

Clear-Air Radioclimatic Modeling of Terrestrial Line-of-Sight Radio-Link in Ethiopia

By: Feromsa Girma
Adviser: Dr. Ephrem Teshale
Co-Adviser: Dr. Feyisa Debo

A Thesis submitted to
School of Electrical and Computer Engineering
Addis Ababa Institute of Technology

in Partial Fulfillment of the Requirements for the Degree of Master of Science in Telecommunications
Engineering - Telecommunication Network Engineering Track



Addis Ababa University
Addis Ababa, Ethiopia
September, 2021



Addis Ababa University
Addis Ababa Institute of Technology
School of Electrical and Computer Engineering

Clear-Air Radioclimatic Modeling of Terrestrial Line-of-Sight Radio-Link in Ethiopia

By
Feromsa Girma
Approved by Board of Examiners

Dr. Ephrem Teshale

Adviser

Date

Signature

Examiner 1

Date

Signature

Examiner 2

Date

Signature

Program chair person

Date

Signature

Dr. Bisrat Derebssa

Dean, School of Electrical and Computer Engineering



Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials are used for the thesis have been fully acknowledged.

Feromsa Girma

Name

Signature

Place : Addis ababa

Date of Submission: _____

This thesis has been submitted for examination with my approval as an advisor.

Dr. Ephrem Teshale

Adviser

Signature

Abstract

Terrestrial radio link is challenged by clear air environmental factors like multipath fading, diffraction fading and atmospheric gaseous losses. These radio link impairments need to be discovered using right meteorological parameters and applying appropriate models so that its result will be used in design of terrestrial radio link of line-of-sight communications. Ethiopia and other countries found in tropical regions are relying on ITU-R database for designing of terrestrial line-of-sight link communication which could end up to over prediction or under prediction of impairments. ITU-R data source was initially prepared from climates of countries located in Temperate region that might not fit for a tropical region.

The investigation of finding clear-air radioclimatic parameters for the terrestrial radio-link requires intensive data collection from local meteorological sources. The input parameters to design radio link that comes from investigation depend on local data is expected to be more reliable when it compares to the ITU-R database. Most researchers have used their local data to investigate secondary radioclimatic parameters, that are used as inputs for the design of terrestrial radio-link. But, the meteorological data are limited to their local weather condition, that may not be applied at different geographic locations.

This thesis has utilized five to ten years, 15 minutes intervals, surface data of temperature and humidity with one year daily data of Radiosonde were collected from the National Meteorological Agency of Ethiopia. Satellite's monthly pressure data of "FLDAS Noah Land Surface Model L4 Global" was used and integrated using the Haversine formula with surface data from the meteorological agency to have full information about temperature, pressure, and humidity of selected 58 geographical places in Ethiopia. The Radiosonde data were used for developing a new vertical atmospheric profile model in Addis Ababa. The secondary parameter of the modeled atmospheric profile result was compared with the result of the ITU-R law latitude model and with the ITU-R database. MAE and RMSE are used as the error comparison between the results of the ITU-R results and the proposed model. The performance of the proposed models is found to be better compared to the other models. ArcMap, ExceLab, Ms-Excel, and Python programming are the tools that are used to analyze and demonstrate results in graphs, charts, and maps.

This thesis work produces results from the investigation of refractivity, point refractivity gradient, geoclimatic factor K, and k-factor at the selected locations in Ethiopia. The distribution of each parameter is presented in monthly, seasonal, and average year time. The curve fitting approximated for the k-factor distribution is Gaussian normal distribution and the corresponding Integral Square Error approach is used for error checking. The maps and databases are generated using Ordinary-kriging with ArcGIS software tool. The resulting database can be used for consumption by radio link designers.

Keywords: *Geoclimatic factor, k-factor, Point refractivity, Vertical refractivity, Atmospheric gas loss*

Acknowledgment

I would like to acknowledge God for His overall guidance, help and provision. I also want to thank my wife, family and friends for their support. I would like to acknowledge my adviser, Dr Ephrem Teshale, I am deeply touched by his guidance and I am grateful for the valuable comments throughout the time of writing this paper. I would like to thank both examiners Dr Yihenew and Dr Murad for their encouragement and comments. Special thanks to Dr Feyisa Debo for the advising, inspiration and the initial idea, where, non of this will come to reality without him. I also want to thank Ethio telecom for the sponsoring of the study.

Contents

List of Figures	vi
List of Tables	viii
1 Introduction	1
1.1 Background	1
1.2 Statement of the problem	2
1.3 Objective	3
1.3.1 General Objective	3
1.3.2 Specific Objectives	3
1.4 Scope and Limitation	4
1.5 Literature Review	4
1.6 Methodology	6
1.7 Contribution of the Thesis	8
1.8 Organization of the Thesis	8
2 Radio Wave Propagation Mechanisms	9
2.1 Diffraction	9
2.2 Reflection	10
2.3 Scattering	10
2.4 Freespace propagation model	11
2.5 Atmospheric Impact on Terrestrial Radio-Link	13
2.5.1 Troposphere	13
2.5.2 Troposphere Effect on Radio-wave Propagation	14
3 Diffraction and Multipath Propagation Models	15
3.1 Diffraction Propagation Models	15
3.1.1 Single knife-edge diffraction model	15
3.1.2 Multiple Knife-Edge Diffraction Models	17
3.1.3 ITU-R Diffraction model	20
3.2 Multipath Propagation Models	22
3.2.1 Morita and Kakita Method	23
3.2.2 Vigant model	24
3.2.3 ITU-R method	24
4 Atmospheric Radio Refractivity and Gas Loss	28
4.1 Refractivity	28
4.1.1 Sub-refraction	30
4.1.2 Supper refraction	31
4.1.3 Ducting	31
4.2 Effective Earth Radius Factor (k-factor)	32



4.3	Geoclimatic factor(K)	34
4.4	Atmospheric Gas Loss	35
4.5	Spatial Interpolation	36
4.5.1	Kriging	36
4.5.2	Inverse Distance Weight(IDW)	37
4.5.3	Radial Bayesian	38
5	Data collection and methodology	39
5.1	Introduction	39
5.1.1	Surface Data Collection(NMA and NASA)	39
5.1.2	Radiosonde data	41
5.2	Steps of finding Radioclimatic parameters	42
5.2.1	Finding vertical Atmospheric Parameters	42
5.2.2	Determination of k-factor and ΔN	44
5.2.3	Determination of Geoclimatic factor K and dN_1	45
5.3	Modeling and Curve fitting of k-factor	46
5.4	Selection of Spatial Interpolation for Mapping	47
5.5	Determination of Atmospheric gas Loss	48
6	Result and Discussion	49
6.1	Analysis of Refractivity	49
6.2	k-factor result from Radiosonde and ITU-R method	51
6.3	Validation of Atmospheric Profile Model	54
6.4	Distribution and Modeling of k-factor	55
6.4.1	Distribution of k-factor	55
6.4.2	Modeling and Curve-fitting	60
6.5	Interpolation and Mapping of k-factor and ΔN	64
6.6	Results of Geoclimatic factor K and dN_1	65
6.7	Interpolation of geoclimatic factor and dN_1	74
6.8	Outage probablity and Fade depth analysis	77
6.9	Atmospheric Gas Loss	79
7	Conclusion and Future work	81

List of Figures

2.1	Layers of atmosphere and vertical structure of atmospheric pressure (hPa) and temperature (K) in the lowest 100km of the atmosphere[11]	13
3.1	Simplified geometry of the knife edge diffraction [49]	16
3.2	Hilly rounded obstacle represented as single knife edge [49]	16
3.3	Family of circles representing Fresnel zones at point along a radio path[20]	16
3.4	The approximation of the resultant knife-edge by two knife-edge obstacles[49]	18
3.5	The Epstein-Peterson method[12]	18
3.6	Construction of the Deygout diffraction method[51]	19
3.7	Construction of Japanese diffraction method[49]	20
3.8	Normalized clearance[9]	21
3.9	Percentage of time, P_w , fade depth, A , exceeded in average worst month[6]	27
4.1	Ground base and Elevated layer ducts[55]	32
4.2	Various k-factor beaming[40]	33
4.3	Total Atmospheric Air spec. attenuation[7]	36
6.1	Annual variation of surface refractivity	49
6.2	daily variation of humidity and refractivity relationship	50
6.3	Hourly variation of H and T	50
6.4	Monthly variation of surface refractivity at different years of time	51
6.5	k-factor comparison of different model	55
6.6	Monthly distribution of mean refractivity at surface and 1000m a.g.l. at Addis Ababa	56
6.7	Monthly distribution of mean k-factor at Addis Ababa	56
6.8	k-factor monthly cumulative distribution at Addis Ababa	57
6.9	Monthly mean distribution of refractivity gradient at 1km above ground at Addis Ababa	57
6.10	Seasonal cumulative distribution of k-factor at 1000 a.g.l at Addis Ababa	58
6.11	Seasonal distribution of vertical refractivity at Addis Ababa	58
6.12	Annual k-factor pdf of Addis ababa	59
6.13	Annual k-factor pdf of Addis ababa	60
6.14	Annual k-factor pdf of Addis ababa	62
6.15	Vertical refractivity gradient map at 50% and 0.1% time of Ethiopia	65
6.16	50% and 99.9% of time value of k-factor map of Ethiopia	67
6.17	Point refractivity distribution at 1% of time	67
6.18	Monthly point refractivity distribution	68
6.19	Seasonal point refractivity at 1% of time	68
6.20	Monthly point refractivity cumulative distribution of Addis Ababa	69
6.21	Point refractivity distribution of Addis Ababa	70
6.22	Point refractivity ITU-R database vs New model	71
6.23	Geoclimatic factor average distribution of Addis ababa	71
6.24	Monthly geoclimatic factor distribution	72



6.25	Worst month and Annual Point refractivity at 1% of time map of Ethiopia	76
6.26	Worst month geoclimatic factor map of Ethiopia	76
6.27	Fade depth vs Distance at 001% outage probability at Addis ababa	78
6.28	Fade depth vs frequency at 0.01% outage probability	78
6.29	Fade depth vs distance different outage probability	78
6.30	Fade depth vs outage probability at Addis ababa	79
6.31	Dry air atmospheric specific attenuation vs frequency at Addis Ababa	80
6.32	Wet air atmospheric specific attenuation vs frequency at Addis Ababa	80
6.33	Total air atmospheric specific attenuation vs frequency at Addis Ababa	80

List of Tables

4.1	Constants for vapor pressure of water and ice	30
5.1	Selected site-names and their GPS coordinate	40
5.2	The sample integrated data at Addis Ababa	41
5.3	Sample raw Radiosonde data for Addis ababa	41
5.4	Sample raw radiosonde data after interpolation	42
5.5	Error result and correlation coefficient	44
5.6	Error Comparison of Interpolation Techniques for $k_{99.9}$ (k-factor at 99.9% of exceedance time)	48
6.1	Refractivity gradient from radiosonde	52
6.2	k-factor calculation from Radiosonde sample data	52
6.3	Using ITU-R Low-latitude annual reference result	53
6.4	Vertical refractivity gradient values at at different exceedance of time	54
6.5	k-factor comparison at different exceedance of time	54
6.6	Error comparison using MAE and RMSE	55
6.7	Seasonal average refractivity at first kilometer above ground level	58
6.8	Annual Exceedance probability of k-factor	60
6.9	Monthly mean distribution of addis ababa	61
6.10	Estimated Gaussian Coefficients and Integral Square Error(ISE) for monthly model approximation	61
6.11	Monthly k-factor distribution of probability density function of Addis ababa	61
6.12	seasonal variation of k-factor	62
6.13	Annual k-factor distribution of probability density function of selected sites	63
6.14	ΔN at 50% of time and ΔN at 0.1% of time	64
6.15	k-factor distribution at 50% and 99.9% of the time for selected sites	66
6.16	Monthly point refractivity distribution	66
6.17	seasonal point refractivity at 1% of time at different years	68
6.18	average seasonal point refractivity at 1% of time	69
6.19	Comparison of worst month point refractivity result and Radiosonde worst month point refractivity data base at Addis ababa	70
6.20	Annual geoclimatic factor distribution	72
6.21	Worst month geoclimatic distribution	72
6.22	Monthly geoclimatic factor distribution of each year	73
6.23	Annual point refractivity distribution and corresponding geoclimatic factor for selected sites	74
6.24	Worst month point refractivity distribution and corresponding geoclimatic factor for selected sites	75
6.25	Summery of link configuration	77

Acronyms

a.g.l above ground level

GIS Graphical Information System

IDS Inverse Distance Square

IDW Inverse Distance Weight

ISE Integral Square Error

ITU-R International Telecommunication Union for Radiocommunication

MAE Mean Average Error

NASA National Aeronautics and Space Administration

NMA National Meteorological Agency

RBF Radial Basis Function

RMSE Root Mean Square Error

Chapter 1

Introduction

1.1 Background

Ethiopia is located between in the tropical section of Equator and Tropic of Cancer with a highly diverse climate from 4000m above sea level to 100m below sea level[1]. This diverse climatic condition needs a careful data collection when it comes to deal with clear air radio climatic modeling for a terrestrial link of millimetric and microwave radio link. The Microwave and millimetric Wave spectrum have biggest interest with telecom operator and designer of backhoulng for cellular mobile transport network system because of the high capacity it could carry and the increasing demand of big bandwidth [2]. Environmental factors like temperature and humidity can cause severe degradation on high frequency signal strength. Humidity takes dominant factor in attenuating radio wave signal[3] atmospheric pressure also has a negative effect on terrestrial radio links. As the atmospheric pressure increases, the attenuation of the radio link also increases[4]. These atmospheric factors are the main impairment of the wave spectrum which will cause propagation losses on the millimetric and microwave line-of-sight link. Multipath fading, Diffraction fading and Atmospheric attenuation are the typical attenuation in clear air environment. Multipath fading is a kind of fading that will happen due to multipath propagation created by diffraction and reflection of radiated signal from the source, whereas Diffraction fading is a shadowing wave caused by obstruction of objects between the transmitted antenna and receiving antenna. Atmospheric gas loss is caused mainly by water vapor absorption and losses due to oxygen gas found in terrestrial line-of-sight link [2] International Telecom Union (ITU-R) for radio communication has developed recommendation for different radio-climatological modeling framework in clear-air environment. Since, the propagation of the radio wave is a complex phenomenon, careful steps of the procedure and following developed models are crucial. Different radio link modeling approach in clean-Air have been developed by the ITU-R p 530 using different types of data in different regions of temperate zones. The ITU-R body has prepared data as an alternative from Temperate region countries, which does not fit for countries in Tropical regions. It is imperative to prepare parameters from locally collected data. Surface Refractivity, point refractivity and refractivity gradients are the building block of geoclimatic factor(K) and effective earth radius(k-factor). Refractive index and radio refractivity data will be discovered from recommendation on ITU-R.P453 and ITU-R.P530 methods[5][6]. The other environmental factor known as atmospheric gas attenuation need to be discovered with the method given on ITU-R-P.676.

Which provides detailed methods to estimate the attenuation of dry atmospheric gases, specific attenuation and wet atmosphere gas attenuation on terrestrial line of sight link[7]. Propagation impairment varies from seasons to seasons as well as months to months. The probability of propagation impairment happening in this condition may also vary from time to time. At least 5 years of data is required to have conclusion on the effects of the impairment of weather condition[8]. Seven to ten years of National Meteorological Agency (NMA) of Ethiopia was taken as raw data for the analysis of clear air attenuation. Ethiopia is found in Tropical region above equator and has unique atmospheric condition. Statistical and physical analysis of data from the ground is crucial for the estimation of the losses. The prediction approaches required for the design document show the steps clearly how to develop the targeted model[9]. Therefore, it is necessary to experimentally determine the necessary parameters for the radio link model for Ethiopia.

Fifty eight sites were selected from National Meteorological Agency (NMA) of Ethiopia ,which have seven to ten years of atmospheric temperature and humidity data collection from ground meteorological stations. FLDAS Noah Land Surface Model L4 Global Monthly 0.1 x 0.1 degree (MERRA-2 and CHIRPS) satellite data is the source of surface pressure data, which is integrated with collected humidity and temperature data using Haversine mathematical formula. The Radiosonde station, which has collected data of several years in Addis Ababa was used for modeling vertical atmospheric profile, which was later used for the discovery of vertical profile of the rest 58 sites. From the result of developed vertical atmospheric profile, vertical refractivity gradient at 1km above ground level and point refractivity at 65m above ground level are discovered. The result of refractivity will help to determine k-factor, worst month geoclimatic factor, and related parameters. Refractivity gradient and k-factor statistics for the first 1km above ground level have been determined in different exceedance from 1% of annual time to exceedance to 99.9% of annual time. The curve fitting of the k-factor probability density distribution of annual monthly and seasonal values of exceedance at 50% of time was presented. Point refractivity distribution at 65m of lower atmosphere and geoclimatic factor (K) were determined. Moreover, the characteristics of Fade depth with other parameters discovered discovered at 0.01% of outage probability. Ordinary Kriging interpolation method was selected for mapping and generating for the place where the data sample was not taken in the country. The resulting data can be used as a reference for consumption of radio link network engineers. The overall result of the Research is to produce a document that can be input parameters to the microwave link design, that will be used in telecom operators to minimize the problem raised by the lack of precise inputs. The result will also encourage researchers for further investigation of the behavior of clear air radio-climatological parameters of the country.

1.2 Statement of the problem

In designing of terrestrial line of site link such as microwave radio link, the attenuation induced by environmental atmospheric factors has to be analyzed so that reliable network between microwave radio links could be achieved[2]. Attenuation effects of primary atmospheric parameters like temperature, pressure and

humidity are the main cause of clear air atmospheric impairment between links of microwave[10]. Currently, the parameters for microwave link design in Tropical region like Ethiopia have been utilizing mainly ITU-R database as a data source. This database was prepared from the countries of Temperate region. The parameters of the ITU-R database were developed from atmospheric conditions of Temperate region countries which might not fit to the environment of the countries of a Tropical region like Ethiopia[11][6]. Reliable research has not yet been conducted for these Tropical countries so that dependable database for parameters to design microwave link become open for investigation. In microwave link design, in-appropriate parameters may end up to unreliable network or costly network that may affect the parameters Key Performance Indicator (KPI) of the system, such as availability of the overall transmission network system[2]. Unfit parameters also directly affect the selection of network equipment for installation, optimization of the radio system and economic requirement in an undesired way. As a result, the expense of the capital and operational cost may increase. Proper planning of terrestrial line-of-sight radio link needs appropriate radio link design parameters[12] [2]. Therefore, it is necessary to address this problem through research and investigation of appropriate parameters.

1.3 Objective

1.3.1 General Objective

The general objective of the Research is to investigate a suitable model for determination of Radio-climatological parameters to design Terrestrial Line-of-Sight links under clear air conditions in Ethiopia.

1.3.2 Specific Objectives

The specific objectives of the thesis are:

- To model vertical atmospheric profile
- To model and characterize the monthly, seasonal and annual values of the k-factor
- Geo-climatic factor determination and modeling for terrestrial line of sight radio link Ethiopia Ethiopia.
- Curve fitting of fade depth and outage probability due to multipath propagation
- To determine the atmospheric gas specific attenuation of Ethiopia

- To interpolate and map the annual values of the k-factor, vertical refractivity gradient, geoclimatic factor and point refractivity of Ethiopia

1.4 Scope and Limitation

Scope

This thesis work focus on the radioclimatic model related to the clear air line of sight. The mathematical model covered in this thesis is vertical atmospheric profile at first 1500m in Addis Ababa, k-factor, climatic factor, point refractivity at 65m above ground level, vertical refractivity gradient of 1000m above ground level to address the impairments of microwave and millimetric propagation.

Limitation

This thesis is limited to clear air time radioclimatic condition and its mathematical formulation of vertical atmospheric profile was created from one year data collected from Addis ababa radiosonde station. The paper doesn't cover the diffraction fading caused by k-factor and related. The resulting databases generated are limited to territory of Ethiopia border. It will not cover the problem related to mitigation technique of radioclimatic impairment clear air and raining time.

1.5 Literature Review

Several researchers have been working on radio wave propagation modeling under clear air conditions. Humidity, temperature and pressure are primary data for modeling clear air radioclimatic line-of-sight links. Feyisa Debo, the first East African researcher on the subject who have used local surface data to model clear air attenuation using ITU-R model[11]. He has been working on radio wave propagation and modeling under raining condition as well as the clear - air atmosphere in Horn of Africa. Geoclimatic factor determination and attenuation measurements from received signal are among his investigation. In his results, he has tried to show that his empirically done research results have a clear difference from ITU-R database developed for the East African region[11]. But, the number of sites used for his analysis was so limited. In 1997, a campaign took place in Brazil to find the cumulative distribution of multipath fading from 4 to 8 GHz frequency and observed strong fading with the highest frequency[13]. Several countries have conducted their own research on the subject. Odedina Peter Kemi, researcher in Southern Africa, also done a remarkable investigation on radio-climatological study, in a clear air condition which could be applicable for design of

terrestrial line-of-sight links. He had selected places from Botswana and South Africa for his data source from Radiosonde for model formulation and terrestrial radio link received signal for model verification[14]. P. K. Odedina and T. J. Afullo, jointly have done research, namely “ A Simplified Statistical Modeling of Radio-climatological Parameters ”. These parameters are: temperature, pressure and humidity to develop the model in terrestrial line-of-sight links with South Africa[15]. Similar investigation has been conducted in Nigeria to discover the impact of secondary radioclimatic parameters[16]

k-factor is one of the clear air radio-climatological parameter which uses secondary parameters to formulate. It is used for design of terrestrial line-of-sight radio links that determines directly the height of a tower for device implementation. AbouAlmal, Abdulhadi and Abed-Alhameed, RAA and Jones, Steven MR and AlAhmad, Hussein are researchers in the UAE and UK have written on k-factor. In their work they have showed the secondary data variation of the vertical refractivity gradient distribution in the first 100m above the ground level using 9 years of primary meteorological data in Abu Dhabi[17]. Whereas, some of these researchers, Abu-Almal, Abdulhadi and Al-Ansari, Kifah, have investigated k-factor from the first 1km refractivity gradient from 14 years of Radiosonde data collected in Abu Dhabi. Despite of the result, they have used only single site data as a source of formulation [17]. Abraham Mutunga Nyate, at University of Kwazulu-Natal in South Africa, has not only discovered k-factor distribution in South Africa by clear-air analytic and empirical k-factor determination and characterization for for line of sight link in South Africa. He also had done modeling, characterizing, interpolating and mapping of the k-factor for the Entire country using the IDW interpolation method. Median k-factor(k50%) and effective k-factor(k99.9%) values were discovered in his work. He used three years data for modeling and characterization and Integral Square Error for his work verification. The professor Thomas J. Affulo has done “On the k-factor distribution and diffraction fading for southern Africa” using radiosonde measurement data obtained in Botswana. The resulting curve fitting of Median k-factor and k99 were different in values with ITU-R global value of $k=4/3$ and its resulting link attenuation[18].

