Master of Spatial Information Science Thesis

A GIS Approach For Mobile Telephone Signal Path-Loss Prediction

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A GIS APPROACH

FOR

MOBILE TELEPHONE SIGNAL

PATH-LOSS

PREDICTION

by

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Signed: ______________________

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ABSTRACT

Signal propagation path-loss prediction is a fundamental problem for the planning and design of a cellular mobile telephone system. Many models, empirical, experimental, or analytical, have been designed and used. The analytical models apply the path-loss prediction formulae to path profiles derived from a digital elevation model to obtain the signal path-loss. The digital elevation model stores detailed terrain height data. The heights can be sampled regularly, or selectively stored to capture important terrain features. The regular sampled elevation database (grid model) has been used for most of the existing analytical path loss prediction models. Carefully examination of the grid model reveals that it is not the only terrain representation. TIN (Triangular Irregular Network) terrain model can be used as an alternative elevation database. With the TIN model, sudden changes and other surface features that are difficult to store in the grid model can be included in the database. More accurate path profiles could be derived and more accurate path loss prediction would be achieved.

Geographical Information Systems (GIS) are a new technology that are often used in applications requiring analysis and manipulation of the spatial conditions and situations. It provides spatial and non-spatial databases, as well as various analytical tools for general application purposes. The characteristics of a GIS are such that it can be used for radio signal path-loss prediction.

This thesis examines the existing analytical path-loss prediction methods. The possibility and feasibility of using GIS analytical tools to predict signal propagation path-loss is discussed. GIS functions, using TIN as a terrain representation are used to carry out qualitative and quantitative analysis of signal propagation based on the analytical prediction models are examined and prototyped. The method is implemented using AML programs in ARC/INFO software, and C functions on a SUN Sparc workstation.

The test is performed on the Hobart area in Tasmania, Australia. Program performance speed and accuracy are analyzed and discussed against the method based on grid terrain model.

ACKNOWLEDGEMENTS

This thesis represents two years full and part time research that was challenging although rewarding; and would have been much more difficult and frustrating without the support and assistance of certain individuals and establishments. I feel it is necessary to acknowledge the people that have helped me with their professional assistance, as well as those that have given me support on a more personal level.

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TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

1.1 GEOGRAPHICAL INFORMATION SYSTEMS (GIS) AND MOBILE TELEPHONE SIGNAL PROPAGATION PREDICTION

Geographical Information Systems (GIS) are an integrated collection of hardware, software, data and liveware which operate in institutional contexts [Maguire, Goodchild & Rhind]. GIS technology provides a set of powerful tools for collecting, storing, retrieving, transforming, and displaying spatial data from the real world for various purposes [Burrough]. Characteristics of a GIS application include the use of computer graphics, image processing, database management and other computer technologies to process geographical data. Objects and phenomena from the real world are referenced in terms of position with respect to a known coordinate system, with attributes that are unrelated to position. Spatial relationships between the spatial objects are stored. Through the use of GIS functionality, spatial and spatially related data can be accessed to produce analysis results.

Mobile telephone signal propagation prediction plays a key role in the planning and design of cellular mobile telephone system. The prediction is conducted through the study of radio signal propagation characteristics. These characteristics, which include free space attenuation, refraction, reflections from Earth and man-made objects, absorption and scattering by atmospheric particles, and diffraction, are highly irregular and depend on the local Earth environment. The particularly close relationship between radio signal propagation prediction and the Earth environment, and the characteristics of GIS technology, suggest that radio signal transmission prediction is a potentially new GIS application area.

1.2 THE MOBILE TELEPHONE SIGNAL PATH-LOSS PREDICTION PROBLEM

The mobile telephone system, during the past decade, has been authorized by regulatory agencies to operate in the 800 to 900 MHz portion of the radio spectrum. To plan a cellular radio telephone at these frequencies, a number of questions have to be answered. They include "what signal strength (or other measure of suitability) is probable over the desired service area?", "what level of interference is likely to be imported to the system?", "what level of interference is likely to be exported from the system?" [Kinch-James], and, particularly during the cellular planning, "what shape and size would a cell be?". Each of these involve a similar process of predicting, for given equipment configuration, the value of some measure at a specific point or region of the receiver. This is carried out by considering the signal path from the information source to the user through each of the intermediate stages. Among them, the equipment parameters, such as the gain of an amplifier or response of a filter, will be known or can be experimentally determined. The transmission path between antennas, however, is far more difficult to characterize.

> For a fixed point to point link the transmitter and receiver locations are static and so the inner-antenna path can be determined with some degree of accuracy. Where broadcast or multi-points (transmitter to multiple fixed receiver points) systems are employed, this path characterization becomes a very demanding task.
>
> [Kinch-James, pp427]

Path characteristics can be obtained through the investigation of the Earth surface. The degree of understanding of the surface characteristics becomes the foundation of accurate prediction for signal strength distribution. In other words, in order to predict signal strength distribution in the desired area, a path-loss distribution caused by the terrain features is required and hence the Earth surface's effect on the signal propagation needs to be considered. The more accurate the terrain features representation, the more accurate the effect from the Earth's surface can be predicted.

The prediction of path-loss values in 800–900 MHz band has been developed during the last decade. The IEEE Vehicular Technology Society Committee on radio propagation [Committee] has generated several models [Committee]. All of these models analyze the effect of terrain, and as a result, the model performance in terms of accuracy and speed vary depending upon the accuracy of the terrain data and the methods used in obtaining, and applied to terrain data.

The terrain data popularly used by these models are Digital Elevation Models (DEM), usually a regularly distributed matrix, which holds ground height data. Each element in the matrix records a height at a point location.

To obtain a reasonable accuracy of prediction, a DEM requires a certain level of resolution. Below this level, the prediction result is not acceptable. Increases in the resolution may result in an increase in prediction accuracy. Therefore, a finer resolution DEM is one factor for achieving an accurate path-loss prediction result.

However, this improvement on prediction accuracy may also increase the data volume, requiring a large amount of data storage, and as a result, increases the prediction time because of the increased data processing required.

How can the required data resolution be obtained, while also minimizing processing time? A method that uses TIN to represent the terrain, and applies a path-loss prediction model on the TIN data is investigated, discussed, and prototyped in this thesis.

The method in this thesis utilizes GIS techniques to conduct path-loss propagation prediction. The study of terrain characteristics is carried out through the application of GIS techniques. The signal propagation mechanisms over terrain profiles are then examined. A signal path-loss model at 800–900 MHz spectrum is applied to the profile, and path-loss values are calculated. The path-loss prediction for a study area is performed through repeatedly applying point to point prediction principle to a series of sample points. Finally, discussion of the method used in the thesis, its limitations, weaknesses, and possible improvements are presented as a conclusion and for further development.

1.3 OBJECTIVES OF RESEARCH

This thesis aims to experiment with the integration of an existing signal propagation path-loss prediction model with the GIS techniques available in the commercial market. In particular, it applies a path-loss prediction model using TIN data. The advantage of the integration and the limitations of the method developed are discussed. The experimental model calculates point to point path loss values, and displays a point-to-area path-loss prediction value using the TIN data. A brief trial on propagation environment analysis will be presented. To achieve this aim the thesis will present:

1. A general examination of radio signal propagation over the Earth's surface.

2. Examination of existing land mobile telephone signal propagation models and their use of terrain data. A model is selected for the experiment.

3. A general examination of GIS methods for storing, manipulating and analyzing spatial and attribute data representing surface characteristics.

4. A description of the GIS approach used to apply an existing path loss prediction model to the terrain data (TIN) model.

5. A discussion and verification of the experiment in terms of data accuracy, data representation structure, and their effects on the path-loss prediction.

1.4 OVERVIEW OF THE THESIS

Chapter 2 introduces the propagation theory of radio waves, especially the characteristics of a VHF/UHF band radio signal which propagates over a path that is close to the Earth surface, accounting for the effect of the Earth surface on mobile telephone signal propagation.

Chapter 3 outlines the existing models for mobile radio signal propagation prediction, and examines the methods for using the terrain data and applying prediction models to the terrain data. A model is selected for the experiment.

Chapter 4 briefly introduces the concept of a GIS, the storage of spatial and aspatial data, the TIN and GRID models, the manipulation and analysis tools, and the methods for using GIS technology and software.

Chapter 5 proposes an integrated method, which applies a mobile telephone signal propagation prediction model on TIN data. The qualitative analysis of the signal propagation state around the assumed transmitting antenna and the quantitative calculation of point-to-point and point-to-area path-loss values are accommodated.

Chapter 6 discusses and analyses factors that may influence the accuracy including of the test results aspects of data accuracy and the method of integration.

Chapter 7 concludes this dissertation.

CHAPTER 2

MOBILE TELEPHONE SIGNAL PROPAGATION PRINCIPLE

AND

PATH LOSS ANALYSIS

Mobile telephone services are one radio communication application. They include cellular phone systems, traditional private mobile radio paging, cordless telephones, maritime-mobile, aero-mobile and satellite-mobile systems. Regardless of the equipment used, all of these systems have a transmitter and receiver that are capable of being moved. This characteristic requires the signal propagation analysis to be flexible to cope with variations in the propagation path.

This chapter summarizes the principle of a land mobile radio system, and briefly introduces the concept of a land mobile telephone service scheme. It then discusses the characteristics of land mobile telephone signal propagation and analysis techniques.

2.1 LAND MOBILE RADIO SYSTEM

Among all mobile telephone applications, the service quality of a land mobile radio system relies heavily on the result of a propagation prediction. Both transmitter and receiver are located on the ground, and the antenna height is usually lower than other service systems. Earth surface features, such as terrain, vegetation, trees, buildings, mountains, and man-made objects, have a strong influence on the signal transmission. If a user moves from one place to another, the signal strength may change. This change can be significant. Hence, the quality of communication alters along with variations in the signal strength when the receiver's location changes. This problem is central to the planning of a land mobile telephone system.

2.1.1 The Frequency Range

The frequency range of the land mobile telephone system has been authorized by the regulatory agencies to take up the 900 MHz and 1.8 GHz frequency range with a bandwidth of 40 kHz for commercial operation. The bandwidth is divided into channels to allow multiple users to make phone calls at the same time while maintaining satisfactory communication quality. One user would occupy each channel if the analog signal were employed. Several users can share the same channel if a digital technique is employed by the system. Regardless of whether analog or digital techniques are being employed, the radiated signal between the base station and the user's hand phone is at either 900 MHz or 1.8 GHz.

2.1.2 The Service Coverage

Because of the limitation in bandwidth, only a certain number of users can occupy a single channel at any time. It is not practical to reduce the bandwidth of each channel to increase the number of users, because of the resulting reduction in communication quality. A frequency re-use scheme is used to solve this problem. The re-use scheme involves the multiple use of the same channel in different locations. A channel with a fixed frequency range is assigned and can be used only in a specified service area. This channel will be re-used in another service area, which is far enough away for it to not cause interference. The frequency re-use scheme is illustrated in Figure 2. 1. Each hexagon is called a cellblock [Lee], and represents an assumed service area. The numbers in the cellblock show the assignment of different channels. All adjacent cells use different channels to avoid interference.

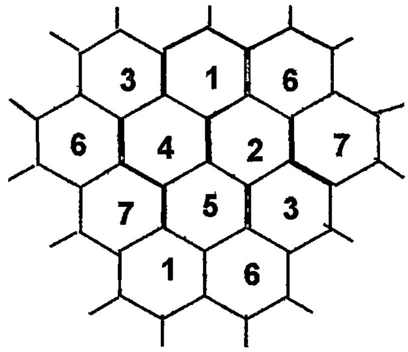


Figure 2. 1 Cellular Telephone Service Coverage

The hexagonal shape is an ideal distribution, showing equalization of the number of channels in each cell for frequency re-use. It is not a practical option, however, because in the real world factors that influence signal propagation are not evenly distributed. The actual shape and size of cells in the service area vary according to planning requirements. For instance, the cellblock tends to be small and densely packed where there are large populations and many mobile telephone users. In rural areas or districts with less mobile phone usage the cellblocks can be large.

Figure 2. 2 shows an actual cell block distribution used in planning a practical operating cellular telephone network [Hovi].

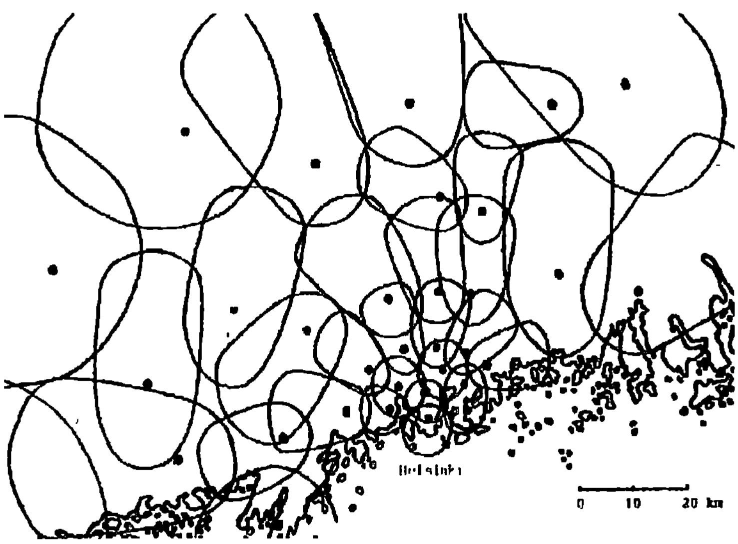


Figure 2. 2 Cellblock Distribution in Real World Terms [Hovi]

The size of cellblocks can vary from a few kilometers to a hundred kilometers. The shape of cells should match the condition of signal strength distribution so that quality communication is maintained, and interference is avoided.

2.1.3 The Usage of a Cellular Mobile Telephone System

Each cellblock has one transmitter to radiate its radio signal. The power of each transmitter is different due to the variable size in cellblocks. To avoid possible interference between signals with the same frequency, and to ensure that the signal can be received at every corner of the cell, the cell size and shape has to be designed to match the signal strength distribution.

When a user moves from one cell to another, the communication continues even though the signal transmission between the user and the transmitter is switched from the first cell's antenna to the second one. The switching is controlled by the telephone system automatically. The basic condition is that the user has to be able to receive the signal from both antennae at the boundary of the two cells. Otherwise, a communication interruption will occur.

2.1.4 Propagation Considerations

To satisfy the switching process, maintain communication quality, and to avoid interference between cellblocks, the signal propagation condition within cells and signal strength distribution in the service area should be considered and predicted.

The cellular mobile telephone signal propagation characteristics and strength distribution are determined by frequency, heights of the transmitter and receiver antennae, and environmental features in the service area.

Since the 900 MHz and 1.8 GHz bands are located in the VHF and UHF range, the characteristics of the VHF/UHF frequency spectrum can be applied to cellular mobile telephone signal propagation

2.2 VHF/UHF SIGNAL PROPAGATION

VHF/UHF radio signals propagate through atmosphere in terms of tropospheric, ground, and ionospheric waves [Committee].

The tropospheric wave propagates through the lower atmosphere or troposphere. This signal is subjected to refractivity and scattering by water vapor, clouds, and dust.

Ground waves propagate under the troposphere and travel very close to the Earth's surface. The signal is absorbed, reflected, refracted, diffracted and scattered by objects on the Earth surface. Signal propagation is largely influenced by ground conductivity. Signal diffraction is the only propagation mechanism for ground waves, which are not attenuated rapidly.

Ionospheric waves propagate in the layers of the ionosphere. VHF/UHF signals usually penetrate the ionospheric layer with little energy being reflected back to Earth.

Because of the relatively short service range of land mobile system, propagation is usually caused by ground and tropospheric propagation.

2.2.1 Propagation Loss

When a VHF/UHF radio signal propagates from the transmitter to a receiver, the received signal strength at the receiver antenna is lower than the signal strength transmitted. The signal strength difference is termed the propagation loss.

The propagation loss consists of device loss and path loss. The device loss is the loss at transmitter and receiver antennas, and any other equipment that is involved in the signal transmission. The path loss is the signal strength difference between output of the transmitter antenna and input of the receiver antenna. Path loss occurs as the signal travels through the atmosphere and the Earth surface. Signal loss is caused by objects within the atmosphere and on the Earth surface.

To measure propagation loss, the device loss and path loss should be calculated. The device loss, including loss caused by transmitter antenna, transmitting device, receiver antenna and receiving device can be determined by device characteristics which can either be obtained from the device manufacture or through laboratory experiments.

The path loss depends on the features of the propagation path. Factors, such as path length, terrain, vegetation, man-made buildings, the density of the atmosphere, and air pressure contribute to the path loss. The location and height of Earth surface objects also contribute to the loss. For example, a higher mountain along the propagation path would cause more signal loss than a lower mountain at the same location.

Other Earth features that are not located in the direct path of the propagation can also cause path loss. Because the radio signal will be reflected from surrounding earth features, the reflected and direct signals may reach the receiving antenna at different times. The reflected signal may interfere with the direct transmitted signal.

To obtain the path loss value over a propagation path, the effect of Earth surface features along the path, and features within the surrounding environment need to be considered. General signal propagation theory is applied to the surface objects, and the signal loss over each object and the surrounding features are calculated. Because each propagation path is different, the path loss calculation becomes tedious and complicated.

Studies have been conducted on the effect of Earth surface feature's on signal propagation path loss. The various propagation paths have been classified and generalized. Radio propagation theory has been applied to paths, and summarized into path loss prediction models [Committee]. Because models have been tested and proven under certain usage conditions, the models can be utilized as tools on a propagation path to produce the estimated path loss as long as the specified usage conditions are satisfied.

2.2.2 The Effect of the Earth Surface On VHF/UHF Signals Propagation

As mentioned in last section, the VHF/UHF signals propagate from a transmitter to a receiver via tropospheric, ground and ionospheric waves. These waves can travel through one or more of the following ways:

- Free space propagation;
- Reflection propagation;
- Refraction propagation;
- Diffraction propagation, and
- Other types propagation.

Each of the above mechanisms produces a different effect on the signal propagation. The presence of each propagation mechanism is dependent on the characteristics of the Earth surface features. Because of the complexity in Earth surface environments, several propagation mechanisms can exist on any one propagation path. The effect of the environment on the propagation will be the combination of all propagation mechanisms.

2.2.2.1 Free Space Propagation

Free space propagation is the ideal condition for signal transmission. The radio signal sent from a transmitter reaches a receiver directly (Figure 2. 3).

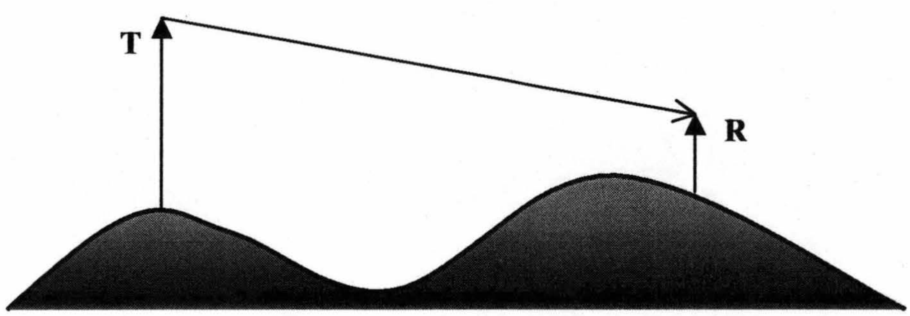


Figure 2. 3 Free Space Propagation

(T: transmitter, R: receiver)

With free space propagation, the Earth surface features that might absorb and reflect radio signals do not exist or can be ignored. The path loss is only caused by atmospheric absorption along the path. Path distance and signal frequency determine the amount of field strength absorbed.

2.2.2.2 Refraction Propagation

Refraction propagation occurs when a VHF/UHF radio signal transmits through more than one media of different density. This situation occurs as radio signals propagate through the atmosphere. If a signal is transmitted horizontally, the height of the signal increases as it moves away from the transmitter. Because air density decreases as height increases, the radio signal will follow a downward curving path as shown in Figure 2. 4.

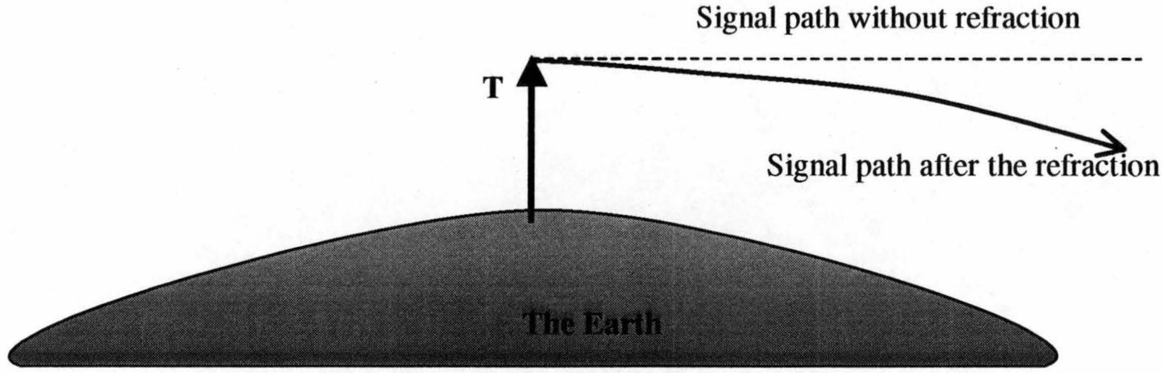


Figure 2. 4 Signal Propagation Path Bent Towards the Earth Due to the Atmosphere Refraction

2.2.2.3 Reflection Propagation

When a radio signal hits the Earth surface, the signal is reflected from the ground. The reflected signal continues traveling until it reaches the receiver (Figure 2.5). The field strength of the reflected signal is weaker than that of the direct transmitted signal.

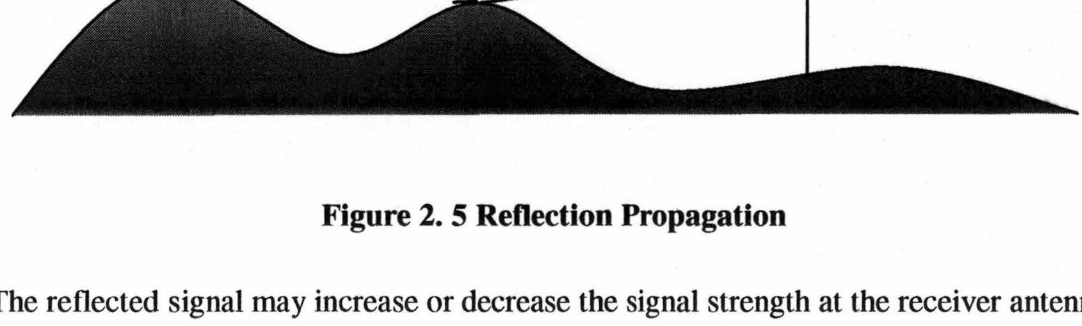


Figure 2. 5 Reflection Propagation

The reflected signal may increase or decrease the signal strength at the receiver antenna, depending upon the path length difference between the direct wave and the reflected wave, the Earth conductivity, incidence angle of the reflected wave, and the signal polarization. Provided that the reflection from the Earth surface does not change the signal phase, the path length difference can cause a phase difference between the direct and the reflected waves. Received signal strength increases when the phase difference is a multiple of $\pi/2$, and decreases when the phase difference is a multiple of π. Earth conductivity and the incidence angel determine the amount of the signal strength which is absorbed when the signal is reflected from the Earth surface.

Reflection propagation is also affected by the Earth's spherical characteristics. If the distance is relatively large between transmitter and receiver, the waves are reflected divergently from the Earth surface, as shown in Figure 2. 6.

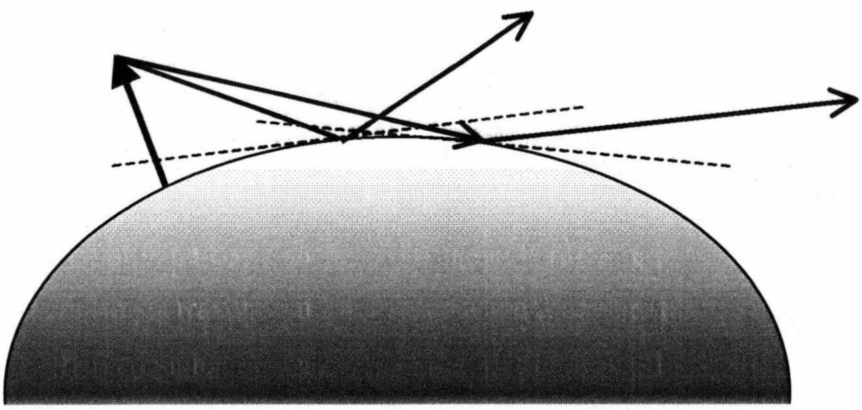
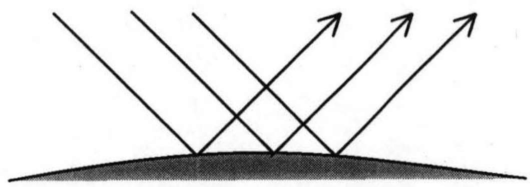


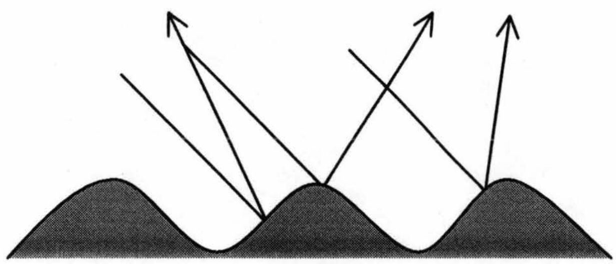
Figure 2. 6 Divergent Reflection over the Spherical Surface

The divergent reflections spread energy in different directions. Only part of the signal reaches the receiver.

Roughness of the Earth surface also influences reflection propagation. When a signal propagates through a smooth surface, spectacular reflection is the dominant effect. As the surface irregularity increases, diffuse reflection becomes significant. Spectacular reflection propagates signal with strength, while diffuse reflection scatters energy. As surface irregularity increases, more energy is dissipated, and the signal strength at the receiver will be lower. Figure 2. 7 illustrates the concept of spectacular and diffuse reflections.



(a) spectacular reflection



(b) diffuse reflection

Figure 2. 7 Spectacular Reflection vs. Diffuse Reflection

2.2.2.4 Diffraction Propagation

When Earth surface features, such as mountains, buildings, etc. obstruct radio signal propagation, the signal bends around these obstacles [Lee]. Diffraction propagation, as illustrated in Figure 2. 8 will propagate the signal into the area within the shadow of the obstacle.

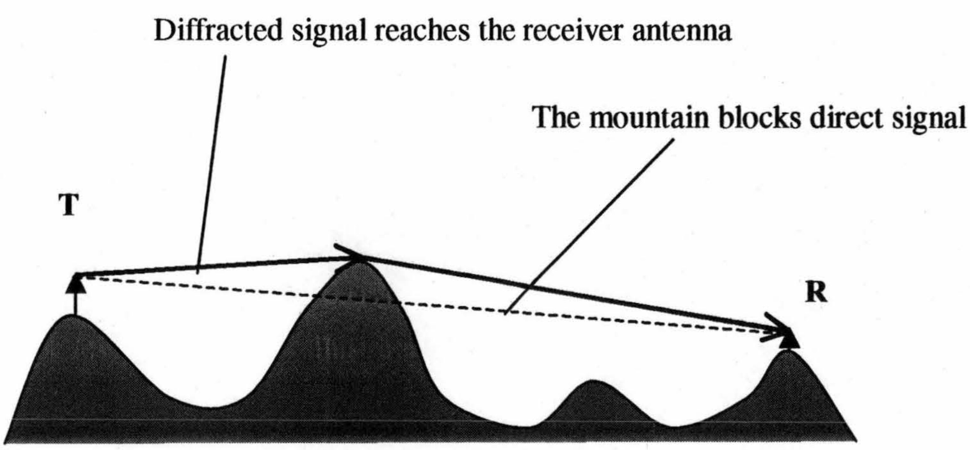


Figure 2. 8 Diffraction Propagated Signal

2.2.2.5 Other Factors that Influence Propagation

In addition to the above mentioned propagation mechanisms, many other factors influence signal propagation. For example, as a signal propagates it is absorbed by the atmosphere, vegetation on the Earth surface, building surfaces, and the ocean. The absorption level is different for each object [Kozono & Watanabe, Lagrone & Chapman]. The signal can also receive interference from other electromagnetic signals. These factors are usually dependent on the environment and are unpredictable, even at the same location. For example, atmosphere absorption may be different in winter and summer, because of differences in the air pressure and humidity. Vegetation absorption may be different because leaf coverage changes from season to season [Lagrone & Chapman].

2.3 PROPAGATION PATH LOSS PREDICTION AND PREDICTION MODELS

VHF/UHF signal propagation, as described in section 2.2, has a common characteristic for all transmission mechanisms — the signal strength decreases along the path. Decreasing levels can not be predicted by a fixed formula because various Earth surface features and other objects can obstruct then absorb the signal energy. The fact that the Earth surface features vary from path to path explains why path loss prediction is conducted based on an understanding of propagation paths. Atmospheric absorption, path location, and time also need to be considered when estimating path loss.

Path loss prediction methods used by the electronic engineer can be classified into three categories — field measurements to determine path loss, empirical and analytical methods. Field measurement requires field tests to obtain the field strength value at the receiver location. The measured result is then subtracted from the transmitted signal strength to obtain the propagation loss.

The empirical method statistically analyzes large amounts of field measurement data from a nominated type of propagation path environment. The statistical results are then applied to other environments with similar characteristics. Factors that can influence path loss are then considered to provide the final prediction value. The empirical method can be found from Hata, Neham, and Okumura, Ohmori, Kawani & Fukuda. A typical environment classification includes large cities, small towns, industrial areas, urban areas, and rural areas. Each category has a series of values listed in a table. When a path loss prediction is required, environment characteristics of the prediction area are analyzed, a category is determined, and the result is derived from the table.

Analytical methods start path loss prediction from theoretical models developed from the electromagnetic principles. The models are verified by actual field experiments. Modification is then made to adapt for any complicating effects of the Earth's environment. The analytical method applies theoretical models to the detailed path profile to calculate path loss. Practical field strength measurements conducted on the path are used to adjust the prediction result. Formulae are generalized after analyzing theoretical and practical results. When a path loss prediction is required, these formulae are applied to the path profile data to calculate the loss.

The analytical models can be found from Tozukat, Palmer, Longley & Rice, Durkin, Causebrook, and Chan, Ong, Ng and Soo. They and some methods described later, emphasize the influence of environmental features on propagation loss. The prediction results vary slightly between models because of differences in the level of inclusion of Earth features, and the use of the terrain data.

2.3.1 Factors Considered in the Propagation Models

In general, path loss prediction models consider one or more of the following factors during the path profile analysis:

- The effective Earth radius;
- The Fresnel zone clearance condition;
- Free space transmission;
- The Earth surface reflection; and
- Other factors.

2.3.1.1 The Effective Earth Radius

Theoretically, radio signal propagation should follow a straight path when it travels in a vacuum or an environment of uniform density. This means that the signal can only transmit within the distance of the Earth's horizon, or 11 kilometers. When the signal travels beyond the Earth horizon, the signal can only be received at high altitudes. The further the signal travels, the higher the signal. Beyond the Earth's horizon, the signal can quickly become too high to be received by an antenna. VHF/UHF radio signals can be received beyond the horizon because of reflection and refraction.

Reflection and refraction will occur when the signal transmits through two medium of different densities according to Snell's law. Snell's law states that ratio of the sine of signal incident angle to the sine of the refraction angle is equal to the ratio of the respective propagation velocities in each media, Equation 2. 1. The value is also equal to a refractive index of the second medium relative to the first medium. The refractive index is determined by the media mass.

$$\frac{\sin\,\theta_1}{\sin\,\theta_2} = \frac{v_1}{v_2} = \rho \qquad [2.1]$$

Where

θ_1: signal incident angle;
θ_2: signal refraction angle;
v_1: signal travel velocity in the first medium;
v_2: signal travel velocity in the second medium;
ρ: Refractive indexes the second medium relatives to the first medium.

When a signal travels from a high to low density medium, and the incident angle is below the boundary reflection angle (critical angle), most of signal will be refracted into the lower density medium. Only a small amount of the signal will be reflected back to the first medium. The closer an incident angle to the boundary reflection angle, the larger the percentage of the signal which will be reflected.

In the Earth's atmosphere, air density decreases as height increases. Radio signals will be refracted as they pass through atmospheric layers of different density. When the signal refracts from a high-density air layer to a low-density layer, the signal is bent toward the Earth (Figure 2. 9).

