GPS SIGNAL BEHAVIOR ANALYSIS IN TUNNELS

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ABSTRACT

This thesis recommends how to transmit a GPS signal down a specific tunnel in Norway. The recommendation is based on two mathematical models set up for GPS signal behavior analysis in tunnels: one is for a straight tunnel using a Ray-Launching/Ray-Tracing technique; the other is for a curved tunnel using waveguide solutions. Both models are verified with data from research papers. A hybrid model is created to simulate the tunnel in Norway. Based on the hybrid model, it is recommended that four GPS repeaters be placed to ensure signal coverage throughout the tunnel in Norway.
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Chapter 1

Background

Radio wave propagation in tunnels has been a research subject for a long time. It still remains as one due to the complexity of radio wave propagation and the various environmental factors in different tunnels. Applications range from road tunnels for normal car traffic to railway tunnels and mine tunnels. This research is mainly concerned with GPS signal propagation in tunnels. The specific application of this thesis is with regard to a tunnel in Norway. By minor adjustments of the mathematical model, it can also be applied to a wider range of applications of wireless signal propagation in tunnels.

All radio-frequency behavior is based on Maxwell’s equations, including Gauss’ law, Faraday’s law, and Ampere’s law. Maxwell’s equations exist in both differential form and integral form (Ulaby, 2007); however, their use to simulate radio wave propagation is cumbersome and heavy in calculation.

The following papers have a significant influence on the method chosen in this research and lay the background of this research.

1.1 Methods of Analysis

1.1.1 Vector Parabolic Equation Method

Using the vector parabolic equation to model urban radio wave propagation was developed by Zaporozhets (1999). It uses a paraxial version of Maxwell’s equations to allow full treatment of three dimensional (3D) electromagnetic scattering. This method is applicable in an
open area and where the object (e.g., buildings) is millions of times bigger than the wavelength. However, the following study manages to use this method and apply it to tunnels.

Subsequently, the application of the vector parabolic equation to radio wave propagation in tunnels, taking into account the cross-sectional shape, wall impedance, slowly varying curvature, and torsion of the tunnel axis, was presented by Popov & Zhu (2000). The authors argued that Geometric Optics Analysis is complicated at long ranges due to the growing number of contributing rays and it breaks down in caustic regions. The authors concluded that this method gives a more complete and accurate description of radio wave propagation than other methods.

The vector parabolic equation method is a more fundamental way of modeling radio wave propagation. Its challenge is in applying it to tunnels, and there are concepts in the method that exceed the level of this investigation. Three more traditional methods are introduced in the following sections.

### 1.1.2 Waveguide Modeling Method

Another modeling technique is to consider the tunnel as a waveguide. A theory was developed modeling UHF propagation in coal mine tunnels (Emslie, Lagace, & Strong, 1975). The prime interests of this study are the nature of the propagation mechanism and the prediction of the radio frequency that propagates with the smallest loss. The kind of propagation model developed in this paper involves the EH11 waveguide mode accompanied by a “diffuse” component in dynamical equilibrium. The theoretical model considered many effects: the exponential decay of the wave; the marked polarization effects in a straight tunnel; the independence of decay rate on antenna orientation; the absence of polarization at the beginning of a cross tunnel; the two-slope decay characteristic in a cross tunnel; and the overall frequency dependence. The result is a standard hybrid waveguide solution.
Another study shows that the tunnel is a transmission channel of high-pass (Chiba, Inaba, Kuwamoto, Banno, & Sato, 1978). The experimental values of the attenuation constants are similar to the theoretical values of the TE01 and EH11 modes when the tunnel is regarded as a circular waveguide with the same cross-sectional area. The obstacle effect in the tunnel is not yet understood. A later study developed an approximate equation for the attenuation constant derived from the point-matching solution so that one can determine or estimate the value without elaborate calculations (Yamaguchi, Abe, Sekiguchi, & Chiba, 1985).

A study was presented analyzing the transmission of VHF electromagnetic waves in a curved mine tunnel using an idealized model in a cylindrical geometry (Mahmoud & Wait, 1974a). The tunnel cross section is assumed to be rectangular and the broad curved walls are imperfectly reflecting. They adopted a model of a rectangular waveguide with curved walls that are assumed to present a constant impedance or admittance to the tangential fields. They found that the lowest-order mode has a whispering gallery character and as a result, the attenuation rate is increased significantly by the curvature.

### 1.1.3 Geometric Optics Modeling Method

Another modeling technique using the geometric ray approach to model electromagnetic wave propagation inside an empty rectangular mine tunnel with imperfect walls was presented by Mahmoud & Wait (1974b). When all of the walls are imperfect, the modal propagation constants are not easy to obtain since the simple modes are intrinsically coupled. For this case, a geometrical ray summation was derived, taking into account the coupling between the horizontally and vertically polarized rays. Later on, they also incorporated the roughness of the wall using a simple method.
1.1.4 Uniform Theory of Diffraction (UTD)

The uniform theory of diffraction (UTD) was developed later to predict narrow-band and wide-band propagation characteristics in tunnels at 900 MHz and 1800 MHz frequencies (Hwang, Zhang, & Kouyoumjian, 1998). The walls of the tunnel were approximated by uniform surface impedance. It is shown that both measurements and simulations indicated the existence of a distinct break point before and after which propagation exhibited different attenuation rates. The measured results have validated the accuracy of the theoretical model. This study is the basis of many investigations of electromagnetic wave propagation in tunnels today.

Another study with regard to the characterization of high-frequency electromagnetic wave propagation in tunnels has mainly focused on the important applications in the field of mobile communication (Mariage, Lienard, & Degauque, 1994). It argued that for short tunnels, one of the most critical points is either the radiation towards free space of a mobile station emitting in the tunnel or, on the contrary, the penetration of an external wave inside the tunnel. Hence UTD is used to solve this type of problem. It concluded that when beyond a few hundred meters, the rays propagating at or near grazing angles relative to the tunnel walls play a dominant role in producing a long-term fading. This conclusion is significant to the Ray-Launching/Ray-Tracing Technique referred to by Kim, Jung, & Lee (2003).

1.1.5 Ray-Launching/Ray-Tracing Technique

The Ray-Launching/Ray-Tracing technique is a new technique developed in the late twentieth century. A ray-launching technique was used and implemented by the uniform theory of diffraction to analyze the path loss and delay spread while entering tunnels (Pallares, Juan, & Juan-Llacer, 2001). For the calculation of each ray contribution, the authors used geometrical optics (GO) theory and UTD to handle the reflected and diffracted rays, respectively. The results
do not depend strongly on the frequency of the transmitted signal, at least at the frequencies the authors are considering and for their specific tunnel dimensions. The paper’s finding does not relate to the research that this thesis presents; however, the technique used in this paper is borrowed. Also the findings of this paper with regard to frequency support future changes of parameters of the model.

Another study also used the ray-tracing method and incorporated both geometric optics theory and the Uniform Theory of Diffraction to analyze the radio wave propagation characteristics in rectangular road tunnels (Kim et al., 2003). The mathematical expression of received power in the tunnel as a function of transmitting power at the entrance of the tunnel can be expressed as follows:

\[
P_r = P_t \left( \frac{\lambda_0}{4\pi} \right)^2 \left( G_d e^{-jkr_0} + \sum_{i=1}^{n} \frac{G_{vi}(\Gamma_{vi})^i e^{-jkr_{vi}}}{R_{vi}} + \sum_{i=1}^{n} \frac{G_{hi}(\Gamma_{hi})^i e^{-jkr_{hi}}}{R_{hi}} \right)^2
\]

The authors simulated radio waves at 800 MHz and 2.4 GHz. Both are validated by experimental data. It is shown that this model can be applied to other tunnels with similar dimensions.