Locally investigation on point refractivity in lower atmosphere also done similarly with temperature, pressure and humidity like wise with k-factor. Bettouche, Yamina and Agba, Basile L and Kouki, Ammar B, are researchers worked on geoclimatic factor and point refractivity evaluation in Canada using data from NOAA/ESRL Earth System Research Laboratory database. Monthly and seasonal variation of point refractivity and geoclimatic factor was presents[19]. Feyisa debo(PhD) had also worked on the geoclimatic investigation from point refractivity and presented the result using contour map resulted from ITU-R method for Ethiopia which the data source was based on 4 geographic locations[11]. k-factor distribution can be modeled using different mathematical model. The curve fitting approach to find the a suitable model is one of most researcher’s approach to find suitable model to approximate the distribution of the parameter. Abraham Mutunga Nyete have done curve fitting and kernel estimation method to model and characterize the k-factor distribution for the first 200m in South Africa. He found curve fitting is better for parametric method while kernel estimation method found to be a better estimation approach for non-parametric technique[20].

Afullo, T. J. and Odedina, P. K. also have done similar job using first 500m above the ground level for Botswana and Derban South Africa using 50% of time and 99.9% time exceedance. In both research on k-factor distribution, the approximate probability density function of the normal distribution is estimated using

the mean and variance of the distribution. Several southern Africa and Nigerian researchers use the lower 100 to 500 meters of the troposphere atmosphere to calculate effective earth radius factor[21][18][22][23][24]. While, Abu Dhabi researches use the first 1 kilometer above ground level to calculate the k-factor of their region[25]. The characterization of k-factor can also be done using a secondary parameter of refractivity analysis for the first 200 meters above ground level[26].

Researches related to atmospheric gas loss are not relatively abundant. There are two existing models to deal with atmospheric gas, these are: Model prepared by Liebe and ITU-R P.676 method. Both approaches are mathematically expensive, but ITU-R method is more popular in many researches. The first report of the Liebe model was in 1977[27], later modified several times until 1989. Where, the atmospheric propagation model reported was designed for millimeter wave, of which the model was prepared in collaboration with telecom and information administration of the US. The result was used to revise data for oxygen line and water vapor line parameters reported in previous work[28]. Many researches based on terrestrial radio link and satellite communication use either of these models for attenuation finding or verification of their work [29][30][31][32].

Vertical modeling of atmospheric profile is important at the place where no data could be collected as a function height. Modeling primary data with altitude, like temperature and humidity, using radiosonde as a function of height was done in different parts of the world. Pressure inclusive regression have been modeled for terrestrial radio link application in Nigeria from the "European Center for Medium-Range Weather-Forecast (ECMWF)" data source [33]. They have applied error formulas to check the accuracy of their model, Whereas model developed for secondary parameter of refractivity as a function of height was done in different parts of the world[34][35][36][37].

Most of the researchers are focusing their investigation limited to their data source area and study locations. ITU-R's contour map is considered as an alternative to the place where the research work was not conducted. In the East African region, investigation of refractivity, point refractivity, k-factor and geoclimatic factor K is at its early stage. This thesis work has covered more geographical area and utilizes several years of meteorological data collection for better prediction of Ethiopia's clear-air radioclimatic parameters. This will reduce the gap created due to lack of well prepared and documented parameters for designing radio-link of the terrestrial line of sight.

1.6 Methodology

The methodology followed in this thesis contains literature review, data collection, data integration, vertical atmospheric profile modeling ,verification and Error calculation using result from Radiosonde, determination of refractivity gradient and k-factor for different exceedance of time , k-factor distribution and modeling using probability density function, determination of point refractivity as well as geoclimatic factor, fade depth and outage probability function determination and atmospheric specific gas attenuation determination.

The literature review work was mainly focus on referring literature papers which are related on clear air propagation model. Other related documents including articles, papers, research works and academic journals and conference papers that are worked on the clear air radio-climatological modeling were also referred and checked their our put results with relative standard documents produced by ITU-R. The data collection includes surface humidity and surface temperature data of seven to ten years were collected from fifty eight sites from National Meteorological Agency(NMA). Ten years of satellite monthly pressure data from "FLDAS Noah Land Surface Model L4 Global Monthly 0.1 x 0.1 degree (MERRA-2 and CHIRPS)" was also collected[38]. Both satellite data and NMA data was integrated using Haversine formula for further analysis. Radiosonde vertical data collection takes place from one site in Addis ababa.

Vertical atmospheric profile is modeling was the first step to use for analysis from primary atmospheric parameters at different altitude above sea level. These are 65m to find secondary data of point refractivity gradient and 1000m to find vertical refractivity gradient. The vertical atmospheric profile formula was prepared for temperature, pressure and humidity to their respective targetted altitude. Verification and error calculation was done using k-factor and vertical refractivity gradient by RMSE and MAE comparing with existing vertical profile modeling from ITU-R with reference of result from Radiosonde data.

Refractivity gradient and k-factor determination for different exceedance of time was done for the selected fifty eight sites so that the value of Refractivity gradient at first kilometer above sea level and median k-factor values was interpolated for the whole country using selected interpolation technique of ordinary kriging with 5km X 5km resolution, which have smallest error rate from other interpolation formulas.

The k-factor distribution and modeling using probability density function was done after the median k-factor and variance of the values were discovered for the whole 58 sites and distribution table of probability density function was generated using mean and variance of each sites. Determination of point refractivity and geoclimatic factor was done from each sites using the newly developed vertical atmospheric profile. From this result map and database was developed for the country at the places where sample data were not collected with the resolution of 0.0458degx0.0458deg latitude and longitude area,which is approximately 5km x 5km resolution pixels.

Fade depth and outage probability were determined at different frequency and distance from geoclimatic factor data. The behavior was given in graphs for comparison. Atmospheric gas specific attenuation determination was done from wet term atmospheric gas specific attenuation and dry term atmospheric gas specific attenuation.The behavior of the total atmospheric attenuation was given in graph by varying different frequency and distance using temperature varying technique.

Different tools and coding were used for analysis in this thesis including python for data accumulation, ArcGis10.8 for data conversion, interpolation ,map generating and database building integrating with GPS positioning, Excel-Lab was used for error analysis, MS-Excel was used for graph generation, data analysis and visual presenting. Finally, conclusion and discussion based on the result from result analysis and theoretical relationship was done. Different results of fifty eight sites are presented on appendix.

1.7 Contribution of the Thesis

This thesis has contributed on different areas:

- The thesis has tried to produce databases of parameters and reference maps for microwave radio link design using locally collected atmospheric data in Ethiopia.
- It can help in preventing over design microwave network or under design microwave network which could end up with unreliable system in telecommunication.
- Help researchers for further study in the subject area and elevate knowledge of practical application of atmospheric refractivity, effective earth radius factor(k-factor) and geoclimatic factor K for radio link designers in Ethiopia
- In the process of discovering atmospheric parameters for input design of terrestrial line of sight link, this thesis proposes the alternative vertical model to ITU-R, way to find vertically collecting atmospheric profiles at desired altitudes above ground level.
- It has presented values of the resulted parameters' pattern in monthly, seasonal and annual distribution and its curve fitting.

1.8 Organization of the Thesis

This thesis work is structured in seven chapters. Chapter one is introduction part of the thesis. Chapter two covered the mechanisms of propagation as well as the lower part of the atmosphere where the microwave signal is passing through. Chapter three is about discussing different models for diffraction and multipath losses. Chapter four covers details of the refractivity at surface and some altitude, k-factor, geoclimatic factor K and little about atmospheric gas losses. Ordinary kriging and other interpolation techniques were covered.

Chapter five covers the detail process and methodology for data collection, data analysis, discovery of refractivity, discovery of k-factor with its curve fitting and geoclimatic factor. It also covers the outage probability and fade depth calculation with curve fitting. The wet and dry atmospheric gas losses also covered with logarithmic approximation of its relationship with distance and frequency variation. Interpolation techniques were compared and selected with error comparison for maps and database producing. Chapter six covers result and discussion where as the last chapter (chapter seven) is concluding the paper and showing future work of possible research area.

Chapter 2

Radio Wave Propagation Mechanisms

Electromagnetic wave transmitted in the air is based on various physical methods. These methods could be, point to point propagation, free-space, diffraction, reflection, using wave guiding and scattering. The loss expected in free-space may result from scattering of energy as it goes far apart from the source of signal transmission. Distance as well as frequency are the main parameters to find the attenuation in free-space. The other attenuation other than free-space loss are, atmospheric gas absorption, vegetation losses, diffraction losses, hydrometer losses and others. Among these causes of free-space attenuation, reflection, scattering, diffraction and free-space propagation are the main sources[39].

2.1 Diffraction

Diffraction happens if there is an obstacle or several obstacles on the way of signal propagation in the atmosphere between source and receiver antenna. Larger dimension relative to the wavelength of the propagating signal causes this secondary wave. This diffracted wave can still arrive at the receiving antenna. Which will have an effect on the line-of-sight communication link [20].

At different frequencies, different characteristics of diffraction can be observed. At below 1GHz the attenuation increasing with obstruction sizes. Whereas above 1GHz the nature of attenuation increment is more rapidly as a function of obstruction increment, which will make the connection more unstable. The area of obstacle determines the total attenuation caused by diffraction, which will affect the propagated energy. A microwave link designer objective is to provide an enough clearance of blockage without notable loss due to the object between the two links. Huygen's principle is the basic formula to use sufficient clearance and the theory of Fresnel's zone to deal with blockage diffraction. At this time, we neglect the gradient effect, so that the medium is homogeneous[40]. Diffraction Attenuation caused by an edge can be expressed by frequency relation in the form of $10 \cdot \log_{10}(f)$. Attenuation caused by diffraction is increasing very visibly at a frequency higher than 15GHz. The following mathematical relation explains more about attenuation

caused by diffraction between two terrestrial line-of-sight links[39].

$$v = h \sqrt{\frac{2}{\lambda} \left(\frac{1}{d1} + \frac{1}{d2} \right)} \quad (2.1)$$

- d1 and d2 are parameters of distances from the point of the edge to the source of the signal transmitting and to the receiving end,
- h is the measurement of the height of the object obstacle. Which is extending above the straight line between the two ends of the path.

From a designer's experience 60% of the first Fresnel zone plus 3 meters is advisable to avoid the diffraction and scattering effect caused by an object between microwave link. In fact, the more blockage clearance is required, the more antenna tower is needed. Which will have an economic and technical impact that has to be considered during design [40].

2.2 Reflection

When an electromagnetic wave travels against a surface of big dimension with a small irregularity compared to the wavelength, such phenomenon is called reflection of a signal. One of the most common type of reflection is Specular reflection, which occurs at all frequencies at the surface of a smooth plane and surface of homogeneous too. Earth ground is a good example of such type of Specular reflection. The other type of reflection is called Diffuse reflection, it's occurring at rough surface and it has height irregularities. The resulting reflection signal will be diffused in different directions. For such reflection type, Rayleigh criterion is the best tool to identify both reflection types[39].

2.3 Scattering

when a signal strikes against a rough surface where the dimensions of the surface is smaller or equal to the incident wave length the phenomenon is called Scattering[41] Scattering is mainly produced by rough surfaces, small objects and other irregularities. during scattering energy of incident signal is spread out in all possible direction. there are computational analysis known for some kind of scattering whose accuracy of the solution is unpredictable. the computational complexity rises if the number of wave length increases. the computational capability of solving the problem of scatterin is limitedthere are places like smooth surfaces that have bigger size than wave length of the incident wave and it is considered as reflective surface which is

described as Fresnel's Reflection Coefficient [42] there are two types of scattering phenomenon, Namely Elastic scattering and Inelastic scattering. Elastic scattering is known by very small loss of energy where as Inelastic scattering creates some change in energy of the incident wave. when a significant energy loss happens the process is called absorption. at the place where scattering happens one place it is called single scattering. but in reality many scattering is happening [43].

2.4 Freespace propagation model

Radio waves are facing attenuation while propagating from source point to destinations. The Free-space path loss model is the mathematical model used to estimate the signal strength arriving at the destinations considering there is no obstacle between the source and destination or clear line of sight along the path of the signal. The signal degradation or attenuation is increasing directly related to the square of the distance and frequency. Free-space loss takes most portion of the cause of signal propagation losses. It is also called Friis free-space path loss model [2].

The free-space loss model considered there are no hindrances in the way of propagation like absorption, reflection or diffusion. The gap between the links is considered as filled with uniform atmospheric gaseous and no reflection coefficient of the earth. But in practice the propagation of wave results in reflection diffraction and scattering [44]. If no obstruction between the two links the loss will be considered as uniform at all possible points. The transmitted power density relation at any distance will go to be

$$Powerdensity = \frac{P_T}{4\pi d^2} \quad (2.2)$$

at the receiving end, with the effective area of antenna A_R , the total PR is equal to the density will be the transmitted power density times the area of the receiving antenna.

$$Powerdensity = \frac{P_T * A_R}{4\pi d^2} \quad (2.3)$$

[44]. The free space loss between links of isotropic antenna is:

$$L_{FSL} = \left(\frac{4\pi d}{\lambda} \right)^2 = \left(\frac{4\pi df}{c} \right)^2 \quad (2.4)$$

d = the path length between transmitting antenna and receiving antenna in meter (m)

λ = operating wavelength (m)

c = speed of light in vacuum (m/s)

f = frequency (Hz)

$$L_{FSL} = 92.45 + 20\log(f_{GHz}) + 20\log(d_{km}) [dB] \quad (2.5)$$

Where,

f = frequency (GHz)

d = line-of-sight (LOS) range between antenna (km)

If the gain of the transmitted antenna is G_{tx} , then the power density will be

$$p = G_{tx} \frac{p_{tx}}{4\pi d^2} \quad (2.6)$$

Where d is the distance between transmit and receive antenna. If the receiving antenna has an aperture is A_{rx} , the receiving power, P_{rx} will be

$$p = A_{rx} G_{tx} \frac{p_{tx}}{4\pi d^2} \quad (2.7)$$

For any isotropic antenna, the effective area or aperture in terms of wave length will be given as $A_e = G \frac{\lambda^2}{\pi}$ where λ is the wave length of the radio signal. When we substitute the above with the previous one we will find the following

$$P_{rx} = G_{rx} G_{tx} \frac{P_{tx} \lambda^2}{(4\pi d)^2} \quad (2.8)$$

This equation is called Friis Transmission equation and applicable to the far field. The separation required for this distance will be given as:

$$d_R = \frac{2L_a^2}{\lambda} \quad (2.9)$$

Where L_a is the biggest size of the antenna. The requirement for far field is the distance between the two links is much greater than the wave length of the radiated signal.[40]

2.5 Atmospheric Impact on Terrestrial Radio-Link

2.5.1 Troposphere

The troposphere is found in the lower part of the earth's atmosphere, where, all possible weather phenomena can occur. The altitude extends on the polar region of the earth is about 9 km above the ground level and on the equator about 17 km above the ground level. Due to its closeness to the ground of the earth and the effect of a natural phenomenon of electromagnetic wave, the troposphere is becoming the main interest area of study for radio climatic instability[11]. The troposphere has inhomogeneous characteristic and constantly changing. Atmospheric parameters including temperature, pressure and humidity are known by affecting the electromagnetic wave propagation by attenuating, scattering, refracting and reflecting when a radio wave is radiated from one transmitting antenna through the atmosphere. The amplitude and phase of the received signal may also be fluctuated randomly due to multipath propagation effect. The polarization of the wave could be changed and noise originating from the atmosphere might be added to the source signal. Gases and vapors are other components exists in the atmosphere surrounding the planet earth that could affect the radio wave.[45]. The earth's surrounding atmosphere is given in the figure(2.1)[11].

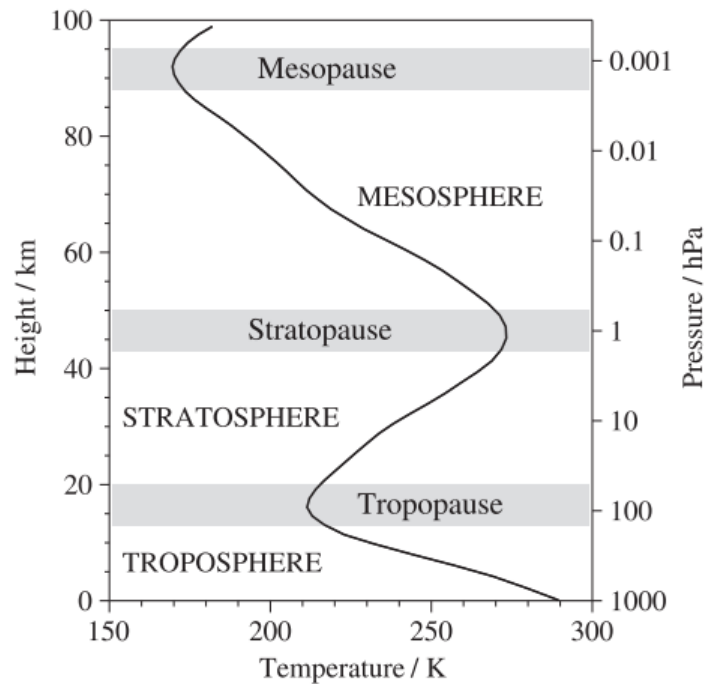


Figure 2.1: Layers of atmosphere and vertical structure of atmospheric pressure (hPa) and temperature (K) in the lowest 100km of the atmosphere[11]

The tropospheric layer is the place where many climatological effects happening, which is located at the lower part of the atmosphere. It consists of 72% of the total mass ratio of the entire atmosphere with wettest and warmest layer[45]. In this part of the atmosphere, the nature of the temperature is decreasing nearly linear with the height increases above the ground as it was shown in the figure(2.1) [46].

2.5.2 Troposphere Effect on Radio-wave Propagation

Troposphere has a refractive index which is greater than unity due to effects of climatic parameters. Temperature, pressure and humidity are the three meteorological parameters can affect how the propagation of wave can behave in troposphere layer of the atmosphere [11]. Any climatic change in the atmospheric parameter such as temperature, pressure and humidity will result to the change of refractive index. As increase the height of the troposphere from the surface of earth, the refractive index decreases due to the variation of the climatic parameters. This may result in bending of electromagnetic wave propagation toward the ground or away from the surface of the ground. Meteorological devices can measure these climatic parameters directly from the ground and could be used as a primary data source to find refractivity of the atmosphere. Secondary parameters like refractivity, refractivity gradient and point refractivity are used to determine effective earth radius factor(k-factor) and geoclimatic factor(K). Losses due to diffraction and multipath fading could be estimated from the k-factor and geoclimatic factor(k) with other parameters[47].

Chapter 3

Diffraction and Multipath Propagation Models

3.1 Diffraction Propagation Models

Diffraction fading is happening where the choice of effective earth radius factor (k-factor) is not properly estimated. Adequate path clearance is very important for designers to do the link budget in order to reduce the chance of diffraction along the radio link path. In most part of the world where the absence of local data, the value of k-factor is taken as 4/3. In most part of the Tropical region, this value is used no matter how far the microwave link is. This might have increasing the probability of diffraction fading occurrence along the path which will result to outage due to diffraction fading. the intercepting object along the path might be single sharp abstraction or multiple sharp obstruction known as single knife-edge or multiple knife-edge diffraction respectively[48]

3.1.1 Single knife-edge diffraction model

Single Knife-edge diffraction model is a kind of diffraction model that could be happening by single sharp object and considered as simplest diffraction phenomenon.

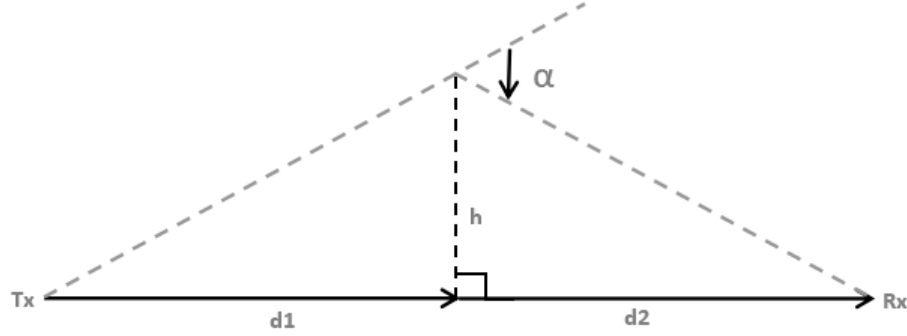


Figure 3.1: Simplified geometry of the knife edge diffraction [49]

The single knife-edge analogy is where a mountain or single hill intercepts the radio link between the two microwave end which will cause shadowing effect known as diffraction fading.

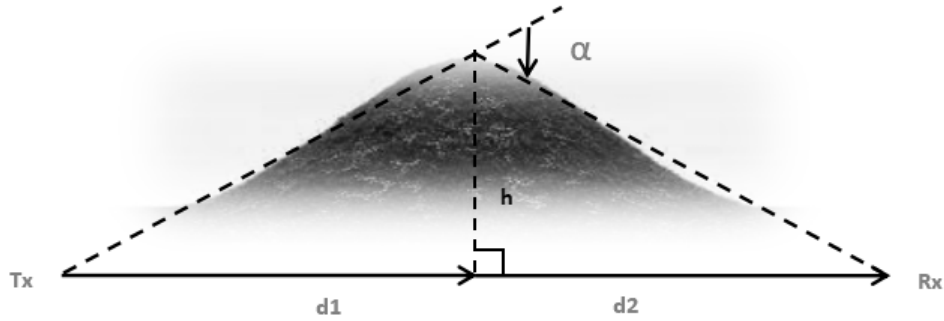


Figure 3.2: Hilly rounded obstacle represented as single knife edge [49]

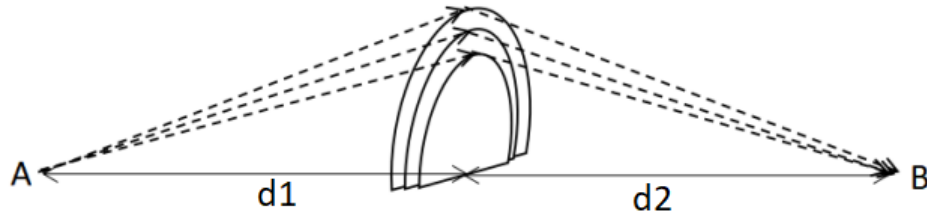


Figure 3.3: Family of circles representing Fresnel zones at point along a radio path[20]

Consider point A is transmitting antenna and point B is receiving antenna as shown in Figure(3.3). If Fresnel zone is represented by consecutive curves, any signal that travels different from straight line from point A to point B have longer path distance. the approximation of excess path can be estimated from Equation(3.1) given[20].

$$\Delta \cong \frac{h^2}{2} \left(\frac{d_1 + d_2}{d_1 d_2} \right) \quad (3.1)$$

where $h \ll d_1, d_2$ the corresponding phase difference is given by

$$\Phi = \frac{2\pi\Delta}{\lambda} = \frac{2\pi}{\lambda} \left(\frac{h^2}{2} \right) \left(\frac{d_1 + d_2}{d_1 d_2} \right) \quad (3.2)$$

The phase difference is usually expressed as v with no dimension,

$$\Phi = \frac{\pi}{2} v^2 \quad (3.3)$$

v is known as the Fresnel-Kirchhoff diffraction.

$$v = h \sqrt{2 \frac{d_1 + d_2}{\lambda d_1 d_2}} \quad (3.4)$$

In practice the diffraction attenuation prediction is based on the theoretical approximation which will be modified by necessary empirical data[49][20].

