SIGNAL STRENGTH PREDICTION IN THE EASTERN REGION OF SAUDI ARABIA

BY

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TABLE OF CONTENTS

List of Tables

List of Figures

ملخص الرسالة

الإسم: ميثم محسن الصفواني

عنوان الرسالة: التنبؤ بقوّة الإشارة في الإقليم الشّرقيّ للمملكة العربيّة السّعوديّة

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نماذج خسارة الطّريق الحاليّة عدّلت و نموذج جديد طور لمناسبة بيانات إنتشار الإشارة المقاسة في الحقل في الإقليم الشّرقيّ. النماذج الجديدة و المعدّلة يمكن أن تحدّ من مشاكل التغطية و التّدخّل التي تحدث يوميًا في دول الخليج العربي. تظهر قوّة الإشارة المتنبّأة اتفاقيّة ممتازة مع البيانات المقاسة حول أبقيق، رأس تنورة و الظهران. موديلات التنبّؤ الجديدة مرنة و يمكن أن تعدّل بسهولة لتطبّق على نطاقات تردّد أعرض و ارتفاعات الإريلات المختلفة.

درجة الماجستير في العلوم

جامعة الملك فهد للبتّرول و المعادن

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ABSTRACT

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The existing path loss models were modified and a new model was developed to fit actual signal propagation data measured in the field and more accurately reflects and predicts Eastern Province propagation conditions. The new and modified models can help to minimize the coverage and interference problems that experience daily in the Gulf States. The predicted signal strength shows an excellent agreement to the measured data around Ras Tanura, Abqaiq and Dhahran radio base stations. The new prediction models are flexible and can be modified easily to be applicable to wider frequency bands and different antenna heights.

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS

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CHAPTER I

INTRODUCTION

1.1 BACKGROUND

The atmosphere is a medium of radio wave propagation. Radio wave propagation, in turn, is affected by frequency, distance, antenna heights, curvature of the earth, surrounding terrain, atmospheric conditions, and presence of hills and buildings. Signal strength prediction techniques are important to radio network designers; estimation of path loss is required to calculate signal to noise or signal to peak distortion ratios, frequency reuse to enhance capacity while keeping the co-channel interferences within acceptable limits. References [1] and [2] investigate the co-channel interference impacts on Vehicle-to-Vehicle Radio Communications.

Several models are used to calculate the signal strength at different frequencies, distances, weather conditions and terrain types. The free-space model is effective in a space devoid on any obstructions between a transmitting and a receiving antenna [1]. Free space path loss is calculated as:

$$\text{Path Loss (dB)} = 32.6 + 20 \log (F_{MHz}) + 20 \log (D_{km}) \qquad (1.1)$$

It is assumed the receiving and transmitting antenna gains are unity. For transmission paths more than a few kilometers (> 5 km) in length, earth curvature and irregular terrain can have a noticeable effect on radio signal attenuation.

Based on extensive radio strength measurements conducted in Japan over more than ten years, Okumura produced a series of graphs showing signal strength of a land mobile radio over frequency ranges of 150 to 2000 MHz for a distance of 1 to 100 Km and for a radio base station antenna height of 30 to 3000m [3]-[4]-[5]-[6]. A mobile antenna height of three meters was used in the measurements. He generated curves that relate field strength to distance and frequency in urban, suburban and open areas [5].

Hata converted Okumura's measurements into empirical relations. These formulas are based on quasi-smooth earth and do not include the effects of terrain conditions on the propagation loss. On the basis of urban area propagation loss, Hata developed correction factors for suburban and open areas [7].

Hata's formulas were built based on quasi-smooth where the 6dB/octave rule of base station antenna height is applicable, this rule, however, is not valid for irregular terrain. Lee found that doubling base station antenna height might not result in increasing the signal level by 6dB over a non-flat terrain. He proved the 6dB/octave rule of base station antenna height could be used only for flat terrain [9].

In order to utilize Hata's formulas in the Eastern Province of Saudi Arabia, other correction factors may be included, such as (1) Roughness of terrain, (2) Hill-diffraction, (3) Land-sea paths and (4) Weather conditions.

The Hata's empirical results were modified to include the diffraction loss in a so-called Epstein-Peterson multiple obstacle diffraction loss model [8].

The propagation test data reported by Okumura, however, cannot be satisfactorily applied to the Eastern Province of Saudi Arabia since the applicable correction curves do not reflect the weather as well terrain aspects of this area on radio signal strength.

Most existing radio signal propagation models are based on measurements conducted outside Saudi Arabia and may not be particularly useful or applicable to desert conditions. Chicon, for example, showed that Urban-Macro model can lead to more accurate estimation of signal strength in 1 km^2 area in Germany compared with those obtained from Hata or Cost-Walfish-Ikegami models [3]. The question arises, whether these models could be affected to conditions in existed in the Eastern Province of the Kingdom of Saudi Arabia?

From the above discussion, we stress the need of a modified propagation model, which could be used for desert terrain, hot and humid weather conditions.

1.2 PROBLEM FORMULATION

Many governmental departments and companies in Saudi Arabia operate and utilize radio systems in the VHF band. Saudi Aramco, as an example, operates many radio systems over areas where the terrain is irregular and composed of very high wedges that obstruct and attenuate radio signals.

The majority of Saudi companies operations and radio networks are located in the Eastern Province, and are surrounded by various Gulf States sharing the same portions of the VHF band for their radio communications.

Most cases of interference occur in the early morning hours and are generally suspected to be the result of a phenomenon referred to as "ducting". An accurate path loss model would be most useful in accounting for and minimizing the effects of such problems.

Poor radio coverage area is another problem facing radio engineers and users. Reducing dead spots and enhancing call-back coverage can be achieved by increasing antenna height, adding more radio base stations or satellite receivers to the radio network.

The above issues should be met during system design when path loss calculations are done. Their appearance after construction implies imperfection in the radio system design and could quite possibly have been avoided by having selected a more applicable path loss model for simulating signal strength around each radio system or base station.

At present, there are many software programs available for calculating signal strength and path loss around radio base stations. These programs do consider weather and terrain data in path loss calculations, possessing various path loss models. An appropriate path loss model should be selected based on frequency band, terrain condition, climate, and base station antenna height.

In the past, Saudi Aramco radio engineers had been advised to apply the Hata/Epstein path loss model for signal propagation calculations in the Gulf. While this model is used in the Gulf of Mexico, studies have shown that it fails to adequately fit actual propagation data collected from the field. Accordingly, it appeared useful to collect more propagation data during different climatic periods to modify this (Hata/Epstein) path loss model so it more closely represents actual conditions encountered.

An appropriately designed path loss model can minimize radio interference problems, control reusing of a radio channel frequency and determine the minimum geographical separation distance required to avoid interference due to the long-distance tropospheric transmission. Moreover, it will minimize the future modification to the radio network.

The target, therefore, is to define a path loss model able to fit actual data measured in the field that more accurately reflects and predicts Eastern Province propagation conditions. A large number of signal strength readings will be obtained, compared, leading, it is hoped, to a model customized to a degree to provide a better outcome. The ensuing model is expected to be the optimum in estimating the path loss for the VHF band in the Eastern Province of Saudi Arabia.

1.3 OBJECTIVE

To develop an appropriate signal prediction model that includes anomalous propagation and surface effects. Our targets are three folds:

1. To include desert and weather conditions into existing propagation models
2. To propose how the link parameters are modified; and
3. To determine how best to incorporate the environmental factors into the field measurements and results.

1.4 SCOPE OF WORK

Three VHF radio base stations were selected to study the available path loss models, they are located in Ras Tanura, Abqaiq and Dhahran area. These base stations are accessible and a part of a high traffic radio network. The equipments required for our study are: VHF radio base station, Mobile equipped with a VHF radio, Communication Test equipment HP-8920 and Global Positioning System (GPS) receiver. A Sedan vehicles equipped with the required test materials was prepared to complete the coverage campaign.

All test equipments used in the study were recently calibrated, and subject test devices (transmitter and receiver) were aligned according to normal industry standards and procedures. The level accuracy of HP-8920 was set to be ± 2.5 dB from the actual as noticed in its specifications manual. The position accuracy for Global Positioning System (GPS) receiver was set by the manufacturer to be 1-5 meters from the correct position. Below is the delineation of the work intended to achieve the stated objective:

1. **Preparing of a Mobile for the Coverage Campaign:** A mobile vehicle will be prepared to record the signal strength in land around the selected radio base stations. The mobile will be equipped with two antennas: 1.0 m height above the ground installed on the trunk and connected to the mobile VHF radio and the other is 1.5 m height above the ground installed at the roof and connected to the Communication Test Equipment. The mobile vehicle will be supplied with a small commercial GPS receiver.
2. **Gathering propagation data using existing radio network base stations and test equipment:** Propagation data will be collected around three existing radio

base stations. For these tests, base station antenna height and gain, type of coaxial cable, transmitter effective radiated power will be logged.

3. **Measuring radio signal strength in the coverage areas during different weather conditions:** The propagation data will be recorded every 500 meters over highways and main roads. The propagation data will be collected under conditions of different temperature and atmospheric pressures.

4. **Obtaining earth coordinates and elevations:** Global Positioning System receiver (GPS) will be used to provide earth coordinates and elevations where the field signal strengths are measured.

5. **Applying EDX program to calculate radio signal strength using different path models:** EDX signal pro is a program utilizing different path loss models to calculate radio signal strength at given locations. This program will be used to calculate radio signal strength attenuation using Okumura (Hata) model and Hata-Epstein model.

6. **Comparing the calculated and measured signal strengths:** The data measured in the field will be compared with the data predicted using Okumura (Hata), Hata-Epstein and Lee model. This test will be

done to identify the best path loss model that fit with acquired measurement.

7. **Determination of whether or not the radio link is affected by intervening terrain irregularities:** Terrain factors can affect propagation of radio signal and introduce more attenuation. The losses due to the terrain will be added to the analysis of field measurement.

8. **Establish whether or not a "duct" is present:** The changes of signal strength due to the change in the weather conditions will be analyzed to identify the presence or absence of the ducting.

9. **Determination of Duct height and thickness:** The pressure, temperature and vapor pressure will be used to calculate the height and the thickness of ducts.

CHAPTER II

MEASUREMENTS and RESULTS

2.1 INTRODUCTION

This chapter describes the measurement method used to obtain field data: signal strength, Cartesian coordinates and elevation above sea level. It also presents part of field measurements obtained for Ras Tanura radio base station.

The measurement campaign started on January 23, 2001 for a selected VHF radio base station located in Abqaiq area. It continued with another radio base station located in Ras Tanura for a period approximately 5 months, from January to May of Year 2001 over the main highways and roads.

2.2 MEASUREMENT METHODS

To have an accurate path loss model, real field data were collected. The signal strength readings were spread over several months and were taken at times. They were recorded using Communication Test Equipment (HP-8920), installed in a mobile with 1.5 m antenna height. In addition, a commercial Global Positioning System (GPS) receiver was used to obtain the Cartesian coordinates at each test point and to find the elevation above sea level at each location. The test equipment setup is shown in Figure (2.1).

The receiving antenna was installed on the top of the mobile vehicle to take normal measurements. The received radio signals from the mobile antenna were led into the signal strength meter of the Communication Test Equipment, and then the measured level, elevation and Cartesian Coordinates are recorded over hard papers.

Propagation data was first collected around an existing, operational VHF radio base station repeater located in the Abqaiq area then a VHF radio base station located in the Ras Tanura area. A mobile radio transmitter, installed in the test vehicle, was employed to activate the base station repeater transmitter. During the repeater transmitter's hold time, signal strength measurements were recorded.

The time and date were recorded for each test point. Weather conditions (i.e., temperature, pressure, vapor pressure, relative humidity) were thereby obtained from Saudi Arabia's meteorological department and keyed to the recorded time and date. In addition, the signal strength level was measured at a fixed point for two days. These measurements were done to correlate changes in atmospheric conditions during the daytime to variations in signal strength level. Line-of-sight distance to the transmitter, azimuth and the elevation above sea level were obtained for each test point using the EDX SignalPro program. It calculates distance and azimuth for each test point using its Cartesian coordinates obtained by the GPS receiver.

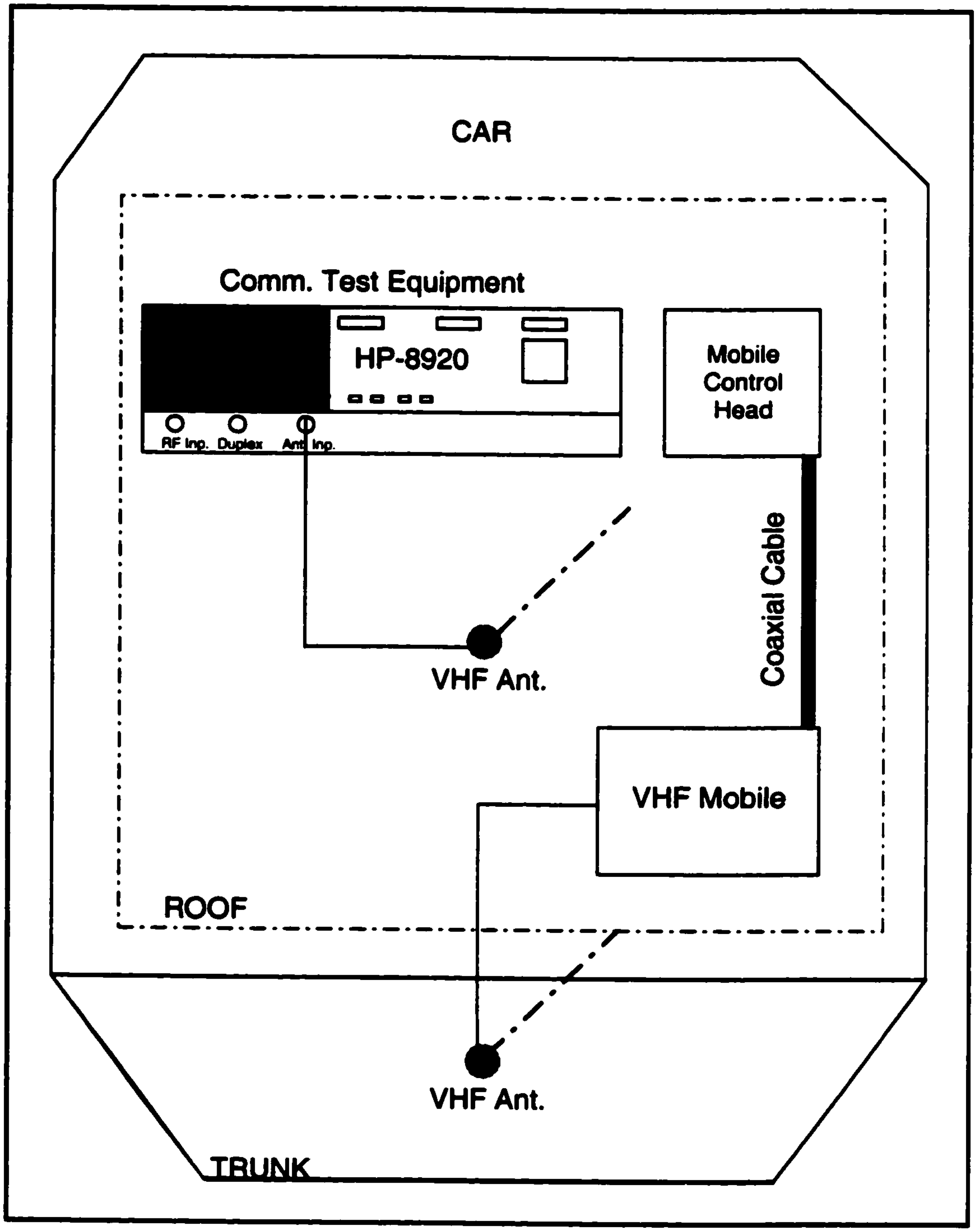

Figure (2.1) Test Equipment Setup

2.2.1 Abqaiq, Ras Tanura and Dhahran Areas

Signal strength measurements were taken in land around three radio base stations located in Abqaiq, Ras Tanura and Dhahran areas. Abqaiq is located in the South of the Eastern Province, 50 km away from the shore; the terrain of this area is irregular and composed of large number of sand dunes and hills, more information about this area can be obtained from Figure (2.2). It exists at a high elevation approximately 100 meters above the Sea Level. The high elevation of Abqaiq area enhances the coverage especially on Abqaiq-Dhahran highway. This area was selected in the coverage campaign because it has:

- Oil Producing Plants: There are many oil producing plants exist in Abqaiq area, the oil is carried through pipelines to Ras Tanura where it is exported to the outside rejoins.

Ras Tanura is a city and a port on the Arabian Gulf located in the eastern of Saudi Arabia, it has a residential area, vegetations, refinery and storage tanks. The average height of building at this area is 4 meters and most of building walls were made from wood. Areas surrounding Ras Tanura have quasi-smooth terrain and composed of sporadic pushes. More about Ras Tanura terrain is shown in Figure (2.3).

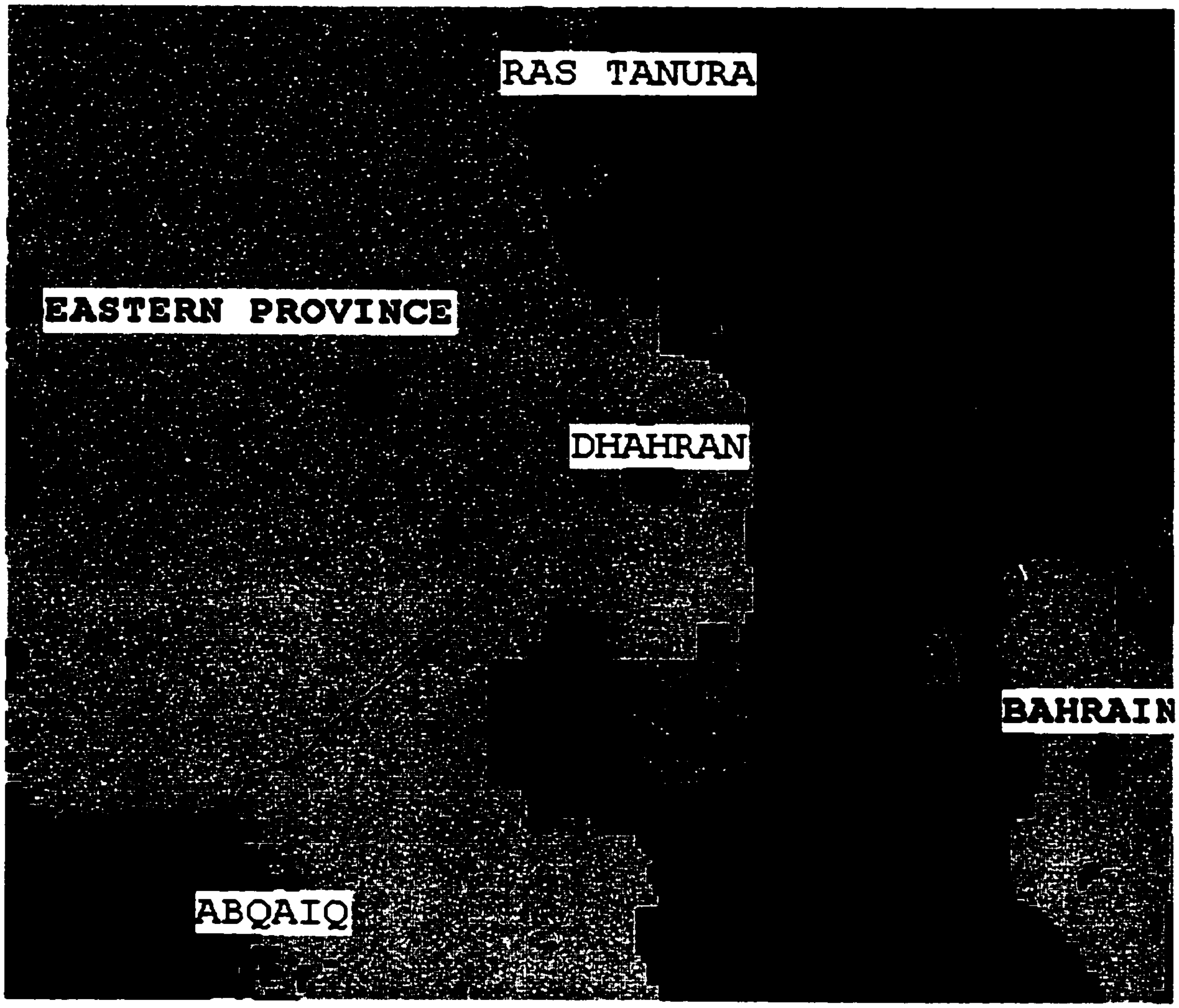

Figure (2.2) Area Covered During the Field Measurements, ABQ

Ras Tanura area was selected for the coverage campaign because of the followings:

- Anomalous propagation: At Ras Tanura, abnormal weather conditions can sharply enhance or degrade the received radio signal.

- Oil Operation: It is one of the major Aramco Oil Operation areas.
- In land routs: It has many inland routs that cover the whole land area and provide maximum number of test points.
- Interference Problems: There are many interference problems experienced in Ras Tanura area. These problems impact the different operations.

The terrain of Dhahran area is irregular and composed of high wedges and hills as shown in Figure (2.2); it has residential areas, farms and foliages. The average height of Dhahran buildings is more than five meters above the ground. The obstacles at Dhahran block and attenuate radio signals traveling on Dhahran-Jubail highway, to improve the coverage on this road, either the transmit power or antenna height is increased. So, it seemed important to have an idea about the coverage on Dhahran-Juabail highway for a radio base station installed in Dhahran area.

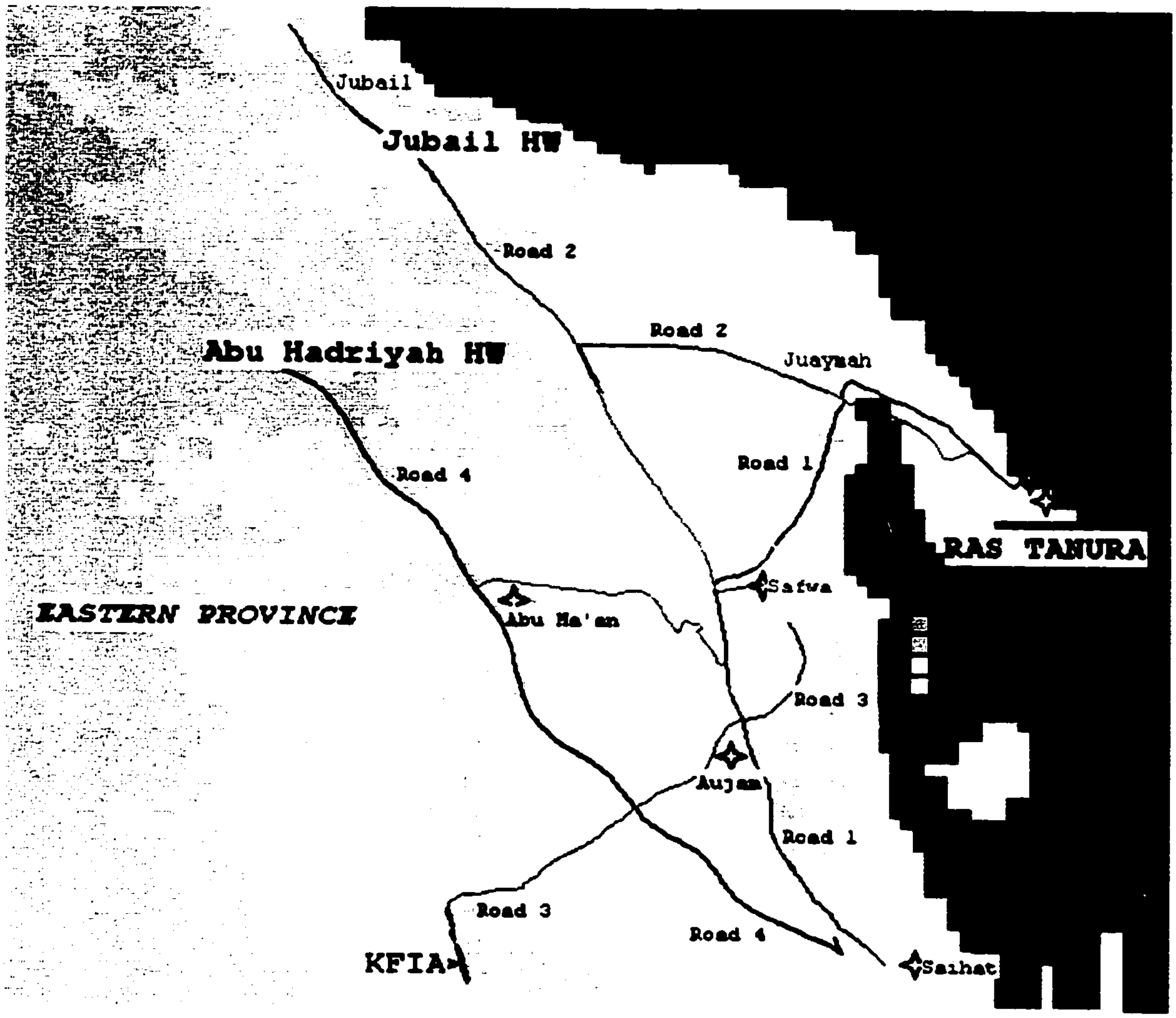

Figure (2.3) Area Covered During the Field Measurements, RT

The signal strength measurements at Abqaiq, Ras Tanura and Dhahran area were done on the following roads:

1. **Abqaiq-Dhahran highway:** Elevation of Abqaiq-Dhahran highway decreases away from Abqaiq then increases near to Dhahran area as shown in Figure (2.4). The signal strength on this highway was measured to study

the propagation over a hilly area that located deeper in the land and to compare the result with the path loss models to be obtained for Ras Tanura area. There are a small number of buildings and trees located on Abqaiq-Dhahran roadsides.

The variations of roads heights around Ras Tanura area are shown in Figure (2.5), these roads are:

2. **Saihat-Ras Tanura Road (1):** This road is a part of Dammam-Jubail highway. In the sides of this roads there are farms and buildup areas. The road increases near to Saihat to reach 22 meters then decreases to 1 meter above sea level at Ras Tanura area. There are some rises and terrain pushes along this road.
3. **Juaymah-Jubail Road (2):** This road is a part of Dammam-Jubail highway. The height of this road increases slightly until it reaches 15 meters above sea level about 40 kilometers away from Juaymah, and then it decreases to 8 meters at Jubail area. There are small numbers of trees beside the road and several buildup areas and pushes.
4. **King Fahd International Airport (KFIA) Road (3):** This road is run over an open area with a small number of rises. There are no trees or buildings in the

roadsides except some fences located at 15 meters away.

