conductivity[5]. Conduction loss gets worse as the moisture content increases. Polarimetric scattering of tunnels is another key factor that needs be carefully examined for a better detection efficiency [6][7]. Since the performance is dependent on multiple parameters, GPR system design is not straight forward. Currently, there is no systematic way to determine the optimal frequency range, power requirement, and sensitivity to design an efficient GPR system for tunnel detections. In this paper; propagation loss, scattering from tunnels, antenna related issues and their effect on GPR system will be presented.

2. TUNNEL GPR SYSTEM BUDGET

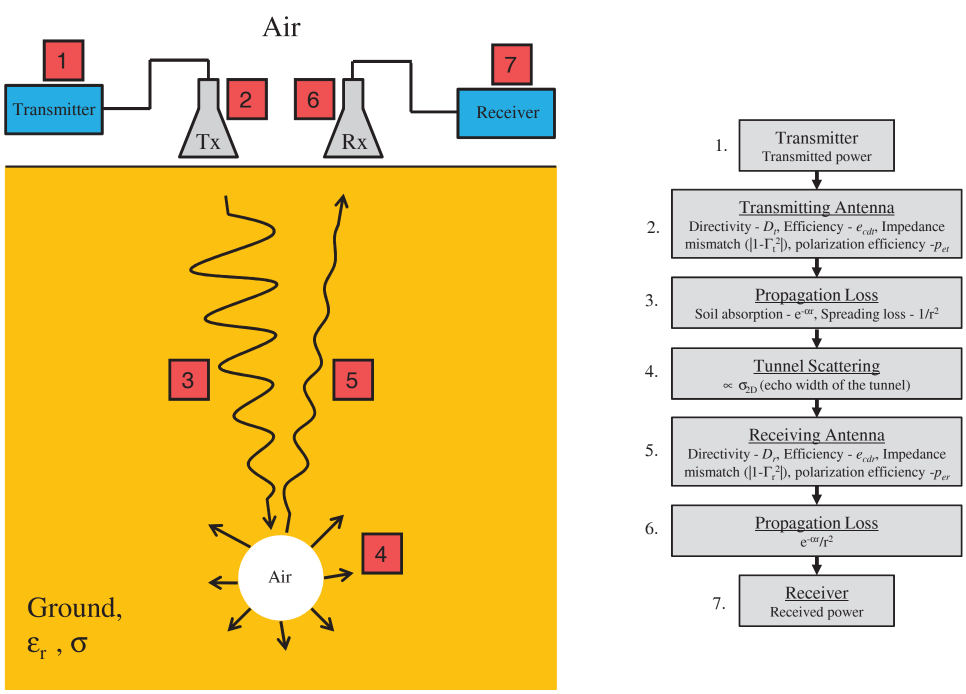


Fig. 1. Basic flow chart used to estimate system budget for tunnel detection.

Fig.1 shows a flow chart to determine key GPR system parameters for tunnel detection. In this chart, "1" represents the transmitter. "2" and"6" denote transmitting and receiving antennas, respectively. It should be noted that same antenna can be used for both transmitting and receiving, if mutual coupling between them is not an issue. "3"and "5" represent propagation loss, which include wave spreading loss and soil absorption loss. "4" refers to the scattering from tunnels. Each one of these mechanisms will be presented with details in subsequent sections.

3. PROPAGATION LOSS

Propagation loss consists of two different loss mechanisms. Spreading loss, even though it is not a real loss, happens due to the spherical nature of the transmitted waves. For spherical waves, power density decays with distance as $1/r^2$, where r denotes the distance between transmitter and observer. This behavior is independent of frequency provided that the observation distance is not within the near field of the radiator. For tunnel detection, this spreading means roughly a decay of $1/r^4$ for the round trip of the waves.

Second mechanism is the losses associated with soil absorption. These losses could reach as much as 100dB or more within couple meters depending on the material properties. Fig.2(a) shows an example of one-way attenuation for EM waves propagating 1m through soils (dB/m) for a few selected dielectric constant and conductivity values. The soil properties are assumed to be independent of frequency (i.e. constant permittivity and conductivity). As can be seen from the figure, lower frequencies has lower attenuations. For one way propagation, this power decay is proportional to $e^{-\alpha r}$, where α is the attenuation constant, and r is the distance (i.e. tunnel depth). Therefore, as the desired detection depth increases, operating at lower frequencies becomes desirable. Such small frequencies force most GPR systems to operate at Rayleigh region [8].

