GIS Aided Radio Wave Propagation Modeling and Analysis

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(ABSTRACT)

The analysis of radio wave propagation is a crucial part in designing an efficient wireless communication system. The Geographic Information System (GIS) can be incorporated into this procedure because most of the factors in radio wave propagation are geographic features.

In this research, a commercial wireless planning software is tested in a field driving test carried out in Montgomery County, VA. The performance of current wireless planning software is evaluated based on field measurement. The received signal strength data collected during this driving test are then analyzed in a GIS environment in a statistical approach. The effects of local geographic features are modeled in GIS by appropriate spatial analyses.

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Chapter 1 - Introduction

Wireless communication has developed into one of the most exciting technologies of the last century since its birth in 1897 as the radio telegram. Wireless communication in the past several decades is better known as cellular network communication. Currently, requirements for providing wireless communication services can be simply described as the “5Ws”. (i.e., Whoever --- sender, Whenever --- time, Wherever --- location, Whatever --- content, Whomever --- recipient.) That means, not only the availability, but also the quality of the network has become a key parameter of wireless communication service. In this case, cellular network design is becoming more and more important since the network quality is highly dependent on the distribution of base stations.

To design a cellular network for a particular region efficiently and accurately, the analysis of radio wave propagation is an important determination. This process is also called wireless planning.

1.1 Objectives of this research

1.1.1 Survey of Prior Engineering Models and Their Relationship to GIS

There are a variety of models created by electrical engineers in the past decades to analyze wave propagation in cellular networks, but none of them could be called a final solution because every one of them has some particular limitations in its application. Most limitations have relationships with the geographic features of the region to which they are being applied, for example, the blockages along radio wave propagation paths, the clutter loss caused by different land covers, etc. Geographic information systems (GIS) can arrange such location-based information efficiently and accurately. So naturally GIS is considered to help solve problems in designing a cellular network conveniently and efficiently.

Since several GIS analyses were initially designed to assist visually spatial data display and management, most of the relevant spatial analysis capabilities of GIS are based on line-of-sight conditions such as “viewshed” or “hillshade” generalization. As shown in Figure 1.1, a radio wave acts differently because its frequency is much lower than visible light. Thus more radio wave propagation phenomena such as diffraction and refraction occur. These phenomena will be covered in the literature review in a physics approach.

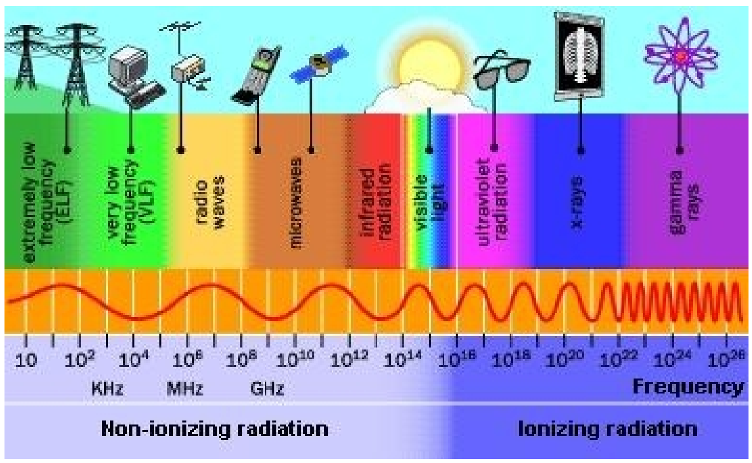

Figure 1. 1 The electromagnetic spectrum

For instance, Figure 1.2 illustrates how GIS arranges signal strength prediction models on a location-oriented basis.

The most appropriate path loss model depends on the location of the receiving antenna relative to the transmitter. For the example below at:

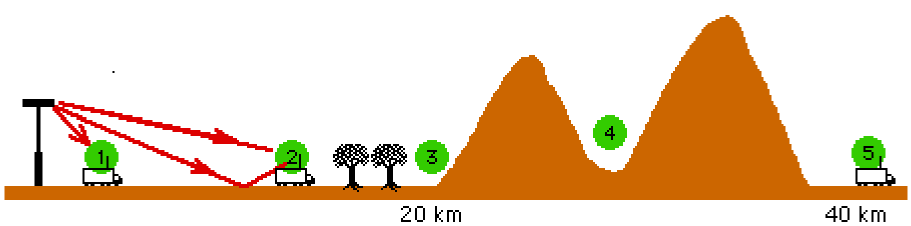

Figure 1. 2 Site and situation of wave propagation

- location 1, free space loss is likely to give an accurate estimate of path loss since there are no physical barriers to wave movement.

- location 2, a strong line-of-sight is present, but ground reflections can significantly influence path loss. The plane earth loss model appears appropriate.
- location 3, plane earth loss needs to be corrected for significant diffraction losses, caused by trees cutting into the direct line of sight, and reradiating the energy in all directions.
- location 4, a simple diffraction model is likely to give an accurate estimate of path loss.
- location 5, loss prediction is likely to be fairly difficult and unreliable since multiple diffraction edges are involved.

There are several widely used models of wave propagation analysis. Since signal strength is the most important parameter in terms of network quality in cellular network design, most of these models deal with the signal strength at receiver points in the study area.

In the analysis stage as well as the prediction process, some radio wave propagation models are used as a theoretical basis. So it is necessary to introduce these models from a wireless planning approach. Some major models currently used in practical wireless planning will be covered in the literature review.

1.1.2 GIS in Wireless Propagation analysis

In this research, GIS-aided data analysis was implemented in an experimental wireless planning project to study the influence of geographic features on the predicted wireless signal strength along roadways in Montgomery County, Virginia. Experimental broadcast antennas were set up and data were collected from three sites by a special receiver that recorded the strength of the signal received from the broadcast antenna while driving. These data were then analyzed in a statistical manner to evaluate the quality of prediction by a commercial modeling package. Very little research on estimating wireless planning quality in a quantitative manner has been done. More details about the statistical methodologies used in this process will be discussed later.

1.1.3 GIS in Drive Testing

GIS modeling also performed a significant role in the analysis of driving test data. Terrain, land cover types and radio wave propagation path were hypothesized among the factors affecting the signal strength at each spot in the study area. To better arrange the necessary driving test in this project, a set of driving test routes were developed in a GIS environment according to local geographic characteristics. GIS provided the most efficiency by taking into account local traffic conditions as well as shortest travel distance to cover all of the designated ““must-go”” test points. The detailed methodology of GIS aided routing in this project will be discussed in later sections.

1.1.4 Empirical Evaluation of the ComSite propagation model

Finally, this research will provide a comparison between these actual driving test data and predicted signal strength data generated by commercial wireless planning software called ComSite. This analysis was carried out in order to discover the potential correlations between prediction errors and a variety of possible geographic factors. The detailed data preparation and methodology information will be discussed below.

Chapter 2 - Literature Review

2.1 The Increasing Significance of Accurately Modeling Propagation

The importance of sound cellular network design is apparent to many engineers engaged in improving the quality of wireless communication services especially since mobile data services have entered the mass market. In addition, the assured stability of networks is of unprecedented value for these new services. To serve an increasing number of users requires an increasing number of base stations. Thus, operators must carefully plan the deployment and configurations of radio base stations to support voice and data traffic at a level of quality expected by customers. (Wagen et. al. 2002)

Engineers have already explored the possibility and necessity of using GIS in this area. They found that more efficient planning of non-voice services or of a mixture of voice and non-voice services requires more accurate propagation-prediction models. “These propagation models are usually based on the computation of the physical interaction of radio waves and the environment. Thus more detailed databases are required, especially in urban environments where most users are located. Although the authors are not GIS specialists, they aim to expose some of the relationship between radio-propagation models used for mobile radio network planning and databases for terrain and buildings. (Wagen et. al. 2002, p. insert page)”

The line of sight (LOS) condition is vastly used to predict the signal strength in some previous GIS based cellular network analysis. But it is not adequate to simply use LOS path loss as an estimate of signal strength for obstructed pathways (Baldassaro, 2001).

To analyze wave propagation in a cellular network, the models have to be applied to the appropriate environment. Thus we must understand some basic concepts in wave propagation modeling.

2.2 Radio Wave Propagation

Propagation mechanisms are very complex and diverse. First, because of the separation between the receiver and the transmitter, attenuation (reduction or loss) of the signal strength occurs. In addition, the signal propagates in different manners, known as diffraction, scattering, reflection, transmission, and refraction.

2.2.1 Diffraction

Diffraction occurs when direct line-of-sight (LOS) propagation between the transmitter and the receiver is obstructed by an opaque obstacle whose dimensions are considerably smaller than the signal wavelength. The diffraction occurs at the obstacle edges where the radio waves are scattered and, as a result, they are additionally attenuated. The diffraction mechanism often allows the reception of weakened radio signals when the LOS conditions are not satisfied (NLoS case), whether in urban or rural environments.