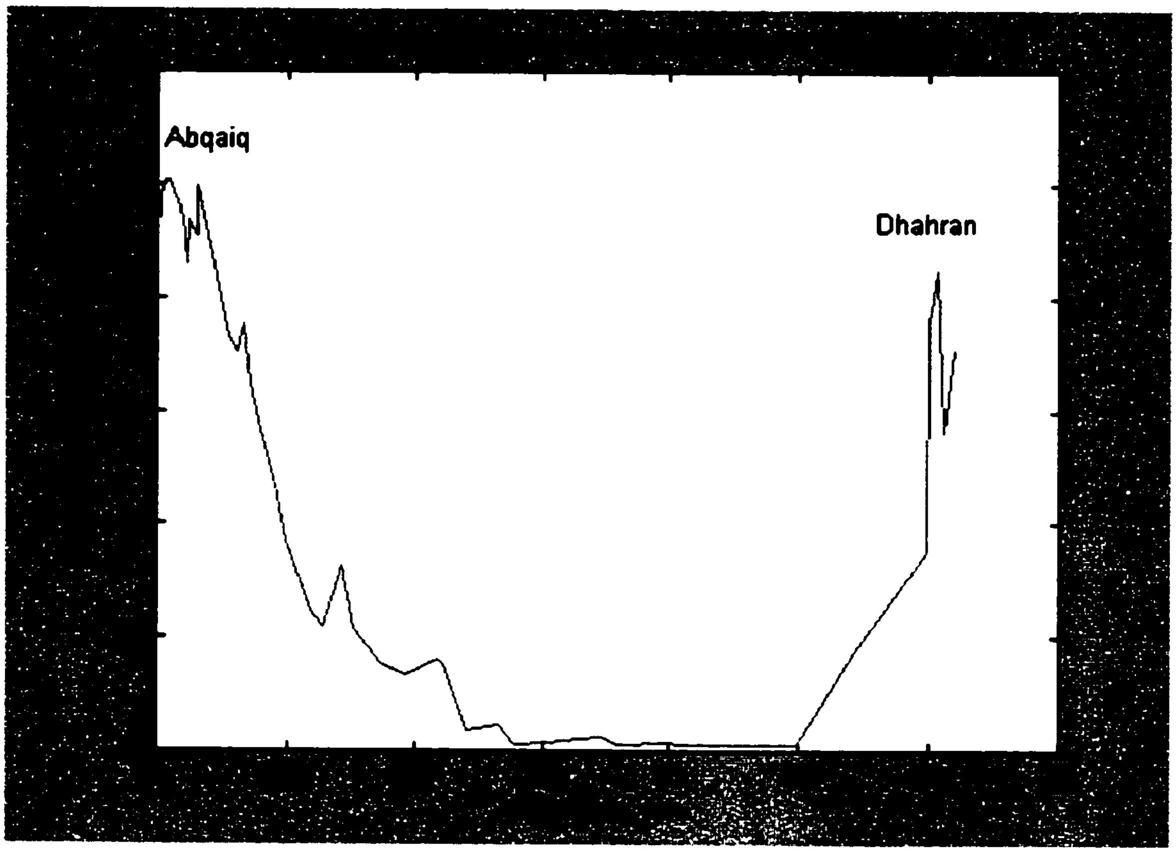

Figure (2.4) Height Variation on Dhahran-Abqaiq Highway

5. **Abu Hadriyah Road (4):** This road is located 23 km away from Ras Tanura radio base station. It provides the right accesses for Saudi vehicles to the main cities located on the North of the Eastern Province. The density of side trees and buildings increases in the South and decreases in the North of Abu Hadriyah highway where the terrain becomes more irregular.

6. **Dhahran-Safwa Road:** This road is a part of Dhahran-Jubail highway. The measurements recorded on this road are for a VHF radio base station located at Dhahran area. Dhahran is an urban area; it has irregular terrain that composes of hills and wedges. There are many buildings located on Dhahran-Safwa roadsides, the density of buildings decreases toward the North. The variation on the height of Dhahran-Safwa road is presented in Figure (2.6)

There are more routes selected to measure the signal strength, these are located in Safwa and Abu Maan areas. They were selected to have additional measurements that can be used to obtain more accurate path loss models for Ras Tanura radio base station.

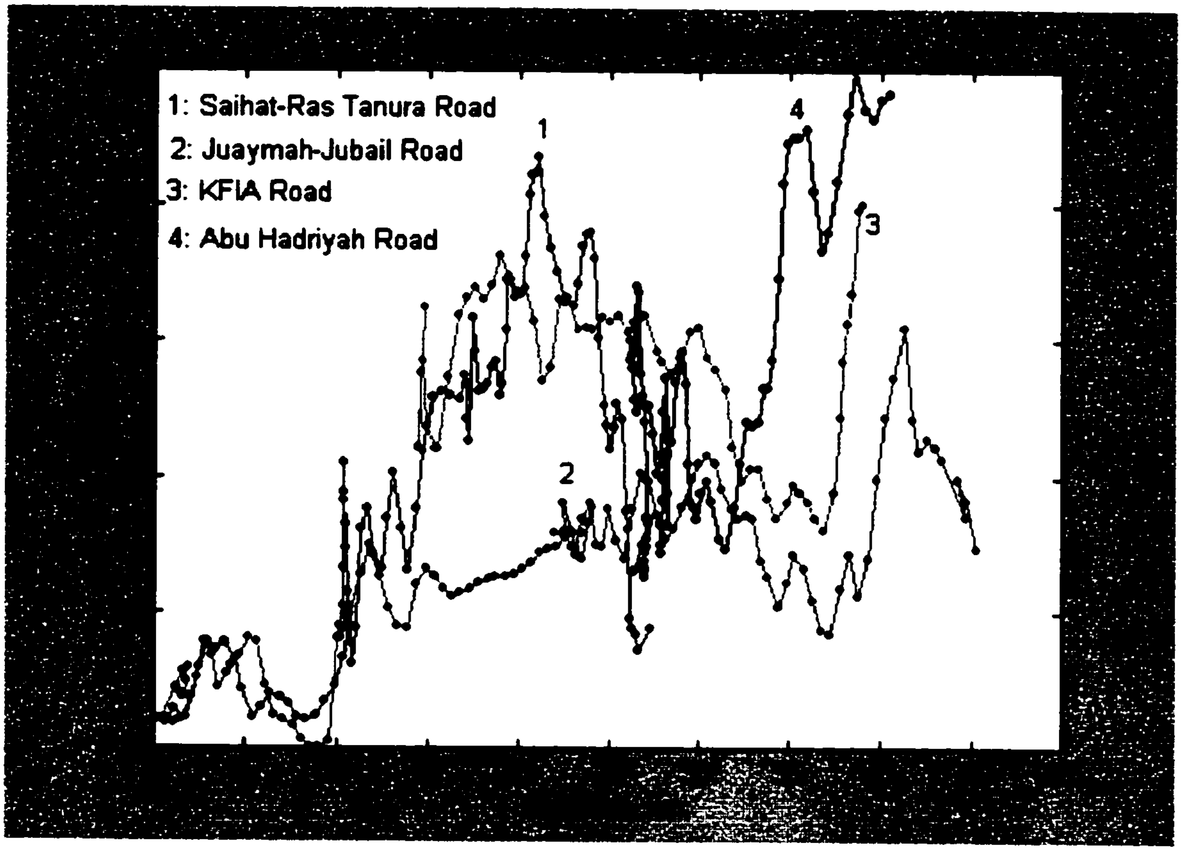

Figure (2.5) Variation of Height of the Selected Routes, RT

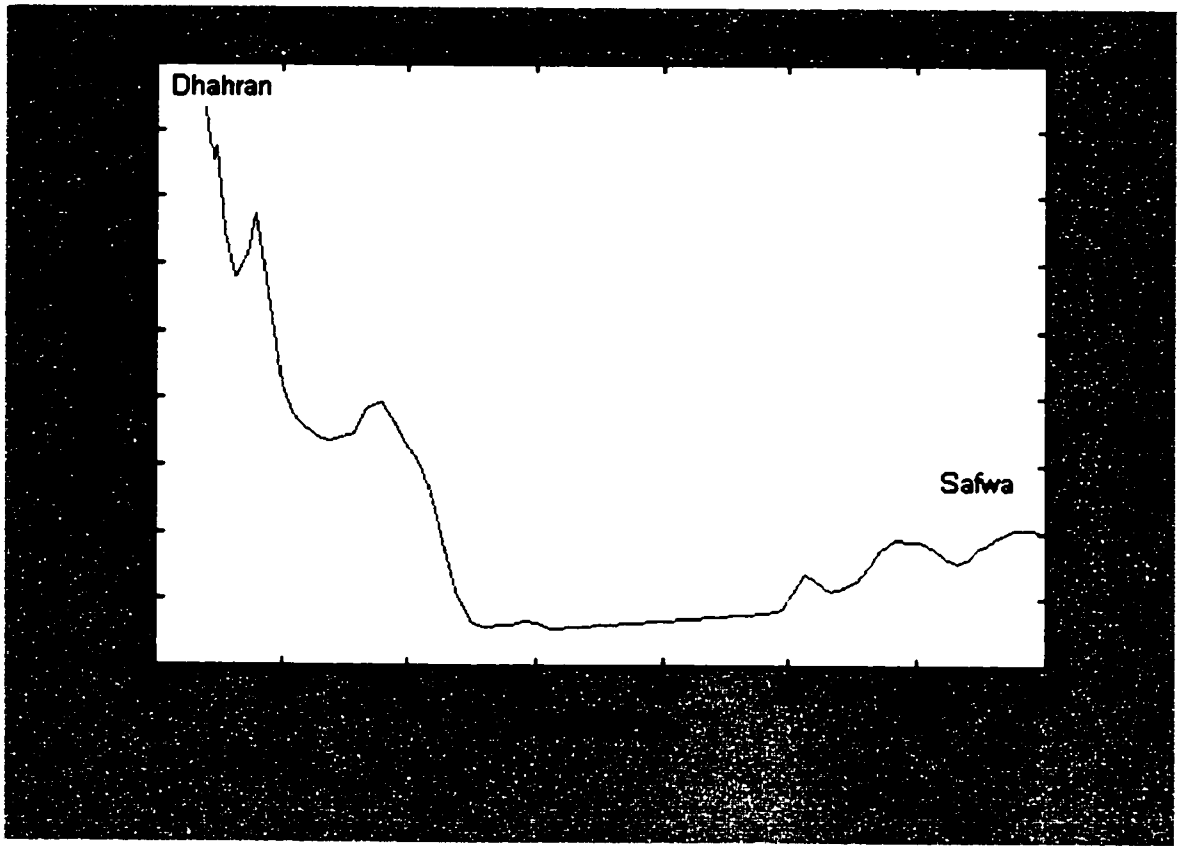

Figure (2.6) Height Variation on Dhahran Abqaiq Highway

2.3 Signal Strength Measurement

Signal strength measurements were started on January 23, 2001 for a VHF radio base station in Abqaiq area, later on a VHF radio base station located in Ras Tanura. A simple radio link is shown in Figure (2.7). The radio base station antenna is side-mounted and the mobile antenna is installed at the center of the vehicle roof.

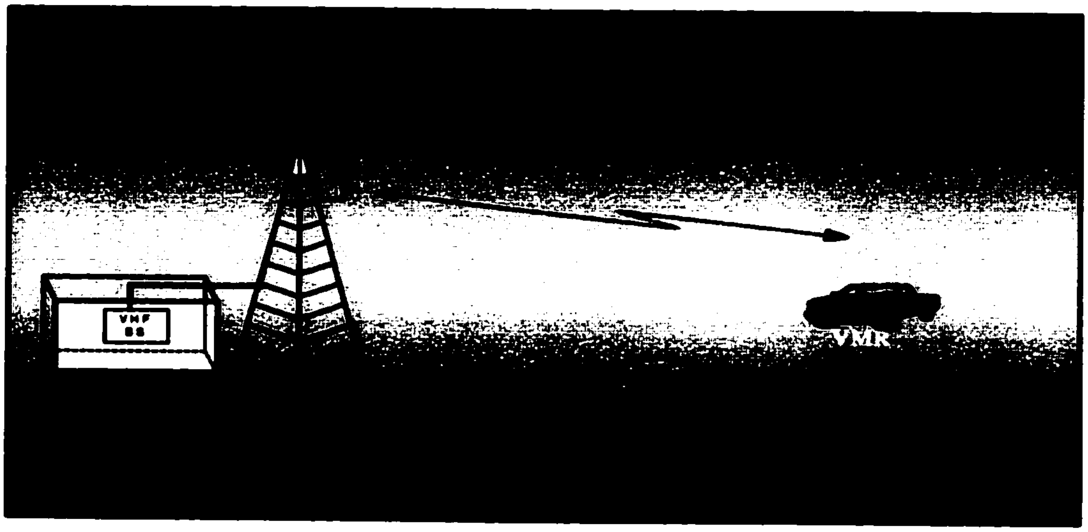

Figure (2.7) A Simple Radio Link

2.3.1 Propagation Data Collected for Abqaiq Radio Base Station (ABQ BS)

The signal strength was recorded for the selected VHF radio base station located in Abqaiq area. A vehicle with antenna at two meters and a communications service monitor (Hewlett-Pakard HP-8920) were used in the measurements. A Global Positioning System (GPS) was used to determine the Cartesian coordinates and the height above sea level for each test point.

The antenna used in the coverage campaign is model ASP177, an omni-directional whip, cut for a frequency of 160 MHz and providing 3 dB gains. The cable and connector losses were found by injecting a 160 MHz, 0 dB signal into one end of the mobile radio cable and measuring the level at the other end. Moreover, a Bird Meter (Watt Meter) was used to measure the output power of the VHF radio base station; it was connected in parallel with the radio base station and the antenna. The other parameters of the radio base station were obtained from the filing where the antenna height and gain, transmission cable type, etc are recorded. The transmission cable loss was calculated using the EDX. In addition, in the communication catalogs, there are tables that illustrate the loss per feet or meter in transmission cables. Table (2.1) contains the details of the Abqaiq radio base station, mobile radio and the test equipment used for field measurements.

TABLE (2.1)

Test Data and Details for Abqaiq Base Station

Base Station Type	VHF GE Master II
Base Station Antenna Height	55.8 m above the ground
Mobile	Suburban
Mobile antenna type	DB 222B
Mobile Antenna Height	2 m above the ground
Effective Radiated Power	9.54 Watt
Transmission Cable	LDF5-50 Foam Coaxial Cable
Transmission Cable Length	70.8 m
Antenna Gain	3 dB
Miscellaneous Losses (Connectors)	2 dB
Transmitter Cable Loss	1.10 dB
Mobile Test Equipment	HP-8920 RF Comm. Test
Mobile Test Equipment	Global Positioning System
Mobile Receiver Cable and Connector Loss	3.77 dB
Frequency	160.000 MHz

2.3.2 Propagation Data Collected for Ras Tanura Radio Base Station (RT BS)

Signal strength was measured around Ras Tanura radio base station using a Sedan vehicle equipped with mobile radio, HP-8920 and GPS. The mobile and HP-8920 antenna heights were established at 1 m and 1.5 m respectively above the ground. Table (2.2) contains the parameters of the radio base station and the test equipment used to measure the received signal strength at different areas. Table (2.3) illustrates the selected roads, time and date of different measurements taken around Ras Tanura radio base station.

2.3.3 Propagation Data Collected for Dhahran Radio Base Station (DH BS)

The equipments used to collect propagation data for Ras Tanura radio base station were used to measure the signal strength and to obtain the locations on Dhahran-Jubail highway. Table (2.4) shows the parameters of Dhahran radio base station.

TABLE (2.2)

Test Data and Details for Ras Tanura Base Station

Base Station Type	VHF GE Master II
Base Station Antenna Height	75.6m above the ground
Mobile	Sedan
Mobile antenna type	DB 222B
Mobile Antenna Height	1.5 m above the ground
Effective Radiated Power	21 Watt
Transmission Cable	LDF5-50 Foam Coaxial Cable
Transmission Cable Length	137.16 m
Antenna Gain	3 dB
Miscellaneous Losses (Connectors)	2 dB
Transmitter Cable Loss	2.14 dB
Mobile Test Equipment	HP-8920 RF Communication Test
Mobile Test Equipment	Global Positioning System (GPS)
Receiver Cable and Connector Loss	3.77 dB
Frequency	160.045 MHz

TABLE (2.3)

Measured Signal Strength around Ras Tanura Radio Base Station

Time	Date	Road
10:12 AM to 05:45 PM	31-Jan-01	Dammam Jubail Highway
06:40 AM to 08:20 PM	1-Feb-01	King Fahd International Airport road
08:20 AM to 01:48 PM	1-Feb-01	Abu Hadriyah Highway
06:30 AM to 07:00 AM	4-Feb-01	Abu Hadriyah Highway
07:05 AM to 08:51 AM	15-Feb-01	Abu Hadriyah Highway
10:20 AM to 11:24 AM	15-Feb-01	Dammam Jubail Highway
06:59 AM to 11:00 AM	22-Feb-01	Ras Tanura and Juaymah areas
08:40 AM to 09:26 AM	2-Apr-01	Juabail-Juaymah Road
10:28 AM to 11:09 AM	2-Apr-01	Juabail-Juaymah Road
08:42 AM to 11:23 AM	19-Apr-01	Dammam Jubail Highway
11:28 AM to 18:54 PM	19-Apr-01	Dhahran area
07:31 AM to 08:00 AM	21-Apr-01	Dhahran area
11:03 AM to 11:19 AM	22-Apr-01	Dhahran area
05:00 AM to 05:55 AM	10-May-01	Abu Hadriyah Highway
06:30 AM to 07:07 AM	10-May-01	Juabail-Juaymah Road
12:57 PM to 01:33 PM	10-May-01	Juabail-Juaymah Road
07:10 AM to 07:31 AM	10-May-01	Juaymah-Safwa
13:39 PM to 13:59 PM	10-May-01	Juaymah-Safwa
07:39 AM to 07:50 AM	10-May-01	Sea-Safwa Road
14:13 PM to 14:31 PM	11-May-01	Sea-Safwa Road

TABLE (2.4)

Test Data and Details for Dhahran Base Station

Base Station Type	VHF GE Master II
Base Station Antenna Height	60.0 m above the ground
Mobile	Sedan
Mobile antenna type	DB 222B
Mobile Antenna Height	1.5 m above the ground
Effective Radiated Power	50 Watt
Transmission Cable	LDF5-50 Foam Coaxial Cable
Transmission Cable Length	75.0 m
Antenna Gain	3 dB
Miscellaneous Losses (Connectors)	2 dB
Transmitter Cable Loss	1.17 dB
Mobile Test Equipment	HP-8920 RF Communication Test
Mobile Test Equipment	Global Positioning System (GPS)
Receiver Cable and Connector Loss	3.77 dB
Frequency	159.610 MHz

2.4 MEASUREMENT RESULTS

High numbers of measurements were collected around Ras Tanura radio base station (Appendix A); some of these measurements are shown in Figure (2.8). These measurements were taken on January and February of year 2001 and they are represented with different colors as follow:

1. Yellow: Stands for data recorded on January 31, 2001 on Dammam-Jubail Highway, starting from Saihat, passing by Ras Tanura and ending at Berri. The measurements were done on this road because it is the main road linking Dhahran with the other cities located at the North of the Eastern Province.
2. Green: Stands for data recorded on February 01, 2001 on Abu Hadriyah Highway and King Fahd International Airport (KFIA) road.
3. Red: Stands for data recorded on February 15, 2001 on Abu Hadriyah and Dammam-Jubail Highways.
4. Blue: Stands for data recorded on February 22, 2001 in Ras Tanura and Juaymah areas.

More tests were carried out to make sure about the measurements recorded in January and February of year 2001, aiming further at explaining the abnormal conditions experienced at Eastern Province area.

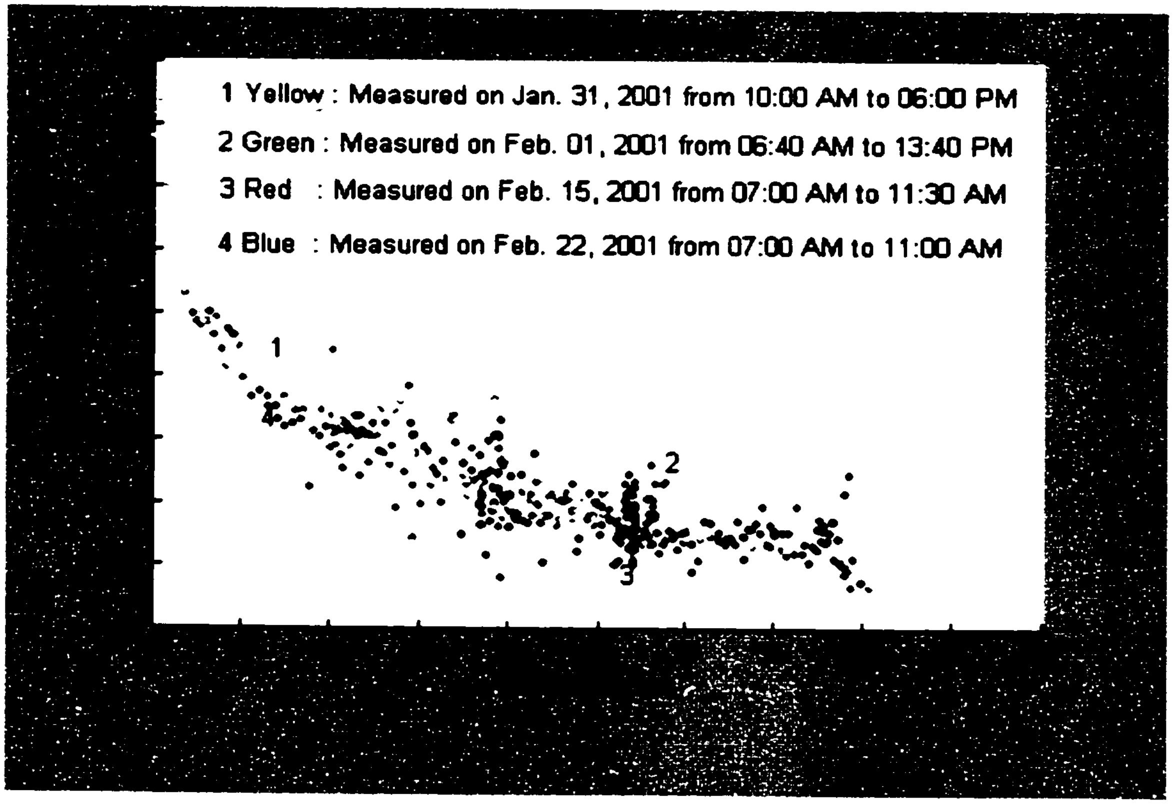

Figure (2.8) The Actual Signal Strength In Different Areas

The coverage test was repeated on a number of selected roads during different weather conditions and periods of time. The weather conditions enhance or degrade the signal strength level. The measured levels on a selected road at different weather conditions are shown in Figure (2.9) and appendix B.

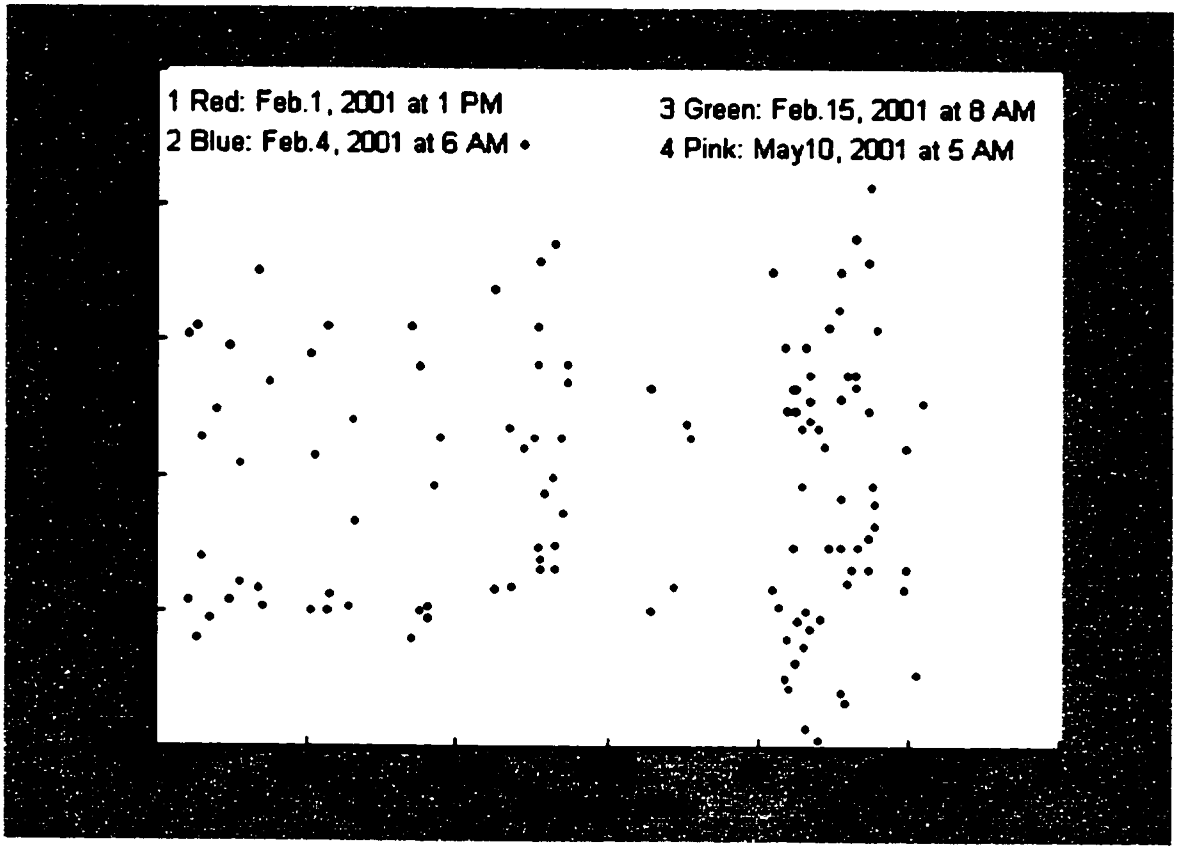

Figure (2.9) Atmospheric effects on Received Signal

2.5 SUMMERY

The signal strengths were measured over various routes during different time conditions. The result is more than 700 measurements that were used to draw the actual signal strength around Ras Tanura with respect to the distance. In the following chapters, the measured signal strength will be compared to the predicted by EDX Signal Pro using different path loss models.

CHAPTER III

COMPARISON WITH EXISTING MODELS

3.1 INTRODUCTION

A path loss model is selected based on operating frequency, antenna height, and area type. In this chapter, three path loss models will be selected to predict the signal strength around Ras Tanura area aiming to compare their outcomes with the measured signal strength in the field.

3.2 PATH LOSS MODELS

There are many path loss models available to estimate radio links path losses. Some of them are highlighted as follow:

3.2.1 Okumura (Hata) Model

Hata translated Okumura measurements into empirical formula known as Okumura (Hata) Model. This model is based on quasi-smooth earth and does not treat the variation of terrain. On the basis of urban area propagation loss, Hata developed the correction equations for suburban and open areas. The Hata formula can be applied to a flat terrain, short distance (30km), transmitter antenna heights within 200m and receiver antenna heights within 10m [8]. It is practical to estimate the path loss for urban, suburban and open areas as follow:

Path loss for urban area is defined by:

$$L_u = 69.55 + 26.16 * \log_{10}(f) - 13.82 * \log_{10}(h_b) - ah_m + (44.9 - 6.55 * \log_{10}(h_b)) * \log_{10}(d) \quad (3.1)$$

Where:

- f : frequency in MHz.
- h_b: base height in meters above average terrain along 3-15 km
- ah_m: mobile height correction factor
- d: distance from transmitter to the receiver in kilometers.