3.1.2 Multiple Knife-Edge Diffraction Models

The mathematical steps to find a model for multiple knife-edge diffraction model are more complex than the single knife-edge diffraction model along the path of radio links. As the height of obstacle in case of single knife-edge increases, the loss diffraction caused by the obstruction increases. When we deal with multiple obstruction, once the diffraction fade happened at first obstruction the signal effect on the consecutive knife-edge become non uniform which will make more complex approach to predict the additional losses due to the multiple knife-edge obstacles. One approach of predicting is, the number of knife-edge is counted and n-dimensional integration of Fresnel equation is going to be implemented for predication. Even if other alternative approaches can be used to estimate, the methods are still complex and limiting. The common applicable practice to estimate the multiple knife-edge diffraction method is more of approximation method. The most common approximation methods are the Japanese method, the Deygout method, Epstein-Peterson method and the Bullington method [20].

Bullington Diffraction model

Bullington diffraction model considers one single knife-edge obstacle, which is considered as the equivalent obstacle of all possible knife edge obstacles on the path of propagation of transmitting signal. The model simplifies the approach to find diffraction loss estimation. Most of the time this approach ends up with

optimistic result[20]. The method is too idealistic to ignore the real world knife-edge obstacle that affects the signal strength of the propagation signal. Single knife-edge is placed the place where main obstruction is found. This ignorance of the presence of other obstruction approach is followed by regular process of formula of single knife-edge diffraction equation. The main benefit of this approach is its simplicity whereas a designer can end up with larger error than other approaches[49].

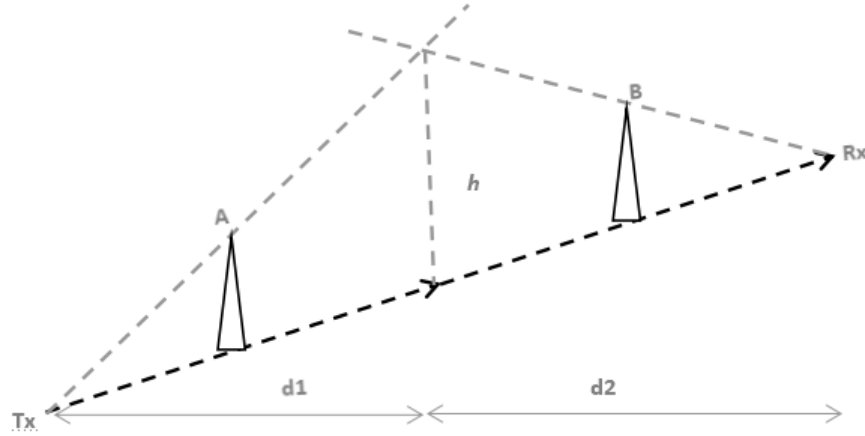


Figure 3.4: The approximation of the resultant knife-edge by two knife-edge obstacles[49]

Epstein-peterson Diffraction model

The approach of Epstein-Peterson method solves some of the Bullington method by considering individually all possible obstacles along the path of radio wave propagation. The approach subdivided the path, considering each obstacle as overlapping hops in between a single knife-edge. It only considered depends on their position of obstruction[12]. Adding the diffraction losses in each hop will be the net diffraction loss of the radio link.

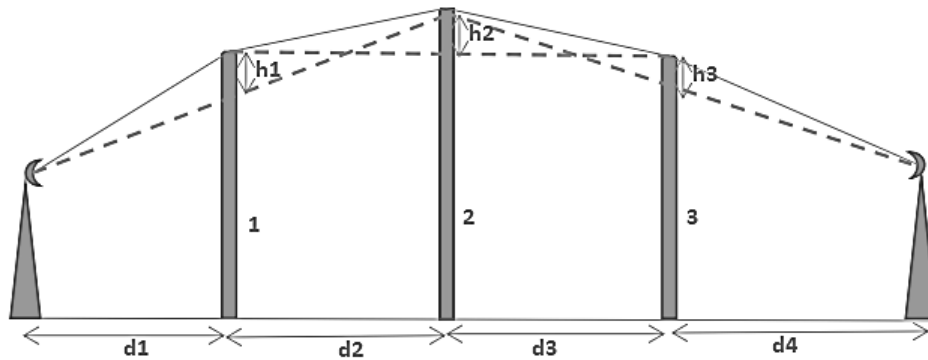


Figure 3.5: The Epstein-Peterson method[12]

Figure(3.5), the radio link in the Epstein-Peterson method. Even though it is more refined method it still uses approximation for calculation. The line from transmitter antenna to obstacle 3 and the diffraction

made by obstacle 1 is going to be calculated using normal single knife-edge diffraction method. In similar fashion the diffraction caused by 3 by linking obstacle 1 and 2 is calculated with similar single knife-edge diffraction method. The diffraction caused by 2 is calculated by joining 3 with the receiver antenna. Finally the total diffraction loss will going to be calculated by adding each losses due to individual obstacle.

Deygout Diffraction model

Deygout diffraction method is similar with Epstein-Peterson method but has differences in a way that, Deygout method is first targeting to identify the dominant obstacle that might produce the highest diffraction losses. The identified largest obstacle is then calculated diffraction losses using a regular single knife-edged method. The method assumes the top of this large obstacle as a virtual transceiver and divides the propagation path in to two sectioned links. For both sectioned path links, the dominant obstacle and diffraction loss will be calculated. This process will be repeated for each dominant obstacle.

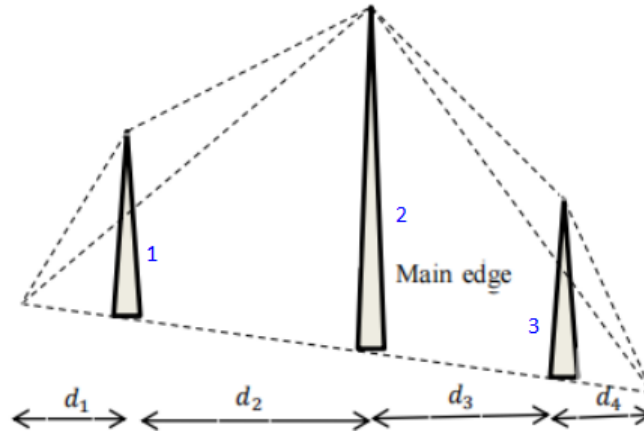


Figure 3.6: Construction of the Deygout diffraction method[51]

In accordance with the model, if a dominant obstacle exists, the Deygout method work better to find the diffraction loss. Due to its good performance, this method is known as main edge method[49].

Japanese Diffraction model

Japanese approach of finding the diffraction loss is quite similar with Epstein-Peterson method but the mathematical way of finding the diffraction loss is different in each obstacle. In Japanese method, the top of obstacle is not the main source of diffraction but the ray projected through that top of obstacle. The total diffraction loss could be found by summing up the effect of each diffraction[49]. Diffraction loss can be calculated by adding up L1, L2 and L3

$$L1 = f(d1, d2, h1)$$

$$L2 = f([d1+d2],d3,h2)$$

$$L3 = f([d1+d2+d3],d4,h3)$$

The model's result is optimistic in receiving signal strength value and assumed to be better than Bullington method and finding the diffraction effect[49].

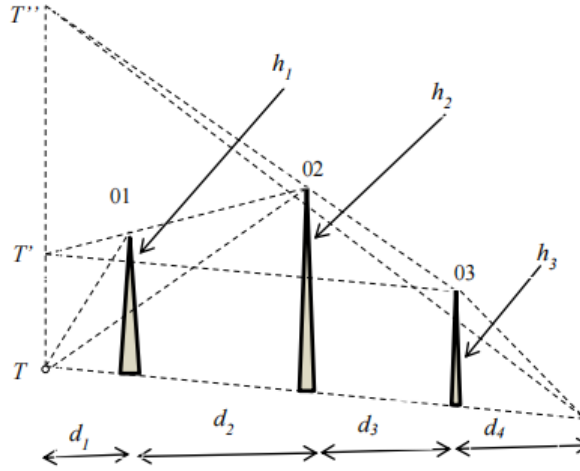


Figure 3.7: Construction of Japanese diffraction method[49]

3.1.3 ITU-R Diffraction model

ITU-R method was prepared for all types of path profile, for smooth or rough terrain, water bodies or sea, where the process of finding diffraction loss is required. ITU-R method adopts some of Bullington method assuming spherical earth diffraction. The method is applied where there is no local information of the terrain and obstacle along the propagation path of the radio wave. A computer application is applied to visualize the path profile from a database of terrain. This is an automatic approach of inspection each characteristics of the path profile and the approach is considered as reliable for all kind of terrain[9]. These upper and lower limits for the diffraction loss are shown in Figure(3.8) Diffraction loss for obstructed line-of-sight microwave radio path.

B is theoretical knife-edge loss curve

D theoretical smooth spherical Earth loss curve, at 6.5GHz and $k_e = 4/3$

A_d empirical diffraction loss based on Equation(3.8) for intermediate terrain

h amount by which the radio path clears the Earth's surface

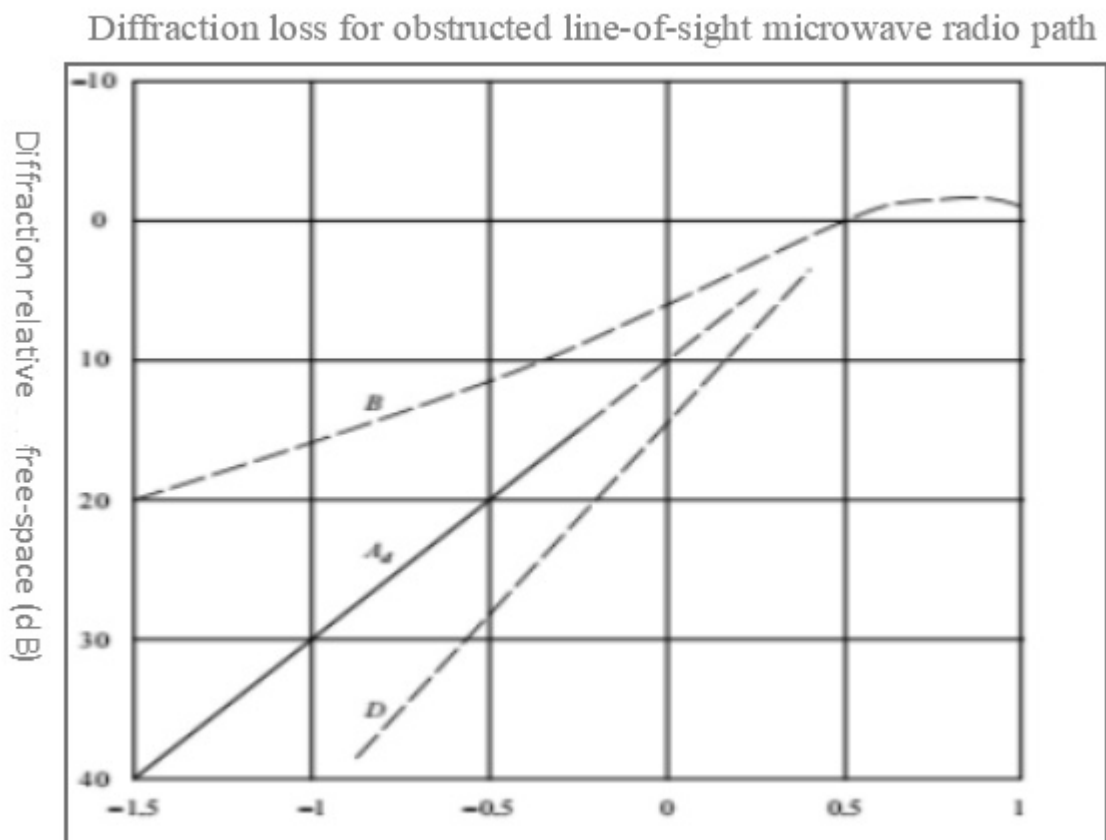


Figure 3.8: Normalized clearance[9]

F1 radius of the first Fresnel zone

On the average terrain the approximate loss greater than 15dB is

$$A_d = -20h/F_1 + 10dB \quad (3.5)$$

h is the height difference(m) between main blockage and path trajectory

F1 is first Fresnel radius of ellipsoid

The first Fresnel ellipsoid is given by

$$F_1 = 17.3 \sqrt{\frac{d_1 d_2}{fd}} m \quad (3.6)$$

f frequency (GHz)

d path length (km)

d1 and d2 distance(km) from the terminal to the path obstruction[6].

3.2 Multipath Propagation Models

Multipath fade happens when a signal transmitted from source antenna takes different ways to arrive at receiving antenna with different times and phases. The fluctuation happens due to multipath effect is random signal at the arriving antenna and depends on the nature of arrival. It is either be constructive or destructive. The occurrence of the destructive interference in multipath signal propagation is the main cause of multipath fading. Deep fading can happen at any place along the path which will be difficult to detect at the receiving antenna[20]. In planning of Line-Of-Sight link, the impact of the clear-air multipath fading caused by refractive atmosphere, starts from 5Km path distance to be considered. Surface multipath and atmospheric multipath are the most common multipath fading in line-of-sight terrestrial link. Specially frequency selective fading caused by beam spreading of the transmitted signal combined with the reflection from the surface of the reflective body produce severe multipath fading[6]. It is the kind of fading commonly faced by Line-of-Sight radio links and considered as the main source of dispersion which is causing fade in digital Line-Of-Sight links. This phenomenon directly affect the signal and results to performance degradation[40]. Multipath fading is depending on various factors including:

- Atmospheric refractivity gradient
- Radio wave frequency

- Percentage of time the fade depth is exceeded
- Antenna heights
- Area terrain roughness and Inclination of the path.

Three widely known for modeling the prediction of terrestrial link multipath fading are: Japanese Morita Method, North American Barnett-Vigants method and ITU-R method for world wide. Currently ITU-R method is used in both Japan and North America by Study Group 3 of the ITU-R sector for its regular updates[50].

3.2.1 Morita and Kakita Method

Morita and Kakita have used several years data collected in Japan to estimate empirical method for the occurrence probability of for the worst season multipath fading. It was derived from the parameter of propagation path distance, path height and inclination of the path to find occurrence probability. The value of occurrence probability and measured occurrence probability was compared in their result. The Morita and Kakita model was prepared over 4GHz microwave link with the equation of

$$P_R = \left(\frac{f}{4}\right)^{1.2} \cdot Q \cdot d^{3.5} (P_R \leq 0.3) \quad (3.7)$$

Where,

P_R is the Rayleigh fading occurrence probability

f is the frequency of the link in GHz

d is the path distance in km

Q is a constant it is known as the propagation terrain factor and its value varies for different types of terrain as

$Q = 2.0 \times 10^{-9}$ over the mountains

$Q = 5.1 \times 10^{-9}$ over the plains

$Q = 3.7 \times 10^{-7} \sqrt{\frac{1}{h}}$, over the sea h is average path height in meters[51][14]

3.2.2 Vigant model

Vigant method brings the space-diversity technique to estimate the fading which will help to find the protection to increase availability of the radio wave transmission system. The space required for antenna separation will be calculated to meet the need for availability objectives. Vigant describes the nature of received signal that the fading cannot be constant and the reviewing signal level is varying throughout the day and even the value of received signal could be zero for some seconds. The total time of fade of particular depth is calculated as:

$$T = rT_0L^2, L < 0.1 \quad (3.8)$$

Where T_0 is the time period of total fade duration, r is the fade occurrence factor and r is calculated for heavy fading months as:

$$r = c(f/4)D^310^{-5} \quad (3.9)$$

The value of c is varying for different type of climate

$c = 4$ over water and Gulf coast, $c = 1$ for average terrain and climate, $c = \frac{1}{4}$ mountains and dry climate.

f is frequency in GHz and

D is path length in mile[52]

3.2.3 ITU-R method

ITU-R method have considered fading data for 251 links in various geoclimatic regions of the world with path lengths d in the range of 7.5 to 185 km. The frequencies f was taken in the range of 450 MHz to 37 GHz. For initial design purpose, single-frequency fading prediction in the average worst month can be used. For large fade depth and all fade depth 'Method for all percentages of time' is suitable and could be interpolated for small fade depths[6].

Method for small percentages of time

Step1: Estimate geoclimatic factor K from average worst month calculated from fading data for target area

$$k = 10^{-4.4-0.0027dN_1} (10 + s_a)^{-0.46} \quad (3.10)$$

where: dN_1 : is point refractivity gradient in the lowest 65 m of the atmosphere not exceeded for 1% of an average year, and s_a is the area terrain roughness

For quick plan, Equation(3.11) can be used

$$k = 10^{-4.6-0.0027dN_1} \quad (3.11)$$

Step2: From the antenna heights h_e and h_r ((m) above sea level), calculate the magnitude of the path inclination $|\varepsilon_p| = \left| \frac{h_r - h_e}{d} \right|$ from: where d is the path length (km)”

The outage probability is calculated as

$$P_w = K d^{3.4} (1 + |\varepsilon_p|)^{-1.03} f^{0.8} x 10^{-0.00076h_L - A/10} \quad (3.12)$$

where:

f: frequency (GHz)

A_L : altitude of the lower antenna (i.e. the smaller of h_e and h_r); and where the geoclimatic factor K is obtained from Equation(3.10)

For quick planning applications as desired , calculate the percentage of time p_w that fade depth A (dB) is exceeded in the average worst month from:

$$P_w = K d^{3.1} (1 + |\varepsilon_p|)^{-1.29} f^{0.8} x 10^{-0.00089h_L - A/10} \quad (3.13)$$

Where, K is obtained from Equation(3.11). The equations are valid up to 45GHz and the lower frequency limit related to the path length.

Method for all percentages of time

The method given here for predicting the percentage of time that any fade depth is exceeded combining of the fade depth distribution which is provided in next section and an empirical interpolation approach to find shallow fade becoming 0 dB[6].

- *Step1*: Using small percentage of time calculate the multipath occurrence factor, P_0

$$P_0 = Kd^{3.4} (1 + |\varepsilon_p|)^{-1.03} f^{0.8} x 10^{-0.00076h_L} \quad (3.14)$$

The expression is applied for detailed link design applications, with K obtained from equation(3.10), and

To use for quick planning

$$P_0 = Kd^{3.1} (1 + |\varepsilon_p|)^{-1.29} f^{0.8} x 10^{-0.00089h_L} \quad (3.15)$$

for quick planning, K is obtained from Equation(3.11). Note that equations equation(3.16) and equation(3.18) are equivalent to equation (3.12) and equation (3.13) respectively with A=0

- *Step2:* Find the value of fade depth, A_t , deep-fading distribution and shallow-fading distribution transition moment

$$A_t = 1.2 \log((P_0)) \quad (3.16)$$

Here, the approach is depending on wheather A is greater than or less than A_t .

- *Step3a:* If the required fade depth, $A \geq A_t$: Calculate the percentage of time that A is exceeded in the average worst month:

$$P_w = P_0 x 10^{-A/10} \quad (3.17)$$

- *Step3b:* If the required fade depth, $A < A_t$:

Calculate the percentage of time, P_t , that A_t is exceeded in the average worst month:

$$P_t = P_0 x 10^{-A_t/10} \quad (3.18)$$

Determine q'_a from the transition fade A_t and transition percentage time P_t :

$$q'_a = -20 \log_{10} \{ -\ln [(100 - P_t) / 100] \} / A_t \quad (3.19)$$

Determine q_t from q'_a and the transition fade A_t :

$$q_t = (q'_a - 2) / \left[\left(1 + 0.3x10^{-A_t/20} \right) 10^{-0.016A_t} \right] - 4.3 \left(10^{-A_t/20} + A_t/800 \right) \quad (3.20)$$

Determine q_a from the required fade A :

$$q_a = 2 + \left[1 + 0.3 \times 10^{-A/20}\right] \left[10^{-0.016A}\right] \left[q_t + 4.3 \left(10^{-A/20} + A/800\right)\right] \quad (3.21)$$

Determine the percentage of time, p_w , that the fade depth A (dB) is exceeded in the average worst month:

$$P_w = 100 \left[1 - \exp\left(-10^{q_a A/20}\right)\right] \quad (3.22)$$

With the correction factor and variation of P_w versus A that could be used to find using simple iteration. Graphical family of curves representation of the method is presented in figure(3.9)

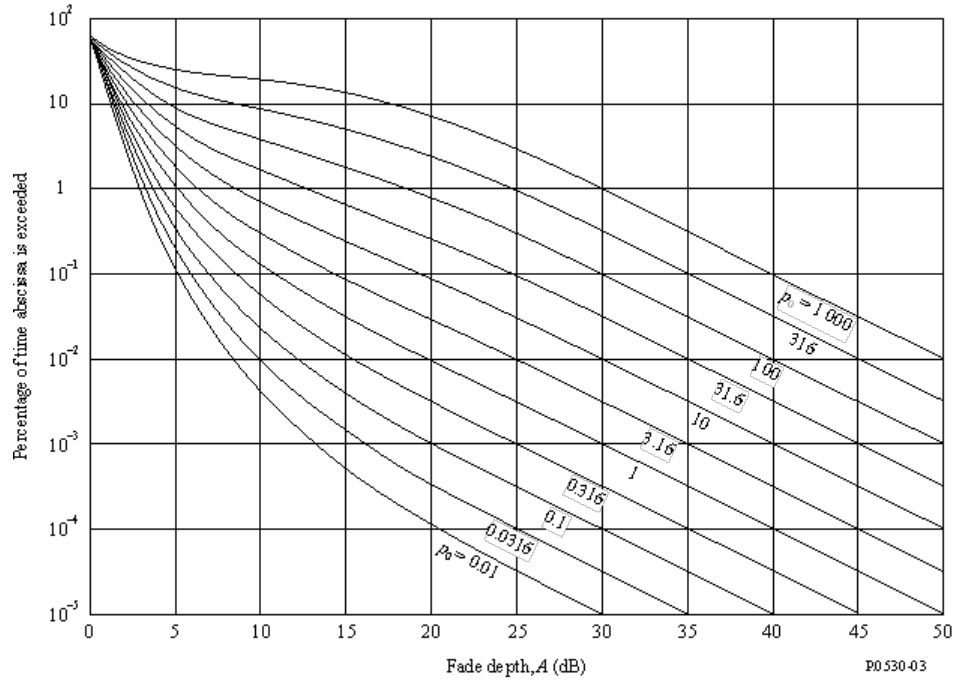


Figure 3.9: Percentage of time, P_w , fade depth, A , exceeded in average worst month[6]

Chapter 4

Atmospheric Radio Refractivity and Gas Loss

4.1 Refractivity

Refractive index, in air atmosphere, is greater than unity by a small fraction. Its value is a function of variation in atmospheric air density. The refractive index of atmospheric air can be measured by the radio refractivity N . It can be more explaining in refractivity of the air atmosphere than refractive index. And its relation with refractive index is explained in ITU-R[5] as Equation(4.1)

$$n = 1 + N \times 10^{-6} \quad (4.1)$$

The characteristics of refractive index depend on the characteristics of the atmosphere in which it passing through[53]. In standard atmosphere the value for the ground refractive index ($n = 1.000315$) and substituted in N yields 315 N-unit[47]. ITU-R p.453 is a general method of global application to estimate the value of radio refractivity characteristics both at surface and at some altitude above ground level. In-terms of meteorological parameters, N could also be expressed in equation(4.2)

$$N = 77.6 \frac{P_d}{T} + 72 \frac{e}{T} + 3.75 \times 10^5 \frac{e}{T^2} (N - units) \quad (4.2)$$

The dry term of the radio refractivity is:

$$N = 77.6 \frac{P_d}{T} \quad (4.3)$$

And the wet term of the radio refractivity is:

$$N = 72 \frac{e}{T} + 3.75 \times 10^5 \frac{e}{T^2} \quad (4.4)$$

And $P = P_d + P_e$ Since $P_d = P - P_e$, equation(4.2) can be rewritten as:

$$N = 77.6 \frac{P_d}{T} - 5.6 \frac{e}{T} + 3.75 \times 10^5 \frac{e}{T^2} \quad (4.5)$$

Equation(4.5) may be approximated with reduced accuracy as:

$$N = \frac{77.6}{T} \left(P + 4810 \frac{e}{T} \right) \quad (4.6)$$

where:

P_d : dry atmospheric pressure (hPa)

P : total atmospheric pressure (hPa)

e : water vapor pressure (hPa)

T : absolute temperature (0K)

Water vapor pressure e is calculated from relative humidity and given by Equation(4.7)[5]:

$$e = \frac{H e_s}{100} \quad (4.7)$$

With:

$$e_s = EF.a.exp \left[\frac{(b - \frac{t}{d}) t}{t + c} \right] \quad (4.8)$$

And:

$$EF_{water} = 1 + 10^{-4} \left(7.2 + P. \left(0.032 + 5.9 \times 10^{-6} t^2 \right) \right) \quad (4.9)$$

$$EF_{ice} = 1 + 10^{-4} \left(2.2 + P. \left(0.0383 + 6.4 \times 10^{-6} t^2 \right) \right) \quad (4.10)$$

Where:

t : temperature (0C)

p : total atmospheric pressure (hPa)

H : relative humidity (H%)

e_s : saturation vapour pressure (hPa) at the temperature t ($^{\circ}\text{C}$) and the coefficients a, b, c and d are given in table(4.1)

Table 4.1: Constants for vapor pressure of water and ice

for water	for ice
$a=6.1121$	$a=6.1115$
$b=18.678$	$b=23.036$
$c=257.14$	$c=279.82$
$d=234.5$	$d=333.7$
valid between -40° to 80°	valid between -80° to 0°

Water vapor pressure e is calculated from vapor density and given by:

$$e = \frac{\rho T}{216.7} \text{ hpa} \quad (4.11)$$

Where ρ is given in g/m^3 .