1.1.6 Curved Tunnel Modeling Technique

Since the focus of this thesis is trying to model a tunnel having two turns, setting up the mathematical model must incorporate the curved parts. The study by Nilsson et al. (1998) involving a model of radio propagation in curved rectangular mine tunnels provides a practical modeling technique. Instead of using a cumbersome method (Mahmoud & Wait, 1974a), they proposed a simple Geometrical Optics (GO) extension to the standard hybrid waveguide solution proposed by Emslie et al.(1975). The study provided loss due to refraction (dB/m) assuming that a (1, 1) mode waveguide is used. The total loss equals to the loss due to a curve and also to
reflection. Although some discrepancies are found, the study provides both an accurate and simple enough model to be implemented in net planning tools.

Another report on the experimental results of radio propagation in two underground coal mines presented a hybrid tunnel propagation model consisting of the free space propagation model and the modified waveguide propagation model (Zhang, Zheng, & Sheng, 2001). The paper concluded that microcellular radio communications systems are feasible in coal mines. An important result of this study is the demonstration that a hybrid model can accurately model signal propagation in tunnels without putting heavy pressure on computing devices.

1.2 The Significance of This Research

The purpose of this thesis is to provide recommendations on how to send a GPS signal (1575 MHz) down a specific tunnel in Norway. This tunnel is of research interest to The Pennsylvania State University Department of Geosciences. The power level of the GPS signal needs to be sufficiently high so that devices in the tunnel can demodulate the GPS signal and extract time information. Thus, all the devices in the tunnel can be synchronized wirelessly. Currently, their synchronization is done using wires which is a traditional Instrument and Control practice.

Also, this study can be applied to different scenarios, making wireless coverage in tunnels possible in other specific applications. There can be coverage of GPS signal, wireless network, or cellular services, etc., in road or railway tunnels, underground mines or building structures; although, the applications require consideration of the many assumptions on which the mathematical model is based.
1.3 Tunnel Dimensions

The tunnel under study was never accurately mapped. Rough measurements were provided by onsite engineers, as shown in Figures 1-1 and 1-2.

Figure 1-1. Tunnel cross-sectional shape and rough dimensions (not to scale)

Figure 1-2. Tunnel birds-eye view (not to scale). The specific measurement of the hollow space is unknown and is not taken into consideration of the mathematical model.
The elevation of the tunnel was provided; however, it is small (a few degrees) and thus it will not be taken into consideration in the mathematical model.

There are devices along the wall of the tunnel such as the one shown in Figure 1-3. The picture also shows the roughness of the wall. Since this is a tunnel for research purposes, there was no effort in smoothing the wall after digging. An approximate standard deviation of the roughness of the wall was estimated as 1 meter by an onsite engineer.

![Figure 1-3. Devices on the wall of the tunnel](image)

1.4 Device Specifications

Two devices are important for the outcome of the mathematical model. The transmitting antenna, which shoots the signal down the tunnel at the entrance, and the GPS signal measurement equipment used to collect data points in the tunnel.

The GPS transmitter is a Wilson 304475 that operates in the frequency range between 915 MHz and 1710 MHz ("Wilson_304475," 2012).
The GPS signal measurement equipment used is LEA u-blox 6 GPS Modules. It comes with software to show measurements on a computer screen. The gain of the antenna is 50 dB and the device sensitivity level is around -150 dBm (“u-blox_LEA-6_DataSheet,” 2012).
Chapter 2
Mathematical Model Set up

2.1 Guiding Principles

1. Practicality

The purpose of this model is to maintain the GPS signal power in a tunnel and to provide an easy to use tool for onsite engineers to run simulations. Many traditional methods used in modeling radio wave propagation are very intensive in calculation. Hence, they do not have the practicality to adjust some of the parameters onsite.

2. Accuracy

This model needs to accurately predict GPS signal behavior so that an optimal solution can be implemented to ensure the synchronization of all devices in the tunnel.

3. Flexibility

To realize the flexibility of the mathematical model, it is important to have a good system overview of the codes. The flexibility of the coding ensures an open solution for other scholars or engineers to implement the model easily.

2.2 Mathematical Model

After comparing different methods, it was decided to use the Ray-Launching/Ray-Tracing technique for the mathematical model set up. Not only does this method provide a relatively accurate result, it also does not put too much burden on the computing devices. It is useful to onsite engineers who can run the simulation multiple times in multiple scenarios without a long waiting period. The specific model chosen incorporates geometric optics theory and Uniform Theory of Diffraction (Kim et al., 2003); however, the model is only applicable to
straight tunnels with smooth walls. Our tunnel has two 45-degree turns, both with a radius as small as 8 meters, which need to be taken into consideration in the mathematical model set up.

As mentioned in Chapter 1, one of the modeling techniques is to use a hybrid waveguide model (Emslie et al., 1975). For this specific tunnel in Norway, it was decided to use a hybrid model. Where the tunnel is curved, a simpler but still accurate method, which is a GO extension to the standard hybrid waveguide solution (Nilsson et al., 1998), is applied.

Note that in order for the hybrid model to work, it is important to connect the model well. Because of the result given by two models (power received by receiving antenna (Kim et al., 2003); dB loss in a turn (Nilsson et al., 1998)), it makes sense to set up the model as if the tunnel is straight and then subtract the dB loss during a turn. In this way, a hybrid model is created. In Chapter 2, this thesis will present the following: a straight-tunnel mathematical model then verified with data provided in an original paper (Kim et al., 2003); a curved-tunnel mathematical model then verified with data provided in an original paper (Nilsson et al., 1998); and a hybrid mathematical model then verified with limited data collect from the tunnel in Norway.

2.2.1 Straight Tunnel

2.2.1.1 Theoretical Background

The straight-tunnel mathematical model set up is based on the method of Kim et al. (2003), which uses a Ray-Launching/Ray-Tracing technique. The simulation is based on the following equation:

\[
P_r = P_t \left( \frac{\lambda_0}{4\pi} \right)^2 \left( \frac{G_d e^{-jkr_0}}{R_0} + \sum_{i=1}^{n} \frac{G_{vi}(\Gamma_{vi})^i e^{-jkr_{vi}}}{R_{vi}} + \sum_{i=1}^{n} \frac{G_{hi}(\Gamma_{hi})^i e^{-jkr_{hi}}}{R_{hi}} \right)^2
\]
A typo in the equation was found in the original paper and it is here corrected. In the original paper, it was \( \sum_{i=1}^{n} \frac{G_{hi}(T_{vi})}{R_{hi}} e^{-jkR_{hi}} \) for the second sum instead of the corrected equation \( \sum_{i=1}^{n} \frac{G_{hi}(T_{vi})}{R_{hi}} e^{-jkR_{hi}} \).