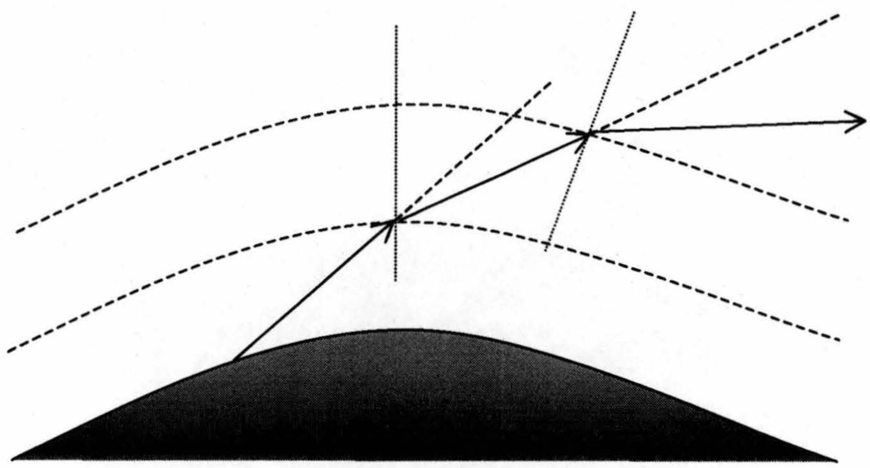


Figure 2. 9 Radio Signal Bends Towards the Earth

Because the refraction mechanism causes the signal to continually bend towards the Earth surface, the signal can travel beyond the Earth horizon. The effect of the Earth's curvature on signal decreases as the path length increases. In other words, the Earth curvature is reduced because of the refraction propagation.

Due to difficulties in representing this mechanism, the phenomenon is described from another point of view. Imagine a radio signal traveling in a straight path, the Earth curvature effects on the signal propagation will be the summarized results of the Earth radius and the bent signal. The Earth curvature effect is named the *Earth bulge*. The Earth bulge is represented by its radius, and termed the *effective Earth radius.* Figure 2. 10 shows the result of the effective earth radius.

The relationship between true Earth radius (r_0) and the effective Earth radius (r) is defined by Equation 2. 2, where K is called the *Earth bulge factor.*

$$K = \frac{effective\_earth\_radius}{true\_earth\_radius} = \frac{r}{r_0} \qquad [2.2]$$

The severity of the refraction propagation varies from season to season and location to location, because the air mass changes in the atmosphere. When planning systems a k value of 4/3 is used, known, known as *normal Earth bulge factor,* and the *effective Earth radius* becomes 8493 km when applying normal Earth bulge factor.

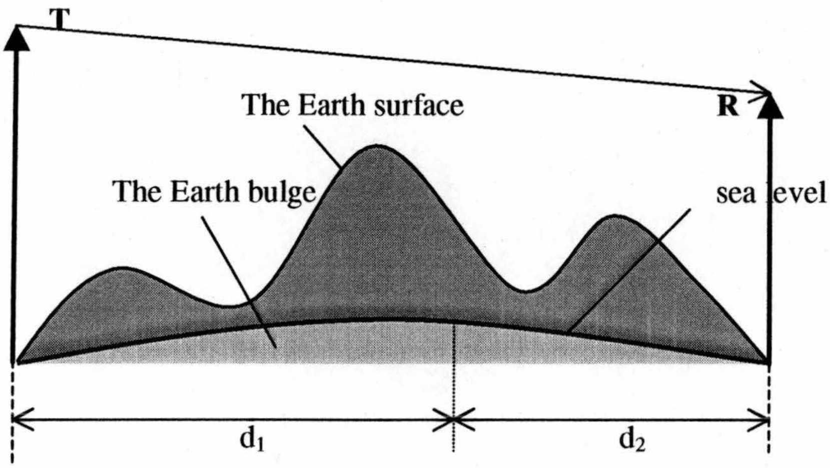


Figure 2. 10 Effect of the Earth Radius

To calculate height of the Earth bulge along the profile, distance of the point of interest to transmitter d_1, and the distance from this point to receiver point d_2, is required.

$$bulge = \frac{d_1 d_2}{12.75K} \qquad [2.3]$$

Equation 2. 3 calculates the bulge height at a point of interest [White].

Where

d_1 and d_2 are in kilometers
bulge is in meters
K is the Earth radius factor under normal atmosphere condition, ie 1.33

2.3.1.2 Diffraction Principle and The Fresnel Zone

One radio signal propagation mechanism is diffraction. Diffraction occurs when an obstacle block the signal and line of sight propagation cannot achieved. Radio signal diffraction can be explained through the theory of electromagnetic wave motion — that a wave front or ray beam has the property of expanding as it travels through space. According to the Huygen's principle, this property results in diffraction and phase transitions as the wave passes over an obstacle, increasing or decreasing the received signal level.

Huygen's principle suggests that when a radio signal propagates, each point on the radio wavefront acts as the source of a secondary wavelet and these wavelets combine to produce a new wavefront in the direction of propagation. The wavefront keeps moving forward in the same form if no obstacles exist along the path. Suppose, however, that the wavefront encounters an obstacle, the wavefront can not produce a secondary wavelet as it normally would, because the obstacle partially blocks the generation of wavelets. Only parts of the wavelets pass the obstacle and form a new wavefront. The new wavefront will have a different strength and phase. The signal that is generated from the wavefront behind the obstacle is the signal diffracted over the obstacle.

The diffracted signal strength after the obstacle is weaker than the signal before the obstacle. Its value decreases as the height of the obstacle increases. The signal phase changes because the diffracted signal has a longer path length. Consider a transmitter T and a receiver R, the transmission can occur via different paths, as shown in Figure 2. 11

The relationship between the height of an obstacle and path length difference between the diffracted signal and the direct propagation can be represented by Equation 2. 4 and 2. 5, assuming the obstacle height is far smaller than distance between the obstacle, the transmitter and the receiver.

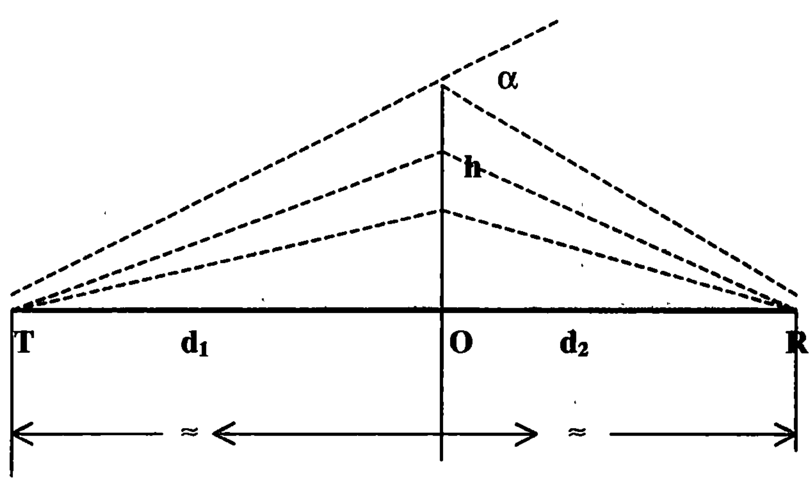


Figure 2. 11 A diagram of a Diffraction Path Compared with Line of Sight Path

$$\Delta \approx \frac{h^2}{2}\frac{d_1+d_2}{d_1 d_2} \qquad [2.4]$$

$$\Phi = \frac{2\pi\Delta}{\lambda} = \frac{2\pi}{\lambda}\frac{h_2}{2}\frac{d_1 + d_2}{d_1 d_2} \qquad [2.5]$$

Any propagation, other than TOR, the direct link between the transmitter T and a receiver R, has traversed a longer path than TOR. The extra path length Δ is given from the geometry of Figure 2. 11 by Equation 2. 6, assuming h << d_1, d_2.

When the path length of a diffracted signal has value of λ/2, λ, 3λ/2... nλ/s, for a given wave length λ, the obstacle height value can be calculated using Equation 2.6.

$$h = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}} \qquad [2.6]$$

Varying n in Equation 2.6, produces a family of ellipsoids related to the distance of the obstacle from the transmitter and receiver [Fowles]. The family of ellipsoids are called Fresnel zones. Specifically, the innermost ellipsoid is called the first Fresnel zone, which corresponds to n = 1 in Equation 2.6, the second inner ellipsoid is then called the second Fresnel zone, etc.

When n is an even number, the signal strength is enhanced by the diffracted signal because the diffracted signal has the same phase as the direct signal. Odd numbers in Equation 2.6 reduce the direct signal strength.

2.3.1.3 Fresnel Zone Clearance Conditions

Diffraction and the Fresnel zone principal explains why radio signals will diffract when an obstacle higher than the line of sight path along the propagation path is encountered. Fresnel zones reflect length differences between the line of sight and the diffraction paths. The diffracted signals can cause field strength to decrease when obstacle heights meet certain conditions. However, experiments have shown that the field strength is weaker for a propagation path with an obstacle height is just below the line of sight path [Popovic]. Hence, signals with line of sight path can not guarantee line of sight transmission. A stronger than line of sight condition was defined [Popovic]. This condition is named *Fresnel Clearance* condition. A propagation path which satisfies the Fresnel clearance condition allows signal transmission with the lowest path loss.

The Fresnel clearance condition is defined by the Fresnel zone clearance ratio. This is defined by the ratio of the height differences between the obstacle and the line of sigh path h and Fresnel radius r [Committee], as indicated in Equation 2.7.

$$r = 548\sqrt{\frac{d_1 d_2}{f(d_1 + d_2)}} \qquad [2.7]$$

Where f is frequency in MHz.

The Fresnel zone clearance ratio is expressed in v (Fresnel parameter) as defined in Equation 2.8. Equation 2. 7 uses wavelength λ instead of frequency f. A radio signal transmission speed 300,000 km/s is used during the conversion.

$$v = \frac{h}{r} = \frac{h}{548}\sqrt{\frac{f(d +_1 d_2)}{d_1 d_2}} = h\sqrt{\frac{2(d +_1 d_2)}{\lambda d_1 d_2}} \qquad [2.8]$$

2.3.1.4 Free Space Transmission

A signal transmitting under the Fresnel clearance path is known as *free space transmission.*

Free Space propagation has little power loss along its transmission path. There is no other signal loss except through atmospheric absorption. Generally, free space conditions can be deemed to prevail if the first Fresnel zone for the path between transmitter, and receiver and reflections is free from surface obstacles eg. hills, trees, buildings, etc. Figure 2. 12 shows an example of the free space propagation path.

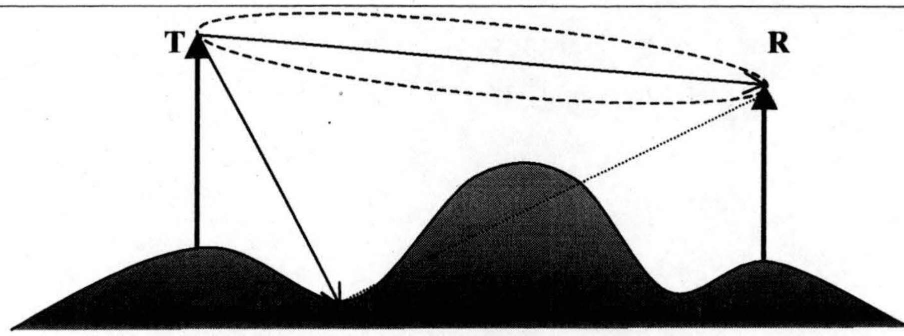


Figure 2. 12 Free Space Propagation

Under free space conditions the transmission loss is caused by distance. Surface waves are attenuated rapidly, and Sky waves pass readily through the ionosphere. In the case of free space propagation, the amount of energy available to an antenna of a given effective area is inversely proportional to the square of the distance from the source [Bullington].

2.3.1.5 Earth Surface Reflection

Surface reflection occurs when a radio signal propagates over a smooth surface, such as lakes, rivers, or an ocean. Spectacular reflected signals also reach the receiver. The reflected signals travels a longer path than the direct transmission. They may enhance or reduce the received signal strength depending on the phase difference caused by the differences in the path length. As path length increases, reflections from the Earth surface become diverged due to the Earth curvature, influence on the received signal strength reduces.

For a rough surface, ie. undulation of the surface is comparable to the signal wavelength [Chan], the surface reflection can be treated as diffuse reflection which causes greater loss to the received signal.

2.3.1.6 Other Factors

Ground and sky waves are included in other factors that are considered in propagation analysis. For a mobile telephone signal, ground waves are usually blocked by terrain, and sky waves usually penetrate through the ionosphere with only small amount of energy reflected back to the Earth.

In general, the mobile signal propagation depends on the terrain propagation path and the surrounding environment. The irregularity of the Earth surface makes propagation analysis extremely complicated because several propagation mechanisms may occur on any given propagation path. The level of involvement of each mechanism varies according to the path geometry, type of surface cover, and the surrounding environment. It is almost impossible to analyze the effect of each single mechanism on the signal propagation. Most of the existing path loss prediction models concentrate on a nominated mechanism, and then use the empirical methods to summarize the influence of the other propagation mechanisms.

The next chapter will discuss details of existing path loss prediction models.

2.4 CONCLUSION

This chapter introduces basic principles used in the mobile telephone signal path loss prediction.

The principle determines that the Earth environment — atmosphere and terrain — contribute significantly to the signal strength loss on a propagation path. Propagation mechanisms were discussed, and factors involved in mobile signal propagation and path loss prediction were described.

The following chapters will discuss methods to analysis propagation mechanism's and models to predict path loss.

CHAPTER 3

REVIEW OF EXISTING MOBILE RADIO SIGNAL PATH LOSS PREDICTION MODELS

The prediction of path-loss is an important step in planning a mobile radio system. Accurate prediction methods are needed to determine the parameters of a radio system required to provide efficient and reliable coverage for a specified service area.

The discussion in the last chapter revealed that in order to make predictions, an understanding of the factors that influence the signal strength are needed. The fundamental problem in finding the influential factors on the signal strength is the analysis of propagation mechanisms. However, the propagation characteristics are irregular and depend on features of the local environment. There is no simple method available to find out how each of the factors affects the signal transmission, because all factors in the real world are related, and cannot be isolated.

Research and experimentation has been conducted to achieve an accurate prediction of path-loss value [Committee]. As mentioned in the last chapter, three categories [Chan] can be classified according to the nature of the method and the principles of analysis. They are empirical prediction models, experimental prediction models and analytical models.

3.1 EMPIRICAL MODELS

Empirical models do not adequately consider local Earth surface features that largely determine the characteristics of radio propagation. Instead, by using many experimental results and statistical processing, empirical formulae, nomograms and charts are derived which permit the prediction of field strengths in an expected area and locations around a given transmitter. The prediction result is achieved from a reference environment in which the properties are similar to the desired prediction area. The criteria for classification are usually the characteristics of the environment, eg. industrial, business, and rural areas. An understanding of the service area characteristics is essential for accurate classification. Appropriate predefined formulae are applied to the service area in order to gain the prediction result. Modification and correction may be needed after the calculation.

Hata [Hata] presented an empirical method which classified the urban environment as a medium—small city with the average receiver height of 4 to 5 meters, and a large city with an average building height above 15 meters. It also provided correction factors for suburban and open areas.

The empirical models are easy to use, but are inaccurate, unless the analyzed area is very similar to the district where the empirical formulae were developed and derived [Chen]. Since the formulae can only be applied within restricted ranges, it is necessary to carefully examine whether the area of interest matches the conditions of the model.

Some of the commonly used empirical models, including CCIR, Egli and Okumura, will be reviewed and summarized in the following sections.

3.1.1 The CCIR Method

The CCIR method was developed and first published in CCIR literature [CCIR]. It contains field strength prediction curves, Figure 3. 1 [Parsons], which are based on statistical analysis of a considerable amount of experimental data collected in many countries. They can be used to predict path loss for the urban districts or areas of rolling hilly terrain with a terrain irregularity within 50 meters. The applicable frequency is 900 MHz, with a mobile antenna height of 1.5 meters, and transmitting antenna height of between 30 and 100 meters. Field strength predication values are given for 50 percent of locations and 50 percent of the time.

For a specific situation, the field strength is determined by referencing field strength curves, and then another to derive a correction factor — a related height difference for when the condition does not exactly match the basic requirement. The standard deviation expressed as functions of distance and terrain irregularity, facilitate estimation of values appropriate to Gaussian distribution quartiles, eg 5 percent, 10 percent, or 90 percent. These are of interest because the value is to be used in conjunction with the assumption that propagation variations due to changes in location and time are characterized in decibel quantities by distribution.

For a mobile antenna of 3 meters instead of the standard 1.5 meters, a height gain factor of 3 dB is suggested.

To calculate path loss between a transmitter and a receiver, the antenna height above the average terrain height and the distance between the transmitter and the receiver is required. The model calculates free space transmission loss, the diffraction effect, and building penetration in the urban area. Output of the model includes field strength, time fading and location variability. However environmental factors, such as terrain, buildings, vegetation, and hill shape are not considered. Reflection and diffraction are not analyzed. These limitations restrict the prediction accuracy. Prediction errors of 10 dB are not uncommon.

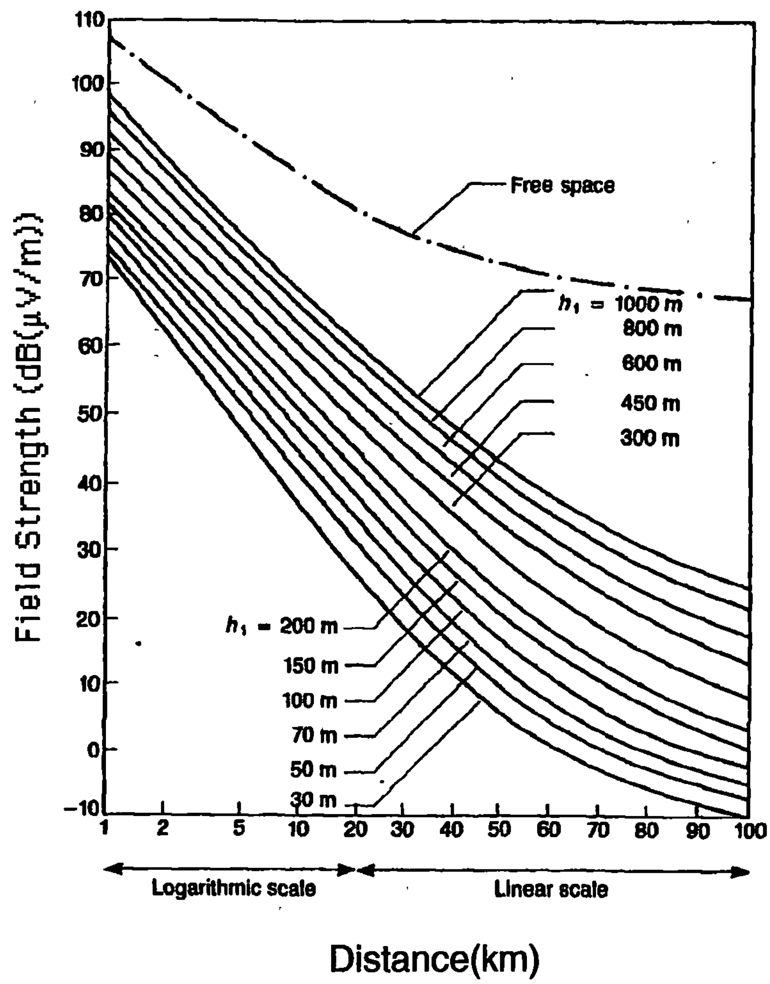


Figure 3. 1 CCIR Field Strength Prediction Curves

for urban areas at 900 MHz. Mobile height = 1.5m
(50% of the time, 50% of locations)

3.1.2 The Egli Model

The Egli model [Egli] consists of empirical formulae that include terrain characteristics and frequency factors. The formulae were derived from a series of measurements over irregular terrain at frequencies between 90 and 1000 MHz. It is based on the plain Earth path-loss Equation [3. 1]. An additional path loss value is added which has been derived from comparisons between measured and theoretical values.

$$L = \frac{P_R}{P_T} = G_T \cdot G_R \cdot (\frac{h_T h_R}{d^2})^2 \qquad [3.1]$$

Where P_R is the power at receiver's antenna
P_T is the power at transmitter's antenna
G_T, G_R are the antenna gains
h_T, h_R are the antenna heights
d is the distance between the transmitter and the receiver

The additional path-loss value is a function of terrain irregularity (β). This deviation was termed the "terrain factor". The terrain irregularity can be derived from the signal frequency using equation [3.2]

$$\beta = (\frac{40}{f})^2 \qquad \text{f in Mhz} \qquad [3.2]$$

For example, a median value of 27.5 dB was calculated at 900 MHz frequency by converting [3. 2] into decibels. The path-loss formula can then be derived.

$$L_{Egli} = G_T \cdot G_R(\frac{h_T h_R}{d^2}) \cdot \beta \cdot \alpha \qquad [3.3]$$

α is the log-normally distributed terrain undulations relevant to the median value. α can be represented as a percentage of the median value.

For a 900 MHz signal, an isotropic antenna, $\beta = -27.5$ dB, $lg\,(G_T G_R) = 0$, [3.4] can be used to calculate the path-loss value for given a distance and antenna height.

$$L_{Egli}\ (\text{dB}) = 20\lg(h_T) + 20\lg(h_R) - 40\lg(d) - 27.5 + \alpha \qquad [3.4]$$

When compared to the CCIR model, the Egli model considers terrain factors over a small area. It still does not consider the actual path condition. Because the terrain factors are derived empirically from actual measured values, it may not be suitable for all terrain conditions.

3.1.3 The Okumura Method

The Okumura model [Okumura, Ohmori, Kawani & Fukuda] is based on measurements taken in Tokyo and its surrounding suburbs. The measurement results were analyzed statistically to determine the distance and frequency dependence of the median field strength, location variability and antenna height gain factors for the base and vehicular station in urban, suburban, quasi-open and open areas over quasi-smooth terrain. Path-specific correction factors were also developed to consider irregular terrain, such as rolling hills, isolated mountains, general sloped terrain, and mixed land sea — paths. The analyzed results were then drawn on reference curves for prediction usage.

The Okumura model gives a method of predicting field strength and service area for a given terrain condition. The applicable frequency is between 150 and 2000 MHz. Base antenna height ranges from 30 to 1000 meters and a receiver height between 1 and 3 meters. The prediction distance is between 1 and 100 km.

When considering the environment restriction, the Okumura model is the most suitable model in an urban area with buildings. It can make area-to-area, as well as path-specific predictions. Path-specific predictions are derived from area predictions accounting for any path specific characteristics.

In summary, the Okumura model differs from other models, because the measurement data [Committee] is obtained from actual land mobile communication systems rather than from theoretical models. When compared to the Egli and CCIR methods, the Okumura model has the advantage of considering the effect of diffraction and surface reflection. However, selecting appropriate environmental factors and path specific features can be complex. This model is difficult to automatic.

Based on the Okumura method, Hata's model [Hata] is a simplified version that converts Okumura's curves into formulae. With environmental correction factors as input, the formulae can be easily implemented with a computer program.

The European Broadcasting Union's Clearance Angle approach [CCIR] & [CCIR80] also allows easy computation of path-specific correction.

3.2 ANALYTICAL MODELS

In contrast to the empirical models, analytical methods use theoretical models, which are appropriately adapted to the local environment, based on selected radio signal measurements. Local terrain databases are also used to analyze the signal propagation path conditions.

Analytical models retrieve a detailed path profile from local environment data. The path profile is analyzed according to signal propagation theory. The result is used as input to a series of formulae, which calculate free space, plane Earth, reflection, diffraction and cluster loss. Cluster loss represents the loss from multiple reflection, and scatter characteristics of surrounding features. The path loss prediction result is the aggregation of the above losses.

The analytical models are quite easy to computerize because the theoretical model usually consist of a series of formulae incorporating the different propagation categories with the environment database is in digital format.

Analytical models can be classified into two types, based on whether they are general or special purpose models. A general-purpose package can make path-loss prediction over a wide range of frequency bands and over a variety of environments. However, special purpose packages that were designed for specified environmental situations, such as areas with a high building density, irregular terrain conditions, or for a particular band of spectrum, often provide a more accurate prediction result.

Many analytical models have been derived from research work. Some of them have been commonly adopted. For example, the Longley-Rice model [Longley & Rice], produced by A.G.Longley and P.L.Rice of Institute for Telecommunication Sciences, Boulder, Colorado, USA, and the JRC method, developed based upon research work by Edwards and Durkin [Edwards & Durkin] and Dadson [Dadson] for the Joint Radio

Committee of Nationalized Power Industries UK, are widely used. Some of these models will be discussed in detail in the following sections.

3.2.1 The JRC Model

The JRC model is a summary of the work from Edwards & Durkin, and Dadson. It considers environmental data by using data in a digitized topographic database which provides a grid—located height reference information. The grid resolution is 500 meters. Figure 3. 2 illustrates the grid data structure.

With the grid database, the JRC model first constructs the ground path profile between the transmitter and a chosen receiver location. The path profile is output by row, column and diagonal interpolation according to the initial terrain analysis.

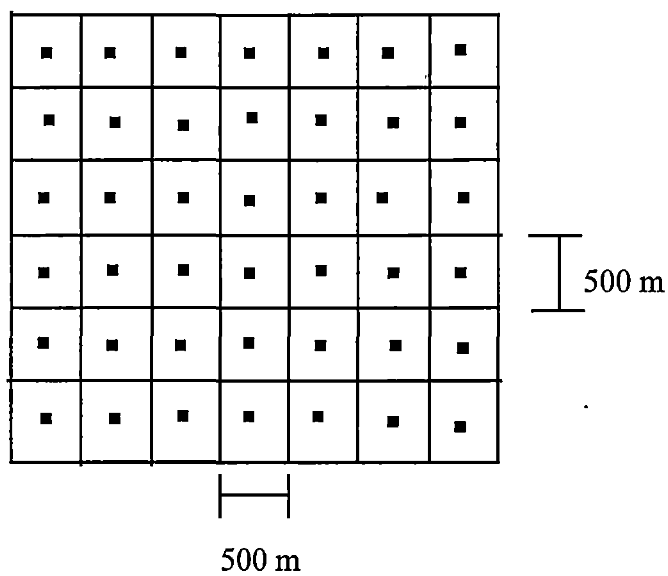


Figure 3. 2 Grid Data Structure With 500-meter Interval and Selected Point within Each Grid

The Line of sight and the Fresnel clearance condition are determined after the path profile has been produced. If the path belongs to line of sight with the first Fresnel clear, either free space loss or plain Earth loss, whichever the larger, is calculated and assigned as the propagation path-loss.

If line of sight exists, without first Fresnel clearance, diffraction loss above the first Fresnel zone is calculated and added to the free space or plain Earth loss.

If the path does not have line of sight, diffraction loss is calculated by applying the Epstein-Peterson [Epstein & Peterson] and the Bullington [Bullington] method, and summing this with the free space loss.

This can be represented with the following formula.

$$path-loss = \begin{cases} \max(L_F, L_P) + L_D \text{.................................. not\_line\_of\_sight} \\ \max(L_F, L_P) \text{...... line\_of\_sight\_with\_Fresnel\_clearance} \end{cases} \quad [3.\ 5]$$

where

L_F is the free space loss
L_P is the plane earth loss
L_D is the diffraction loss

The JRC method is implemented as a computer program so that path profile production, profile analysis and calculation are automatically completed.

3.2.2 The Longley-Rice Model

The Longley-Rice model was published as an ESSA technical report in 1968 [Longley & Rice], and was improved by an NTIA report [Hufford, Longley & Kissick] and the Hufford report [Hufford]. The Longley-Rice model is used for prediction of median transmission loss over irregular terrain between 20 and 10000 MHz, a distance between 1 km and 2000 km and a base station antenna height between 0.5 and 300 meters. The initial application is open areas, towns and small cities with irregular terrain topography. In urban areas, a correction factor is used [Longley & Reasoner] & [Longley].

Two parts make up the entire model — the point-to-point prediction model and the area prediction model. The point-to-point prediction procedure requires detailed terrain profiles. From the profiles, the distances to the respective radio horizon, the horizon elevation angles and the effective antenna heights are determined. These distances, angles, and heights are then supplied as input to the computer program.

The area prediction model uses randomly selected point to point paths, where variations in the terrain elevation are characterized statistically. This model predicts characteristics of any variations with respect to location and time. The model also gives an estimate of the standard error.

As in the JRC model, the terrain grid resolution is the "standard" [Longley & Rice], with 500 meters being used to construct the path profile. Other input parameters include

- Frequency,
- Polarization,
- Path length,
- Antenna heights above ground,
- Surface refractivity,
- Effective Earth radius,
- Climate,
- Ground conductivity,
- Ground dielectric constant,
- Effective antenna heights (antenna height adjusted for Earth radius, distance and terrain condition),
- Horizon distances of the antennas,
- Horizon elevation angles,
- The angular distance for a Trans-horizon path, and
- Terrain irregularity of the path.

The prediction steps of the Longley-Rice model, after the path profile is produced and initial parameters are input, are as follows.

Path Parameter Definition:

1. The Atmosphere Effect:

Refractivity (N_s) in the atmosphere is simulated and calculated according to formula [3.6] to give the atmosphere parameter.

$$N_s = N_0 e^{-0.1057 h_s} \quad [3.6]$$

Where N_0 is the refractivity at sea level,
h_s is the altitude above mean sea level in kilometers

2. Terrain Parameter: *Δh (d)*

Δh (d) is used to determine the degree of the terrain irregularity. *Δh (d)* is calculated using

$$\Delta h(d) = \Delta h(1 - 0.8 e^{-0.02d}) \quad [3.7]$$

where *Δh(d)* and Δh are in meters and the distance d is in kilometers. Δh can be derived from the details at the path profile if they are available. Otherwise, a table of estimates for Δh can be used as reference: for example, Δh = 5 — 20 meters for smooth plains, Δh = 40 — 80 meter for rolling plains and Δh = 150 — 300 meters for mountains. The second estimate is very useful for area prediction.

Δh (d) is provided for effective antenna height determination.

3. Line of sight distance D is calculated from the effective antenna heights.

Median Transmission Loss Predictions:

The first step in calculating the medium transmission loss prediction is to determine the medium reference values A_{cr} of attenuation below free space. The reference values L_{cr} of transmission loss are then summed with the free space basic transmission loss L_{bf}, and the reference attenuation relative to free space A_{cr} :

$$L_{cr}(dB) = L_{bf} + A_{cr} \quad [3.8]$$

The free space basic transmission loss is

$$\boxed{L_{bf}(dB) = 32.45 + 20\log(f) + 20\log(d)} \qquad [3.\ 9]$$

where

A_{cr} is attenuation below free space loss
L_{cf} is the reference attenuation relative to the free space loss
L_{bf} is the free space transmission loss
the radio frequency f is in megahertz,
the distance d is in kilometers.

The reference attenuation A_{cr} is computed using methods based on different propagation mechanisms for three distance ranges. Well within radio line of sight, the formulae of two-ray optics is used to compute attenuation relative to free space. Just beyond line of sight, diffraction is the dominant mechanism. The prediction method computes a weighted average, A_d, of estimates of diffraction attenuation over a double knife-edge, and over irregular terrain. At greater distances, well beyond the radio horizon, the dominant propagation mechanism is usually scattering. The prediction method at this distance is a modification of the scatter computations described by Rice et al. [Rice, Longley, Norton & Barsis]. The reference attenuation A_{cr} for trans horizon paths is either the diffraction attenuation A_d or the scatter attenuation A_s, whichever is smaller. The distance at which diffraction and scatter losses are equal is defined as d_x.

Equation [3. 10] is used to calculate A_{cr}. The equation requires path profile data, and the following parameters:

- frequency f in MHz,
- path distance d in km,
- antenna heights above ground h_{g1} and h_{g2} in meters,
- polarization,
- surface refractivity N_s,
- terrain irregularity Δh,
- ground constant σ (conductivity),
- dielectric constant ε,

- effective antenna height $h_{e1,2}$,
- horizon distances $d_{L1,2}$, and
- Horizon elevation angles $\theta_{e1,2}$.

$$A_{cr}(dB) = A_e + k_1 d + k_2 \log(d) \qquad [3.\ 10]$$

A_e and k_1, k_2 are obtained from [3. 11] (details of the formulas from Longley and Rice [Longley & Rice]). The distance d_0 is chosen to approximate the greatest distance at which the attenuation below free space is zero. The distance d_1 is greater than d_0 but well within the range in which the two ray optics formulas are valid. A_0, and A_1 are the estimates of attenuation at d_0 and d_1 respectively.

$$A_e(dB) = A_0 - k_1 d_0 - k_2 \lg(d_0) \qquad [3.\ 11]$$

The diffraction attenuation A_d is then computed by combining estimates of knife-edge diffraction, based on Fresnel-Kirchhoff theory, with a modification of the method for computing diffraction over smooth terrain developed by Vogler [Vogler]. The diffraction attenuation for irregular terrain A_d is computed as the weighted average of the diffraction attenuation over the bulge of the Earth in the far diffraction region A_r and the knife-edge attenuation A_k.

$$A_d(dB) = (1 - w)A_k + wA_r \qquad [3.\ 12]$$

$$w = \left\{ 1 + 0.1 \left[\frac{\Delta h(d)}{\lambda} \left(\sqrt{\frac{h_{e1}h_{e2} + c}{h_{g1}h_{g2} + c}} + \frac{a\theta_e + d_L}{d} \right) \right]^{0.5} \right\}^{-1} \qquad [3.\ 13]$$

where c = 0.

The Longley and Rice model also discusses the concept of the signal variability. Three basic types of variability are defined and combined into four variability modes. The three types of variability are:

- time variability : variations of local medians on specific path with time;

- location variability : variations in long-term statistics that occur from path to path;
- situation variability : variations in location variability that may occur in different situations.