4.1.1 Sub-refraction

Sub refraction happens when the gradient is greater than -40 N-units/km and results in upward of signal bending, this is happening during fog or cloud air passes over the hot earth[11].

$$\frac{dN}{dh} > -40, \text{ or } \frac{4}{3} > k > 0 \quad (4.12)$$

It is also known as inverse beam bending. The refractive contribution of water droplets is less than water vapor. This causes the air dielectric constant to vary. Dielectric constant at surface of the earth are higher than at elevation, which will cause upward elevation of radio wave. Such a phenomenon is expected to happen in coastal area[54].

4.1.2 Supper refraction

Supper refraction is the effect results to the signal bending downward. This phenomenon happens during an increment of temperature (inversion) or decreasing humidity with height or both cases. supper refraction happens commonly when the radio wave is bending greater than normal refraction. Temperature inversion, which happens when temperature increase with height[54].

$$-157 < \frac{dN}{dh}, or \frac{4}{3} < k < \infty \quad (4.13)$$

4.1.3 Ducting

Ducting refraction is kind of refraction happens when a radio wave is being guided by surrounding atmospheric effect over long distances. The troposphere atmosphere become like a waveguide to the radio wave. This phenomenon happens when radio wave in higher refractive index remaining in that layer because of the wave encountered the nature of the atmosphere reflection and refraction in its boundary. These rare events formed layers with strong ducting in the order of ten meters in vertical extent and covered by locally created turbulence and behaving horizontally up to hundreds of kilometers[55]. The resulting k-factor range of ducting refraction range is

$$\frac{dN}{dh} \leq -157, -\infty < k < 0 \quad (4.14)$$

Three types of ducting structure is commonly happening as shown in Figure(4.1).

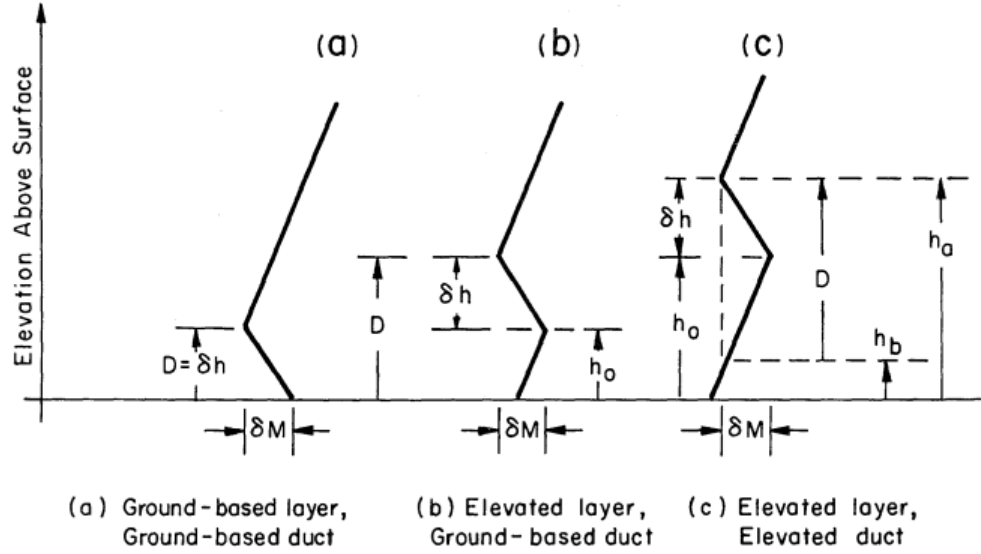


Figure 4.1: Ground base and Elevated layer ducts[55]

4.2 Effective Earth Radius Factor (k-factor)

The radiation of propagation signal is assumed to be straight line relative to effective earth radius. But the path line is modified by the effect of atmospheric refractivity gradient on the path of radiation. The effective earth radius is the result from earth radius multiplied by the earth radius factor k calculated from the refractivity gradient. As the earth's surface is not flat, the propagation signal is not traveling straight line. The average radius of the oblate spheroid shape of the earth is about 6371 km. If the propagation signal travels parallel with the surface of the earth, the value of k becomes unity. But, in reality, the k -factor is related to refractive index or atmospheric refractivity gradient given as equation(4.15).

$$k = \frac{1}{1 + a \frac{dn}{dh}} \quad (4.15)$$

where a is Earth's radius (6371km), n is refractive index of the troposphere atmosphere, h is height above ground level.

$$k = \frac{157}{157 + \frac{dN}{dh}} \quad (4.16)$$

Alternatively, the median k can be calculated from the median ΔN as given in equation(4.17) below[48].

$$k = \frac{157}{157 + \Delta N}, \text{ where } \Delta N = \frac{dN}{dh} \quad (4.17)$$

ΔN is also called vertical refractivity gradients. Statistical analysis of vertical gradient in the lower part of the atmosphere is important for estimation of path clearance in the first kilometer layer of the atmosphere from the surface of the earth the radio refractivity change will be $\Delta N = N_s - N_1$ where N_1 is the value of the radio refractivity at 1 km above the ground. According to ITU-R, in Temperate atmospheric region,

- Temperate continental atmosphere; where $\frac{dN}{dh} = -40N - \text{unit}/\text{km}$
- Well-mixed atmosphere; where $\frac{dN}{dh} = -21N - \text{unit}/\text{km}$

Which will results $k = 4/3$ and 1.15 respectively[5].

In practice, the study shows, the probability of value of k -factor is less than 0.6 in regions of temperate zone is less than 1%. But for the same value of k -factor in the countries of tropical zone, the probability of occurrence is 5% to 10%. These values shows than there is high probability of extreme k -factor in tropical climate than temperate climatic zone. In this tropical region the chance of getting obstruction between radio link with small value of k -factor is higher. When path length of radio link is longer, the expected value of k -factor will be equivalent with values of k -factor from standard atmosphere[20].

Ray beam bending for different k -factor given in figure(4.2).

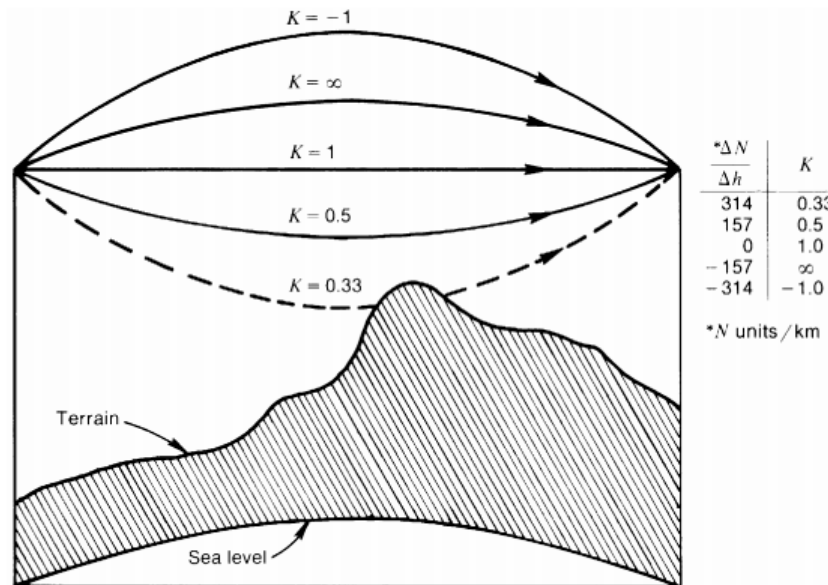


Figure 4.2: Various k -factor beaming[40]

4.3 Geoclimatic factor(K)

Geoclimatic factor determination is important for clear air multipath propagation model. The factor itself depend on the other parameters such as refractivity and refractivity gradient. According to ITU-R p.453, meteorological parameter such as temperature, pressure and humidity are components of atmospheric data which will help to find the refractivity and refractivity gradient in the first 100m above ground level[6][5]. In the absence of local data, variation of refractivity as a function of height was usually taken from global reference of the ITU-R recommendation. It was prepared from the long-term dependence of atmospheric refractive as a function of height(h) which was expressed as

$$N_s = N_0 e^{-h_s/h_0} \quad (4.18)$$

Where N_0 is average value of atmospheric refractivity generalize to sea level, and h_0 is in km. The global mean of the height profile of refractivity may be defined by: $N_0=315$ and $h_0=7.35$ km for terrestrial paths.

The Geoclimatic factor is depend on point refractivity gradient in the lowest layer of troposphere air atmosphere which is very important input for estimation for multipath on terrestrial line of sight.

$$\frac{dN}{dh} = \frac{N_2 - N_1}{h_2 - h_1} \quad (4.19)$$

Where,

N_1 is the lower atmospheric refractive index

h_1 is the ground level

N_2 is the atmospheric refractive index at 65m above ground level

h_2 is height at 65m above ground level

$\frac{dN}{dh}$ equivalent with dN_1 [25]. Therefore, the geoclimatic factor can be calculated from the approach given by ITU-R[6].

$$K = 10^{-4.6-0.0027dN_1} \quad (4.20)$$

where dN_1 is point refractivity gradient in the lowest 65 m of the atmosphere not exceeded for 1% of an average year.

4.4 Atmospheric Gas Loss

The lower part of the earth is covered by an atmosphere composed of gases that absorb energy of radio wave at different frequency range. This is different by its nature from other types of attenuation, like multipath fading, diffraction fading or rain attenuation[56].

Atmospheric gas has attenuation effect on terrestrial radio link by absorption. This absorption effect is considered by microwave link designer as atmospheric gas attenuation in their link-budget analysis. In calculating propagation loss above 10GHz, oxygen and water vapor are main atmospheric component which have significant atmospheric gas loss effect by absorbing millimetric wave. According to ITU-R the attenuation calculation, it is mainly derived from water vapor density and atmospheric pressure. The other gaseous absorption has considered a negligible effect on attenuation. Some of these gaseous are pollutants including SO₂, NO₂, N₂O and O₃. The volume of oxygen ratio is stable whereas the ratio of water vapor density varies depend on seasonal and regional factors[57]. Mean air pressure considered globally referred to sea level is 1013hPa.

Atmospheric attenuation of path is calculated from specific attenuation between the path of radio link[7].

$$A = \gamma r_o = (\gamma_0 + \gamma_w) r_o \text{ dB}, \quad (4.21)$$

Where,

r_o is path length (km)

γ_0 is dry air specific atmospheric attenuation

γ_w is wet air specific atmospheric attenuation

Using world average data Pressure = 1 013.25 hPa; Temperature = 15°C; Water Vapour Density = 7.5 g/m³ specific attenuation due to atmospheric gas given in figure(4.3) Estimation of atmospheric gaseous absorption, ITU-R P.676 is widely used in most regions of the world. Liebe mathematical model based on reactivity model is an alternative approach to find specific atmospheric attenuation[27]. ITU-R presents step-by-step calculation procedure for the spectral line for both dry air and wet air specific attenuation finding. Both models are computationally intensive and targeted specific attenuation in dB/km and depend on atmospheric pressure, water vapor density and temperature[29].

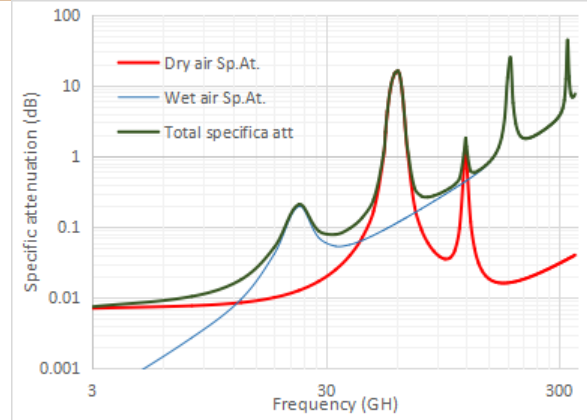


Figure 4.3: Total Atmospheric Air spec. attenuation[7]

4.5 Spatial Interpolation

Spatial interpolation is the process of estimating data at the location where there was no sample data was taken or was not able to find. Local method and global methods are the two interpolation method where local method is too specific for estimating the missing data. Radial Basis Function, Kriging and Inverse Distance Weight(IDW) are some of the local interpolation methods[58]. The performance of spatial interpolation techniques can be measured using different error function. Mean error, Root-Mean-Square, Mean Standardize STD, RMS standardize and Average Standard error are some of possible error function to be used for comparison.

4.5.1 Kriging

Kriging is a kind of spatial interpolation method which is used for estimation of places where no sample data was taken and using linear combination at closer place of sample taken. The consideration of the influence from surrounding taken sample data are: distance of the sample taken, spatial arrangement and the pattern correlation of the sample data with the intended location[59]. Locally measured data that is near to geographical location is more closer which will result to small value of semivariogram value and smaller lags. Kriging depends on the value of the surrounding locally collected data values, semivariogram structure correlation determines the value at the target. During interpolation, the actual value will be replaced by the fitted result of semivariogram model. Which will help finding the possible error from the model [60]. The kriging interpolation method originally comes from the study of geostatistics which is statistical expression of geological phenomenon in 1950s and 1960s. It was applied in different field of studies like hydrogeology, geophysics, GIS and remote sensing[59].

Ordinary kriging is one type of kriging used to estimate value using neighbourhood of the sampled data point. The sum of the weight computed from the neighbourhood will be unity.

$$\lambda_{ok} = Z_{ok}^{-1} M_{ok} \quad (4.22)$$

Where,

λ_{ok} is the weight matrix

Z_{ok}^{-1} is covariance matrix of the sample data

M_{ok} is covariance vector matrix between sample data and estimated values

$$k_{ok}^*(x, y) = \sum_{i=1}^N \lambda_{oki} K_{oki}(x_i, y_i) \quad (4.23)$$

Where,

$K_{oki}(x_i, y_i)$ is sample data value at (x_i, y_i)

λ_{oki} is the weight related with K_{oki}

N is number of neighbouring sample data

Commonly, the weight value is calculated by minimizing the interpolation error[20].

4.5.2 Inverse Distance Weight(IDW)

The IDW uses for prediction of the unsampled location by surrounding sampled data so that the nearest data have more influence on the estimation value than sampled data found in far apart. IDW considers, each sampled data has influence that decreasing with distance giving bigger weighting point for closer data set for estimation. The decreasing influence function of sample data is named as Inverse Distance Weight. Since the weight is inversely related to the distance, the power value of the distance increases the weight decreases rapidly. Therefore, the weight value λ_i of neighbourhood is depend highly on the power value[20]

$$k(x, y) = \sum_{i=1}^N w_i k(x_i, y_i) \quad (4.24)$$

Where,

$k(x, y)$ is IDW estimator

N is the number of sample data

$k(x_i, y_i)$ is the know sampled data at point (x_i, y_i) location of sampled data

w_i is weight given to $k(x_i, y_i)$

The weight w_i is given as equation(4.25)

$$w_i = \frac{d_i^p}{\sum_{i=1}^N d_i^p} \quad (4.25)$$

Where, d is euclidean distance between estimated value and sampled data. All sum of weighted sum is calculated to unity.

$$\sum_{i=1}^N w_i = 1 \quad (4.26)$$

4.5.3 Radial Bayesian

Radial Basis Function(RBF) is fast deterministic interpolation type which is exact. It has much flexibility than IDW, but more parameter decisions. The interpolating surface has to be pass through each sample data. Commonly, the function is considered as special case of splines which conceptually the same as fitting a rubber membrane through sampled data[61][20]. The straight forward equation from interpolant is given in equation(4.27) below[61].

$$s(\underline{x}) = \sum_{k=1}^N \lambda_k \phi(\|\underline{x} - \underline{x}_k\|) \quad (4.27)$$

Where,

$\|\underline{x} - \underline{x}_k\|$ is Euclidean distance between the sample data and estimated point.

$\phi(r)$ is some radial function

λ_k is expansion coefficient calculated from $s(\underline{x}_k) = y_k$

Chapter 5

Data collection and methodology

5.1 Introduction

Effective earth radius factor (k-factor) and geoclimatic factor (K) play important role in design of terrestrial microwave communication link. The variation of k-factor at lower atmosphere is crucial for the radio link planning work. The meteorological parameters are varying with times of the seasons, geographical location and altitude above the ground level[20]. Determination of geoclimatic factor helps to determine the fade depth and outage probability of a radio link, which is derived from point refractivity at first 65m above the ground level. k-factor is derived from refractivity at first 1km above ground level. The global average value of the k-factor given by ITU-R is 4/3, that determined from the temperate climate atmosphere. In general, both parameters should be determined from local data set so that the result value will help minimize the possibility of outage of the microwave links related to diffraction fading and fade depth problem, which could result to expensive link design. Surface data and Radiosonde data are the two data source for this paper. Both raw data collected need to be processed before utilizing in any models or calculations.

5.1.1 Surface Data Collection(NMA and NASA)

The surface data collection takes place at different representative climatic locations in Ethiopia. Table(5.1) contains the site names and their corresponding GPS location. The selected altitude of the sites are as low as 319 meters above sea level to 3248 meters above sea level. The variation of different altitude and climatic conditions of the sites are expected to be representative locations of Ethiopia's climate.

Table 5.1: Selected site-names and their GPS coordinate

Name	Lat	Long	Name	Lat	Long	Name	Lat	Long
Abala	13.34	39.70	Dilla	6.37	38.30	Kebri Dehar	6.73	44.30
Abomsa	8.47	39.84	Dillo	4.26	37.70	Lalibela	12.04	39.04
Adama	8.55	39.28	Dubity	11.75	41.10	Limu	8.07	36.95
Addis Ababa	8.99	38.79	Endabaguna	13.94	38.00	Maichew	12.78	40.00
Agayo	8.02	36.30	Erer	9.56	41.38	Mankush	11.27	35.29
Aman	6.95	36.00	Filtu	5.11	41.00	Mehoni	12.80	39.65
Ambo	8.98	38.00	Finch Wuha	5.42	38.27	Meiso	9.23	40.75
Arba Minch	6.06	37.56	Fugnido	7.65	34.42	Mekele	13.47	39.53
Areka	5.33	37.00	Gelemso	8.81	40.53	Metehara	8.86	39.92
Assaita	11.53	41.53	Gidayana	9.53	36.62	Metema	12.77	36.41
Assosa	10.00	34.52	Ginir	7.15	40.71	Moyale	5.05	39.03
Aisha	10.75	42.55	Gode	5.55	43.35	Neghele	5.42	39.57
Bahir Dar	11.60	37.36	Gore	8.16	35.55	Omorate	4.80	36.00
Bale-Robe	7.13	40.05	Gursum	9.35	42.40	Shahura	12.03	36.55
Berahale	13.83	40.02	Hagere Mariam	5.63	38.23	Sherekole	10.80	35.00
Bure	8.27	35.05	Harar	9.30	42.08	Shewa Robit	10.00	40.00
Burji	5.29	37.52	Harokelo	5.55	39.38	Teferi Ber	9.78	43.22
Chercher	12.54	39.76	Humera	14.10	36.52	Wachile	4.66	39.00
Combolcha	11.08	39.72	Jijiga	9.33	42.78			
Diffo	8.03	36.40	Kebri Beya	9.11	43.17			

The other source of surface data was satellite data provided by NASA. TFLDAS Noah Land Surface Model L4 Global Monthly 0.1 x 0.1 degree (MERRA-2 and CHIRPS) was the specific database used for monthly surface pressure data source[38]. Which is later integrated with humidity and temperature from NMA.

Surface Data Process

National Meteorological Agency (NMA) of Ethiopian is the source of surface data, which contains relative humidity in percentage and temperature in degree Celsius. It was collected from the fifty-eight selected sites as given in table(6.9) from NMA database. Five to ten years of surface data with interval of 15 minutes recorded were taken. The data integration between NMA and FLDAS-NOAH01-C-GL-M was done using “Haversine formula”, which is given in equation(5.1).

$$d = 2r \times \arcsin \left(\sqrt{\sin^2 \left(\frac{\phi_1 - \phi_2}{2} \right) + \cos(\phi_1) \cos(\phi_2) \sin^2 \left(\frac{\lambda_1 - \lambda_2}{2} \right)} \right) \quad (5.1)$$

Where, d is the distance between two points with longitude and latitude (ϕ, λ) , r is the radius of the Earth. Table(5.2) presented the resulting integrated data from 15 minute data of NMA and monthly data of

FLDAS-NOAH01-C-GL-M with nc4 file format was converted to csv file format using ArcMap-10.8 software.