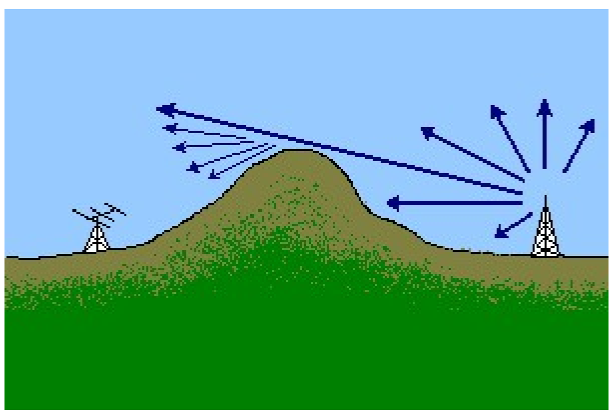

Figure 2. 1 Radio Wave Diffraction

Sometimes, effects of diffraction help to receive radio waves in areas located in the "shadow" of obstacles like behind a hill. Signals will be weak but still readable.

2.2.2 Scattering

Scattering occurs when the propagation path contains the obstacles whose dimensions are comparable to the wavelength. The nature of this phenomenon is similar to diffraction, except that the radio waves are scattered in a greater number of directions. Of all the mentioned effects, scattering is the most difficult to predict.

2.2.3 Reflection

Reflection, very similar to its optical counterpart, appears when a wave makes contact with a surface more or less thick or dense. A reflection can either decrease or increase the signal level at the reception point. At locations where many reflected waves exist, the received signal level tends to be very unstable. This phenomenon is commonly referred to as multipath fading, and the signal is often Rayleigh distributed.

2.2.4 Transmission

Transmission occurs when the radio wave encounters an obstacle that is to some extent transparent for the radio waves, like a glass window is to visible light. This mechanism allows the reception of radio signals inside buildings in cases in which the actual transmitter locations are either outdoors or indoors.

2.2.5 Refraction

Refraction is very important in macrocell (bigger scale, usually consists of many smaller cells) radio system design. Due to an inconstant refractive index of the atmosphere, radio waves do not propagate along a straight line, but rather along a curved one. Therefore, the coverage area of an actual transmitter is usually larger than that predicted by LOS. However, as a result of the fluctuations of the atmosphere parameters, the received signal strength level fluctuates widely as well. (Neskovic, et. al., 2000)

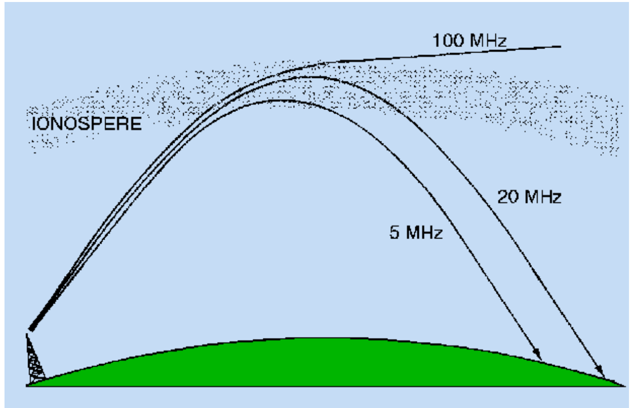

Figure 2. 2 Radio Wave Refraction

As this diagram shows, the effect of refraction also depends on radio wave frequency. More discussion of this phenomenon will appear in later sections.

2.3 Classic Propagation Models

Initial techniques to predict signal strength in shadowed regions relied heavily on classical Fresnel theory and the concept of single knife-edge diffraction (Schelleng et al., 1933; Bachynski, 1963).

As a simple explanation, a Fresnel Zone is the area around the visual line-of-sight that radio waves spread out into after they leave the transmitting antenna (Figure 2.3). This area must be clear or else signal strength will weaken. A Fresnel zone can be simplified as an ellipsoid indicating Radio Line of Sight from the transmitter to receiver. In this project, a blockage refers to an obstacle blocking the radio line of sight instead of visual line of sight to implement the effect of Fresnel Zone.

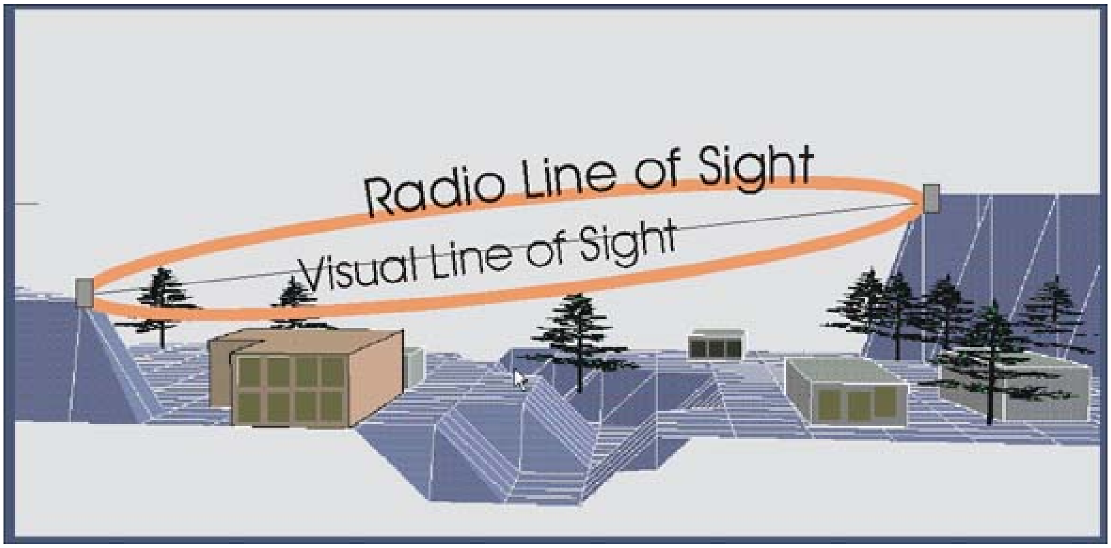

Figure 2. 3 Fresnel Zone

Below is the introduction of some popular radio wave propagation models

2.3.1 The OKUMURA Model

The Okumura et al. method is based on empirical data collected in detailed propagation tests over various situations of an irregular terrain and environmental clutter. The results are analyzed statistically and compiled into diagrams. The basic prediction of the median field strength is obtained for the quasi-smooth terrain in an urban area. A correction factor for either an open area or a suburban area is also taken into account. Additional correction factors, such as for a rolling hilly terrain, an isolated mountain, mixed land-sea paths, street direction, general slope of the terrain etc., make the final prediction closer to the actual field strength values. (Neskovic, et. al., 2000)

2.3.2 The Lee Model

W. C. Y. Lee proposed this model in 1982. In a very short time it became widely popular among researchers and system engineers (especially among those employed by U.S. companies) mainly because the parameters of the model can be easily adjusted to the local environment by additional field calibration measurements (drive tests). By doing so, greater accuracy of the model can be achieved. In addition, the prediction algorithm is simple and fast.

(Neskovic, et. al., 2000) This is the model used in ComSite specifically for this project.

2.3.3 The Hata Model

The Hata Model (Hata, 1980) is an empirical formulation of the graphical path loss information provided by Okumura. Hata presented the urban area propagation loss as the standard formula and supplied correction equations to the standard formula for application to other situations (Sweeny, 2003).

2.3.4 ComSite and the GIS Models used in this research

In this research, ComSite was used to analyze the signal strength distribution instead of simply using a line of sight (LOS) condition, typical in analytical modeling. By using ComSite, the Lee model and its other factors were taken into account in an empirical manner, including distance, shadowing or diffraction loss, and scattering or clutter loss (Sweeny, 2003). The ComSite model is not complete however; it's also suggested that taking into consideration the vegetation and ray-tracing would provide more accurate result in signal strength prediction. (Baldassaro, 2001)

In the analysis portion of this project, a Free Space model was also used as a theoretical supplement to the practical prediction model used in ComSite during the prediction stage in order to provide a straightforward comparison basis.

"The free space propagation model is used to predict received signal strength when the transmitter and receiver have a clear, unobstructed line-of-sight path between them. Satellite communication and microwave line-of-sight radio links typically undergo free space propagation. As with most large-scale radio wave propagation models, the free space model predicts that received power decays as a function of T-R separation distance raised to some power (i.e. a power law function). (Rappaport, 1996, p. insert page)."

In order to reduce the complexities of estimating the signal strength in shadowed areas, the concept of "knife-edge" (also called running-edge) was also introduced to the GIS modeling in this project (Figure 2.4).

“Estimating the signal attenuation caused by diffraction of radio waves over hills and buildings is essential in predicting the field strength in a given service area. Generally, it is impossible to make very precise estimates of the diffraction losses, and in practice prediction is a process of theoretical approximation modified by necessary empirical corrections. When shadowing is caused by a single object such as a hill or mountain, the attenuation caused by diffraction can be estimated by treating the obstruction as a diffracting knife-edge. (Rappaport, 1996, p. insert page) ”

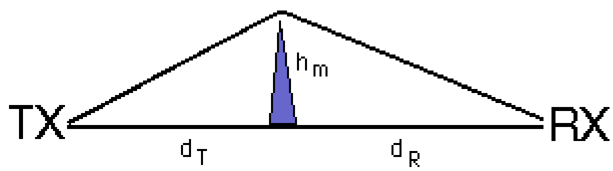

Figure 2. 4 Path profile model for (single) knife edge diffraction

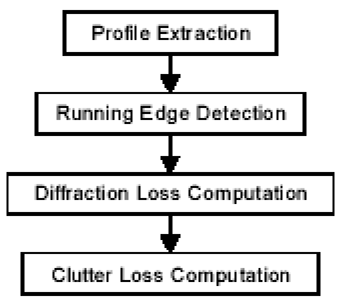

Figure 2. 5 Signal Strength Prediction Procedure

Figure 2.5 is a typical flow chart for a signal strength prediction method. As shown in the bottom, clutter loss, which is caused by objects such as trees or buildings, is an inevitable factor in radio wave propagation.