The following list defines the different parameters and equations used in the straight-tunnel mathematical model:

- **\( P_r \)**: Power received by the receiving antenna in terms of watts
- **\( P_t \)**: Power transmitted by the transmitting antenna in terms of watts
- **\( \lambda_0 \)**: Wavelength in free space
- **\( H, W \)**: Height and width of the tunnel
- **\( \varepsilon_r^* \)**: Complex permittivity of concrete
- **\( G_t, G_r \)**: Gains of the transmitting antenna and receiving antenna
- **\( G_d = \sqrt{G_t \cdot G_r} \)**: Geometric mean of the transmitting and receiving antenna gains for the direct wave
- **\( R_0 \)**: LOS path length between transmitting antenna and receiving antenna
- **\( n \)**: Number of reflections
- **\( \theta_{vi} = \tan^{-1} \frac{H(i+1)}{2R_0} \)**: Grazing angle of the i-th wave on the top and bottom surfaces
- **\( \theta_{hi} = \tan^{-1} \frac{W(i+1)}{2R_0} \)**: Grazing angle of the i-th wave on the wall surfaces
- **\( G_{vi} = \sqrt{G_t(\theta_{vi}) \cdot G_r(\theta_{vi})} \)**: Geometric mean of the transmitting antenna gain as a function of the grazing angle and the receiving antenna gain as a function of the grazing angle
- **\( \Gamma_{vi} = \frac{\varepsilon_r^* \sin(\theta_{vi}) - \sqrt{\varepsilon_r^* - (\cos \theta_{vi})^2}}{\varepsilon_r^* \sin(\theta_{vi}) + \sqrt{\varepsilon_r^* - (\cos \theta_{vi})^2}} \)**: Reflection coefficient for vertically polarized waves reflected from the top and bottom surfaces.
\[ R_{vi} = \sqrt{(R_0)^2 + (i \cdot H)^2} \]: Path length of the i-th wave reflected between the top and bottom surfaces

\[ G_{hi} = \sqrt{G_t(\theta_{hi}) \cdot G_r(\theta_{hi})} \]: Geometric mean of the transmitting antenna gain as a function of grazing angle and the receiving antenna gain as a function of grazing angle

\[ \Gamma_{hi} = \frac{\sin(\theta_{hi}) - \sqrt{\varepsilon_r - (\cos \theta_{hi})^2}}{\sin(\theta_{hi}) + \sqrt{\varepsilon_r - (\cos \theta_{hi})^2}} \]: Reflection coefficient for horizontally polarized waves reflected from the walls

\[ R_{hi} = \sqrt{(R_0)^2 + (i \cdot W)^2} \]: Path length of the i-th wave reflected wave between the walls

More equations are involved in this model which are not mentioned by the author. They are common in the communication field but not always in electrical engineering.

\[ G_{dBi} = 10 \cdot \log_{10} G \]: \( G \) is the gain of the antenna in dB while \( G_{dBi} \) is the gain of the antenna in dBi

\[ G_{hip} = G \cdot \left( \frac{\cos \left( \frac{\pi}{2} \cos(\theta_{hi}) \right)}{\sin(\theta_{hi})} \right)^2 \]: Antenna gain as a function of the grazing angle for horizontally polarized waves (Zhang, Hwang, & Kouyoumjian, 1998)

\[ G_{vip} = G \cdot \left( \frac{\cos \left( \frac{\pi}{2} \cos(\theta_{vi}) \right)}{\sin(\theta_{vi})} \right)^2 \]: Antenna gain as a function of the grazing angle for vertically polarized waves (Zhang et al., 1998)

Since the author did not provide the equations for \( G_t(\theta_{hi}), G_r(\theta_{hi}), G_t(\theta_{vi}), G_r(\theta_{vi}) \) and all references of the paper did not mention \( G_t(\theta_{hi}), G_r(\theta_{hi}), G_t(\theta_{vi}), G_r(\theta_{vi}) \), this thesis instead uses \( G_{hip} \) and \( G_{vip} \), which should produce similar results.
2.2.1.2 MATLAB Coding Approach

Since the equation gives the power received as a function of distance from the entrance of the tunnel, $R_0$ is set as an array from 0 to the distance from the entrance.

The next step uses two for loops to calculate $\sum_{i=1}^{n} \frac{g_{vi}(\Gamma_{vi})^i e^{-jKR_{vi}}}{R_{vi}}$ and $\sum_{i=1}^{n} \frac{g_{hi}(\Gamma_{hi})^i e^{-jKR_{hi}}}{R_{hi}}$.

The dummy used “r” as the number of reflections. After each loop, two new parameters “sumhorizontal” and “sumvertical” are acquired. They are then plugged into the big equation.

2.2.1.3 Parameters

The parameters used in this mathematical model are presented below. All these parameters are from the original paper. The goal is to verify the result and make sure that the model works.

1. $P_t = 0 \text{ dBm}$
2. $R_0 = 365 \text{ m}$
3. $\lambda_0 = \frac{3 \times 10^8}{2.45 \times 10^9}$
4. $G_t = G_r = 10^{\frac{n}{10}} \text{ dB}$
5. $\varepsilon_r^* = 7 - 0.85 \times 1i$
6. $H = 6.15 \text{ m}$
7. $W = 14.7 \text{ m}$
8. $n = 25$

The MATLAB code used is provided in Appendix A.
2.2.1.4 Conclusion

A comparison of simulation models for a straight tunnel, using the paper of Kim et al., (2003) in contrast to the MATLAB simulation of this thesis, is shown in Figures 2-1 and 2-2, respectively. For both tunnels, the parameters are the same as those specified in the previous section, but a different antenna gain grazing angle equation is used as mentioned in the theoretical background.

As we can see from the two figures, both simulations for the 2.45 GHz signal drop significantly in the first 50 meters. At around 100 meters, the received power levels are both around -60 dBm. The trend flattens after around 50 meters. Both simulations end between 60 dBm and 70 dBm. The simulation in MATLAB ends slightly lower. As previously mentioned, small variations are expected due to the difference of antenna gain grazing angle equations.

After a comparison, it is concluded that the straight-tunnel mathematical model works. It can present a fairly accurate estimation of radio wave propagation in straight tunnels.

Figure 2-1. Signal power received simulation result for straight tunnel from Kim et al., (2003)
2.2.1.5 Limitations

The straight-tunnel mathematical model has the following limitations:

1. The wall is made of concrete and it is expected to have a roughness standard deviation between 1 to 5 millimeters.
2. The tunnel is assumed to have a rectangular cross-sectional shape.
3. No other radio frequency is assumed present in the tunnel.