The predicted deviation and error are then defined for specific times, locations or situations.

In summary, with or without a 500-meter interval path profile, signal transmission loss can be calculated over irregular terrain for quite a wide range of frequency bands. Signal variability is also considered for specific conditional path-loss calculations. However, no provision is made for determining corrections due to local environmental factors, such as factors near a mobile receiver, or the effects of buildings or foliage.

3.2.3 The TIREM Model

TIREM (Terrain Integrated Rough Earth Model) is one of a series of point-to-point propagation models in the Master Propagation System (MPS 11) developed by the office of United States Department of Commerce, National Telecommunications and Information Administration [MPS 11]. It predicts propagation loss between two points taking into account the frequency, atmospheric and ground constants, and the characteristics of the terrain profile between the two points. A digitized database of terrain elevations gives necessary information on the profile, and the model then selects the appropriate propagation algorithm to calculate the loss.

The TIREM model uses the terrain profile to compute values of basic transmission loss. It then evaluates the profile between the transmitter and the receiver, and based on its geometry, selects a mode of propagation and applies this to compute the path loss. If more than one propagation mode is selected, a weighted combination of losses is computed.

Propagation Mode:

To select an appropriate propagation mode, TIREM first examines the path terrain. Geometric properties, and path related parameters are extracted. These parameters, together with radio horizon distance from the transmitter, effective antenna heights, path angular distances, the refractive effects of the atmosphere, and the first Fresnel clearances distance, are used to branch the selection of the propagation mode into two main modes. These are line of sight and beyond line of sight.

1. Line Of Sight Modes

Equation [3. 14] combines the three modes used for the line of sight path condition:

$$path-loss=\begin{cases} free\ space\ loss & (h/r \geq 1.5) \\ empirical\ rough\ earth\ loss & (h/r \leq 1.5) \\ weighted\ combinition\ of\ above\ two & (0.5 < h/r < 1.5) \end{cases} \qquad [3.\ 14]$$

where r is the first Fresnel clearance height
h is the distance from terrain points to the link line between the transmitter and the receiver
h/r is minimum ratio of h to r along the entire path

When h/r >= 1.5, the ray is well above the terrain. When h/r <= 0.5, the ray is close to the Earth's surface. The line of sight modes are suitable for actual path distances within the radio horizon, which have no obstacles between the direct link of the transmitter and the receiver.

2. Beyond Line Of Sight Modes

If the propagation path extends beyond the radio horizon, the wave can reach the receiving antenna by diffracting around the terrain or from scattering by the troposphere. The path-loss can be obtained from the following:

$$path - loss = \begin{cases} knife\text{ - }edge\ diffraction\ loss \\ rough\ earth\ diffraction\ loss \\ effective\ knife\text{ - }edge\ diffraction \\ effective\ knife\text{ - }edge\ /\ rough\text{ - }earth\ diffraction \\ tropospheric\ scatter \\ effective\ double\ knife\text{ - }edges \\ diffraction\text{ - }scatter\ 1 \\ diffraction\text{ - }scatter\ 2 \\ diffraction\text{ - }scatter\ 3 \end{cases} \quad [3.15]$$

$\text{Note : path} - \text{loss may be the sum of the above 2 or 3 modes}$

When the transmitter and the receiver are within the same radio horizon, but h/r < 0.5 (knife-edge diffraction mode), or the transmitter and the receiver are in different radio horizons but the angular distance is too small (effectively knife-edge diffraction mode), knife-edge diffraction plus ground reflection loss is calculated.

When the distance is beyond the radio horizon, with no obstacles along the path (rough-earth diffraction mode or effective knife-edge / rough-earth diffraction mode), rough Earth diffraction loss is calculated if the terrain irregularity detected is high. The extra troposcatter loss (tropospheric scatter mode) is added to the Earth diffraction loss if the path distance is well beyond the radio horizon.

When the distance is over the radio horizon, but there are obstacles or there is no first Fresnel clearance along the path (effectively double knife-edge mode), double knife-edge diffraction loss is computed.

When the diffraction loss amount is close to troposcatter loss (diffraction-scatter 1 mode), the combined loss is calculated. If the path is rough with high obstacles (diffraction-scatter 2 mode), the loss is the combined diffraction and troposcatter losses with effective double knife-edge losses. If the path distance is well over the radio horizon and there is a rough path condition (diffraction-scatter 3 mode), the combined troposcatter and effective double knife-edge losses are used.

Input Parameters:

1. Environment Information:

- Transmitter and receiver coordinates,
- Terrain profile derived from topographic databases, the profile having points at a fixed interval. The interval is 1/5 of the distance, between antennae or at least 10 points,
- Ground properties,
- Atmosphere,
- Permitivity and ground conductivity constant,
- Surface refractivity.

2. Equipment Information:

- Radio frequency,
- Polarization,
- Structure heights of antennas.

Output Results:

The program returns the path profile elevation list, the selected propagation modes and the respective path loss values for each.

The TIREM model analyses the path profile and classifies the profile into different categories for better path loss prediction. It extracts the derived parameters from the program automatically (which requires user input in the Longley-Rice model). But it has similar disadvantages to the Longley-Rice model, due to the usage of path loss formulas from the Longley-Rice model and other common references.

3.2.4 Chen's Propagation Model for Cellular Radio System

In 1991, Chen published a paper [Chen] describing a model used for the cellular radio system propagation and coverage prediction of the UHF band. The whole system was designed for computerization and thus consists of a propagation prediction model, a database containing terrain data, and a subsystem for output of the cellular coverage patterns for Singapore.

The propagation prediction model analyses the path profile derived from a terrain database, calculates the path transmission loss, computes additional clutter loss from local environment influences, and plots the path profile and prediction results.

The system can make point to point and point to area propagation loss predictions. The point to area prediction is implemented by repeatedly applying the point to point prediction method at sample locations in the area of interest. Sample points are selected from along radial path profiles. Results of the calculations are stored with the selected sample points.

The Propagation Prediction Model

The model calculates radio signal propagation loss from a transmitter to a receiver using the terrain profile. The total propagation loss is composed of radio path transmission loss, and clutter loss.

1. The path profile is used to determine the transmission loss. The profile is classified into one of the following three categories:

- Line of sight path,
- Line of sight with inadequate Fresnel zone clearance,
- Not line of sight path.

An appropriate equation is then applied for each type of profile to obtain the radio path transmission loss.

Line Of Sight Path

A line of sight path is a profile with adequate Fresnel zone clearance. The terrain profile between transmitter and receiver is modified to include the Earth bulge effect. The maximum Fresnel parameter (v) of the profile is calculated. If v is smaller than –0.8, the path is a line of sight path.

The line of sight path loss can be calculated using equation [3. 16].

$$loss = 20\log[d^2{}_{TR} /(h_R * h_T)] \qquad [3.\ 16]$$

where d_{TR} is the distance between the transmitter and receiver;
h_R is the effective antenna height for the receiver;
h_T is the effective antenna height for the transmitter.

The Loss value is then compared with free space loss. The larger loss is taken as the radio path transmission loss.

Line Of Sight with Inadequate Fresnel Zone Clearance

When the maximum Fresnel parameter of the earth bulge modified path profile has a value between –0.8 and 0, the path profile is in line of sight with inadequate Fresnel zone clearance category. The radio path transmission loss is calculated with:

$$loss = free\_space + 6.02 + 9v + 1.65v^2, \quad -0.8 \leq v < 0 \qquad [3.\ 17]$$

Not Line of Sight Path

A path is recognized as not line of sight path when the maximum Fresnel parameter is greater than zero (0). Diffraction loss along the path is calculated. The calculation starts by counting the number of obstacles along the path. Each obstacle is treated as knife-edge during the diffraction loss calculation. The obstacles are identified if they have peaks with heights greater than line of sight between the transmitter and the receiver. In the case of single obstacle, the radio path transmission loss is calculated using:

$$loss = free\_space + \begin{cases} 6.02 + 9.11v - 1.27v^2 & 0 \le v \le 2 \\ 13 + 20\log v & v > 2 \end{cases} \qquad [3.\ 18]$$

For a path with two or more obstructions, the diffraction attenuation is determined using Deygout's method [Deygout].

Deygout Diffraction Loss Calculation Method

The Fresnel diffraction parameter is first calculated for each obstacle edge alone, as if all other edges were absent. The edge having the largest value of v is termed the main edge and its loss is calculated in the standard way.

Then the diffraction losses for other edges other than main edge are found with respect to a line joining the main edge to the transmitter T and receiver R and are added to the main edge loss to obtain a total.

As an example, two obstacles are assumed to exist between the main edge and the transmitter T and the receiver R, Figure 3. 3. The subsidiary main edge is decided from these two obstacles. The loss over the main edge and the transmitter is evaluated. The same procedure is repeated until no subsidiary main edge can be found in the remaining obstacles. In practice, it is common to compute the total loss as the sum of three components only, the main edge and the subsidiary main edges on either side.

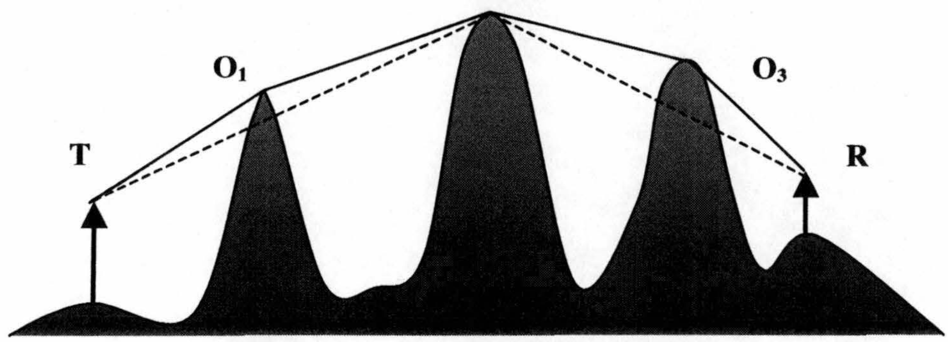


Figure 3. 3 The Deygout Method

The Deygout diffraction loss at each knife-edge is summed with the free space loss to obtain the radio path transmission loss, equation [3. 19].

$$\boxed{Loss = free\_space + Deygout\_diffraction\_loss} \qquad [3.\ 19]$$

If more than three obstructions are counted, the empirical formulae for small cities described by Hata [Hata] are used to calculate the radio path transmission loss.

2. Clutter Loss

The clutter loss is added to the radio path transmission loss. The clutter loss represents the summarized influences of the surrounding trees and buildings. Two types of clutter loss are considered.

For point to point or small point to area (route less than 100 meters) prediction, a modified knife-edge diffraction loss model is applied. The model requires a user who is familiar with the local environment to input the clutter distance that represents the distance from the receiver to the nearest obstruction along the transmission path. The clutter distance should be much smaller in comparison to the distance between the transmitter and the obstacle. Under this condition, the Fresnel parameter (v) calculated by equation [3. 20] can be simplified to equation [3. 21].

$$v = h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} \qquad [3.20]$$

$$v = h\sqrt{\frac{2}{\lambda d_2}} \qquad [3.21]$$

The previous equations [3. 17] & [3. 18] are then applied to calculate the clutter loss.

For a point to area (route 300 to 500 meters) prediction, a generalized clutter loss correction factor is added to the calculated path loss to account for the average clutter loss over the area. The correction factor is based on frequency. If frequency is less than 600 MHz, the correction factor is 25 dB, otherwise it is 21 dB.

The Terrain Database

A terrain database is used to retrieve path profile information, which is then input to the propagation prediction model.

The terrain is derived from topographic maps with a 20-meter contour interval. Supplementary data includes contours at 5 and 10 meters, plus survey data for buildings and obstacle heights. The data is organized into matrix of 500 X 500 meter resolution. Elevation data is the height at the center of each matrix square. It includes actual ground elevation, plus building or tree heights.

Output of the Prediction

The point to point prediction result is presented along with the path profile using a two-dimensional graph. The X-axis represents the distance from transmitter to receiver. Two Y-axises, with one representing elevation height and the other the transmission loss value are drawn. This presentation illustrates the relationship between the path profiles geographical shape and the propagation loss.

The point to area prediction can be presented in terms of coverage pattern plot. It indicates two states of the received signal strength for every point in the area on each radial, starting at the receiver. The two states correspond to whether the received signal strength exceeds a given desired signal level or not.

3.3 OTHER MODELS

It is impossible to list all the path-loss prediction models suitable for 900 MHz over irregular terrain. The three empirical and analytical models described are the most widely used. Other models are similar in their principles, and some cover the same research work as Longley-Rice model and TIREM models, or have very similar theoretical foundations.

The Carey Curve, developed in 1964 [Carey], is another model derived from the CCIR method and has been used for cellular radio licensing applications.

The NBS Tech. Note 101 [Rice, Longley, Norton & Barsis] model consists of curves, theoretical equations and empirical formulas for predicting cumulative distributions of sector transmission loss for a wide range of frequencies over almost any type of terrain and several climatic regions. Many specific ideas presented in this model are utilized in others, such as the Longley-Rice and TIREM models.

The Federal Communications Commission (FCC) developed the FCC R-6602 model [Damelin, Daniel, Fine & Waldo]. It calculates the field strength as a function of distance and base station antenna heights. Mobile antenna height is 1.8 m, but an equation is given for adjusting heights within the range of 1.8 and 9 m.

The Lee transmission prediction model has two components [Lee]: a point-to-area path-loss prediction, and point-to-point prediction for each distance. The constants provided are a 30-meter base antenna height and 3 meter mobile antenna height. Transmission loss expressions are different for different cities. A typical example is for Philadelphia where median transmission loss is given by

$$\boxed{L(dB) = 142.3 - 20\lg(h) + 36.8(D)} \qquad [3.22]$$

Corrections for sloping terrain and a path obstruction are also given.

Bertoni and Walfisch's theoretical model was developed specifically to predict the effect of buildings on the median transmission loss [Bertoni & Walfisch]. It applies to those urban and suburban environments where the buildings are of fairly uniform height and are built in rows with small separation between neighboring buildings. For level terrain well within the radio horizon, the median transmission loss at 900 MHz between half-wave dipoles is predicted to be

$$\boxed{L = 147.2 + A - 18\lg(h - h_b) + 38\lg(D)} \qquad [3.23]$$

Where

$$\boxed{A = 5\lg[\left(\frac{d}{2}\right)^2 + (h_b - h_m)^2] - 9\lg(d) + 20\lg\{\tan^{-1}[2(h_b - 2h_m)/d]\}} \qquad [3.24]$$

Here h_m is the height of the mobile antenna, h_b is average building height, and d is the center-to-center spacing of the rows of buildings. For example if k = 50 meters, h_b = 12 meters, h_m = 1.5 m, then A = -9 dB.

Alternatively, the model accounts for local terrain slope in the vicinity of the mobile. It does not, however, incorporate terrain roughness, or treat obstructing terrain features, such as hills.

3.4 CONCLUSION

This chapter has briefly reviewed three empirical and three analytical models for path-loss prediction. Other methods with extension to these models were introduced. The models were developed from various perspectives and with different intentions although they all aim to predict the median signal strength either at a specified receiving point, or in a small area. As a result, the models require different environmental and path parameters, account for different propagation factors, and have different complexities in their formulae. Each model will certainly return different levels of prediction accuracy.

The empirical models, generally speaking, rely on fitting curves or analytical expressions to sets of measured data and have the advantage of implicitly taking all factors into account. The disadvantage of a completely empirical model is the lack of generality, as conditions in the area must match those of the original test area. If this condition is not met, carefully selected corrections must be used.

The theoretical model's approach is through the application of theoretical equations to the environment profile in which the radio propagation occurs. Ideally, the theoretical model should provide a more accurate prediction result than empirical ones because environmental features are what cause the propagation loss. However, it is not usually possible to provide highly accurate terrain data over a large area in a form suitable for propagation prediction purposes. To reduce this restriction, combined empirical formulas and theoretical equations applying to the limited environment propagation profile have been developed.

Different analytical models introduced in this chapter usually have similar analysis principles, and improved or modified formulae. Because they are the result of the combination of both theoretical and empirical models, they have advantages over both individual approaches. This approach is the most commonly used for predictive purposes, however, the empirical models are still used for area prediction, because of their simplicity and convenience.

Computerization is another aspect to consider when selecting a model for prediction. As mentioned before, environmental features play an important role in radio propagation path-loss. To increase the accuracy of the prediction result more environmental information needs to be considered. However, it is time-consuming and tedious for manual prediction to include the effects from detailed environment features. Computer programs and environment databases provide the ability to use environmental information in propagation path-loss predictions. Some of the analytical models have been computerized, such as the Longley-Rice, TIREM model and JRC models. By using computerized models, large area prediction and interference calculation becomes feasible.

However, a shortage of information on environmental features and the resolution restriction (most of 500 m) may cause information loss and prediction deviation.

One solution to this problem is through the use of a GIS system, which utilizes spatial and attribute databases. A GIS can analyze Earth surface characteristics, apply an analytical prediction model to quantitative and qualitative analyse, and then compute the mobile telephone path-loss.

The following chapters will introduce the principle of GIS, a spatial and attribute database, and GIS analysis methods. The GIS approach to predicting path-loss values will then be discussed.

CHAPTER 4

SPATIAL DATA REPRESENTATION

AND

GIS APPROACH

The review and analysis of existing land mobile radio signal path-loss prediction models has pointed out that the predictive accuracy can potentially be improved through consideration of Earth's features that influence signal propagation. This would require the description of the Earth surface features and their effects on the signal transmission, which could not be provided by a normal textual database. One solution is to employ a method derived from GIS principles. Using the GIS method, Earth surface feature details are stored and manipulated in a spatial database. Spatial functions are provided to conduct spatial analysis. Other spatial related functionality, such as a path loss prediction model, can be added to customize the analysis facility.

A spatial database, a collection in digital form of the spatial related information, is the fundamental component in the computerized path loss prediction system. Environmental features, such as terrain data, vegetation, man-made buildings, and atmospheric conditions, are stored in a spatial database, then retrieved and queried when needed.

Data representation style, known as the data format, is decided from the nature of the spatial objects, collection methods, data sources, database structure limitations, and the application requirements. Data analysis efficiency and object storage simplicity determines the format of the data representation. The application methodology is developed according to the data availability and representation.

This chapter will outline some of the most commonly used spatial data representations and their operations. Emphasis will be on the vector and Triangulated Irregular Network (TIN) structure because these are the data formats to be used in the propagation prediction model. A comparison of different data representations and useful techniques for mobile signal propagation prediction system will be discussed.

4.1 SPATIAL DATA REPRESENTATION

4.1.1 Overview

Spatial data is the generalized and simplified representation of an environmental aspect of the real world. Storage of environmental data is unique in that every feature will have location relationships [Martin] (eg. bearing, distance, connectivity), in addition to the logical and functional relationships which may be expected to exist in non-geographic databases. The idea of the world in terms of features and their linked attributes is essentially a vector-oriented view. It has a specially structured spatial database in which the location characteristics of features are stored, along with as a separate attribute database for non-location characteristics.

The raster approach to data representation and storage imposes rather a different view of the world, as it is basically coverage and not feature orientated. The coverage consists of many cells. Every cell in a coverage has some attribute values, and individual features are not separately recorded. Consequently, raster storage is a database merely consisting of a group of geo-referenced coverages, each of which represents the values of a different attribute at every cell location.

TIN is a special approach for storing models of surface-type phenomena, such as surface height information. The Earth's surface is represented by a series of triangles with properties of area, slope and aspect.

Other spatial data representation, such as object-oriented data structures, can be applied and implemented through vectors, raster or TIN. These models are not relevant to the radio propagation project, so they are not discussed in this thesis.

4.1.2 Vector Format

The vector data format, as mentioned in 4.1.1, is a feature-oriented data structure. The vector representation of an object is an attempt to represent the object as closely as possible [Burrough]. The coordinate is an assured analog system, allowing all positions, lengths and dimensions to be defined precisely, in practice this may not be feasible, because of limitations in the length of a computer storage unit (single precision, or double precision) when representing coordinates.

4.1.2.1 Vector Concepts

Spatial features are represented as point, line or polygon shapes which are stored in vector format as structured points, lines, and areas, or in other words as points, arcs and polygons. Any spatial features can be represented as either a single entity or a combination of any three basic entities.

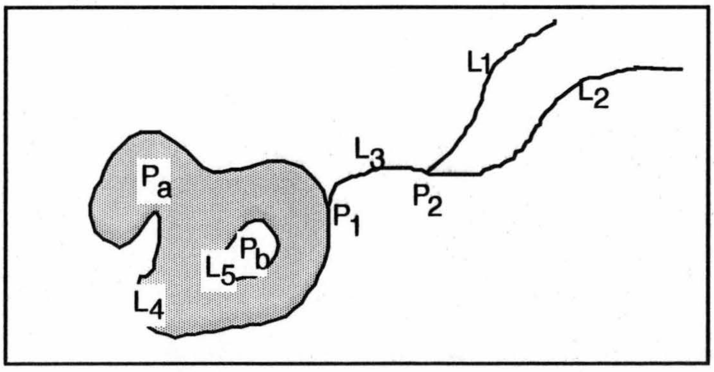


Figure 4. 1 Spatial Feature Represented in Vector Format

Example 4.1 is an example of how spatial features can be subdivided into points, arcs and polygons. It is a diagram of a lake, an island in the lake, and streams running down to the lake. The objects and their relationships can be represented in vector style as:

Polygons:

P_a — the lake

P_b — the island

Arcs:

L_1, L_2, L_3, L_4, L_5— different sections of the stream

Points:

P_1, P_2 — the junction between the lake and the rivers

Each category of objects has at least one associated attribute table, representing the geographical location, the characteristics and descriptions of the object. Point objects, for example, have items of location which are positioned by a single pair of X, Y coordinates, the ID number to identify every point, and items that describe the type, the symbols used when showing on a map, the name of the object, etc. Table 4. 1 lists some of the items in the point attribute table.

point-id	x-coordinate	y-coordinate	type	symbol	scale	orientation
1	526000	5260000	node	3	1:25000	....
2	....	....	....	....	....	....

Table 4. 1 A Point Attribute Table

An arc is used for representation of spatial features with linear characteristics. The shape, location and length of an arc are embraced in a set of points with X, Y coordinates in pairs. One arc has at least two pairs of X, Y, a start point and an end point. The arc, as a spatial object, has one or more attribute tables (Table 4. 2).

line-id	points-id	length	type	symbol	scale
1	1,2,3,...	734.56	line	2	1:25000
2	....		....	....	....

Table 4. 2 Arc Attribute Table

A polygon, in vector format, is used to represent the spatial object with the topological property of area. Its geometrical properties require the boundary to consist of arcs joined at their ends. The result in the polygon attribute table is the polygon identifier with the line IDs which form the boundary (Table 4. 3).

polygon-id	Lines-id	length	type	symbol	scale
1	1,2,3,...	10456.56	lake	2	1:25000
2	....		....	....	....

Table 4. 3 Polygon Attribute Table

The list of line IDs in the polygon attribute table references the respective line tables in which point IDs can be referred to the corresponding point attribute tables. The stream of geographical coordinate pairs indicate the location and the shape of the objects.

Text and related graphical items are stored in the object attribute tables as well as the position information. They contain the description of the spatial object with which the table is linked. The definitions of the items are determined according to the requirements of the application.

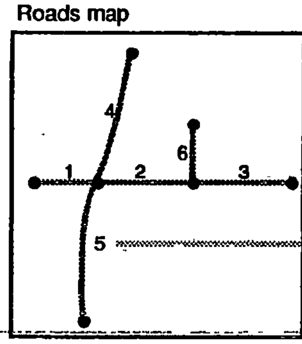
Spatial objects on the Earth's surface, such as rivers, lakes, coastlines and roads, are often stored in vector line and polygon format. Some phenomena with the property of area distribution can be represented as polygon data with the attributes of the polygon describing the phenomena. For example, air pressure can be represented as polygons with each polygon containing a region with a similar range in the air pressure. The temperature can be represented as contour lines of arc type.

The vector data with spatial and non-graphical attributes is physically stored in corresponding spatial and text databases. The method for storage, retrieval, and querying is determined by the specific GIS system that manages the data and provides the tools for operation.

4.1.2.2 Vector Data and ARC/INFO

The vector data and its attributes can be stored either in one table or in two separate tables: one keeps the spatial items, the other stores non-spatial attributes. The ID item is the link between the two tables. ARC/INFO, a GIS system developed by Environmental Systems Research Institute Inc. (ESRI), consisting of ARC, a spatial database and manipulation package, and INFO, a commercial relational database management system (DBMS) [Morehouse], applies this principle by storing a vectors spatial and attribute data separately. Figure 4. 2 and Figure 4. 3 represent the vector line and polygon, as well as the tables [ESRI]. Figure 4. 2 illustrates the relationship and the link between a spatial object and its attribute tables, and Figure 4. 3 demonstrates the principle of storing polygon objects in terms of line IDs.

Roads map



Feature coordinates

FEATURE-NO	X,Y pairs
1	3,5 5,5
2	5,5 8,5
3	8,5 11,5
4	6,9 5,8 5,7 5,6 5,5
5	5,5 4,4 4,1
6	8,5 8,7

Feature attributes

FEATURE-NO	ROAD-TYPE	SURFACE	WIDTH	LANES	NAME
1	2	Asphalt	48	4	N Main ST
2	2	Asphalt	48	4	N Main ST
3	2	Asphalt	48	4	N Main ST
4	1	Concrete	60	4	Highway 42
5	1	Concrete	60	4	Highway 42
6	4	Asphalt	32	2	Elm ST

Figure 4. 2 Representation of Line in ARC/INFO [ESRI]

Vector data in ARC/INFO format is employed by the propagation prediction project for representing many environmental features.

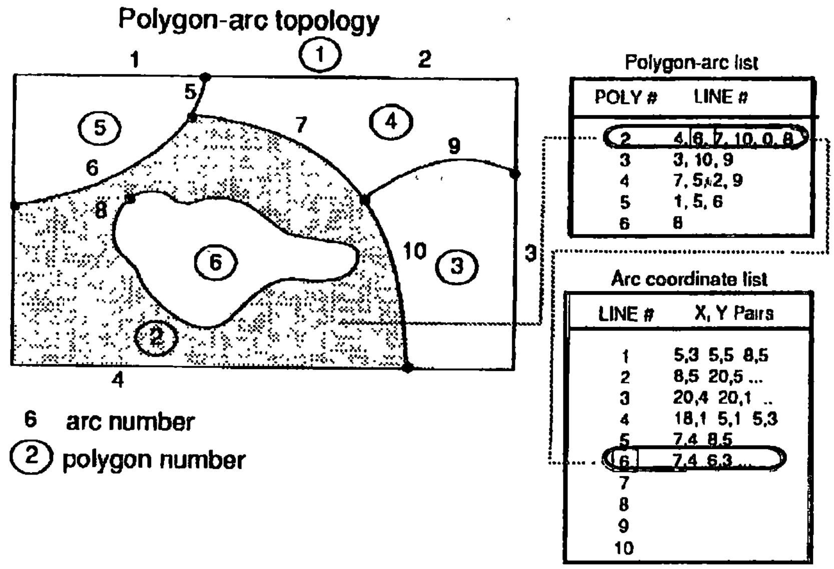


Figure 4. 3 Representation of Polygon in ARC/INFO [ESRI]

4.1.3 Raster Format

Unlike vector representation, raster representation does not encode the world through identification of separate spatial entities, but use thematic coverages [Martin]. The grid coverage is divided into a matrix of cells. A data value is assigned to every cell of a geo-referenced matrix, covering the entire data plane. Point and linear entities may be encoded in such a data structure, but the result is a whole entity. For example, in a raster structure, a grid cell represents a single point, a line by a number of neighboring cells strung out in a given direction, and an area by an agglomeration of neighboring cells.

The use of cells to represent the Earth's surface means that each cell is by implication associated with a portion of land. Because the attribute value within each cell is assigned uniformly, the cell structure simulates the analog world through a digital representation. The resolution, or scale, of the raster data, is the relation between the cell size in the database and the size of the cell on the ground.

The choice of resolution is dependent on the purpose of the study and the study area. The resolution should be set so that each cell is small enough to capture the required detail, but large enough to allow computer storage and analysis to be performed efficiently. The more homogeneous an area, the larger the cell size that can be used with accuracy.

The value in each cell is a number representing the type or value of the attribute being mapped. Cells with the same attribute value belong to the same zone. Each zone, in turn, represents the same or similar characteristics.

To represent different features in the same study area, layers are used. One layer corresponds to one feature. Figure 4. 4 illustrates the idea of using layers to represent different items, vegetation distribution, road expansion, building location, and Earth surface elevation.

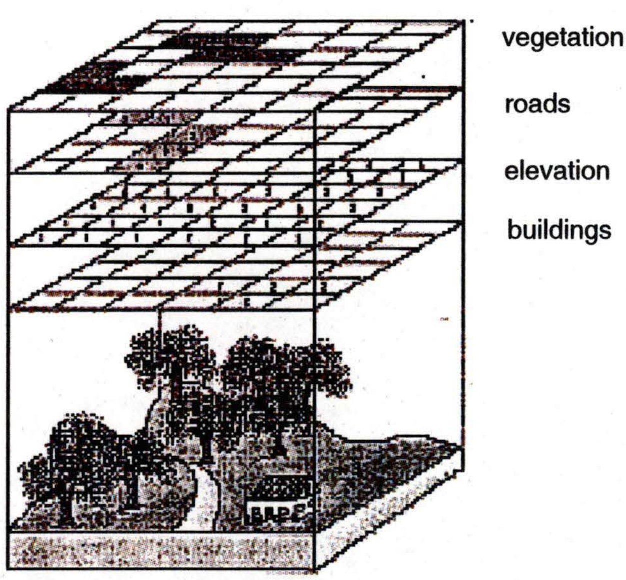


Figure 4. 4 Raster Layer Representation [ESRI_GRID]

The raster format can be used for many data representation purposes, from administrative data such as census tracts or political subdivisions to terrain information, land use, soil, and other natural resource data. Among the uses, is elevation data. It provides methods for visualization, surface shading, Digital Elevation Model (DEM) and grid analysis.

The utilization of the Earth surface data through a matrix elevation database, in existing models to calculate radio signal path loss, is comparable to raster data representation. In a matrix database, a point is used to represent a portion of the Earth's surface, while the raster uses a cell. They are considered similar because the value at each cell is exactly the same at each matrix point, if the same classification values apply and the same resolution is chosen. Furthermore, the matrix of points can be recognized as the center points of the raster cells. The similarity between matrix elevation database and a raster data representation, would indicate that raster ordered data could be used in propagation prediction. However, any limitations and restrictions of the matrix database application are likely to exist in raster analysis. For example, sudden changes in elevation which are not reflected in a given size grid.

Advantages of using raster data representation are very obvious. The raster is easy to implement. No special data structure is required to store raster data. However, it requires a large capacity storage device, and can lead to data redundancy.

4.1.4 Triangulated Irregular Networks (TIN)

Although the raster data format can represent elevation information on the Earth surface, it has limitations, as mentioned in 4.1.3, of not representing sudden changes that occur in a small area, eg. within one cell. Raster data cannot express sudden changes until the cell size is reduced. This will require additional information due to the increased resolution of a given raster map. This information is often not available over the entire area. An alternative method of altitude data representation, specifically developed for the storing the Earth surface elevation, is Triangulated Irregular Networks (TIN).

TIN is one implementation of a Digital Terrain Model (DTM). DTM was developed for the purpose of storing elevation data, displaying three-dimensional surface views, analyzing visibility from given points, planning roads, dams, and the other objects by quantitative and qualitative analysis of the terrain situation and specifications. It also provides functions for other surface features, such as shading, changing the orientation of surface features, and producing contour lines. These functions and operations be extended to other objectives. For example, visibility analysis can be adapted to radio propagation line of sight determination. This will be discussed in later chapters.

4.1.4.1 Concept

TIN was developed by Peuker and his team [Peuker, Fowler, Little & Mark]. It is a system for digitally modeling the elevation distribution of the Earth surface. By using a sheet of continuous and connected angular facets based on Delaunary triangulation of irregularly spaced nodes or observation points, a TIN terrain model avoids the data redundancies of the altitude matrix. Delaunary triangulation is a proximal method that requires a circle drawn through the three nodes of a triangle to contain no other point. This means that all sample points are selected with their two nearest neighbors to form triangles.

The TIN model overcomes the resolution restriction of the raster matrix by allowing extra information to be gathered in areas of complex relief without the need for large amounts of redundant data to be gathered from areas of simple relief. Specifically, a TIN can represent the extreme features of the Earth surface, such as, ridges, stream lines, shorelines and other important topological features because forced sampling areas, lines or points with accurate coordinates can be used to build the TIN model. The important features, or "high information" [ESRI_TIN] ground objects, additional to the original optimum sample locations, no matter whether lines or polygons, can be converted to points with X, Y, Z coordinates. TIN is constructed from those points (nodes), with the triangle edges maintaining the positions of the "high information" feature boundaries.