One of the major problems in predicting field strength in the terrestrial point-to-area environment is the variation in losses due to local land clutter. Most prediction algorithms consider a single number to characterize the loss over an entire area. Given the availability of land clutter databases produced by remote sensing techniques, it is appropriate to characterize the losses due to land clutter on a per-category basis (Figure 2.6) (Rubinstein,1998).

Table IV
Recommended Clutter Loss Values

Category	162 MHz SigStr Diff (dB)			460 MHz SigStr Diff (dB)			860 MHz SigStr Diff (dB)		
	SCA	NWW	ATL	SCA	NWW	ATL	SCA	NWW	ATL
11	13.71		13.95	15.58			18.77	21.15	25.59
12	13.66		12.05	14.86			17.08		24.37
13	15.83			11.81			13.03		
14	15.18		12.47	16.54			18.55		25.78
16	16.21			17.23			17.25		
17	14.79			16.59			17.71	19.88	
21								17.61	
24								18.32	
32	9.10			9.57			19.25		
41								25.30	
43			8.06					26.28	25.72
76	6.91			12.18			16.22		

Figure 2. 6 Clutter loss values suggested for land cover types (Rubinstein,1998)

According to the clutter loss values provided by this chart shown above, amongst three dominating land cover categories (forest, grass, residential) in the study area of this project, residential areas have the most significant effect on radio wave path loss.

2.4 GIS Data

In terms of data preparation, LIDAR and DEM data are two important resources for terrain data. LIDAR data, although more expensive, could be usable in ray tracing in the modeling analysis (Sweeny, 2003) and freely available DEM data could do a great job in LOS prediction (Qian, 2002). In this project, nation wide data availability and easy accessibility were considered as a significant issue for data preparation. So, freely available data sources such as the USGS Digital Elevation Model (DEM) data and the National Land Cover Data (NLCD) data were selected (http://edc.usgs.gov/geodata/). Because NLCD data were not initially developed for radio wave propagation analysis, some reclassification work was necessary to better incorporate these data into this research. The details will be discussed in the data preparation section.

Chapter 3 - Data and Methodology

3.1 Signal Strength Prediction

The prediction of signal strength in the study area was implemented by ComSiteDesign™. ComSiteDesign™ for PC/NT/2000/XP is a computer-aided engineering and planning tool for radio communications engineers and planners (http://www.rcc.com/comdesign.html). For each selected transmitter, ComSite's predicted signal strength is given on a geographic location basis as a grid file that can be exported and analyzed in ArcMap. The input for this prediction procedure includes DEM (Digital Elevation Model) and NLCD (National Land Cover Data) data as well as some user customized antenna parameters.

3.2 Driving Test Route Development

In order to validate the predicted signal strength dataset, a strategically designed driving test is necessary.

Using auxiliary GIS-based software along with ComSiteDesign™, presented the capability of guiding the user's driving test by assigning some "must-go" areas which are unusually complicated in terms of terrain characteristics and land cover types. These "must-go" areas were depicted as a set of tiles that must be driven through along the drive test route. A series of driving test routes were then derived from the designated "must-go" tiles to cover most of the areas where the signal strength is expected to be hard to predict. Also, in order to cover more terrain feature diversity for a better representative performance in future analysis, some base layers were also taken into account when developing the driving test routes.

To maintain wide possible usage in the future in other locations, only widely available data sources were used in developing an efficient route going through all of the “must-go” tiles.

In this project, the road data came from the TIGER files (www.census.gov/geo/www/tiger). DEM and NLCD data were used as the reference of terrain and cover features. All of these data forms are available nationwide.

The weakness of these original data is also obvious though. The TIGER roads data, for example, proved not to have complete connectivity in some rural areas. This deficiency had to be corrected before the roads network could be used as a basis in developing a driving route.

This routing work was executed in a Geographic Information System (GIS) environment to efficiently develop the driving test routes and to provide necessary navigation information. ArcGIS 8.3, a software package developed by ESRI, Inc, was chosen as the GIS platform to implement the routing work because of its powerful network analysis function.

Because the routing algorithm requires nodes for driving destinations, a program was developed in ArcGIS using the VBA (Visual Basic for Applications) programming language to extract all of the road nodes in tiles that had to be visited as predetermined above. Then the routing task was implemented in the Network Analysis module of ArcInfo Workstation. Figure 3.1 is an example of the routes developed in this procedure.

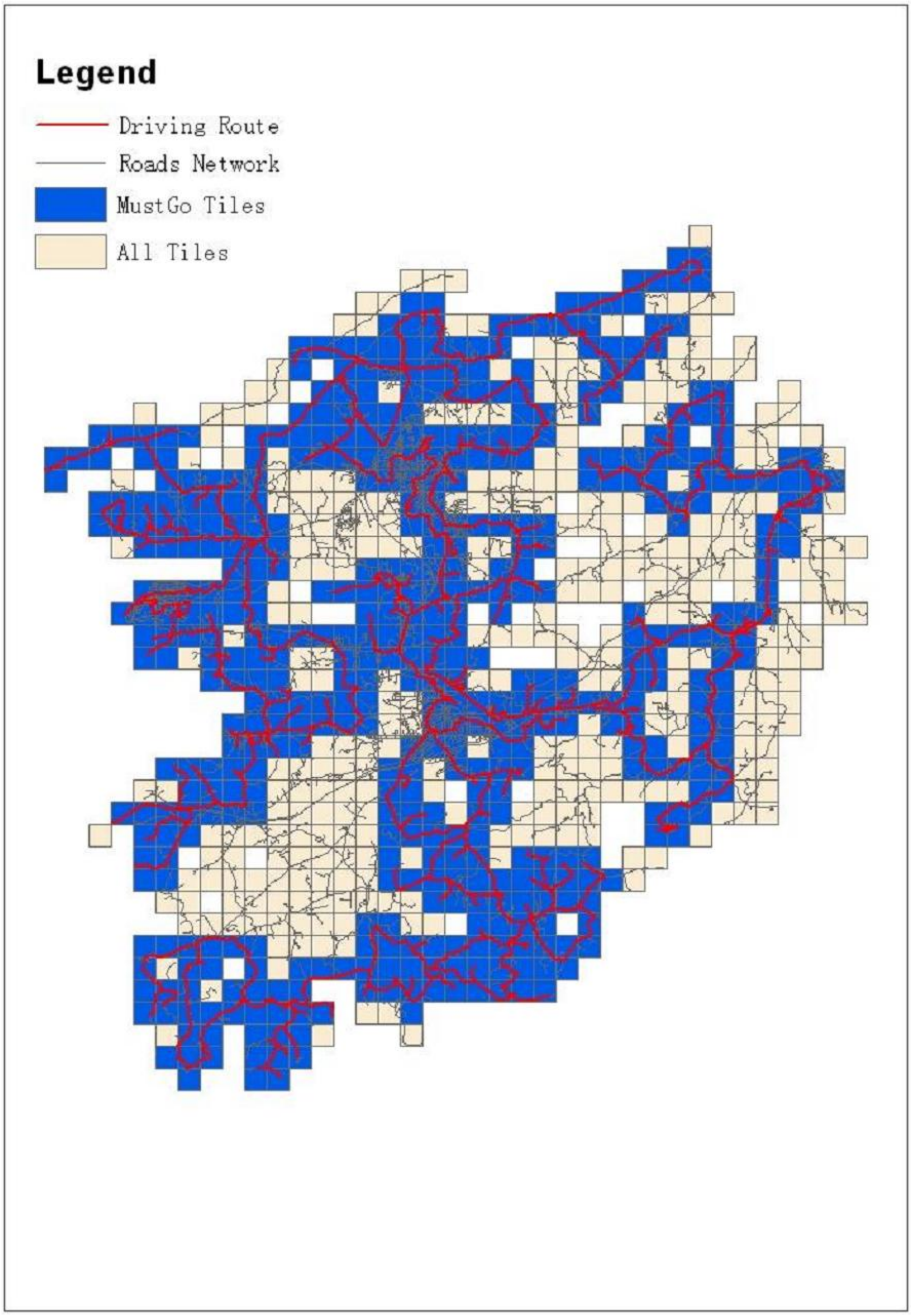

Figure 3. 1 Driving Test Route developed in Arc workstation

The transmitter locations adopted in this project were selected based on the site quality for radio wave propagation as well as on practical accessibility. The driving test route for each particular transmitter site included both the nodes from the “must-go” tiles, and also nodes selected by using GIS layers to involve as many geographic factors as possible including:

- Distance from transmitter
- Land cover diversity along propagation path
- Terrain variance

The TOUR function in ArcInfo then provided the most efficient driving route to pass through all the selected destination nodes. A set of maps as well as a driving directions printout were also developed in ArcMap to navigate the driving test vehicle.