2.2.2 Curved Tunnel

2.2.2.1 Theoretical Background

The curved-tunnel mathematical model set up is based on the method used in Nilsson et al. (1998), which is a waveguide modeling technique. The simulation is based on the following equations:

\[ \text{Loss}_{\text{total}} = \text{Loss}_{\text{curve}} + \text{Loss}_{\text{ref}} \] (dB/m)
\[ \text{Loss}_{\text{total}} = \text{Total attenuation in the curved tunnel} \]

\[ \text{Loss}_{\text{curve}} = \text{Loss due to the curvature of the tunnel} \]

\[ \text{Loss}_{\text{ref}} = \text{Loss due to refraction} \]

\( r \): Radius of curvature

\( a, b \): Tunnel width and height

\( m, n \): Mode numbers (only the (1, 1) mode is used)

\( x' \): Constant denoting the greatest distance between the outer wall and the ray

\[ n_{\text{ref}} = \frac{1}{2\sqrt{r^2 - (x')^2}} \]: Number of reflections per meter for a ray

\[ \theta = \frac{\pi}{2} - \tan^{-1}\left(\frac{r^2 - (x')^2}{r - x'}\right) \]: Ray’s angle of incidence

\( \Delta h \): Standard deviation of the tunnel’s roughness

\( \phi = \frac{\pi}{2} - \theta \): Grazing angle of incidence

\[ \rho = e^{(-2\frac{\sin(\phi)\Delta h}{k})^2} \]: Modification coefficient

More equations are involved in this model which are not mentioned by the author. They are common in the communication field but not always in electrical engineering.

\[ \gamma = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \]: Ordinary reflection coefficient for perpendicular incidence. This equation was not provided by the author. It is determined as shown after discussion with Penn State EE Department Ph.D. candidate Ravi K. Arya (Balanis, 1989). It should produce a similar result compared to the result in the original paper.

\[ \eta = \sqrt{\frac{\mu}{\varepsilon}} = \sqrt{\frac{\mu_0 \varepsilon_0}{\varepsilon_r \varepsilon_0}} \epsilon_0 = 8.854 \times 10^{-12} F/m, \mu_0 = 4 \cdot \pi \times 10^{-7} V \cdot s/(A \cdot m) \]
2.2.2.2 MATLAB Coding Approach

Because the simulation in the paper has the radius as its x axis and the loss (dB/km) as its y axis, the array “r” in the code needs to be the radius. “x” in the code is also an array which is from 1 to 10 and represents the width of the tunnel. The code should contain a big for loop which calculates the $Loss_{curve}$ by averaging the result from different “x” of the ray from the outer wall. Each time, the loop stores this $Loss_{curve}$ in an array called lossdBpm.

After getting the result of lossdBpm, $Loss_{total}$ is easy to calculate by adding lossdBpm to $Loss_{ref}$. Please note that the $Loss_{curve}$ and $Loss_{ref}$ calculated are all negative values since the loss should be negative. The graph in the paper shows positive values so both need to be inverted.

2.2.2.3 Parameters

The parameters used in this mathematical model are presented below. All these parameters are from the original paper. The goal is to verify the result and make sure the model works.

1. $a = 10$ m
2. $b = 5$ m
3. $f = 925$ MHz
4. $\Delta h = 0.125$ m
5. $\varepsilon_r = 8$

The MATLAB code used is provided in Appendix B.
2.2.2.4 Conclusion

A comparison of simulation models for a curved tunnel, using the paper of Nilsson et al., (1998) in contrast to the MATLAB simulation of this thesis is shown in Figures 2-3 and 2-4, respectively. For both tunnels, the parameters are the same as those specified in the previous section, but a different $\gamma$ is used as mentioned in the theoretical background.

As we can see from the two figures, both graphs have the shape of a negative exponential function. At around 200 meters radius, the loss is around 110 dB in simulation of the paper while 125 dB in simulation of the MATLAB code. At around 500 meters radius, the loss is around 40 dB in simulation of the paper while 50 dB in simulation of the MATLAB code. At around 800 meters radius, both simulations have a loss of around 30 dB.

As mentioned in theoretical background part, some variations are expected due to the different $\gamma$ values used. The variations are negligible, especially in applications where the distance traveled in a turn is short.

After comparison, it is concluded that the curved-tunnel mathematical model works. It can present a fairly accurate estimation of radio wave propagation in tunnels.
Figure 2-3. dB loss/km vs. radius simulation result for curved tunnel from Nilsson et al., (1998)

Figure 2-4. dB loss/km vs. radius simulation result for curved tunnel from the MATLAB code
2.2.2.5 Limitations

The curved-tunnel mathematical model has the following limitations:

1. The tunnel is assumed to have a rectangular cross-sectional shape.
2. No other radio frequency is assumed present in the tunnel.

2.2.3 Hybrid Model

2.2.3.1 Theoretical Background

With both straight-tunnel and curved-tunnel mathematical models verified, the next step is to combine them to create a hybrid model.

Note that $Loss_{ref}$ (loss due to refraction) in the curved-tunnel mathematical model is essentially counted in the straight-tunnel mathematical model. To create a hybrid model, $Loss_{ref}$ will be replaced by the result from the straight-tunnel mathematical model.

The new $P_r$ becomes:

$$P_r = P_r - Loss_{curve}$$

Also, because only $Loss_{curve}$ is needed for specific curvature, the code is modified to get this value.

The hybrid model simulates the power of the signal till the second turn. This is where the signal dies according to data collected for the tunnel in Norway. Then a comparison will be made to verify the hybrid model.
2.2.3.2 MATLAB Coding Approach

Following the code for the previous two models, two for loops should be added. The first for loop calculates $P_r$ when going through the turn. The second for loop calculates $P_r$ after the turn and to the end of the tunnel.

2.2.3.3 Assumptions

Due to the limitations of both mathematical models and the irregular shape of the tunnel in Norway, the following assumptions are made about the tunnel to produce better simulation results.

1. The wall of the tunnel is smooth. Because the straight-tunnel mathematical model does not incorporate the roughness of the wall, it is a better practice to assume that the wall is smooth in both models. Although the curved-tunnel mathematical model incorporates the roughness of the wall, the model is not designed to model standard deviation as big as one meter. Trials were run with $\Delta h = 1 \text{ m}$. The hybrid model produces no signal power; hence, it is assumed that the wall of the tunnel is smooth.

2. The cross-sectional shape is assumed to be rectangular with width of 4 meters and height 6 meters. Although the cross-sectional shape of the tunnel is arched, the height to width ratio is not too big. We can assume that the cross-sectional shape of the tunnel is rectangular for the simplicity of this application.

3. The transmitting antenna has an antenna gain in the function of grazing angle of

$$G_{hip} = G \cdot \left(\frac{\cos \frac{n}{2} \cos (\theta_{hi})}{\sin (\theta_{hi})}\right)^2 \text{ and } G_{vip} = G \cdot \left(\frac{\cos \frac{n}{2} \cos (\theta_{vi})}{\sin (\theta_{vi})}\right)^2.$$
4. The ordinary reflection coefficient for perpendicular incidence is \( \gamma = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \).

2.2.3.4 Parameters

The parameters used are all for the tunnel from Norway with the above specified assumptions:

1. \( P_t = 0.04 \) W: This value is not exact since the only way to find out the real signal power transmitted is with the use of a spectrum analyzer. After discussion with Penn State EE Department Ph.D. candidate Mike Conway, it was decided to use 0.04 W.

2. \( R_0 = 810 \) m

3. \( \lambda = \frac{3 \times 10^8}{1575 \times 10^6} \)

4. \( G_d = \sqrt{G_t \cdot G_r} = \sqrt{10^{15} \cdot 50} \)

5. \( \varepsilon_r^* = 7 - 0.85 \times 1i \)

6. \( \varepsilon_r = 7 \)

7. \( H = 6 \) m

8. \( W = 4 \) m

9. \( n = 40 \)

10. The radius of the first curvature is 8 m.

11. The distance traveled at the first curvature is 5 m.

The MATLAB code used is provided in Appendix C.
2.2.3.5 Data Collected from the Tunnel in Norway

Limited data with regard to GPS signal strength is provided. Because the tunnel was never mapped, the distance from the entrance is estimated. The dB value from the software is only a relative value of signal-to-noise data instead of the real signal power received. The approximate average value of the available satellites’ dB value is taken as a reference point to verify the hybrid mathematical model.