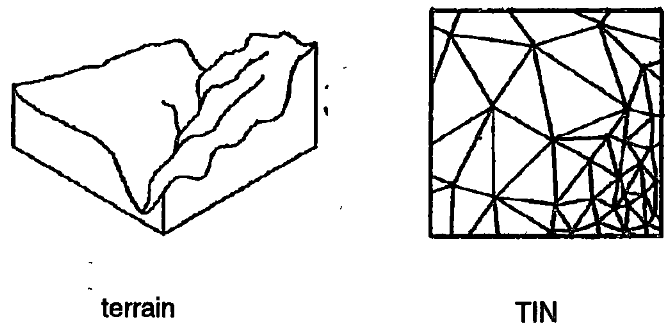


Figure 4. 5 Earth Surface and Its TIN Representation [Martin]

Figure 4. 5 demonstrates a TIN model with the corresponding terrain model. The resolution of the TIN adjusts to the amount of irregularity in the ground surface.

4.1.4.2 TIN's Structure

TIN is a model that keeps the coordinates of sampled ground points and constructs triangular facets from these points. A TIN model is composed of nodes, edges, triangles, hull polygons and topology. Nodes, edges, triangles and hull polygons are contained in triangle structure and topological relations are built into the database by constructing pointers from each node to each of its neighboring nodes.

Nodes are the fundamental building blocks of a TIN model. The nodes originate from the points and arc vertices contained within input data sources, such as point coverage and contour line coverage. Every node is incorporated into TIN triangulation. Every node in the TIN surface model must have a Z value and not be coincident with any other node.

Edges are formed, according to the Delaunary criterion, by joining nearest neighbor nodes. Each edge must have two nodes and a node must have two or more edges attached to it. The edge, in most situations, is constructed by linking nodes that are closest together. They also can be created from other data sources if there is sudden change that is not reflected in existing nodes.

Triangles consist of the edges joining the closest nodes. A triangle facet represents corresponding portions of the Earth's surface. Entire sets of triangles represent any desired region of the Earth's surface. Analysis of the triangles can be regarded as analysis of that portion of the Earth surface, assuming all sample points and edges are selected adaptively to give the best possible simulation of the surface.

Hull polygons define the study zones of the TIN, specifically interpolation zones. They include the set of data points used to construct the TIN. All operations, interpolation and analysis take place within the hull polygons. The hull polygon defines the boundary of the TIN model.

The vector characteristics and topological structure of a TIN determines that the TIN's storage "is defined by combining information defining each triangle's nodes, edge numbers and type, and adjacency to other triangles. For each triangle, TIN records:

- the triangle number
- the numbers of each adjacent triangle
- the three nodes defining the triangle
- the X, Y coordinates of each node
- the surface Z value of each node
- the edge type of each triangle edge..." [ESRI_TIN]

A triangle's edge type refers to the importance and the functionality of the specific lines. Two types are used in building a TIN model, soft and hard. The use of soft and hard edges maintain smoothness and continuity of the surface model. A hard type edge, eg hard break line, interrupts the surface smoothness. The elevation value is forced to follow the values of the hard break line, regardless of the adjacent surface values. Hard break lines are typically used to define streams, ridges, shorelines and building footprints, etc. The soft edge provides reference data during TIN's construction and operations. It does not influence smoothness and continuity. For example, soft break lines are used to ensure that known Z values, along linear features, are maintained in the TIN, or that polygon edges are maintained in the TIN surface model by enforcing the break line as TIN edges.

Surface feature types other than hard and soft break line include soft replace, hard replace, soft clip, hard clip and soft erase, hard erase. Hard and soft break lines, as mentioned, are used to force the triangle edges to follow the break line arcs. Soft and hard replace are defined such that, if triangle nodes and edges fall within REPLACE polygons, their altitude value or Z value will be affected by the value of REPLACE polygon. In contrast, soft and hard erase types remove all the Z values and create holes in the TIN at the points and edges which fall with in the ERASE polygon. Soft clip and hard clip extract that part of the TIN that lies inside the clipping polygon.

In summary, TIN is a surface terrain model constructed using important surface features and a distribution of sample points according to the Delaunary triangulation criteria. Most important features on the Earth surface can be reflected in the TIN model. The topological relationship is obtained and represented during TIN construction. We can treat a TIN model as a representation of a part of the Earth's surface.

The characteristics of a TIN model and its approximation of the Earth's surface will be useful in the radio propagation path-loss prediction since the terrain feature's effect on the radio signal transmission can be simulated and analyzed, taking into account the effects of important surface features.

4.2 SPATIAL INFORMATION SYSTEMS AND SPATIAL DATA OPERATIONS

Spatial data and its attributes form the data model in the database. Operations used by applications to access the database include data retrieval, coordinate system transformation, display map format conversion, and manipulation and analysis of spatial and non-spatial attributes. A spatial information system manages spatial databases with many possible formats, provides tools for operations on the database and helps in development.

4.2.1 GIS and ARC/INFO

A GIS is a spatial information system that deals with geographical information. It is defined as organized collection of computer hardware, software, geographic data, and personal designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information [ESRI]. The definition considers GIS from two perspectives. The first consists of the existing components, including hardware, software and geographical data which lay the foundation and provide the tools for application development. The second deals with the specific programs that compile analyzing techniques to meet application requirements.

ARC/INFO is a GIS software package developed by Environmental System Research Institute, Inc. It provides the spatial and conventional databases management system (DBMS). Spatial data can be stored in vector, raster, grid or TIN format. A conventional DBMS is used to store attribute data. Applications, such as ARC, ARCPLOT, ARCEDIT, TIN and GRID, and other specialized software, are provided to perform various operations. This software provides functions and facilities to model terrain data in TIN or GRID format, store and modify two dimensional geographic data, provide answers for geographic analysis (including surface analysis) and spatial queries, and present spatial data and analysis results. In addition, it supplies facilities for developing customized functions to be used with existing analysis tools.

The following sections will introduce some commonly applied operations on vector and TIN structures. The operations for grid and raster data are not detailed since the implementation of the radio propagation path loss prediction model is only concerned with vector and TIN data.

4.2.2 Operations on TIN

Because TIN is a special data format used to represent elevation information, operations include building the TIN, surface analysis using TIN, surface viewing processes and surface display.

4.2.2.1 Building a TIN Model

A TIN is built by constructing triangles from sample points with X, Y, Z coordinates, in which Z is the elevation above sea level. A variety of three-dimensional data sources can be used to build TIN surface models. These include point and line coverages, ASCII files, such as X, Y, Z photogrammetric data, pre-existing TINs, and sample points extracted from other data sources, such as digital elevation models and images. Figure 4. 6 lists some data sources used to build TIN models.

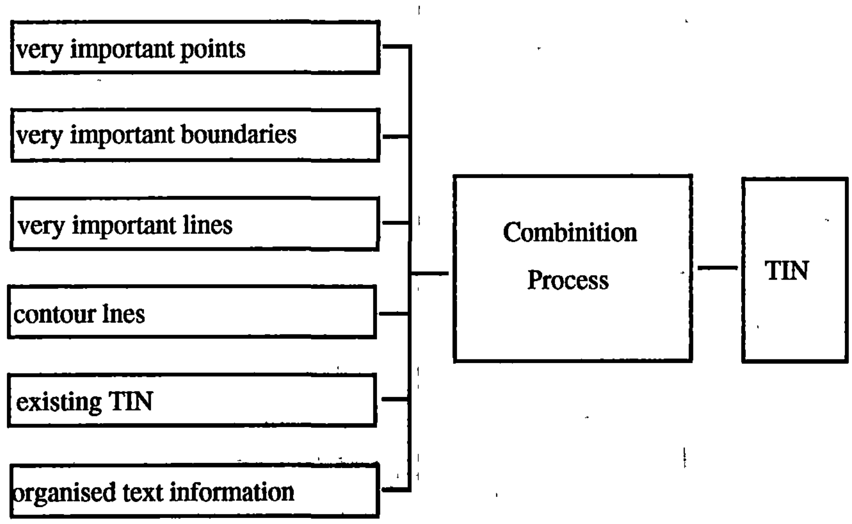
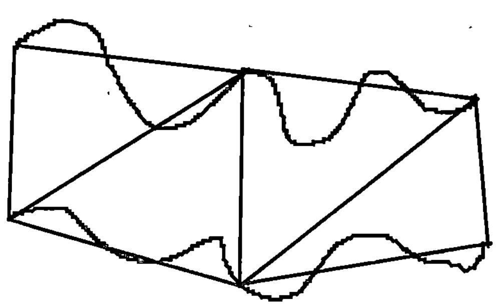


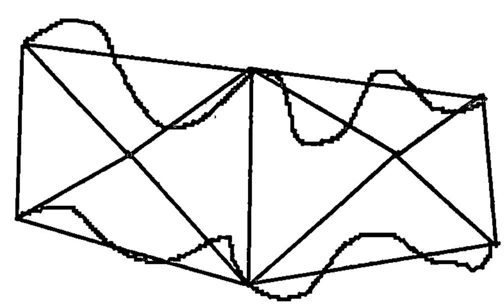
Figure 4. 6 Data Resources For TIN

Data sources can be used independently or combined with others. 'Very important objects' refer to mountain ridges, peaks, rivers, creeks and other surface features. These combined with contour line or sampling points, result in a TIN model that approximates a region of the Earth surface.

Figure 4. 7 demonstrates how triangles in a model can be constructed by contour line (a) and by sample points with contour lines (b). In diagram (a), elevations between contour lines are derived from the contour heights. Depending upon the algorithm used, it may or may not be correctly model the terrain. In diagram (b) when two more sample points are added, the heights between contour lines do not strictly follow the derivation algorithm. Eight triangle facets, instead of four, will be a more accurate approximation of the terrain in that area. For similar reasons, the more sample point data used, the closer the model will approximate the terrain, provided that the sample data is correct and terrain is irregular.



(a) contour only



(b) contour + sample points

Figure 4. 7 TINs Created From Contour Data and Sample Points

Access times, however, will be increased for a larger or denser TIN model because retrieval, saving, and in particular, manipulating TIN data will reference an increased amount of data.

4.2.2.2 Interpolation and Generalization in TIN Models

Since the data source of TIN models is usually irregularly spaced sample points and lines, the density of points depends on changes in the surface height and sample point numbers. As discussed in the previous section, theoretically, more sample points are required where there is an undulating Earth surface. It is impossible to store a Z value for every required location on the surface, with interpolation of Z values at surface locations where no samples have been taken. The result will however be a TIN model which contains much more data than is actually required to accurately represent the features. Generalization is needed to limit the amount of high-density data to improve application performance.

4.2.2.2.1 Methods of Interpolation

Interpolation is a process whereby an estimate of a Z value is derived for a non-sampled point based on the known Z values of points surrounding it. Linear and quintal are the commonly used interpolation methods. They are both implemented by programmed mathematical formulae.

Linear interpolation assumes the surface to be continuously faceted, with a slope throughout the extent of each triangle facet. It assumes that Z values vary linearly between the known sample points — nodes of each triangle facet. The three nodes define a plane containing the triangle facet. The surface Z value at a point is obtained by intersecting a vertical line through the point on the triangle facet [ESRI_TIN]. All interpolated Z values within one triangle facet are calculated based solely on the Z values of the nodes of the triangle.

$$Ax + By + Cz + D = 0 \qquad [4.\ 1]$$

Equation 4.1 representing the plain of triangle facets, is used to calculate the Z value by given x and y values. The coordinates of the three triangle nodes determine the constants A, B, C and D.

Quintic interpolation assumes that the surface model continues with smoothness, ie. the normal of triangle facet has continuous changes with adjacent triangles.

It uses a bi-variate fifth-degree polynomial in X & Y to produce smooth surface behavior. The smoothing effect is created by considering the characteristics of the neighboring triangles. Hard break lines act as a barrier to the interpolator, interrupting the smoothing function at the point where the surface meets a hard break line. The surface exhibits linear behavior where it crosses a hard break line. Surface smoothing continues on the other sides of the hard break line, considering only the triangles on that side [ESRI_TIN].

The smoothing effect is maintained by calculating contributions from the neighboring triangles to the prediction point. Equation [4.2] [Akima] is the formula used by ARC/INFO's TIN package, in which six triangle nodes from the center and adjacent triangles are counted.

$$Z(x,y) = \sum_{j=0}^{5} \sum_{k=0}^{5} q_{jk} x^j y^k \qquad [4.2]$$

4.2.2.2.2 Methods of Generalization

Generalization is used to remove sample points that make no or very little contribution towards the TIN's representation of the terrain.

Proximal tolerance is defined as the "minimum distance in ground units separating all point locations on the horizontal plane. If two or more points are found within proximal tolerance distance of each other, only the first point read is passed for further processing" [ESRI_TIN]. Proximal tolerance controls the shortest distance between sample points.

Weed tolerance is defined as the distance in ground units to reduce the number of points along the individual line features — arcs.

The weed tolerance distance is compared to the trend line along each arc. Those vertices within the specified distance of the trend line are dropped from further processing. Nodes are always retained [ESRI_TIN].

Weed tolerance is specifically useful when converting contour lines to a TIN model.

4.2.2.3 Surface Analysis on TIN

The purpose of surface analysis based on the TIN model is to obtain information around a region of the Earth surface that cannot be determined with two-dimensional analysis. Surface analysis includes the following functions:

- interpolation of Z values;
- calculation of slope and aspect;
- calculation of surface area and surface length;
- determination of the inter-visibility between two points;
- analysis of what is visible from one or more observation points;
- generation of profiles across single or multiple surfaces; and
- generation of contour lines and contour bands.

Other surface analysis functions exist which are not of concern here and have been omitted.

4.2.2.3.1 Interpolation of Z Values

The purpose of Z interpolation is to return Z values at each given X, Y coordinates. The interpolation is based on the principles described in 4.2.2.2.

The Interpolation operation is executed when a user supplies a position from any input equipment, such as mouse, cursor, or digitizer. The result is the elevation in the map units where the TIN is used.

The interpolation operation operates in the TIN model only. No Z value would return if the user-given points were outside of the surface area.

4.2.2.3.2 Calculation of Slope and Aspect

Slope refers to the maximum rate of change in Z values across a region of the surface that can be expressed in degrees or as a percentage. The aspect of a surface is the compass direction facing the direction of the maximum rate of decent of Z values. Like slope, aspect is associated with and stored in each triangle. The aspect unit is measured clockwise in degrees, with 0 degrees at north.

Slope and aspect are two important surface characteristics, which reveal the degree of uniformity in the region of the Earth surface.

4.2.2.3.3 Calculation of surface Area and Surface Length

The surface area and the surface length are the area of a region and the length of linear features over an Earth surface. These values take into account the variation in Z values, and they are greater than their corresponding plain values because variations increase the measured values.

The calculation of surface area is determined from a summary of triangle facet areas in the required region, and the calculation of surface length is produced by summing the length of the triangle facets that are intersected by the required linear features.

4.2.2.3.4 Determination of the Inter-Visibility of Two Points

The inter-visibility of two points, gained simply by checking whether two points can see each other, is a very useful analysis tool. ARC/INFO provides commands to decide whether two points will meet the line-of-sight condition.

4.2.2.3.5 Analysis of What is Visible From One or More Observation Points

Visibility analysis over a region of the Earth surface classifies the surface region into small areas such that each area has a unique combination of visibility from one or more observation points. One observation point is the simplest case in visibility analysis, which will result in the visible and non-visible area.

Parameters that control the analysis details can be specified for each particular application.

4.2.2.3.6 Profile Production

Profile is a vertical sectional view of a surface derived by sampling the surface value along a section line. It demonstrates the shape of the Earth surface along the path between two points. The path is either a straight line or a given line feature, such as a profile which can produce output along a specified road section in order to analyze the incline of the road.

4.2.2.3.7 Contour Line and Contour Band Generation

A contour is vectored data used to represent terrain topography. Once a surface has been generated, a series of lines can be created by connecting points of equal elevation. These contour lines are generated at a specified interval of Z.

Polygons representing zones of similar elevation, called contour bands, provide another way of representing surface terrain. The boundary of each polygon band is defined by two contour lines, and the region it occupies represents a range of elevation values.

Both contour lines and bands reflect surface feature characteristics. The density of contour lines or narrow polygons at contour bands indicates a steep surface.

A contour can not only be used to represent surface elevation information, but its principles can also be adopted to represent other values in applications where the operation of contour line production can be applied.

In summary, ARC/INFO's surface operations on the TIN model provide basic tools for complex analysis, which require the use of a combination of tools, and the derivatives of these tools. The radio propagation path loss prediction model will employ these tools, with analysis to produce propagation models.

4.2.3 Analysis and Manipulation Over Plain Coverages

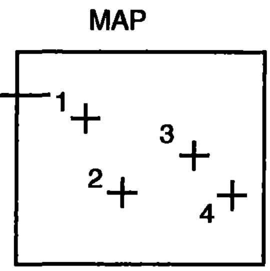
The spatial objects stored in a vector data structure are known as coverages in ARC/INFO. There are point, line and polygon coverages. Two types of table are associated with a coverage, a coordinate table and an attribute table. The coverage, attribute table and coordinate table are linked by a unique ID that identify each object on the map. When one or more spatial objects are selected, their attached attributes are selected using the unique ID. Similarly, when attribute values are selected, the locations of their associated spatial features are highlighted from spatial coverages.

Figure 4. 8 demonstrates a point coverage, with its corresponding coordinate and attribute tables.

Manipulation on a coverage includes techniques that create, modify and update the spatial data and attribute values on the objects in the coverage or between coverages. Analysis uses these techniques, applies application logic, and produces results that satisfy the application requirements. Operations on coverages include data manipulation and analysis, such as data retrieval, buffering, overlay and classification.

4.2.3.1 Data Retrieval

Data retrieval is an operation that examines the existing spatial and attribute data so as to extract data sets that fulfil the user-given conditions. The result of the data retrieval will be a subset of the attribute, and coordinate tables.



SPATIAL DATA

pt-id	x,y
1	2,4
2	3,2
3	5,3
4	6,2

ATTRIBUTE DATA

pt-id	well depth
1	200
2	150
3	230
4	190

Figure 4. 8 Relationship between Map, Its Spatial Data, and Attribute Data

Data retrieval operates through selection, reselection, and additional selection in the attribute table or the spatial map. Those objects that meet the conditions are highlighted for further operations. Boolean logical operations on spatial and text data sets are applied for data retrieval. Selecting operations corresponding to Boolean AND creates a new table that is the subset of the original table. Additional selection using ASELECT in ARC/INFO, acts as Boolean OR operator, appending the selected records by adding new records that did not match the previous conditions. Not selected, commanded as NSELECT, acts as the Boolean NOT operator and drops all previous selected records and catches those not selected from the database table.

4.2.3.2 Buffer Generation

Buffer generation is a form of proximate analysis where zones of a given distance are generated around coverage features. Both constant-width and variable-width buffers can be generated surrounding the selected features based on their attribute values. The resulting buffer zones create polygons — areas that are inside or outside the specified buffer distance from each feature. The input buffered features can be polygon, line, or point.

4.2.3.3 Topological Overlay

A topological overlay is a spatial operation which overlays one object coverage onto another to create a new coverage. The spatial data and their associated attributes are joined to derive a new topological relationship. An overlay of one or more layers is allowed.

There are three types of overlay depending on the spatial objects involved : point-in-polygon, line-in-polygon and polygon overlay.

A point-in-polygon overlay is an operation in which points of coverage are overlaid on the polygons of another to determine which points fall within the polygons. Attributes of the polygons are associated with those of the points that are in the resulting point coverage.

A line-in-polygon overlay is an operation in which arcs of a coverage are overlaid on the polygons of another to determine which arcs fall wholly or partially within the polygons. Attributes of the polygons are associated with corresponding arcs in the resulting line coverage.

A polygon overlay combines two polygon coverages to produce a new polygon coverage and joins the attribute tables so that the new table corresponds to the new coverage created.

Point-in-polygon overlay and line-in-polygons overlay are useful to answer such questions as what characteristics exist at certain locations or along specified routes, and how many sites or line objects match the join conditions within certain areas?

Polygon overlay is used to analyze spatial relationship between objects in two polygons.

4.2.3.4 Reclassification

Reclassification is an operation that changes the topological relationship of the existing coverage by reorganization the attribute values. The result of a reclassification will be reflected in both the spatial map and the associated attribute tables.

Dissolve and clip techniques are used in reclassification analysis. Dissolve is the process of removing boundaries between adjacent polygons having the same value for a specific attribute. The attribute items can be added after the coverage is created. By assigning the appropriate values to each record in the attribute table, ie. assigning codes for each spatial object, the coverage topology can be changed accordingly.

A clip extracts data from a coverage that resides entirely within the boundary of features in another coverage, the clip coverage, which has to be polygon coverage. The clip operation is often used for extracting some interesting area so those more centralized regions can be used for further processing. Operations performed over a clipped coverage will be more efficient because of the smaller data set involved.

4.3 CONCLUSION

This chapter introduced the spatial database structure, data format, their use in GIS, and the principles of GIS analysis of spatial and associated attribute data.

Using a spatial database, features can be stored in either two-dimensional coverages or three-dimensional TIN models. Analysis and manipulation are applied according to the requirements of application. The functionality is organized into a spatial model in which real world activities related to the Earth features are simulated and monitored. The simulation is conducted based on spatial and non-spatial data stored in the database, to generates results, such as maps, tables and reports.

The problem of mobile telephone radio signal propagation path loss prediction is considered just such a project. The model simulates the radio propagation over a specified study area from the nominated transmitter. The propagation characteristics are summarized through analysis of the terrain effects and possible propagation mechanisms involved, and these in turn, determine path loss prediction values.

The next chapter will introduce the theory and the consistency of the mobile telephone signal propagation path-loss model that has been implemented using ARC/INFO GIS software.

CHAPTER 5

THE METHOD FOR MOBILE TELEPHONE PROPAGATION ANALYSIS

USING GIS APPROACH

5.1 INTRODUCTION

Examination of existing radio propagation path loss models has revealed that the Earth elevation matrixes, often with 500-meter resolution, have been used to analyze terrain influences on radio signal propagation. Path profiles have been derived from the elevation matrixes, their geometrical characteristics have been analyzed, and conditional formulae are the applied to calculate path loss values. However, some problems with use of the elevation matrix have been found [Kinch-James] & [Committee]. This has included prediction deviation caused by 500-meter resolution matrix which, as analysis has shown, is too large to contain detailed terrain information to meet the prediction accuracy requirements of 800–900 MHz signals. The raster terrain matrix may not contain features on the Earth surface where sudden changes in elevation take place within one grid, as discussed in the previous chapter. In addition, existing models have not adequately examined reflections from the terrain surface. One way to improve the prediction accuracy is to reduce the matrix resolution so more surface feature details are included. This method may cause data redundancy and decrease performance, as described in the previous chapter.

Through the use of an alternative terrain elevation model, such as TIN, a new path loss prediction method may improve prediction accuracy. This method will employ the principles of an analytical method, apply the prediction model to the chosen terrain representation, and calculate the path loss prediction. It aims at using a terrain model that contains the necessary surface detail, while not increasing analysis and calculation complexity. A GIS approach is selected which is used in the method design and implementation because of its unique emphasis on spatial data representation and spatial analysis. In addition, qualitative analysis of signal propagation mechanisms over a terrain model are discussed and prototyped. With functions supplied with the GIS application, some analysis tasks that are time consuming and tedious using existing models can be carried out quickly and easily. Line of sight determination from many transmitters to a specified service area is an example.

This chapter discusses the feasibility of a GIS approach, selects an analytical path loss prediction and terrain model, and describes a prototyping experiment in which the analytical model is applied to the selected terrain using a GIS approach to achieve quantitative and qualitative analysis path loss prediction.

The method is only concerned with path loss prediction for digital cellular mobile telephone signal. All assumptions are made based on the 800 to 900 MHz frequency range.

5.2 SELECTION OF TIN AS THE TERRAIN MODEL

As discussed in the last chapter, a terrain elevation can be modeled in either a regular grid format, or a TIN structure. The grid model has the advantage of simplicity in data retrieval and storage, but may lose details of elevation changes when large grid resolutions are used. The TIN model, on the other hand, is designed to reflect the irregular nature of terrain. It can overcome the grid model's disadvantages if detailed elevation variations are included in the creation process. Although the TIN structure increases the storage complexity, an interface has been provided in ARC/INFO to hide the difficulties of retrieval and storage from the user. In addition, using ARC/INFO's TIN application, multiple data sources can be used as input to form a TIN. The analysis and manipulation tools simplify the elevation data retrieval and presentation. As a result, a TIN model provides a flexible choice for representation of terrain and Earth surface features.

For example, to build a terrain model using TIN structure, contour data derived from a topographic map forms the fundamental structure. Tree heights, building locations and heights, cliffs, holes and peaks from various sources can all be used as input for the TIN creation procedure to enhance the model's accuracy. For mobile signal path loss prediction, peaks, tall buildings, and cliffs play a significant role in signal refraction and diffraction. Their presence in the TIN model will therefore increase path loss prediction accuracy.

In addition, it has been found [Kidner, Jones, Knight & Smith] that a TIN representation requires less storage than other models for equivalent data accuracy. Grid and mathematical representations of terrain retrieve path profiles faster, but a TIN representation maintains a lower error rate during interpolation for profile retrieval. This will provide a smaller error in path-loss prediction for a 900 MHz frequency signal.

TIN's complexity can be reduced after rationalization of the requirements of the model. For mobile radio signal propagation prediction, an experienced user can determine what kind of data will be used. This data will be included in the model; other irrelevant data can be discarded. In a flat area, less of data is required. As terrain becomes irregular data complexity and volume will be increased. Areas that are close to the transmitter and receivers contribute more to path loss prediction than those that are further away. Cliffs and peaks that may block the line of sight transmission generate diffraction loss, and should be retained in the model. High rise buildings will block or reflect the signal along the path, they should be included in the model, and so on. Other factors are also involved in TIN creation. Exploration and experiments are required to balance data requirements, data availability and performance.

In general, terrain data requirements for the radio path loss prediction varies according to the frequency range of the signal. To get a reasonable degree of path-loss prediction accuracy, the sample point resolution and elevation data accuracy should not exceed certain values for the upper frequency limits of the spectrum range. Usually, a sample data resolution of 250 times the signal wavelength, and elevation accuracy of 25 times the wavelength, gives optimum accuracy for diffraction loss prediction [Kinch-James]. For a signal of 900 MHz this leads to a sample point resolution of less than 85 meters, and height accuracy within 8 meters.

Applying this rule to a terrain model, the largest sampling distance should be such that at least one point exists every 85 meters, in undulation or hilly areas with height accuracy less than 8 meters. However, on an area of plain surface, the sample distance can be greater than 85 meters because interpolation values can replace the actual sample values, as long as the important features (break lines) are maintained.

When data is converted from other data sources, the original resolution or accuracy of the data should be checked to ensure the required level of data accuracy.

Although most existing path loss prediction methods use the regular grid model as the terrain representation, several models perform path loss prediction using a TIN model. As data availability increases, TIN's advantages described above and other experimentation [Kidner, Jones, Knight & Smith] support the idea of using TIN as terrain model in path loss prediction.

5.3 TEST AREA SELECTION AND TERRAIN MODEL CONSTRUCTION

5.3.1 Test Area Selection

A test area covering 5 km by 11 km around the city of Hobart, Tasmania was selected. The area contains hilly terrain with the city center lying on the flat plain. A river flows through the area. These terrain characteristics ensure that multiple propagation mechanisms exist along the propagation path. Line of sight propagation will exist in the plane area when a transmitter is placed on top of the mountain. Signal diffraction will occur in the hilly areas within the shadow of the higher peaks. Figure 5. 1 shows the location of the test area and its surface characteristics.

The test area in Figure 5. 1 is represented in the AMG coordinate system, ranging from (520,000,5,250,000) to (532000,5,257,000) in Zone 56. The 100-meter AMG grid is included in the map to provide distance and location references. Coordinates from the map can be derived from the map grid on the top right.

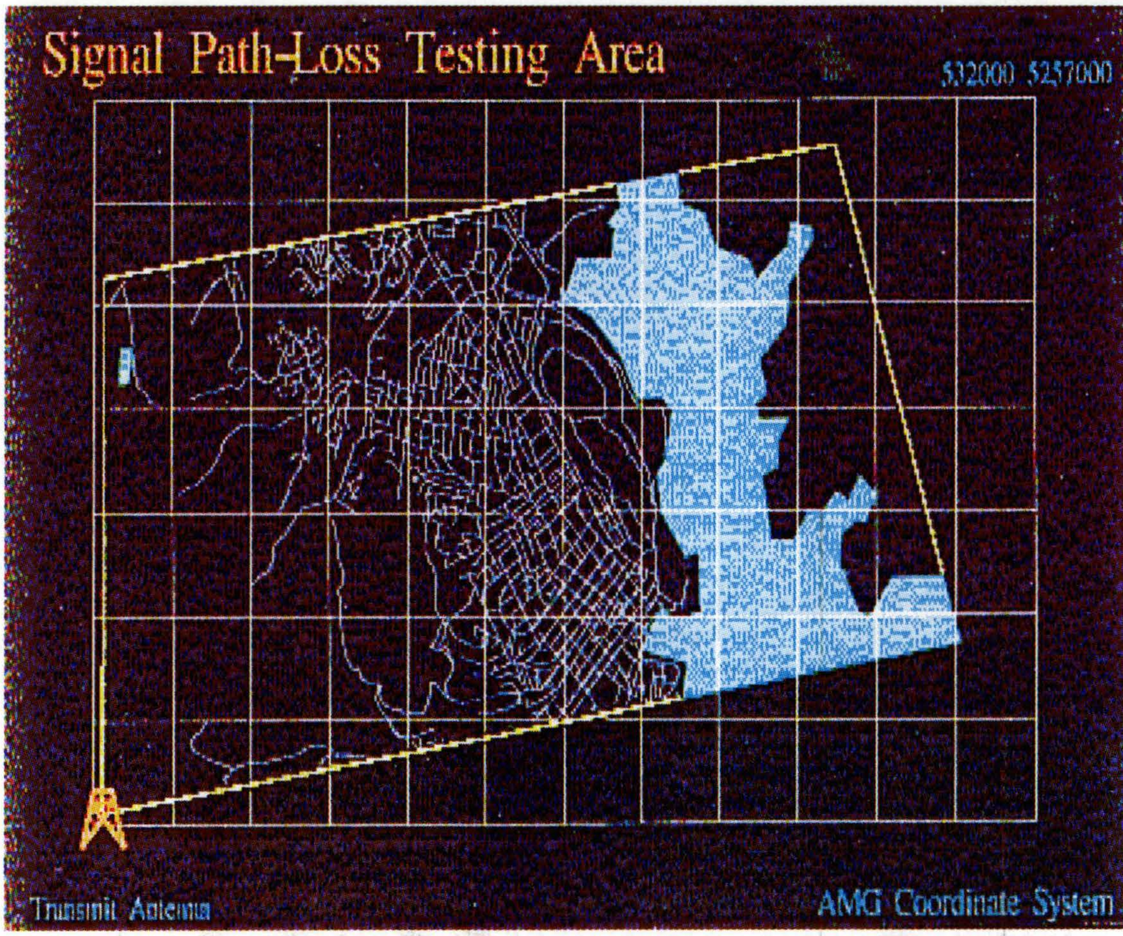


Figure 5. 1 The Signal Path Loss Testing Area

In the map, river and lake areas are shaded. Urban areas can be recognized through an increase in road density, with the remaining areas being suburban and rural. The red symbol at the lower left corner is an arbitrary transmitter antenna location used for area path loss prediction, located on the highest mountain within the test area.

5.3.2 TIN Construction

A TIN model can be constructed from different data sources, as described in the last chapter. The test TIN model was built using on 10-meter contour map using ARC/INFO version 6.1 software. The source data was scanned from 1:25,000 topographic maps, as shown in Figure 5. 2.