The mobile height correction factor at a <u>medium-small city</u> (Open or Suburban areas) is estimated by:

$$ah_m = (1.11 * \log_{10}(f) - 0.7) * h_m - (1.56 * \log_{10}(f) - 0.8) \quad (3.2)$$

The mobile height correction factor at a <u>large city</u> (Urban area) is:

$$ah_m = 8.29(\log_{10}(1.54h_m))^2 - 1.10 \qquad \text{for } f \le 200MHz \quad (3.3)$$

$$ah_m = 3.20(\log_{10}(11.75h_m))^2 - 4.97 \qquad \text{for } f \le 400MHz \quad (3.4)$$

Where:

h_m: Mobile antenna height above ground (meters)

For Suburban area, the correction to be added to the urban path loss model is:

$$L_{su} = L_u - 2\left(log_{10}\left(\frac{f}{28}\right)\right)^2 - 5.4 \ \ dB \qquad (3.5)$$

For rural, quasi-open areas, the correction to be added to the urban path loss model is:

$$L_{ro} = L_u - 4.78 * [log_{10}(f)]^2 + 18.33 * log_{10}(f) - 35.94 \ \ dB \qquad (3.6)$$

For rural, open-areas, the correction to be added to the urban path loss model is:

$$L_{ro} = Lu - 4.78 * [log_{10}(f)]^2 + 18.33 * log_{10}(f) - 40.94 \qquad (3.7)$$

3.2.2 Hata-Extended/Epstein-Peterson Diffraction

This model was built based on the Okumura (Hata) Model. This model can be used for a 300 km distance range, frequency 30 to 1500 MHz and base station antenna height of 30 to 1000 meters [8]. It adjusted Okumura (Hata) Model to fit with various distances and antenna heights as follow:

If d > 20 km,

$$L_{E-E} = L_{HATA} + 10.5 + 0.15 log_{10}(400h_b)(d-20) \qquad (3.8)$$

If d > 64.36 km,

$$L_{E-E} = L_{HATA} - 0.28(d - 64.36) \qquad (3.9)$$

If h_b > 300 meters,

$$L_{H-E} = L_{HATA} - 4.7\left|\log_{10}\left(\frac{6.2}{d}\right)\right|\left(\frac{h_b - 300}{600}\right) \qquad (3.10)$$

For more accurate estimation, the following correction should be considered:

If d > 40.2

$$L_{H-E} = L_{HATA} - 0.18\log_{10}\left(\frac{1500}{f}\right)(d - 40.2) \qquad (3.11)$$

Where:

L_{HATA}: Path loss in dB computed using Okumura/ Hata Model
L_{H-E}: path loss in db with the extension to Okumura/Hata Model
f : frequency in MHz.
d : distance from transmitter to receiver in km.
h_b : effective base height in meters.

The model calculates diffraction losses using Epstein-Peterson multiple obstacle diffraction loss method.

3.2.3 Lee's Model

The path loss model derived by William Lee is generally used to estimate and predict the path loss over a flat terrain. For an irregular terrain, a correction error should be included. This model is based on two factors, the power at a 1-mile (1.6 km) point of interception and γ, the path loss slope [10]. The received power at d km from the transmitter is expressed as:

$$P_r = 10 * \log_{10}\left[P_{r0}\left(\frac{r}{r_0}\right)^{-\gamma}\left(\frac{f}{f_0}\right)^{-n}\alpha_0\right] \qquad (3.12)$$

Where

P_r *Field strength of the received signal at a distance r from the transmitter*

P_{r0} *The received at 1 mile from the transmitter (1.6 km)*

r *The distance between the transmitter and the receiver*

r_0 *1 mile (1.6 km)*

γ *Path loss slope (expermintally determined)*

f *actual carrier frequency*

f_0 *nominal carrier frequency, 900 MHz*

n *The value of in is between 2 and 3,* $2 \le n \le 3$. $n = 2$, *For suburban or open area with* $f < 450MHz$ *and* $n = 3$ *in urban area with* $f > 450$ *MHz.*

α_0 *Correction factor accounts for antenna heights, transmit power and antenna gain that differ from the nominal values.*

3.2.3.1 Lee's Nominal Conditions

The nominal conditions assumed in the Lee's path loss model are:

Frequency f_o = 900 MHz

Base station antenna height = 30.48 m (100 ft)

Base station transmitter power = 10 Watts

Base antenna gain = 6 dB reference to a dipole gain.

Mobile station antenna height = 3m

Mobile station antenna gain = 0 dB above a dipole gain.

3.2.3.2 Lee's Correction Factor (α_0)

Lee's Model can be applied for a frequency above 30 MHz; the correction factor is used for conditions different from the nominal [10]. The correction factor of Lee is:

$$\alpha_0 = \alpha_1\alpha_2\alpha_3\alpha_4\alpha_5 \quad (3.13)$$

$$\alpha_1 = \left(\frac{\text{new BS antenna height (m)}}{30.48m}\right)^2 \quad (3.14)$$

$$\alpha_2 = \left(\frac{\text{new MS antenna height (m)}}{3m}\right)^v \quad (3.15)$$

$$\alpha_3 = \left(\frac{\text{new transmitter power (W)}}{10W}\right) \quad (3.16)$$

$$\alpha 4 = \left(\frac{\text{new BS antenna gain respect to a } \lambda/2 \text{ dipole antenna}}{4}\right) \quad (3.17)$$

$$\alpha_5 = \text{different antenna - gain correction factor at mobile unit} \quad (3.18)$$

The value of v is specified as:

$$v = \begin{cases} 2 \text{ for MS antenna height} > 10 \text{ m (30 ft)} \\ 1 \text{ for MS antenna height} < 3 \text{ m (10 ft)} \end{cases}$$

Table (3.1) demonstrates the empirically derived γ and P_{r0} for different areas and propagation environments;

TABLE (3.1)

SAMPLE OF EMPIRICAL CONSTANT OF LEE'S MODEL

Propagation Environment	P_{r0} (dBm)	γ
Free Space	-45	2
Open Area	-49	4.35
US Suburban Area	-61.7	3.84
Philadelphia, PA (urban)	-70	3.68
Newark, NJ (urban)	-64	4.31
Tokyo, Japan (urban	-84	3.05

3.3 PATH LINK SIMULATION TOOLS

Two Programs were used to study the path loss and signal strength in the Eastern Province area: EDX SignalPro and Matlab. The EDX SignalPro is a tool used to model and design wireless communication system. It predicts the surface area and path performance using advanced propagation models that account for terrain and groundcover features. This tool can also be used to simulate cellular systems, paging, broadcast or PCS (Personal Communication System) [8]. It was applied to simulate the signal strength for Ras Tanura radio base station.

Matlab program is another software program applied in the simulation; it was used to calculate the path loss for Ras Tanura radio base station and to compare between the calculated and actual path losses. In addition, it provides the tools to modify the available path loss models based on the real field measurements.

3.4 PREDICTED SIGNAL STRENGTHS

Using EDX SignalPro and Matlab programs, the signal strength was estimated for Ras Tanura radio base station.

3.4.1 The Predicted Signal Strength for Ras Tanura Radio Base Station

Matlab program was used to calculate the signal strength around Ras Tanura radio base station using different path loss models. The signal strength around Ras Tanura is:

$$SGN = 10*\log_{10}(P_t)+G_r+G_t-L_m-L_{tca}-L_{tco}-L_{rcc}-L_{ro}$$
$$= 10*\log_{10}(21000mW) +3+3-1-2.14-1-3.77-L_{ro}$$
$$= 43.22+3+3-1-2.14-1-3.77-L_{ro} = 41.35-L_{ro} \qquad (3.19)$$

Where:

SGN: Signal Strength
P_t: Transmit power, (21000 mW).
G_r: Receiver antenna gain, (3 dB)
G_t: Transmitter antenna gain, (3 dB)
L_m: Miscellaneous Loss, (1 dB)
L_{tca}: Coaxial cable loss, (2.14)
L_{tco}: Connector loss, (1 dB)
L_{rcc}: Receiver cable and connector loss, (3.77 dB)
L_{ro}: Path loss

Hata/Okumura Model: This model assumed quasi-smooth terrain. Ras Tanura area is considered as quasi-open area so equations (3.1), (3.2), (3.3) and (3.19) were used to do the simulation. The height of the transmitting antenna is the height along the ground averaged over a distance 3 to 15 km from the transmitter. Ras Tanura area was assumed uniform, a 15 km path was selected, 50 height readings were obtained between a distance of 3 to 15 km, and the average height was calculated and subtracted from the transmitter height above the ground to obtain the effective height of the transmitting antenna. The average height of the selected path is ***4.1*** meter. The transmitter antenna height above the ground is ***76.6*** and therefore the effective antenna height is ***76.6 - 4.1 = 72.5*** meters. In Figure (3.1), the predicted signal strength is shown. The predicted signal strength does not match the field measurements; this seems to be caused by the foliages that result in more attenuation in the received signal. The Root of the Mean Squared Difference (RMSD) is a quantity used to calculate the difference between the actual and predicted signal strengths, this quantity is also used to compare between the different path loss models, which will be applied later to estimate the signal strength around Ras Tanura, Abqaiq and Dhahran radio base stations. The RMSD for Hata/ Okumura model is:

$$RMSD = \sqrt{\frac{\sum_{n=1}^{656}(Actual(n) - Predicted(n))^2}{656}} = \sqrt{\frac{20562}{656}}$$
$$= \sqrt{31.4} = 5.6$$

The result is acceptable but can be modified for better fit.

Hata/ Epstein Model: EDX SignalPro Program was also used to simulate the signal strength around Ras Tanura radio base station. In the simulations, 4/3 effective earth's factor and 6 dB fade margin were considered. The signal strength values predicted by EDX Signal Pro is drawn in Figure (3.2) using Matlab program. The model selected for this simulation is Hata/ Epstein Model. This model results in a satisfactory outcome and RMSD of **6.7.**

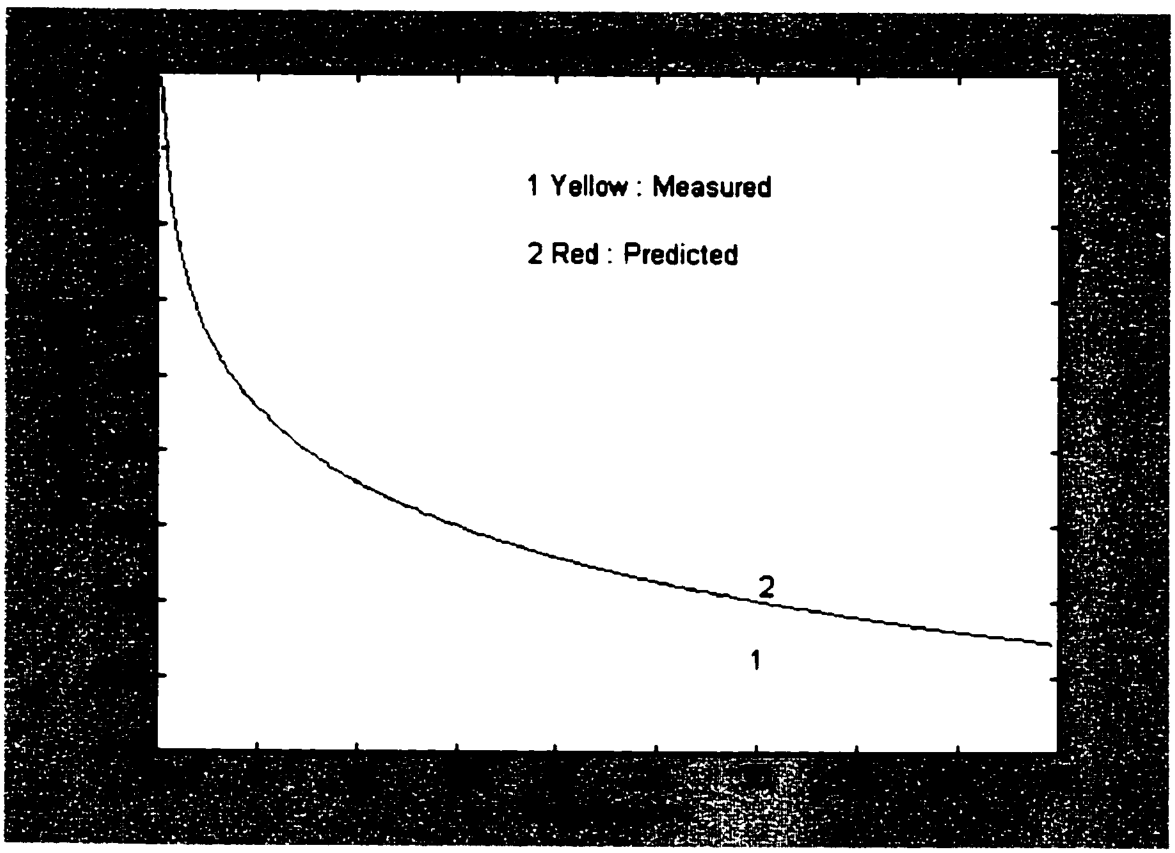

Figure (3.1) Actual and Predicted Signal Strengths Using Hata

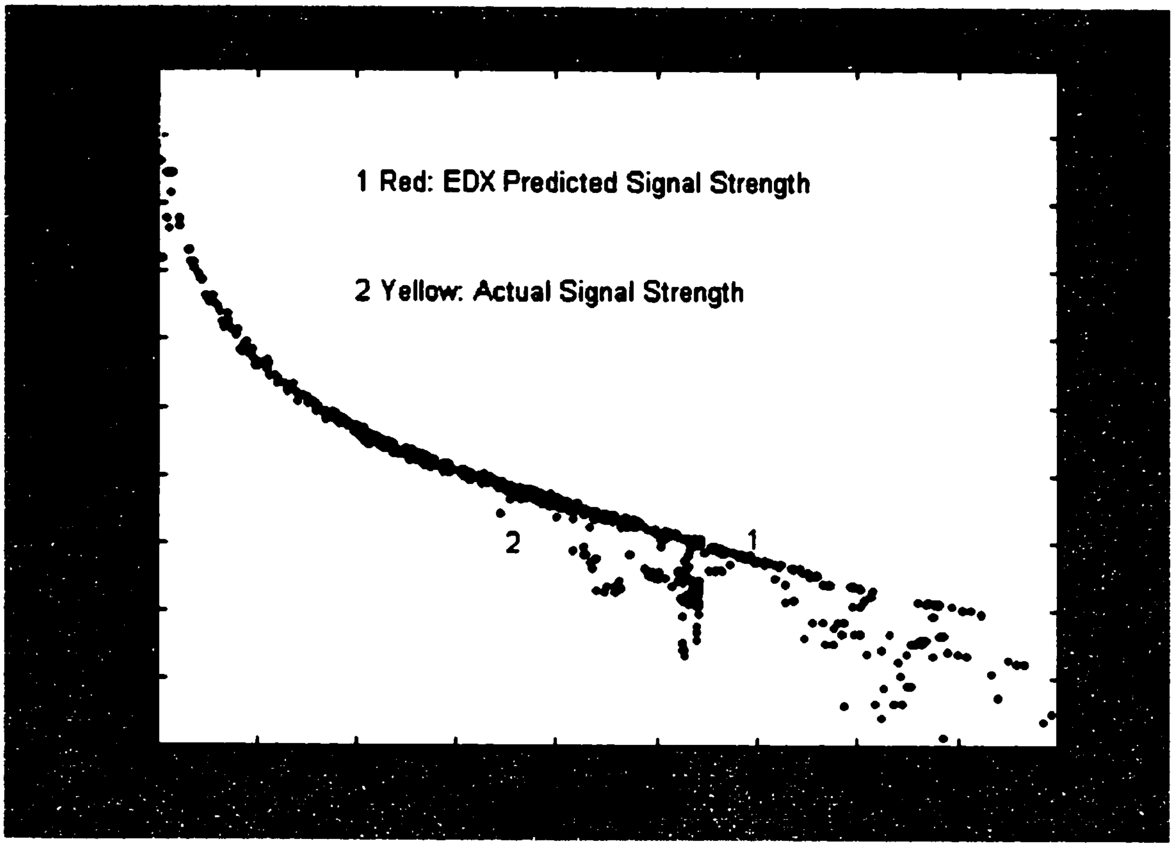

Figure (3.2) Actual and EDX Predicted Signal Strengths

Lee Model: The signal strength around Ras Tanura radio base station was calculated using Equations (3.12), (3.13) and (3.19). The value of **n** is 2 because f < 450 MHz. P_{r0} was obtained from the actual signal strength data. P_{r0} is the received signal strength level at a distance of 1.6 km from a radio base station. The path loss slope (γ) was found through iteration process, the measured and predicted signal strengths were compared through changing the value of γ to result in best match. Process start with $\gamma = 4$, then this value was decreased until $\gamma = 3.62$.

The path loss and correction factor for Ras Tanura radio base station are expressed as:

$$L_p = 40-(-50)+10*3.62*10*\log_{10}\left(\frac{d}{1.6}\right)+10*2*\log_{10}(160/900)$$
$$-10*\log_{10}(\alpha_0) \quad (3.20)$$

$$\alpha_0 = \alpha_1\alpha_2\alpha_3\alpha_4\alpha_5 = \left(\frac{75.6}{30.48}\right)^2*\left(\frac{1.5}{3}\right)*\left(\frac{21}{10}\right)*\left(\frac{3}{4}\right)*(1) \quad (3.21)$$

The simulation result is shown in Figure (3.3). There are large discrepancies between the measured and calculated signal strengths. Lee model is not recommended to calculate the signal strength around Ras Tanura area. The model shows less loss compared with the measured values, modifying this model by shifting it down, can result in better approximation to the measured signal. The RMSD is ***20.8***:

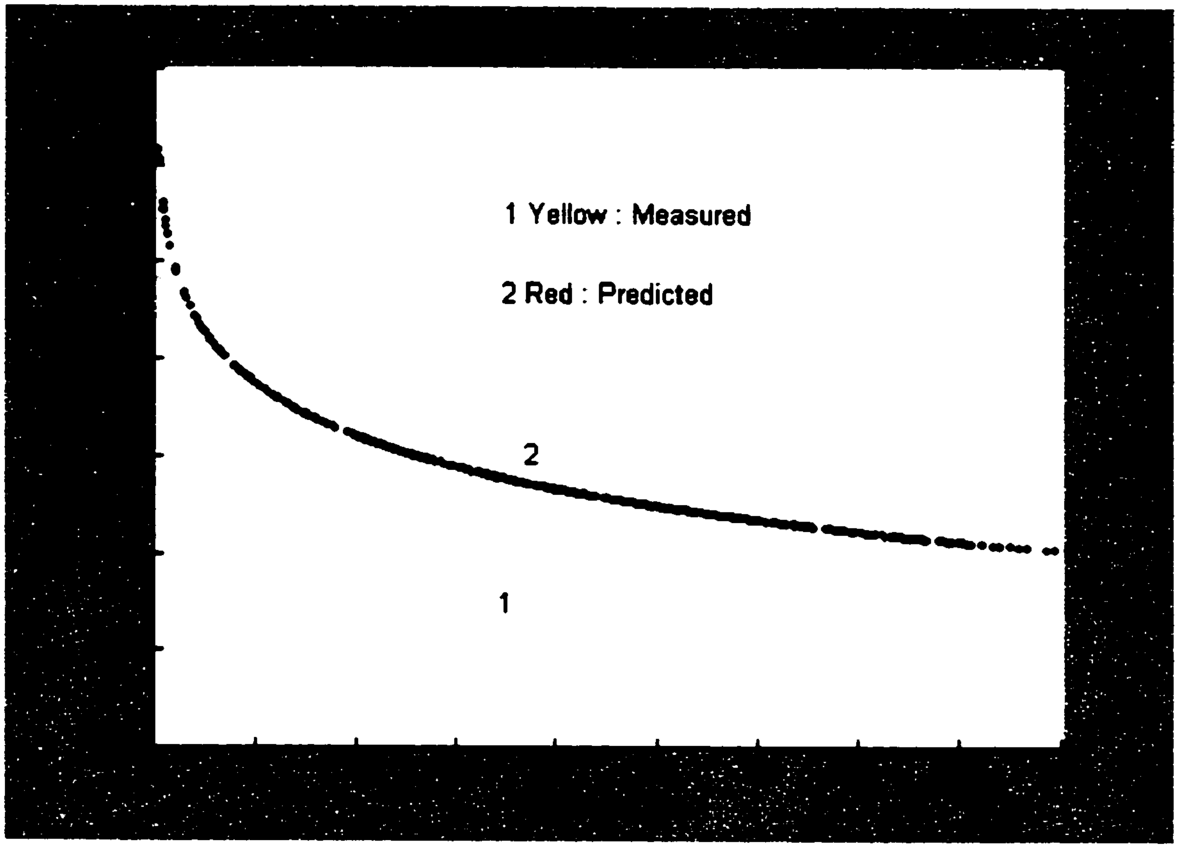

Figure (3.3) The Predicted Signal Strength Using Lee

3.5 COMPARISON RESULTS

The selected path loss models do not match with the actual propagation data collected from the field. Hata/Okumura and Hata/Epstein Models show the best fit to the actual data but the differences from the actual data are still high. In most of radio system designs at the Eastern Province, these models are used; the aim is to modify these models to result in better fit with the field measurements taking into account the terrain and weather condition encountered in the Eastern Province.

3.6 SUMMERY

Three path loss models were selected, described and applied to predict the signal strengths around Ras Tanura area. The results show high discrepancies from the field measurements. In the next chapter the selected path loss models will be modified to fit better with the measured signal strength.

CHAPTER IV

MODEL DEVELOPMENT

4.1 INTRODUCTION

In this chapter, we seek to modify and develop new path loss models for the Eastern Province area. We generated formulas to relate the distance, the frequency, the transmitter and the receiver antenna heights to the actual propagation data obtained at Ras Tanura, Abqaiq and Dhahran. Moreover, we proposed correction factors that can be obtained from the field readings for new frequency or antenna height.

The actual propagation data is compared to the predicted using different path loss models to determine correction factors required for Ras Tanura, Abqaiq and Dhahran area. The discrepancies between the actual and predicted signal strength are obtained and the median of the differences is added to the modified path loss model so that a better estimation of the actual signal strength is obtained.

Furthermore, field measurements over different paths will be compared to identify the effect of Sea path on the received radio signal.

4.2 STRATEGY OF MODIFYING PATH LOSS MODELS

The actual and predicted signal strengths were compared to find the net differences between them; the median of the differences was added to the prediction model to minimize the discrepancies from the actual signal strengths. The added quantity was increased and decreased through iteration process to result in more accurate prediction.

4.2.1 Signal Strengths For Ras Tanura Area

Modified Hata Model (MHM): Ras Tanura area has many high structures e.g. Gas Plant, Power Plant, Work Shops, Oil Tanks, trees and etc. The propagation data taken in this area contains the contribution of these structures as gain or loss. The area around Ras Tanura can be divided into two regions, the first region where the distance is less than 5 km, has buildings, trees and fences. The density of the buildings decreases after a distance of 5 km, but there are some high structures (Oil Tanks, Plants), trees, sporadic pushes and fences that degrade the signal strength level. Ras Tanura area is considered as quasi-open area. The correction factor for quasi-open area obtained by Hata was modified to reflect the environment at Ras Tanura that causes more attenuation in the received signal.

Modifications done to Hata/Okumura's path loss model are:

1. Path loss around Ras Tanura radio base station was predicted using Hata path loss formula for urban area, Equation (3.1), Hata Mobile height factor, Equation (3.2), and Hata quasi-open area correction factor, Equation (3.6).
2. The predicted signal strength does not match the actual field measurements. The discrepancies were caused because of the environment at Ras Tanura area, there are more losses produced by buildings, trees and terrain pushes.
3. The actual and predicted path losses were compared; the median of differences between them was calculated and added to the quasi-open area correction factor. Through iteration process, the added amount was increased or decreased until the RMSD between the actual and predicted path losses reached the minimum. The amount added to the area correction factor is

4.5; it results in best match to the actual field measurements.

The new quasi-open area correction factor for Ras Tanura is:

$$L_{ro} = L_u - 4.78*[\log_{10}(f)]^2 + 18.33*\log_{10}(f) - 35.94 + 4.5 \qquad 00<d<50\ km \qquad (4.1)$$

For f = 160.045 MHz:

$$L_{ro} = L_u + 17.17 - 31.44 = L_u - 14.27 \qquad 00<d<50\ km \qquad (4.2)$$

The predicted and actual signal strengths are shown in Figure (4.1). The RMSD between the actual and the predicted signal strengths is ***3.45,*** the simulation program is shown in appendix c. The Modified Hata model results in better fit to the measured signal strength compared with Hata/ Okumura path loss model. There were many trails to modify the model more but they failed to result in better outcome.

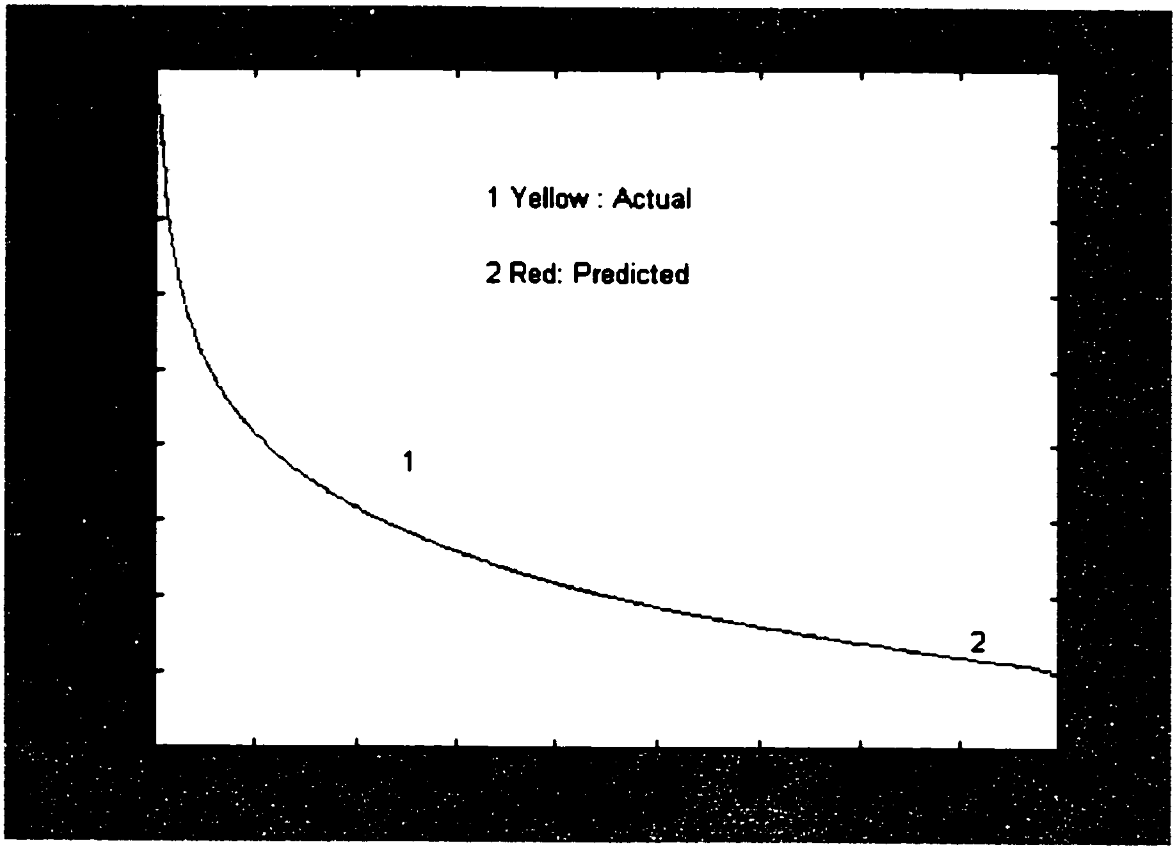

Figure (4.1) Signal Strengths for RT Using MHM

Hata/ Okumura model is the right choose to simulate the signal strength in Ras Tanura area, it requires a slight modification to consider the attenuation of trees, buildings and terrain pushes. The areas in the North of the Eastern Province have similar terrain as Ras Tanura. At these areas, the new path loss model is expected to be useful to predict signal strengths for VHF radio systems.

To fit better with the actual propagation data, we also modified the third term in the right hand side of

Equation (3.1) increasing and decreasing the constant 44.9, but it resulted in greater discrepancies from the actual path loss in open area.

Modified Lee Model (MLM): Lee path loss model was modified to fit better with the measured signal strength level recorded at Ras Tanura area. The pursued procedures to modify Lee model are:

1. Path loss around Ras Tanura radio base station was estimated using Equations (3.20) and (3.21)
2. The median of differences between the measured and predicted signal strength was calculated and added to the path loss formula equation (3.20). Through iteration process, the added amount was increased or decreased until the RMSD between the actual and predicted path losses reached the minimum. The amount added to Lee model is **21.2**. The result is an excellent match to the actual field measurements as shown in Figure (4.2). The new path loss formula is:

$$L_p = 40-(-50)+10*3.62*10*\log_{10}\left(\frac{d}{1.6}\right)+10*2*\log_{10}(160/900)$$
$$-10*\log_{10}(\alpha_0)+21.2 \qquad (4.3)$$

The new RMSD is ***3.56***. The simulation program is shown in appendix c.