When choosing operating frequency low frequency, window effect should also be taken into account. For a hertzian dipole which lays along z axis, the theta component of the electric field can be calculated analytically. If the electric field associated with such a dipole is plotted with respect to frequency (at $\theta = 0°, r = 1m$) as Fig. 2(b), an interesting phenomena called window effect is observed. At very low frequencies (i.e. $kr << 1$), the quasi-stationary term is dominant (Fig. 2(c)). As the frequency gets higher, the far-field term becomes dominant (Fig. 2(d)). The overall increase at higher operation frequencies should not mislead the reader. This is due to increase in aperture size of the antenna, and due to the fact that higher order modes are not included in the analytical expression.

4. SCATTERING FROM TUNNELS

The scattering of tunnels are similar to that of dielectric cylinders, which can be obtained analytically from [9]. In Fig.3 (a) incident plane wave and tunnel orientation is depicted. For a TM polarized ($H_z = 0$) wave, incident field is characterized by $E_z^i = E_0 e^{-jkx}$. For a TE polarized ($E_z = 0$) wave, incident field is characterized by $H_z^i = H_0 e^{-jkx}$. Analytical normalized echo width, which is defined in (1), of a tunnel with diameter a in a lossless ambient medium (ϵ_r) is provided in Fig.3 (b).

$$\sigma_{2D} = \lim_{\rho \to \infty} \left[2\pi\rho \frac{|E^s|^2}{|E^i|^2} \right] = \lim_{\rho \to \infty} \left[2\pi\rho \frac{|H^s|^2}{|H^i|^2} \right] \quad (1)$$

As discussed in propagation loss section, deep tunnel GPR systems operate at Rayleigh regions where ka is very small. Using small argument approximations, simple analytical formulas of echo width can be obtained. Using these simple expressions, low frequency echo widths may be replotted as given in Fig. 4. In this figure, bottom plot shows the ratios of TE and TM modes as a function of frequency. It is observed that, the tunnel has three times bigger echo width when it is illuminated by a TE polarized wave. Examining scattering parameters has another importance, as it shows resonance frequencies of the tunnel, which may be used for identifying the tunnel.

5. ANTENNA EFFECT

Antennas are the other key elements of GPR systems. As mentioned in the propagation loss section, GPR systems need to operate at very low frequencies. Ideally, effective radiation from an antenna requires an approximate size to be at least half wavelength at the frequency of interest. For instance, a system which operate at 10 MHz up would require a 50 ft long antenna if it's in free space. This dimension should be scaled by $\sqrt{(\epsilon_r + 1)/2}$ when it is on a ground with dielectric constant of ϵ_r. Thus, the same antenna would require around 23 ft, when it is placed on ground which has dielectric constant of 9. Obviously such antenna sizes are not suitable for mobility. Generally, the antennas are limited by around 6 ft as the dimension. This calls for careful miniaturization. Dielectric loading and meandering the antenna arms can be applied to reduce the antenna size.