Table 5.2: The sample integrated data at Addis Ababa

Date	Time	(% RH)	Temp(°C)	pressure
12/28/2011	11:45:00 PM	61.4	11.5	780.5584
12/28/2011	11:30:00 PM	61.1	11.6	780.5584
12/28/2011	11:15:00 PM	60.4	11.8	780.5584
12/28/2011	11:00:00 PM	58.6	12.1	780.5584
12/28/2011	10:45:00 PM	57.6	12.2	780.5584

5.1.2 Radiosonde data

Radiosonde data was collected from National Meteorological Agency(NMA) of Ethiopia, which has been daily launched from 2:00 PM to 3:00 PM in the afternoon at Addis Ababa site with gps location of 8.9853 latitude and 38.785683 longitude. The original data collected from radiosonde device of NMA was in text file format. The required data is extracted using notepad application from daily recorded data and converted to csv file format. The converted csv file is processed b python code programming to accumulate monthly data and yearly data to single file from each daily recorded source. The data of Radiosonde were not uniformly collecting with height increasing as it is shown in table(5.3). The irregularity of data collection as the height increases above the ground requires vertical distance based interpolation for the targeted height.

Table 5.3: Sample raw Radiosonde data for Addis ababa

Gpm	Hecto -Pa	Dry air °C	Humidity %	Wet air °C
2324	774.8	22.2	18	-3.2
2398	768.2	18.7	11	-12.3
3578	667.3	7.3	21	-13.5
4019	632.4	5.3	3	-38.2
4102	626	5.5	2	-40.9
4763	577	1	23	-18
5318	538.1	-2.4	1	-51.3

Radiosonde data process

Inverse Distance Weight is widely used for vertical distance interpolation technique at a place where vertical point data is missing. In this paper, for Radiosonde data, this Inverse Distance Weight is applied to extract data at 65m and 1km above the ground level for further analysis.

Inverse Distance Weighted(IDW) techniques is a distance base weighting of data where each sampling point has a nearby influence that estimates the value where the sampling data point could not be recovered and it is weighted by an inverse function of the distance from the point of interest to the available sample data weighted[62].

$$\lambda_i = \frac{\left(\frac{1}{d_i^p}\right)}{\sum_{i=1}^n \left(\frac{1}{d_i^p}\right)} \quad (5.2)$$

$$z(x_0) = \sum_{i=1}^n \lambda_i Z(x_i) \quad (5.3)$$

λ_i is weight and Z is the value we have tried to determine at position x . From the equation(5.2) and equation(5.3), if p is 2, then the method is called Inverse Distance Square. Table(5.4) shows sample result after the application of IDS interpolation to find values at 65m above ground level and 1km above ground level.

Table 5.4: Sample raw radiosonde data after interpolation

	Gpm	Hecto -Pa	Dry air 0C	Humidity %
Ground Level	2323	774.8	22.2	18
At 65m a.g.l	2388	768.18	18.7	11
At 1km a.g.l	3323	666.21	7.61	17.04

Using Table(5.4) as a data source surface refractivity, the point refractivity at 65m and the refractivity gradient at 1Km above the ground level can be calculated for that specific location.

5.2 Steps of finding Radioclimatic parameters

5.2.1 Finding vertical Atmospheric Parameters

There is a Radiosonde station, which is the source of data available for this research, located in Bole, Addis Ababa. The daily launched radiosonde device can reach up to 40km above the ground level. From this data source it was possible to develop equations that could fit a curve for vertical atmospheric profiles such as temperature (H), pressure (T) and humidity (P) as a function of height. For the purpose of modeling T , P & H vertically as a function of height, data of collected 2019 year was used from Radiosonde.

The targeted parameters to determine are: point refractivity at 65m above ground level and vertical

refractivity gradient at 1km above ground level. The equation developed from Radiosonde data source was limited to 1.5km above ground level. This is because of the targeted refractivity results are found within the range.

- Temperature profile: The behavior of temperature as a function of height is linearly decreasing for the first 200m and the nature of decreasing is changed after 200m to 1500m a.g.l.. The resulting linear equations found are in two parts.

From 0-200m

$$T(h) = T_s - 0.0268h \quad (5.4)$$

From 200-1500m

$$T(h) = T_s - 0.0358h + 1.8 \quad (5.5)$$

Where, T_s is Temperature value at surface of the ground and h is height above the ground level in meter

- Pressure profile: The behavior of pressure changing as a function of height is almost linearly decreasing up to 1500m.

$$P(h) = P_s - 0.0836h \quad (5.6)$$

Where, P_s is atmospheric pressure value at surface of the ground and h is height above the ground level in meter

- Humidity profile: The change of humidity as a function of height above ground level has different vertical characteristics.

For the first 65 meter

$$H(h) = H_s - 0.1842375h \quad (5.7)$$

For the next height above 100 meter to 1400 meter.

$$H_s - 1.90 \times 10^{-5}h^2 + 0.0356h - 2.26 \quad (5.8)$$

Where, H_s is humidity value at surface of the ground and h is height above the ground level in meter.

In finding the curve fit for the vertical atmospheric parameters, the regression approach was followed by maximizing correlation coefficient and minimizing possible error results of MAE and RMSE[63]. As it was given in table(5.5).

Table 5.5: Error result and correlation coefficient

h is in meter	MAE	RMSE	Correlation coefficient
Temp 0<h<200	1.006	1.249	0.863
Temp 200<h<1500	5.901	56.970	0.988
Humidity 0<h<65	2.560	13.900	0.887
Humidity 65<h<1400	3.714	21.660	0.822
Pressure 0<h<1500	1.137	2.257	0.999

5.2.2 Determination of k-factor and ΔN

According to researches, k-factor can be calculated from vertical refractivity gradient at first kilometer above the surface ΔN also expressed as N_1 and from surface refractivity, N_s . The mathematical relationship of the ΔN expressed in given equation(5.9). [25].

$$\Delta N = \frac{N_s - N_1}{h_s - h_1} \quad (5.9)$$

ΔN can also be approximated as $\frac{dN}{dh}$. The steps to find effective earth radius factor determination are:

Step 1: Find atmospheric refractivity N_s at surface using equation (4.6) and at altitude using temperature, pressure and humidity at surface and given point expressed in subsection 5.2.1, which is new vertical atmospheric profile.

Step 2: Find vertical refractivity gradient for first kilometer above ground level.

Step 3: Calculate k-factor using approximated equation(4.17).

From ITU-R P.453-14 atmospheric refractivity will be calculated from the dry term radio refractivity and wet term radio refractivity as it was calculated from equation(4.6) given by

$$N = \frac{77.6}{T} \left[P + 4810 \frac{e}{T} \right] \quad (5.10)$$

Where,

Pd: dry atmospheric pressure (hPa)

P: total atmospheric pressure (hPa)

e: water vapour pressure (hPa)

T: absolute temperature (K)

For water vapor pressure e_w is given by

$$e_w = 6.1121 \exp \left[\frac{\left(\frac{18.678 - \frac{t}{234.5}}{t + 257.14} \right) t}{t + 257.14} \right] \quad (5.11)$$

Where, t is temperature in degree-Celsius.

The main purpose of finding k-factor is to get appropriate antenna height for terrestrial radio-link design and estimation of diffraction fading. ITU-R 530 recommended choosing the antenna height based on the following criteria suggesting different types of k-factors usage[6].

- For path clearance is 100% of first fresnel zone (F_1) above the obstacle, median values of k-factor can be used, which is 50% of exceedance values. The antenna height is determined based on the clearance criteria.
- For path clearance of 60% of the first fresnel zone (F_1), use k-factor 99.9% of exceedance value and corresponding antenna height. For path greater than 30km at Tropical climate or path clearance of 30% of F_1 of radio link for Temperate climate, use the effective value of k-factor, which is 99.9% of exceedance value.
- Choose bigger antenna height result from the two above for link design

5.2.3 Determination of Geoclimatic factor K and dN_1

The equation given for geoclimatic factor determination is given in equation(4.20) to calculate. Where, dN_1 is the point refractivity gradient in the lowest 65 m of the atmosphere, which is not exceeded for 1% of an average year of time [6]. Determination of dN_1 and geoclimatic factor K is based on the values of atmospheric parameters of pressure, temperature and humidity at 65m above ground level and at the surface of the ground. The main steps and methodology used to find the parameters are:

- Determine surface refractivity from surface data of pressure, temperature and humidity collected from meteorolgy equation(4.6) and equation(5.11)
- Determine refractivity at 65m above ground level using data resulted from equation(5.4), equation(5.6) and equation(5.7).

- Determine point refractivity gradient in the lowest 65m of atmospheric dN1 using equation(4.19) in dN1(N-unit/km).
- Determine geoclimatic factor, K using equation(4.20)

5.3 Modeling and Curve fitting of k-factor

The method of data modeling can be carried out using curve fitting and minimizing error relative to measured data in all possible ways. Commonly, the curve fitting can be done using mean, variance, median and standard deviation[22]. Gaussian curve fitting is applied for k-factor distribution at Addis Ababa site and other sites. In this thesis, curve fitting for seasonal and annual distribution at Addis Ababa is explained and annual approximation curve fitting of all fifty eight sites are given in table(6.13).

The purpose of curve fitting is to describe a set of data using an equation that fits which can be characterized by coefficients derived from data set. Most of the time, this analysis is used using plotting the nearest possible curve. Therefore, it is a kind of best line finding method out of possible curves.

For this thesis work, the values of k-factor at 1000 meter a.g.l is chosen for characterization and curve fitting. EXCELAB 7.0 software is used for manipulation and error calculation provided by ExcelWorks LLC. The software is windows application known as Calculus Functions Powerhouse Add-in. ISE is the continuous integral function formula where the software modeled for discrete data to handle.

The estimated Gaussian approximation function can be expressed as:

$$f_{es}(k) = Ae^{-a(k-\mu_k)} \quad (5.12)$$

$A = \frac{1}{\sqrt{2\pi\sigma^2}}$, $\alpha = \frac{1}{2\sigma^2}$ and are conditions for normal distributions. Where σ^2 is standard deviation of the data set, μ_k is the mean of the data set from k-factor. The following expressions are the general characteristic of normal Gaussian distribution[64]:

$$\int_{-\infty}^{\infty} f_{es}(k)dk = \int_{-\infty}^{\infty} Ae^{-a(k-\mu_k)}dk = 1 \quad (5.13)$$

The expectation of k will be the mean value of the function. It is given as equation(5.14).

$$E\{k\} = \int_{-\infty}^{\infty} kAe^{-a(k-\mu_k)}dk = \mu_k \quad (5.14)$$

The value of coefficient A is found where $k = \mu_k$, given as equation(5.15)

$$A = f_{es}(k) |_{k=\mu_k} \quad (5.15)$$

From above conditions of normal distribution, we can get the necessary characteristics of a normal Gaussian distribution. It is a bell shaped density curve expressed by mean and standard deviation. Based on the data, the approximate curve fitting for the distribution of k-factor will be presented in the following table. Integral of square error (ISE) in 1000 a.g.l. For this thesis, the error criterion to find the accuracy of curve, the formula used is the integral of square error (ISE) is used which is given as[58][20].

$$ISE = \int_{-\infty}^{\infty} [f(x) - f_{es}(x)]^2 \quad (5.16)$$

Where, $f(x)$ is measured data set and $f_{es}(x)$ estimated curve.

5.4 Selection of Spatial Interpolation for Mapping

Spatial interpolation technique will help to find values at the place where sample data were not taken. In this thesis, fifty eight sites were selected for analysis. Aside from the selected sites, interpolation was used for mapping and data generating for the rests of the country of Ethiopia.

The $\Delta N_{50}, \Delta N_{99.9}, dN1$, k-factor and geoclimatic factor k tables contains limited values of selected sites. So that, it is important to apply interpolation technique to get the values of these parameters at a given resolution for the desired coverage area. For this thesis, country of Ethiopia, within its boundary is the targets of the interpolation.

Available spatial interpolation techniques are compared on table(5.6). ArcMap v10.8 was used for spatial interpolation error comparison, Map generation and producing database with 0.04580×0.04580 degree resolution which will produce 44,369 data per interpolation[65]. ArcMap10.8 is one of the powerful tool of ArcGIS produced by Esri Inc, which was used by this thesis for data manipulation. k-factor at 99.9 percentage of time was used for comparison of interpolation techniques to select which techniques is best fit to interpolate. Table(5.6) presents the error comparison using different model of error check, where Ordinary Kriging become better performer in comparison. Hence, Ordinary Kriging was applied for all types of interpolation techniques[66].

Table 5.6: Error Comparison of Interpolation Techniques for $k_{99.9}$ (k-factor at 99.9% of exceedance time)

$k_{99.9}$	Ordinary Kriging	IDW	Radial Bayesian	Empirical Bayesian kriging
Mean	0.00859792	0.015464	-0.00170016	-0.01538018
Root-Mean-Square	1.26887	1.370812	1.311547	1.27459
Mean Standardize STD	0.0066599			-0.01235678
RMS standardize	0.9978748			1.012767
Average Standard error	1.275754			1.263187

From the table, Ordinary Kriging has least error, which was the condition to select a suitable technique that could be used for application of spatial interpolation.

5.5 Determination of Atmospheric gas Loss

The formula for finding specific atmospheric attenuation by ITU-R 676-4 has been detailed and includes a number of secondary parameter considerations. This thesis considers the procedure given in simplified algorithm prepared for frequency range 0 to 350 GHz.

The algorithm for finding specific attenuation caused by dry air and water vapour covers sea level up to 5 km above sea level. The procedures were developed based on curve-fitting to the line-by-line calculation given on the ITU-R standard document[7]. Overall summery of the equation to find atmospheric air specific attenuation is given in equation(5.17),

$$A = \gamma r_o = (\gamma_0 + \gamma_w) r_o \text{ dB} \quad (5.17)$$

given in dB/km as it was described in equation(4.21). The total path loss is then multiplied by distance in kilometer[7].

Chapter 6

Result and Discussion

6.1 Analysis of Refractivity

Recorded data from the surface at Addis Ababa site of relative humidity and temperature along with pressure data collected from satellite were combined and used for refractivity calculation. The result are seen as the distribution of refractivity on average year in figure(6.1).

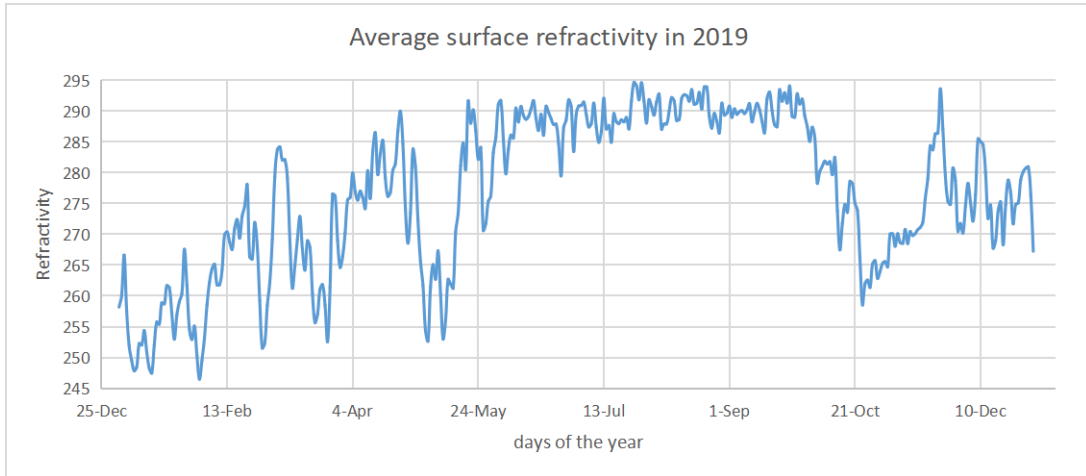


Figure 6.1: Annual variation of surface refractivity

From the figure, the months June to September have the higher refractivity than the rest of months because of the high humidity value at the summer season in Ethiopia. Whereas the refractivity recorded on month of January is the lowest. The monthly variation of surface refractivity distribution in different years was given in figure(6.4) at Addis ababa site.

The relation ship of primary data of humidity with surface refractivity distribution, daily in a given year of time is given in figure(6.2), which have strong relationship.

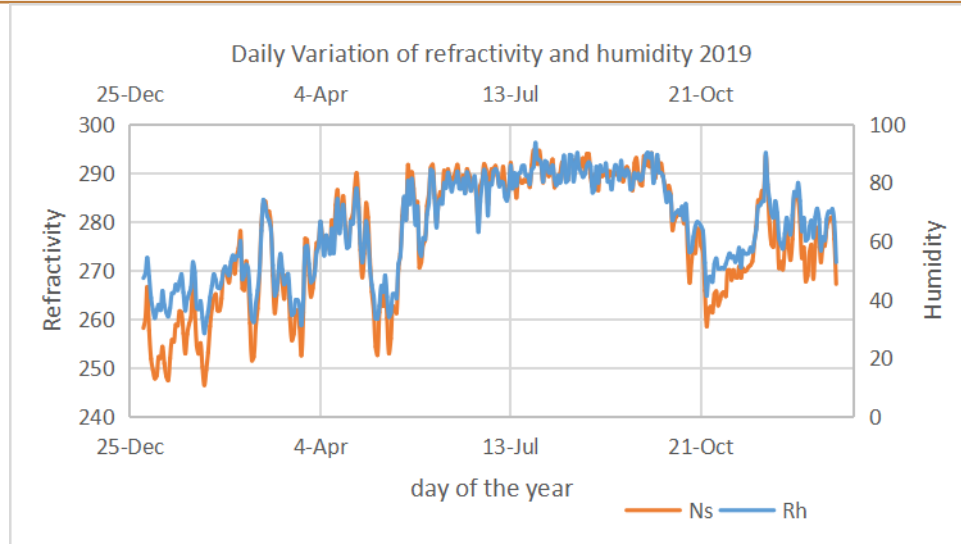


Figure 6.2: daily variation of humidity and refractivity relationship

The primary data of humidity and temperature hourly relationship is given in figure(6.3).

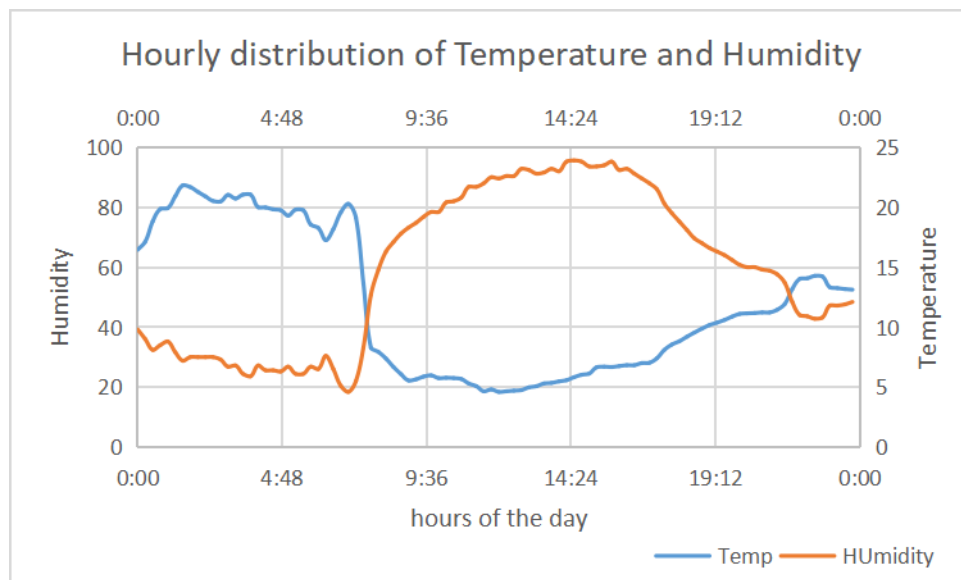


Figure 6.3: Hourly variation of H and T

It is difficult to represent the whole variation by this data set within a day. But the data set available from NMA surface data was presented with 15 minutes interval can show better detail of the variation of atmospheric events of temperature and humidity during 24 hours of one day taken in Dec 2011 recorded at Addis Ababa site.

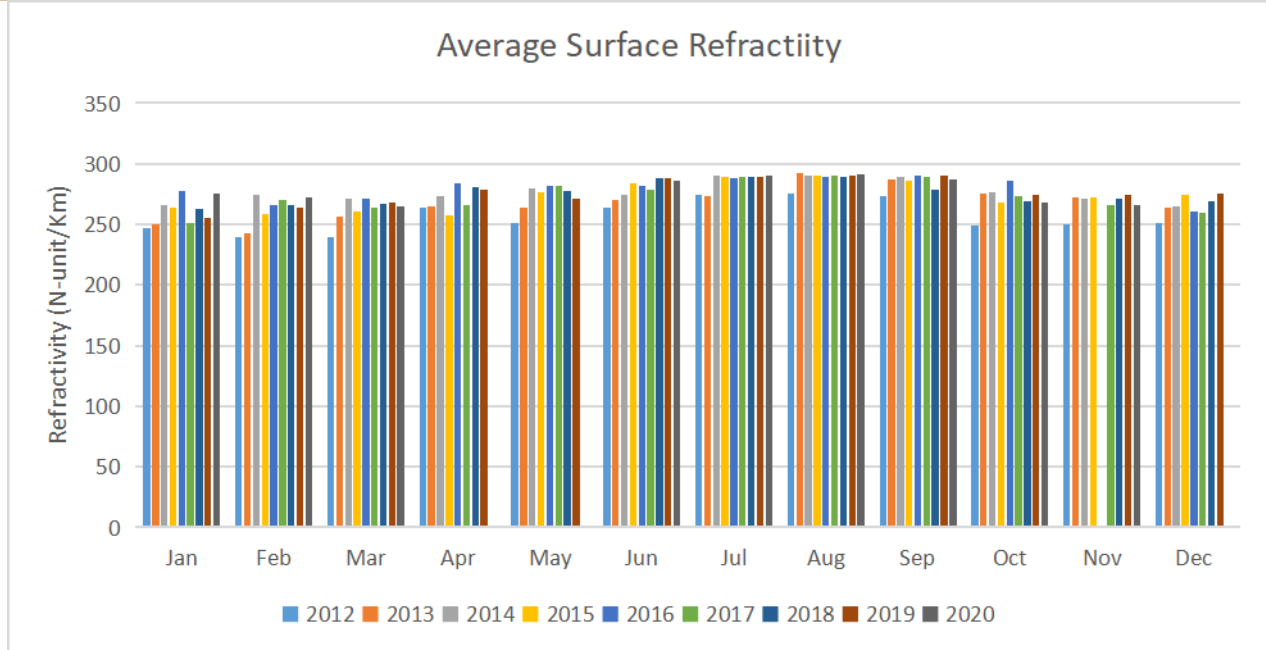


Figure 6.4: Monthly variation of surface refractivity at different years of time

From the overall result, the refractivity distribution of average year presented in figure(6.1) and the monthly variation of surface refractivity distribution given in figure(6.4) at Addis Ababa site, it shows the months June, July and August are the highest refractivity recorded on the surface of the ground. In Ethiopia, these months are highly rainy months which resulted in high water vapor density. Among the atmospheric parameters, based on equation(4.6), the value of refractivity is highly depending on the water vapor density. The result found was because of the higher water vapor value at these times. Refractivity value presented during these months is the highest. Figure(6.4) further shows the direct relationship between refractivity and humidity in average year time. But, temperature on the other hand, according to the result, has an inverse relation with the refractivity. Figure(6.3) shows the hourly variation of temperature and humidity relationships.