3.3 Driving Test

The measurement of signal strength in the study area was carried out by stratified sampling, based on various terrain and land cover characteristics, such that the spots with geographic features most typical of the local environment were selected. A location's degree of typicality is dependent on the factors hypothesized to affect radio wave propagation in the Montgomery County region. For example, elevation, land cover, building edges and other features collectively called "clutter" are be taken into account as significant geographic features in wave propagation modeling. Some of the known propagation models also required line-of-sight (LOS) or even Fresnel Zone clearance conditions. In this case, the relationship between a sample spot and possible base stations as well as the sample spot itself were considered.

DEM data were used in this research to generate the terrain surface map with the information about vegetation and clutter.

"The USGS Digital Elevation Model (DEM) data files are digital representations of cartographic information in a raster form. DEMs consist of a sampled array of elevations for a number of ground positions at regularly spaced intervals. These digital cartographic/geographic data files are produced by the U.S. Geological Survey (USGS) as part of the National Mapping Program. (USGS, 2005, p. insert page) "

NLCD data were used as the land cover type reference in this process as well as in future statistical analysis.

Derived from the early to mid-1990s Landsat Thematic Mapper satellite data, the National Land Cover Data (NLCD) is a 21-class land cover classification scheme applied consistently over the United States. The spatial resolution of the data is 30 meters and mapped in the Albers Conic Equal Area projection, NAD 83. A hierarchical land cover classification scheme of 21 classes (a modified Anderson Land Cover Classification) was developed and applied in a consistent manner across the entire United States (USGS, 2005) .

The NLCD classification scheme is seen in table 3.1

Digital	Value Class
11	Open Water
12	Perennial Ice/Snow
21	Low Intensity Residential
22	High Intensity Residential
23	Commercial/Industrial/Transportation
31	Bare/Transitional
32	Quarries/Strip Mines/Gravel Pits
33	Bare Rock/Sand
41	Deciduous Forest
42	Evergreen Forest
43	Mixed Forest
51	Shrubland
61	Orchard/Vineyards/Other
71	Grasslands/Herbaceous
81	Pasture/Hay
82	Row Crops
83	Small Grains
84	Fallow
85	Urban/Recreational Grasses (parks, golf course, cemetery, etc)
91	Woody Wetland
92	Herbaceous Wetlands

Table 3. 1 NLCD Classification Scheme
(ASPRS --- American Society for Photogrammetry and Remote Sensing)

The transmitter/ receiver system used in this project was from WinRadio™ (Figures 3.2 and 3.3). It recorded the field signal strength and the correlated location coordinates simultaneously on an interval basis of 1 second.

Figure 3. 2 Experimental Transmitter

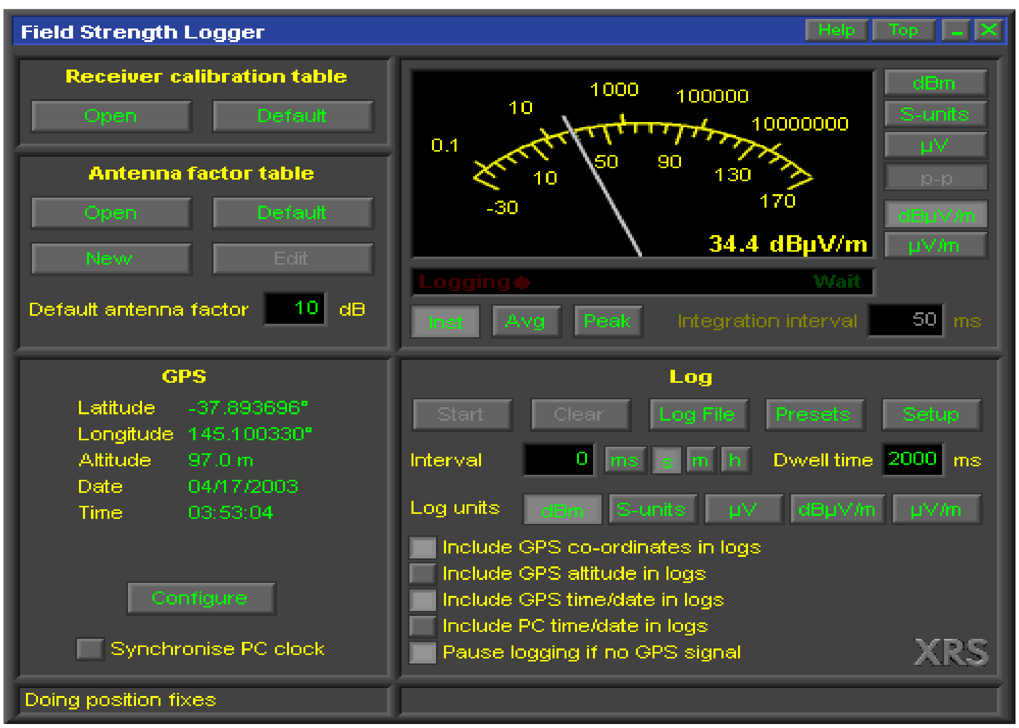

Figure 3. 3 Signal Strength Recorder Interface

The radio frequency of the experimental transmitter was set at 806MHz due to its availability in Montgomery County as well as the desire to study radio wave propagation effects in its band.

Field signal strength data were recorded for all three antenna sites in three consecutive days in early June 2004 to maintain similar atmospheric conditions and land cover circumstances such as leaf cover.

3.4 Data Processing

The signal strength data analysis is based on statistics conducted on the residuals between the ComSite predicted signal strength and the actual field signal strength values obtained in the driving tests. A variety of geographic features were taken into account to determine potential correlations between these errors and receiver site or path related factors. Depending on the characteristics of the different factors, the statistical analysis was conducted with a series of strategically designed quantitative methodologies.

Below is a description of radio wave propagation factors considered in this project. The methodology of developing these data from the original data sources is also discussed here. These data were then used as independent variables in the statistical analysis with the error in signal prediction as the dependent variable.

3.4.1 Distance to the antenna site

The distance from each sample point to the antenna site was easily calculated in ArcMap according to the coordinates recorded for each sample point during the driving test. Distance is the only concern in free space modeling and a significant factor in all other modeling procedures.

3.4.2 Blockage Number

Blockage number is a GIS implementation of the knife edge concept in radio wave propagation. These numbers were derived from a GIS application program by counting the obstacles along the direct paths from the transmitting antenna to each specific sample point. The elevation value of each pixel extracted from a DEM raster file along the signal path was compared with the radio line-of-sight at that pixel to determine whether or not the pixel blocks the radio line-of-sight. For each case in which a cell blocked the path, the number of blockages was incremented by one. If adjacent cells all blocked the path creating a “wide” blockage, no increment was made. The result is the total number of spatially separated interferences along the entire path (Personal communication, Carstensen, 2005) This variable provides an index of how severely the sample point is blocked from transmitter by the terrain in between.

3.4.3 Land cover related variables

Numeric data displaying the travel distance of the radio signal over each specific land cover category along its path was extracted from the original NLCD land cover raster data. Then the percentages of the travel distance on each land cover category were derived from these distance data. Since several land cover types dominate the whole study area (Figure 3.4), only these land cover types were selected to carry out the land cover effect analysis.

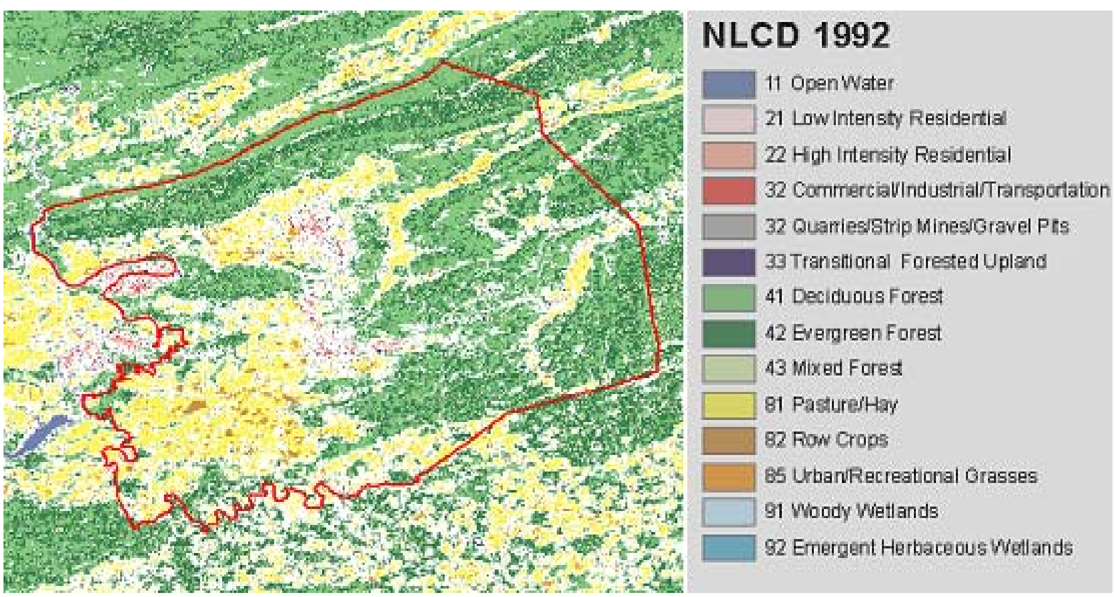

Figure 3. 4 Land Cover Types of Montgomery, VA

Due to the similarity of some land cover types in terms of their effect on radio wave propagation, the dominant land cover types in the study area were then grouped into 3 major categories: forest, grass and residential.