See Appendices D, E, F, G, H for the screen captures of the software.

It is provided that the GPS signal completely dies at second turn. The screen capture at this point is not provided.

The data are listed in below Table 2-1.

<table>
<thead>
<tr>
<th>Time stamp</th>
<th>Approximate distance from entrance</th>
<th>Average relative dB value</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:08:25</td>
<td>Near antenna</td>
<td>49 dB</td>
</tr>
<tr>
<td>14:11:45</td>
<td>Near 30 meters</td>
<td>35 dB</td>
</tr>
<tr>
<td>14:13:45</td>
<td>Near 100 meters</td>
<td>39 dB</td>
</tr>
<tr>
<td>14:23:25</td>
<td>Near 300 meters</td>
<td>30 dB</td>
</tr>
<tr>
<td>14:31:00</td>
<td>Near 600 meters</td>
<td>5 dB</td>
</tr>
<tr>
<td>NA</td>
<td>810 meters, second turn</td>
<td>Completely dies</td>
</tr>
</tbody>
</table>

Table 2-1. GPS signal receiver (u-blox) data points from the tunnel in Norway
2.2.3.6 Simulation Result Analysis

The MATLAB simulation result of the hybrid model is shown in Figure 2-5. The parameters used are all for the tunnel in Norway which are specified in the previous section.

Because the values collected from the tunnel in Norway are just relative values of signal-to-noise data, while the simulation model produces the real GPS signal power, the only reasonable way to compare them is through the dB drop. The dB drop in the software is the dB drop of the real signal power per u-blox customer service.

As we can see after comparing Figure 2-5 and Table 2-1, there is a big dB drop in the simulation while not so much in the table. It is believed that this is due to the fact that u-blox was saturated near the antenna. If the signal free-space propagation equation is applied, the power
transmitted is expected to have a big drop at the beginning. Since this is the case, we are going to drop the first data point.

From 30 meters to 100 meters, there is around 10 dB drop in simulation while the table has a slight increase in power. After reviewing the progression video of the software, it is shown that the real value in the tunnel is fluctuating between 30 meters and 100 meters. As the simulation shows, it is always a noisy result when propagating in tunnels. Overall, there should be a steady trend of dB value drop, but a slight increase due to reflections and diffractions of the signal is likely.

From 100 meters to 300 meters, there is around 8 dB drop in simulation while the table shows a consistent result of 9 dB drop.

From 300 meters to 600 meters, there is around 10 dB drop in simulation while the table shows a drop around 25 dB. However, there are many points in simulation along 300 meters to 600 meters, like the point at 515 meters, that show a drop as big as around 20 dB. It is not surprising to see a 25 dB drop in the table.

From 600 to 800 meters, there is around 5 dB drop in simulation while the table also shows a 5 dB drop.

In total, there is around 33 dB drop from 30 meters to 810 meters in simulation. This is consistent with the 35 dB drop from the table, showing that the signal will die at the second turn.

**2.2.3.7 Conclusion**

As we can see, the MATLAB simulation shows a consistent dB drop between 30 meters and 800 meters with the data collected from the tunnel in Norway. There are slight variations between 30 meters and 800 meters, but they are consistent with the noisy results of the simulation. It is concluded that the hybrid model can predict GPS signal behavior in tunnels.
Chapter 3

Recommendations

Because the sensitivity of u-blox is -150 dBm, according to the hybrid model simulation with an antenna transmitting signal power at 0.04 W, the GPS signal should be able to get to the end of the tunnel. (At 810 meters, the signal power is around -90 dB, which is well beyond -150 dBm).

Part of the purpose of this thesis is to provide feasible recommendations on how to send the GPS signal to the end of the tunnel. Because no GPS repeater would be required, assuming that the wall is smooth and the cross-sectional shape is rectangular, this thesis went one step further to present a more feasible recommendation.

3.1 Assumptions

1. Minimum signal power level is reached at around 300 meters. As we can see from the data collected for the tunnel, at around 300 meters the software is still showing a green color. Assuming that this is the signal power level we want to maintain in the tunnel, a GPS repeater can be place at 300 meters.

2. GPS repeaters are the same as the transmitters set at the entrance. From a practical point of view, usually the same transmitters are used as GPS repeaters as the transmitting antenna at the entrance of the tunnel. Hence, we are going to use the same specifications in modeling the GPS repeaters.

3. The GPS repeater has an effective range of around 400 meters. The real data collected from the tunnel suggest that one transmitter can cover about 300 meters with one turn. So
it is reasonable to assume that one GPS repeater can cover around 400 meters in a straight tunnel.

4. Cable loss is ignored. Usually when setting up GPS repeaters, cables carrying the GPS signal to the repeater will have a cable loss. This recommendation assumes no cable loss.

### 3.2 Possible Set Up

A possible set up of GPS repeaters is shown in Figure 3-1. The number of GPS repeaters needed depends on the result of the simulation.

![Figure 3-1. Possible set up for GPS repeaters](image)

### 3.3 MATLAB Coding Approach

First, the code was extended to simulate the whole tunnel by simply setting array $R_0$ from 0 to 1610 and adding the effect of the second turn.
A new for loop was set up to simulate the straight tunnel propagation for the GPS repeater with an effective range of 400 meters.

Use one for loop to simulate one GPS repeater, and use one for loop to add the effect of the tunnel turn.

The result would be an effort of trial and error, by adding one GPS repeater at a time and verifying the effective distance.

### 3.4 Parameters

The parameters for these calculations are all for the tunnel in Norway with the above specified assumptions:

1. \( P_t = 0.04 \) W
2. \( R_0 = 1610 \) m
3. \( \lambda = \frac{3 \times 10^8}{1575 \times 10^6} \)
4. \( G_d = \sqrt{10^{70} \times 50} \)
5. \( \varepsilon_r^* = 7 - 0.85 \times 1i \)
6. \( \varepsilon_r = 7 \)
7. \( H = 6 \) m
8. \( W = 4 \) m
9. \( n = 80 \): Number of reflections for the whole tunnel. Since this is simulating the whole tunnel, the number of reflections doubled.
10. \( n_2 = 80 \times \left( \frac{400}{1610} \right) \): Number of reflections for the straight-tunnel effect from the GPS repeater. The number of reflections is positively correlated with the distance.
11. The radius of the first curvature is 8 meters.
12. The distance traveled at the first curvature is 5 meters.

13. The radius of the second curvature is 8 meters.

14. The distance traveled at the second curvature is 5 meters.

15. The transmitter has an effective range of around 400 meters.

The MATLAB code used is provided in Appendix I.

3.5 Simulation Result Analysis

The MATLAB simulation results of the hybrid model with two and four GPS repeaters are shown in Figures 3-2 and 3-3, respectively. The parameters used are all for the tunnel in Norway which are specified in the previous section.
Figure 3-2. Signal power received simulation result after adding two GPS repeaters

As we can see from Figure 3-2, assuming that the GPS repeater has an effective range of 400 meters is a good assumption. The received signal power returns to the power level at 300 meters after propagating around 400 meters. In this case, the second GPS repeater has to cover the second turn, making the received signal power an acceptable level at around 1000 meters.

After adding the third repeater at 1000 meters, the received power is still too low at 1610 meters. A fourth GPS repeater is added and the result is shown in Figure 3-3.
As we can see from Figure 3-3, with four GPS repeaters added, the received power signal should be able to get to the end of tunnel.