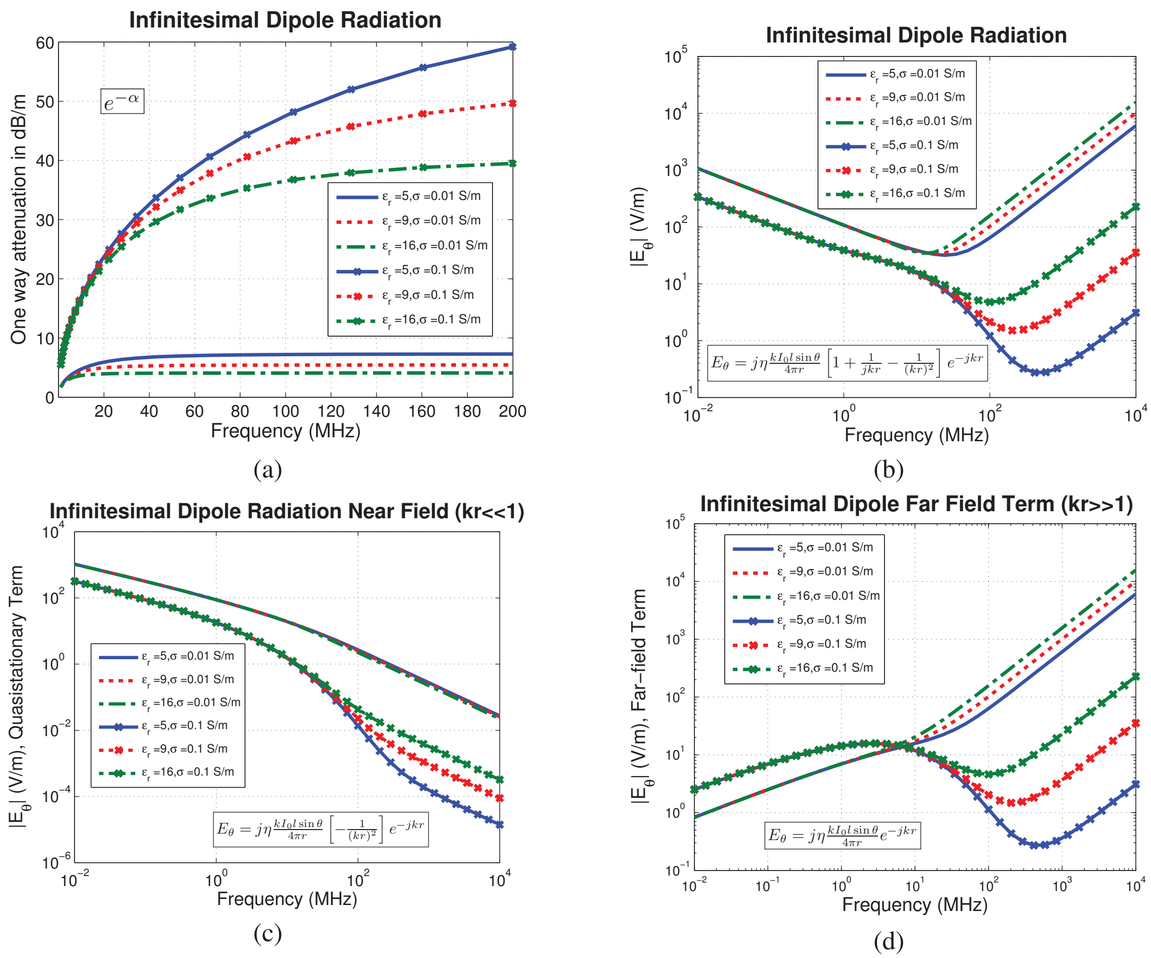


Fig. 2. (a) One way attenuation due conductivity of the ambient medium for a few select soil parameters. (b) Hertzian dipole radiation at $\theta = 0°, r = 1m$. (c) Quasi-stationary term. (d) Far-field term.

However, for such sizes, we are still limited by physical limitations [10] [11]. Even for carefully miniaturized antennas, gains can be around -20dBi to -10dBi at the low frequency end.

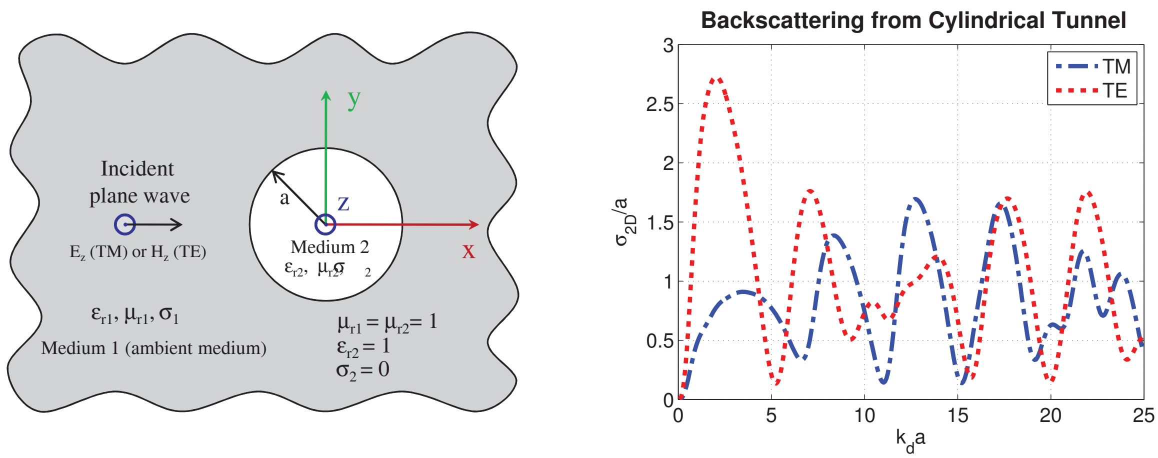
Another consideration about the system antenna is the antenna polarization. As discussed in scattering section, tunnel scattering has polarization dependent behavior. For blind testing, where tunnel orientation is not known a priori, two different measurements need to be taken to take polarization effects into account. In practice, single polarized antennas are commonly used. Therefore two different scans may be required to efficient detection. Using dual linear polarized or circularly polarized antennas can deduce the measurement time by two.