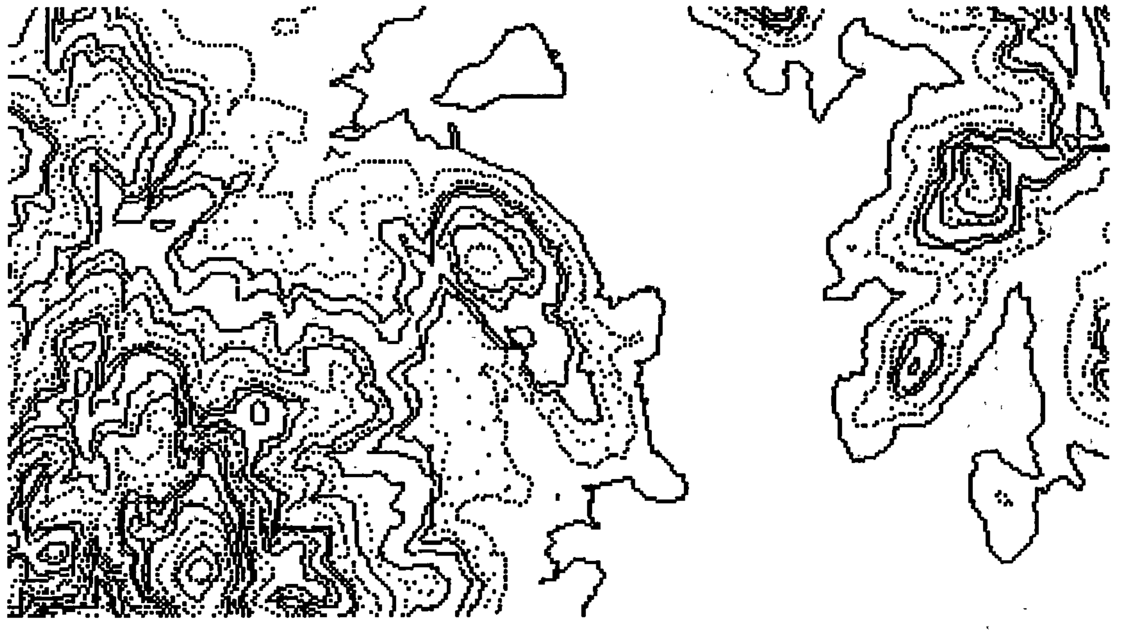


Figure 5. 2 A Part of Hobart Contour Map As TIN's Source Data

Contour maps were edited to eliminate errors, such as dashed lines, and discontinued contours. The output was then modified to account for the river boundary. A unique value of zero was assigned to enforce the correct river elevation. Sixteen separate scanned contour maps were joined into a single oriented contour map, which was then clipped and used to build the TIN model. During the creation of the TIN model, generalization was applied at a distance of 85 meters. This eliminated unnecessary data for 900 MHz radio signals and reduced the size of TIN model. Height was increased three fold to enhance the surface variation and distinguish the effects on propagation from terrain features. The result of the TIN model for test purposes is illustrated in Figure 5. 3.

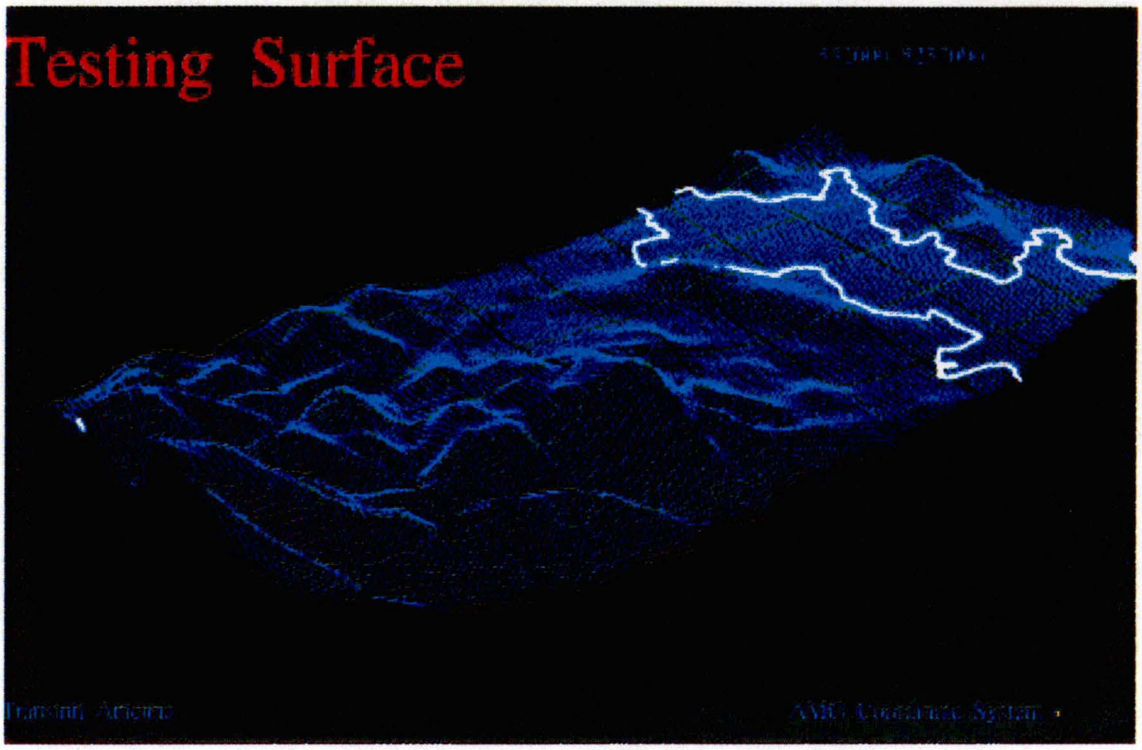


Figure 5. 3 Testing Surface TIN Model

The TIN in Figure 5. 3 is presented in a three-dimensional projection. Water boundaries are included as reference. Because of the exaggeration in height, elevation changes are emphasized.

5.4 SELECTION OF AN EXISTING PATH LOSS PREDICTION

To achieve the goal of predicting path loss using a GIS method, the emphasis will be on the design and development aspects of using existing GIS tools to apply a path loss prediction model to the terrain elevation data stored and managed by the GIS application.

The model prediction accuracy is not the main focus of this thesis. Therefore, an existing path loss prediction model was chosen as a representative of all existing computerizable path loss prediction models. The advantages and disadvantages of using the GIS method to predict path loss on the chosen path loss prediction model can be extended to the other prediction models at the same frequency range.

Chen's model was chosen as the path loss prediction model for this thesis to be implemented for point to point and point to area quantitatively path loss prediction. This model was chosen because it was designed for mobile telephone signal propagation, and the model has been used and tested in the real world. Chen's model has classified transmission loss prediction formula for an undulating environment [Chen], which simplifies the propagation loss prediction method by excluding the loss contribution from the transmitter and receiver antennas. The only contribution to the transmission loss is the terrain features. As a result, the following assumptions can be made.

5.5 ASSUMPTIONS OF THE MODEL

5.5.1 Antenna Assumptions

A radio propagation system consists of a base station antenna which radiates an electromagnetic signal, a medium through which the signal propagates, and at least one receiving antenna which captures the propagated signal. Signal strength differences between the transmitter power and the received power are taken to be the transmission loss caused by the Earth's environment. Effects from antenna type, gain, radiation direction, and height are also included in the transmission loss.

The propagation path loss is defined as the energy difference or power difference between base station antenna and receiving antenna according to equations [5. 1] or [5. 2]. The energy or power radiated at a transmitter depends on the antenna parameters that specify the radiated signal strength, and the radiating direction. The antenna gain and direction are irrelevant to propagation path loss analysis, and should not be included in the path loss value because the purpose of path loss study concentrates on the affects of the Earth's environment. Both base station and receiving antennae are assumed to be of the isotropic type. That is, a transmitting antenna radiates in all horizontal directions (360 degrees) from the antenna position and the antenna gain is 1 (no signal amplification or reduction). A receiving antenna that captures signal from all directions has antenna gain equal to 1. The transmitter antenna height has been assigned to 20 meters, the receiving antenna to 3 meters.

$$path\_loss(dB) = 20\lg \frac{field\_density\_at\_receiver}{field\_density\_at\_transmitter} \quad [5.1]$$

$$path\_loss(dB) = 10\lg \frac{power\_at\_receiver}{power\_at\_transmitter} \quad [5.2]$$

The influence of different antenna types and antenna heights could be included in the model if required.

5.5.2 Refraction from the Atmosphere

Radio signal propagation via the atmosphere does not follow a straight path due to refraction in the air. Air density decreases as height increases and this causes the signal to be bent towards the Earth. The degree of bending is not uniform since climatic conditions, such as temperature, air pressure and humidity, influence air density. This phenomenon, as discussed in previous chapters, is represented by replacing the actual Earth's radius with an effective Earth radius. The effective Earth radius that is determined by the local air refractivity at sea level determines the Earth bulge effect.

In order to simplify the calculation of the Earth's bulge height, the normal Earth bulge factor, ie. the K in formula [3.4] is assigned to 4/3 at all times. The effective Earth radius is then equal to 8493 km given an actual Earth radius of 6370 km. The Earth bulge can be calculated using equation [5.3]

$$\text{bulge} = \frac{d_1 d_2}{12.75 * 1.33} \quad [5.3]$$

where d_1 and d_2 in kilometers, are plane distances to the transmitter and receiver respectively from a location along the path profile, bulge is in meters.

5.5.3 Assumption For Land Mobile Telephone Signal at 800–900 MHz Frequency Band

The land mobile telephone systems introduced in Chapter 2, is a radio communication system that connects the transmitter and receiver at low altitude. In other words, the propagation of the land mobile telephone signal takes place via space waves [Committee]. For the 800–900 MHz band signal, ionospheric waves pass readily through the ionosphere with little energy being reflected back; troposphere waves are represented with the effective Earth radius, and surface waves are attenuated very rapidly with distance. Space waves therefore dominate the propagation mechanisms.

5.5.4 Assumption of the Radio Horizon

Radio signals are blocked by the Earth's surface when they propagate over a certain distance. This distance is termed the radio horizon. The value of the radio horizon varies according to the heights of the antenna. Figure 5. 4 demonstrates the principle of the radio horizon.

$$d = d_T + d_R = 2.9\left(\sqrt{2h_T} + \sqrt{2h_R}\right) \quad [5.\ 4]$$

where h_T in meters, represents the height of transmitting antenna,
h_R in meters, represents the height of receiving antenna
d_T, d_R in kilometers, as shown in the Figure 5. 4
d in kilometers, represents the radio horizon of h_T, and h_R

The radio horizon can be calculated through equation [5. 4], derived by Lee [Lee]

A 25 km radio horizon is obtained by substituting 20 meters and 3 meters for h_T, h_R respectively. The effect of radio horizon was neglected during the test run of the radio path loss prediction model as the test area (11 km by 5 km) was completely contained within the radio horizon distance.

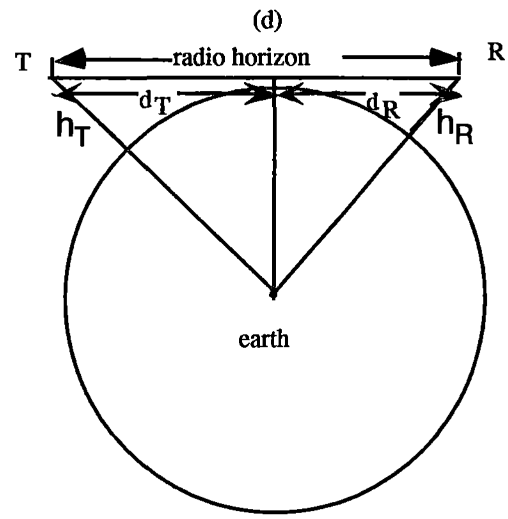


Figure 5. 4 Radio Horizon Concept

5.5.5 The Earth's Surface Features Assumption

Earth surface features include terrain, vegetation, buildings and other natural and man-made objects. Each of these objects has a different effect on the attenuation of the propagated radio signal due to their shape, orientation, and surface material. The attenuation calculation over each object is very complicated and time consuming. Furthermore, the same object results in different signal strength reductions for different types of signals. For example, signals from different directions passing the same building may have different path loss because the orientation of the building is different relative to the signals [Bertoni & Walfisch], [Walfisch & Bertoni] and [Chrysanthou & Bertoni]. Similar principles apply to trees [Weissberger]. It is almost impossible to compute a signal path loss value for each object because of the complexity in the signal transmission.

To simplify the effect of trees and buildings on path loss, it is assumed, in this thesis, that the height of trees and buildings are included in the TIN surface model, ie. terrain elevation, heights of buildings and trees are considered in one altitude value. The calculation of the path loss for a point and area will only consider the final elevation contribution.

5.5.6 Other Assumptions

Assumptions that apply to particular problems will be noted during model discussion.

5.6 PATH LOSS CALCULATION

The mobile radio signal propagation analysis consists of two parts, the path loss calculation and the general propagation analysis. The path loss calculation utilizes functions outlined in Chen's model which calculates the path loss value between a transmitter and a receiver based on the path profile. The calculation is termed a point-to-point path loss prediction. Path loss prediction over a designated region from a given base station antenna is called point-to-area prediction.

Point-to-point and point-to-area path loss predictions in this thesis require a spatial database. The path profiles is retrieved from a TIN surface model located in the spatial database, radio propagation theory is applied to the profiles, and then analysis of the Earth surface's effects on the signal propagation is conducted.

The point-to-point path loss prediction calculates free space, plane Earth, Fresnel diffraction and diffraction loss. The point-to-area path loss prediction applies the point-to-point calculation method on a series of sample points that are irregularly distributed in the area of interest. The selection of these sample points is based on the spatial characteristics of the analysis area. Details of selecting sample points will be addressed later.

General propagation analysis classifies radio signal propagation characteristics over a large area. Instead of calculating path loss quantitatively, the propagation analysis qualifies one or more aspects of radio propagation. Because of complexity and time required in performing an analysis for a large area, the existing path loss prediction models usually calculate the combined results from all propagation mechanisms. Using GIS functions supplied in ARC/INFO software, the process is simplified and performance time is reduced. The qualitative analysis explored in this thesis includes line of sight condition classification, radio signal reflection simulation, and time delay inspection.

5.6.1 Point-To-Point Path loss Prediction

Since signal propagation attenuation on the path is highly irregular and heavily dependant on features of the local environment, the terrain profile that is generated from the TIN model between the given transmitting and receiving antennas, is carefully examined. Point-to-point path loss calculation formulae are used appropriately according to the results of the profile analysis.

Five major steps are involved in point-to-point path loss prediction. They are path profile generation, path profile analysis, path loss calculation, and cluster loss modification and the display of results. The path loss prediction model described by Chen is incorporated in these steps. Formulae and methods in Chen's model are listed and described in detail for implementation purposes. Figure 5. 5 outlines these procedures with a flow chart diagram.

Note that the condition diamonds in the diagram use left branch to indicate a condition is satisfied, the right branch when it is not.

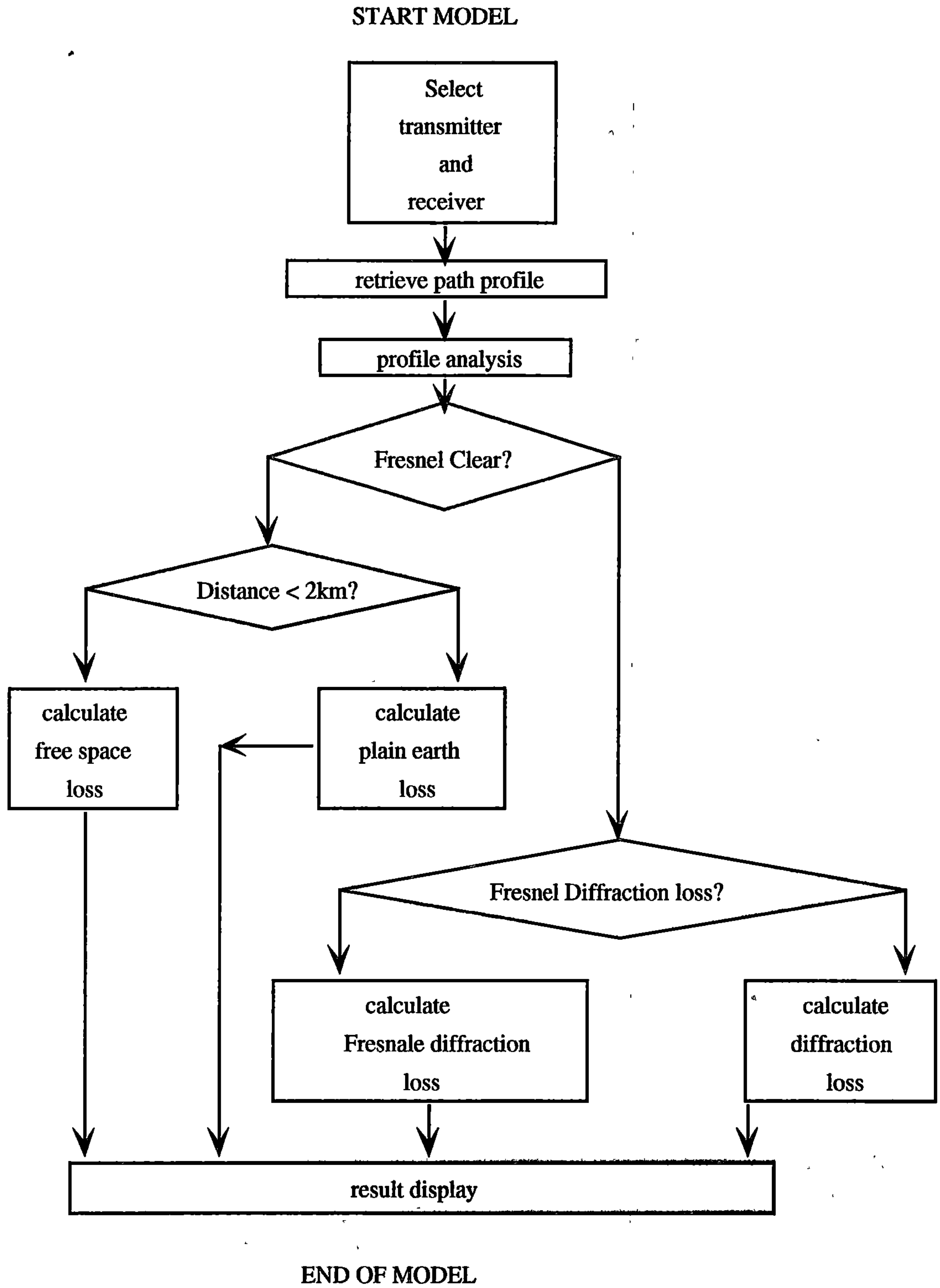


Figure 5. 5 Flow Chart of the Point to Point Calculation

5.6.1.1 Path Profile Generation

Giving a transmitter and receiver location, a path profile can be generated using an existing function provided by ARC/INFO software.

The path profile consists of a X, Y, Z coordinates list. X, Y coordinates represent the plane locations that start from the transmitter X_T & Y_T, and end at the receiver X_R & Y_R. The points are chosen at a fixed interval, determined by the prediction accuracy required, or by ARC/INFO's default setting, whichever is the smaller. The smallest possible interval is the TIN's weed tolerance. It would be meaningless to choose an interval that is less then the TIN's precision determined from the actual sample data.

The Z value at each X, Y location is initially obtained from either actual elevation if at TIN's nodes, or interpolated from the TIN model. Note that the elevation value retrieved from the TIN model has included tree or building heights if they exist. Finally, the Earth bulge is added along the profile. Figure 5. 6 illustrates path profile construction.

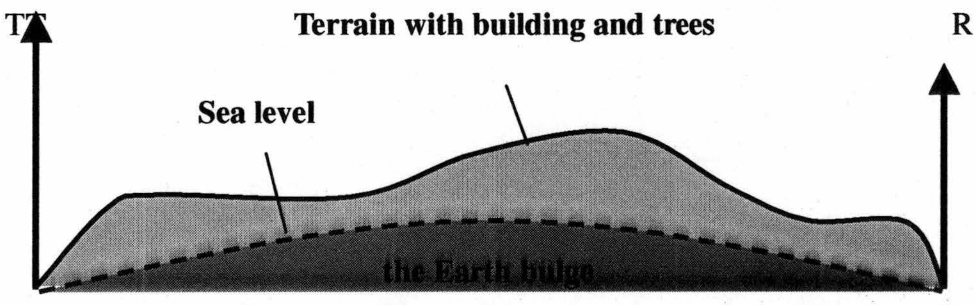


Figure 5. 6 The Path Profile Construction

The Earth's bulge is calculated using Equation [2.3]. Z values in the path profile list are the sum of the Earth's bulge and terrain elevations retrieved from the TIN model. Table 5. 1 gives an example of the resulting path profile data between a transmitter and a receiver.

The distance listed in the table represents the plane distance from the transmitter to the sample point. This value is the calculated path derived from the path profile generation function. It is retained, along with the elevation value Z because of its usefulness in calculation of the Earth bulge, and path profile analysis.

unit: metre

X	Y	Z	Distance
...	...	...	...
527393	5253649	30	900
527293	5253648	34.171	1000
527193	5253646	61.222	1100
527093	5253645	79.944	1200
526993	5253644	84.973	1300
526893	5253642	111.141	1400
526793	5253641	146.381	1500
526693	5253639	183.607	1600
526593	5253638	232.411	1700
526493	5253636	245.381	1800
526393	5253635	254.729	1900
526293	5253634	267.965	2000
526193	5253632	246.389	2100
526093	5253631	193.266	2200
...	...	...	...

Table 5. 1 Part of the Path Profile Table

5.6.1.2 Path Profile Analysis

The purpose of profile analysis is to determine the Fresnel clearance condition. A path profile can be one of the three types — line of sight, line of sight with inadequate Fresnel zone clearance, and line out of sight. The Fresnel clearance is decided from the maximum value of the Fresnel parameter. A path with the maximum Fresnel parameter less than –0.8 is line of sight. A path with the maximum Fresnel parameter greater than 0 is of line out of sight, and a path with a maximum Fresnel parameter between the above two values is line of sight with inadequate Fresnel zone clearance.

The Fresnel parameter v is calculated at every sample point along the profile. Equation [5. 5] is applied at each point.

$$v_i = h_i \sqrt{\frac{2(d_{i1} + d_{i2})}{\lambda d_{i1} d_{i2}}} \qquad [5.\ 5]$$

In [5. 5], subscript i indicate values at a specific sample point i. v_i is the Fresnel parameter value at point i. h_i is the height from the terrain of a fictional line drawn between the transmitter and the receiver, as shown in Figure 5. 7. h_i is represented in meters. d_{i1} is the plane distance from the transmitter to the sample point i, and d_{i2} is the plane distance from the sample point to the receiver. Both d_{i1} and d_{i2} are in kilometers. λ is the signal wavelength represented in meters.

To calculate h_i, the height at the sample point along the fictional line is subtracted from the terrain elevation with the Earth bulge. A negative h value indicates the terrain elevation (including the Earth bulge) is lower than the line, and vice-versa.

The maximum absolute value, *Vmax* is determined after all parameters are calculated. This value is then used to decide the profile type.

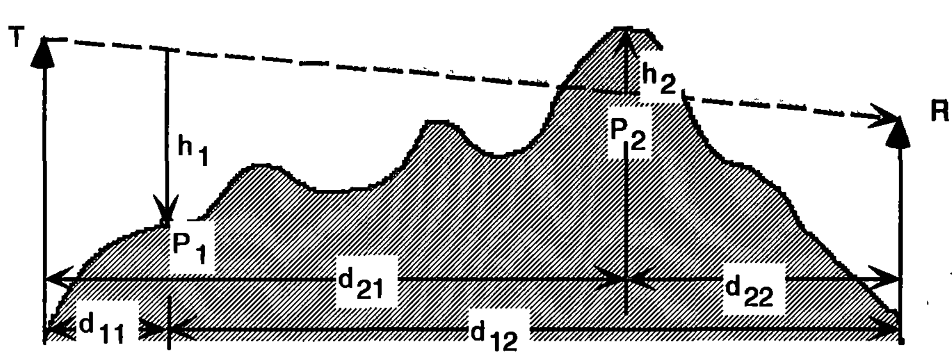


Figure 5. 7 Calculation of Fresnel Parameter

The line out of sight profile is further processed to calculate diffraction loss. The number of peaks that can be treated as knife-edge obstacles are counted, and input to the Deygout diffraction loss calculation. The process of counting knife-edge peaks is demonstrated in Figure 5. 8.

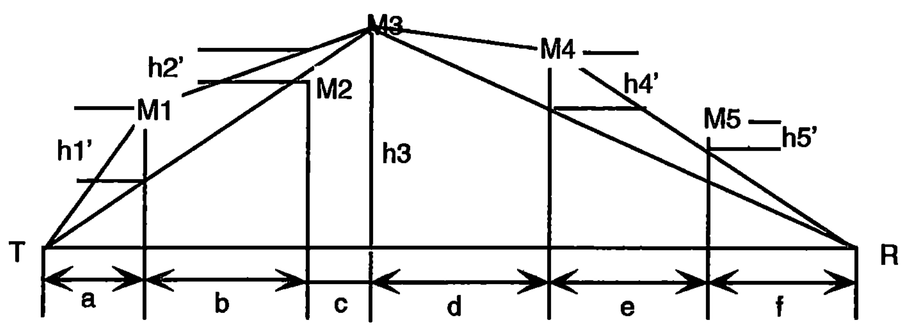


Figure 5. 8 The Determination of The Knife-Edge Peaks

M_1, M_2, M_3, M_4, and M_5 are peaks along the profile. Because the path profile has been classified as line out of sight, at least one peak, eg. the highest peak (M_3), blocks the line of sight transmission. This peak definitely contributes to the diffraction path loss. Other peaks, M_1, M_2, M_4, and M_5 may or may not make contribution. It is important to determine which, if any of the other peaks may cause additional diffraction loss. According to the Deygout's method [Deygout], a peak contributes to the diffraction loss if:

- It is the highest peak; or
- It is a peak without relative Fresnel clearance.

The process to determine if a knife-edge obstacle exist involves dividing the path profile into two sections — from transmitter to the highest peak forming one section, and the highest peak to the receiver as the other. Peaks in both sections are examined to determine Fresnel clearance using the end of each section as the transmitter and receiver. If peaks in a section are not Fresnel clear, the highest peak is located, the section is divided, and the relative Fresnel clearance is again determined. This process will repeat until all peaks in a section satisfy Fresnel clearance. The process can be illustrated using Figure 5. 8 as an example.

1. Assume all mountain peaks are knife-edge peaks. M_3 is identified as the highest peak (knife-edge peak), v is calculated;
2. The whole path profile is divided into two sections, the left and right sides of M_3;
3. For peaks in the left section M_1 and M_2, Fresnel clearance v_{M1} and v_{M2} are calculated from the profile section between the transmitter and M_3. v_{M1} is positive. v_{M2} is less than –0.8. This eliminates peak M_2 from the knife-edge peak list;
4. Examining the right section, direct path M_3R is formed. v_{M4}, and v_{M5} are calculated and both are retained in the list;
5. Comparing v_{M4} and v_{M5}, v_{M4} has the largest Fresnel parameter value. M_4 is the dominant peak, which will contribute the most diffraction loss among all peaks in the right section. M_4 is counted as a knife-edge peak;
6. Form a path between M_4 and the receiver R to determine v_{M5}. If v_{M5} is greater than –0.8, M_5 is another knife-edge peak. Otherwise, it is eliminated. No more peaks exist on the left side of the path and therefore the process is completed.

Peak M_1, M_3, M_4 and M_5 are recognized as knife-edge peaks. Their relative Fresnel parameter values are recorded for the diffraction loss calculation. The inputs used to calculate the relative Fresnel parameters are listed in Table 5. 2..

	M1	M2	M3	M4	M5
d1	a	b	a+b+c	d	c
d2	b+c	c	d+e+f	e+f	f
h	h1'	h2'	h3	h4'	h5'

Table 5. 2 Diffraction Loss Calculation [Deygout]

To determine knife-edge peaks in the prototype, all sample points along the path profile with a positive Fresnel clearance parameter are located. Only some of the points identified are mountain peaks. The slopes at each side of a nominated point are calculated. Points with a positive then a negative slope are recognized as peaks. The procedure described above is then applied to determine knife-edge peaks.

The results of the path profile analysis will be used to then calculate path loss.

5.6.1.3 Path loss Calculation

Path loss is calculated from equation [5. 6], using Chen's path loss prediction model.

$$path-loss = \begin{cases} free\ space\ loss; & v < -0.8\ \&\ d_{TR} < 2 \\ plain\ earth\ loss; & v < -0.8\ \&\ d_{TR} \geq 2 \\ free\ space\ loss + diffraction\ loss1; & -0.8 \leq v < 0 \\ free\ space\ loss + diffraction\ loss2; & 0 \leq v < 2 \\ free\ space\ loss + diffraction\ loss3; & v \geq 2 \end{cases} \qquad [5.\ 6]$$

In [5. 6], the path loss is considered to be free space loss if the path is Fresnel clear and the length of the path is less than 2 km. In this situation the effect of the Earth's surface is negligible, and the path can be treated as a straight line between the transmitter and receiver.

The following section will explain each item in equation [5. 6].

Free space loss calculation is derived from radio theory, for a tropospheric antenna where $G_R G_T = 1$.

$$P_r = P_0 / (4 p d_{TR} / \lambda)^2 \qquad [5.\ 7]$$

because $\lambda = \frac{c}{f}$

$$\frac{P_r}{P_0} = \left(\frac{c}{4 p f d_{TR}} \right)^2 \qquad [5.\ 8]$$

$$free\_space\_loss = 10\log\left(\frac{P_r}{P_o}\right) \quad [5.\ 9]$$

Replace P_r/P_o by [5. 8] and c by the speed of light in air, [5. 9] is transferred into [5. 10].

$$free\_space\_loss = 32.44 + 20\log(d_{TR}) + 20\log(f) \quad [5.\ 10]$$

Where d_{TR} is in kilometers, f is in MHz.

Plane_earth_loss is free space loss with additional absorption, reflection and refraction from the atmosphere and the Earth surface.

$$plain\_earth\_loss = 20\log\left[\frac{d_{TR}^{2}}{(h_R h_T)}\right] \quad [5.\ 11]$$

diffraction_loss1 refers to the Fresnel diffraction loss at the line of sight condition without Fresnel clearance. It is calculated by the empirical formula in [5. 12] [CCIR74].

$$diffraction\_loss1 = 6.02 + 9v + 1.65v^2 \quad [5.\ 12]$$

diffraction_loss2 and **diffraction_loss3** sum the Fresnel diffraction losses caused by knife-edge peaks. They can be calculated using equations [5. 13] and [5. 14] [Chan] respectively, depending on the level of Fresnel clearance.

$$diffraction\_loss2 = 6.02 + 9.11v - 1.27v^2 + other\_relative\_diffraction\_loss \quad [5.\ 13]$$

Where 0 =<v < 2

$$diffraction\_loss3 = 13 + 20\log(v) + other\_relative\_diffraction\_loss \quad [5.\ 14]$$

Where v >= 2

The "*other_relative_diffraction_loss*" in equation [5. 13] and [5. 14] is only applicable if more than one knife-edge peak is located. The value will be zero if only one knife-edge peak exists along the path. Otherwise, the relative diffraction losses for all knife-edge peaks are summarized. The relative diffraction loss for each knife-edge peak is calculated through either equation [5. 13] or [5. 14]. The value of the relative Fresnel clearance parameter decides which equation to be used. The relative Fresnel clearance parameters for knife-edge peaks in example Figure 5. 8 were calculated using equation [5. 6] with arguments listed in Table 5. 2. Figure 5. 9 explains this process using a flow chart.

When the path profile is calculated, a correction factor is added to account for multi-path effects that result in additional signal fading. The multi-path effect is a result of reflections from surface objects, such as buildings, trees, mountains, etc. A 21dB loss is used as the multi-path correction factor [Chan].

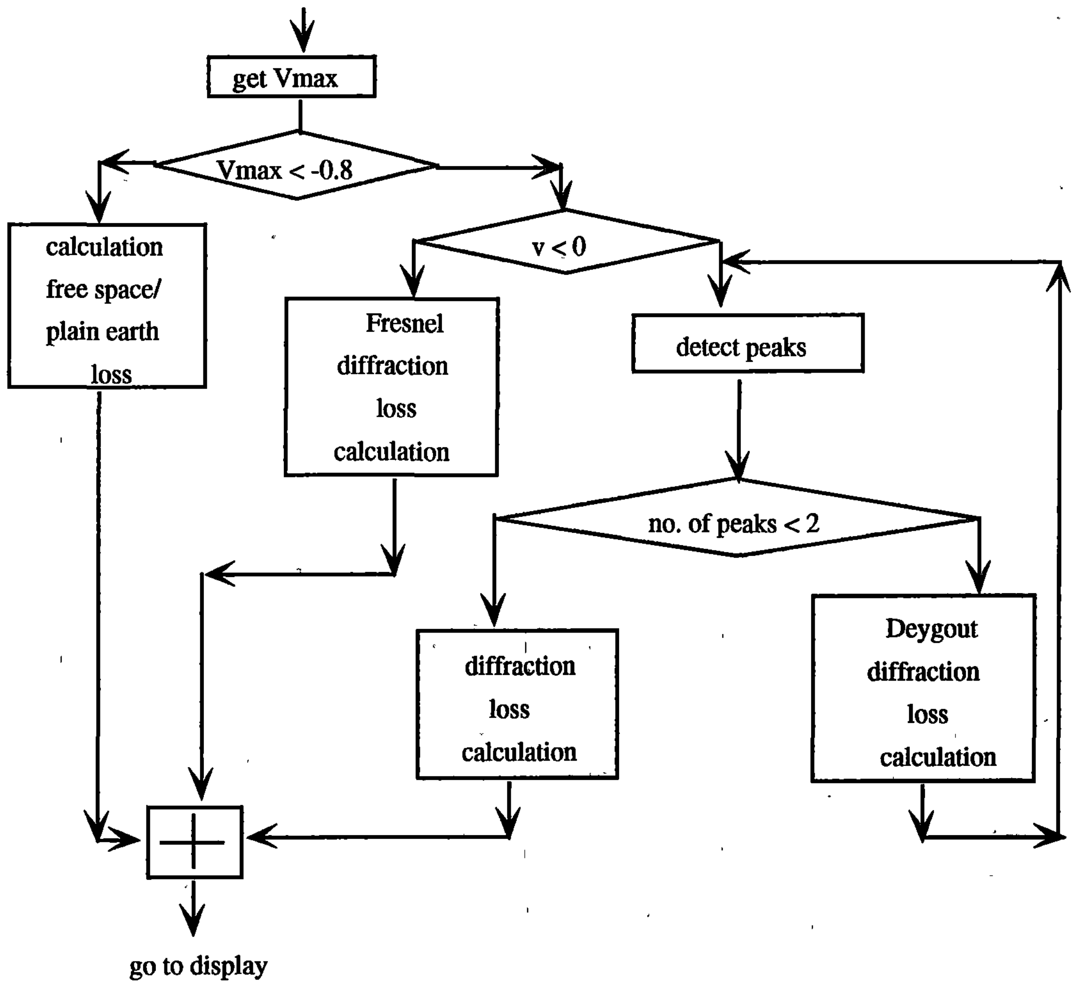


Figure 5. 9 The Flow Chart of Path Loss Calculation

5.6.1.4 Display of Path Loss Calculation Results

The result of a point to point path loss prediction is displayed using existing GIS visual display functions. The path loss result can be viewed along with other spatial features in both two-dimensional and three-dimensional graphic formats. The graphic display of the spatial features with the path loss prediction result provides more information than a single number. Spatial features that can be displayed include the transmitter and receiver antennae, roads, municipal district boundaries, etc. The path profile is shown along with the path loss value. Figure 5. 10 shows an example of a point to point path loss prediction result.