6.2 k-factor result from Radiosonde and ITU-R method

From processed radiosonde sample data, ΔN and k-factor can be calculated and shown on table(6.1) and table(6.2).

Table 6.1: Refractivity gradient from radiosonde

Date	GPM	hpa	T _{dry}	H%	T _{wet}	N _{dry}	N _{wet}	N	Δ N
8-Jan-19	2323	773.2	24.7	15	-3.7	201.45	19.59	221.04	
8-Jan-19	3323	664.1	9.97	15.15	-17.04	182.02	7.53	189.55	-31.49
9-Jan-19	2323	773.3	23.4	21	-0.2	202.354	25.59	227.95	
9-Jan-19	3323	684.33	11.18	26.17	-7.74	186.77	15.80	202.57	-25.37

Table 6.2: k-factor calculation from Radiosonde sample data

Date	GPM	hpa	T _{dry}	H%	T _{wet}	e _w	N _{dry}	N _{wet}	N	k-factor
8-Jan-19	surface	773.2	24.7	15	-3.7	4.66	201.44	19.59	221.04	-
8-Jan-19	1km a.g.l	662.57	9.58	14.24	-18	1.52	181.85	7.08	188.93	1.26
9-Jan-19	surface	773.3	23.4	21	-0.2	6.03	202.35	25.59	227.95	-
9-Jan-19	1km a.g.l	689.77	11.33	26.39	-7.4	3.51	188.15	16.20	204.35	1.18

ITU-R p835-6 method for Low-latitude annual reference atmosphere has alternative vertical profile model where there is no locally collected data. According to the ITU-R, for the countries of the Low-latitude smaller than 22° [67], The temperature is in kelvin, T(K), at altitude in kilometer above ground level, h(km), which is given by:

$$T(h) = T_s - 6.3533h + 0.005886h^2 \text{ for } 0 < h < 17 \quad (6.1)$$

while the pressure P (hPa):

$$P(h) = P_s - 109.0338h + 3.6316h^2 \text{ for } 0 < h < 10 \quad (6.2)$$

For water vapor density ρ (g/m3):

$$\rho(h) = \rho_s \exp[-0.2313h - 0.1122h^2 + 0.01351h^3 - 0.0005923h^4] \text{ for } 0 < h < 15 \quad (6.3)$$

The atmospheric refractivity at height(h) above ground can be calculated from atmospheric pressure and water vapor pressure at height(h) using equation(6.4).

$$N(h) = \frac{77.6}{T} [p(h) + 4810 \frac{e(h)}{T(h)}] \quad (6.4)$$

Based on ITU-R 835 method, water vapor pressure can be calculated from water vapor density and temper-

ature at height(h) given by equation(6.5)

$$e(h) = \frac{\rho(h)T(h)}{216.7} \quad (6.5)$$

At surface of the ground, the water vapor pressure is given by equation(6.6). which is calculated from equation(4.8), equation(4.9) and table(4.1).

$$e = \frac{He_s}{100} \quad (6.6)$$

$$e_s = EF \times 6.1121 \exp\left[\frac{(18.678 - \frac{t}{234.5}) \cdot t}{t + 257.14}\right] \quad (6.7)$$

which is valid between -40^0 to $+50^0$

$$EF_{water} = 1 + 10^{-4}[7.2 + p(0.032 + 5.9 \cdot 10^{-6}t^2)] \quad (6.8)$$

For the comparison purpose, the data taken to calculate using Low-latitude annual reference atmosphere was eighth and ninth of January 2019 afternoon, to make similar date and time for data sampling. The resulting k-factor determined from Law latitude ITU-R atmospheric modeling is given in table(6.3).

Table 6.3: Using ITU-R Low-latitude annual reference result

Date	Time	(% RH)	T	P(hPa)	N(h)	dN/dh.km-1	k-factor
1/9/2019	2:00 PM	18.7	23	839.67	213.33	-29.03	1.23
1/9/2019	2:15 PM	18.7	23	839.67	213.33	-29.03	1.23
1/9/2019	2:30 PM	19.4	23	839.67	214.04	-29.31	1.23
1/9/2019	2:45 PM	21.3	23	839.67	215.68	-29.84	1.23
1/9/2019	3:00 PM	22.5	23	839.67	216.72	-30.17	1.24
1/8/2019	2:00 PM	11.7	25	839.67	206.95	-27.14	1.21
1/8/2019	2:15 PM	12.1	25	839.67	207.33	-27.28	1.21
1/8/2019	2:30 PM	12.3	25	839.67	207.53	-27.35	1.21
1/8/2019	2:45 PM	12.9	25	839.67	208.11	-27.58	1.21
1/8/2019	3:00 PM	13.4	26	839.67	208.64	-27.87	1.22

6.3 Validation of Atmospheric Profile Model

Once, the calculation done using a new model, ITU-R Low-latitude model and annual ITU-R p.453-14 database of Addis Ababa, the results were used for comparison with result from Radiosonde of the reference result using vertical refractivity at 1km above ground level. The comparison is given in table(6.4).

Table 6.4: Vertical refractivity gradient values at at different exceedance of time

Exceedance probability	New Model	Radiosonde result	ITU-R low latitude	ITU-R database
del N 0.1	-4.28	10.2	-26.93	-13.18
del N 1	-13.36	-4.72	-29.56	-15.89
del N 10	-24.17	-21.19	-33.09	-18.28
del N 50	-35.48	-37.15	-37.15	-30.7
del N 90	-45.02	-49.76	-40.96	-40.61
del N 99	-52	-58.2	-43.89	-51.02
del N 99.9	-56.2	-63.600	-45.890	-61.780

The corresponding k-factor results from table(6.4) are given in table(6.5).

Table 6.5: k-factor comparison at different exceedance of time

Exceedance probability	New Model	Radiosonde result	ITU-R low latitude	ITU-R database
k=0.1%	1.028	0.94	1.21	1.09
k=1%	1.093	1.03	1.23	1.11
k=10%	1.182	1.16	1.27	1.13
k=50%	1.292	1.31	1.31	1.24
k=90%	1.402	1.46	1.35	1.35
k=99%	1.491	1.59	1.39	1.48
k=99.9%	1.557	1.68	1.41	1.65

Graphically the k-factor result comparison is given in figure(6.5)

The result presented in table(6.5) and graph in figure(6.5) clearly shows, how close the new model with the result from measured Radiosonde data. Compare resulting errors with Mean Absolute Error(MAE) and Root Mean Square Error(RMSE) further explains numerically the closeness of the results[63].

$$MAE = \left(\frac{1}{n}\right) * \sum |y_i - x_i| \quad (6.9)$$

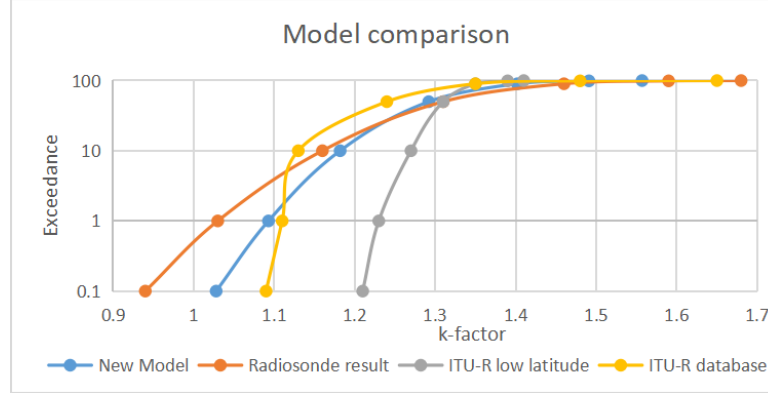


Figure 6.5: k-factor comparison of different model

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{2}} \quad (6.10)$$

The resulting of the three error comparison result is expressed in table(6.6)

Table 6.6: Error comparison using MAE and RMSE

ERROR	New model	ITU-database	Using ITU model of low Latitude
MAE	0.0673	0.0829	0.1657
RMSE	0.0764	0.0924	0.1890

Data collected from surface and satellite were analysed using different models and compared with the result from Radiosonde data. The newly developed vertical model for atmospheric profile found to be performing better compared with other models. The table(6.6) shows the error comparison of new model with other models, and further proves the model has less error with the two error checking methods.

6.4 Distribution and Modeling of k-factor

6.4.1 Distribution of k-factor

k-factor and vertical refractive gradient at 1km above ground level are presented in seasonal , monthly and annual distribution.

Monthly Distribution

The monthly distribution of vertical refractivity and corresponding k-factor is given in Figure (6.6) and chart given in figure(6.7) respectively. The cumulative distribution of k-factor at different exceedance of time is given in figure(6.8) and vertical refractivity gradient distribution at 50% exceedance given in figure(6.9) .

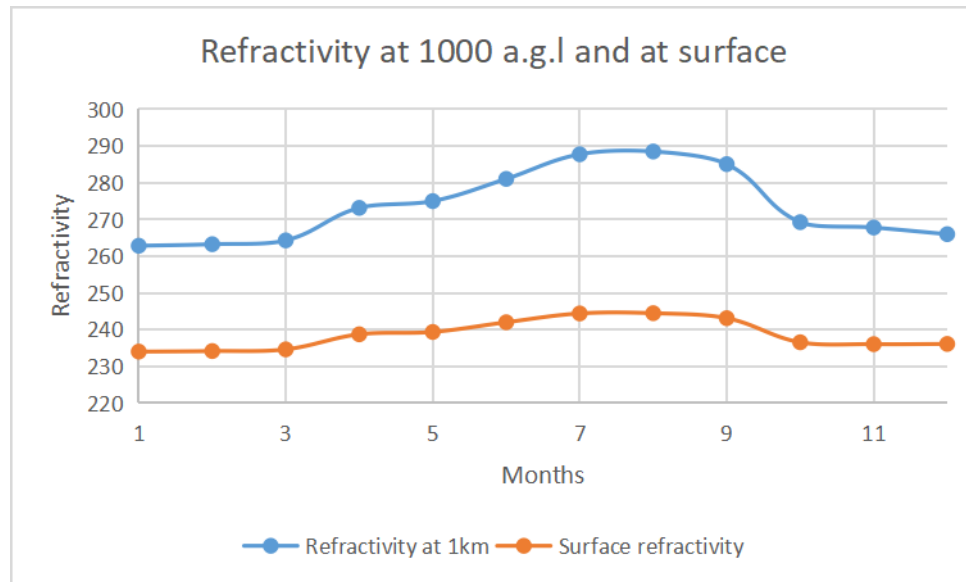


Figure 6.6: Monthly distribution of mean refractivity at surface and 1000m a.g.l. at Addis Ababa

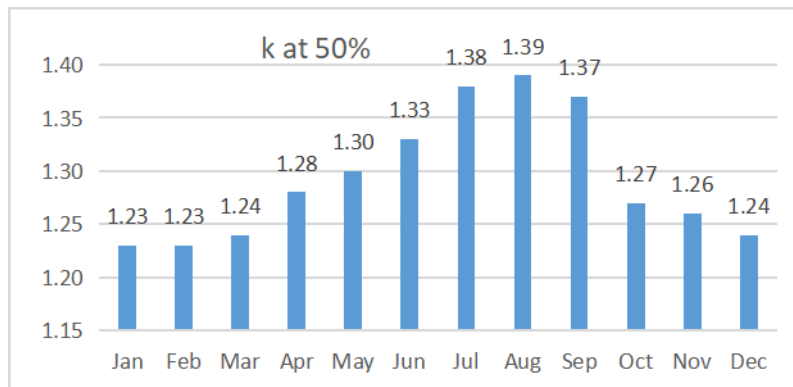


Figure 6.7: Monthly distribution of mean k-factor at Addis Ababa

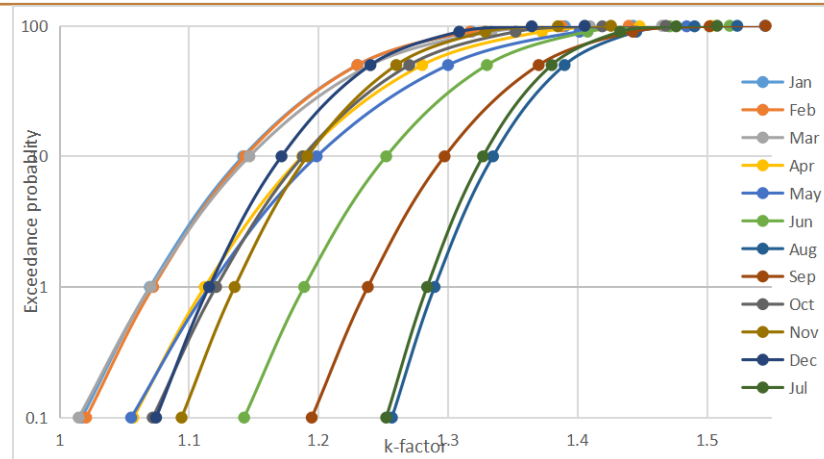


Figure 6.8: k-factor monthly cumulative distribution at Addis Ababa

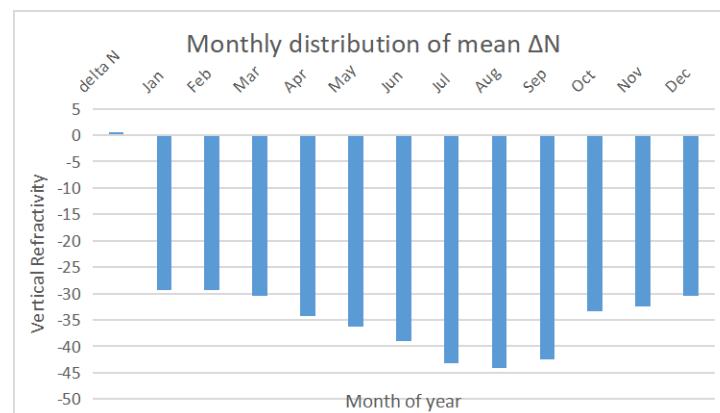


Figure 6.9: Monthly mean distribution of refractivity gradient at 1km above ground at Addis Ababa

In determination of k-factor, the monthly distribution shows, the month of August has the biggest k-factor value of 1.39 whereas the month of January records the smallest value of 1.23 as it was presented in figure(6.7). The cumulative distribution graph also confirms the variation between months.

Seasonal distribution

Seasonal distribution of mean k-factor for the first 1km above ground level is presented using seasons of Ethiopia:

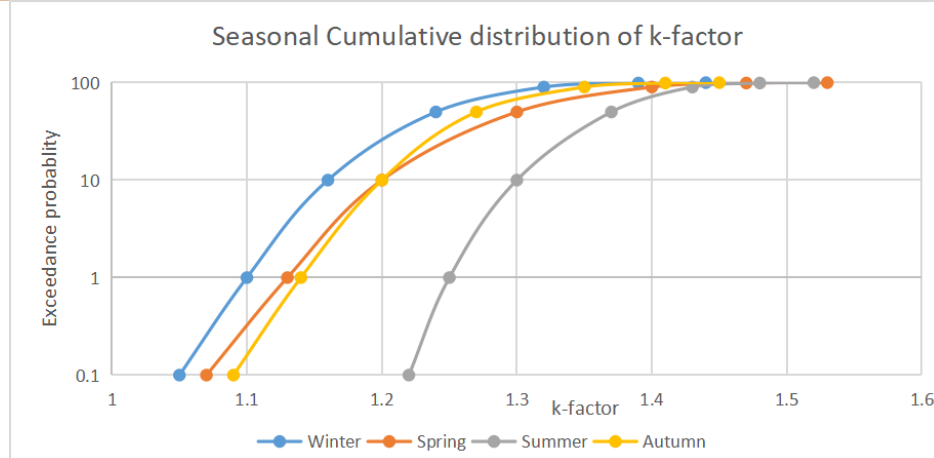


Figure 6.10: Seasonal cumulative distribution of k-factor at 1000 a.g.l at Addis Ababa

Table 6.7: Seasonal average refractivity at first kilometer above ground level

Season	Average ΔN (N-unit/km)	k-factor
Winter	-30.71	1.24
Spring	-36.06	1.3
Summer	-42.08	1.37
Autumn	-33.65	1.27

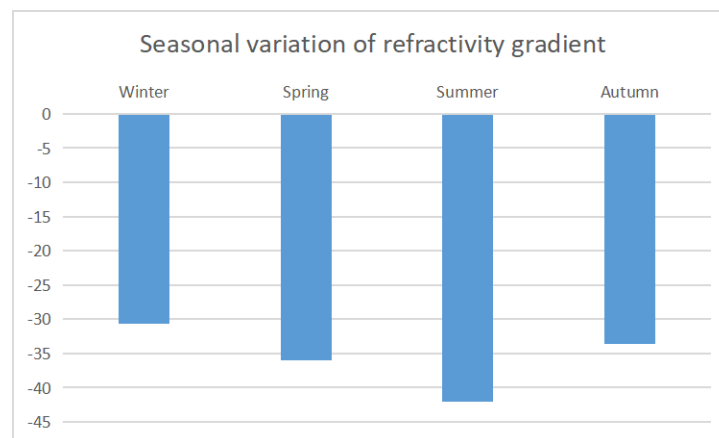


Figure 6.11: Seasonal distribution of vertical refractivity at Addis Ababa

Kiremt (Summer) June, July and August are known as the summer season. In this season, the region expects heavy rainfalls, which will result to high k-factor than other season.

Tseday (spring) September, October and November are known as the spring season of Ethiopia. It is known as the harvest season with higher k-factor result.

Bega (winter) December, January and February are the dry season with smaller k-factor.

Belg (autumn) March, April and May are the autumn season with occasional rainfall. But, May is the hottest month in Ethiopia and average k-factor result is similar to Winter season.

The cumulative distribution of k-factor at each season are given in figure(6.10). Table(6.7) explains the seasonal mean k-factor cumulative distribution graphically at Addis Ababa site and corresponding chart is given in figure(6.11).

The seasonal k-factor distribution result from figure(6.10) explains the seasonal mean and k-factor cumulative distribution graphically at Addis Ababa site which spring season has bigger k-factor and summer season has the biggest. The k-factor value given in table(6.7) shows the average k-factor values at each season and corresponding chart is given in figure(6.11). Both figure and chart shows k-factor is highest in summer. This is because of the increasing value of water vapor density value in summer. Since $\frac{4}{3} < k < \infty$ has super refraction effect, the value calculated from k-factor of summer season has the effect of super refraction occurrence. The rest of the seasons have, on average, sub refraction($\frac{4}{3} > k > 0$) occurrence.

Annual Distribution

The annual PDF distribution and cumulative distribution of k-factor are given in figure(6.12) and figure(6.13). The exceedance probability and it's corresponding k-factor of annual distribution is given in table(6.8).

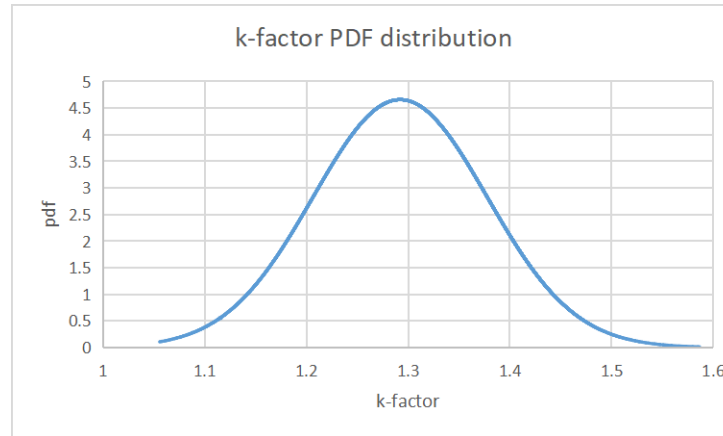


Figure 6.12: Annual k-factor pdf of Addis ababa

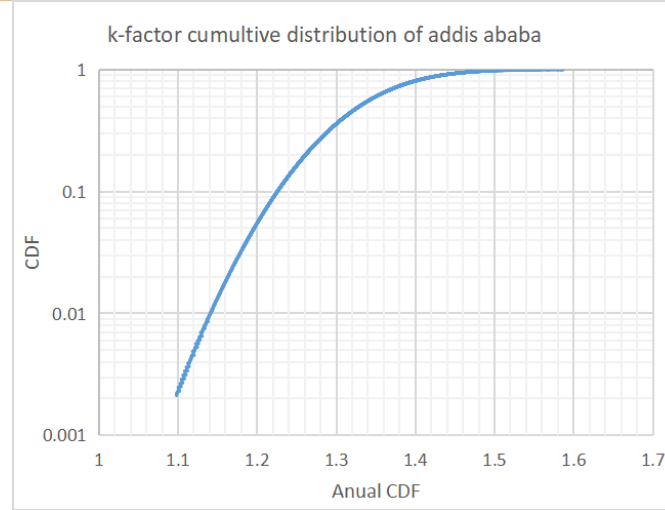


Figure 6.13: Annual k-factor pdf of Addis ababa

Table 6.8: Annual Exceedance probability of k-factor

% Exceedance	k-factor
0.1	1.028
1	1.093
10	1.182
50	1.292
90	1.402
99	1.491
99.9	1.557

The resulting k-factor of Addis Ababa at 50% of time is 1.29, which is almost similar with global average of ITU-R value (4/3). The variation in refractivity at first kilometer above the ground level directly affects the value of k-factor as it was given in equation(4.17).

From the overall distribution of the country which the recorded sites altitude varies from 319 m above sea level to 3248 m above sea level. The k-factor varies from 0.936 to 1.576, which are found to be in the range of sub refraction and supper refraction. There is no indication that the altitude above sea level is related to k-factor values, since there are small and big values of k-factor are determined for both extremes of altitudes.

6.4.2 Modeling and Curve-fitting

Gaussian model is chosen for k-factor due to the bell-shaped nature of the k-factor distribution observed.

Table 6.9: Monthly mean distribution of addis ababa

Month	Median k-factor	Month	Median k-factor	Month	Median k-factor
Jan	1.23	May	1.30	Sep	1.37
Feb	1.23	Jun	1.33	Oct	1.27
Mar	1.24	Jul	1.38	Nov	1.26
Apr	1.28	Aug	1.39	Dec	1.24

The coefficients of monthly distributed data inputs for Gaussian Normal distribution is given in table(6.10).

Table 6.10: Estimated Gaussian Coefficients and Integral Square Error(ISE) for monthly model approximation

Months	μ	σ	A	α	ISE
Jan	1.23	0.069	5.78	105	0.000671
Feb	1.23	0.068	5.87	108.1	0.000631
Mar	1.24	0.073	5.46	93.8	0.002821
Apr	1.28	0.072	5.54	96.5	0.008988
May	1.3	0.079	5.05	80.1	0.000799
Jun	1.33	0.061	6.54	134.4	0.008882
Jul	1.38	0.041	9.73	297.4	0.011755
Aug	1.39	0.043	9.28	270.4	0.001788
Sep	1.37	0.057	7	153.9	0.00699
Oct	1.27	0.064	6.23	122.1	0.007531
Nov	1.26	0.054	7.39	171.5	0.016362
Dec	1.24	0.054	7.39	171.5	0.006678

The corresponding PDF estimation of Gaussian approximation is given in table(6.11).