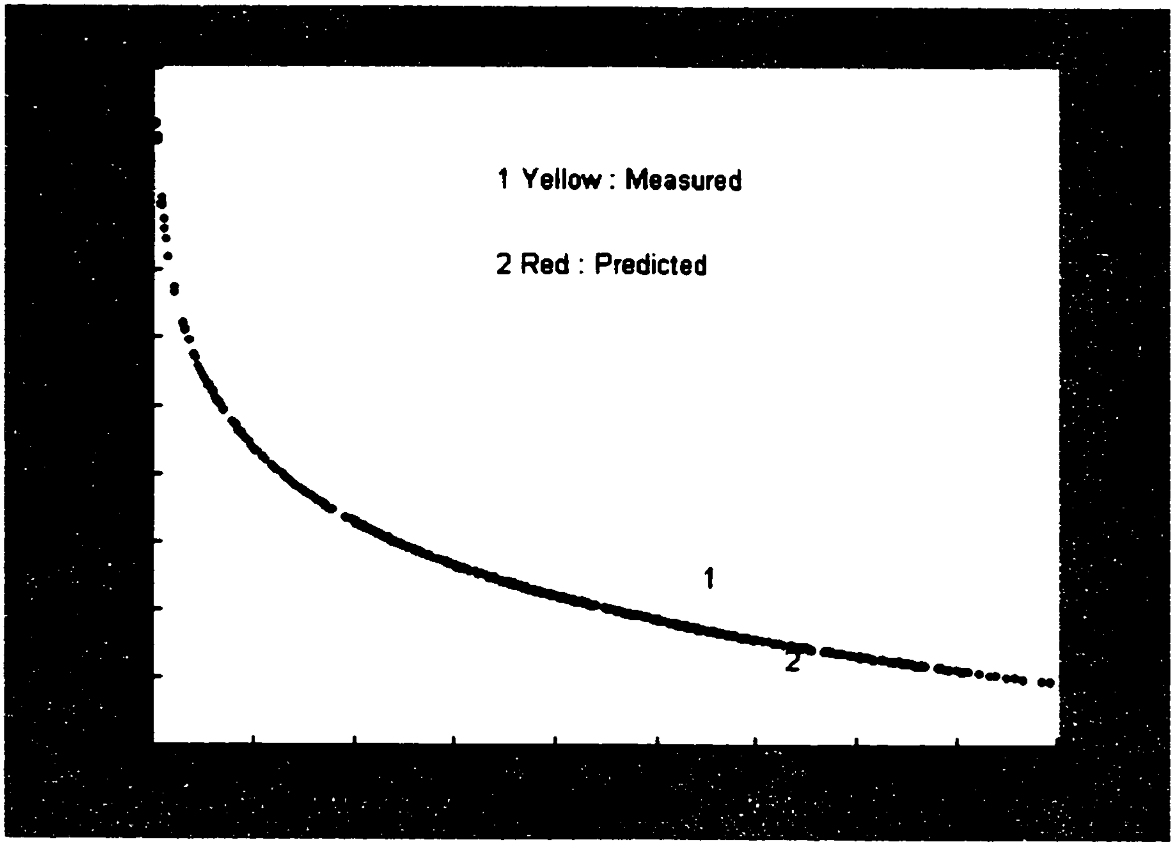

Figure (4.2) Signal Strengths For RT Using MLM

3. More modifications were done to Equation (4.3), the terrain effect on the received signal was included. The new amount added to Equation (4.3) is $c*\log_{10}(hma/10)$, ***hma*** is the heights of the test points above 0 level (the 0 level at this area is the same as the Sea level) and the ***10*** is the average of the heights. The process was started with $c = 1/6$ and through iteration process, ***c*** was increased until ***c =***

14/6 where the path loss resulted in the best signal strength estimation. The path loss is expressed by:

$$L_p = 40-(-50)+10*3.62*10*\log_{10}\left(\frac{d}{1.6}\right)+10*2*\log_{10}(160/900)$$

$$-10*\log_{10}(\alpha_0)+\frac{14}{6}\log10\left(\frac{hma}{10}\right)+21.2$$

$$c = 21.2 \quad \textbf{for Ras Tanura area} \qquad (4.4)$$

The measured and predicted signal strengths using Equations (3.19) and (4.4) are shown in Figure (4.3) and the new RMSD is ***3.46***. The simulation program is shown in appendix c.

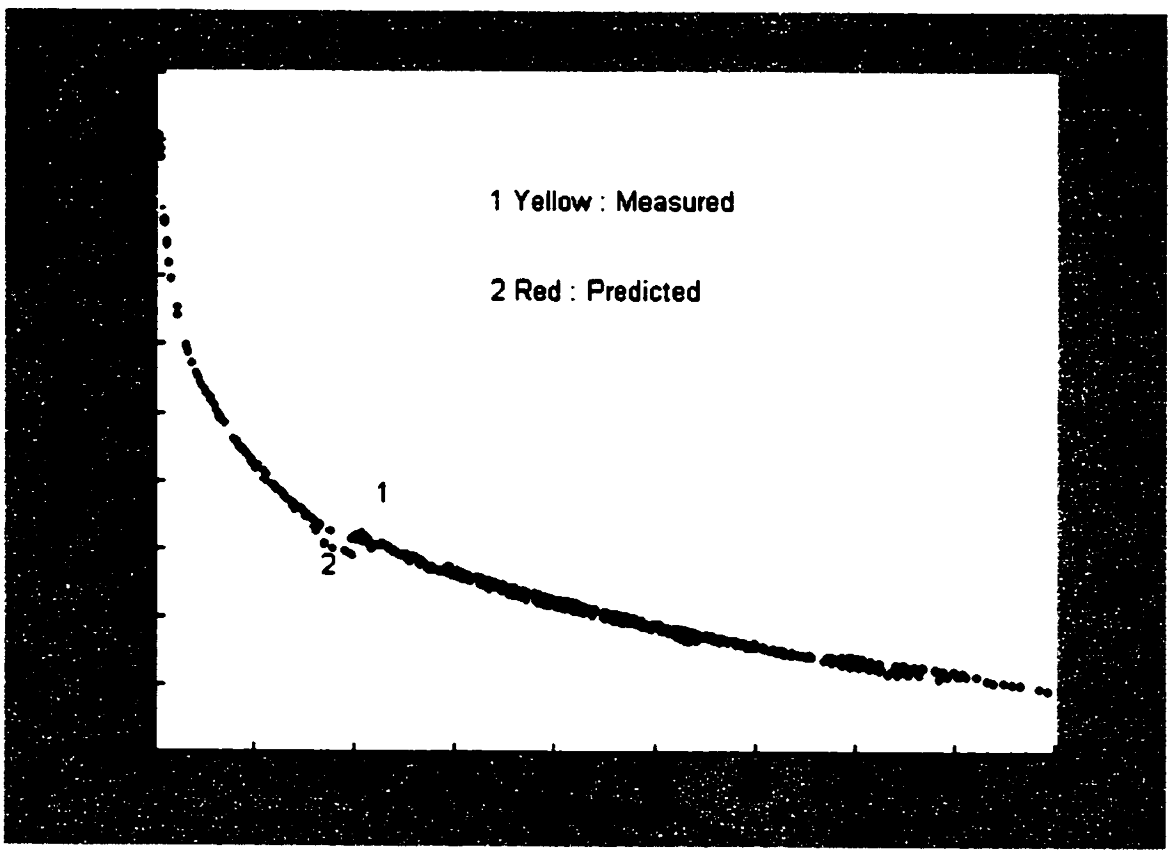

Figure (4.3) Signal Strengths Using MLM and Terrain Data

Maitham Path Loss Model (MPLM): The main factor affecting the path loss is the distance between the transmitter and the receiver. The dependency of the loss on distance is defined as path loss slope. Two mathematical formulae were obtained to represent the actual path loss. The developments of these formulae were done through the following procedures:

1. The actual path loss of Ras Tanura radio base station was compared to ***10*α*log10(c*d)***, ***c*** and ***α*** are constants and ***d*** is a matrix contains distances of the test points from the radio base station.
2. Through iteration processes, the comparison between the actual and predicted path losses was measured based on the median of differences obtained between them.
3. The constants: ***c*** and ***α*** were increased and decreased until ***c = 231.3*** and ***α = 3.44***, these resulted in the best fit of the distance parameter into the measured data. The parameters of h_b, h_m and f were taken from the free space model. The new path loss model is expressed as:

$$L = 10 * \log_{10}\left((231.3 * d)^{3.44}\right) - 20 * \log_{10}\left(h_b * h_m\right) + 20 * \log_{10}(f) + C \quad (4.5)$$

C=0   For Ras Tanura Area

The predicted signal strength is shown in Figure (4.4), the RMSD is ***3.48***. More modifications were done to Equation (4.5) to include the terrain factor. The new amount added to Equation (4.5) is $(7.3/6) * \log_{10}(hma/10)$. The new RMSD is ***3.34*** and the new simulation result is shown in Figure (4.5). The simulation programs with and without terrain factor are shown in appendix c.

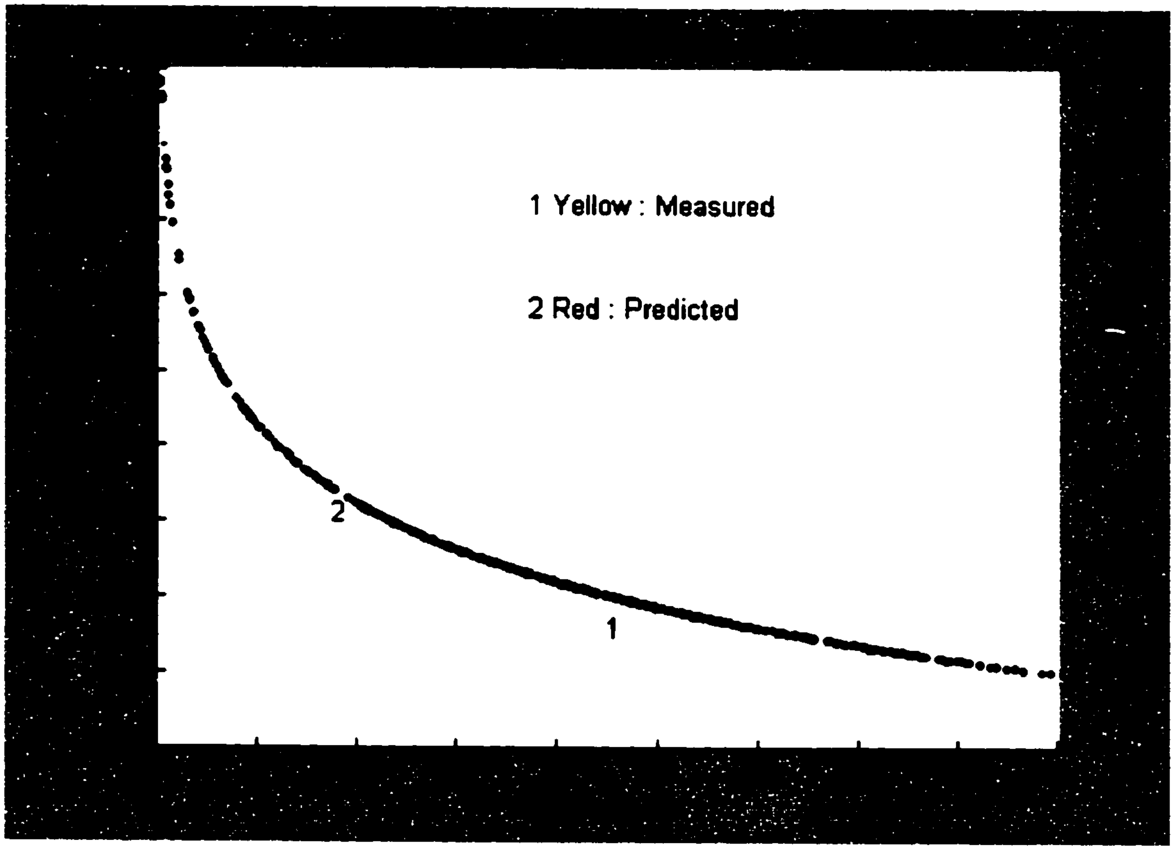

Figure (4.4) Signal Strengths For RT Using MPLM

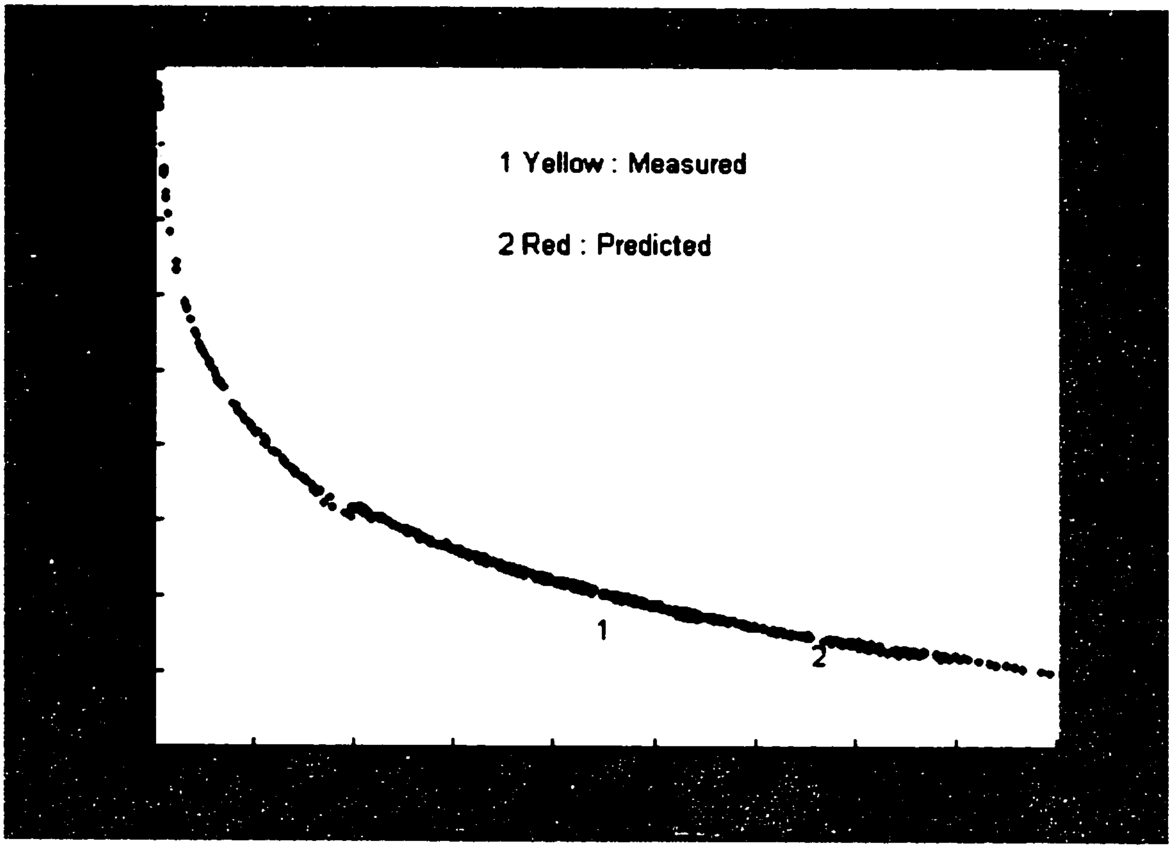

Figure (4.5) Signal Strengths For RT Using MPLM And Terrain Data

The RMSD value reveals the high accuracy of Maitham model in predicting the path loss for Ras Tanura radio base station. If Ras Tanura radio base station conditions are considered the nominal, for a new operating frequency f_n, there should be an amount of $c\log_{10}(f_n/160)$ added to Maitham path loss model, this amount will consider the contribution of the new frequency in the path loss, c is a negative constant. Also, for a new antenna height h_{bn}, an amount of

$b\log_{10}(h_{bm}/75.6)$ should be added to the Maitham model, b is a positive constant. The constants c and b can be obtained from the comparison between the actual and the predicted signal strengths for various frequencies and different antenna heights.

4.2.2 Signal Strength For Abqaiq Area

The signal strength for Abqaiq radio base station is calculated by:

$$\begin{aligned} SGN &= 10 * \log_{10}(P_t) + G_r + G_t - L_m - L_{tca} - L_{tco} - L_{rcc} - L_{ro} \\ &= 10 * \log_{10}(9540mW) + 3 + 3 - 1 - 1.1 - 1 - 3.77 - L_{ro} \\ &= 39.80 + 3 + 3 - 1 - 1.1 - 1 - 3.77 - L_{ro} = 38.96 - L_{ro} \end{aligned} \quad (4.6)$$

Where:

SGN: Signal Strength
P_t: Transmit power, (9540 mW).
G_r: Receiver antenna gain, (3 dB)
G_t: Transmitter antenna gain, (3 dB)
L_m: Miscellaneous Loss, (1 dB)
L_{tca}: Coaxial cable loss, (1.1 dB)
L_{tco}: Connector loss, (1 dB)
L_{rcc}: Receiver cable and connector loss, (3.77 dB)
L_{ro}: Path loss

Modified Hata Model (MHM): The path loss for Abqaiq radio base station was calculated using Modified Hata path loss model, Equation (4.1). The propagation data for Abqaiq were obtained on Dhahran-Abqaiq highway, which was described in chapter II. From Figure (2.2), the effective transmitter antenna height was taken as its height above the ground plus the average height of ground over a distance of 0 to 5 kilometers; this range was considered because the terrain declines sharply after 5 kilometers from the transmitter. The actual height for Abqaiq radio base station is 58.8 + 95.4 = **151.7** meters.

The predicted signal strength using Equations (4.1) and (4.6) is represented by the red curve in Figure (4.6). To fit better with the actual field measurements, Equation (4.1) was slightly modified to be:

$$Lro = Lu - 4.78*[\log_{10}(f)]^2 + 18.33*\log_{10}(f) - 35.94 + 3.3 \qquad 00 < d < 50 \text{ km} \qquad (4.7)$$

The simulation result obtained for Abqaiq area using Equation (4.7) is represented by the green curve in Figure (4.6), the RMSD of this curve is calculated by:

$$RMSD = \sqrt{\frac{\sum_{n=1}^{656} (Actual(n) - Predicted(n))^2}{24}} = \sqrt{\frac{631}{24}} = \sqrt{26.29} = 5.13$$

The simulation program is shown in appendix c.

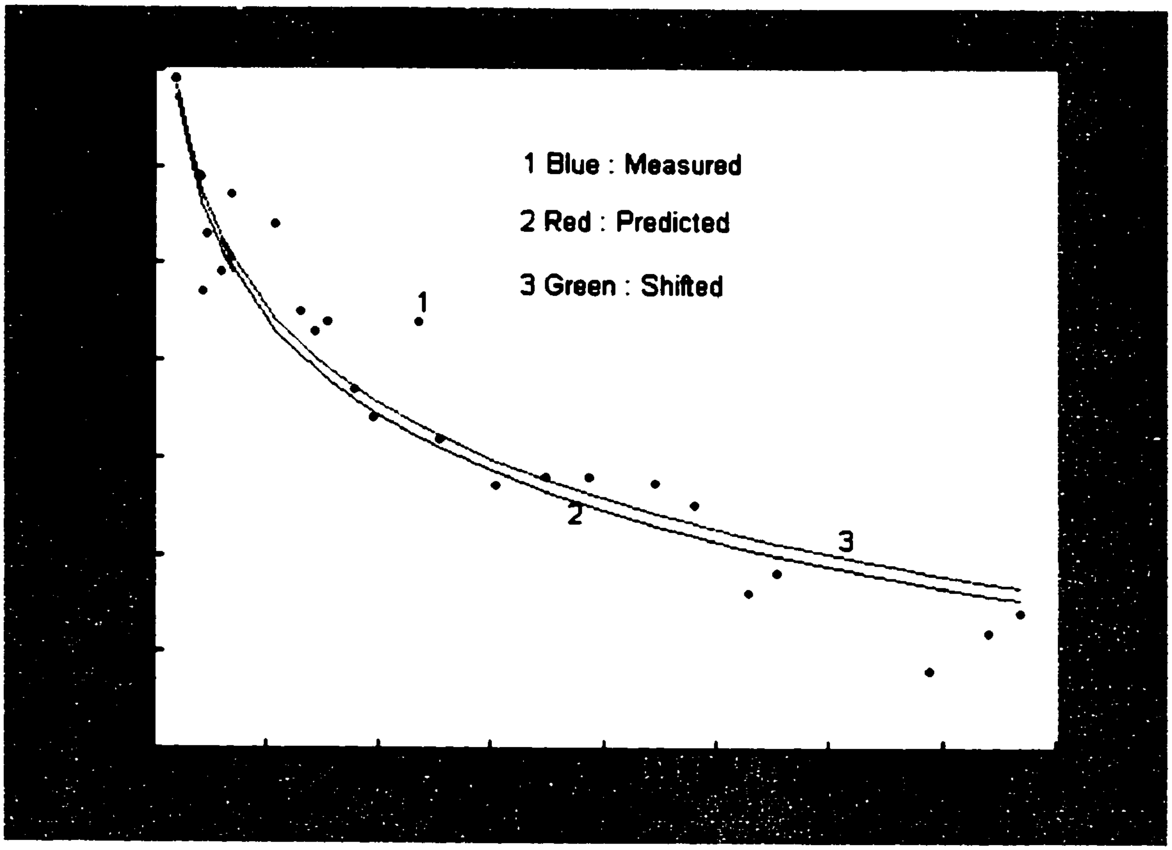

Figure (4.6) Signal Strengths for ABQ Using MHM

Modified Lee Model (MLM): The predicted signal strength for Abqaiq radio base station using the modified Lee path loss model is represented by the red curve in Figure (4.7). The RMSD between the red curve and the measured signal strength is ***5.22***. The comparison between the predicted and actual signal strengths shows that by shifting the red curve down by **1.2 dB**, it will result in better fit to the field measurements, the result of shifting the red curve is the green curve in Figure (4.7), the green curve has RMSD of ***5.1*** and is represented by:

$$\alpha_0 = \alpha_1\alpha_2\alpha_3\alpha_4\alpha_5 = (\frac{151.7}{30.48})^2 * (\frac{2}{3}) * (\frac{9.54}{10}) * (\frac{3}{4}) * (1)$$

$$L_p = 40-(-50)+10*3.62*10*\log_{10}\left(\frac{d}{1.6}\right)+10*2*\log_{10}(160/900)$$
$$-10*\log_{10}(\alpha_0)+\frac{14}{6}\log_{10}(\frac{hma}{10})+c$$

$c = 22.4$ **for Abqaiq area** (4.8)

The simulation program is shown in appendix c.

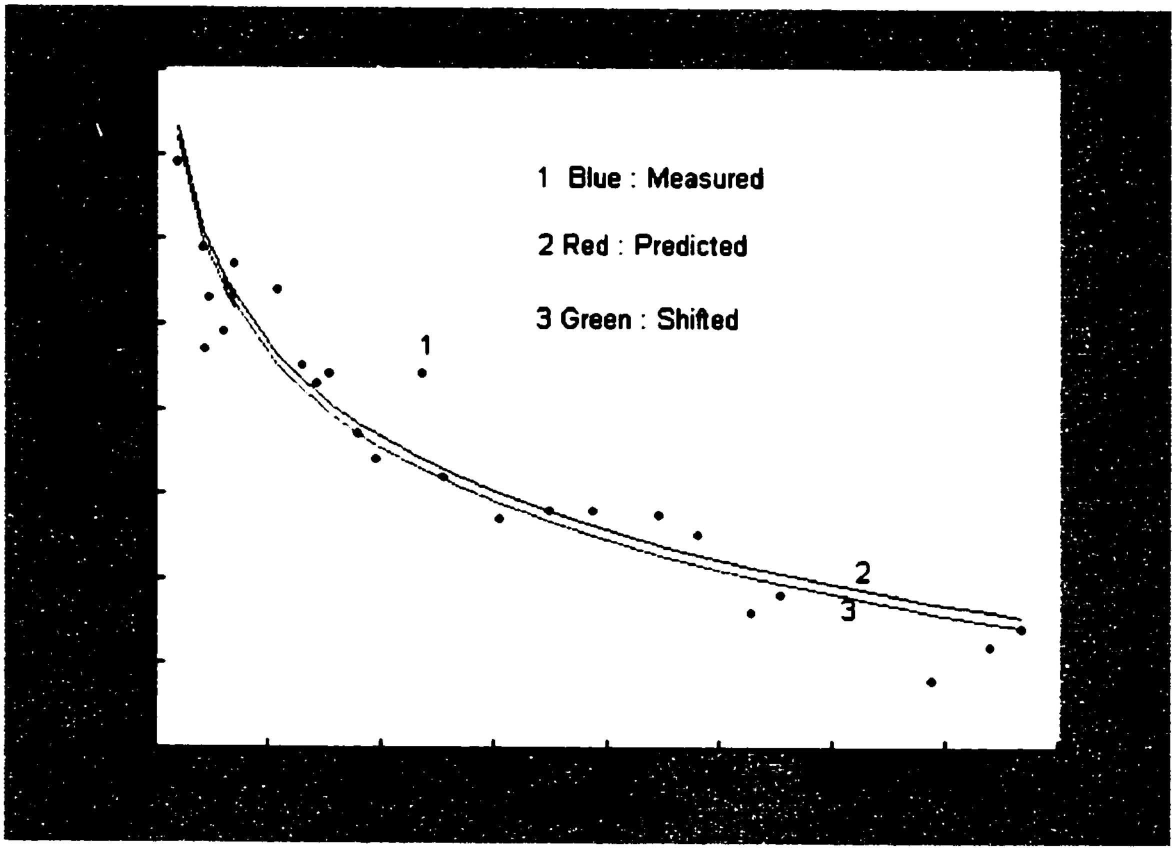

Figure (4.7) Signal Strengths For ABQ Using MLM

<u>**Maitham Path Loss Model:**</u> This model was used to predict the signal strength for Abqaiq radio base station; ***c***

was obtained to be **3.3** with RMSD of ***5.0***. The Maitham path loss for Abqaiq area is expressed as:

$$L = 10 * \log_{10}\left((231.3 * d)^{3.44}\right) - 20 * \log_{10}\left(h_b * h_m\right) + 20 * \log_{10}(f) + C$$

$$C = 3.3 \quad \textbf{For Abqaiq Area} \tag{4.9}$$

The actual and predicted signal strengths are shown in Figure (4.8). The simulation program is shown in appendix c.