In Figure 5. 10, the terrain is viewed using a three-dimensional projection. The test area is displayed with a 45-degree rotation horizontally from the true north, and with a 45-degree vertical view angle. The path profile is shown in the graph with the X-axis representing plane distance (in meters) from the transmitter to the receiver. The Y-axis shows the three-fold exaggeration of the elevation in meters.

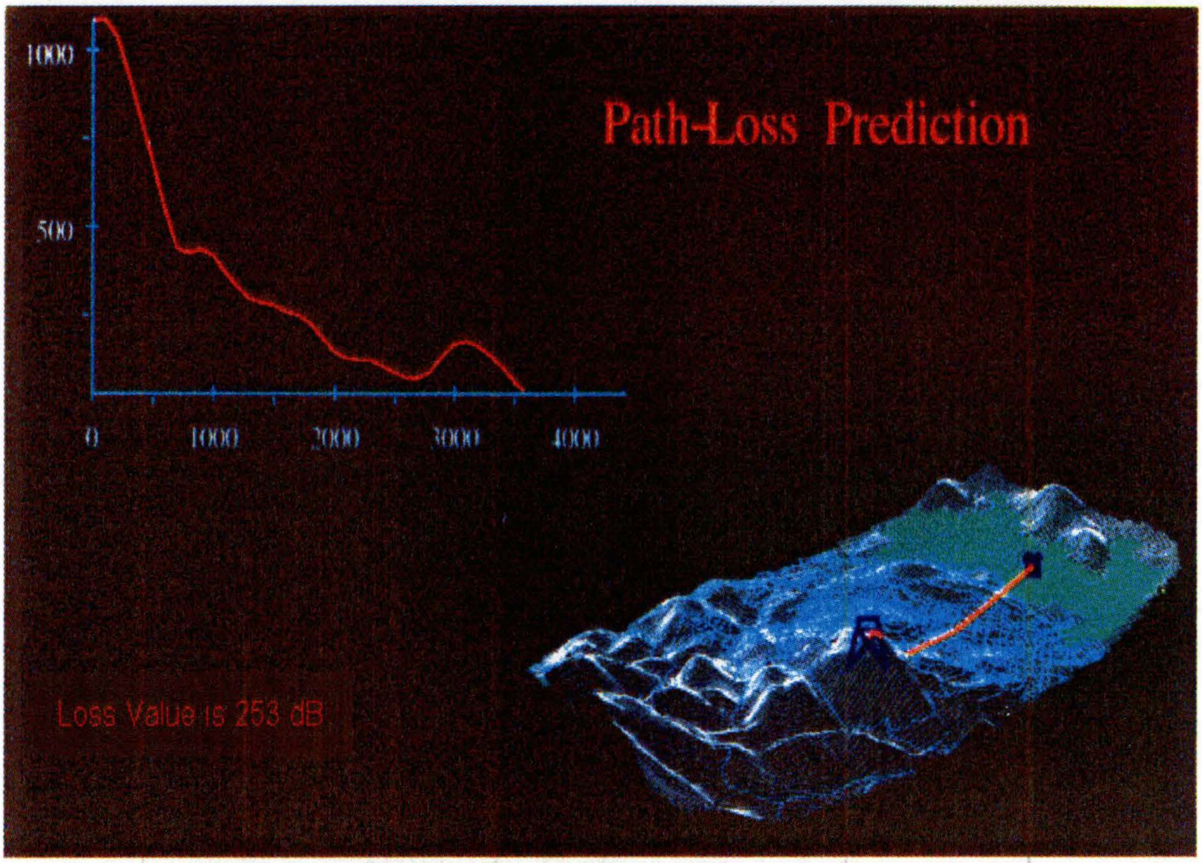


Figure 5. 10 Result of Point To Point Path Loss Calculation

Other spatial features and map legends can be included. These are outside of the scope of this thesis and will not be discussed in detail.

5.6.2 Point to Area Path loss Distribution Calculation

The purpose of the point to area propagation prediction is to plot a path loss distribution diagram within a service area, from a given transmitter antenna.

The area prediction applies point to point path loss calculation formulae to a series of sample points distributed in the study area. Each sample point represents a single sample area, and the sum of the sample areas forms the study area. The path loss value at each sample point is used as the path loss in the sample area. Unlike the existing path loss prediction models that select sample point regularly, the sample points selected in this thesis are irregularly distributed within the study area.

Because VHF/UHF signal propagation is dependent on terrain and path loss calculation is the result of profile geometry analysis, the path loss value varies as the terrain geometry changes. Therefore, more sample points are required in hilly areas than in a flat plane. In other words, sample point selection will be environment dependent. In this thesis, sample points are selected such that they reflect terrain geometrical characteristics. Slope and aspect are selection criteria that are used to determine sample points. As a result, the sample point density changes as the terrain geometry changes. Each sample area is not required to be square or rectangular as needed in existing models. The sample areas are composed of triangles, which vary according to the terrain. Large triangles were formed in the plane areas where changes in the terrain are small. Slim triangles are used in areas where sudden changes are found. Hilly terrain results in small triangle areas.

The irregular sample point distribution has two advantages. Denser sample points provide path loss details in hilly areas where rapid path loss changes may occur. In low-density sample point areas with little change in path loss values, less calculation will be required.

To perform point to area path loss prediction, the following procedures were used during the prototype experiment:

- Sample point selection;
- Path loss calculation; and
- Display of results.

Path loss prediction calculates the path loss value for every selected sample point using the point to point method described in the last section. Sample point selection and the display of the results will be discussed in the following sections.

5.6.3 Selection of the Sample Points

Sample points, representing the study area are selected so that the entire area of interest is included, and the geometric characteristics of the Earth's surface are reflected. Terrain features that are likely to have a significant effect on propagation should be included.

The following criteria is used to select the sample point locations:

- The sample points are selected, so that the entire service area is represented;
- At least one point should be selected to represent each region that has the same slope;
- At least one point should be selected to represent each region that has the same aspect;
- Points should be selected to reflect sudden changes in the Earth's surface, ie. points should be placed at peaks, ridges, creeks or along the rivers;
- The point should be in the center of the area being represented;
- Points should be selected that can easily be stored in the spatial database;
- Points should be stored, along with other important non-spatial attributes.

Selection of the sample points is carried out after studying the TIN surface model. The above criteria can be satisfied or derived directly from the TIN model. The terrain surface is constructed after combining irregular distributed points, lines and polygons [ESRI_TIN]. These correspond to peaks, pits, passes, points with a change in slope, ridges, stream channels, and shore lines. When input to the TIN model, lines and polygons are converted to points with X, Y, Z coordinates. The points are known as nodes. Nodes in the TIN model are connected into a series of triangles or facets. The Earth surface is then approximated by the continuity of all TIN facet mosaics.

The TIN model created using ARC/INFO satisfies the Delaunay criteria [ESRI_TIN], which requires that a circle drawn through the three triangle nodes does not contain any other points. Triangle node density was derived from the data source. For a TIN created using contour lines as the main source, (such as the test TIN model), each hilly area is represented by dense contour lines, and more triangle nodes are extracted. These nodes, with any additional outstanding points and lines are used to construct TIN triangles. Important surface features, such as break lines, are enforced with triangle edges to maintain the terrain geometry.

Because a TIN triangle facet represents a small portion of the terrain surface, points in a facet have the same slope and aspect values. Through TIN triangle faces, slopes and aspects can be calculated using the triangle nodes. Changes in adjacent triangle facets describe terrain changes. Sudden changes in terrain have already been incorporated in the TIN model through the triangle edges. The TIN facets are easily converted into point coverage or polygon coverage with the sample points as identifiers. Both coverages can be used to store sample point locations and path loss values. In addition, triangle facets cover the whole study area because triangles are the fundamental structure of the TIN model that represents the terrain surface over the study area. The midpoint of each triangle facet can be nominated as the representative sample point.

These conditions satisfy the sample point selection criteria. As a result, triangle facets can be used as sample areas for calculating path loss prediction. Midpoints of each facet can be used during the point to point calculation.

Figure 5. 11 shows an example of a polygon coverage converted from TIN triangles. Points in the triangles are sample points used for path loss calculation.

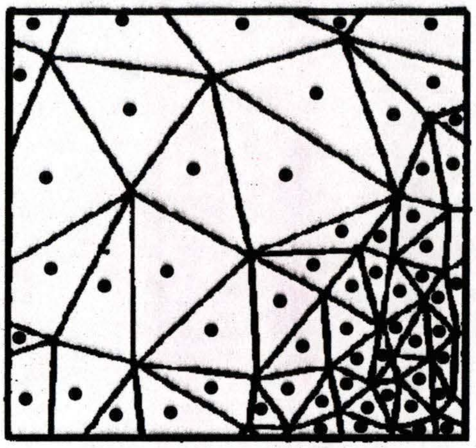


Figure 5. 11 Sample Point Used For Area Path Loss Prediction

Sample point coordinates can be derived from triangle facet nodes. Node coordinates (X1, Y1), (X2, Y2) and (X3, Y3) can be retrieved from the TIN model. The mid-point, with coordinates (Xk, Yk, Zk) is calculated using equation [5.15].

$$X_K = \frac{X_1 + X_2}{2} + \frac{\left(X_3 - \frac{X_1 + X_2}{2}\right)}{3} = \frac{X_1 + X_2 + X_3}{3}$$

$$Y_K = \frac{Y_1 + Y_2}{2} + \frac{\left(Y_3 - \frac{Y_1 + Y_2}{2}\right)}{3} = \frac{Y_1 + Y_2 + Y_3}{3} \qquad [5.\ 15]$$

$$Z_K = \frac{Z_1 + Z_2}{2} + \frac{\left(Z_3 - \frac{Z_1 + Z_2}{2}\right)}{3} = \frac{Z_1 + Z_2 + Z_3}{3}$$

The principle is illustrated in Figure 5. 12.

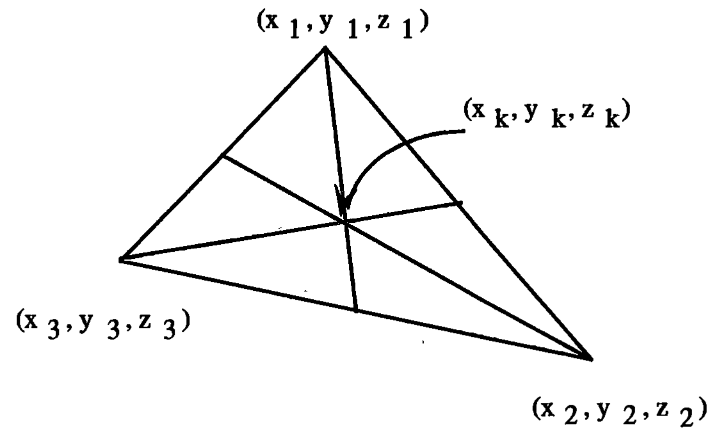


Figure 5. 12 Calculation of the Middle Point of a Triangle

The results of the sample point selection are stored as attributes of the triangle polygon coverage.

5.6.3.1 Area Prediction Result Display

Area path-loss calculation results can be graphically displayed using the GIS. In ARC/INFO, polygons can be presented according to a specified attribute item, the *pathloss attribute* for example, using different colors or shading. Since each triangle polygon has a path loss value associated, a range of the path loss value can be defined, and each range can be displayed using distinct colors. The range can be an equal interval starting from a minimum value to the maximum. It can also be determined such that number of sample points is equal in every category. More practically, the user can define the category to be displayed. All options can be achieved easily using tools provided with ARC/INFO. In the prototype experiment, an evenly distributed category was applied because of the exaggeration in the terrain elevation that makes path loss prediction impractical for real world applications.

Another useful way of displaying area path loss prediction results is with a use of a three-dimensional projection. The classified path loss value can be draped onto the three-dimensional surface view. The path loss values can be viewed along with changes of the terrain shape. Figure 5. 13, and Figure 5. 14 demonstrate the two types of result presentation.

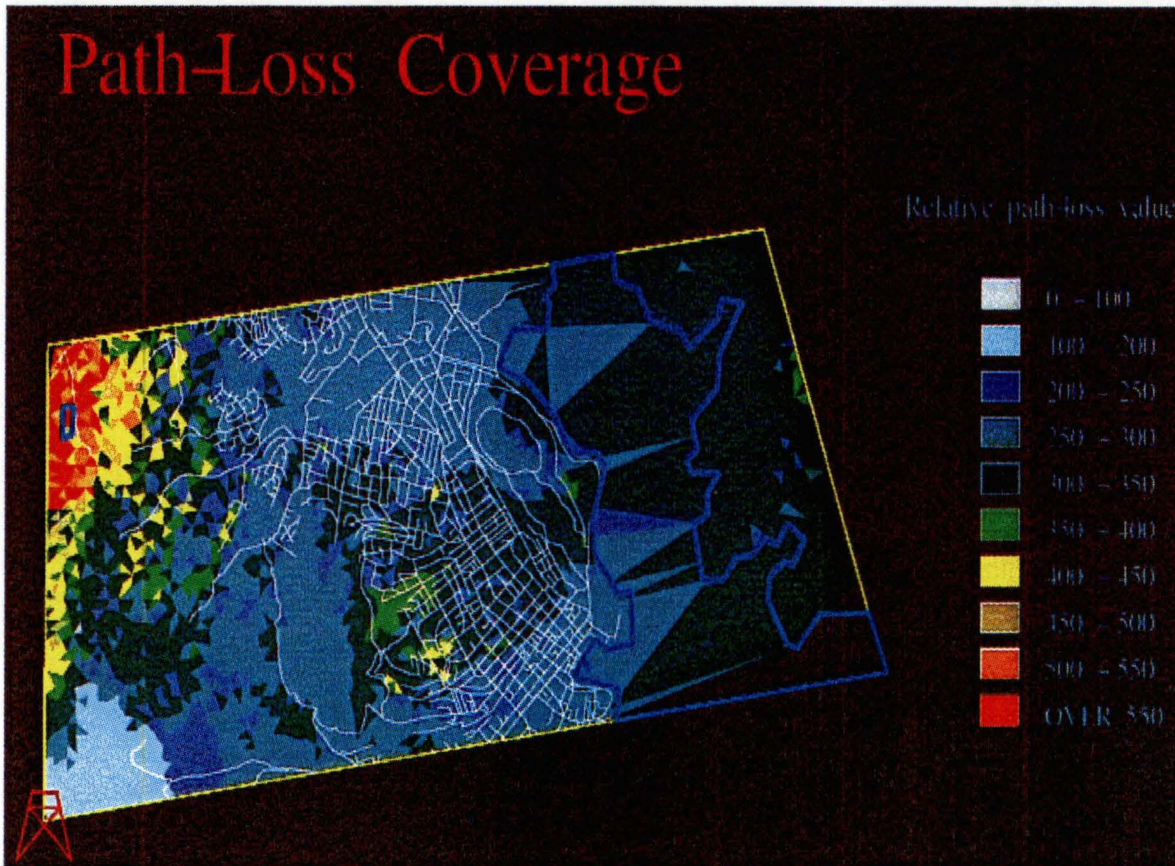


Figure 5. 13 Point to Area Path Loss Prediction Result Displayed in 2-D Map

Figure 5. 13 shows the path-loss prediction results in a two-dimensional format. Note that the classification range is represented in dB, derived from the exaggerated elevation model.

Although the exact path loss values may not correct, the relative values between sample areas reveal that:

- Path-loss increases as the distance from the transmitter increases;
- That hilly areas cause a larger loss than plane areas, even when the hilly area is closer to the transmitter.
- Some areas closer to the transmitting antenna have larger path-loss values than those further away.

Figure 5. 14 shows the relationship between the path loss and the terrain surface irregularity. Path loss values are much higher in hilly areas, as shown in the area at the top

left of the map. Losses can be seen to be larger in the shadow of a mountain, even if they are closer to the antennae as shown in the lower center of the display.

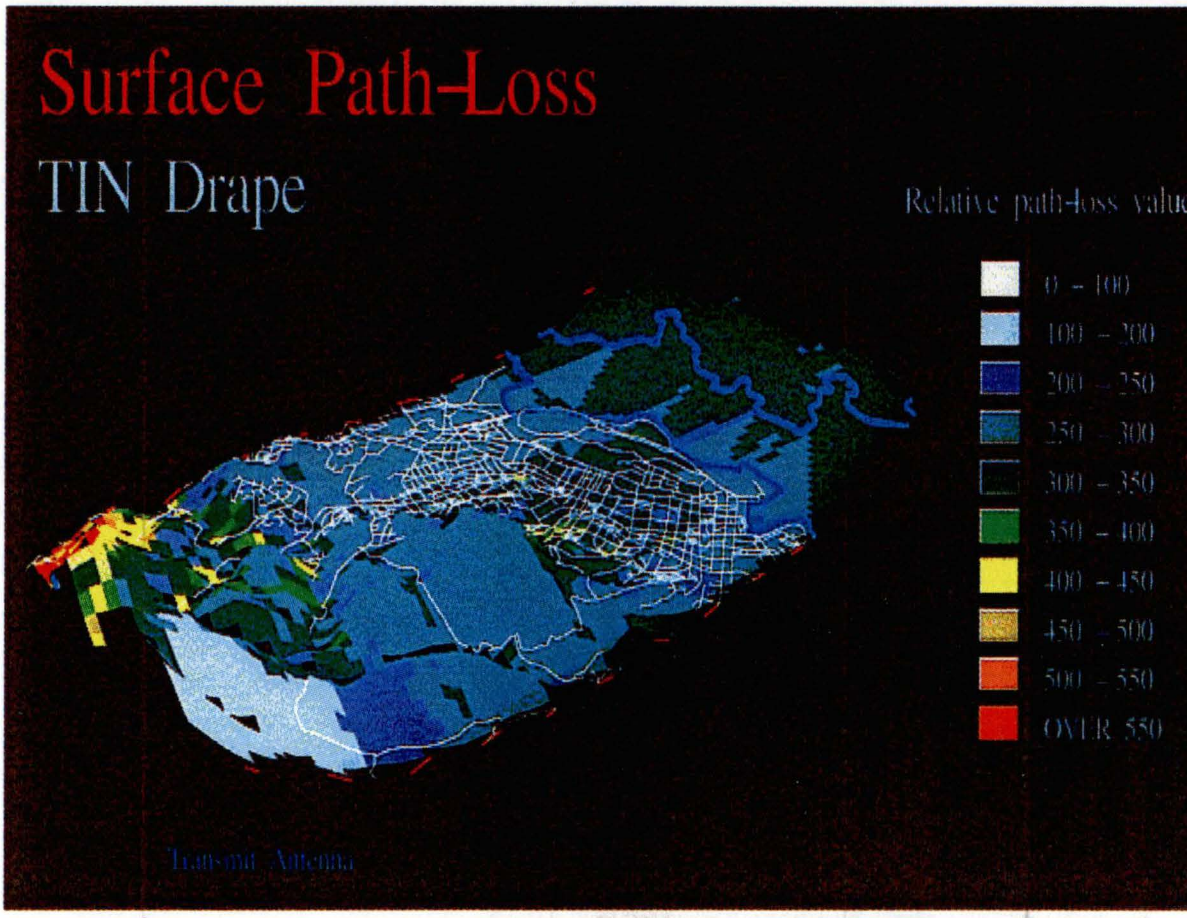


Figure 5. 14 Point To Area Path Loss Prediction Result Displayed in 3-D Map

5.7 QUALITATIVE ANALYSIS OF RADIO SIGNAL PROPAGATION

Through the use of a GIS, the radio propagation path loss prediction model can not only quantitatively calculate the path loss value, but also qualitatively analyze the radio signal propagation in an area through the terrain model. Unlike some of the existing models that use statistical or empirical method to summarize terrain effects on signal propagation, qualitative analysis emphasizes and analyzes one aspect of the terrains effect. This enables an understanding of the effects caused by a signal propagation mechanism.

The qualitative propagation prediction model put forward, can analyze the line of sight condition in a study area from a nominated transmitting antenna; produce signal reflection conditions, and study the possible interference for two or more signal transmitting stations within the service area. Results of the analysis along with other spatial information, such as census data, can be used as a reference for the design of mobile telephone systems.

5.7.1 Line of Sight Analysis

Line of sight analysis is a function that determines the possible visibility in the service area from one or more nominated observer locations. The analysis creates a polygon coverage representing the study area in which visible and non-visible regions are identified. An item that indicates the visibility status is defined in the attribute table associated with the output coverage.

The line of sight function was originally designed for optical visibility analysis. The similarity between optical and electromagnetic waves enables the function to be extended to radio signal line of sight analysis, although some assumptions have to be made. For mobile telephone signal propagation, line of sight analysis can be used to divide the service area into visible and invisible areas for a given transmitting antenna. The visible area could be considered as the initial shape of the mobile cell. Other antennae could then be planned to cover the non-visible areas.

5.7.1.1 The Principle of Visibility Analysis Using GIS Tools

Line of sight analysis functions provided with GIS application software, such as ARC/INFO, are included as part of visibility analysis [ESRI_TIN]. The visibility analysis identifies areas with visual exposure, and produces a shaded polygon result. Observation locations can be point(s), such as transmitter antenna locations, or linear features, such as highways, power lines, etc. The visibility analysis of a linear feature is calculated by ARC/INFO software using a series of single observation points.

The initial shaded polygon shows areas that can be seen by one or more observer locations or linear features. The area visibility status is stored in an attribute table associated with the resultant polygon. The visibility status describes whether and by which individual observation object each area in the polygon can be seen. The visibility status can be viewed graphically. The area of interest is subdivided into small grid cells. Each grid cell has an attribute which indicates which observation objects have line of sight. This functionality enables visibility analysis to be produced using all observation objects, a single observation object, or any combination of observation objects.

In addition, any high objects that have not been included in the TIN model within the area of interest can be incorporated into the visibility analysis. The object heights can be added to the terrain elevation before the visibility analysis is performed. For example, to perform visibility analysis in a built-up area, the building heights are known to the city council. If the TIN model over the study area does not include any building heights, they could be included for the accurate analysis of visibility performance.

To perform visibility analysis, at least one observation location and area of interest need to be specified. Other information can be entered if required [ESRI_ARC]. These include observation object height offset (OFFSET A), target object height offset (OFFSET B), the horizontal observation angles (AZIMUTH1, AZIMUTH2) which limit the direction of visibility horizontally, the vertical observation angles (VERT1, VERT2) which limit the tilt angle of the observation, and finally, the range radius (RADIUS1, RADIUS2) which restricts the area of interest so that only the area within the specified radius's is used.

Although the visibility analysis provided by the ARC/INFO, was designed for visual exposure analysis, it can also be applied to radio signal propagation analysis, because of the similarity between visual, ie. optical signal propagation and radio signal propagation.

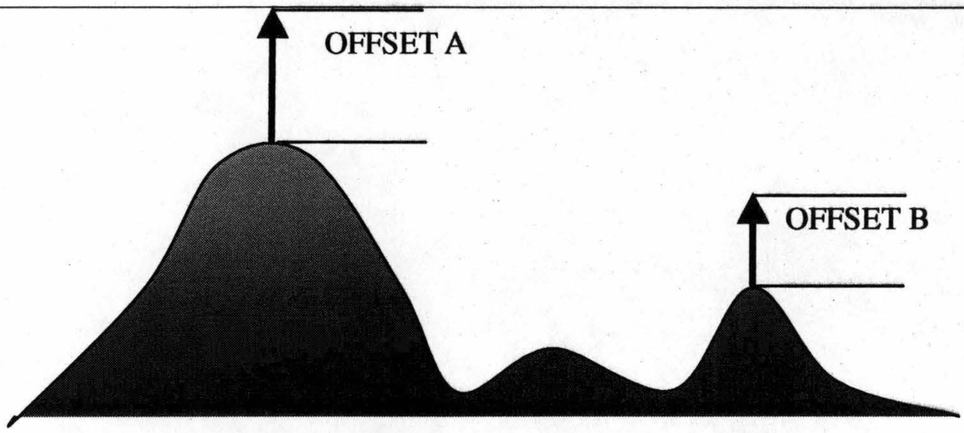
The OFFSET A, OFFSET B, AZIMUTH1, AZIMUTH2, VERT1, VERT2 and RADIUS1 & RADIUS2 are illustrated in Figure 5. 16.

5.7.1.2 Visibility Analysis Applied To Radio Signal Line of Sight Analysis

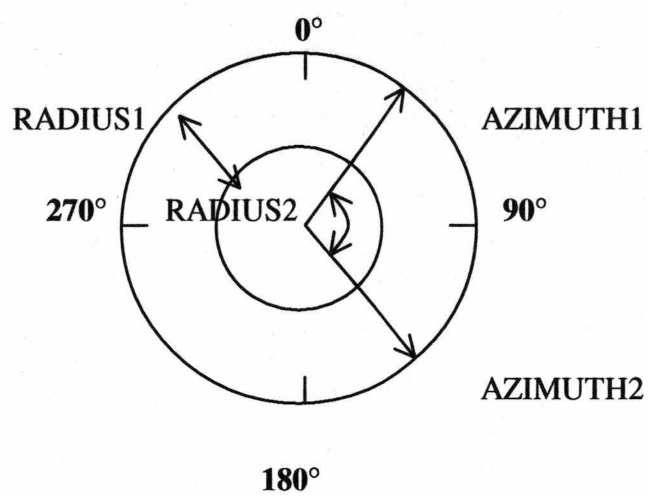
Visibility analysis can be applied to radio signal line of sight analysis because of the similarity between the light wave and radio signal propagation. A radio wave is a kind of electromagnetic wave, as is light. The concept of visibility analysis from one observation point to a particular target position is the line of sight condition analysis. The target is visible from the observation point if the line of sight condition is satisfied. This principle can be extended to multiple target locations. Each target location can be examined for the line of sight condition. When the density of the target locations is increased until the points can be considered an area, the examination of the line of sight condition becomes visibility analysis.

After the following replacements, the line of sight analysis from a nominated transmitter to a mobile service area can be carried out using existing line of sight analysis tools:

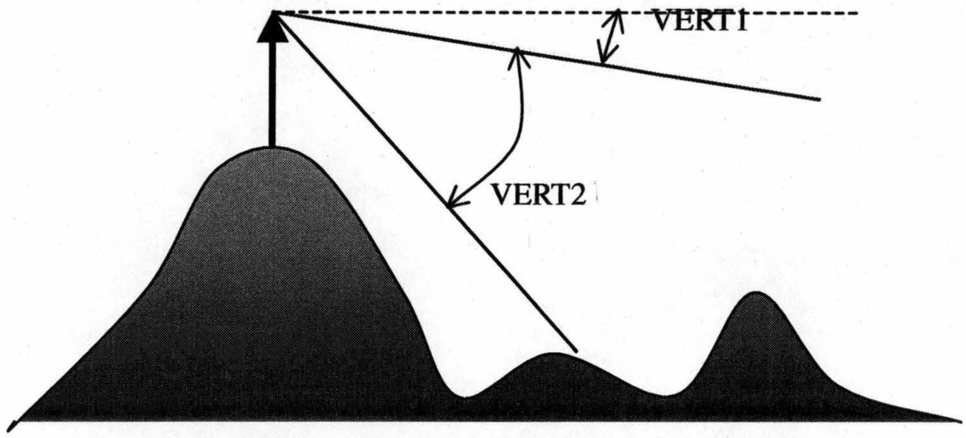
- Replacing the observation point with the transmitter location;
- Replacing the area of the target with the service area;
- Replacing the OFFSET A with the transmitter antenna height above the ground;
- Replacing OFFSET B with the receiver antenna height above the ground;
- Replacing the horizontal observation angles (AZIMUTH1 & 2) with the horizontal radiation pattern of the transmitter antenna; and
- Replacing the vertical observation angles (VERT1 & 2) with the vertical radiation pattern.



(a) Offset A & B Diagram



(b) Azimuth1 & 2 and Radius 1 & 2Diagram



(c) Vert1 & 2 Diagram

Figure 5. 16 Visibility Analysis Parameters

Strictly speaking, the radio propagation line of sight analysis has more restricted conditions than that of optical signal line of sight analysis. The optical line of sight analysis predicts a target is visible as long as no object is higher than the straight line between the observation and target locations. However, the radio propagation line of sight condition has to satisfy the Fresnel zone clearance condition. Figure 5. 17 shows a path between a transmitter and a receiver which meets the requirement of a visual line of sight condition, but fails the radio line of sight condition. In other words, the line of sight condition for light can be represented by Fresnel clearance parameter of zero (0), ie. the h in the Fresnel clearance parameter equation is zero. The radio propagation line of sight condition occurs when the Fresnel clearance parameter < -0.8 [Chen].

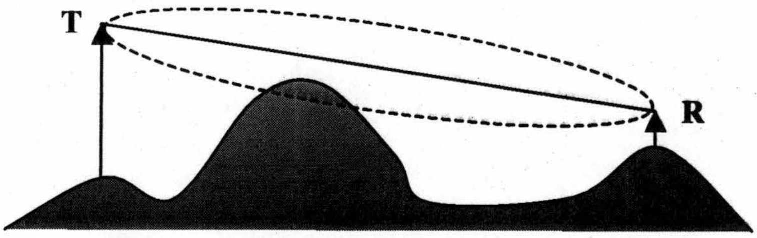


Figure 5. 17 Optical vs. Radio Line of Sight Condition

Experiments [Lee] show that the diffraction loss with a Fresnel clearance between –0.8 and 0 is below 4 dB, and therefore relatively small compared to the total path loss value. Figure 5. 18 shows the relative path loss value caused by inadequate Fresnel clearance

(<-0.8<v<0) compared to the free space loss. As a result, for the purposes of qualitative analysis, the line of sight analysis tools for light can be used as approximation of line of sight analysis for radio signal.

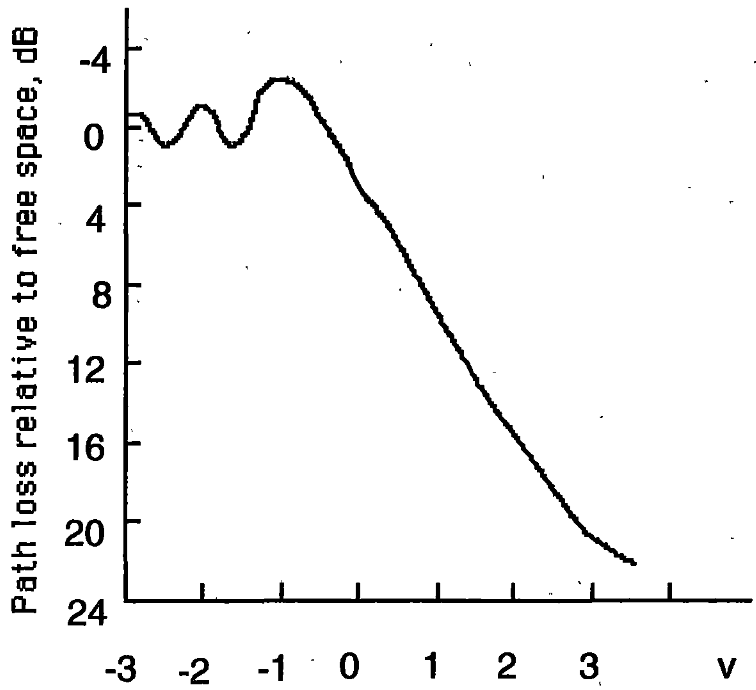


Figure 5. 18 Relative Diffraction Loss At A Single knife-edge To the Free Space Loss Represented by Fresnel Parameter(v)

To analyze the line of sight condition using ARC/INFO software, the transmitter location coordinates (X_T, Y_T) are required, the antenna height HT above the earth surface is to be provided, with the actual elevation value Z_T interpolated from (X_T, Y_T). The desired service area is sub divided into a matrix of cells, with each cell referenced to an assumed target location. The observer is at (X_0, Y_0, Z_0) where

$$\begin{aligned} X_0 &= X_T \\ Y_0 &= Y_T \\ Z_0 &= Z_T + H_T \end{aligned} \qquad [5.16]$$

Each cell row by row, column by column, is now identified as a line of sight, or blocked line of sight cell. Figure 5. 19 demonstrates the concept of the line of sight analysis.