Table 6.11: Monthly k-factor distribution of probability density function of Addis ababa

Month	predicted curve	Month	predicted curve
Jan	$f_{es}(k) = 5.78e^{-105.0(k-1.23)}$	Jul	$f_{es}(k) = 9.73e^{-297.4(k-1.38)}$
Feb	$f_{es}(k) = 5.87e^{-108.1(k-1.23)}$	Aug	$f_{es}(k) = 9.28e^{-270.4(k-1.39)}$
Mar	$f_{es}(k) = 5.46e^{-93.80(k-1.24)}$	Sep	$f_{es}(k) = 7.00e^{-153.9(k-1.37)}$
Apr	$f_{es}(k) = 5.54e^{-96.50(k-1.28)}$	Oct	$f_{es}(k) = 6.23e^{-122.1(k-1.27)}$
May	$f_{es}(k) = 5.05e^{-80.10(k-1.3)}$	Nov	$f_{es}(k) = 7.39e^{-171.5(k-1.26)}$
Jun	$f_{es}(k) = 6.54e^{-134.4(k-1.33)}$	Dec	$f_{es}(k) = 7.39e^{-171.5(k-1.24)}$

The seasonal approximation of curve fitting is given in table(6.12).

Table 6.12: seasonal variation of k-factor

Season	predicted curve	Season	predicted curve
Winter	$f_{es}(k) = 6.23e^{-122.1(k-1.23)}$	Summer	$f_{es}(k) = 7.25e^{-165.3(k-1.37)}$
Autumn	$f_{es}(k) = 5.05e^{-80.1(k-1.27)}$	Spring	$f_{es}(k) = 5.18e^{-80.1(k-1.31)}$

The annual distribution of Addis ababa is approximated to $f_{es}(k) = 4.64e^{-67.6(k-1.29)}$ and its corresponding plot is given on figure(6.14).

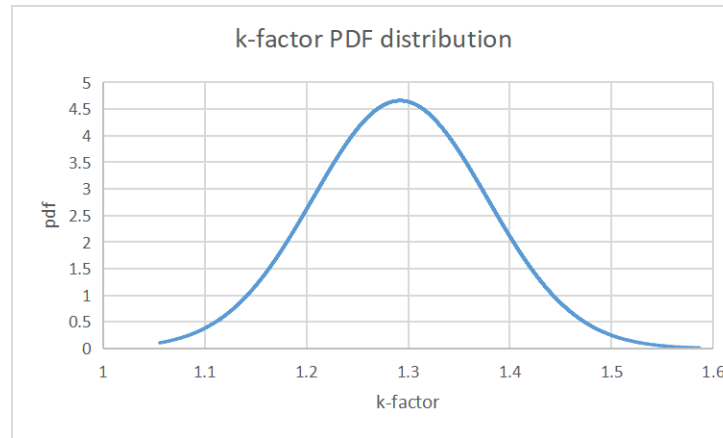


Figure 6.14: Annual k-factor pdf of Addis ababa

For the rest of fifty eight sites the approximation of each Gaussian function is given in table(6.13).

Table 6.13: Annual k-factor distribution of probability density function of selected sites

Location	Predicted curve	Location	Predicted curve
Abala	$f_{es}(k) = 4.23e^{-56.10(k-1.28)}$	Gidayana	$f_{es}(k) = 3.17e^{-31.60(k-1.35)}$
Abomsa	$f_{es}(k) = 4.17e^{-54.70(k-1.32)}$	Ginir	$f_{es}(k) = 3.76e^{-44.30(k-1.41)}$
Adama	$f_{es}(k) = 3.78e^{-44.90(k-1.32)}$	Gode	$f_{es}(k) = 2.49e^{-19.60(k-1.36)}$
Addis Abba	$f_{es}(k) = 4.66e^{-68.20(k-1.29)}$	Gore	$f_{es}(k) = 4.02e^{-50.80(k-1.39)}$
Agayo	$f_{es}(k) = 3.50e^{-38.50(k-1.44)}$	Gursum	$f_{es}(k) = 3.46e^{-37.60(k-1.32)}$
Aman	$f_{es}(k) = 4.13e^{-53.60(k-1.51)}$	H/ Mariam	$f_{es}(k) = 4.01e^{-50.50(k-1.39)}$
Ambo	$f_{es}(k) = 3.31e^{-34.30(k-1.34)}$	Harar	$f_{es}(k) = 2.18e^{-15.00(k-0.99)}$
Arba Minch	$f_{es}(k) = 3.14e^{-31.00(k-1.43)}$	Harokelo	$f_{es}(k) = 3.47e^{-37.70(k-1.38)}$
Areka	$f_{es}(k) = 3.01e^{-28.40(k-1.40)}$	Humera	$f_{es}(k) = 1.87e^{-10.90(k-1.29)}$
Assaita	$f_{es}(k) = 3.08e^{-29.80(k-1.31)}$	Jigiga	$f_{es}(k) = 4.32e^{-58.70(k-1.29)}$
Assosa	$f_{es}(k) = 2.40e^{-18.10(k-1.38)}$	Kebri Beya	$f_{es}(k) = 2.02e^{-12.90(k-1.25)}$
Aisha	$f_{es}(k) = 2.64e^{-21.90(k-1.38)}$	KebriDehar	$f_{es}(k) = 2.04e^{-13.10(k-1.41)}$
Bahir Dar	$f_{es}(k) = 3.18e^{-39.6(k-1.19)}$	Lalibela	$f_{es}(k) = 3.76e^{-44.30(k-1.41)}$
Bale-Robe	$f_{es}(k) = 5.15e^{-83.50(k-1.30)}$	Limu	$f_{es}(k) = 3.50e^{-38.50(k-1.41)}$
Berahale	$f_{es}(k) = 3.18e^{-31.80(k-1.33)}$	Maichew	$f_{es}(k) = 0.52e^{-0.90(k-1.28)}$
Bure	$f_{es}(k) = 3.21e^{-32.40(k-1.46)}$	Mankush	$f_{es}(k) = 1.75e^{-9.60(k-1.38)}$
Burji	$f_{es}(k) = 3.58e^{-40.20(k-1.37)}$	Mehoni	$f_{es}(k) = 3.90e^{-47.90(k-1.29)}$
Chercher	$f_{es}(k) = 3.84e^{-46.20(k-1.29)}$	Meiso	$f_{es}(k) = 11.17e^{-392.3(k-0.96)}$
Combolcha	$f_{es}(k) = 4.13e^{-53.50(k-1.32)}$	Mekele	$f_{es}(k) = 3.41e^{-36.50(k-1.32)}$
Diffa	$f_{es}(k) = 3.57e^{-40.10(k-1.41)}$	Metehara	$f_{es}(k) = 3.09e^{-30.00(k-1.35)}$
Dilla	$f_{es}(k) = 1.19e^{-4.50(k-1.45)}$	Metema	$f_{es}(k) = 1.78e^{-9.90(k-1.36)}$
Dillo	$f_{es}(k) = 2.94e^{-27.20(k-1.36)}$	Moyale	$f_{es}(k) = 3.50e^{-38.50(k-1.36)}$
Dubity	$f_{es}(k) = 3.40e^{-36.40(k-1.33)}$	Neghele	$f_{es}(k) = 0.31e^{-0.30(k-1.32)}$
Endabaguna	$f_{es}(k) = 2.65e^{-22.10(k-1.30)}$	Omorate	$f_{es}(k) = 2.29e^{-16.40(k-1.41)}$
Erer	$f_{es}(k) = 3.83e^{-46.10(k-1.28)}$	Shahura	$f_{es}(k) = 2.99e^{-28.10(k-1.32)}$
Filtu	$f_{es}(k) = 2.99e^{-28.00(k-1.37)}$	Sherekole	$f_{es}(k) = 1.76e^{-9.70(k-1.39)}$
Fincha	$f_{es}(k) = 4.29e^{-57.70(k-1.34)}$	Shewa Robit	$f_{es}(k) = 2.93e^{-27.00(k-1.12)}$
Fugnido	$f_{es}(k) = 1.96e^{-12.10(k-1.58)}$	Teferi Ber	$f_{es}(k) = 3.56e^{-39.80(k-1.34)}$
Gelemso	$f_{es}(k) = 4.01e^{-50.50(k-1.33)}$	Wachile	$f_{es}(k) = 2.89e^{-26.20(k-1.41)}$

The mean value of k-factor is calculated from 50 percent time of exceedance where k-factor is occurring. From the result, it is clearly seen that the resulting data of the average year is plotted as belly shaped. The plot indicates the equation(5.12) is good estimation for the curve fitting, which is Gaussian distribution function. From annual k-factor distribution, it is possible to approximate to normal Gaussian distribution function from mean and standard deviation of the k-factor values. In the same manner, monthly and seasonal approximation could be developed as it was given in table(6.11) and table(6.12).

6.5 Interpolation and Mapping of k-factor and ΔN

Table 6.14: ΔN at 50% of time and ΔN at 0.1% of time

Name	ΔN_{50}	$\Delta N_{0.1}$	Name	ΔN_{50}	$\Delta N_{0.1}$
Abala	-34.34	-57.13	Gidayana	-41.05	-66.87
Abomsa	-38.15	-59.85	Ginir	-45.65	-66.67
Adama	-37.79	-61.44	Gode	-41.9	-72.5
Addis Abba	-35.48	-56.17	Gore	-43.64	-64.21
Agayo	-48.2	-69.58	Gursum	-38.15	-63.38
Aman	-52.68	-69.97	Hagere Mariam	-43.64	-64.27
Ambo	-40.27	-65.61	Harar	-42.82	-66.3
Arba Minch	-47.36	-70.93	Harokelo	-42.82	-66.3
Areka	-44.78	-70.21	Humera	-35.11	-76.45
Assaita	-36.79	-65.03	jigiga	-35.67	-57.63
Assosa	-43.23	-74.06	Kebri Beya	-31	-72.41
Aisha	-43.15	-71.95	Kebri Dehar	-45.34	-78.89
Bahir Dar	-38.95	-65.61	Lalibela	-31.3	-54.65
Bale-Robe	-36.32	-55.05	Limu	-45.57	-67.9
Berahale	-38.06	-70.02	Maichew	-34.44	-113.87
Bure	-49.39	-71.81	Mankush	-43.23	-81.74
Burji	-42.49	-65.45	Mehoni	-35.2	-59.18
Chercher	-35.39	-59.61	Meiso	-39.4	-95.21
Combolcha	-41.81	-61.68	Mekele	-38.33	-63.77
Diffa	-45.81	-67.64	Metehara	-40.36	-67.03
Dilla	-48.42	-93.64	Metema	-41.56	-80.56
Dillo	-41.13	-68.5	Moyale	-41.81	-65.45
Dubity	-38.78	-64.1	Neghele	-37.88	-127.27
Endabaguna	-36.23	-68	Omorate	-45.49	-76.36
Erer	-34.06	-58.81	Shahura	-37.7	-66.2
Filtu	-42.07	-68.75	Sherekole	-44.13	-81.99
Finch Wuha	-40.1	-60.74	Shewa Robit	-16.82	-55.12
Fugnido	-57.38	-85.77	Teferi Ber	-40.1	-64.1
Gelemso	-38.6	-60.92	Wachile	-45.97	-71.67

For the place where sample data was not taken, figure(6.15) was produced using ArcMap10.8 software tools, which were utilized from available tools. The generated points are available in a soft copy with the resolution of 0.0458 x 0.0458 degree latitude and longitude within Ethiopia boundary.

The k-factor calculated at 50% of the time and k-factor at 99.9% of the time for selected fifty-eight sites are given in table(6.15).

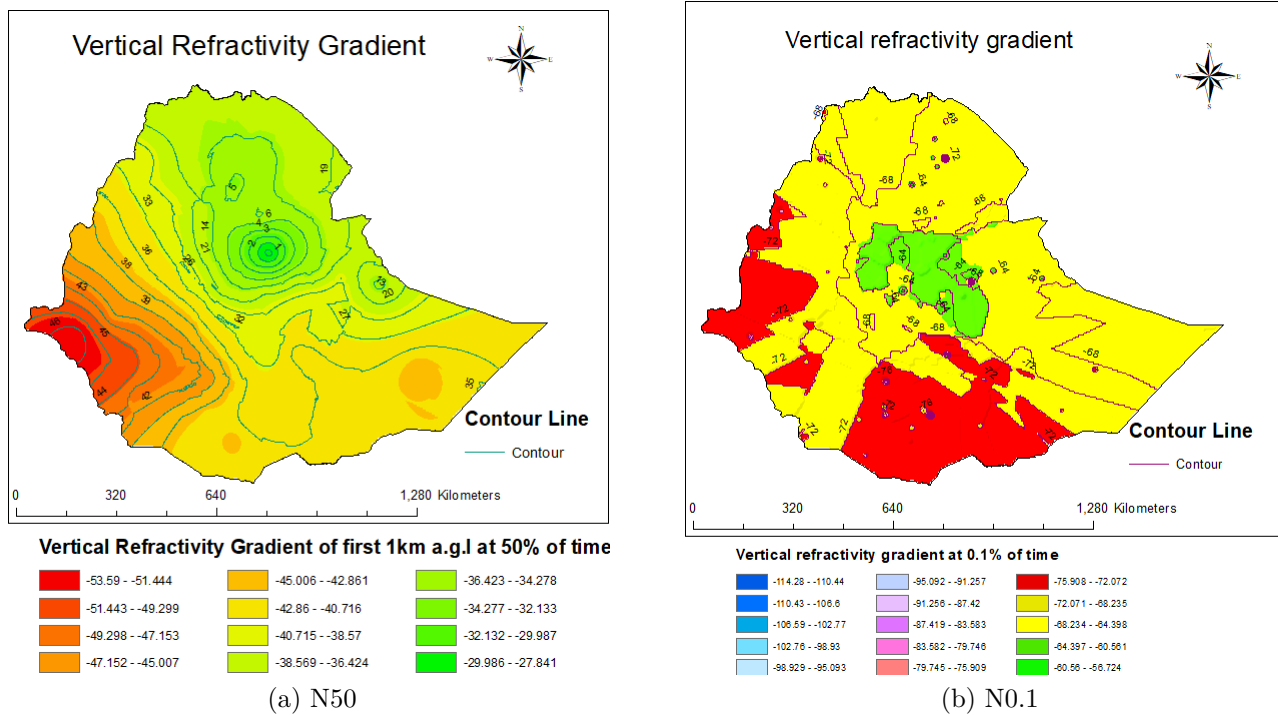


Figure 6.15: Vertical refractivity gradient map at 50% and 0.1% time of Ethiopia

Similar to vertical refractivity gradient, here, Kriging interpolation technique and ArcGis10.8 were deployed for map and data generating. Map is given in figure(6.16). The generated data is presented with 0.0458 x 0.0458 degree resolution in soft copy.

6.6 Results of Geoclimatic factor K and dN_1

Monthly Distribution

The average monthly distribution of point refractivity is shown in figure(6.17), table(6.16) and figure(6.18).

Table 6.15: k-factor distribution at 50% and 99.9% of the time for selected sites

Name	k ₅₀	k _{99.9}	Name	k ₅₀	k _{99.9}
Abala	1.28	1.572	Gidayana	1.354	1.742
Abomsa	1.321	1.616	Ginir	1.413	1.741
Adama	1.317	1.643	Gode	1.364	1.858
Addis Abba	1.292	1.557	Gore	1.385	1.692
Agayo	1.443	1.796	Gursum	1.321	1.677
Aman	1.505	1.804	Hagere Mariam	1.385	1.693
Ambo	1.345	1.718	Harar	0.99	1.555
Arba Minch	1.432	1.824	Harokelo	1.375	1.731
Areka	1.399	1.809	Humera	1.288	1.949
Assaita	1.306	1.707	jigiga	1.294	1.58
Assosa	1.38	1.893	Kebri Beya	1.246	1.856
Aisha	1.379	1.846	Kebri Dehar	1.406	2.01
Bahir Dar	1.33	1.718	Lalibela	1.249	1.534
Bale-Robe	1.301	1.54	Limu	1.409	1.762
Berahale	1.32	1.805	Maichew	1.281	3.64
Bure	1.459	1.843	Mankush	1.38	2.086
Burji	1.371	1.715	Mehoni	1.289	1.605
Chercher	1.291	1.612	Meiso	0.963	1.073
Combolcha	1.315	1.614	Mekele	1.323	1.684
Diffo	1.412	1.757	Metehara	1.346	1.745
Dilla	1.446	2.478	Metema	1.36	2.054
Dillo	1.355	1.774	Moyale	1.363	1.715
Dubity	1.328	1.69	Neghele	1.318	5.281
Endabaguna	1.3	1.764	Omorate	1.408	1.947
Erer	1.277	1.599	Shahura	1.316	1.729
Filtu	1.366	1.779	Sherekole	1.391	2.093
Finch Wuha	1.343	1.631	Shewa Robit	1.12	1.541
Fugnido	1.576	2.204	Teferi Ber	1.343	1.69

Table 6.16: Monthly point refractivity distribution

Month	0.10%	1.00%	10.00%	50.00%	90.00%	99.00%	99.90%
Jan	-340.109	-305.23	-257.525	-199.01	-140.495	-92.79	-57.911
Feb	-349.085	-316.237	-271.309	-216.2	-161.091	-116.163	-83.315
Mar	-357.378	-325.52	-281.947	-228.5	-175.053	-131.48	-99.622
Apr	-344.484	-317.771	-281.235	-236.42	-191.605	-155.069	-128.356
May	-345.46	-318.689	-282.073	-237.16	-192.247	-155.631	-128.86
Jun	-327.464	-304.143	-272.245	-233.12	-193.995	-162.097	-138.776
Jul	-306.377	-287.876	-262.57	-231.53	-200.49	-175.184	-156.683
Aug	-305.854	-287.264	-261.838	-230.65	-199.462	-174.036	-155.446
Sep	-317.579	-296.034	-266.566	-230.42	-194.274	-164.806	-143.261
Oct	-326.927	-299.133	-261.119	-214.49	-167.861	-129.847	-102.053
Nov	-329.677	-299.597	-258.455	-207.99	-157.525	-116.383	-86.303
Dec	-324.934	-293.018	-249.365	-195.82	-142.275	-98.622	-66.706

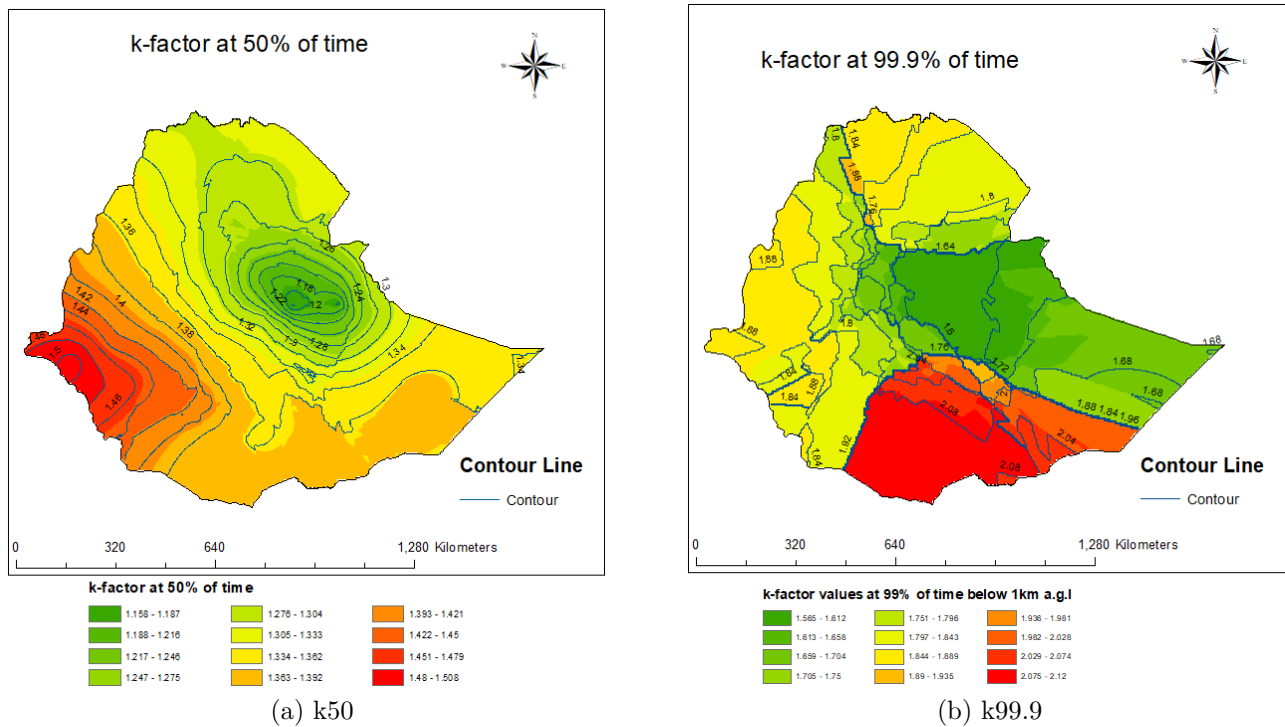


Figure 6.16: 50% and 99.9% of time value of k-factor map of Ethiopia

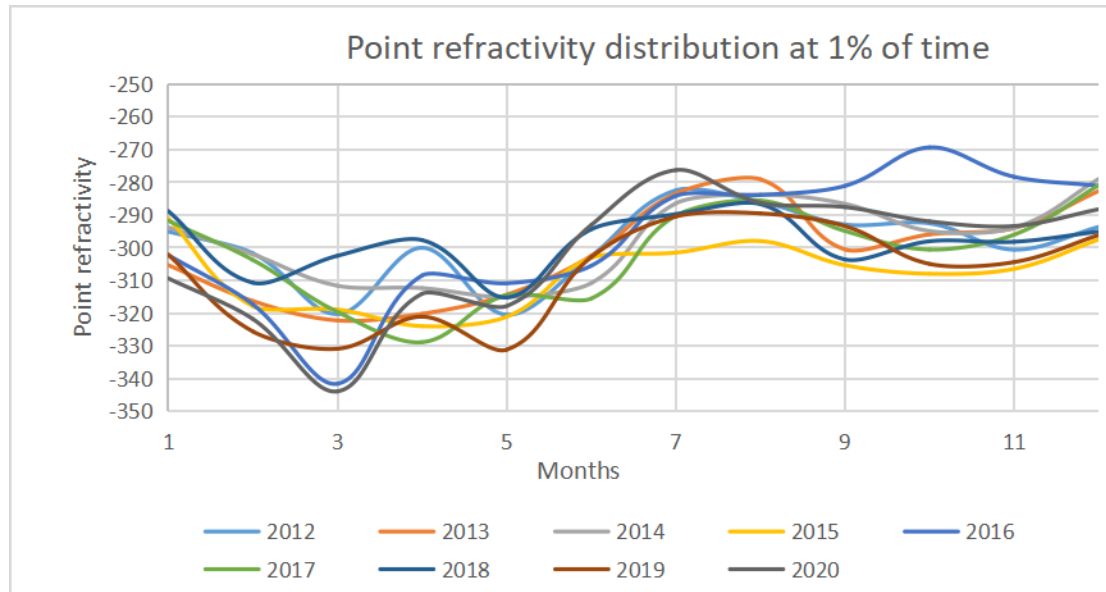


Figure 6.17: Point refractivity distribution at 1% of time

The monthly point refractivity distribution at 1% of time is given in the figure(6.18). The month of August has worst point refractivity for the 65m of lower part of atmosphere.