3.6 Conclusion

From the result of the simulations, it is concluded that at least four GPS repeaters, each transmitting at a power of 0.04 W, should be added to ensure adequate coverage of the GPS signal in the tunnel. Do note that the sensitivity of u-blox (-150 dBm) is high compared to most other commercial products (-100 dBm). Also, cable loss was ignored in this simulation. On the other hand, the assumption was made that the signal level at 300 meters is the floor. Since there is
no data point available between 300 meters to 600 meters, it is possible that the floor might be somewhere in between. Considering the above factors, it is recommended to do a field test with three to four repeaters. Depending on which of those factors mentioned above plays a dominant role, one or two repeaters might need to be added or reduced.
Appendix A: MATLAB Code Used for Straight-Tunnel Model

%Boni Li

clc;
clear all

Pt=.001;
lamda = 3e8/(2.45*10^9)
Gd = (10^(8/10)*10^(8/10))^0.5;
k=2*pi/lamda;
R0=0:365;
a = 7-0.85*1i; %permitivity
b = 0.0239; %conductivity
H=6.15;
W=14.7;

%for loop for horizontal
sumhorizontal = 0;
for r = 1:25;
    Rhi=(R0.^2+(r.*W).^2).^0.5;
    anglehi=atan(W.*(r+1)./(2.*R0));
    reflectionhi = ((sin(anglehi))-a-(cos(anglehi)).^2).^0.5)./(sin(anglehi)+(a-(cos(anglehi)).^2).^0.5);
    Ghi=6.3*(cos(pi./2.*cos(anglehi))./sin(anglehi)).^2
    horizontal = (Ghi.*(reflectionhi).^j).*exp(-j.*k.*Rhi))./Rhi;
    sumhorizontal = sumhorizontal + horizontal;
end

sumhorizontal

%for loop for verticle
sumvertical = 0;
for r = 1:25;
    Rvi=(R0.^2+(r.*H).^2).^0.5;
    anglevi=atan(H.*(r+1)./(2.*R0));
    reflectionvi = (((a.*sin(anglevi))-a-(cos(anglevi)).^2).^0.5)./((a.*sin(anglevi))+(a-(cos(anglevi)).^2).^0.5));
    Gvi=6.3*(cos(pi./2.*cos(anglevi))./sin(anglevi)).^2
    vertical = (Gvi.*(reflectionvi).^j).*exp(-j.*k.*Rvi))./Rvi;
    sumvertical = sumvertical + vertical;
end

sumvertical
\[ Gd \cdot \exp(-j k R_0) / R_0 \]
\[ \text{Pr} = Pt \cdot (\lambda / (4 \cdot \pi))^2 \cdot \text{abs}((Gd \cdot \exp(-j k R_0) / R_0) + \text{sumhorizontal} + \text{sumvertical})^2 \]

```matlab
figure
plot(R0, 10 * log10(1000 * Pr));
grid;
xlabel('distance (m)');
ylabel('dBm');
```

```matlab
%}
```
Appendix B: MATLAB Code Used for Curved-Tunnel Model

%@Boni Li

close all;
c1c;
clear all

Pt=.001;
lamda = 3e8/(925*10^6);
Gd = (10^(6.3/10)*10^(6.3/10))^0.5;
k=2*pi/lamda;
R0=0:365;
a = 7-0.85*1i; %permittivity
b = 0.0239; %conductivity
H=6.15;
W=14.7;

%for loop for horizontal
sumhorizontal = 0;
for r = 1:25;
    Rhi=(R0.^2+(r.*W).^2).^0.5;
    anglehi=atan(W.*(r+1)./(2.*R0));
    reflectionhi = ((sin(anglehi))-(a-(cos(anglehi)).^2).^0.5)./(sin(anglehi)+(a-(cos(anglehi)).^2).^0.5);
    Ghi=6.4*(cos(pi./2.*cos(anglehi))./sin(anglehi)).^2;
    horizontal = (Ghi.*(reflectionhi.^j).*exp(-j.*k.*Rhi))./Rhi;
    sumhorizontal = sumhorizontal + horizontal;
end

sumhorizontal;

%for loop for vertical
sumvertical = 0;
for r = 1:25;
    Rvi=(R0.^2+(r.*H).^2).^0.5;
    anglevi=atan(H.*(r+1)./(2.*R0));
    reflectionvi = (((a*sin(anglevi))-(a-(cos(anglevi)).^2).^0.5)./(a.*sin(anglevi))+(a-(cos(anglevi)).^2).^0.5)));
    Gvi=6.4*(cos(pi./2.*cos(anglevi))./sin(anglevi)).^2;
    vertical = (Gvi.*(reflectionvi.^j).*exp(-j.*k.*Rvi))./Rvi;
    sumvertical = sumvertical + vertical;
end

sumvertical;
Gd.*exp(-j.*k.*R0)./R0
(lamda./(4.*pi)).^2

Pr = Pt.*(lamda./(4.*pi)).^2.*(abs((Gd.*exp(-j.*k.*R0)./R0)+
sumhorizontal + sumvertical).^2)

figure
plot(R0, 10.*log10(1000.*Pr));
grid;
xlabel('distance (m)');
ylabel('dBm');

dummy = 1
for r = 100:900;
    radius=r;
x=[1:10];
nrefl=1./(2.*(radius.^2-(x-radius).^2).^0.5)
    angleincidence=pi./2-atan((radius.^2-(x-radius).^2).^0.5./(radius-x));
%angle of incidence
angleloss=pi./2-angleincidence;
    yita=4*pi*10^(-7)/(8.854e-12);
y=(((yita./8).^0.5)-(yita).^0.5)./((yita./8)^0.5+(yita).^0.5)
deltah=.125;
p=exp(-2.*(2.*pi.*sin(angleloss).*deltah./lamda).^2)
20.*nrefl.*log10(y.*p)