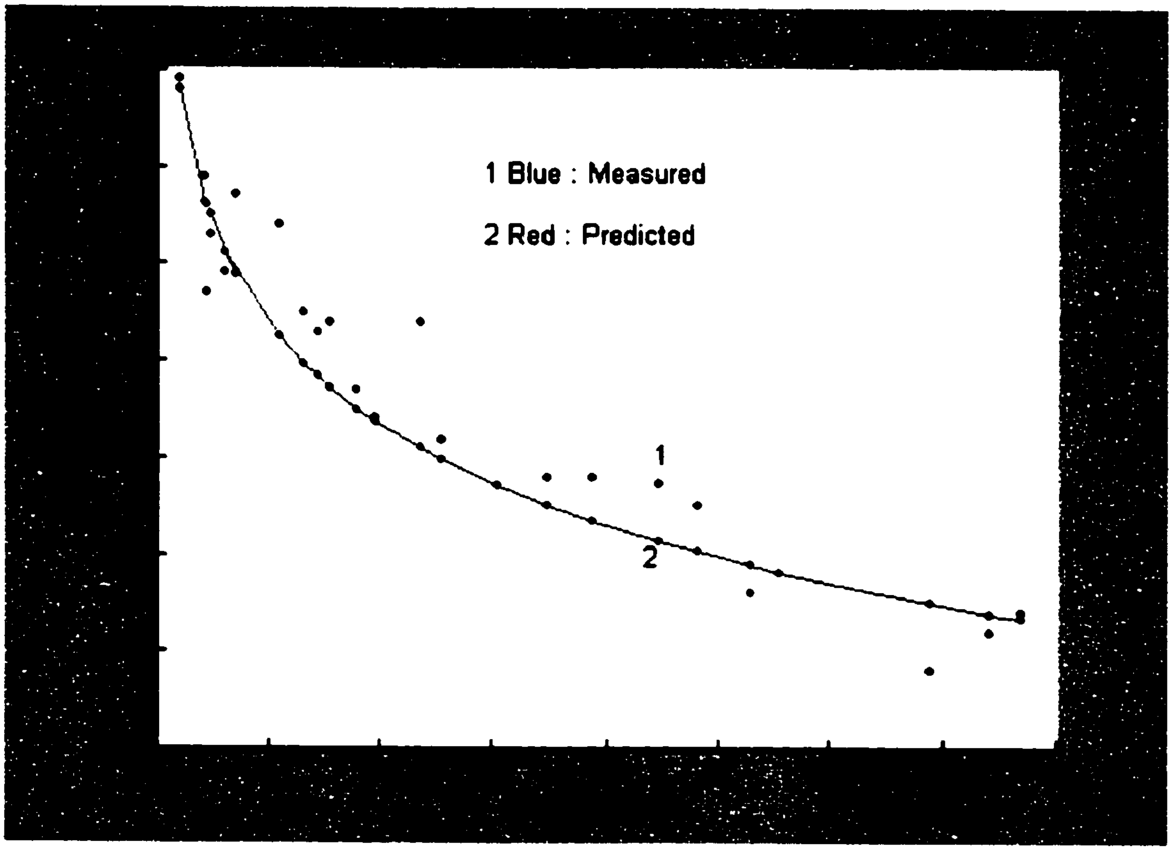

Figure (4.8) Signal Strengths For ABQ Using MPLM

4.2.3 Signal Strengths For Dhahran Area

Modified Hata Model (MHM): The signal strength data for Dhahran radio base station were obtained on Dhahran-Jubail highway, which was described in chapter II. Dhahran area has very irregular terrain and many high wedges and obstacles that exist in the radio signal paths, these wedges and obstacles are located at more than 20 meter height above the mobile receiver antenna. They result in a high attenuation to the received radio signal level. In the Dhahran-Jubail highway, many buildings and foliages exist; they degrade the radio signal due to the diffraction from objects that have dimension lengths of more than one wavelength. The density of buildings near Dhahran area is higher compared with Ras Tanura or Abqaiq. Dhahran area is considered Urban. To simulate the signal strength for Dhahran radio base station, urban model obtained by Hata was selected; more losses were added to this model to compensate for obstructions and to result in good fit with the measured data. From Figure (2.6), the effective transmitter antenna height is its height above the ground plus the average height of ground over a distance of 0 to 5 kilometers; this range was considered because the terrain declines sharply. The actual height for Dhahran radio base station antenna is

68.36 + 60 = **128.4** meters. The signal strength for Dhahran radio base station is calculated by:

$$SGN = 10*\log_{10}(P_t)+G_r+G_t-L_m-L_{tca}-L_{tco}-L_{rcc}-L_{ro}$$
$$= 10*\log_{10}(50000mW)\ +3+3-1-1.17-2-3.77-L_{ro}$$
$$= 46.99\ +3+3-1-1.17-2-3.77-L_{ro} = 45.03-L_{ro} \quad (4.10)$$

Where:

SGN: Signal Strength
P_t: Transmit power, (50000 mW).
G_r: Receiver antenna gain, (3 dB)
G_t: Transmitter antenna gain, (3 dB)
L_m: Miscellaneous Loss, (1 dB)
L_{tca}: Coaxial cable loss, (1.17 dB)
L_{tco}: Connector loss, (1 dB)
L_{rcc}: Receiver cable and connector loss, (3.77 dB)
L_{ro}: Path loss

The Modified Hata path loss model for Dhahran area is:

$$L_u = 69.55 + 26.16*\log_{10}(f)-13.82*\log_{10}(h_b)-ah_m +(44.9-6.55*\log_{10}(h_b))*\log_{10}(d)+5.4 \quad (4.11)$$

Figure (4.9) shows the measured and predicted signal strengths on Dhahran-Abqaiq highway using MHM model. The RMSD value is:

$$RMSD = \sqrt{\frac{\sum_{n=1}^{656}(Actual(n)-Predicted(n))^2}{51}} = \sqrt{\frac{1020}{51}}$$
$$= \sqrt{19.25} = 4.5$$

The simulation program is shown in appendix c.

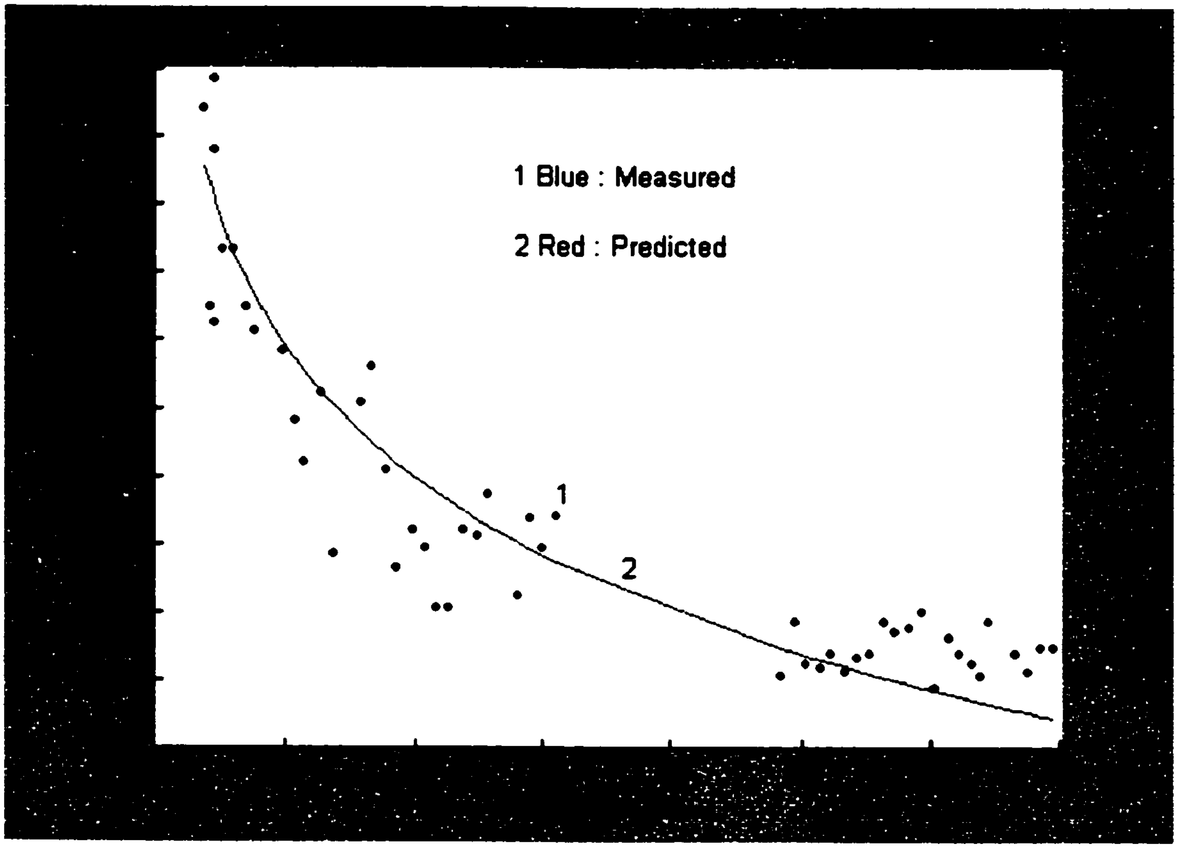

Figure (4.9) Signal Strengths For Dhahran Using MHM

<u>**Modified Lee Model (MLM)**</u>: The predicted signal strength for Dhahran radio base station using the modified Lee path loss model is represented by the red curve in Figure (4.10). The RMSD between the red curve and the measured signal strength is ***5.1***. The Lee correction factor and model for Dhahran area are:

$$\alpha_0 = \alpha_1\alpha_2\alpha_3\alpha_4\alpha_5 = \left(\frac{128.6}{30.48}\right)^2 * \left(\frac{1.5}{3}\right) * \left(\frac{50}{10}\right) * \left(\frac{3}{4}\right) * (1)$$

$$L_p = 40-(-60)+10*3.62*10*\log_{10}\left(\frac{d}{1.6}\right)+10*2*\log_{10}(160/900)$$
$$-10*\log_{10}(\alpha_0)+\frac{14}{6}\log10\left(\frac{hma}{10}\right)+c$$
$$c = 36.4 \text{ for Dhahran Area} \qquad (4.12)$$

The simulation program is shown in appendix c.

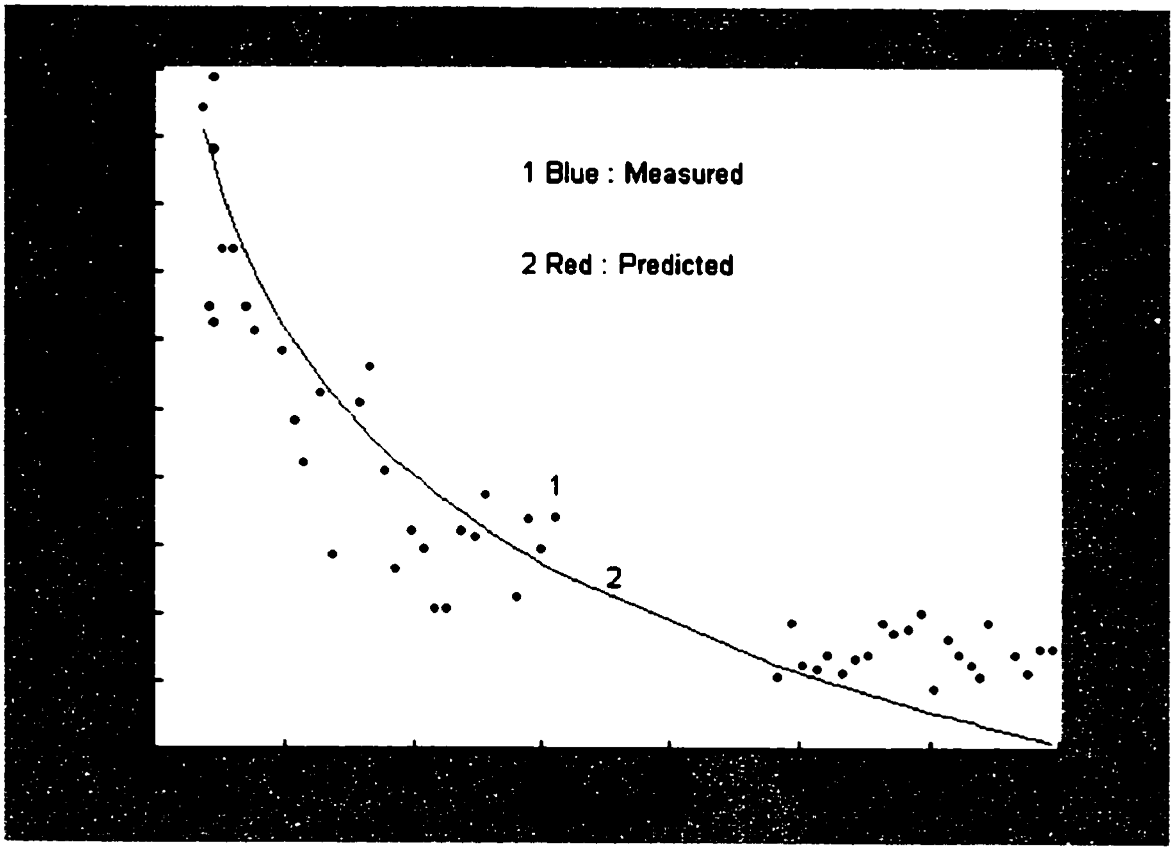

Figure (4.10) Signal Strengths For Dhahran Using MLM

__Maitham Path Loss Model (MPLM):__ This model was used to predict the signal strength for Dhahran radio base station; *c* was obtained to be **__20.4__** for Dhahran area. The RMSD is ***4.7***. The actual and predicted signal strengths are shown in Figure (4.11). The Maitham path loss for Dhahran is:

$$L = 10 * \log_{10}\left((231.3 * d)^{3.44}\right) - 20 * \log_{10}\left(h_b * h_m\right) + 20 * \log_{10}\left(f\right) + C$$

$C = 20.40$ **For Dhahran** (4.13)

The simulation program is shown in appendix c.

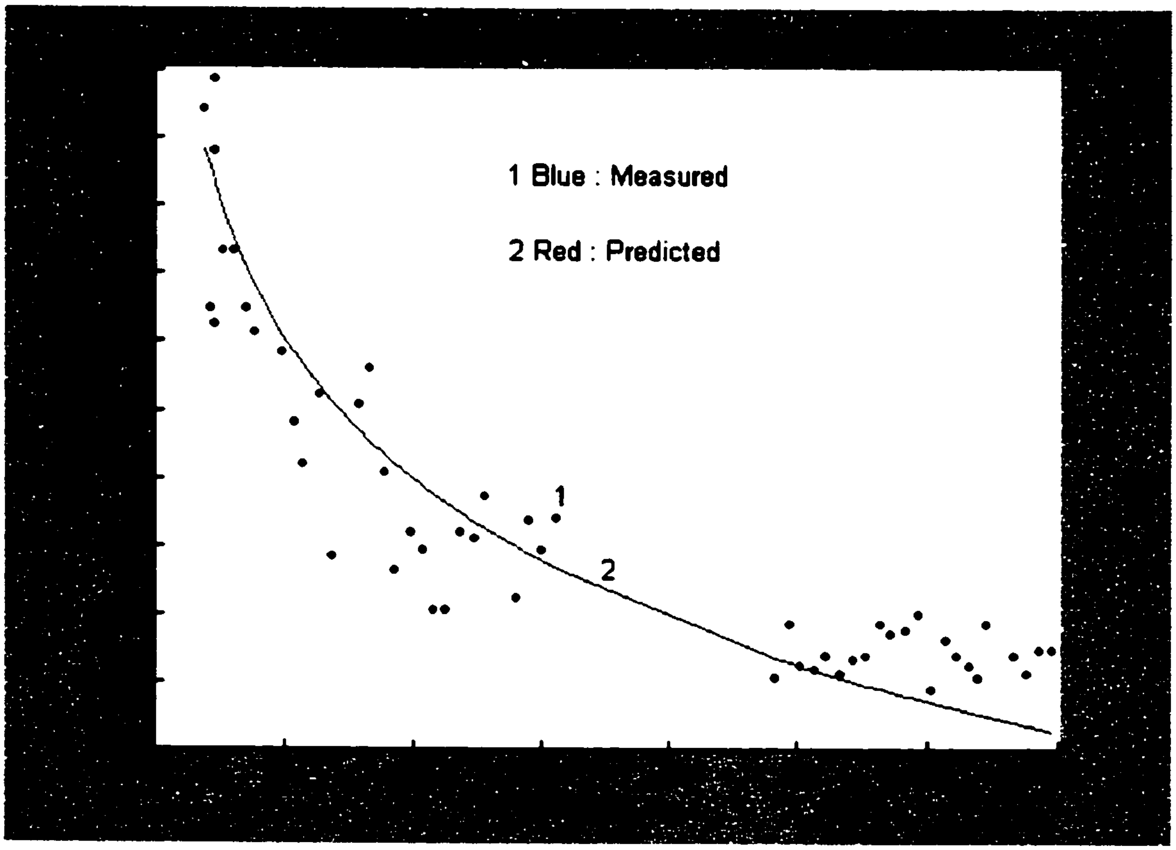

Figure (4.11) Signal Strengths For Dhahran Using MPLM

4.3 COMPARISON BETWEEN MODELS

The modified path loss models show good fit with the measured signal strengths, these models were modified with constants, and each constant was added to compensate for the differences between the actual and predicted signal strengths. The result of simulation using the modified Hata, Lee and Maitham are shown in Table (4.1) for three areas: Ras Tanura, Abqaiq and Dhahran. There are no large discrepancies between the different prediction results. The RMSD values in Table (4.1) show that Maitham path loss model results in the best fit to the measured signal strengths at Ras Tanura and Abqaiq, and Hata is the best in predicting the signal strength at Dhahran area.

4.4 RADIO PROPAGATION OVER DIFFERENT PATHS

The field propagation data were collected on two different types of path: Sea-Land and Land. Part of these data were used to compare the propagation over the two paths, the result of comparison is shown in Figure (4.12), the red curve was obtained to fit with the field measurements taken over Sea-Land path and expressed by:

$$asl = -36 \log_{10} (12 * d)$$

Where:

asl: Signal Strength Measurements over Sea-Land path

D: Distance in km

The blue curve in Figure (4.12) is used to represent the measurements taken over land path. It is calculated by:

$$al = -38 \log_{10}(11 * d)$$

Where:

al: Signal Strength Measurements over Land path

Figure (4.12) shows that Sea-Land path results in less attenuation to a radio signal compared with Land path. The median of differences between the signal strength measured on Sea-Land and Land path is 3.29 dB, this value was found by comparing the red curve with the blue.

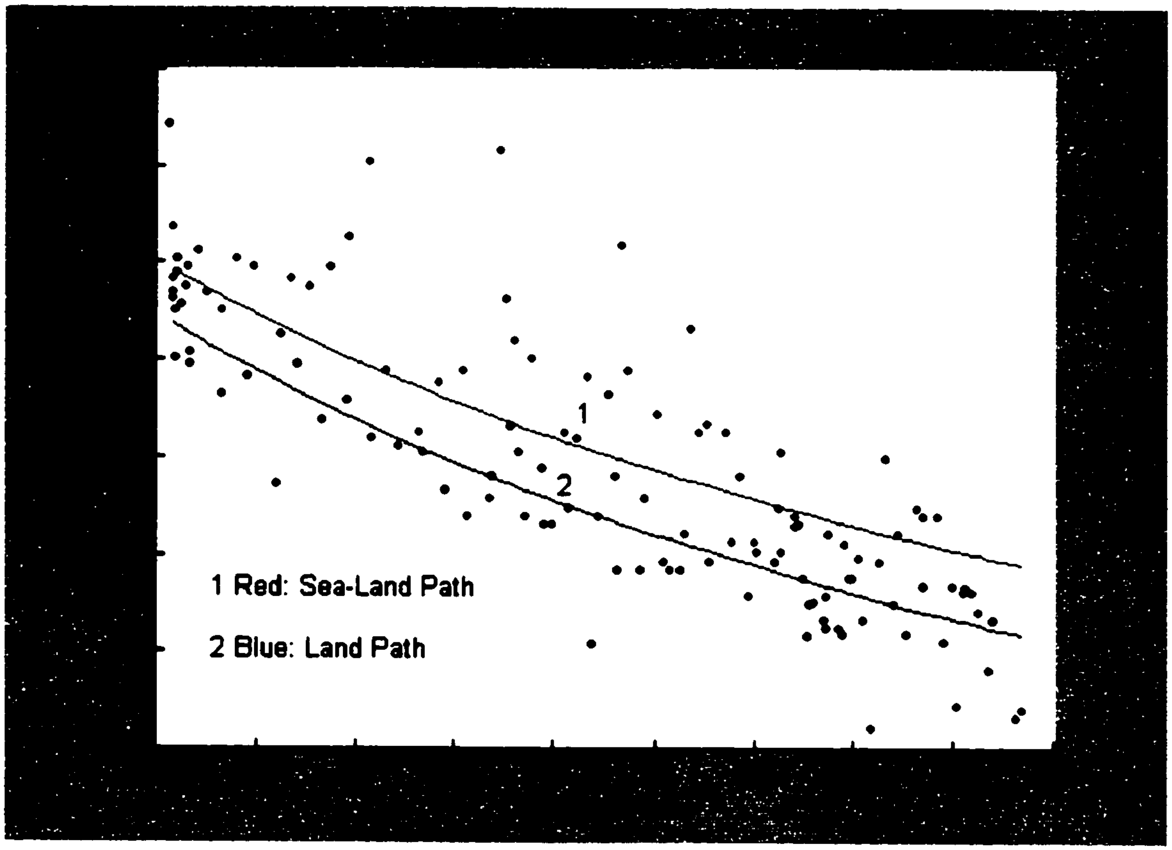

Figure (4.12) Signal Strength Over Different Paths

TABLE (4.1)

The Root of the Mean Square Difference

Radio Base Station	Hata RMSD	Lee RMSD	Maitham RMSD
Ras Tanura	3.45	3.46	3.44
Abqaiq	5.13	5.1	5
Dhahran	4.5	5.1	4.7

4.5 SUMMERY

The available path loss models were modified to result in accurate predictions of signal strengths for different areas in the Eastern province. The comparison results reflect the high accuracy of the modified models in estimating the signal strengths for Ras Tanura, Abqaiq and Dhahran radio base stations. Furthermore, the signal strength level over Sea-Land and Land paths was analyzed. A radio signal will experience more attenuation over Land path compared with Sea-Land path.

CHAPTER V

ANOMALOUS PROPAGATION

5.1 INTRODUCTION

In this chapter, we will investigate the change in the signal strength due to the variation in the weather condition. The weather condition at the surface and in the upper air will be analyzed. The upper air conditions will be investigated based on the Metrological department weather data obtained at 3:00 AM and 3:00 PM.

5.2 OBSERVATIONS ON THE RECEIVED SIGNAL STRENGTHS

Intensive investigations were done to study the effect of the weather conditions on the received radio signal. One field point was selected where the signal strength level was measured and recorded during different periods of daytime. In Figure (5.1), the measurements shown were recorded on April 19, 2001; the test was started at 11:00 AM and completed at 19:00 PM. The measured signal strength was fluctuating within ± 2dB. At the same point, the signal strength measurements were recorded from 7:30 AM to 8:00 AM on April 21, 2001; the result of the measurements is shown in Figure (5.2). Through these two Figures, the signal strength was fluctuating within ± 5 dB. This change in the signal strength can result in interference to other users and limit the reuse of a radio channel.

On May 10, 2001, Signal strength measurements around Ras Tanura radio base station were taken during the morning and afternoon over different roads; there were big differences between the two measurements. The morning and afternoon readings were presented in Figure (5.3).

In the following, the atmospheric conditions at the surface and in the upper air will be analyzed to identify the reasons that can cause the variation in the received radio signal.

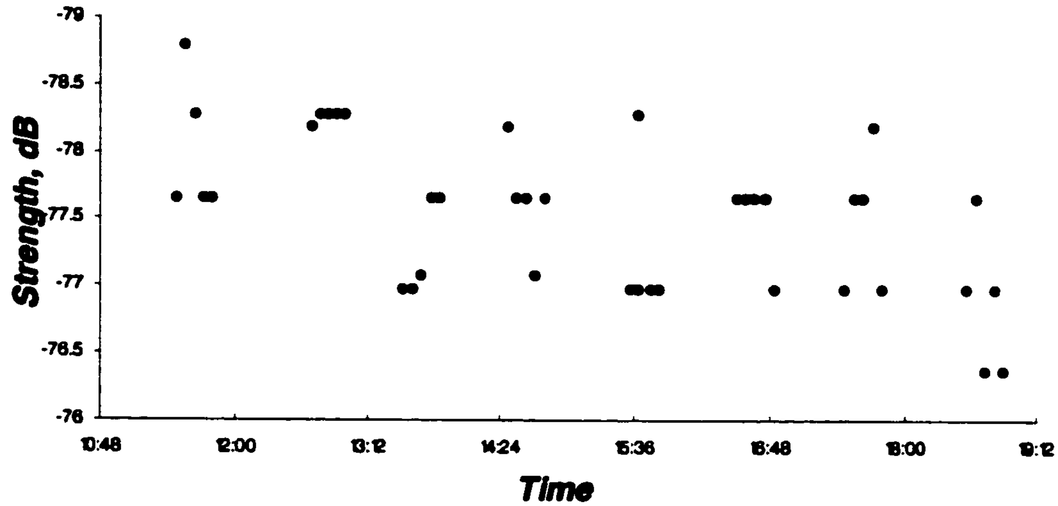

Figure (5.1) Measured Signal Strength on the Afternoon and the Evening at the same Test Point

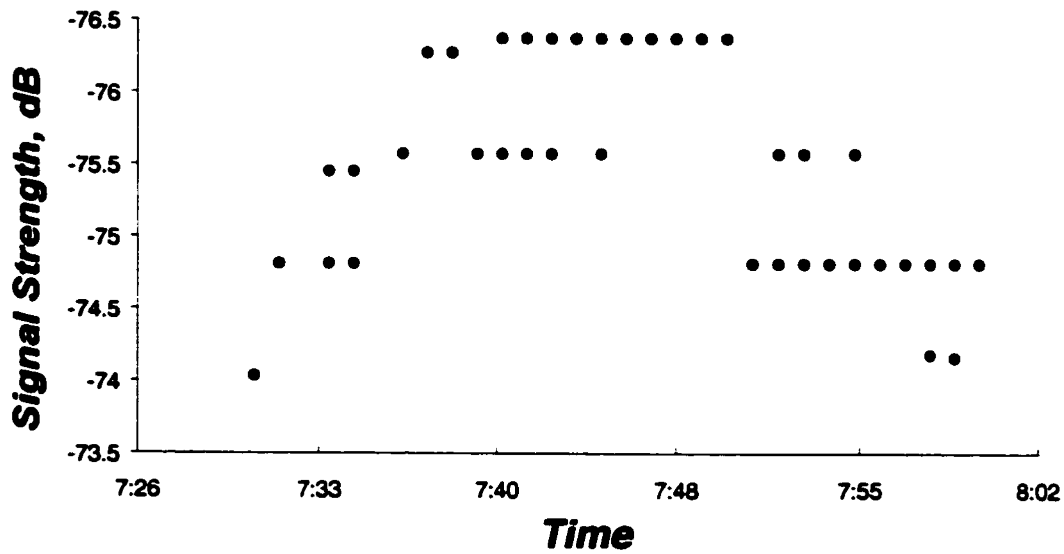

Figure (5.2) Measured Signal Strength on the Afternoon and the Morning at the same Test Point

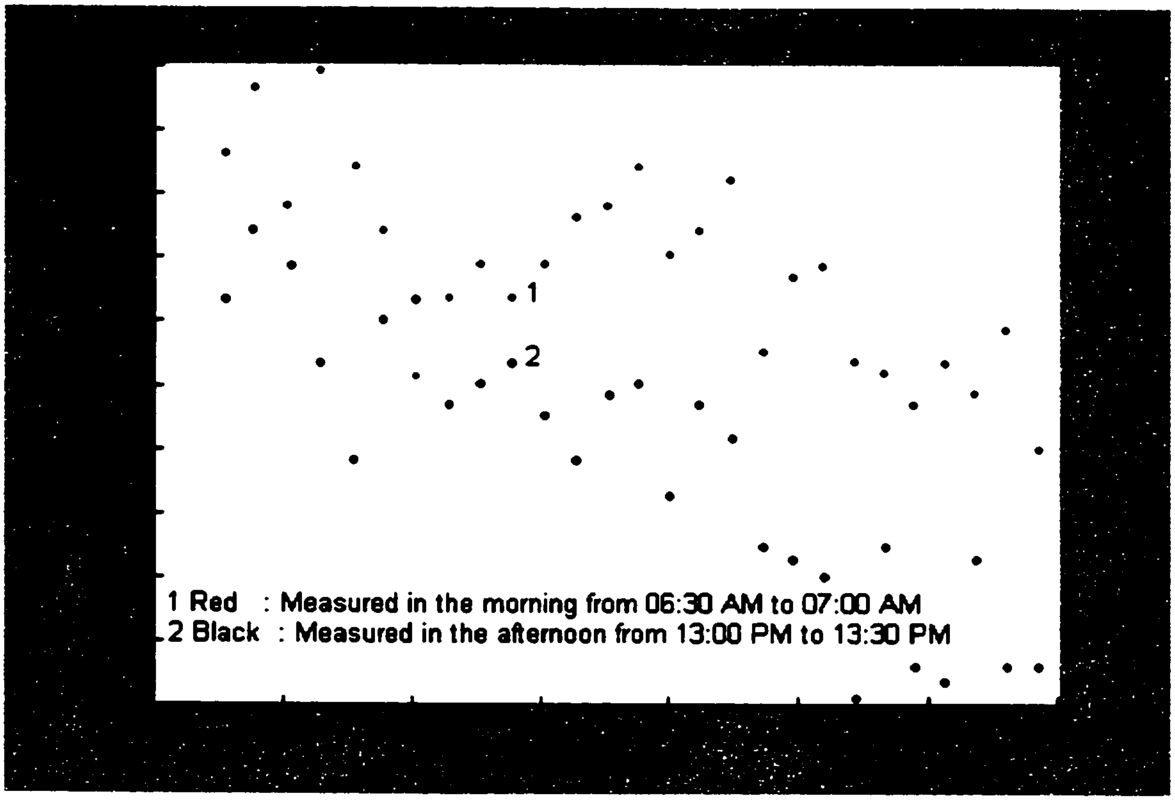

Figure (5.3) Variation on the received Signal at a selected road

5.3 SURFACE WEATHER CONDITIONS

To study the effect of the atmosphere on the received radio signal, it is essential to analyze the weather conditions on the surface and in the upper air. The study of the atmosphere around a radio base station requires data of Temperature, Pressure, Vapor Pressure and Relative Humidity. Atmospheric data were obtained from the Metrological Department at Dhahran. The radio refractivity was calculated by:

$$N = N_{dry} + N_{wet} = 77.6\,\frac{P}{T} + 3.732 * 10^{5}\,\frac{e}{T^{2}}$$ [12] (5.1)

Where:
P: Atmospheric Pressure (hPa)
e: Water Vapor Pressure (hPa)
t: Absolute Temperature (K)

The vapor pressure was calculated by:

$$e = \frac{H * e_s}{100}$$ [12] (5.2)

$$e_s = 6.1121 * \exp\left(\frac{17.502 * t}{t + 240.97}\right)$$ [12] (5.3)

Where:

H: Relative Humidity
t: Celsius Temperature (°C)
e_s: Saturation Vapor Pressure (hPa) at the temperature t (°C)

The refractive index gradient at the surface was calculated by:

$$\frac{dN}{dh} = -7.32 e^{0.005577 N_s}$$ [12] (5.4)

Where:

N_s: refractive Index at the Surface

The refractive index gradient in the upper air was calculated by:

$$\frac{dN}{dh} = \frac{N_2 - N_1}{h_2 - h_1}$$ [12] (5.5)

Where:

N_1: Lower atmospheric refractive index
h_1: Lower height
N_2: Upper atmospheric refractive index
h_2: Upper height

The Effective Earth Radius Factor (k) was calculated by:

$$k = \left[1 + \left(\frac{dN}{dh}\right)/157\right]^{-1} \qquad [12] \qquad (5.6)$$

The k factor can identify the path condition, as illustrated in Figure (5.4), If k is greater than 1, the ray is bent and refracted downward toward the earth, If k is less than 1, the ray is bent and refracted away from the earth, and no refraction will take place if k equals to 1. The commonly used k values are illustrated in Table (5.1). The k factor values at the surface for all days of measurements are shown on Figure (5.5) and the average of k values is 1.4.