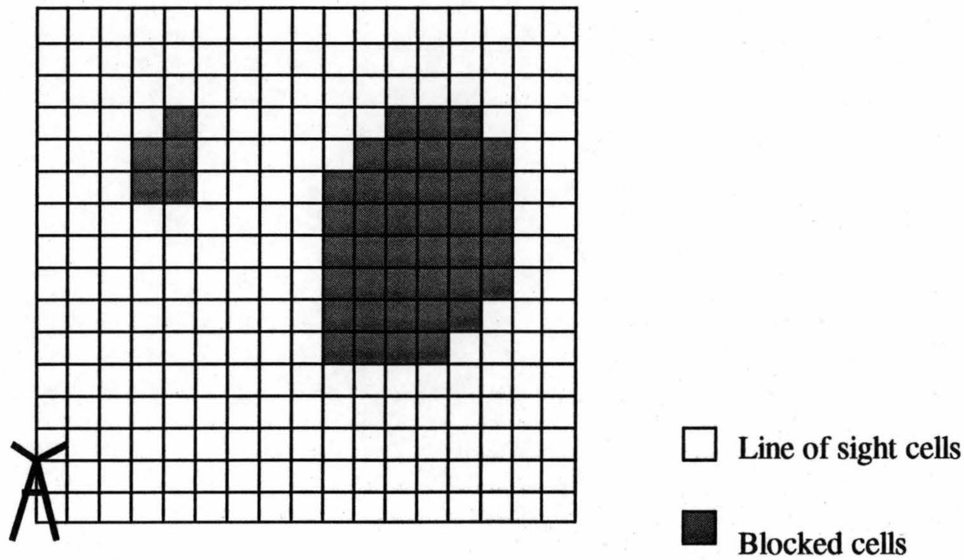


Figure 5. 19 The Line of Sight Analysis

The result of the line of sight forms a polygon coverage where adjacent cells with the same status are grouped as a polygon with the line of sight attribute sets. Figure 5.20 is an example output of line of sight analysis.

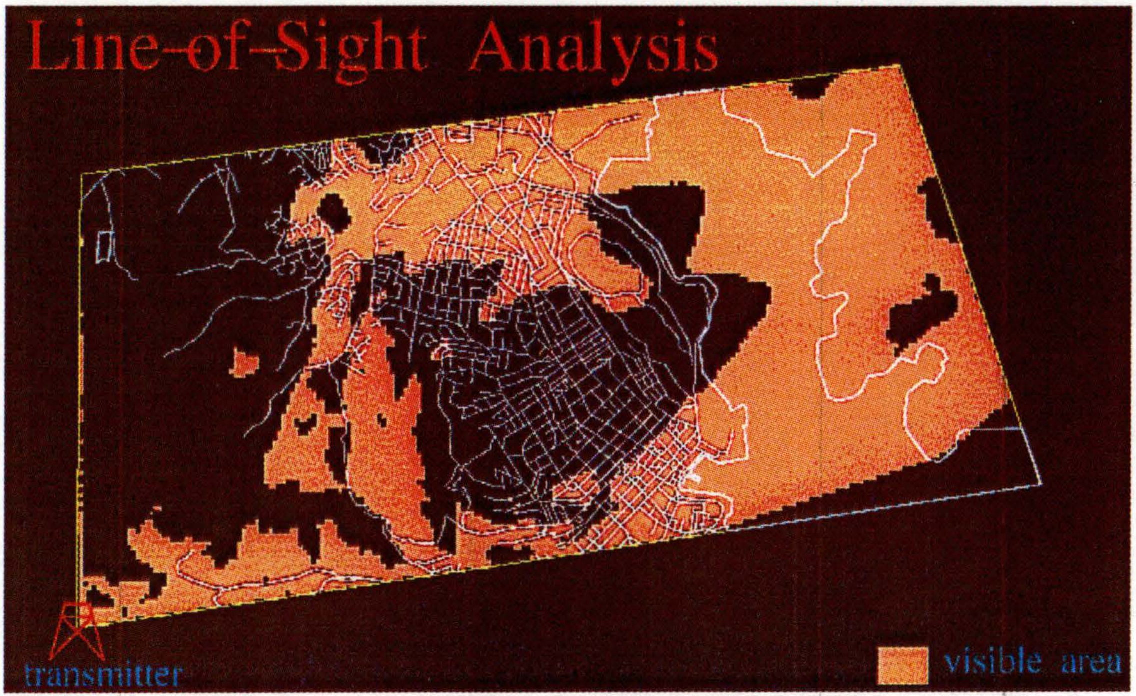


Figure 5. 20 Line of Sight Analysis Result

In addition to the radio line of sight condition analysis, the visibility analysis function can be extended to simple interference analysis over a service area from two or more transmitter antennae. This situation is important because of frequency reuse in the cellular mobile telephone systems. For 800-900 MHz mobile telephones, the bandwidth for each channel is 40 kHz. These is no limit to the number of channels that can be used, and to the extent of the mobile service area as long as the base station is connected to the telephone control centers. However, reusing channels may cause communication errors because of interference between reused signals, ie. two signals with the same carrier frequency, which are transmitted from different base stations. Errors can be reduced or prevented by analyzing the potential interference situations from the assumed antennae.

By setting transmitter antenna locations as multiple observation points, and assuming that the transmitter propagates on co-channel or adjacent channels, and the service area is the analysis area for visibility analysis, the service area can then be classified. Areas that have line of sight for one transmitter, imply that the receiver will receive high quality mobile services. Areas that satisfy the line of sight condition for more than one transmitter may result in unwanted signals for the receiver. Areas that do not have line of sight for any transmitters may not receive the signal strength necessary for effective communication.

Because interference analysis is complex, time-consuming and tedious work, the visibility analysis using GIS tools provides a quick solution to indicate which areas require further interference analysis. It also aids in selection of various transmitter sites and comparison of the service condition, due to the simplicity in changing observation points and re-performing the analysis.

5.7.2 Reflection Analysis Function

Reflection analysis is a function which examines the possible reflections in the area of interest from an assumed base station antenna. It reads the transmitter coordinates (X_T, Y_T), estimates the points of reflection on the Earth surface at a particular direction or angle. Secondary reflections can also be located if they are discovered in the area of interest. A map of reflection locations is plotted and can be saved in the spatial database for further processing. The reflection loss, ie. the absorption by the Earth's surface, the free space loss from the transmitter to the reflection point, and free space loss from reflection point to the receiver can be calculated. A simulation of the probable diffuse reflection can be calculated, which will estimate the deviation from the spectacular reflection.

The reflection analysis function, as a part of the general propagation analysis, aims to study the hill terrain affects on the radio signal propagation by approximating the radio wave's motions in space. Further examination, such as polarization analysis and multi-path analysis, can be done on this basis.

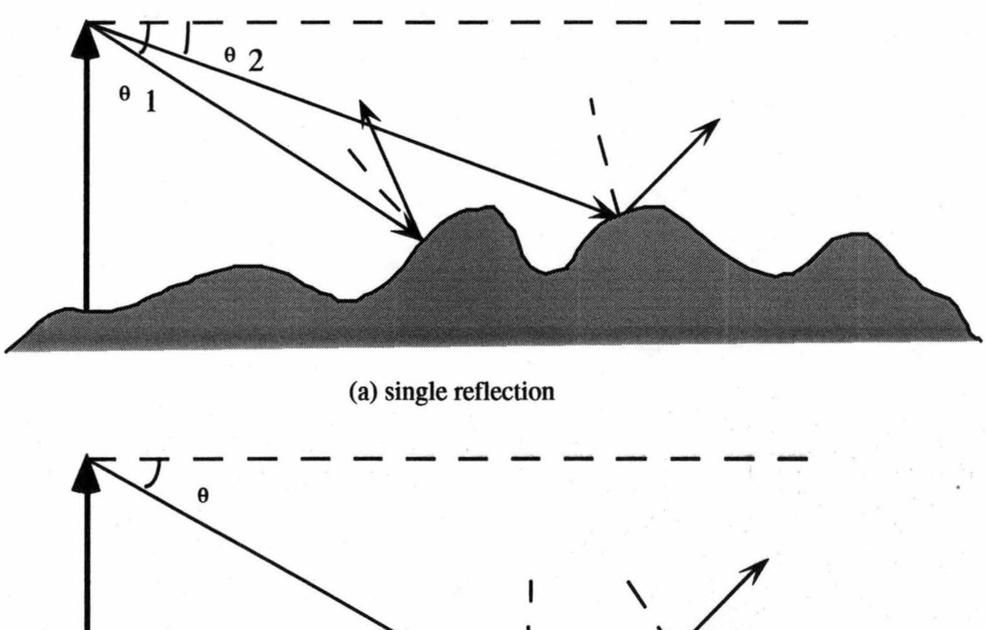
5.7.2.1 Reflection Analysis

Reflections on the Earth surface are located through the analysis of the geometrical relationship between the radio wave and the Earth's surface. Figure 5. 21 illustrates the principle of reflection from the Earth's surface. Diagram (a) shows two ray beams from the transmitter hitting the ground and being reflected, diagram (b) shows a ray reflected twice from the Earth's surface.

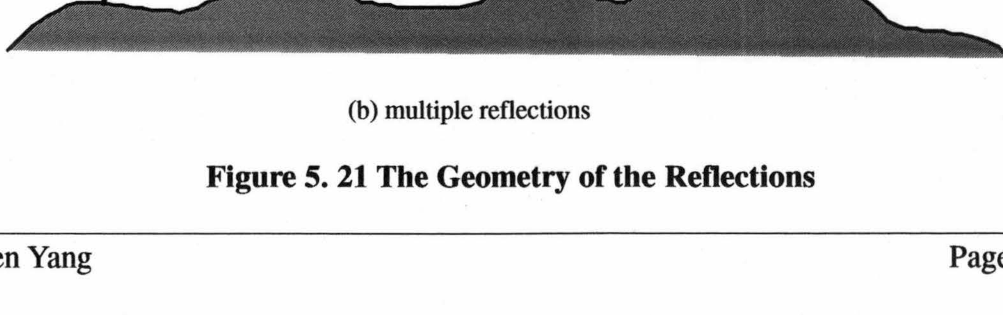
To detect reflection points, hypothetical ray paths are used to find the intersection with the Earth's surface. A ray path can be determined with vertical angle θ, as shown in Figure 5. 21, after the azimuth angle has been defined. Definitions of the azimuth angle α and vertical angle θ are illustrated in Figure 5. 22.

Figure 5. 21 shows that an intersection can be found by calculating the position where the imaged ray path intersects with the terrain model. The directions of the reflection are then obtained by computing the incident and reflected angles with the normal of the terrain surface at the point of intersection.

Three-dimensional vector theory is then applied to calculate the reflection from the Earth's surface.



(a) single reflection



(b) multiple reflections

Figure 5. 21 The Geometry of the Reflections

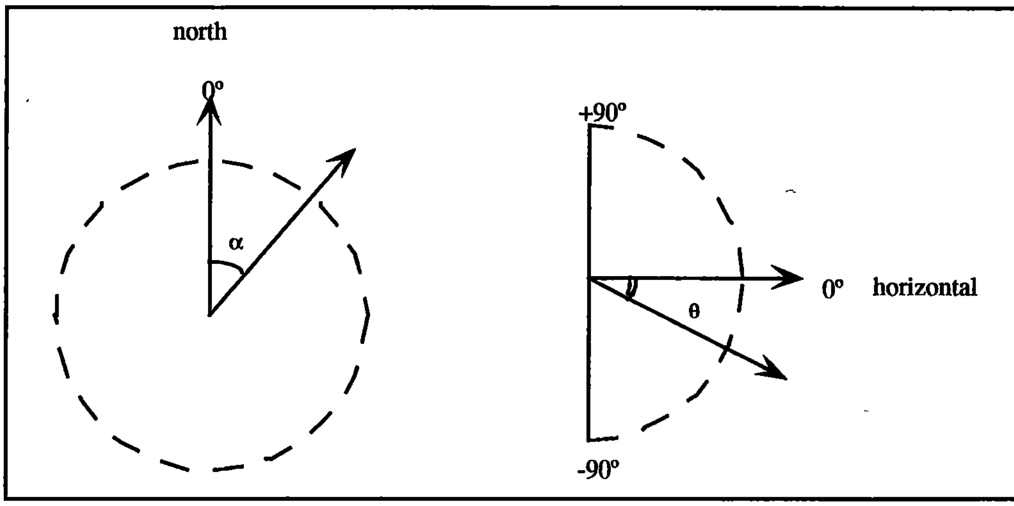


Figure 5. 22 The Definition of θ & α

A ray transmitted from the base station is represented in vector form $\vec{I}(a,b,c)$. The vector elements a, b & c can be calculated using formula [5.17], in the coordinate system shown in Figure 5. 23.

$$\begin{cases} a = x = \sin\alpha \bullet \cos\theta \\ b = y = \cos\alpha \bullet \cos\theta \\ c = z = \sin\theta \end{cases} \qquad [5.17]$$

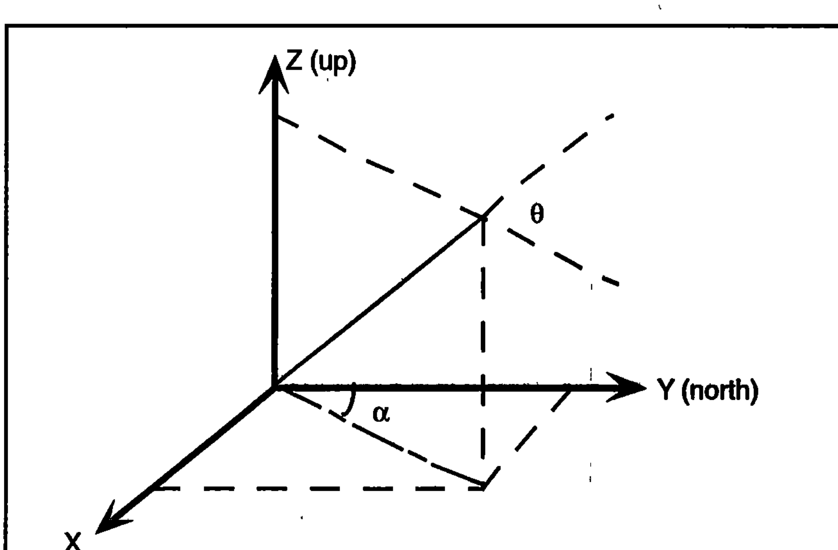


Figure 5. 23 The Map Coordinate System

The normal of the Earth's surface at location (x,y,z) can be represented by $\vec{S}(A,B,C)$, where A,B,C are the coefficients of plane equation [5.18]. Formula [5.18] is the triangle facet plain equation in the TIN model that contains the reflection point (x,y,z).

$$A_x + B_y + C_z + D = 0 \qquad [5.18]$$

By substituting the three coordinates into [5.18], equations [5.19] are solved to obtain the value of A, B, C & D, where (x_1, y_1, z_1), (x_2, y_2, z_2) & (x_3, y_3, z_3) are the respective point coordinates.

$$\begin{cases} Ax1 + By1 + Cz1 + D = 0 \\ Ax2 + By2 + Cz2 + D = 0 \\ Ax3 + By3 + Cz3 + D = 0 \end{cases} \qquad [5.19]$$

$\vec{R}$(m, n, p) is assumed as a vector whose direction represents the direction of the reflected ray of the radio signal. Figure 5. 24 illustrates the relationship between the triangles facet normal $\vec{S}$, incident ray $\vec{I}$ and reflected ray $\vec{R}$.

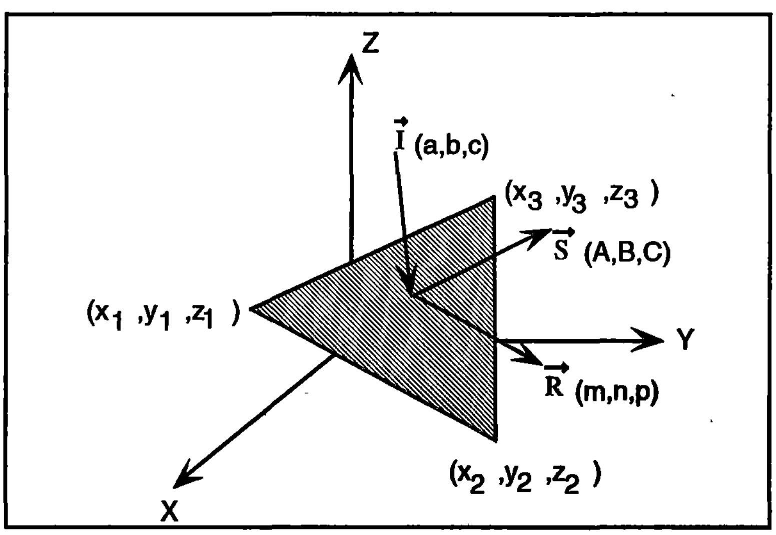


Figure 5. 24 The Vector Representation of the Incident, Reflecting and the Normal of the Reflection Plane

Reflection vector $\vec{R}$ in Figure 5. 24 is obtained by vector calculation (some vector calculation formulae used in this thesis are listed in the Appendix A). Formulae [5.20] to

[5.23] compute vector $\vec{R}$, and Figure 5. 25 illustrates the steps used to obtain the vector $\vec{R}$.

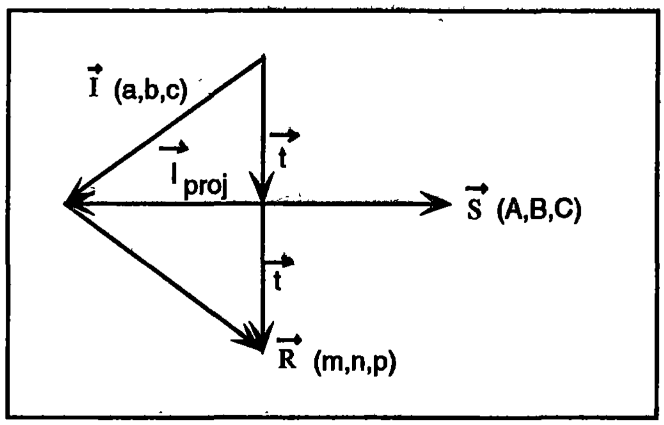


Figure 5. 25 Diagram of the Vector Calculation of the Reflected Ray

In Figure 5. 25, $\vec{S}$, $\vec{I}$ and $\vec{R}$ represent the normal of a triangle facet, incident ray, and reflected ray, (a,b,c), (A,B,C) and (m,n,p) are the quantitative representations of each vector. $\vec{I}_{proj}$ is the projection vector of $\vec{I}$ on $\vec{S}$, then

$$\boxed{\vec{t} = \vec{I} - \vec{I}_{proj}} \quad [5.20]$$

from above three vectors, also

$$\boxed{\vec{t} = \vec{I}_{proj} + \vec{R}} \quad [5.21]$$

from lower three vectors

$$\boxed{\vec{I} - \vec{I}_{proj} = \vec{I}_{proj} + \vec{R}} \quad [5.22]$$

combining [5.20] & [5.21]

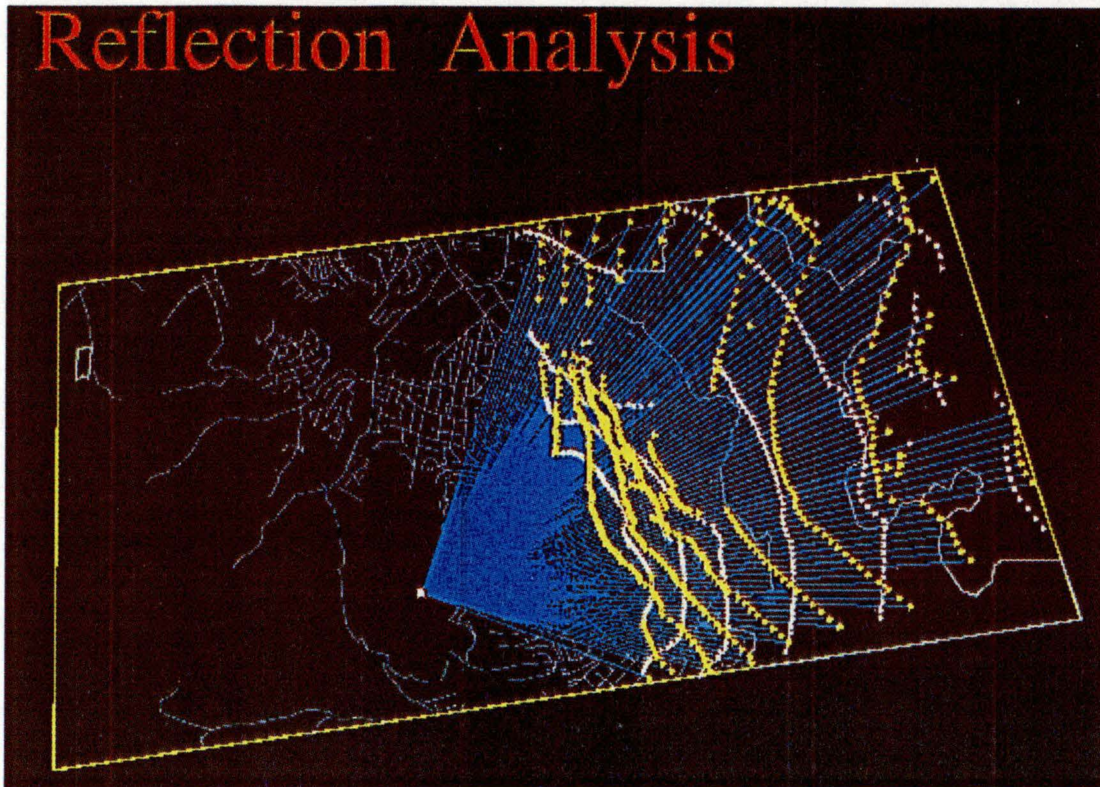
$$\boxed{\vec{R} = \vec{I} - 2\vec{I}_{proj}} \quad [5.23]$$

Formula [5.23] indicates that the reflected vector can be calculated from the incident vector and its projection vector on the surface normal, ie. it can be used to analyze the reflection condition at a particular incident direction. This equation can also be used to derive the secondary reflection ray from the first reflected signal, shown in the Figure 5. 21 (b), by substituting the first reflected ray as the incident vector. The same process can be applied to the third or further reflections if required.

However, equation [5.23] only produces a result for a specific incident signal. In the real world, a base station usually radiates radio signals in a range of directions. The simulation of a given range of incidents can be made through the repetition of the process, changing the incident angles α and θ.

If a circular situation is to be analyzed, the calculation starts at $\alpha = 0°$ until 359°. The angular interval depends on the requirement of the study. For a particular direction, the reflection simulation can cease when the signal leaves the area of interest, goes beyond the boundaries of the TIN model, or reaches the free air limits.

Figure 5. 26 is an example of running reflection model on the Hobart TIN surface model which detected first and second reflection points using a 1° interval. The first reflection from the transmitter and the second reflection from the first reflected signals are represented using different symbols.



the first reflection the second reflection

radio ray connecting from the first reflection to the second reflection

Figure 5. 26 Map of Reflection Points Distribution

5.7.2.1.1 Locating Reflection Points

The principle used in PhotoGIS* for detecting reflection points is used [Driessen & Zwart1], [Driessen & Zwart2], [PhotoGIS] and [Driessen & Boden]. PhotoGIS simulates radio signal transmission through a series of lines extending from the transmitter over the signal propagation area. These lines represent radio beams radiated from the antenna. A single line is created for each angle over the azimuth range and on each angle of azimuth, a range of lines is drawn for each defined tilt angel. A 1° interval

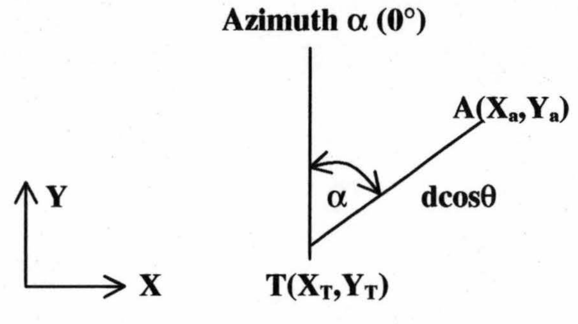
* The author would like to thank Mr. S. Quan for providing the source code for detection of intersection locations.

is used in both vertical (tilt) and horizontal (azimuth) directions. Each line is extended until it intersects the Earth surface. At the intersection, a reflection line is defined. The reflection direction is derived from the incident angle, the Earth surface slope and aspect at the intersection. The reflected line is then extended at the reflection angle until it intersects with the Earth. The second reflection angle and line can then be derived again using the same principle as the first reflection. The process can be repeated until a predefined threshold is met.

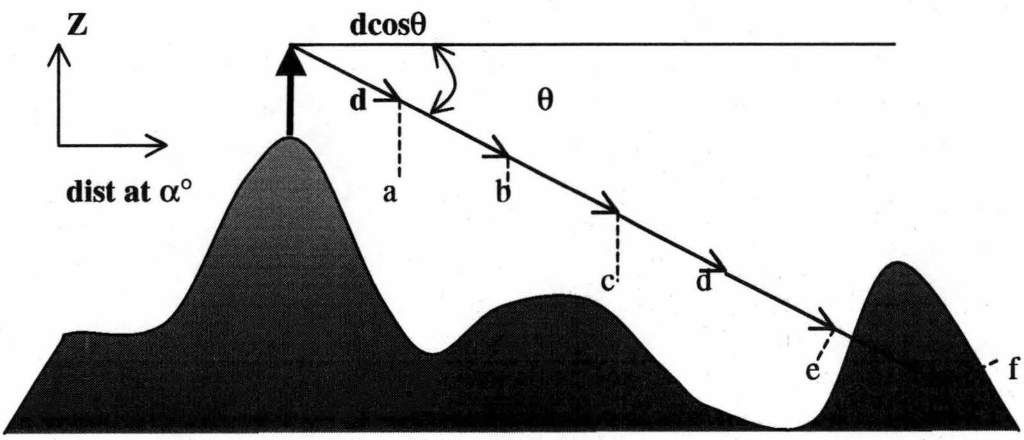
To determine where each line intersects the Earth surface, it is extended along the pre-determined horizontal and vertical radiation angles from the transmitter location. As intervals are added, a check is performed to determine if the line hits the Earth. If no hit is found, the line increases its length again in the same direction with the same interval. The line keeps increasing until a hit is found. Figure 5. 27 illustrates the principle of finding reflection locations. Note that points *a, b, c, d, & e* are points where intersection is tested in Figure 5. 27. The diagram represents one single hypothesis line T*e* for a given azimuth α and vertical angle θ. A path profile is extracted from the transmitter T, in the direction of azimuth. The extension interval *d* is assumed. The x, y coordinates at point *a* were calculated from θ (vertical angle with the horizon line), α (azimuth) and (X_T, Y_T) by [5.24]. A theoretical height Z_i at point *a* is calculated using [5.25]. The actual elevation value Z_a is interpolated from the profile at location Xa, Y_a. If the difference between Za and Zi is positive, ie. the line has not intersected the surface yet, another d is added to the line, the calculation is then repeated using 2d instead of d in equation [5.24] & [5.25]. This process is repeated by adding interval of length d to the line, until the calculated difference is zero or negative. Point *f* in Figure 5. 27 indicates a reflection point has been identified X_f, Y_f, Z_f are then recorded

$$\begin{cases} x_a = x_T + d\cos\theta\sin a \\ y_a = y_T - d\cos\theta\cos\alpha \end{cases} \qquad [5.24]$$

$$z_a = z_T + antenna\_height - d\sin\theta \qquad [5.25]$$



(a) Horizontal View



(b) Vertical View

Figure 5. 27 Searching For a Reflection Point

The point where the intersection occurs may not be an exact reflection point. However, the difference can be ignored if d is insignificant in comparison to the distance between the transmitter and the reflection point. The extension distance *d*, is determined according to the size of the service area, data resolution, data accuracy, and performance time required from the program.

Multiple reflection locations can be studied by applying this procedure repeatedly. To look for the second reflection, the angle between the reflected signal and the horizontal line is calculated by [5.26], and used as the θ in the [5.24] & [5.25]. Figure 5. 28 illustrates the method to calculate the reflection angle.

In Figure 5. 28, θ is the vertical radiation angle from the transmitter T, β is the slope of the path profile at the reflection location, i is the incident angle, and r is the reflected. R can be calculated using equation [5.26].

$$\boxed{R' = 2\beta + 6} \qquad [5.26]$$

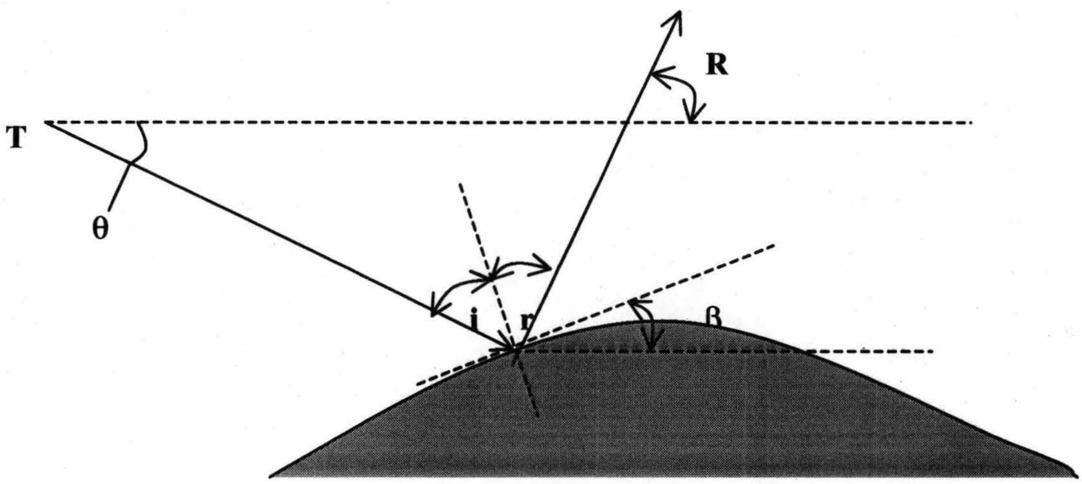


Figure 5. 28 Calculation the Reflected Angle

5.7.2.1.2 Area Reflection Analysis

An area reflection analysis can be carried out by repeatedly applying the reflection model at every azimuth degree from 0° to 360°, with a vertical degree between -90° and 90° at 10° intervals. The vertical and horizontal range can then be re-defined from the default value. For example, when a transmitter is located at the edge of the service area, there is no need to calculate areas that are outside of the service area, and therefore the azimuth range can be reduced so that only the service area is covered.

The intervals can be defined depending upon the level of detail required. Results of the area reflection analysis can be stored for further analysis or display purposes.

5.7.2.2 Reflection Loss

When a radio wave strikes the Earth's surface and reflects, the signal strength of the reflected wave is lower than the incident wave. The energy difference between the incident and reflected signal is absorbed by the Earth surface. While reflection does occur, the Earth surface is not a perfect reflector, and energy is refracted into the Earth. When an electromagnetic wave crosses the interface of a less dense media into a denser media, part of the wave is reflected, and rest is refracted into the denser media (Figure 5. 29). This holds for radio signals that propagate through the air and reflect on the Earth's surface because the Earth's ground density is much larger than density of air.

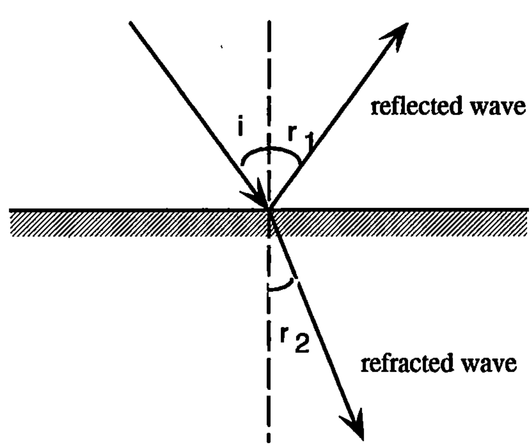


Figure 5. 29 An Electromagnetic Wave Travels From a Lighter Mass Media Into a Heavier Mass Media

where $\angle r_1 = \angle i$ according to the Snell's law.

$$\boxed{\frac{\sin i}{\sin r_2} = \frac{\sin r_1}{\sin r_2} = \frac{n_r}{n_i} = \frac{n_2}{n_1}} \qquad [5.27]$$

where the n_1 and n_2 are the index of refraction for the respective media,

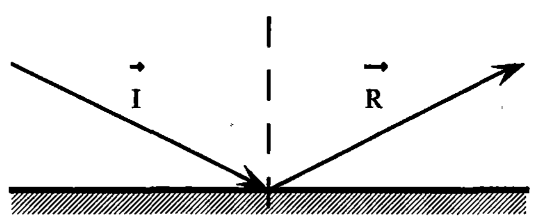
$$\boxed{\because\ n = {}^{c}/_{v}} \qquad [5.28]$$

where c is the speed of light in the air, and v is the wave speed in the material

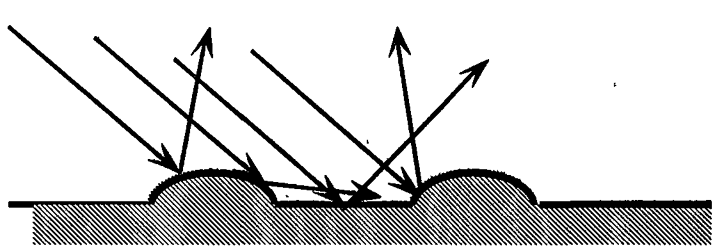
$$\therefore \frac{\sin r_1}{\sin r_2} = \frac{n_2}{n_1} = \frac{\frac{c}{v_2}}{\frac{c}{v_1}} = \frac{\frac{c}{v_2}}{\frac{c}{c}} = \frac{c}{v_2} = \frac{c}{v_{earth}} \quad [5.29]$$

The angle of refractivity is determined by the materials of the Earth's surface which in turn, determines the amount of the energy been refracted. The smaller r_{earth}, the more energy is refracted, and the less reflected.