6. TUNNEL GPR SYSTEM BUDGET - REVISITED

The flow chart given in Fig.1 can be written in a mathematical form as given in (2)[12]:

$$P_r = P_t e_{cdt}(1-|\Gamma_t|^2)D_t(\theta,\phi)\frac{e^{-\alpha r}}{4\pi r^2}\sigma\frac{e^{-\alpha r}}{4\pi r^2}e_{cdr}(1-|\Gamma_r|^2)D_r(\theta,\phi)\frac{\lambda^2}{4\pi} \tag{2}$$

By putting accurate estimates for each expression in (2), a budget analysis can be conducted. By putting expressions in the equation, it is now easy to guess how much input power is needed for a desired detection depth, or how deep can a tunnel be detected for a given power and tunnel diameter.



(a) (b)

Fig. 3. (a) Incident plane wave and cylinder (i.e. tunnel) orientation (b) Normalized scattering echo of a tunnel having radius a as function of frequency. $\epsilon_{r1} = 9$. k_d is the wavenumber for the ambient medium.

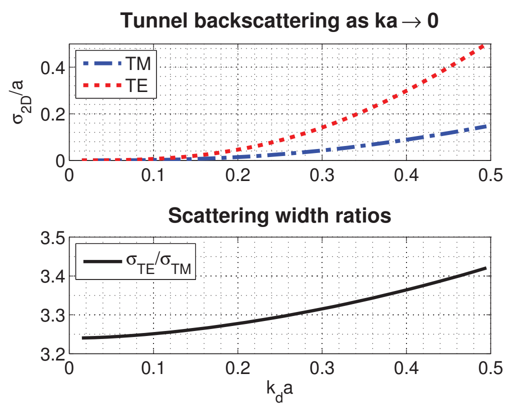


Fig. 4. Scattering width behavior for very small ka.

7. REFERENCES

[1] A.P. Annan, "Radio Interferometry depth sounding: Part1. Theoretical Discussion.," *Geophysics*, vol. 38, pp. 557–580, 1973.

[2] L. Peters, Daniels J. J., and J.D. Young, "Ground Penetrating Radar as a Subsurface Sensing Tool," in *Proc. IEEE*, 1994.

[3] J.C. Cook, "Radar Transparencies of Mine and Tunnel Rocks," *Geophysics*, vol. 40, pp. 865–885, 1975.

[4] K.C. Roe and Ellerburch D.A., "Development and testing of a microwave system to measure coal layer thickness up to 25 cm," in *Nat. Bur. Stds. Report No.SR-723-8-79*, 1979.

[5] D. J. Daniels, *Ground Penetrating Radar*, IET, 2004.

[6] S. J. Radzevicius and J. J. Daniels, "Ground Penetrating Radar Polarization and Scattering from Cylinders," *Journal of Applied Geophysics*, vol. 45, pp. 111–125, 2000.

[7] B. Baumgartner, J. Munk, J. Daniels, and Chen C-C., "GPR Scattering of Dielectric Cylinders," in *The Seventh International Biannual GPR Conference*, 1998.

[8] M. I. Skolnik, *Radar Handbook*, McGraw-Hill, 2008.

[9] R.F. Harrington, *Time-Harmonic Electromagnetic Fields*, McGraw-Hill, 1985.

[10] L. J. Chu, "Physical limitations of omnidirectional antennas," *J. Appl. Phys.*, pp. 1163–1175, 1948.

[11] B.A. Kramer, C-C. Chen, M. Lee, and J. L. Volakis, "Fundamental Limits and Design Guidelines for Miniaturizing Ultra-Wideband Antennas," *IEEE Antennas and Propagation Magazine*, vol. 51, pp. 57–69, 2009.

[12] C. A. Balanis, *Antenna Theory*, Wiley-Interscience, 2005.