The values of k at the surface indicate that any radio signal travels from the transmitter to the receiver is subjected to a slight refraction toward the earth. There was no noticeable change on the k factor at the surface that can explain the variation on the signal strength level between the morning to the afternoon and this leads us to study the upper air atmospheric conditions. The upper air atmospheric conditions during the measurement time are unavailable, they are accessible only at 3:00 AM and 3:00 PM for every day.

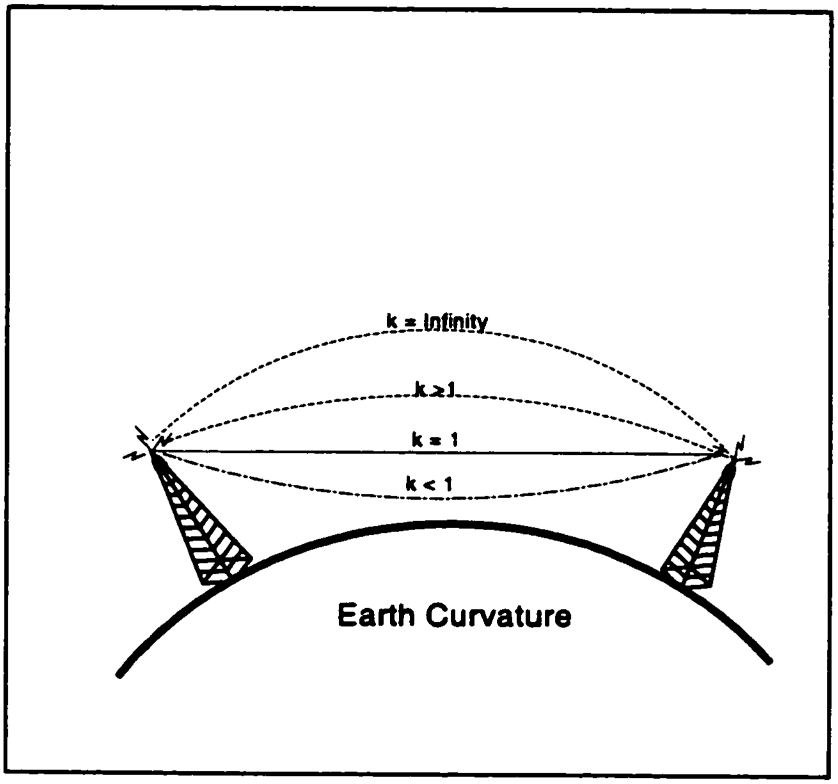

Figure (5.4) Radio Signal Path as a Function of *k*

TABLE (5.1)

COMMONLY USED k FACTORS

K Factor	dN/dh (N-UNITS/km)	Atmospheric Condition	Microwave Propagation
5/12	220	Humidity Inversion (Large Positive Gradient)	Extreme Earth's Bulge
1/2	157	Moderately Sub refractive	Moderate Earth's Bulge
2/3	80	Slightly Sub refractive	Slight Earth's Bulge
1	0	Homogeneous	No Refraction
1.25	-30	Dry Atmosphere	Standard (Mountainous)
4/3	-40	Standard Atmosphere	Standard
1.6	-58	Humid Atmosphere	Standard (Coastal)
∞	-157	Moderate Negative Gradient	Flat Earth
-1	-314	Sharp Gradient	Possible Blackout
-0.5	-470	Extreme Gradient	Blackout

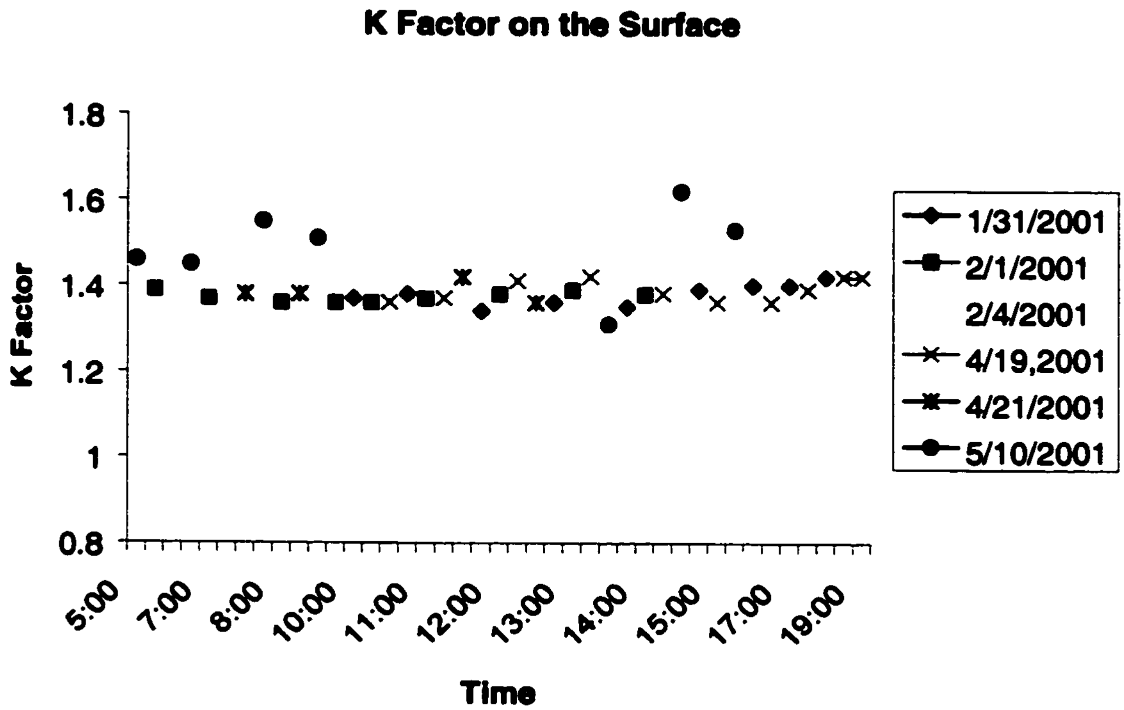

Figure (5.5) K Factor on the Surface

5.4 UPPER AIR CONDITIONS AT 3:00 AM AND 3:00 PM

The Metrological Department launches two balloons every day, one at 3:00 AM (0 GMT) and the other at 3:00 PM (12:00 GMT). The Balloon is used to record the upper air data every 10-second at different height. For selected days on April and May of year 2001, the effective earth's factor (k) was drawn with respect to the height above the Sea Level in Figures (5.6) and (5.7). The green line in Figure (5.6) stands for the upper atmospheric data at 3:00 AM of May 10, 2001, the high value of the k factor at 207 m ASL indicates that the radio wave front travels at this height has the same slope of the earth curvature, this phenomenon is referred to as flat propagation. With a high k value, the radio wave front travels over the horizon increasing the coverage radius. The red line in Figure (5.7) shows the upper atmospheric layers formed at 3:00 AM on April 02, 2001. The k values are negative at 69, 116 and 220 m heights ASL, which indicate the presence of super-refractive layers. The first two layers can be considered as a duct of, 116 - 69 = 47 m thickness. The Green line in Figure (5.7) illustrates the upper air layers at 3:00 AM of April 19, 2001. At 220 m ASL, a duct was present; the duct's thickness was 58 m. The pink line in Figure (5.7) corresponds to the atmospheric data of the upper air obtained at 3:00 AM for April 21, 2001, the k values are greater than 1 and the wave front is bent downward toward the earth increasing the path clearance. The k factor values are greater than 1 at 400 m ASL and above, they cause the radio wave front to refract toward the earth.

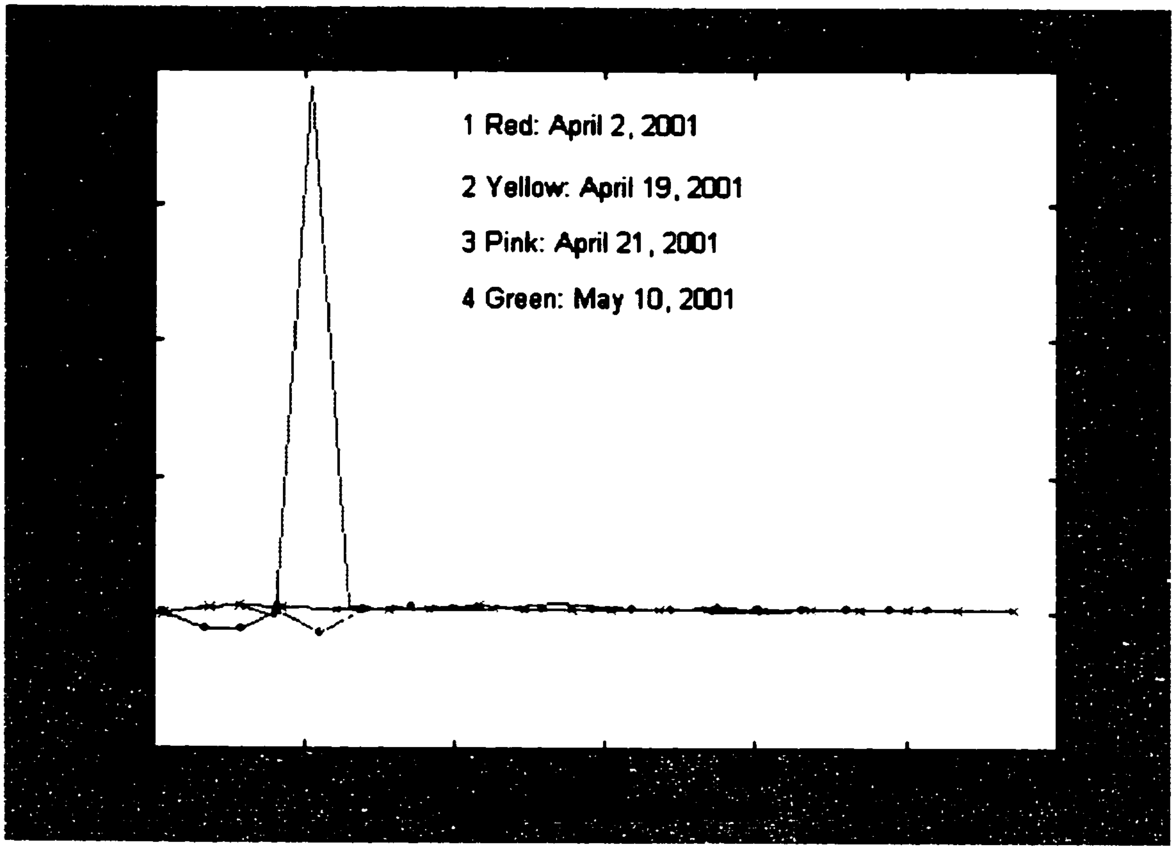

Figure (5.6) K Factors At the Upper Atmosphere At 3:00 AM

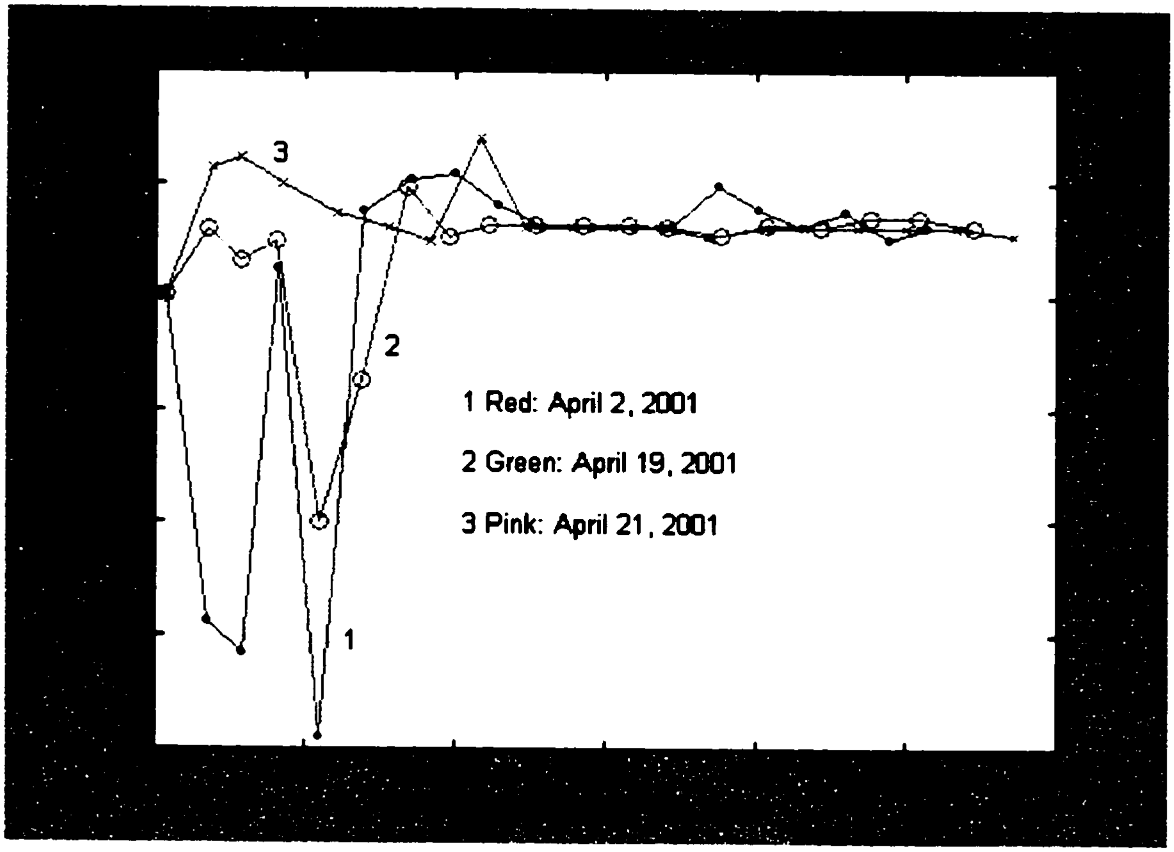

Figure (5.7) K Factors At the Upper Atmosphere At 3:00 AM

The k values obtained at 3:00 PM for the upper air and during April 2, 19, 21 and May 10 of year 2001 are drawn with respect to the height above the Sea Level in Figure (5.8). The calculated effective earth factor values are greater than 1 and less than 2, this indicates that a slight refraction will occur in the afternoon hours to a radio signal traveling in the upper air layers.

The change in the weather condition in the upper air between the morning and the afternoon seems to be a significant factor that explains the change in the signal strength during the daytime. The ducts and flat earth radio path appeared in the morning as shown Figure (5.7), these disappeared in the afternoon as shown in Figure (5.8). Enhancement on the signal strength in morning hours is caused by ducting and flat earth propagation.

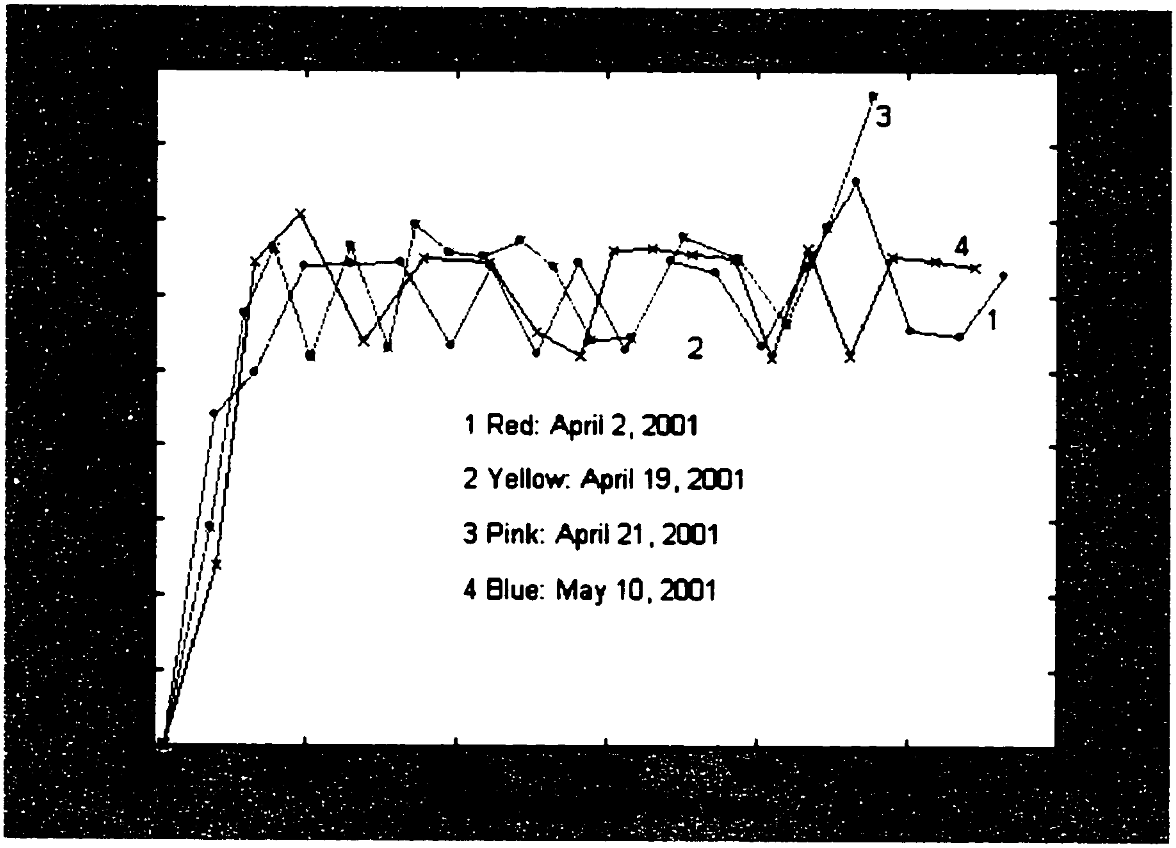

Figure (5.8) K Factors At the Upper Atmosphere At 3:00 PM

5.5 SUMMARY

It is not an easy task to correlate change on the signal strength at the surface to the upper atmospheric layers, each layer has its own contribution, but it is possible to predict an increase or decrease in the signal strength. No upper atmospheric data were available for the measurement time, they were presented only for 3:00 AM and 3:00 PM, using such data to estimate the effect of the weather on the signal strength can lead to some errors, it is required to have the upper atmospheric data during the measurement time.

Moreover, the abnormal atmospheric conditions seen in the morning were disappeared in the afternoon. These conditions cannot be controlled, they usually occur in the costal area where the temperature and Relative Humidity are commonly high [12].

CHAPTER VI

CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSION

Two issues impair radio communication: poor coverage and interference. Poor coverage might blocks a part of radio users from communicating with each other, but the Interferece blocks the communication in a radio network. The above issues should be assessed during radio system design when path loss calculations are done. Their appearance after construction implies imperfection in the radio system design. Most existing radio signal propagation models are based on measurements conducted outside Saudi Arabia, which may not be particularly useful or applicable to desert conditions. In order to utilize the existing path loss formulae in the Eastern Province of Saudi Arabia, more corrections were included.

The available path loss models were used to predict and modified to fit the actual propagation data of Abqaiq, Ras Tanura and Dhahran radio base stations. Maitham path loss model, a new model, was developed based on real field propagation data to match the actual path loss. This model needs more modifications, which can be achieved by obtaining real field propagation data for different frequencies and various antenna heights.

The modified path loss models result in high accurate estimation of the signal strengths around the selected radio base stations.

Moreover, The atmospheric conditions at the surface and in the upper air layers were studied to analyze the change on signal strength during the daytime. There were more changes in the upper air condition that were taken as an explanation to the variation on the measured radio signal.

6.2 The Difficulties Faced In This Work

We faced the following difficulties during the coverage campaign, they are:

- Collecting Signal Strength Data: I had to stop beside the road to record the signal strength every 500 meters. The covered distance under this test was more than 600 km. In some area, the signal strength was recorded more than two, three or four times.
- Maintaining Global Positioning (GPS) System Height Above Sea Level: Commercial GPS receiver was used to obtain the Cartesian and height above sea level at each test point. The GPS height data was not stable, for a single point and within 30 seconds; the height above the sea level was changing from 23 to 30 meters. In some cases, there were approximately 20-meter difference between Height data recorded in the afternoon and those recorded in the morning.
- Obtaining Signal Strength From EDX: The EDX coverage map was used to obtain the signal strength levels. To find the signal strength for any test point, I put the cursor on the EDX coverage map at the Cartesian of the point, and then the signal strength at the selected point appears in the screen. This way was applied for 650 test points.

- Presenting The Roads And Highways In The EDX Coverage Map: About 650 test points were inputted into the EDX coverage map to draw the main roads and highways.
- Recording Data And Transferring Them To Soft Copies: A Thousand of readings were obtained from the field and transferred into soft copies.

6.3 RECOMMENDATIONS AND FUTURE WORK

Many radio networks, which operate in different bands, are available in the Eastern Province. The design of these networks is usually done using free space, Hata/Okumura or Hata/Epstein path loss models. Issues like radio channel inter-modulation, radio interference and fading were discussed by different identities requesting real solutions to eliminate and resolve such problems that appear in their radio networks. To minimized such issues and to have a better radio link we recommend the following:

1 Cooperation between KFUPM and Other Organizations Using Mobile Radio Network: It is very important for KFUPM to continue their researches in radio signal propagation and for other organizations using mobile radio network (such as Saudi Aramco) to build their radio system studies based on accurate path loss

models. KFUPM specialists can help in obtaining more accurate path loss models, if they participate in the signal propagation studies.

2 Various Frequencies and Antenna Heights: Propagation data for various frequencies and different antenna heights are required to define correct relations between path loss model and the operating frequencies, base station and mobile antenna heights.

3 Define the Eastern Province Terrain: It is an emerging issue to place propagation studies around the Eastern Province and to define the terrain and weather conditions, which should help in identifying the right path loss models.

4 Using Differential GPS: To eliminate the height errors, it is essential to use differential GPS. From a fixed station and through a radio link, the error in the GPS reading is sent to the differential GPS in the mobile to split up.

5 Automated Signal Strength System: To integrate the GPS and HP-8920, it requires having a system that is automatically capable to record signal strengths, the height above the sea level and the Cartesians of the tested points into soft copies. Collecting propagation data manually consumes time and exposes to danger.

The study of defining path loss models can lead to a high amount of information but it requires more works and contributions. The communication tower in the KFUPM as an example can be utilized to define the accurate path loss models at Dhahran area for different heights, operating frequencies, and weather conditions. The change on the signal strength due to the change on the weather condition should be analyzed based on real weather data obtained at the time of measurement. It is also necessary to obtain a mathematical relation for the Arabian Gulf that can express the signal strength as a function of atmospheric condition.