In addition, two types of the reflection occur in the real world, spectacular reflection and diffuse reflection Figure 5. 30 (a) and (b). It is obvious from the Figure 5. 30 that diffused reflection will cause more energy loss than spectacular reflection. In practice, diffuse reflection occurs in hilly areas or on rough surfaces, and spectacular reflection on smooth surfaces, such as water.



(a) spectacular reflection



(b) diffuse reflection

Figure 5. 30 Diagrams of Spectacular Reflection and Diffuse Reflection

To include the contribution to radio signal energy fading from the above two reflection phenomena, a reflection coefficient is used to denote the refraction ratio for the Earth surface material, and an index of divergence to represent the Earth's surface roughness.

A series of formulae are employed to represent the reflection loss. If E_0 is the transmitted energy at the antenna, E_i is the energy of the incident signal, $E_r = \rho \bullet E_i$, the energy of reflection signal, and E the energy at the receiver, then E_i can be obtained by subtracting the plane Earth loss and free space loss from E_0, where E is the reduced value of E_r. Figure 5. 31 illustrates the relationship between E_0, Ei, Er and E. The amount of path loss is calculated using formula [5.30].

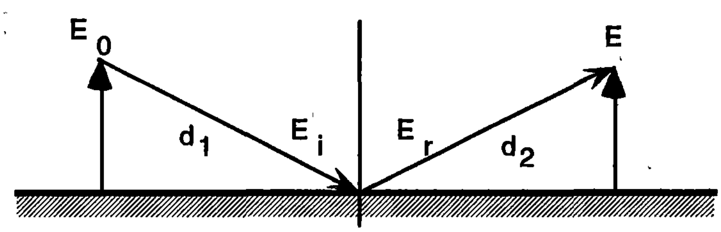


Figure 5. 31 The Energy Decrement in the Reflection

$$\begin{aligned} path - loss &= 20\log\frac{E}{E_0} = 20\log\frac{c}{4pfd_2}\bullet\frac{E_r}{E_0} \\ &= 20\log\frac{c}{4pfd_2}\bullet\rho\frac{E_i}{E_0} \\ &= 20\log\left(\rho\frac{c}{4pfd_2}\right)\frac{c}{4pfd_1}\frac{E_0}{E_0} \\ &= 20\log\rho + freespace\_loss1 + freespace\_loss2 \end{aligned} \qquad [5.30]$$

where *freespace_loss1* is the free space loss from transmitter to the point of the reflection, *freespace_loss2* is the free space loss from reflection to the receiver.

Reflection coefficient ρ is the result of [5.31].

$$\rho = \sqrt{\rho_h^2 + \rho_v^2}$$
$$\rho_h = \frac{\sin\psi - \sqrt{\varepsilon_c - \cos^2\psi}}{\sin\psi + \sqrt{\varepsilon_c - \cos^2\psi}} \qquad [5.31]$$
$$\rho_v = \frac{\varepsilon_c \sin\psi - \sqrt{\varepsilon_c - \cos^2\psi}}{\varepsilon_c \sin\psi + \sqrt{\varepsilon_c - \cos^2\psi}}$$

where ρ_h is the effects from horizontal polarization and

ρ_V is the effects from vertical polarization signal.

$e_c = e_r - j60ls$ is the complex dielectric constant

e_r : dielectric constant of reflection surface

l : wavelength

s : consuctivity of reflection surface

ψ : is the incident angle

$$\psi = 90° - \theta = 90° - \cos^{-1}\frac{(-IA)}{|I||A|}$$

where

I : vector of incident ray

A : vector of surface normal

$$\psi = 90° - \cos^{-1}\frac{(-a_1i_1 - a_2i_2 - a_3i_3)}{\sqrt{a_1^2 + a_2^2 + a_3^2}\sqrt{i_1^2 + i_2^2 + i_3^2}}$$

5.7.2.2.1 Reflection Loss Calculation

The implementation of [5.30] and [5.31] is quite time-consuming because it involves a complex calculation. To simplify the computing of the reflection loss, look-up tables were used. Table 5. 4 lists the smooth Earth reflection coefficient for horizontal and vertical polarization. Table 5. 3 lists the hill Earth coefficient for frequencies between 800 and 900 MHz. Both tables were derived from Shibuya's graph [Shibuya].

Type	Desert	Flat Forest	Forest	Undulated Forest	Industry	Stone Mountain
Coefficient	0.580	.0370	0.195	0.150	0.082	0.080

Table 5. 3 Reflection Coefficient Look-Up Table for Rough Earth Surface

Grazing	**Sea**	**Water**	**Damp**	**Ground**	**Fertile**	**Land**	**Dry**	**Land**
Angle Ψ	**h**	**v**	**h**	**v**	**h**	**v**	**h**	**v**
10′	1.000	0.940	1.000	0.960	0.990	0.980	1.000	1.000
20′	1.000	0.875	1.000	0.950	0.980	0.960	1.000	0.990
30′	1.000	0.825	1.000	0.920	0.980	0.940	1.000	0.980
40′	1.000	0.775	1.000	0.900	0.975	0.925	1.000	0.975
50′	1.000	0.745	1.000	0.875	0.975	0.910	1.000	0.970
1.0°	1.000	0.700	1.000	0.860	0.975	0.890	0.995	0.960
1.5°	0.990	0.550	.0990	0.750	0.960	0.850	0.990	0.950
2.0°	0.980	0.485	0.980	0.675	0.960	0.775	0.980	0.900
3.0°	0.970	0.375	0.970	0.550	0.950	0.685	0.970	0.850
4.0°	0.965	0.270	.0960	0.450	0.940	0.620	0.950	0.760
5.0°	0.960	0.175	0.960	0.350	0.935	0.540	0.930	0.700
6.0°	0.960	0.085	0.955	0.300	0.930	0.480	0.900	0.630
7.0°	0.960	0.050	0.950	0.220	0.930	0.420	0.880	0.580
8.0°	0.950	0.150	0.940	0.150	0.930	0.370	0.860	0.540
9.0°	0.950	0.225	0.935	0.100	0.920	0.320	0.840	0.500
10°	0.950	0.280	0.930	0.050	0.900	0.280	0.830	0.450
15°	0.945	.0550	0.910	0.200	0.850	0.050	0.810	0.410
20°	0.940	0.575	0.880	0.320	0.800	0.100	0.740	0.230
30°	0.900	0.770	0.850	0.460	0.720	0.250	0.670	0.080
40°					0.650	0.350	0.580	0.070
50°					0.600	0.420	0.500	0.150
60°							0.450	0.220

Table 5. 4 Reflection Coefficient Look-Up Table for Smooth Earth Reflection

5.7.2.3 Time Delay

A time delay occurs at the receiving antenna between the radio wave propagated through the reflected path and the signal via the direct path, as shown in Figure 5. 32. It is caused by the path length difference between the reflected ray d_1d_2 and the direct ray dd. This influences the signal strength at the receiver if both signals reach the receiver without being blocked. In other words, the reflected signal may increase or decrease the direct signal depending upon the relationship between the time delay and the period of the signal. If the delay is half the period of the signal, the direct wave strength decreases because of the reflected wave, otherwise, the direct signal strength increases. This characteristic is represented in the phase difference of the two signals.

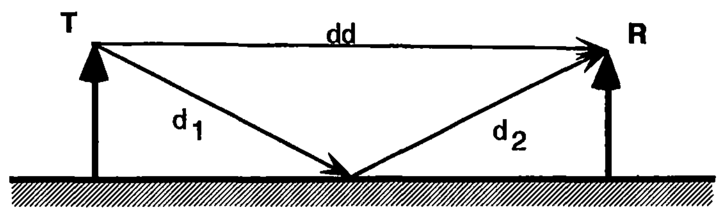


Figure 5. 32 The Propagation With Direct Transmission and Reflection

Time delay can be calculated in formula [5.32] by supplying the path difference value Δd.

$$\Delta t = \frac{\Delta d}{c} = \frac{\Delta d}{3\times 10^8 m/s} = \frac{d_1 + d_2 - dd}{3\times 10^8 m/s} \quad [5.32]$$

The phase difference at Δt is Δp, because

$$\frac{\Delta t}{T} = \frac{\Delta p}{360^\circ}$$

∴

$$\Delta p = \frac{\Delta t}{T} 360 = 360 \frac{\Delta t}{l} c = 360 f \Delta t$$

[5.33]

5.8 CONCLUSION:

This chapter discussed a path loss prediction model for cellular mobile telephone signal using a GIS approach. With GIS analysis and manipulation tools, the effects of terrain on radio signal propagation can be determined quantitatively. In particular, with GIS analysis tools, simple qualitative analysis can also be conducted. The GIS method also provides advantages in displaying the prediction and analysis results over existing commercial software.

The path loss computing methods were explained. Point-to-point path loss values can be calculated by analyzing the features along the path profile. The area distribution of the path loss values from a given transmitting antenna in the service area can be studied through area prediction, which stressed the surface features' influences. The value resulting from the area analysis can be plotted on a map so that the result can be presented in a straightforward fashion.

Reflections in the service area can be analyzed in the model by searching for possible reflection positions, calculating reflection loss and estimating the time delay specifications between direct and reflected signals.

The model, if compared with the commonly used prediction method, emphasizes the terrain's influences, such as the Earth's surface features. By using GIS software, the model has an enhanced capability to qualitative and quantitative analyze radio propagation conditions.

CHAPTER 6

DISCUSSION OF USING A GIS METHOD TO PREDICT PATH LOSS FOR 800 – 900 MHZ RADIO SIGNAL

The path loss prediction model described in the last chapter provides an alternative method for predicting path loss values for 800-900 MHz radio signals. The conventional path loss or field strength prediction models apply theoretical or empirical models over a regular terrain model. The resolution of this grid is usually 500 meters. Discussion in the last chapters emphasized the advantages of using TIN over the regular terrain model GRID. However, it might be argued that the TIN structure representing the terrain elevation may also miss important Earth features because the appropriate data may not be available during the creation of the TIN representation. The resolution used to build the triangular network may also cause important features to be discarded.

In addition, assumptions and simplifications have been made during the design and implementation of the model. Although this has simplified the implementation, these may also impact on the accuracy of the predication results.

More importantly, field trials should be conducted to verify the path loss prediction. This could be done as an extension to this thesis.

This chapter attempts to discuss the factors that were not considered and simplifying assumptions that have been made. It analyzes the positive and negative effects of these factors on the thesis design and implementation. Further, studies are proposed which account for these additional factors, and which may lead to an increase in the prediction accuracy. Additional functions are also discussed for enhancing the model using existing GIS functionality.

6.1 TIN VS. GRID

As indicated in Chapter 4, TIN was chosen in this thesis as the digital terrain model to provide the path profile used for path loss prediction. The advantage of using a TIN structure as the terrain model is that it represents important features in the terrain environment. In particular, sudden changes can be retained in the model, even when a relatively course resolution is used. This is because the TIN model can be implemented to enforce the representation of important features. In addition, the TIN model contains adaptively sampled point data in which the density changes according to the degree of variation in the Earth's surface.

This keeps surface continuity by using high-density sample points for hilly areas and low-density distribution for planes. The varying density characteristics result in less storage space required to store the TIN model. More importantly, the triangular facets in the TIN model provide the sample point locations for the area path loss prediction, as they are formed based on a known elevation location. Because facets incorporate the important elevations in the model, the sample points derived from the facets provide an easy way to capture the features that reflect the important characteristics of the terrain surface. The method of selecting sample points for area path loss prediction implies the sample points reflect the Earth surface features that contribute to the path loss during the radio signal's propagation.

6.1.1 Factors That Effect Path Loss Accuracy Using the TIN Method

Although the TIN model has the ability to store important Earth surface and other man made features, the data has to be available for inclusion in the TIN model. For example, digital elevation data is derived from contour data, which is either digitized or scanned from existing topographic maps. The TIN model in this thesis was generated using contour data digitized from a 1:25,000 scale topographic map. Data correction and errors during data capture may result in a TIN model that does not accurately model the Earth's surface. This in turn will lead to path loss prediction errors.

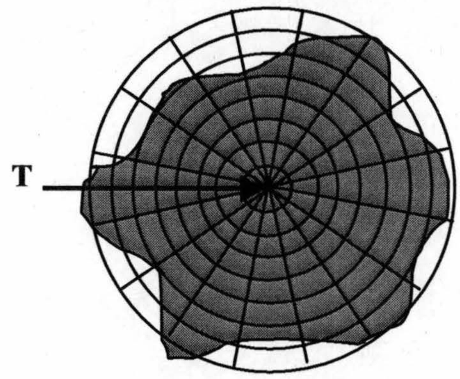
Another factor that may cause a deviation in the area path loss prediction result, is the method of selecting sample points based on triangle facets. In a plane area, terrain variation is small, and less sample points are required to build the TIN model, therefore, the triangle facet may result in a large area. This is more obvious when resolution is large during the creation of the TIN model. In this situation, field strength value at the center of a large triangle facet may not accurately represent the field strength for all areas within the triangle.

To improve the path loss prediction accuracy and reduce the influence of the above factors, a smaller resolution can be used during the creation of the TIN model. The Earth features that influence the path loss prediction, such as mountain peaks, lakes, and high rise buildings should be incorporated into the TIN model if possible. Triangle facet analysis could be added as an enhancement of the sample point selection for area path loss prediction. The facet size and shape could be examined to determine if additional sample points for large or long triangle facets are required.

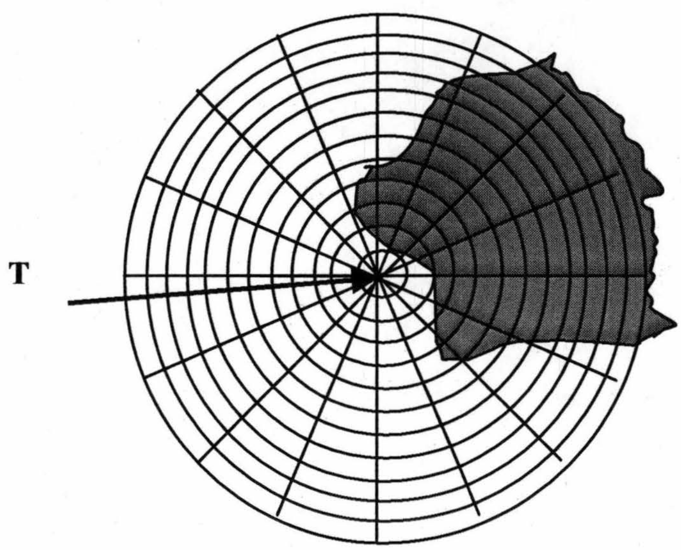
6.1.2 Sample Point Selection Method and Its Alternatives

This thesis uses the sample point selection method derived from the TIN structure. The method has the advantage of simplicity, because the triangle facets created contain the important terrain features — the triangle node points are selected from the features entered during the TIN creation, such as mountain peaks, ridges. This method uses less sample points for area path loss prediction compared to the regular sample point selection methods in plane areas, or smooth Earth surface environment. In hilly undulation area, the method may employ a similar amount or more sample points compared to the regular grid terrain model. In this situation, a regular grid terrain model could be used. The sample points could be derived from grid, and stored with the grid, or by simply using the terrain grid cells as the sample points. In addition, the grid terrain model can replace the TIN model if different resolutions can be used. In hilly areas, a finer resolution is chosen, and a large resolution used for plane areas. This reduces data redundancy in the GRID model and simplifies storage and model maintenance.

However, both methods of sample point selection require a path profile to be produced for each sample location to determine the path loss. For a large area, performance may be slow because of the large amount of sample points. For each sample point, a path profile is required. As an alternative, a regular radial sample point selection method could be considered. Sample points are selected from radial lines from the transmitter location to the edge of the study area. Points along the radial lines are selected at regular distances. The radial lines can be constructed in regular degree intervals starting from one edge of the study area to the opposite side. If the transmitter is within the study area, radial lines can be built 360° around the transmitter. The method is illustrated in Figure 6.1 (a) and (b). Figure 6.1(a) has a transmitter which is included the study area. Figure 6.1(b) has a transmitter that lies outside the study area. All sample points are represented as the intersection between the radial line and concentric circles, with their center as the transmitter.



(a) Transmitter is inside the service area



(b) Transmitter is outside the service area

Figure 6. 1 Selection of Sample Points Using Radial and Concentric Circles

Figure 6.1 illustrates the principle of the intersection of the concentric circles and radial lines starting from the transmitter. The concentric circles and radial lines can be constructed so that only points within the service area are used to speed up the calculation process. Some additional radial lines can be added if the study area is large. For a large study area, distances between intersections change as the distance from the transmitter changes. Additional sample points can be added as the distance from the transmitter increases. This can be done by adding additional radial lines, as illustrated in Figure 6.2.

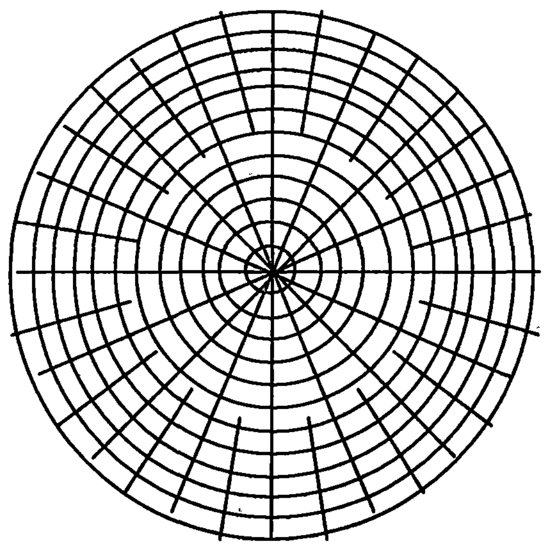


Figure 6. 2 Additional Radial Lines Added For Additional Sample Points

The radial selection of sample points can reduce the time required to perform area path loss prediction. Path profiles are only generated along the radial lines from the transmitter to the end of the lines. Many sample points on a radial line can use the same path profile data to calculate path loss values because samples along the radial line share the same profile. For a specific sample point, profile section from the transmitter to the sample point and profile characteristics up to the sample point are used. Because the path profile generation and profile shape analysis is only conducted once, the performance time can be improved for the area prediction process.

6.2 PATH LOSS PREDICTION

In chapter 5, methods of quantitative path loss prediction and qualitative analysis of radio signal transmission were discussed. The qualitative path loss prediction applies an existing path loss prediction model to a series of sample points selected from the TIN to predict path loss values for the study area. Chen's model was selected for testing purposes. Because the implementation of the prototype separates the path loss prediction model from the sample point selection and path profile extraction processes, other path loss prediction models can be used. This flexibility allows multiple path loss prediction models to be used on the sample path profile for a selected sample point. Comparison between different models can then be performed.

The path loss prediction method can be extended to include field strength prediction by adding the transmitter antenna and receiver antennae specifications. This will help in the planning of mobile telephone and other VHF/UHF radio services.

6.2.1 Assumptions Related To the Path Loss Prediction Result

As indicated in previous chapters, various assumptions were made during the design and implementation of the prototyping process of the path loss prediction analysis. These assumptions may influence the path loss prediction results in both the qualitative and qualitative analysis processes.

Transmitter and receive antenna heights were assumed to be 20 meters and 3 meters respectively. In real situations, transmitter height can vary. A higher antenna height may change the results of the path loss calculation and line of sight analysis. To overcome this limitation, transmitter and receiver antenna heights can be entered by the user before the profile analysis begins.

Transmitter and receive antennas were assumed to be tropospheric. This assumes the transmitter antenna radiates the same signal strength in all directions both in the horizontal and vertical plane. Antenna's can not achieve the tropospheric antenna specification. As a result, this model ignores the signal loss caused by the antenna. To solve this problem, two options can be used. Firstly, instead of calculating path loss, the field strength value at the receiver can be calculated. The transmitted field strength and the radiation patterns for both antennae can be included in the field strength calculation. The second option is to scale the path loss result according to the ratio of the transmitter and receiver antenna radiation patterns to a uniform tropospheric antenna specification.

Straight-line distance was used in the path loss calculation distance. The Earth surface curvature was not considered because of the assumption on Earth bulge. In addition, the Earth surface curvature has not been included in the prototype study because of the study area size of 5 X 11 km width by length. The Earth surface horizon is 25 km using the assumed antenna height assumptions. The study area is within the Earth horizon distance. The surface curvature distance is the straight-line distance, and the Earth horizon can be ignored. However, for larger areas, the Earth surface distance should be used instead of straight-line distance to reduce the prediction deviation in line of sight and reflection analysis.

No Fresnel clearance was applied to the line of sight analysis. Although justification has been made in Chapter 5 for the line of sight analysis principle, this assumption will enlarge the line of sight area. Further improvement can be made by modifying the algorithm to include the Fresnel zone clearance factor.

The effect of Earth bulge, atmospheric absorption, Earth surface features, man made objects, and the soil type were ignored and unified for the line of sight and reflection analysis. These factors will all cause deviation in the predicted path loss value.

6.3 PATH LOSS PREDICTION RESULT COMPARISON BETWEEN VARIOUS PREDICTION MODELS AND EVALUATION WITH FIELD TESTING

The thesis was designed to conduct path loss prediction for mobile telephone signals using a GIS. It, therefore, emphasized the influence of the Earth surface features on VHF/UHF radio propagation. Some qualitative analysis methods predicting the VHF/UHF radio signal transmission using a GIS approach were also discussed. As explained in the Chapter 5, the methodologies to predict line of sight conditions, and radio signal reflection, were derived based on VHF/UHF radio communication theory and implemented using existing commercial GIS software.

In the prototype, a point to point and a point to area path loss prediction were designed and implemented on the selected study area. Chen's path loss prediction method was chosen. The model was programmed so that for a given terrain model, the user can nominate a transmitter antenna and receiver locations. The path profile including the Earth bulge modification was displayed, and the path loss value for the specified transmitter and receiver locations was calculated. An example of the process is shown in Figure 5.11. The nomination of transmitter and receiver locations provides a flexible method for path loss calculation.

For an area prediction, a user selects a transmitter location, and a path loss for the whole study area was then calculated. Results of the area production can be stored and presented in different formats, Figure 5.14 and 5.15 illustrate two methods of result presentation.

The independence of the terrain model and path loss prediction model enables the comparison of path loss prediction results using different prediction models. As indicated in the previous chapters, various path loss prediction models have been designed and published. The complexity in the effect of surface features on VHF/UHF signal propagation requires the use of multiple path loss prediction models during the engineering design process. Each different model will have a different emphasis on the effect of the Earth surface features. To provide more accurate prediction, it is necessary to apply additional path loss prediction models to the same terrain model. In addition, more specific Earth surface features are required for some prediction models. An extension of this thesis could be the implementation of other path loss prediction models to verify the prediction results.

Field-testing to verify the results of the computerized prediction model is another important process. No matter how accurate the terrain TIN model represents the Earth surface, there are always assumptions and simplifications made when implementing computer models. Only field experiments can prove the accuracy of the model. The field test results can also be analyzed and used as the supplementary amendment to the results.

Note that field experimentation was not included in the prototype design because the emphasis has been on using a GIS method in path loss prediction within existing frameworks. The exaggeration of the terrain elevation in the prototype TIN model also prevented the comparison of computerized results with actual field tests. Furthermore, the model would need to consider antenna specifications, the use of different path loss prediction models, and the use of a real life terrain model to ensure an adequate comparison.

CHAPTER 7

CONCLUSION

This thesis analyzed VHF/UHF radio signal propagation characteristics, and Earth surface features, in particular the terrain elevation, contribution to signal propagation loss. Various propagation path loss prediction models have been developed based on VHF/UHF radio communication theory by telecommunications engineers. Most of the models apply a series of derived formula to a terrain model which is usually stored in a regular matrix pattern with a resolution of 500 meters.

Trying to approach the path loss prediction problem from the GIS point of view, an alternative method to perform path loss prediction for 800/900 MHz mobile telephone signals were discussed and prototyped. The method was designed and developed due to the mobile telephone signal's propagation properties and the specialization of the GIS approach. The mobile telephone signal employs 800/900 MHz radio signal, and thus possesses all the propagation characteristics of VHF/UHF radio transmission. Therefore, existing path loss propagation prediction models for VHF/UHF can be applied to 800/900 MHz mobile telephone signal.

When summarizing existing path loss prediction models, three categories are found. — experimental, empirical, and analytical. The experimental tests field strength values using electronic devices. The empirical model's apply statistical results to a classified area to estimate the path loss. Analytical models combine the statistical results with theoretical formula to generate a new series of formulae to utilize with the prediction area and path profile analysis. Because of the complexity of and variety in the Earth surface's effect on the radio signal propagation, empirical models have restricted usage.

Analytical models have been automated, as discussed in the previous chapters. The automated analytical models can perform point to point and point to area path loss prediction, with some calculating the field strength at the nominated receiver location. With point to point prediction, the path profile is retrieved from a terrain elevation database and the geometric characteristics of the profile are analyzed to calculate transmission loss. The point to area prediction is conducted by repeatedly applying the point to point prediction to a regular selected point matrix.

Because path loss prediction is dependent on the Earth surface environment, the process is ideal for the use of a GIS. The Geographic Information System, as indicated from the name, manages, manipulates and queries spatial and spatially related non-spatial information. Commercial GIS application software supply query and data manipulation functions that can be used in path loss and propagation predictions. This thesis designed and implemented a prototype to demonstrate that the GIS approach can be used in path loss prediction and propagation prediction as an alternative method to conventional path loss prediction methods.

The prototype experience shows that the GIS method can approach VHF/UHF radio signal propagation path loss prediction from two aspects. The quantitative calculation for point to point and point to area path loss prediction can be implemented using existing propagation model formulae. GIS functions were combined into a conventional propagation path loss prediction model to provide efficient terrain and other environment data management and manipulation.

The conventional path loss prediction method using a grid as the terrain model could be implemented using existing GIS packages, with some additional programming to include path loss calculation formulae. However, an alternative method using a TIN was provided in this thesis. With the TIN model providing the base triangle structure that represents the study area, the sample point selection process for area prediction is simplified. Because the triangle structure reflects terrain shape changes, it provides dense sample points in hilly areas where path loss changes are high and fewer points in plane areas. In addition, the TIN model can incorporate important Earth surface features. The sample points derived from the triangle facets can be used to calculate the path loss at that point. These characteristics provide a simple sample point selection method while also retaining important Earth surface features.

Using the existing GRID model, the regular sample distribution results in data redundancy or a loss of accuracy. A large resolution can reduce data redundancy in plane areas, but with a consequential loss in prediction accuracy in hilly terrain. A lower resolution will increase prediction accuracy in hilly areas, but also increases data redundancy in plane areas. The TIN model overcomes these limitations by providing a variable resolution. In hilly terrain where path loss changes are large, smaller triangle facets are generated resulting in a higher sample point density. In plane areas where path loss changes are smaller, larger triangle facets are generated, resulting in a lower sample point density.

The above argument is based on the assumption that there are details of Earth surface features available, and that the data has been used when creating the TIN data. The effectiveness of the TIN model is reduced if it does not accurately reflect sudden changes in elevation, or other important surface line or point features. However, the TIN model is more likely to represent such features accurately. In a GRID model only those features which can be represented within the resolution of the grid cell be used.

The second aspect, which the prototype attempted to explore, is qualitative analysis of VHF/UHF radio signal propagation. The qualitative propagation path loss analysis does not provide numerical prediction results. Because of the tedious and time consuming characteristics of calculating path loss prediction for a large study area, this thesis designed and implemented functionality aimed at providing a means to classify propagation analysis results in a reasonably short time. The functions included line of sight and reflection analysis. Because these processes can access large areas, for example a 500-km area, in a relatively small amount of time, it can be used to indicate areas where further detailed calculations should be performed.

The prototype in this thesis has shown that a GIS approach can be used in the VHF/UHF radio propagation prediction. It has the potential to simplify the process and provide further functionality using existing, or extensions of existing GIS functionality. For example, with the graphical presentation function, the path loss prediction result can be presented in many different formats, eg. A two-dimensional plane map, a three-dimensional view, or a simple text file. The other advantage of using a GIS is that both spatial and non-spatial data can be accessed using GIS software. Building location and orientation, and other surface objects or characteristics can be saved in the spatial database. Forestry details can be saved according to the seasons. Atmosphere refractivity and ground refractory can be accessed to calculate reflection and absorption, and so on.

In summary, radio signal path loss prediction and propagation analysis for cellular mobile telephone signals has been prototyped. The analysis process was simplified through the use of existing GIS functionality, and additional analysis tools compared to the conventional path loss calculations. In addition, results can be presented in a variety of formats for easy interpretation. However, further experiments are required to explore the prediction accuracy, and performance efficiency. Field tests should be considered. Although propagation prediction analysis using a GIS will need to be expanded from that presented here, its strengths for use in telecommunications environment have been demonstrated, through spatial data access, data management and spatial analysis. These factors make the GIS method an important part in the telecommunication industry.

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Appendix A

Vector Calculation

A vector can be represented its scalar value with the direction. It is often stored as one row or one column matrix.

Vector Addition:

If

$$\vec{a} = [a_1, a_2, a_3]$$
$$\vec{b} = [b_1, b_2, b_3]$$

then

$$\vec{c} = \vec{a} + \vec{b}$$
$$= [c_1, c_2, c_3]$$

where

$$c_1 = a_1 + b_1$$
$$c_2 = a_2 + b_2$$
$$c_3 = a_3 + b_3$$

Scalar of the Vector:

If

$$\vec{a} = [a_1, a_2, a_3]$$

then

$$n\vec{a} = [na_1, na_2, na_3]$$

Scalar Multiply of the Vectors:

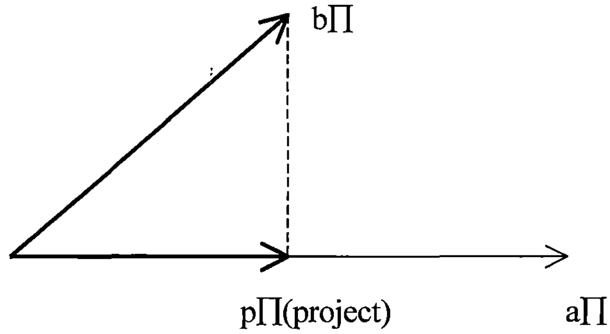
If

$$\vec{a} = [a_1, a_2, a_3]$$
$$\vec{b} = [b_1, b_2, b_3]$$

then

$$\vec{c} = \vec{a} \bullet \vec{b}$$
$$= a_1 b_1 + a_2 b_2 + a_3 b_3$$

Vector Projection:



Let $\vec{a}$ and $\vec{b}$ be vector in $\vec{R}n$ with $\vec{a} \neq 0$

The vector projection of $\vec{b}$ on $\vec{a}$ is $\vec{p}$

then

$$\vec{p} = \frac{\vec{a} \bullet \vec{b}}{\vec{a} \bullet \vec{a}} \vec{a}$$

the scalar component of $\vec{b}$ along $\vec{a}$ is

$$\|\vec{p}\| = \frac{\vec{a} \bullet \vec{b}}{\|\vec{a}\|}$$

in other words, if

$$\vec{a} = [a_1, a_2, a_3]$$

$$\vec{b} = [b_1, b_2, b_3]$$

$$\vec{p} = [p_1, p_2, p_3]$$

$\because$

$$\vec{a} \bullet \vec{b} = a_1 b_1 + a_2 b_2 + a_3 b_3$$

$$\vec{a} \bullet \vec{a} = a_1 a_1 + a_2 a_2 + a_3 a_3$$

$\therefore$

$$p_1 = \frac{a_1 b_1 + a_2 b_2 + a_3 b_3}{a_1 a_1 + a_2 a_2 + a_3 a_3} a_1$$

$$p_2 = \frac{a_1 b_1 + a_2 b_2 + a_3 b_3}{a_1 a_1 + a_2 a_2 + a_3 a_3} a_2$$

$$p_1 = \frac{a_1 b_1 + a_2 b_2 + a_3 b_3}{a_1 a_1 + a_2 a_2 + a_3 a_3} a_3$$