3.4.4 Field Signal Strength

The signal strength measured at each sample point in field during the driving test. As introduced in the driving test section, the coordinate information was recorded along with the actual signal strength at that spot simultaneously by the WinRadio equipment (Table 3.2). Thus it was possible to import all of the field signal strength data into the geographic information system easily.

	A	B	C	D	E	F	G
1	Freq	Receiver	LDX	SigStr	Lat	Lon	Elev
2	806 MHz	FMN	DX	-81.5	37.210278	-80.428882	599.0
3	806 MHz	FMN	DX	-81.5	37.210278	-80.428882	599.0
4	806 MHz	FMN	DX	-81.5	37.210278	-80.428882	599.0
5	806 MHz	FMN	DX	-79.8	37.210278	-80.428882	599.0
6	806 MHz	FMN	DX	-103.1	37.210278	-80.428882	599.0
7	806 MHz	FMN	DX	-78.6	37.210278	-80.428882	599.0
8	806 MHz	FMN	DX	-80.9	37.210284	-80.428891	598.1
9	806 MHz	FMN	DX	-80.9	37.210284	-80.428891	598.1
10	806 MHz	FMN	DX	-99.8	37.210284	-80.428891	598.1
11	806 MHz	FMN	DX	-103.8	37.210284	-80.428891	598.1
12	806 MHz	FMN	DX	-78.8	37.210277	-80.428891	597.5
13	806 MHz	FMN	DX	-78.6	37.210283	-80.428889	596.7
14	806 MHz	FMN	DX	-78.8	37.210283	-80.428889	596.7
15	806 MHz	FMN	DX	-76.9	37.210283	-80.428889	596.7
16	806 MHz	FMN	DX	-82.2	37.210283	-80.428889	596.7
17	806 MHz	FMN	DX	-106.6	37.210283	-80.428889	596.7
18	806 MHz	FMN	DX	-104.1	37.210283	-80.428889	596.7
19	806 MHz	FMN	DX	-80.9	37.210283	-80.428889	596.7
20	806 MHz	FMN	DX	-79.8	37.210283	-80.428889	596.7
21	806 MHz	FMN	DX	-99.3	37.210283	-80.428889	596.7
22	806 MHz	FMN	DX	-79.8	37.210282	-80.428878	596.8
23	806 MHz	FMN	DX	-79.8	37.210269	-80.428880	597.0

Table 3. 2 Field Signal Strength Log File

(Freq: Radio Frequency; Receiver: not relevant; LDX: not relevant; SigStr: Received Signal Strength in dBm; Lat: GPS Latitude; Lon: GPS Longitude; Elev: GPS Elevation)

3.4.5 Predicted signal strength

This variable was extracted from the raster file created by ComSite. Because of the limited manner in which ComSite exports its results, these data were only available in limited regions of the study area and only in categorized as opposed to precise form. Results were in classes of 10 dBm. (Figure 3.5).

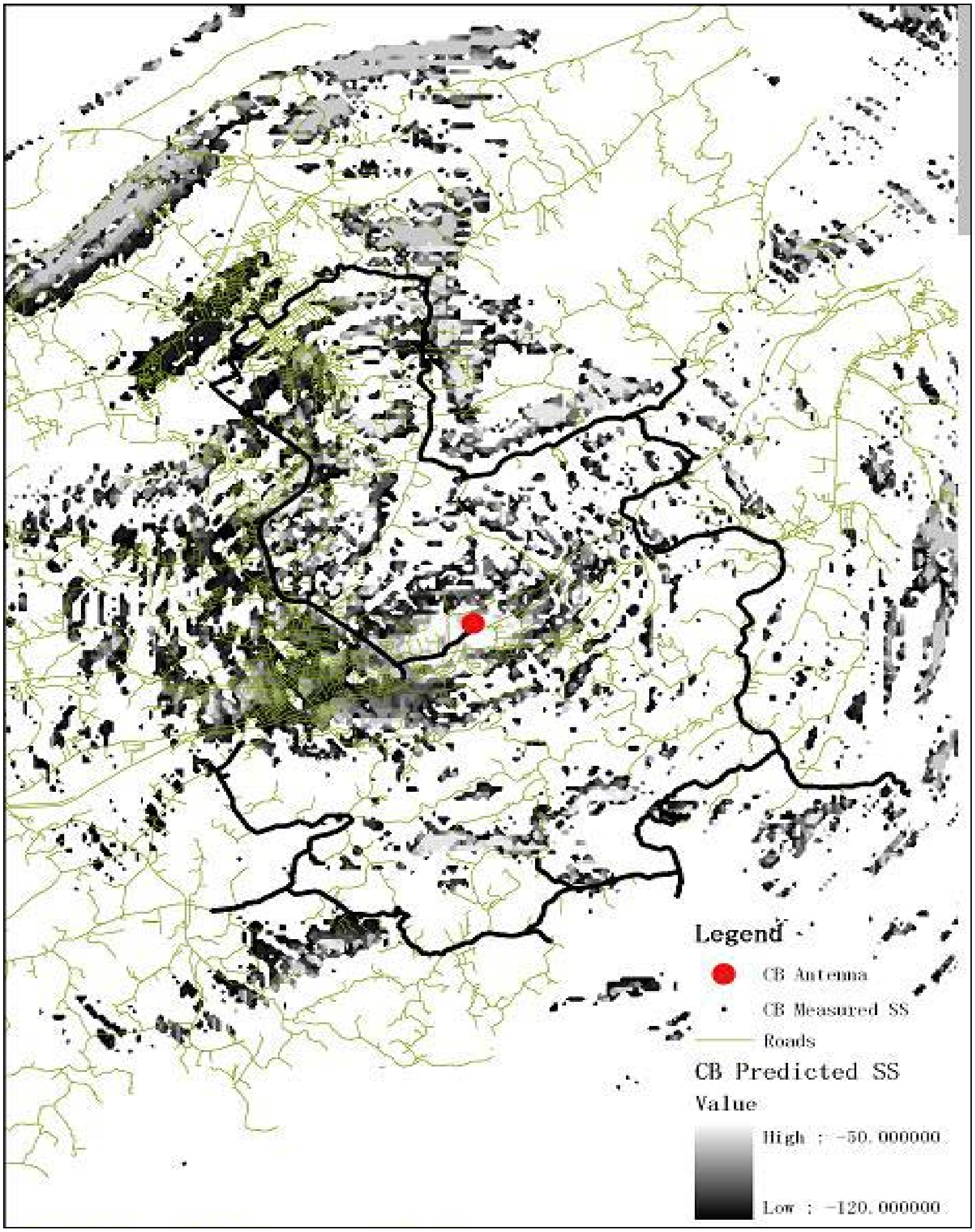

Figure 3. 5 Predicted Signal Strength Map

3.4.6 Signal strength calculated in free space model

In order to account for the distance effect when analyzing land cover type or blockage effects, the field signal strength needs to be compared to a function of distance from the transmitter. Because the path loss of signal strength in this project was measured in decibels, the path loss caused by distance could not be standardized by a simple division by distance; the procedure must be more in line with theory. Thus its reasonable to compare the residuals of ComSite predicted signal strength with the residuals of free space model results to evaluate the performance of ComSite in terms of taking into account more local features than solely distance.

This variable of signal strength in the free space model was used to show the theoretical optimal signal strength expected at each sample point. As introduced before, the free space model only takes into account distance as the concern of signal loss during propagation and assumes a clear path between the transmitter and the receiver. The formula of received signal strength at each sample point used in this research:

Pr(dBm) = ERP(dBm) + Gr(dB) – Cable Loss(dB) – Path Loss(dB)

Pr is the modeled signal strength at a specific sample point. ERP - Effective Radiated Power from the transmitter. Gr is the gain at receiver end and Cable Loss is the power loss caused by the recorder. All of the first three independent variables are irrelevant to the sample point and only correlated to the radio system used in this project. ERP, Gr and Cable Loss are constant for this system at 43.86dBm, 4.60dB, 2.50dB respectively. (Personal communication, Mullikin, 2005)

Path loss is the attenuation undergone by an electromagnetic wave in transit between a transmitter and a receiver in a communication system. Figure 3.6 illustrates the path loss equation for free space modeling.

$$\text{Path Loss} = 20 * \log_{10}\left[\frac{4 * \Pi * d}{\lambda}\right] \ \{\text{dB}\}, \quad \text{where} \left| \begin{array}{l} d = \text{distance } \{\text{same units as } \lambda\} \\ \lambda = \text{wavelength } \{\text{same units as } d\} \end{array} \right.$$

Figure 3. 6 Free Space Path Loss Equation (rfcafe.com)

In this research Path Loss is computed by a common industrial approximation known as the Friis formula:

Path Loss = 32.44 + 20 * Log(Dist. - km) + 20 * Log(Freq. - MHz)

In this project the test frequency was constantly 806MHz, hence signal strength in free space model for each sample point is simply a function of distance to the transmitter. It was easily calculated in an ArcMap attribute table column.