APPENDIX A

FIELD MEASUREMENTS AT RAS TANURA AREA

LOCATION						D	H	M	LOCATION						M	H	D
LATITUDE			LONGITUDE			(km)	(m)	(dB)	LATITUDE			LONGITUDE			(dB)	(m)	(km)
26	28	23.9	50	0	55.3	27.38	4.4	-98	26	35	5.9	49	50	26.8	-93	12.4	28.08
26	28	39.8	50	0	38.1	26.72	3.6	-96	26	35	16.6	49	50	15.7	-90.8	13.6	28.19
26	28	50.3	50	0	25.9	26.51	4.2	-93	26	35	29.8	49	50	4.4	-90.8	10.9	28.27
26	28	57.4	50	0	16.2	26.38	4.4	-92	26	35	43.8	49	49	54.7	-91.8	8.2	28.32
26	29	8.8	49	59	57.9	26.22	4.8	-92	26	35	58.7	49	49	46.7	-87.2	9.4	28.31
26	29	17.6	49	59	43.4	26.1	8.1	-97.8	26	36	13.4	49	49	40.7	-89.9	10.8	28.27
26	29	25.5	49	59	30.1	26	8.7	-91.7	26	36	28.8	49	49	36.2	-90.8	10.5	28.2
26	29	39.5	49	59	19.6	25.71	12.1	-88.1	26	36	46.4	49	49	31.4	-89.5	9.9	28.11
26	29	52.2	49	59	11.8	25.43	12.7	-88.1	26	37	0.3	49	49	27.6	-84.1	9.2	28.05
26	30	3.5	49	58	55.5	25.29	11.8	-87.6	26	37	16.8	49	49	23.1	-91.8	8.2	27.98
26	30	14.8	49	58	44.5	25.11	11	-94.2	26	37	32.8	49	49	18.6	-95.4	7.5	27.93
26	30	28.5	49	58	33.9	24.85	11.9	-92.6	26	37	47.8	49	49	13.4	-93.5	7.2	27.92
26	30	38.6	49	58	26.2	24.67	12.6	-85.2	26	38	4.1	49	49	6.2	-93	8.3	27.96
26	30	55.1	49	58	13.9	24.38	15.1	-99	26	38	17.3	49	48	59.1	-93.5	9.1	28.03
26	31	9.4	49	58	3.2	24.14	18	-90.3	26	38	32.3	49	48	49.7	-93.5	10.5	28.15
26	31	23.3	49	57	52.9	23.91	19	-91.3	26	38	45.2	49	48	40.1	-92.6	11.4	28.31
26	31	34.9	49	57	44.1	23.73	18.9	-93.8	26	38	58.7	49	48	28.5	-98	11.3	28.52
26	31	51.6	49	57	31.7	23.47	18.5	-92.2	26	39	12.7	49	48	16.2	-87.2	13.5	28.76
26	32	5.7	49	57	24.5	23.22	17.1	-92.5	26	39	24	49	48	7.1	-86.8	13.9	28.93
26	32	19.1	49	57	21.4	22.93	16.3	-88.5	26	39	39.3	49	47	56.5	-94.6	14.6	29.13
26	32	35.8	49	57	21.4	22.51	16.4	-87.6	26	39	53	49	47	48	-95	13.4	29.29
26	32	55.1	49	57	22.3	22.01	17.5	-89.4	26	40	7.1	49	47	40	-95.7	10.5	29.44
26	33	6.2	49	57	21.7	21.74	18.4	-86	26	40	20.6	49	47	32.4	-97.5	9.1	29.58
26	33	20.9	49	57	19.6	21.42	19.6	-83.8	26	40	35.2	49	47	24.2	-95	8.9	29.75
26	33	36.9	49	57	17.9	21.06	21.8	-83.4	26	40	50.1	49	47	15.4	-95	8.4	29.94
26	33	53.2	49	57	5.4	20.89	21.2	-83.8	26	41	3.7	49	47	5.5	-94.6	9.4	30.17
26	34	6.9	49	56	57.7	20.71	21.1	-78.5	26	41	17.4	49	46	53.4	-101	9.8	30.47
26	34	21.4	49	56	49.6	20.53	20.4	-90.8	26	41	27	49	46	42.9	-99.3	9.1	30.74
26	34	36.2	49	56	43.5	20.31	18.1	-90.8	26	41	39	49	46	27.2	-93	7.7	31.15
26	34	50.8	49	56	38.8	20.08	16.7	-82.8	26	41	46.9	49	46	14.3	-93.5	7.3	31.5
26	35	7.1	49	56	33.9	19.83	16.8	-87.2	26	41	56.3	49	45	58	-95	8.9	31.93
26	35	24.4	49	56	32.3	19.5	17.2	-80.6	26	42	6.1	49	45	42.7	-96.6	10.5	32.35
26	35	36.3	49	56	28	19.34	17.2	-74.1	26	42	16.1	49	45	29.9	-95.7	12	32.7
26	35	52.9	49	56	16.8	19.24	15.4	-86	26	42	27.9	49	45	17.5	-93	11.9	33.03
26	36	8.5	49	56	10.1	19.09	13.4	-81.8	26	42	42.7	49	45	5	-95.3	12	33.38
26	36	24.2	49	56	4.8	18.91	13	-88.1	26	42	57.2	49	44	55.8	-94.2	13.3	33.64

LOCATION						D	H	M	LOCATION						M	H	D
LATITUDE			LONGITUDE			(km)	(m)	(dB)	LATITUDE			LONGITUDE			(dB)	(m)	(km)
26	37	28.4	49	55	57.7	17.96	13.2	-88.5	26	43	53.1	49	44	21.5	-96.6	20.8	34.67
26	37	40.4	49	55	56.5	17.8	13.1	-88.5	26	44	4.6	49	44	14.5	-93.8	22.3	34.89
26	38	0.7	49	55	53.2	17.58	14.6	-80	26	44	19.7	49	44	5.4	-95	22.5	35.19
26	38	16.2	49	55	50.4	17.43	15.8	-88.1	26	44	33.1	49	43	56	-97.5	22.5	35.49
26	38	43.2	49	55	44.6	17.22	11.3	-79.1	26	44	46.6	49	43	44.2	-98.3	22.8	35.86
26	38	52.2	49	55	42.9	17.15	12.1	-83.5	26	44	58.7	49	43	31.1	-98	20.5	36.26
26	39	2.7	49	55	41	17.07	13.4	-76.9	26	45	10.9	49	43	14.6	-98	18.3	36.76
26	39	21.2	49	55	37.9	16.95	13.7	-69.2	26	45	17.7	49	43	3.6	-99.5	19	37.09
26	39	34.4	49	55	41.1	16.73	12.8	-87.2	26	45	25.6	49	42	47.7	-97.5	20.9	37.56
26	39	39.3	49	56	0.4	16.18	13	-80.6	26	45	32.6	49	42	29.5	-96.3	23.4	38.09
26	39	42	49	56	17.3	15.71	13.1	-81.2	26	45	36.9	49	42	15	-99.1	25	38.5
26	39	45.7	49	56	32.5	15.27	12.9	-83.8	26	45	42.6	49	41	55.2	-101	23.5	39.07
26	39	56.4	49	56	53	14.63	10.9	-80.6	26	45	47	49	41	39.7	-104	23.2	39.51
26	40	5.7	49	57	3.2	14.27	8.8	-69.8	26	45	52	49	41	22.2	-103	23.9	40.01
26	40	17.9	49	57	13.8	13.88	6.5	-73.7	26	45	56.5	49	41	6.5	-103	24.1	40.46
26	40	30.6	49	57	24.6	13.48	8.1	-75.2	26	39	19.2	49	48	12	-96.6	14	28.83
26	40	43.7	49	57	35.9	13.08	10.1	-76.3	26	39	30.2	49	48	31.6	-96.6	12.8	28.23
26	40	56.3	49	57	46.6	12.7	8.4	-75.9	26	39	33.3	49	48	49.6	-95.3	11	27.73
26	41	10.3	49	57	50.4	12.5	6.6	-78.8	26	39	32.2	49	49	10.1	-95.7	9.6	27.18
26	41	22.5	49	58	7.9	11.96	7.1	-75.2	26	39	30.3	49	49	26.9	-95	9.5	26.74
26	41	36.1	49	58	17.4	11.64	8.8	-74.8	26	39	28.4	49	49	44.6	-94.6	9.6	26.27
26	41	50.5	49	58	26.3	11.34	8.1	-77.5	26	39	26.4	49	50	2.7	-91.3	8.4	25.8
26	42	6.3	49	58	35	11.06	4.4	-76.6	26	39	24.3	49	50	21.4	-93.6	7.6	25.31
26	42	20.1	49	58	41.6	10.86	3.1	-74.5	26	39	22.5	49	50	38.1	-92.2	7.6	24.87
26	42	35.6	49	58	48.1	10.68	5.7	-75.2	26	39	20.4	49	50	57.2	-93	8	24.38
26	42	51.1	49	58	53.7	10.54	7.3	-77.3	26	39	18.6	49	51	14.5	-91.3	8.7	23.93
26	43	7.4	49	58	58.4	10.46	8.2	-75.6	26	39	16.5	49	51	33.5	-89.4	7.1	23.43
26	43	22.8	49	59	2.8	10.4	9.1	-77.5	26	39	14.7	49	51	49.5	-89.9	6.3	23.02
26	43	39.1	49	59	7.4	10.37	10.5	-75.9	26	39	12.6	49	52	8.3	-89	7.6	22.54
26	43	55.1	49	59	12	10.36	9.4	-73.3	26	39	10.5	49	52	28.4	-99.5	8.8	22.02
26	44	11.3	49	59	16.7	10.38	6.6	-76.9	26	39	10.5	49	52	36.3	-90.4	9.3	21.81
26	44	24.5	49	59	21.7	10.38	5.2	-76.6	26	39	11.6	49	52	44.5	-89.9	9.9	21.59
26	44	33.2	49	59	35.1	10.13	4.5	-70.9	26	39	16.1	49	52	59	-93.5	9.5	21.16
26	44	46.4	49	59	34.7	10.3	4	-67.8	26	39	17.3	49	53	19.5	-92.7	8.7	20.61
26	45	4.9	49	59	31.5	10.63	4.9	-76.3	26	39	11.1	49	53	36.6	-91.3	8.2	20.22
26	45	19.5	49	59	37.3	10.7	4.5	-80.3	26	39	0.6	49	53	48.4	-90.8	10.4	20.01
26	45	24.4	49	59	52.7	10.41	3.3	-80	26	38	48.1	49	53	56.6	-89.9	13.6	19.92
26	45	17.3	50	0	9.6	9.897	2.3	-75.5	26	38	34.5	49	54	5.6	-92.6	14.7	19.84
26	45	10.1	50	0	26.3	9.389	1.7	-76.3	26	38	21.5	49	54	16.2	-89	15	19.72
26	45	2.6	50	0	43.8	8.857	1.2	-74.8	26	38	2.3	49	54	29.8	-102	13.9	19.62

LOCATION						D	H	M	LOCATION						M	H	D
LATITUDE			LONGITUDE			(km)	(m)	(dB)	LATITUDE			LONGITUDE			(dB)	(m)	(km)
26	44	34.3	50	1	49	6.874	1.8	-70.9	26	38	13.5	49	55	12.3	-86.9	15	18.41
26	44	27.4	50	2	4.7	6.397	2	-70.9	26	38	9.6	49	55	8.1	-86.4	14.9	18.56
26	44	20.4	50	2	20.9	5.907	1.5	-69.1	26	38	7.1	49	55	3.1	-85.6	14.8	18.72
26	44	14	50	2	35.8	5.459	1.1	-67.1	26	38	2.9	49	55	6.8	-86.8	14.8	18.69
26	44	4.3	50	2	53.3	4.893	2.1	-67.2	26	37	56.7	49	55	13.2	-90.8	14.9	18.61
26	43	54.2	50	3	4.7	4.454	3.2	-67.2	26	37	48	49	55	16.7	-89	14.9	18.65
26	43	41.1	50	3	19.4	3.889	3.8	-61.6	26	37	41.6	49	55	23.8	-91.7	14.6	18.57
26	43	32.1	50	3	29.4	3.505	3.6	-61.6	26	37	34.9	49	55	31.4	-88.1	14.4	18.49
26	43	19.7	50	3	43.1	2.98	3.9	-61.7	26	37	21.1	49	55	39.1	-90.8	14.8	18.52
26	43	8.3	50	3	56	2.494	2.9	-57.6	26	37	12	49	55	41.6	-93.8	15	18.61
26	42	58.4	50	4	7.1	2.081	1.8	-57.6	26	37	8.6	49	55	46.2	-93.8	14.7	18.56
26	42	47	50	4	19.1	1.639	1	-46.8	26	37	10.5	49	55	55.4	-86.4	13.7	18.31
26	42	33	50	4	35	1.11	1.4	-40	26	38	56.7	49	57	19.9	-95.7	16.2	14.66
26	42	23.6	50	4	45.3	0.836	1	-40.5	26	32	53.2	49	53	13.9	-89	16	26.69
26	42	21.1	50	4	55.5	0.591	1	-35.3	26	32	36.8	49	53	28.7	-92.6	14.1	26.73
26	42	31.4	50	5	5.7	1.913	2.9	-24	26	32	27.5	49	53	39.6	-93.5	14.6	26.71
26	42	28.5	50	5	11.3	1.757	2.8	-33	26	32	17.6	49	53	53.6	-94.2	16.8	26.65
26	42	34.4	50	5	9.1	1.826	2.4	-30.5	26	32	9.2	49	54	9	-96	17	26.54
26	42	37.9	50	5	13	1.732	1.9	-31.7	26	32	1	49	54	24.7	-95	15.7	26.43
26	42	36	50	5	17	1.615	1.8	-51.5	26	31	53.9	49	54	38.4	-94.2	14.5	26.34
26	42	31.8	50	5	21.5	1.478	2	-41.9	26	31	43.9	49	54	55.5	-96	14.3	26.26
26	42	21.8	50	5	31.4	1.223	2.1	-37.2	26	31	34.4	49	55	8.7	-94.7	15	26.25
26	42	20	50	5	30.9	1.248	2.2	-38.5	26	31	22.2	49	55	22.6	-94.6	14	26.3
26	42	9.1	50	5	22.4	1.576	2.8	-37.9	26	31	9.7	49	55	34.1	-95	12.8	26.41
26	42	15.5	50	5	23.3	0.476	1	-26.5	26	30	56.9	49	55	44.4	-95	12.4	26.55
26	42	27.6	50	5	11.4	0.108	1	-32.2	26	30	43.7	49	55	55	-92.7	12.7	26.71
26	42	32.7	50	5	7.3	0.241	1	-28.5	26	30	32.2	49	56	4.2	-95	13	26.86
26	42	49.5	50	5	3.2	0.712	0.9	-33.6	26	30	18	49	56	17.1	-94.2	12	27.02
26	43	0.3	50	4	51.4	1.165	0.9	-42.9	26	30	6.8	49	56	30.5	-90.8	9.9	27.11
26	43	3.3	50	4	34.3	1.543	1	-48.5	26	29	57.1	49	56	45.5	-87.6	8.4	27.15
26	43	0	50	4	29.8	1.572	1	-50.3	26	29	49.6	49	57	0.8	-86.7	8.5	27.13
26	42	57.9	50	4	24.2	1.661	1	-53.2	26	29	42.6	49	57	17.3	-92.7	7.7	27.09
26	42	53.3	50	4	14.3	1.835	1.1	-56.4	26	29	34.6	49	57	35.7	-95.7	6.7	27.07
26	43	7.2	50	3	58.6	2.415	2.6	-63	26	29	29.4	49	57	48.2	-96.9	6.9	27.05
26	43	10.4	50	3	46.1	2.766	3.9	-60	26	29	22	49	58	5.6	-96	7.5	27.04
26	43	30.2	50	3	32.9	3.392	3.6	-66.5	26	29	16.1	49	58	19.7	-97.5	6.3	27.04
26	43	42.7	50	3	18.6	3.936	3.9	-69.2	26	29	7.8	49	58	39.1	-92.7	6.5	27.05
26	43	22	50	3	32.5	3.267	3.4	-57.6	26	29	1.9	49	58	53	-95	6.9	27.06
26	43	15.7	50	3	16.7	3.568	2.2	-62.3	26	28	53.4	49	59	11.7	-98	7.4	27.11
26	43	10.6	50	2	57.3	4.01	2.7	-62.3	26	28	45.7	49	59	25.2	-93.5	8.3	27.2

LOCATION						D	H	M	LOCATION						M	H	D
LATITUDE			LONGITUDE			(km)	(m)	(dB)	LATITUDE			LONGITUDE			(dB)	(m)	(km)
26	43	51.6	50	2	12.5	5.643	3.9	-65.8	26	35	51.3	49	56	13.9	-90.7	15.4	19.34
26	43	59.4	50	1	59.5	6.072	2.3	-68.5	26	35	48.8	49	56	14.8	-90.7	15.6	19.37
26	44	7.6	50	1	41.9	6.62	1.2	-70.9	26	35	47.9	49	56	15.1	-90	15.7	19.38
26	44	14.6	50	1	26.8	7.089	1	-71.9	26	35	45.2	49	56	15.8	-85.7	16.1	19.42
26	44	22.3	50	1	10.2	7.605	0.8	-74.1	26	35	39.4	49	56	16.5	-81.6	16.3	19.52
26	44	29.6	50	0	54.3	8.098	0.3	-74.5	26	35	37.5	49	56	16.7	-88	16.4	19.55
26	44	33.5	50	0	37.3	8.57	0	-76.3	26	35	36.6	49	56	16.8	-79.8	16.8	19.57
26	44	44	50	0	23.2	9.064	0	-80	26	35	35.5	49	56	17	-79.3	16.5	19.58
26	44	48.5	50	0	4.4	9.589	0.2	-74.5	26	35	32.3	49	56	17	-77	16.5	19.65
26	44	45.9	49	59	45	10.04	4	-74.5	26	35	28.7	49	56	19	-77	16.7	19.68
26	44	54.5	49	59	32.2	10.47	4.4	-74.8	26	35	27	49	56	18.3	-83.6	16.7	19.73
26	44	58.8	49	59	24.6	10.71	4.9	-79.7	26	35	27.1	49	56	16.6	-83.2	16.7	19.76
26	45	6.1	49	59	3.3	11.34	6.4	-81.8	26	35	25.7	49	56	13.6	-83.6	16.6	19.85
26	45	12	49	58	46.7	11.83	7.5	-80.9	26	35	24.6	49	56	11.4	-90	16.7	19.92
26	45	18.9	49	58	27.7	12.4	6.3	-86.4	26	35	17	49	56	0	-89	16.9	20.31
26	45	24	49	58	13.4	12.82	5.1	-80.3	26	33	21.9	49	53	54.7	-90.7	15.7	25.26
26	45	30.2	49	57	56.3	13.33	4.5	-83.2	26	33	20.4	49	53	52.4	-88.6	15.7	25.34
26	45	36.1	49	57	39.8	13.82	4.4	-82.1	26	33	18.3	49	53	49.3	-88.3	15.8	25.45
26	45	42.5	49	57	22.2	14.34	6	-84.1	26	32	53	49	53	13.5	-88.6	16	26.7
26	45	48.8	49	57	4.5	14.87	6.6	-84.5	26	32	47.5	49	53	18.4	-90.7	15.6	26.72
26	45	54.8	49	56	48	15.36	6.3	-84.8	26	32	43.6	49	53	21.8	-90.1	15	26.73
26	46	1.2	49	56	32.5	15.83	5.9	-86.8	26	32	39.6	49	53	25.3	-91.4	14.3	26.74
26	46	6.5	49	56	16.7	16.29	5.6	-88.1	26	32	27.2	49	53	39	-93.5	14.6	26.73
26	46	12.2	49	56	0.1	16.78	5.7	-86	26	32	17.6	49	53	52.5	-94.1	16.8	26.67
26	46	17.3	49	55	40.7	17.34	5.9	-84.8	26	32	8.9	49	54	8.2	-94.9	16.9	26.56
26	46	18.9	49	55	24.2	17.77	6.1	-85.7	26	32	1.3	49	54	22.9	-94.9	15.7	26.45
26	46	20.9	49	55	3.7	18.32	6.2	-87.6	26	31	52.7	49	54	39.5	-94.9	14.3	26.34
26	46	22.6	49	54	46.9	18.76	6.3	-94.6	26	31	44.1	49	54	54.4	-95.3	14.2	26.27
26	46	24.4	49	54	27.8	19.27	6.3	-90.8	26	31	33.7	49	55	8.7	-93.1	15	26.26
26	46	25.8	49	54	10.9	19.72	6.4	-90.8	26	31	22.5	49	55	21.4	-94	14	26.31
26	46	25.8	49	53	52.6	20.19	6.6	-90.4	26	31	8.5	49	55	34.4	-94.4	12.7	26.43
26	46	25.8	49	53	36.1	20.62	6.8	-89	26	30	56.9	49	55	43.7	-95.3	12.4	26.56
26	46	25.8	49	53	16.8	21.11	7.2	-90.4	26	30	44.3	49	55	53.9	-93.1	12.6	26.71
26	46	25.8	49	52	59.7	21.56	7.3	-89.4	26	30	30.5	49	56	5	-94.1	13	26.89
26	46	25.8	49	52	40.8	22.05	7.4	-89.9	26	30	18	49	56	16.5	-94.9	12.1	27.03
26	46	25.8	49	52	21.9	22.54	7.8	-89.9	26	30	7.2	49	56	29.2	-94	10	27.12
26	46	25.8	49	52	4.4	23	7.9	-91.3	26	30	6.2	49	56	30.5	-93.5	9.9	27.13
26	46	25.8	49	51	47.1	21.88	7.9	-92.2	26	30	5.4	49	56	31.5	-92.7	9.7	27.13
26	46	25.6	49	51	24.9	23.45	7.9	-93.9	26	30	2.6	49	56	35.6	-92.3	9.3	27.15
26	46	16	49	51	29.8	24.03	8.9	-91.3	26	30	1.2	49	56	37.7	-90.4	9	27.15

LOCATION						D	H	M	LOCATION						M	H	D
LATITUDE			LONGITUDE			(km)	(m)	(dB)	LATITUDE			LONGITUDE			(dB)	(m)	(km)
26	45	15.2	49	52	3	22.83	8	-88.6	26	29	42.3	49	57	16.7	-92.7	7.7	27.11
26	45	4.9	49	52	11.3	22.44	9	-90.4	26	29	34.9	49	57	33.9	-95.3	6.8	27.08
26	45	14.6	49	51	59.3	22.53	8	-84.8	26	29	28.7	49	57	48.7	-99.4	6.9	27.07
26	45	30.5	49	51	51.2	22.87	7.4	-88.1	26	29	22.8	49	58	3.7	-97.8	7.6	27.04
26	45	42.3	49	51	45.3	23.12	7.1	-94.2	26	29	14.6	49	58	21.9	-95.4	6	27.05
26	45	59.9	49	51	36.5	23.49	8.4	-89	26	29	7.4	49	58	38.9	-96.4	6.5	27.06
26	46	14.8	49	51	28	23.85	9	-89.5	26	29	0.9	49	58	54.2	-99.8	6.9	27.08
26	46	29.9	49	51	18.7	24.23	7.5	-93.5	26	28	53.9	49	59	9.8	-98.4	7.4	27.12
26	46	40.3	49	51	10.7	24.54	7.4	-90.4	26	28	45.2	49	59	25.2	-97.4	8.3	27.21
26	46	53.5	49	51	0.4	24.94	8.8	-89	26	28	24.4	50	0	39.2	-97.8	4.6	27.17
26	47	8.3	49	50	47.3	25.44	7.6	-91.7	26	28	38.5	50	0	27.5	-97.3	4	26.85
26	47	19.1	49	50	36.7	25.82	7	-94.6	26	28	48.8	50	0	16	-95.3	4.2	26.64
26	47	30.8	49	50	24.2	26.27	8.8	-91.7	26	28	57.5	50	0	57.6	-99.8	6.5	26.05
26	47	43.3	49	50	9.2	26.8	10.1	-93.4	26	29	8.9	49	59	42.6	-96.3	8.1	26.36
26	47	53	49	49	56.4	27.24	9.8	-98.5	26	29	17.9	49	59	30.2	-99.4	7.5	26.22
26	48	3.8	49	49	41.5	27.74	8.6	-96.3	26	29	25.4	49	59	19.6	-95.8	8.8	26.11
26	48	13.8	49	49	28.4	28.19	7.7	-93.8	26	29	39.4	49	59	10.8	-92.7	12.6	25.81
26	48	24.1	49	49	14	28.68	8.1	-93.4	26	29	53.1	49	59	55	-89.7	8.6	24.96
26	48	34.3	49	49	1.1	29.13	8.9	-92.2	26	30	3.7	49	58	43.2	-91.9	12.5	25.43
26	48	47.7	49	48	46	29.67	9.9	-94.2	26	30	16.3	49	58	34.3	-95.3	11.1	25.19
26	48	58.1	49	48	35.4	30.07	10.5	-95.6	26	30	27.7	49	58	24.6	-94	11.8	24.99
26	49	9.7	49	48	24.6	30.48	10.8	-94.2	26	30	42.3	49	58	23.5	-92.3	12.8	24.6
26	49	22.6	49	48	13.7	30.92	10.5	-95.3	26	30	44.2	49	58	19.6	-90.4	12.9	24.6
26	49	35.5	49	48	3.9	31.33	9.5	-94.9	26	30	49.4	49	58	5.7	-88.6	14.4	24.64
26	49	51.8	49	47	52.7	31.83	8.8	-91.7	26	31	6	49	58	51.9	-91.4	17.2	23.6
26	50	3.8	49	47	44.7	32.18	8.4	-90.3	26	31	24.4	49	57	44.1	-95.8	18.9	24
26	50	19.6	49	47	34.4	32.65	8.6	-94.6	26	31	34.9	49	57	35	-97.8	18.3	23.86
26	50	32.2	49	47	26	33.03	8.4	-95	26	31	47.1	49	57	25	-93.5	18.8	23.69
26	50	47.5	49	47	15.7	33.5	6.9	-96.9	26	32	4	49	57	21.2	-88.6	17.2	23.32
26	50	59.7	49	47	6.9	33.89	6.3	-96.6	26	32	19.3	49	57	21.4	-92.7	16.3	22.92
26	51	13.6	49	46	55.6	34.37	5.2	-96.6	26	32	36.1	49	57	22.3	-90.4	16.6	22.48
26	51	26.2	49	46	44.4	34.82	6.1	-98.8	26	32	52.8	49	57	21.7	-92.2	17.2	22.08
26	51	37.7	49	46	33	35.27	7.1	-97.7	26	33	6	49	57	19.7	-89.7	18	21.78
26	51	50.3	49	46	19.1	35.79	6.6	-97.5	26	33	22.5	49	57	17.8	-88.6	19.6	21.41
26	52	0	49	46	6.5	36.24	5.4	-99.5	26	33	27	49	57	5.9	-82.4	18.8	21.5
26	52	10.5	49	45	53.5	36.71	4.3	-100	26	33	52.2	49	57	57	-89	20.6	20.02
26	52	20.4	49	45	38.8	37.21	4.2	-101	26	34	6.6	49	56	49.4	-85.6	20.1	20.87
26	52	30.3	49	45	22.5	37.75	5.9	-102	26	34	21.6	49	56	43.4	-91.9	20	20.64
26	52	38.5	49	45	8.6	38.21	7.1	-101	26	34	36.3	49	56	38.7	-92.2	17.7	20.4
26	52	48.5	49	44	53	38.74	5.6	-103	26	34	51.1	49	56	34.2	-93.9	16.4	20.16