lossdBpm (dummy) = mean(-20.*nrefl.*log10(y.*p))
dummy= dummy+1;
end

lossref=8.686.*lamda^2.*(1/(2*1000)*real(1/(7^0.5))+1/(2*5^3)*real(8/(7^0.5)))
figure
plot(100:900,lossdBpm.*1000-lossref*1000)
grid
xlabel ('radius (m)');
ylabel ('loss(dB/km)');
Appendix C: MATLAB Code Used for Hybrid Model

```matlab
% Boni Li

close all;
c1c;
clear all

Pt=.04;
lambda = 3e8/(1575*10^6);
Gd = (10^(7/10)*50)^0.5;
k=2*pi/lamda;
R0=0:810;
a = 7-0.85*1i; \text{ \% permittivity}
b = 0.0239; \text{ \% conductivity}
H=6;
W=4;
l1=40 \text{ \% number of reflections}

cr = 8; \text{ \% radius of 1st curvature}
d1=5; \text{ \% distance traveled of 1st curvature}

cr2 = 8; \text{ \% radius of 2nd curvature}

% for loop for horizontal
sumhorizontal = 0;
for r = 1:l1;
    Rhi=(R0.^2+(r.*W).^2).^0.5;
    anglehi=atan(W.*(r+1)./(2.*R0));
    reflectionhi = ((sin(anglehi)) - (a - (cos(anglehi)).^2).^0.5)/(sin(anglehi)+(a - (cos(anglehi)).^2).^0.5);
    Ghi=5.01*(cos(pi./2.*cos(anglehi))./sin(anglehi)).^2;
    horizontal = (Ghi.*(reflectionhi.^j).*exp(-j.*k.*Rhi))./Rhi;
    sumhorizontal = sumhorizontal + horizontal;
end

sumhorizontal;

% for loop for vertical
sumvertical = 0;
for r = 1:l1;
    Rvi=(R0.^2+(r.*H).^2).^0.5;
    anglevi=atan(H.*(r+1)./(2.*R0));
    ...
```

```matlab
...```
reflectionvi = (((a*sin(anglevi))-(a-
(cos(anglevi)).^2).^0.5)/((a.*sin(anglevi))+(a-
(cos(anglevi)).^2).^0.5));

Gvi=5.01*(cos(pi./2.*cos(anglevi))./sin(anglevi)).^2;

vertical = (Gvi.*(reflectionvi.^j).*exp(-j.*k.*Rvi))./Rvi;

end

sumvertical = sumvertical + vertical;

Gd.*exp(-j.*k.*R0)./R0
(lamda./(4.*pi)).^2

Pr1 = Pt.*(lamda./(4.*pi)).^2.*abs((Gd.*exp(-j.*k.*R0)./R0)+
sumhorizontal + sumvertical).^2)

figure
plot(R0,10.*log10(Pr1));
grid;
xlabel('distance (m)');
ylabel('dB');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%
dummy1=1;
for r = 1:.1:4;
  x = r;
  radius=cr;
nrefl1=1./(2.*(radius.^2-(x-radius).^2).^0.5);

angleincidence = pi./2-atan((radius.^2-(x-radius).^2).^0.5./(radius-
x)); %angle of incidence
angleloss = pi./2-angleincidence;

yita=4*pi*10^(-7)/(8.854e-12);

y=-(((yita./7).^0.5)-(yita).^0.5)/((yita./7)^0.5+(yita).^0.5);
deltah=0;
p=exp(-2.*(2.*pi.*sin(angleloss).*deltah./lamda).^2);

-20.*nrefl.*log10(y.*p)
lossdBpm(dummy1) = -20.*nrefl.*log10(y.*p);
dummy1 = dummy1+1;

% lossref=8.686.*lambda^2.*(1/(2*1000)*real(1/(7^0.5))+1/(2*5^3)*real(8/(7 ^0.5)))

end

lossdBpm
lossdBpmr = mean (lossdBpm)

for r = 1:d1
    Pr1(9+r) = 10^((10*log10(Pr1(9+r)) - lossdBpmr * r)/10);
end

for r = (10+d1):811
    Pr1(r) = 10^((10*log10(Pr1(r)) - lossdBpmr*d1)/10);
end

10.*log10(Pr1);
figure
plot(R0,10.*log10(Pr1));
grid;
xlabel('distance (m)');
ylabel('dB');
Appendix D: Screen Capture at 14:08:25 Near Antenna
Appendix E: Screen Capture at 14:11:45 Near 30 Meters
Appendix F: Screen Capture at 14:13:45 Near 100 Meters
Appendix G: Screen Capture at 14:23:25 Near 300 Meters
Appendix H: Screen Capture at 14:31:00 Near 600 Meters
Appendix I: MATLAB Code Used for Hybrid Model with Four GPS Repeaters

%Boni Li

close all;
c1c;
clear all

Pt=.04;
lamda = 3e8/(1575*10^6);
Gd = (10^((7/10)*50)^0.5;
k=2*pi/lamda;
R0=0.1610;
a = 7-0.85*1i; %permitivity
b = 0.0239; %conductivity
H=6;
W=4;
l1=80 %number of reflections

cr = 8; %radius of 1st curvature
d1=5; %distance traveled of 1st curvature

cr2 = 8; %radius of 2nd curvature
d2=5; %distance traveled of 1st curvature

repeater1 = 300;
d1 = 400;
repeater2 = 700;
repeater3 = 1000;
repeater4 = 1400

%for loop for horizontal
sumhorizontal = 0;
for r = 1:l1;
    Rhi=(R0.^2+(r.*W).^2).^0.5;
    anglehi=atan(W.*(r+1)./(2.*R0));
    reflectionhi = ((sin(anglehi))-a-(cos(anglehi)).^2).^0.5)./(sin(anglehi)+(a-(cos(anglehi)).^2).^0.5);
    Ghi=5.01*(cos(pi./2.*cos(anglehi))./sin(anglehi)).^2;
    horizontal = (Ghi.*reflectionhi.^j).*exp(-j.*k.*Rhi)./Rhi;
    sumhorizontal = sumhorizontal + horizontal;
end

end
sumhorizontal;

%for loop for verticle
sumvertical = 0;
for r = 1:l1;
    Rvi=(R0.^2+(r.*H).^2).^0.5;
    anglevi=atan(H.*(r+1)./(2.*R0));
    reflectionvi = (((a.*sin(anglevi))-(a-(cos(anglevi)).^2).^0.5)./((a.*sin(anglevi))+(a-(cos(anglevi)).^2).^0.5));

    Gvi=5.01*(cos(pi./2.*cos(anglevi))./sin(anglevi)).^2;

    vertical = (Gvi.*(reflectionvi.^j).*exp(-j.*k.*Rvi))./Rvi;
    sumvertical = sumvertical + vertical;
end

horizontal = sumhorizontal;

Gd.*exp(-j.*k.*R0)/R0
(lamda./(4.*pi)).^2

Pr1 = Pt.*(lamda./(4.*pi)).^2*(abs((Gd.*exp(-j.*k.*R0)/R0)+
sumhorizontal + sumvertical).^2)

figure
plot(R0,10.*log10(Pr1));
grid;
xlabel('distance (m)');
ylabel('dB');

 dummy1=1;
for r = 1:.1:4;
    x = r;
    radius=cr;
    nrefl=1./(2.*(radius.^2-(x-radius).^2).^0.5);

    angleincidence = pi./2-atan((radius.^2-(x-radius).^2).^0.5./(radius-x));
    angleloss = pi./2-angleincidence;

    yita=4*pi*10^(-7)/(8.854e-12);

\[
y = -\frac{(\gamma \eta / 7)^{0.5} - (\gamma \eta)^{0.5}}{(\gamma \eta / 7)^{0.5} + (\gamma \eta)^{0.5}};
\]

deltah = 0;
\]
\[
p = \exp(-2 \cdot 2 \cdot \pi \cdot \sin(\text{angleloss}) \cdot \text{deltah} / \lambda)^2);
\]
\[
-20 \cdot nrefl \cdot \log10(y \cdot p)
\]

\[
\text{lossdBpm} \text{ (dummy1)} = -20 \cdot nrefl \cdot \log10(y \cdot p);
\]
\[
dummy1 = \text{dummy1} + 1;
\]

\[
\text{lossdBpm}
\]
\[
\text{lossdBmpr} = \text{mean} (\text{lossdBpm})
\]

\[
\text{for} \ r = 1:d1
\]
\[
\text{Pr1} (9+r) = 10^{(10 \cdot \log10(\text{Pr1} (9+r)) - \text{lossdBmpr} \cdot r) / 10};
\]
\[
\text{end}
\]

\[
\text{for} \ r = (10+d1):1611
\]
\[
\text{Pr1} (r) = 10^{(10 \cdot \log10(\text{Pr1} (r)) - \text{lossdBmpr} \cdot d1) / 10};
\]
\[
\text{end}
\]

\[
\% \text{Second turn for loop}
\]
\[
\text{for} \ r = 1:d2
\]
\[
\text{Pr1} (809+r) = 10^{(10 \cdot \log10(\text{Pr1} (809+r)) - \text{lossdBmpr} \cdot r) / 10};
\]
\[
\text{end}
\]

\[
\text{for} \ r = (810+d2):1611
\]
\[
\text{Pr1} (r) = 10^{(10 \cdot \log10(\text{Pr1} (r)) - \text{lossdBmpr} \cdot d2) / 10};
\]
\[
\text{end}
\]

\[
\% \text{straight tunnel effect for repeater}
\]

\[
\text{PR} = \text{Pt};
\]
\[
\text{R0R} = 0:de;
\]
\[