After computation, all of these tabular variables were tied by ArcMap with their geospatial identity at each sample point. A series of statistical analyses was then conducted to detect the possible relationship between them and the dependent variable (signal strength) separately. The detailed methodology as well as the results of these analyses will be discussed in the next chapter.

Chapter 4 - Data Analysis and Results

All of the variables were then incorporated into a database file to perform statistical analysis. As discussed before, radio wave propagation is a complicated phenomenon and affected by many terrain factors. So it is necessary to separate the effect of each specific factor by strategically implementing this analysis process.

4.1 Clutter Loss Effect

According to the previous work done by other researchers, clutter loss plays a more significant role in radio wave propagation on paths for which the Fresnel Zone clearance is satisfied. Thus in this research only the unblocked sample points were selected to carry out statistical analysis on the effects of different land cover types.

Using the land cover based signal travel distance data extracted from NLCD and an auxiliary program (Carstensen, 2005), each sample point's attribute table record was given a set of fields showing how many cells of each specific land cover type the signal travels over along the path between the transmitter and each sample point collected during the drive test. Similar land cover types in terms of radio wave propagation effect were grouped together and three major land cover categories were developed: forest, grass, and residential. For example, deciduous and mixed forest were grouped together as "forest" because they were the major two forest land cover types(evergreen forests are very sparse in Montgomery County, VA) and there is not a big difference between the two in interrupting radio waves since the driving test was done in leaf-on conditions in the summer. Based on the statistics, the land cover categories selected in this analysis covered more than 95 percent of the study area. Thus, the grouping should not cause any intolerable error to the entire analysis process.

The percentages of residential and forest along the paths were then used as the major independent variables in the land cover type effect analysis to find some possible correlation between land cover types and signal strength prediction quality.

According to “Clutter Losses and Environmental Noise Characteristics Associated with Various LULC Categories” (Rubinstein, 1998), residential areas have a more significant effect on radio wave propagation than do forest and grass land. So the percentage of the path distance over residential land cover along the path (**%res**) was selected at first as a land cover type variable. Figure 4.1 illustrates the signal strength prediction residuals against %res. Figure 4.2 shows the signal strength prediction residuals against the percentage of the path that is over forest (**%for**). As indicated by these scatter plots, no significant correlation between ComSite prediction residuals and land cover types under radio signal propagation path exists in this dataset. This unexpected result most likely occurred because ComSite had already taken into account land cover caused clutter loss in its prediction procedure. Thus no further study evaluating ComSite prediction quality in regard to land cover effects was performed.

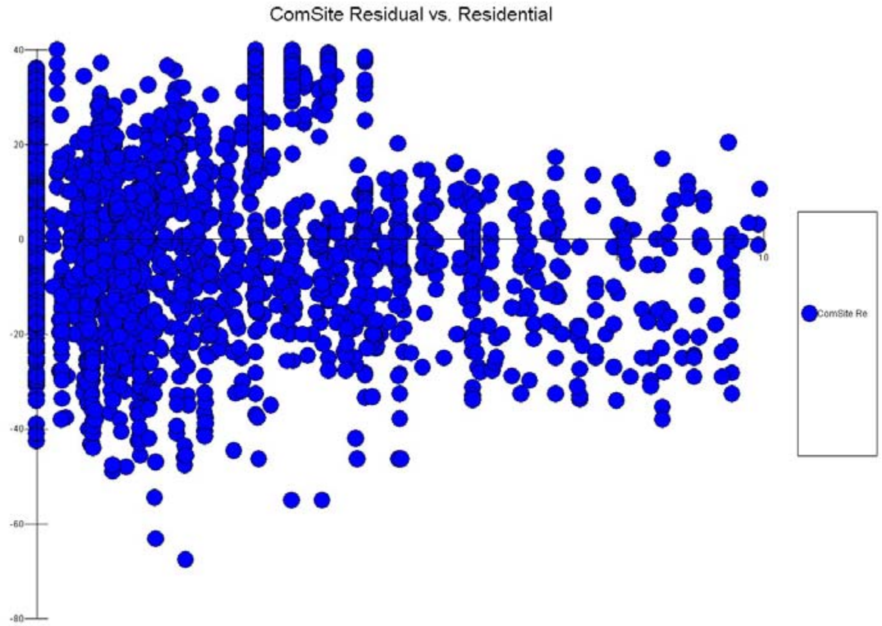

Figure 4. 1 scatter plot of ComSite prediction residuals

(predicted signal strength – field measurement) on the Y-axis against %res on the X-axis

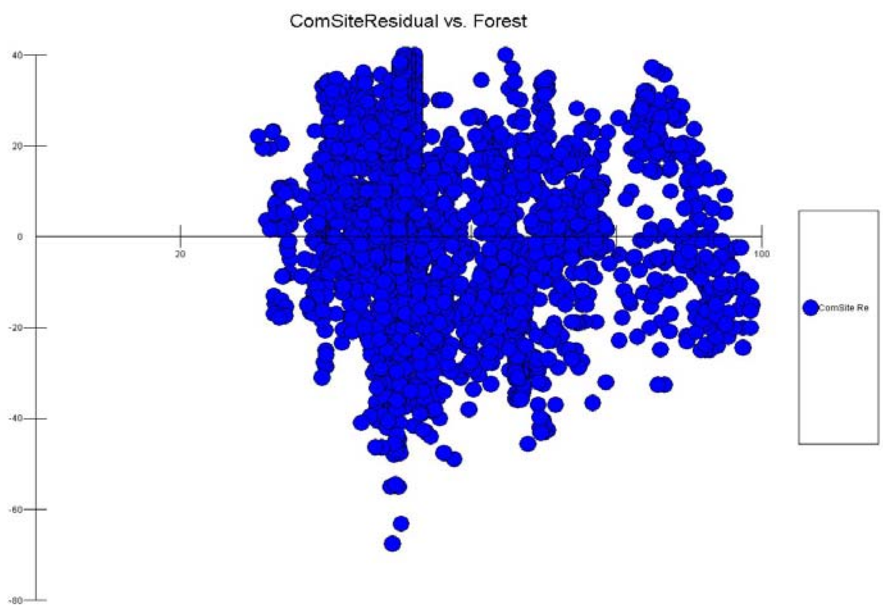

Figure 4. 2 scatter plot of ComSite prediction residuals (Y-axis) against %for (X-axis)

To check the hypothesis that the land cover had already been described by the ComSite Lee model, similar scatter plots were also displayed when analyzing the residuals of free space model predicted signal strength (figures 4.3 and figure 4.4).

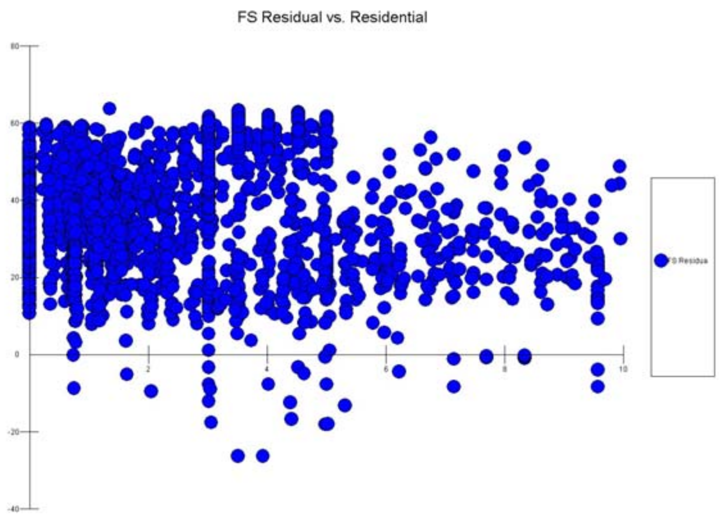

Figure 4. 3 scatter plot of free space model residuals (free space modeled signal strength – field measurement) (Y-axis) against %res (X-axis)