LOCATION						D	H	M	LOCATION						M	H	D
LATITUDE			LONGITUDE			(km)	(m)	(dB)	LATITUDE			LONGITUDE			(dB)	(m)	(km)
26	53	31.3	49	44	1.2	41.18	13.6	-103	26	35	38.8	49	56	26.5	-79.3	17.1	19.32
26	53	45.8	49	43	47.6	41.65	15.5	-101	26	35	52.9	49	56	16.8	-91.4	15.4	19.24
26	53	58.9	49	43	36.6	42.03	12.1	-102	26	36	8.1	49	56	10.4	-85	13.5	19.09
26	54	10	49	43	28.1	42.47	10.9	-102	26	36	25.1	49	56	4.6	-98.4	13.1	18.9
26	54	23.7	49	43	18.7	42.91	11.4	-98.3	26	36	39.7	49	56	1.5	-88	14.1	18.7
26	54	38.1	49	43	9.5	43.35	11.1	-99.3	26	36	55.7	49	55	59.7	-90	14	18.46
26	54	52	49	43	0.7	44.68	10.6	-101	26	36	12.6	49	55	58.6	-87.6	12.2	19.26
26	54	59	49	42	51.8	44.24	8.5	-101	26	37	27.7	49	55	57.8	-86.6	13.2	17.97
26	55	19.8	49	42	42	44.69	9.9	-100	26	37	43.4	49	55	56	-89	13	17.77
26	55	32	49	42	31.2	45.25	9.1	-98	26	37	59.6	49	55	53.3	-83.9	14.5	17.59
26	55	45.5	49	42	16.9	22.44	7.3	-99.5	26	38	15.6	49	55	50.5	-95.3	15.9	17.43
26	45	7	49	52	0.9	22.11	8.8	-86.8	26	39	14.7	49	56	38.9	-76.3	14	16.99
26	44	50.5	49	52	9.1	21.8	10.4	-86.8	26	39	32	49	56	39.1	-77	13.4	16.8
26	44	34	49	52	17.3	21.51	11.7	-88.9	26	39	38.1	49	56	53.2	-83.6	13.8	16.38
26	44	18.7	49	52	25	21.23	12.5	-88.1	26	39	41.3	49	56	13.9	-84.6	13.1	15.8
26	44	4.6	49	52	32.7	20.94	12.6	-90.8	26	39	44.8	49	56	29.7	-81.1	13	15.36
26	43	50.3	49	52	41.5	20.64	12.2	-89.5	26	39	53.2	49	56	48.5	-79.3	11.5	14.78
26	43	37.1	49	52	50.7	20.33	12.9	-90.8	26	40	2.4	49	57	0	-71.8	9.7	14.39
26	43	23.9	49	53	0.7	20	13.3	-88.1	26	40	15.8	49	57	12.1	-74.2	6.2	13.94
26	43	10	49	53	11.5	19.72	12.3	-92.2	26	40	28.9	49	57	23.3	-75.6	7.9	13.53
26	42	58	49	53	20.7	19.39	12.1	-91.8	26	40	41.2	49	57	33.8	-77.7	9.7	13.15
26	42	43	49	53	32.3	19.12	11.6	-100	26	40	54.4	49	57	45.1	-75.6	8.7	12.75
26	42	30.5	49	53	42	18.84	12.6	-88.6	26	41	7	49	57	55.7	-77.6	6.9	12.38
26	42	17.4	49	53	52.1	18.55	13.5	-87.6	26	41	19.3	49	58	5.5	-79.3	6.6	12.04
26	42	2.9	49	54	3.3	18.29	11.2	-86.8	26	41	33.6	49	58	15.7	-76.4	8.5	11.69
26	41	49.7	49	54	13.5	18.06	9.6	-88.1	26	41	45.7	49	58	23.4	-76.4	9.3	11.43
26	41	37.2	49	54	23.1	17.82	9.5	-87.6	26	42	2.5	49	58	33	-78.2	5.3	11.12
26	41	24.2	49	54	33.2	17.58	10.3	-86.4	26	42	15.4	49	58	39.4	-77.7	2.4	10.92
26	41	10.7	49	54	43.7	17.35	9.9	-88.1	26	42	32.2	49	58	46.7	-77	5	10.71
26	40	56.6	49	54	54.6	17.16	8.9	-86.4	26	42	47.7	49	58	52.4	-79.8	7.2	10.57
26	40	44.4	49	55	4.1	16.99	8.4	-86.4	26	43	2.4	49	58	56.9	-78.8	7.9	10.48
26	40	30.2	49	55	13.6	16.89	9.5	-84.8	26	43	18.7	49	59	1.6	-77	8.8	10.41
26	40	15.2	49	55	21.5	16.85	11.2	-82.8	26	43	34.1	49	59	6	-77.7	10	10.38
26	39	59.1	49	55	27.7	16.97	10.8	-84.1	26	43	50.4	49	59	10.7	-79.3	10.1	10.36
26	39	26.2	49	55	35.1	17.3	12.7	-75.2	26	44	4.2	49	59	14.6	-78.8	7.8	10.37
26	39	15.2	49	55	26.7	16.76	11.7	-97.5	26	44	19.7	49	59	19.5	-77.7	5.6	10.38
26	39	16.4	49	55	47.2	16.16	15.7	-86.8	26	44	31.8	49	59	32.7	-76.4	4.6	10.17
26	39	18.9	49	56	9.2	15.74	14.2	-82.2	26	44	38.9	49	59	37.2	-66	4.3	10.14
26	39	22.4	49	56	24.2	15.22	13.8	-79	26	45	1.4	49	59	30.9	-77	4.8	10.59
26	39	25	49	56	43.3	14.6	13.7	-82.5	26	45	13.5	49	59	33.8	-82.8	5.1	10.69

LOCATION						D	H	M	LOCATION						M	H	D
LATITUDE			LONGITUDE			(km)	(m)	(dB)	LATITUDE			LONGITUDE			(dB)	(m)	(km)
26	38	22.1	49	57	51.3	14.43	11.1	-80.3	26	45	5.9	50	0	35.8	-78.8	1.4	9.098
26	38	7.6	49	58	1.4	14.54	11	-82.5	26	44	57.4	50	0	55.5	-75.6	0.1	8.499
26	37	52.9	49	58	8	14.64	13.8	-77.5	26	44	51	50	1	10.2	-75.6	1.1	8.051
26	37	38.8	49	58	15.3	14.84	14.2	-79.4	26	44	43.7	50	1	27.1	-73.4	1.4	7.538
26	37	21.3	49	58	21.9	15.36	11.8	-82.5	26	44	37.4	50	1	41.5	-77.1	1.7	7.099
26	36	59.4	49	58	18.3	15.47	11	-81.5	26	44	29.8	50	1	59.1	-74.9	2	6.566
26	36	54.8	49	58	17.4	16.07	11	-82.2	26	44	23.5	50	2	13.8	-72.6	1.8	6.122
26	36	34.3	49	58	9.1	16.59	13.6	-85.6	26	44	15.8	50	2	31.6	-73.4	1.1	5.585
26	36	20.3	49	57	57.6	17.06	15.9	-86.4	26	44	8.6	50	2	47.6	-70.4	1.5	5.098
26	36	8.2	49	57	47.1	17.5	16.6	-80.6	26	43	56.6	50	3	1.9	-63.7	3	4.56
26	35	57.5	49	57	35.6	18.04	16.9	-86.4	26	43	46.2	50	3	13.5	-69	3.9	4.113
26	35	46.5	49	57	21.3	18.52	16.5	-85.2	26	43	35.3	50	3	25.8	-61.1	3.6	3.642
26	35	37.4	49	57	6.9	18.97	17	-82.8	26	43	23.6	50	3	38.8	-61.5	3.7	3.144
26	35	33.6	49	56	48.8	19.35	18.1	-80.3	26	43	10.7	50	3	53.4	-61.5	3.2	2.593
26	35	31.9	49	56	31.9	19.77	17.4	-73.7	26	43	0.5	50	4	4.9	-57.7	2	2.165
26	35	27	49	56	16.2	20.28	16.6	-84.1	26	42	53.3	50	4	14	-57.1	1.1	1.842
26	35	17.5	49	56	1	20.8	16.9	-86	26	43	5.2	50	4	0.6	-60.4	2.4	2.337
26	35	4.3	49	55	49.2	21.25	15.7	-88.5	26	43	16.8	50	3	47.6	-62.1	3.8	2.827
26	34	49.6	49	55	41.6	21.69	13.5	-89.4	26	43	22.9	50	3	32.8	-60.1	3.4	3.274
26	34	35	49	55	35.1	22.16	14	-86.8	26	43	15.6	50	3	17.6	-63.7	2.2	3.544
26	34	19.3	49	55	28	22.63	16.5	-89.4	26	43	11.3	50	2	59.4	-66	2.6	3.962
26	34	5.6	49	55	19	23.17	16.6	-89.9	26	43	8.7	50	2	45.3	-62.9	3	4.308
26	33	52.8	49	55	6	23.65	15.4	-89.9	26	43	23.8	50	2	37	-63.7	3.3	4.675
26	33	43.5	49	54	51.6	24.06	15.5	-87.2	26	43	36.9	50	2	28	-65.5	3.8	4.909
26	33	37.7	49	54	37.7	24.54	15.4	-89.9	26	43	48	50	2	16.7	-67.1	4.4	5.49
26	33	32.4	49	54	19.1	25.03	15.8	-92.6	26	43	59.2	50	1	59.4	-72.6	2.3	6.072
26	33	25.9	49	54	2.1	25.49	15.7	-90.3	26	44	6.4	50	1	44.1	-73.4	1.3	6.549
26	33	17.5	49	53	48.1	26.09	15.9	-91.7	26	44	13.3	50	1	29.4	-74.9	1	7.01
26	33	5.6	49	53	30.7	26.49	15.3	-93.4	26	44	21.2	50	1	12.3	-78.3	0.9	7.535
26	32	57.5	49	53	19.3	27	15.7	-93.8	26	44	28	50	0	57.7	-77.7	0.4	7.992
26	32	47.3	49	53	4.6	27.66	15.9	-93.8	26	44	35.4	50	0	41.7	-77.1	0	8.489
26	32	34.3	49	52	45.8	27.94	14.6	-96.6	26	44	41.6	50	0	28.2	-87.7	0	8.907
26	32	29.2	49	52	37.2	28.5	14.2	-96.6	26	44	48.3	50	0	5.5	-75.6	0.2	9.559
26	32	18.1	49	52	21.1	28.96	13.8	-95	26	44	47.9	49	59	53.8	-78.3	0.2	9.843
26	32	9	49	52	8.1	29.51	14.4	-96	26	44	49	49	59	34.3	-75.6	4.1	10.34
26	31	58.1	49	51	52.3	29.98	15.3	-95	26	44	58.7	49	59	24.4	-84.7	4.9	10.72
26	31	48.7	49	51	38.6	30.47	15.5	-96.3	26	45	4.2	49	59	8.1	-81.6	6.1	11.2
26	31	41	49	51	22.8	30.97	14.4	-96.6	26	45	10.8	49	58	49.9	-86	7.3	11.74
26	31	33.3	49	51	6.2	31.47	13.9	-95.7	26	45	16.4	49	58	34.3	-84	7.1	12.2
26	31	25.6	49	50	49.6	31.92	13.2	-95.3	26	45	22.7	49	58	16.8	-82	5.3	12.72

LOCATION						D	H	M	LOCATION						M	H	D
LATITUDE			LONGITUDE			(km)	(m)	(dB)	LATITUDE			LONGITUDE			(dB)	(m)	(km)
26	30	41.4	49	49	59.9	33.89	10.3	-99.1	26	45	46.7	49	57	10.4	-87.3	6.8	14.69
26	30	35.2	49	49	42.7	34.31	9.2	-94.2	26	45	52.3	49	56	54.8	-90.4	6.4	15.16
26	30	32.9	49	49	25	34.87	8.4	-95	26	45	58.8	49	56	38	-87.3	6.1	15.66
26	30	30.8	49	49	0.4	35.19	9	-96.9	26	46	5.3	49	56	21.2	-90	5.6	16.32
26	30	28.2	49	48	48	35.55	9.7	-94.6	26	46	10.6	49	56	4.4	-86.6	5.6	16.66
26	30	26.3	49	48	32.6	35.98	9.4	-95	26	46	16.5	49	55	46.8	-86.6	5.9	17.17
26	30	24	49	48	14.9	36.4	9	-95	26	46	18.4	49	55	29.8	-87.3	6	17.63
26	30	21.7	49	47	57.4	36.85	8.4	-90.8	26	46	19.8	49	55	15.8	-81.6	6.2	18
26	30	18.2	49	47	40	37.36	8	-96.6	26	46	22	49	54	53.4	-89.3	6.2	18.59
26	30	6.7	49	47	26.7	37.75	9.4	-96.9	26	46	24	49	54	33.6	-93.1	6.3	19.12
26	29	50	49	47	23.4	37.93	12.2	-92.7	26	46	25.4	49	54	18.4	-94	6.3	19.52
26	29	36	49	47	27.5	38.14	14.2	-94.6	26	46	25.9	49	53	57.2	-89	6.5	20.07
26	29	20.1	49	47	32.3	38.34	15.6	-96	26	46	25.9	49	53	42.8	-92.7	6.7	20.44
26	29	4.7	49	47	37.1	38.73	16.7	-95	26	46	25.9	49	53	22.7	-93.1	7.1	20.96
26	28	40.6	49	47	42.1	38.88	19.8	-95.7	26	46	25.9	49	53	3.5	-92.2	7.3	21.46
26	28	30.1	49	47	45	39.15	20	-99.5	26	46	25.9	49	52	44.7	-93.5	7.3	21.95
26	28	12.6	49	47	49.7	39.33	19.8	-88.5	26	46	25.8	49	52	27.8	-92.2	7.6	22.39
26	28	2.3	49	47	51.2	39.53	18.7	-85.6	26	46	25.8	49	52	9.7	-94	7.9	22.86
26	27	46.2	49	47	58.6	39.24	17.1	-99.1	26	46	25.8	49	51	51.7	-94	7.9	23.33
26	27	54.3	49	48	4.2	39.1	17.9	-101	26	44	45.4	49	59	33.1	-78.2	4	10.33
26	28	4.9	49	48	0	38.54	19	100.1	26	44	28.9	49	59	22.5	-76.4	4.9	10.4
26	28	46.6	49	47	45.3	38.41	19.7	-93	26	44	15.5	49	59	16.5	-78.2	5.9	10.42
26	29	8.5	49	47	30.5	37.97	17	-93	26	43	55.2	49	59	10.5	-79.3	9.4	10.4
26	29	29	49	47	32.2	37.81	14.7	-93.8	26	43	44.3	49	59	7.4	-78.2	10.9	10.4
26	29	41	49	47	28.4	37.55	13.5	-96	26	43	26.1	49	59	2.3	-77.7	9.4	10.43
26	29	57.6	49	47	25.8	26.61	10.9	-94.2	26	43	10.4	49	58	57.8	-78.8	8.3	10.48
26	33	11	49	53	0.5	26.59	14.7	-89.9	26	42	53.8	49	58	52.9	-77	7.5	10.57
26	33	25.6	49	52	47.8	26.59	14.6	-87.2	26	42	39.4	49	58	48	-80.3	6.2	10.68
26	33	36.9	49	52	37.6	26.63	15.5	-94.6	26	42	23.6	49	58	41.7	-76.4	3.7	10.85
26	33	48.7	49	52	25.7	26.74	15.8	-91.3	26	42	9.7	49	58	35.2	-78.8	3.7	11.05
26	34	2	49	52	9.8	26.86	13.8	-90.8	26	41	53.4	49	58	26.5	-78.8	7.6	11.32
26	34	11.1	49	51	57.2	27.03	13	-85.6	26	41	40.8	49	58	18.9	-79.8	9.3	11.58
26	34	20.4	49	51	42.6	27.25	12.7	-89	26	41	27.4	49	58	9.8	-78.8	7.7	11.88
26	34	28.9	49	51	26.9	27.47	12.6	-94.2	26	41	13.2	49	57	59.1	-79.3	6.2	12.25
26	34	36.8	49	51	11.5	27.72	11.6	-95.7	26	40	59.5	49	57	47.6	-79.8	8	12.65
26	34	45.8	49	50	54.8	27.9	10.1	-94.6	26	40	49.8	49	57	39.3	-82.4	9.6	12.94

APPENDIX B

SIGNAL STRENGTH MEASUREMENTS (dB) OVER A SELECTED ROAD

Distance	1-Feb-01	4-Feb-01	15-Feb-01	10-May-01
26.691	-88.97	-77.81	-88.62	-85.92
26.732	-92.58	-81.44	-90.72	-86.59
26.713	-93.45	-82.12	-90.1	-88.62
26.652	-94.23	-83.12	-91.43	-88.27
26.54	-96.02	-84.52	-93.5	-88.62
26.427	-94.99	-84.52	-94.1	-87.97
26.335	-94.23	-82.47	-94.89	-86.59
26.256	-96.02	-84.52	-94.89	-87.62
26.245	-94.68	-84.84	-94.89	-88.62
26.296	-94.64	-85.25	-95.29	-89.62
26.406	-94.99	-85.59	-93.05	-89.28
26.551	-94.99	-86	-94.01	-90.4
26.71	-92.65	-84.52	-94.43	-85.92
26.856	-94.99	-86.78	-95.29	-88.62
27.021	-94.23	-82.47	-93.1	-87.62
27.112	-90.84	-82.47	-94.1	-86.27
27.148	-87.64	-82.13	-94.89	-84.61

APPENDIX C

THE MATLAB PROGRAMS

The below Matlab programs have been used to calculate the path losses around Ras Tanura, Abqaiq and Dhahran radio base stations. The median of the differences obtained between the measured and predicted signal strengths is added to the predicted values. Through iteration process, the added amount is increased and decreased in step 1 for the minimum RMSD.

LIST OF DEFINITIONS

```
% a:       The Actual Signal Strength
% d:       Distance for the base station of each test point,
%          Matrix size of 656*1.
% hm:      The Mobile antenna height at each test point,
%          Matrix size of 656*1.
% hb:      base station antenna height in meter
% f:       Frequency in MHz
% ahm:     ITU-R-370 mobile height gain factor. for
% Lu:      Hata path loss formula for urban area
% Lro:     Hata open area correction factor
% Gro:     the calculated signal strength around RT BS
% RMSD:    The root of the mean square differences between
%          the actual and predicted signal strength
% hma      The height of tests points above zero level,
%          Matrix of 1*656
% P        Power
```

RAS TANURA RADIO BASE STATION

```
%       MODIFIED HATA MODEL

RMSD = 0
hb = 72.5
f = 160.045
hm = 1.5

% STEP 1
ahm = (1.11*log10(f)-0.7)*hm-(1.56*log10(f)-.8)
Lu = 69.55 + 26.16*log10(f)-13.82*log10(hb)- ahm+(44.9-
6.55*log10(hb))*log10(d)
Lro = Lu - 4.78*(log10(f))^2 + 18.33*log10(f)-35.94+4.5
Gro = 41.35 - Lro
m = a - Gro
median(m)
RMSD
s = (sum(m.^2)/656)
RMSD = (s.)^0.5
%       STEP 2
hold
plot(d,a,'y.')
plot(d,Gro,'r.')
xlabel('Distance, km')
ylabel('Signal Strength,dB')
Title('Measured and Predicted Signal Strengths')
gtext('1')
gtext('2')
gtext('1 Yellow : Measured')
gtext('2 Red : Predicted')
%       MODIFIED LEE MODEL WITHOUT TERRAIN DATA
```

```
hb=72.5
f=160.045
hm=1.5
P = 21
RMSD = 0
```

% **STEP 1**

```
a0 = (hb/30.48)^2*(hm/3)*(P/10)*(3/4)
L=10*log10(10000)+50+10*3.62*log10(d/1.6)+20*log10(160/900)-
10*log10(a0)+21.2
Gro = 41.35 - L
m = a - Gro
median(m)
RMSD
s = (sum(m.^2)/656)
RMSD = (s.)^0.5
```

% **STEP 2**

```
hold
plot(d,a,'y.')
plot(d,Gro,'r.')
xlabel('Distance, km')
ylabel('Signal Strength,dB')
Title('Measured and Predicted Signal Strengths')
gtext('1')
gtext('2')
gtext('1 Yellow : Measured')
gtext('2 Red : Predicted')
```

% **MODIFIED LEE MODEL WITH TERRAIN DATA**

```
hb=72.5
f=160.045
hm=1.5
P = 21
RMSD = 0
```

% STEP 1

```
a0 = (hb/30.48)^2*(hm/3)*(P/10)*(3/4)
L=10*log10(10000)+50+10*3.62*log10(d/1.6)+20*log10(160/900)-
10*log10(a0)+21.2-(14.0/6)*log10(hma/10)
Gro=41.35-L
m=a-Gro
median(m)
s = (sum(m.^2)/656)
RMSD = (s.)^0.5
```

% STEP 2

```
hold
plot(d,a,'y.')
plot(d,Gro,'r.')
xlabel('Distance, km')
ylabel('Signal Strength,dB')
Title('Measured and Predicted Signal Strengths')
gtext('1')
gtext('2')
gtext('1 Yellow : Measured')
gtext('2 Red : Predicted')
```

% MODIFIED MAITHAM MODEL WITHOUT TERRAIN DATA

```
hb=72.5
```

```
f=160.045
hm=1.5
RMSD = 0
```

% STEP 1

```
L = 10*log10(231.3^3.44*d.^3.44)+20*log10(f)-
20*log10(72.5*1.5)
m = a - Gro
Gro = 41.35 - L
lmi= sum(m.^2)
m = a - Gro
median(m)
RMSD
s = (sum(m.^2)/656)
RMSD = (s.)^0.5
```

% STEP 2

```
hold
plot(d,a,'y.')
plot(d,Gro,'r.')
xlabel('Distance, km')
ylabel('Signal Strength,dB')
Title('Measured and Predicted Signal Strengths')
gtext('1')
gtext('2')
gtext('1 Yellow : Measured')
gtext('2 Red : Predicted')
```

% MODIFIED MAITHAM MODEL WITH TERRAIN DATA

```
hb=72.5
f=160.045
hm=1.5
```

```
RMSD = 0
```

% STEP 1

```
L = 10*log10(231.3^3.44*d.^3.44)-
(7.3/6)*log10(hma/10)+20*log10(f)-20*log10(72.5*1.5)
m = a - Gro
Gro = 41.35 - L
lmi= sum(m.^2)
m = a - Gro
median(m)
RMSD
s = (sum(m.^2)/656)
RMSD = (s.)^0.5
```

% STEP 2

```
hold
plot(d,a,'y.')
plot(d,Gro,'r.')
xlabel('Distance, km')
ylabel('Signal Strength,dB')
Title('Measured and Predicted Signal Strengths')
gtext('1')
gtext('2')
gtext('1 Yellow : Measured')
gtext('2 Red : Predicted')
```

ABQAIQ RADIO BASE STATION

% MODIFIED HATA MODEL

```
hb = 151.7
f = 160
hm = 2
```

```
RMSD = 0
```

% STEP 1

```
ahm = (1.11*log10(f)-0.7)*hm-(1.56*log10(f)-.8)
Lu= 69.55 + 26.16*log10(f)-13.82*log10(hb)- ahm+(44.9-
6.55*log10(hb))*log10(d)
Lro = Lu - 4.78*(log10(f))^2 + 18.33*log10(f) - 35.94 + 4.5
Gro = 38.955 - Lro
m = a - Gro
median(m)
RMSD
s = (sum(m.^2)/23)
RMSD = (s.)^0.5
```

% STEP 2

```
m1 = a - (Gro + 1.2)
s1 = (sum(m1.^2)/23)
RMSD1 = (s.)^0.5
hold
plot(d,a,'b.')
plot(d,Gro,'r')
plot(d, Gro + 1.2,'g')
xlabel('Distance, km')
ylabel('Signal Strength,dB')
Title('Measured and Predicted Signal Strengths')
gtext('1')
gtext('2')
gtext('3')
gtext('1 Blue : Measured')
gtext('2 Red : Predicted')
gtext('3 Green : Shifted')
```

% MODIFIED LEE MODEL

```
hb = 151.7
f = 160
RMSD = 0
hm = 2
P = 9.54
```

% **STEP 1**

```
a0=(hb/30.48)^2*(hm/3)*(P/10)*(3/4)
L0=10*log10(10000)+48+10*3.62*log10(d/1.6)+20*log10(f/900)-
10*log10(a0)+21.2
Gro = 38.955 - L0
m=a-Gro
median(m)
RMSD
s = (sum(m.^2)/23)
RMSD = (s.)^0.5
```

% **STEP 2**

```
m1 = a - (Gro - 1.2)
s1 = (sum(m1.^2)/23)
RMSD1 = (s.)^0.5
hold
plot(d,a,'b.')
plot(d,Gro,'r')
plot(d,Gro-1.2,'g')
xlabel('Distance, km')
ylabel('Signal Strength,dB')
Title('Measured and Predicted Signal Strengths')
gtext('1')
gtext('2')
gtext('3')
gtext('1  Blue : Measured ')
```

```
gtext('2 Red : Predicted')
 gtext('3 Green : Shifted')
```

% **MODIFIED MAITHAM MODEL**

```
hb = 151.7
f = 160
RMSD = 0
hm = 2
RMSD = 0
```

% **STEP 1**

```
L = 10*log10(231.3^3.44*d.^3.44)+20*log10(f)-
20*log10(hb*hm)+3.3
m =  a - Gro
Gro = 38.955 - L
s = (sum(m.^2)/23)
RMSD = (s.)^0.5
```

% **STEP 2**

```
hold
plot(d,a,'b.')
plot(d,Gro,'r')
xlabel('Distance, km')
ylabel('Signal Strength,dB')
Title('Measured and Predicted Signal Strengths')
gtext('1')
gtext('2')
gtext('1 Blue : Measured')
gtext('2 Red : Predicted')
```

DHAHRAN RADIO BASE STATION

```
%     MODIFIED HATA MODEL

hb = 128.4
f = 159.61
hm = 1.5
RMSD = 0

%     STEP 1
ahm=(1.11*log10(f)-0.7)*hm-(1.56*log10(f)-.8)
Lu= 69.55 + 26.16*log10(f)-13.82*log10(hb)- ahm+(44.9-
6.55*log10(hb))*log10(d)+4.4
Gro = 44.03 - Lu
m=a - Gro
median(m)
s = (sum(m.^2)/51)
RMSD = (s.)^0.5

%     STEP 2
hold
xlabel('Distance, km')
ylabel('Signal Strength,dB')
Title('Measured and Predicted Signal Strengths')
plot(d,a,'b.')
plot(d,Gro,'r')
gtext('1')
gtext('2')
gtext('1 Blue : Measured')
gtext('2 Red : Predicted')

%     MODIFIED LEE MODEL
```

```
hb = 128.4
f = 159.61
hm = 1.5
RMSD = 0
P = 50
```

% STEP 1

```
a0 = (hb/30.48)^2*(hm/3)*(P/10)*(3/4)
L = 10*log10(10000)+60+10*3.62*log10(d/1.6)+20*log10(f/900)-
10*log10(a0)+35.4
Gro = 44.03 - L
m = a  -  Gro
median(m)
s = (sum(m.^2)/51)
RMSD = (s.)^0.5
```

% STEP 2

```
hold
xlabel('Distance, km')
ylabel('Signal Strength,dB')
Title('Measured and Predicted Signal Strengths')
plot(d,a,'b.')
plot(d,Gro,'r')
gtext('1')
gtext('2')
gtext('1 Blue : Measured')
gtext('2 Red : Predicted')
```

% MODIFIED MAITHAM MODEL

```
hb = 128.4
f = 159.61
```

```
hm = 1.5
RMSD = 0
```

% STEP 1

```
L = 10*log10(231.3^3.44*d.^3.44)+20*log10(f)-
20*log10(hb*hm)+19.4
Gro = 44.03 - L
m = a  -  Gro
median(m)
s = (sum(m.^2)/51)
RMSD = (s.)^0.5
```

% STEP 2

```
hold
xlabel('Distance, km')
ylabel('Signal Strength,dB')
Title('Measured and Predicted Signal Strengths')
plot(d,a,'b.')
plot(d,Gro,'r')
gtext('1')
gtext('2')
gtext('1 Blue : Measured')
gtext('2 Red : Predicted')
```

----------------------------END----------------------------

NOMENCLATURE

TERM	MEANING
f	Frequency
d	Distance
ABQ	Abqaiq
RT	Ras Tanura
DH	Dhahran
BS	Base Station
L	Path Loss
h_b	Base station antenna height above the ground
h_m	Mobile antenna height above the ground
ah_m	Mobile height correction factor
P_r	Received power
P_t	Transmit Power
r	The distance between transmitter and receiver
α_0	Lee correction factor
γ	Path loss slope
SGN	Signal Strength
G_r	Receiver antenna gain
G_t	Transmitter antenna gain
L_m	Miscellaneous Loss
L_{tca}	Coaxial cable loss
L_{tco}	Connector loss

L_{rcc}	Receiver cable and connector loss
RMSD	Root of the Mean Squared Difference
MHM	Modified Hata Model
MLM	Modified Lee Model
Hma	Heights of test points
MPLM	Maitham Path Loss Model
P	Atmospheric Pressure (hPa)
e	Water Vapor Pressure (hPa)
t	Absolute Temperature
H	Relative Humidity
e_s	Saturation Vapor Pressure (hPa) at the temperature t (°C)
N_s	Refractive Index at the Surface
k Factor	The Effective Earth Radius

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VITA

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