\text{l2} = 40 \cdot (\text{de}/1610); \quad \% \text{number of reflections}
%for loop for horizontal
sumhorizontal = 0;
for r = 1:l2;
    Rhi=(R0R.^2+(r.*W).^2).^0.5;
    anglehi=atan(W.*(r+1)./(2.*R0R));
    reflectionhi = ((sin(anglehi))-(a-
    (cos(anglehi)).^2).^0.5)./(sin(anglehi)+(a-
    (cos(anglehi)).^2).^0.5);
    Ghi=5.01*(cos(pi./2.*cos(anglehi))./sin(anglehi)).^2;
    horizontal = (Ghi.*(reflectionhi.^j).*exp(-j.*k.*Rhi))./Rhi;
end
sumhorizontal = sumhorizontal + horizontal;

%for loop for vertical
sumvertical = 0;
for r = 1:l2;
    Rvi=(R0R.^2+(r.*H).^2).^0.5;
    anglevi=atan(H.*(r+1)./(2.*R0R));
    reflectionvi = (((a*sin(anglevi))-
    (a-(cos(anglevi)).^2).^0.5)./((a.*sin(anglevi))+(a-
    (cos(anglevi)).^2).^0.5));
    Gvi=5.01*(cos(pi./2.*cos(anglevi))./sin(anglevi)).^2;
    vertical = (Gvi.*(reflectionvi.^j).*exp(-j.*k.*Rvi))./Rvi;
end
sumvertical = sumvertical + vertical;

PrR = PR.*(lamda./(4.*pi)).^2.*(abs((Gd.*exp(-j.*k.*R0R)./R0R)+
    sumhorizontal + sumvertical).^2)

%for loop if put one repeater
dummy2=1
for r = (repeater1): (repeater1 + de)
    Pr1(r) = Pr1(r) + PrR(dummy2);
    dummy2=dummy2+1;
end

%for loop if put second repeater
dummy3=1
for r = (repeater2): (repeater2 + de)
    Pr1(r) = Pr1(r) + PrR(dummy3);
    dummy3=dummy3+1;
end

%Second turn for loop
for r = 1:d2
    Pr1(809+r) = 10^((10*log10(Pr1(809+r)) - lossdBpmr * r)/10);
end
for r = (810+d2):1611
    Pr1(r) = 10^((10*log10(Pr1(r)) - lossdBpmr*d2)/10);
end

%for loop if put third repeater
dummy4=1
for r = (repeater3): (repeater3 + de)
    Pr1(r) = Pr1(r) + PrR(dummy4);
    dummy4=dummy4+1;
end

%for loop if put forth repeater
dummy5=1
for r = (repeater4): 1611
    Pr1(r) = Pr1(r) + PrR(dummy5);
    dummy5=dummy5+1;
end

figure
plot(R0,10.*log10(Pr1));
grid;
xlabel('distance (m)');
ylabel('dB');

**************************************************************************
REFERENCES


ACADEMIC VITA

Boni Li

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Education

B.S., Electrical Engineering, 2012, The Pennsylvania State University, University Park, Pennsylvania

Professional Experience

ENGINEERING EXPERIENCE

SIEMENS Energy (E F I E 1 5 9 RMT), Alpharetta, GA 06/12 - 08/12
Engineering, Intern
- Managed and manipulated complex engineering database (I/O list and cable list) with Access
- Executed Release for Manufacturing and I&C (Instrument and Control) Design Changes as a liaison position between engineering and manufacturing
- Utilized AutoCAD Electrical to review and edit designs for control system of gas turbine, steam turbine and combined turbine power plants

Invensys Operations Management, Foxboro, MA 05/11 - 12/11
Hardware Engineer, Co-op position
- Implemented the operational process of technical document control and transfer system per nuclear industry Quality Assurance plan
- Served as liaison position between Invensys and customer during important meetings to improve technical communication efficiency between two parties
- Researched nuclear power industry engineering standards and product dedication process
- Created working procedures to teach other engineers nuclear industry documentation standards

CNPE Co., Ltd, Beijing, China 06/10
Procurement Contract Negotiator
- Served on team to negotiate a purchase of a power plant generator valued at $1 million
- Utilized engineering procedures and mathematic models to determine potential product issues with selected suppliers
- Interpreted corporate contract payment methods and debt reduction strategies

AREVA, Tianwan Nuclear Power Plant, Lianyungang, China 06/09 – 07/09
Spare Parts Testing and Storage Specialist

- Completed technical on-board training in nuclear grade and non-nuclear grade I&C systems
- Handled and tested redundancy system spare parts of a nuclear grade I&C system
- Assisted department manager and professional engineer to troubleshoot nuclear power plant control instrument parts

BUSINESS EXPERIENCE

Advance Risk and Portfolio Management Bootcamp by Attilio Meucci, NYC 08/15/11 - 08/20/11
- Familiarized with knowledge in various aspects including: Market modeling, Multivariate statistics, Factor modeling, Pricing, Risk analysis and Portfolio construction

Wall Street Boot Camp, University Park, PA 01/11 – 05/11
- Selected for membership through demonstrated analytical skills and leadership via a competitive application process (the only engineer admitted to the program)
- Trained in different aspects of business field including Investment Banking, Sales & Trading, Capital Markets, Private Equity, Asset Management, Private Wealth Management

Sino Resources Investment Co., Ltd, Beijing, China 12/10 – 01/11
Private Equity Technical Advisor
- Interpreted venture capital and private equity fund raising procedures by advising on communications systems and GPS locators of millions-dollar private equity project
- Analyzed stocks of AT&T, China Mobil and China Communication Network with related technical information

LEADERSHIP

Engineering Ambassador, University Park, PA 08/10 – present
Professional development organization with an outreach mission
- Selected as one of 40 engineering students to serve as ambassador for the College of Engineering in high school recruitment efforts
- Completed advanced communications training for use in a variety of public speaking situations
- Presented to parents and prospective students on behalf of the College of Engineering
- Trained fellow Engineering Ambassadors from other universities in communication and leadership

Tutor, University Park, PA 01/11 – present
- Worked closely with Finance Professor Gregory Pierce to tutor students in Introduction to Finance, Corporation Finance and Financial Management of the Business Enterprise classes

Mentor, International Student Services, University Park, PA 08/09 – 05/10
| AWARDS & ACTIVITIES | Member, Student Chapter of the Institute of Electrical and Electronics Engineers  
|                     | Member, Student Chapter of Eta Kappa Nu (Electrical and Computer Engineering Honor Society) |