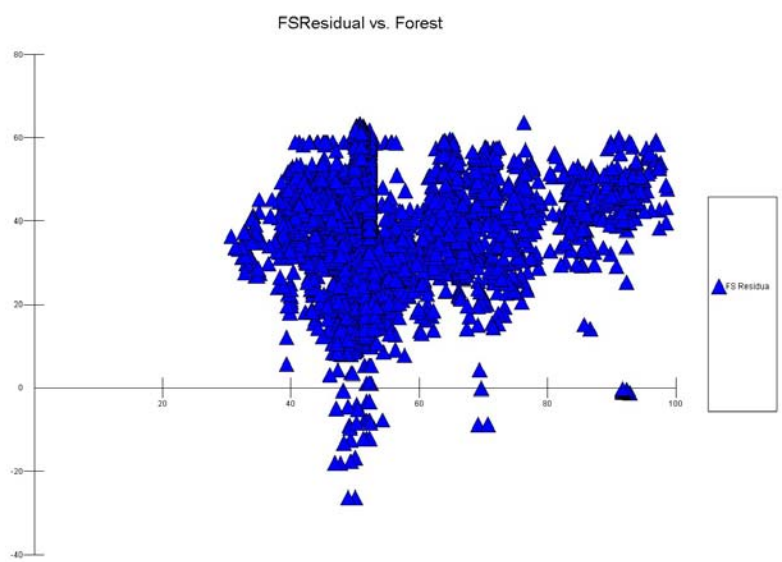

Figure 4. 4 scatter plot of free space model residuals (Y-axis) against %for (X-axis)

However, according to the pattern of the percentage data shown in these scatter plots, different land cover categories in this project were not evenly distributed, i.e., the percentage of residential was always very low compared to the other two and the percentage of forest land cover was always more than 50% on every path. The residential sample points were found in only two percent of the total paths, thus the data points were not evenly distributed enough to make this analysis successful. The reason for this data distribution pattern was caused by the study area itself. The study area is not very urbanized and most of the developed residential communities are located around two town centers. Therefore, all of the residential classified land cover was at one of two locations making for nearly constant distances from the transmitters.

These issues made it difficult to perform a correlation analysis between the free space model residuals and the two land cover percentages individually. After further review of the data distribution, the forest and residential land cover categories were combined as a “clutter” land cover category (%cltr) to more generally represent the land cover effect in this research. Figure 4.5 shows a scatter plot pattern indicating a positive correlation between the free space model and clutter land cover effect as expected (r = 0.055). Because the free space model does not consider the path loss caused by different land cover types, higher residuals should be produced when the radio wave propagates along a path having more clutter land cover types rather than “open” space such as grass land in this project.

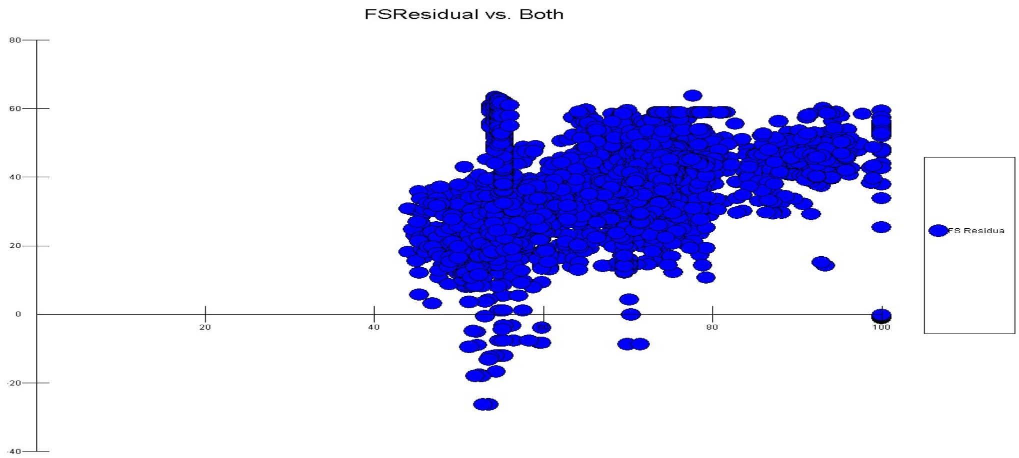

Figure 4. 5 scatter plot of free space model residuals (Y-axis) against %cltr (X-axis)

Based on the fact that the correlation between free space residuals and clutter land cover effect exists, a linear regression model analysis was implemented to build a mathematic model for this correlation. Figure 4.6 illustrates the linear correlation described above.

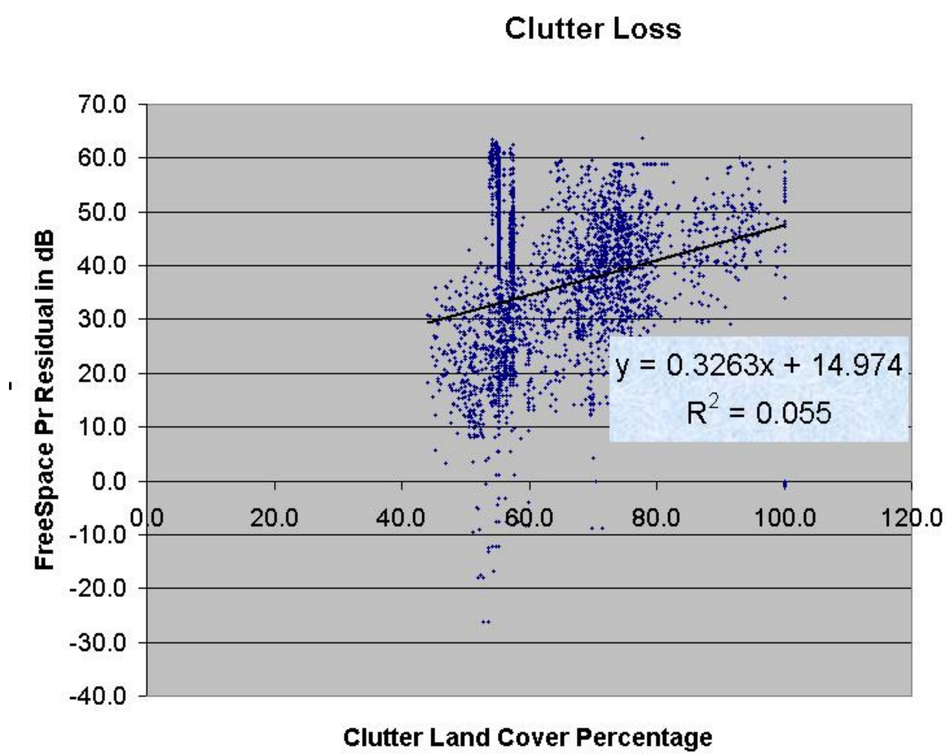

Figure 4. 6 regression of free space model residuals against the percentage of clutter land cover travel distance

As displayed in figure 4.6, the residual of signal strength predicted by free space model (Y) is correlated to the percentage of clutter land cover travel distance (X) by:

$$\mathbf{Y = 0.3263 * X + 14.974}$$

The R-squared value (5.5%) shows the percentage of movement that can be explained by this linear regression. As expected, though the expected trend is present, this correlation is not very strong suggesting that the sample points collected in this project were affected by many other factors than simply clutter loss along the paths.

4.2 The Knife-edge Number Effect

In order to isolate the effect of knife-edge blockages and the number of such blockages along a path on signal strength prediction quality, the other factors such as clutter loss and distance should be controlled.

In ArcMap, it is convenient to select database records by an attribute. After joining the blockage table to the original database file, the blocked points were selected and indexed by their specific number of blockages. This blockage table was extracted from the DEM file by running an ArcMap application which computes the number of blockages along the propagation path to each sample point (Carstensen, 2005) These blockages reflect the knife-edges along the propagation path to each sample point.

A scatter plot of the residuals between the field signal strength and the predicted signal strength with respect to blockage numbers was then made to illustrate the potential correlation between prediction quality and knife-edge occurrences (Figure 4.7).

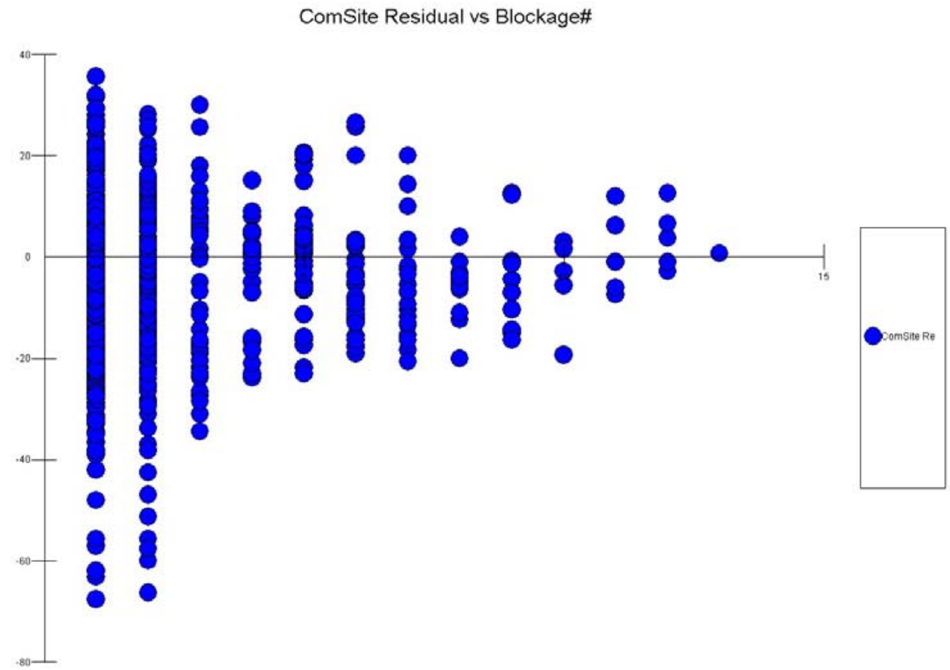

Figure 4. 7 Predicted Signal Strength Residual (Y-axis) and Blockage Number (X-axis) Scatter Plot

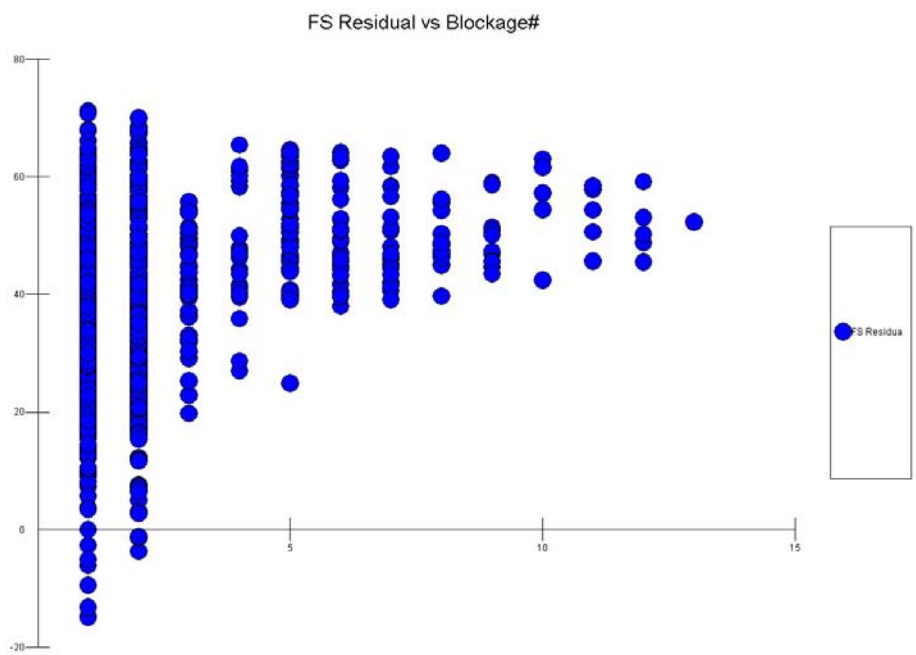

Figure 4. 8 Free space model residual (Y-axis) and blockage number (X-axis) scatter plot

In order to diminish the effect of distance, these residuals were compared to the free space model residuals with respect to the number of blockages (Figure 4.8).

4.3 Estimation of the quality of the results from ComSite

Initially in this research, I hypothesized that a more complex local feature oriented signal strength prediction software such as ComSite should drastically reduce the residuals when compared to a theoretical signal strength prediction model like free space model. By comparing the average residuals of both ComSite and free space model predictions when the number of blockages is the same, the performance of ComSite prediction in terms of computing path loss caused by all other factors including clutter loss and blockage effect was estimated (Figure 4.9 & Table 4.1).

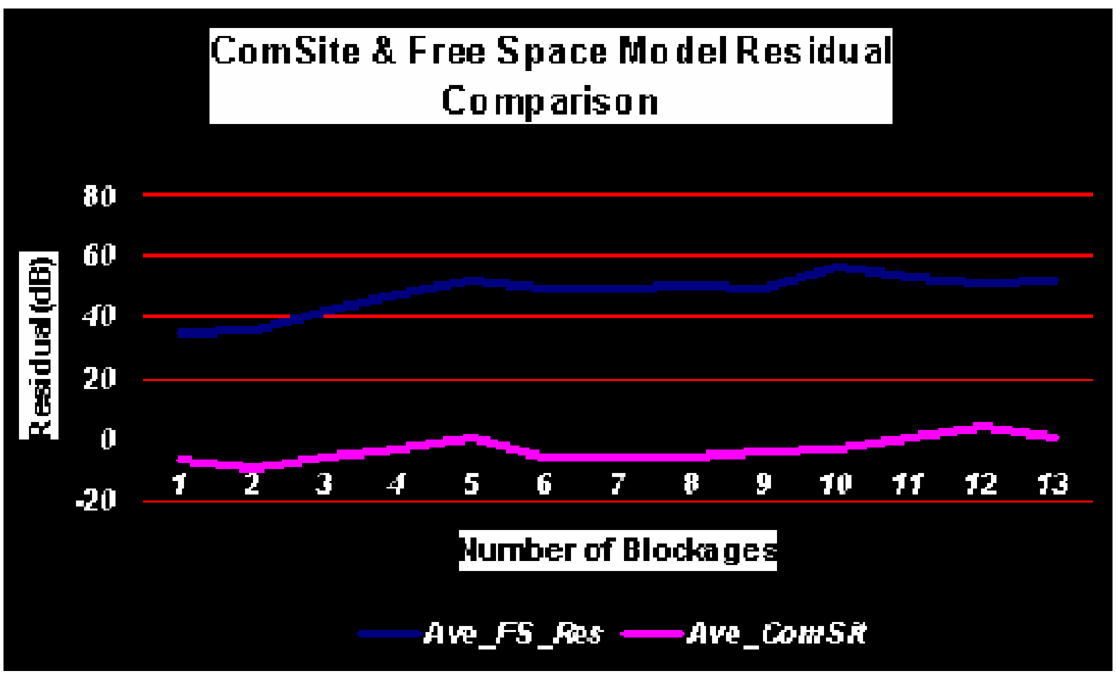

Figure 4. 9 A comparison of average residuals of ComSite and free space model

BlockNum	Cnt_BlockN	Ave_ComSite_Residual	Ave_FS_Residual
1	503	-7.0109	34.9597
2	349	-9.6003	35.7984
3	40	-5.7950	41.6470
4	25	-3.3640	47.2591
5	42	0.6405	51.9681
6	32	-5.1625	49.4811
7	22	-5.7682	49.1327
8	12	-6.1000	50.1822
9	11	-4.1545	49.3491
10	6	-3.5833	56.6927
11	5	0.7600	53.3304
12	5	3.8200	51.2880
13	1	0.7000	52.2378

Table 4. 1 Comparison of ComSite Model and Free Space Model Residuals

According to this quantitative analysis, a GIS oriented signal strength prediction software such as ComSite does dramatically improve the radio wave propagation model beyond that of a simple free space model and reduces the average residuals to an acceptable level. Also it is found that the prediction residuals are higher when the blockage number is lower. So more driving test points in the areas where the signal is blocked by only 1 or 2 knife-edges need to be provided in the areas where the signal is blocked by only 1 or 2 knife-edges when collecting corroborative driving test data in the future. Beyond the first few blockages, both the ComSite and free space model predictions were much closer to the actual measurements. This is likely because of the distance factor was much stronger when the number of blockages became greater.

Chapter 5 - Conclusion

5.1 Results of the survey of prior engineering models

Wireless network design, also known as wireless planning, is a very complicated task for engineers and most results do not inspire a high level of confidence since there has never been a general theory that can be used in every geographic location because of the diversity of circumstances.

Radio wave propagation modeling, a major part of designing a macro scale wireless network, is a very complex process and it is affected by many factors. Most of these factors have been studied in some qualitative manners. This project made an attempt to analyze some geographically related factors of this process in a quantitative manner by applying the strong spatial analysis capability of Geographic Information Systems. A literature review was completed to guide the experiments in this research. Models were analyzed for their relevance to this study and two were selected, the Lee model and the free-space model.

5.2 GIS in improving Wireless Planning

GIS, with the support of statistics, has the capability to analyze a variety of geographic related factors simultaneously and efficiently. Since these factors vary drastically in reality, it is difficult to analyze them independently. A regression model was built during this research to represent the correlation between the residuals of free space model predicted signal strength and land cover effect. More experiments can be designed to carry out similar research in the future so more geographic features can be analyzed in this quantitative manner to help understand the mechanism of radio wave propagation.

5.3 Empirical Evaluation of the ComSite propagation model

However, as the major purpose of this project, this research does provide some interesting findings on estimating the quality of a typical commercial signal strength prediction software package, ComSite. It is found that GIS oriented signal strength prediction software such as ComSite can significantly improve prediction quality compared to the theoretical free space model which does not take into account any local terrain feature effects. Also, the prediction quality of ComSite was analyzed quantitatively and it shows that ComSite's performance is better when there are more knife-edges along the propagation path. Thus, it is natural that in future prediction procedure, a user can improve the accuracy of ComSite prediction by providing more driving test data in the areas computed to have fewer blockages beforehand. This will make the user's future driving test more efficient.

5.4 Implications for future research

This project also suggests that future research in radio wave propagation modeling and analysis should be carried out in a more strategic way and field measurement should provide more even representation of land cover types in order to make the statistical analysis more efficient. Thus, the driving test routes need to be designed individually so a specific factor can be studied without any fuzzy variation caused by the other factors.

The procedures of this research should provide benefits to both geographers and engineers. As GIS is a visual medium, these results should be intuitively understandable by engineers. This clarity is an important advantage to the traditional mathematical empirical modeling.

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Vita

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