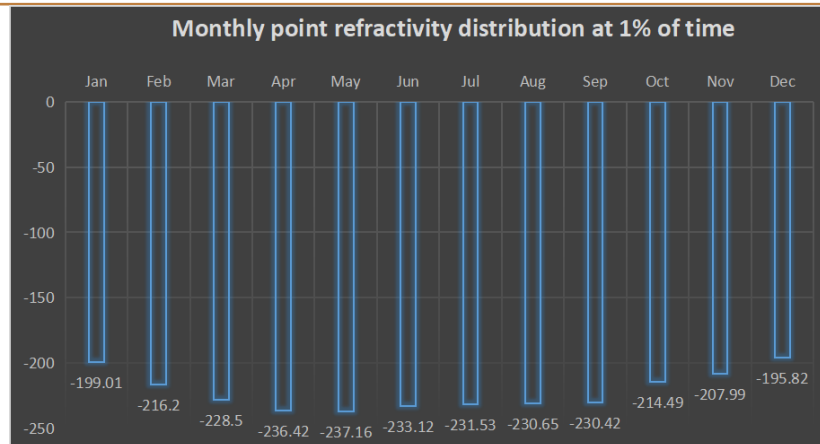


Figure 6.18: Monthly point refractivity distribution

Seasonal Distribution of point refractivity

The seasonal distribution of point refractivity at different years of Addis Ababa given in table(6.17), figure (6.19) and tabl(6.18).

Table 6.17: seasonal point refractivity at 1% of time at different years

	2012	2013	2014	2015	2016	2017	2018	2019	2020
Autumn	-295.36	-296.84	-291.81	-306.6	-276.27	-297.16	-299.94	-300.92	-290.98
Winter	-296.81	-301.43	-291.62	-302.13	-300.23	-292.14	-298.19	-307.94	-306.47
Spring	-301.83	-300.13	-304.11	-308.58	-300.2	-306.76	-299.78	-308.17	-295.73
Summer	-290.33	-288.37	-293.69	-300.87	-291.2	-297.12	-290.28	-294.29	-285.21

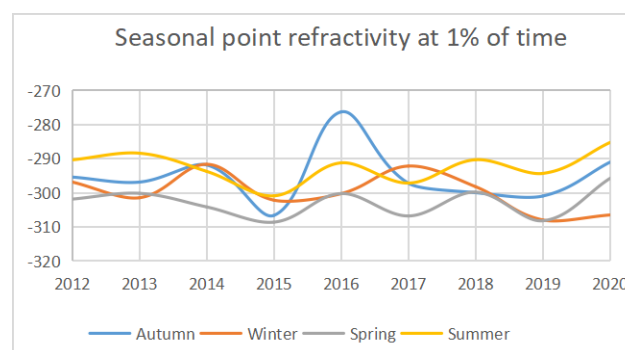


Figure 6.19: Seasonal point refractivity at 1% of time

Table 6.18: average seasonal point refractivity at 1% of time

season	point refractivity
Autumn	-295.1
Winter	-299.66
Spring	-302.61
Summer	-292.37

Spring is the worst point refractivity season recorded at 1% of time, which is -302.61 unit/Km.

Cumulative Distribution of Point Refractivity

The monthly and annual cumulative point refractivity at different exceedance is given in figure(6.20) and figure(6.21) consecutively.

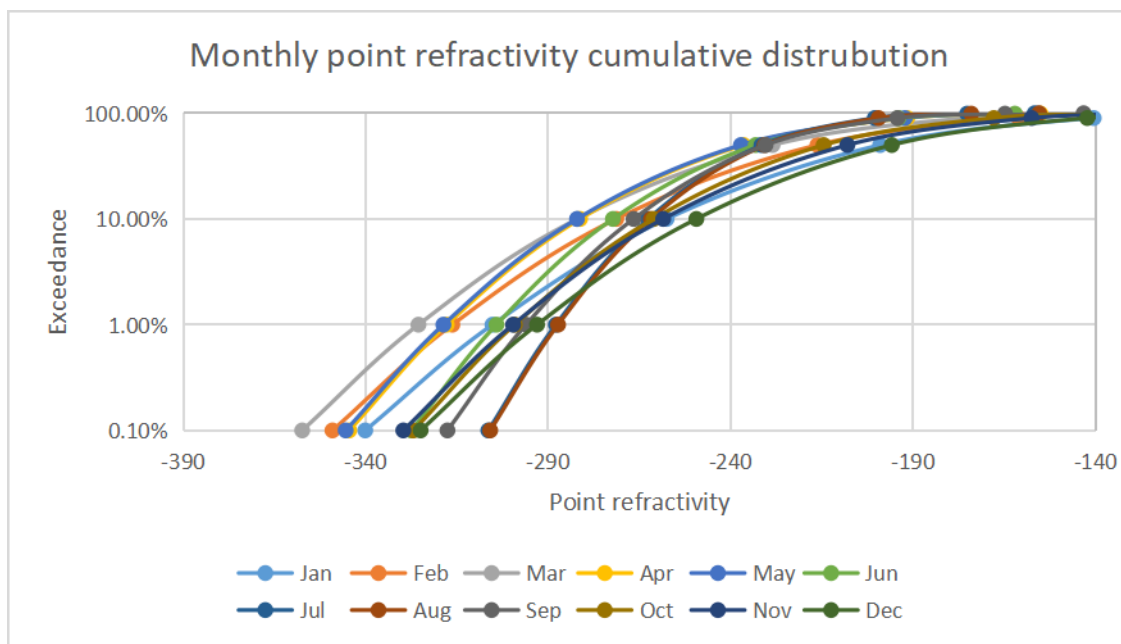


Figure 6.20: Monthly point refractivity cumulative distribution of Addis Ababa

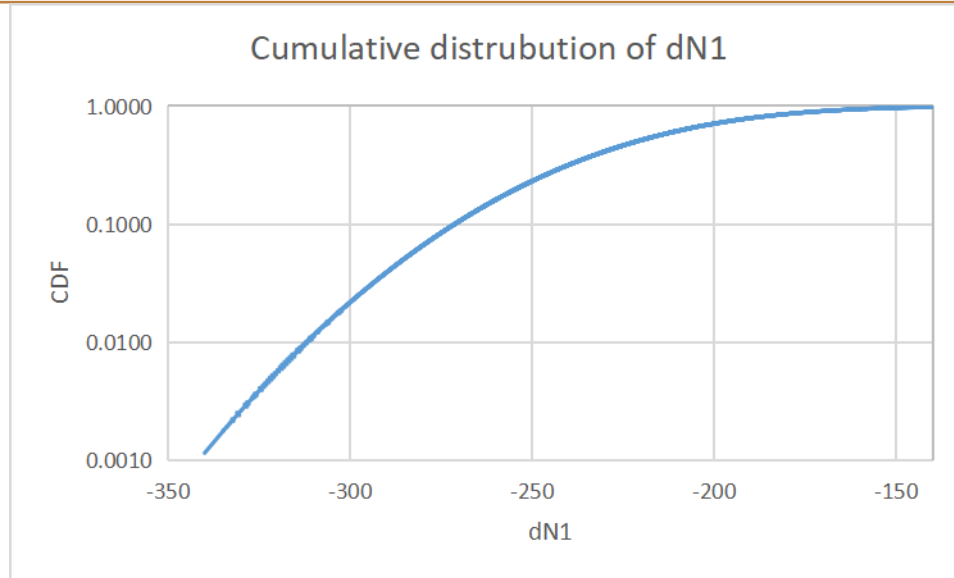


Figure 6.21: Point refractivity distribution of Addis Ababa

The worst month point refractivity result is compared with Radiosonde refractivity result at different exceedance of time and presented on table(6.22) and corresponding graph is given in figure(6.22).

Table 6.19: Comparison of worst month point refractivity result and Radiosonde worst month point refractivity data base at Addis ababa

worst month ex- ceedance (%)	Using new model	Using Radiosonde
0.1	-345.473	-473.734
1	-318.698	-390.35
10	-282.078	-276.301
50	-237.16	-136.408
90	-192.242	3.485
99	-155.622	117.533
99.9	-128.847	200.918

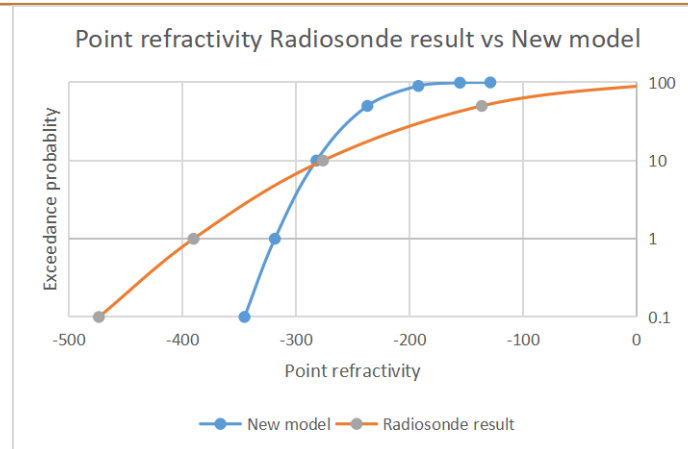


Figure 6.22: Point refractivity ITU-R database vs New model

Further details of point refractivity for each fifty-eight sites are given.

Geoclimatic Factor K Results and Analysis

The geoclimatic factor K for the annual and average worst month is calculated from equation(3.11). Average geoclimatic factor distribution in different year and months are given in figure(6.23).

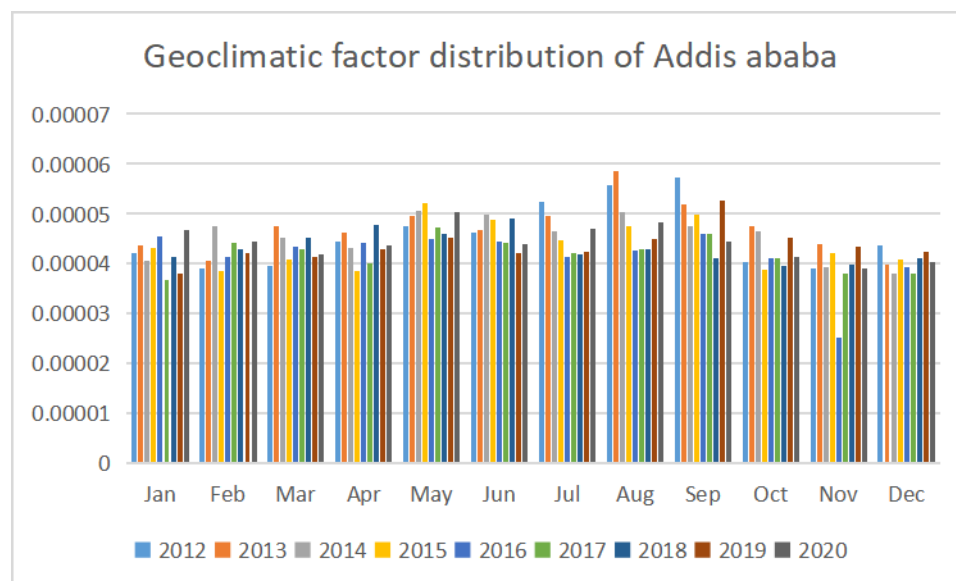


Figure 6.23: Geoclimatic factor average distribution of Addis ababa

The annual point refractivity distribution and corresponding geoclimatic factor, K, distribution are given in table(6.20) and the worst month values are given in table(6.21) respectively.

Table 6.20: Annual geoclimatic factor distribution

Percentage ceedance (%)	ex-	Annual point refractivity	Geo-climatic factor
0.1		-341.561	0.0002100
1		-311.88	0.0001746
10		-271.284	0.0001357
50		-221.489	0.0000995
90		-171.694	0.0000730
99		-131.099	0.0000568
99.9		-101.418	0.0000472

Table 6.21: Worst month geoclimatic distribution

Percentage ceedance (%)	ex-	Worst month point re- fractivity	Geo-climatic factor
0.1		-345.473	0.0002152
1		-318.698	0.0001822
10		-282.078	0.0001451
50		-237.16	0.0001097
90		-192.242	0.0000830
99		-155.622	0.0000661
99.9		-128.847	0.0000560

Distribution and variation of an average month for geoclimatic factor K is given in figure(6.24) and detail distribution of monthly variation in a different year of time is given in table(6.22).

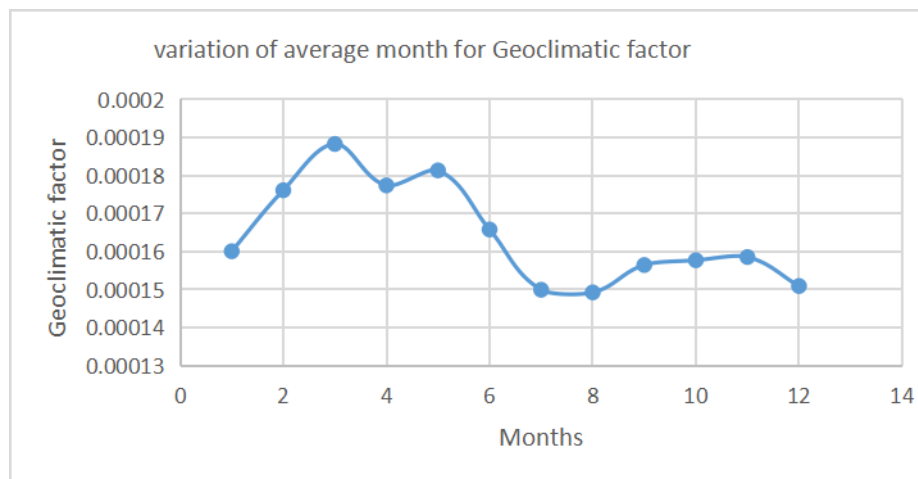


Figure 6.24: Monthly geoclimatic factor distribution

The detail discovery of seasonal, monthly and annual distribution and variation of geoclimatic factor

Table 6.22: Monthly geoclimatic factor distribution of each year

	2012	2013	2014	2015	2016	2017	2018	2019	2020
Jan	1.57E-04	1.68E-04	1.56E-04	1.53E-04	1.64E-04	1.54E-04	1.51E-04	1.64E-04	1.72E-04
Feb	1.64E-04	1.79E-04	1.64E-04	1.81E-04	1.81E-04	1.66E-04	1.73E-04	1.90E-04	1.86E-04
Mar	1.84E-04	1.86E-04	1.74E-04	1.82E-04	2.10E-04	1.83E-04	1.65E-04	1.97E-04	2.13E-04
Apr	1.62E-04	1.84E-04	1.75E-04	1.88E-04	1.71E-04	1.94E-04	1.60E-04	1.85E-04	1.77E-04
May	1.84E-04	1.77E-04	1.78E-04	1.85E-04	1.74E-04	1.78E-04	1.78E-04	1.97E-04	1.81E-04
Jun	1.65E-04	1.65E-04	1.73E-04	1.65E-04	1.68E-04	1.79E-04	1.57E-04	1.65E-04	1.55E-04
Jul	1.45E-04	1.46E-04	1.49E-04	1.64E-04	1.47E-04	1.53E-04	1.52E-04	1.53E-04	1.40E-04
Aug	1.49E-04	1.42E-04	1.47E-04	1.60E-04	1.47E-04	1.48E-04	1.49E-04	1.52E-04	1.49E-04
Sep	1.55E-04	1.63E-04	1.49E-04	1.68E-04	1.44E-04	1.57E-04	1.66E-04	1.56E-04	1.50E-04
Oct	1.55E-04	1.58E-04	1.57E-04	1.70E-04	1.34E-04	1.63E-04	1.60E-04	1.67E-04	1.54E-04
Nov	1.63E-04	1.56E-04	1.56E-04	1.69E-04	1.42E-04	1.58E-04	1.60E-04	1.67E-04	1.56E-04
Dec	1.56E-04	1.46E-04	1.42E-04	1.60E-04	1.44E-04	1.44E-04	1.57E-04	1.58E-04	1.51E-04

for fifty-eight sites are prepared in soft copy appendix (4), appendix (5) and appendix (6).

For fifty-eight sites the point refractivity at 1% time of annual and monthly values with their corresponding geoclimatic factor K are presented on table(6.23) and on table(6.24) respectively.

Further details of geoclimatic factor k for each fifty-eight sites are prepared in soft copy appendix (4), appendix (5) and appendix (6).

The value of geoclimatic factor K was calculated from point refractivity of first 65 meter above the ground level. 1% percent time of exceedance is the target value of point refractivity for designing terrestrial line-of-sight radio link. The annual geoclimatic distribution and worst month geoclimatic distribution with its point refractivity are given in table(6.20) and table(6.21) respectively. The point refractivity in the worst month was recorded in location of Teferiber with the value of -628.943 N.unit/km and corresponding geoclimatic factor K value is found to be 0.001254. Annual point refractivity value was led by Teferiber with -573.47 and recorded geoclimatic factor value of 0.000888. As the value of refractivity getting worst the geoclimatic factor k getting increasing.

In particular to Addis ababa, in the monthly distribution of geoclimatic factor K given in figure(6.24), the value of March month is found to be the highest value. Whereas the value of August month becomes the smallest among the other months.

Table 6.23: Annual point refractivity distribution and corresponding geoclimatic factor for selected sites

Name	Annual dN_1 at 1%	Geo- climatic factor	Name	Annual dN_1 at 1%	Geo- climatic factor
Abala	-422.002	0.0003463	Gidayana	-332.047	0.0001979
Abomsa	-391.783	0.000287	Ginir	-338.41	0.0002059
Adama	-378.89	0.0002649	Gode	-532.061	0.0006864
AddisAbba	-311.88	0.0001746	Gore	-322.819	0.0001869
Agayo	-409.383	0.0003201	Gursum	-342.832	0.0002117
Aman	-401.595	0.000305	H/Mariam	-342.112	0.0002107
Ambo	-341.768	0.0002103	Harar	-340.293	0.0002083
ArbaMinch	-429.78	0.0003634	Harokelo	-330.447	0.000196
Areka	-361.501	0.0002377	Humera	-554.467	0.000789
Assaita	-711.841	0.0020988	jigiga	-393.153	0.0002894
Assosa	-393.465	0.00029	Kebri Beya	-545.936	0.0007482
Aisha	-523.872	0.0006523	Kebri Dehar	-503.775	0.0005757
Bahir Dar	-393.344	0.0002898	Lalibela	-300.246	0.0001624
Bale-Robe	-293.917	0.0001562	Limu	-373.679	0.0002564
Berahale	-556.146	0.0007972	Maichew	-308.856	0.0001714
Bure	-358.868	0.0002339	Mankush	-498.778	0.0005581
Burji	-344.329	0.0002136	Mehoni	-393.89	0.0002907
Chercher	-381.159	0.0002686	Meiso	-437.691	0.0003817
Combolcha	-376.918	0.0002616	Mekele	-361.441	0.0002376
Diffa	-390.089	0.0002839	Metehara	-504.319	0.0005776
Dilla	-434.109	0.0003733	Metema	-532.152	0.0006868
Dillo	-451.317	0.0004155	Moyale	-383.138	0.0002719
Dubity	-606.775	0.0010922	Neghele	-377.528	0.0002626
Endabaguna	-389.455	0.0002828	Omorate	-549.514	0.000765
Erer	-479.677	0.0004956	Shahura	-320.644	0.0001844
Filtu	-393.338	0.0002897	Sherekole	-527.521	0.0006673
Fincha	-352.915	0.0002254	Shewarobit	-462.06	0.0004442
Fugnido	-533.245	0.0006915	Teferi Ber	-573.468	0.0008879
Gelemso	-371.936	0.0002536	Wachile	-451.665	0.0004164

6.7 Interpolation of geoclimatic factor and dN_1

Annual point refractivity at 1% of time and worst month point refractivity at 1% of time for the whole country is interpolated using kriging spatial interpolation technique and ArcMap v10.8 was applied to generate map and generate data. The map is presented in figure(6.25), whereas, the data generated was presented with the resolution of 0.0458 x 0.0458 degree in soft copy.

Annual geoclimatic factor K and worst month geoclimatic factor for the whole country is interpolated

Table 6.24: Worst month point refractivity distribution and corresponding geoclimatic factor for selected sites

Name	Worst month dN1 at 1%	Geo- climatic factor	Name	Worst month dN1 at 1%	Geo- climatic factor
Abala	-414.878	0.000394	Gidayana	-333.269	0.000199
Abomsa	-402.663	0.000372	Ginir	-341.255	0.00021
Adama	-391.827	0.000345	Gode	-553.676	0.000785
AddisAbba	-318.698	0.000215	Gore	-338.467	0.000206
Agayo	-411.3	0.000407	Gursum	-342.116	0.000211
Aman	-433.751	0.000474	H/Mariam	-345.988	0.000216
Ambo	-353.788	0.000271	Harar	-342.99	0.000212
ArbaMinch	-446.607	0.0005	Harokelo	-342.724	0.000212
Areka	-365.538	0.000285	Humera	-628.943	0.001254
Assaita	-764.852	0.002918	jigiga	-384.584	0.000274
Assosa	-384.197	0.000274	Kebri Beya	-428.025	0.000359
Aisha	-570.475	0.000872	Kebri Dehar	-521.008	0.000641
Bahir Dar	-378.533	0.000264	Lalibela	-303.181	0.000165
Bale-Robe	-291.742	0.000154	Limu	-386.623	0.000278
Berahale	-569.832	0.000868	Maichew	-340.093	0.000208
Bure	-372.722	0.000255	Mankush	-519.235	0.000634
Burji	-348.742	0.00022	Mehoni	-403.634	0.000309
Chercher	-388.031	0.00028	Meiso	-432.669	0.00037
Combolcha	-377.595	0.000263	Mekele	-378.701	0.000265
Diffa	-415.624	0.000333	Metehara	-517.138	0.000626
Dilla	-615.57	0.001154	Metema	-553.219	0.000783
Dillo	-488.917	0.000525	Moyale	-417.985	0.000338
Dubity	-413.21	0.000328	Neghele	-371.634	0.000253
Endabaguna	-403.744	0.000309	Omorate	-582.306	0.000938
Erer	-493.706	0.000541	Shahura	-324.518	0.000189
Filtu	-397.942	0.000298	Sherekole	-521.898	0.000644
Fincha	-359.441	0.000235	Shewarobit	-471.392	0.000471
Fugnido	-576.836	0.000907	Teferi Ber	-592.559	0.001
Gelemso	-370.471	0.000251	Wachile	-466.135	0.000456

using kriging spatial interpolation technique and ArcMap v10.8 was applied to generate map and generate data. The map is presented in figure(??) and figure(6.26) respectively, whereas, the data generated was presented with the resolution of 0.0458 x 0.0458 degree in soft copy.

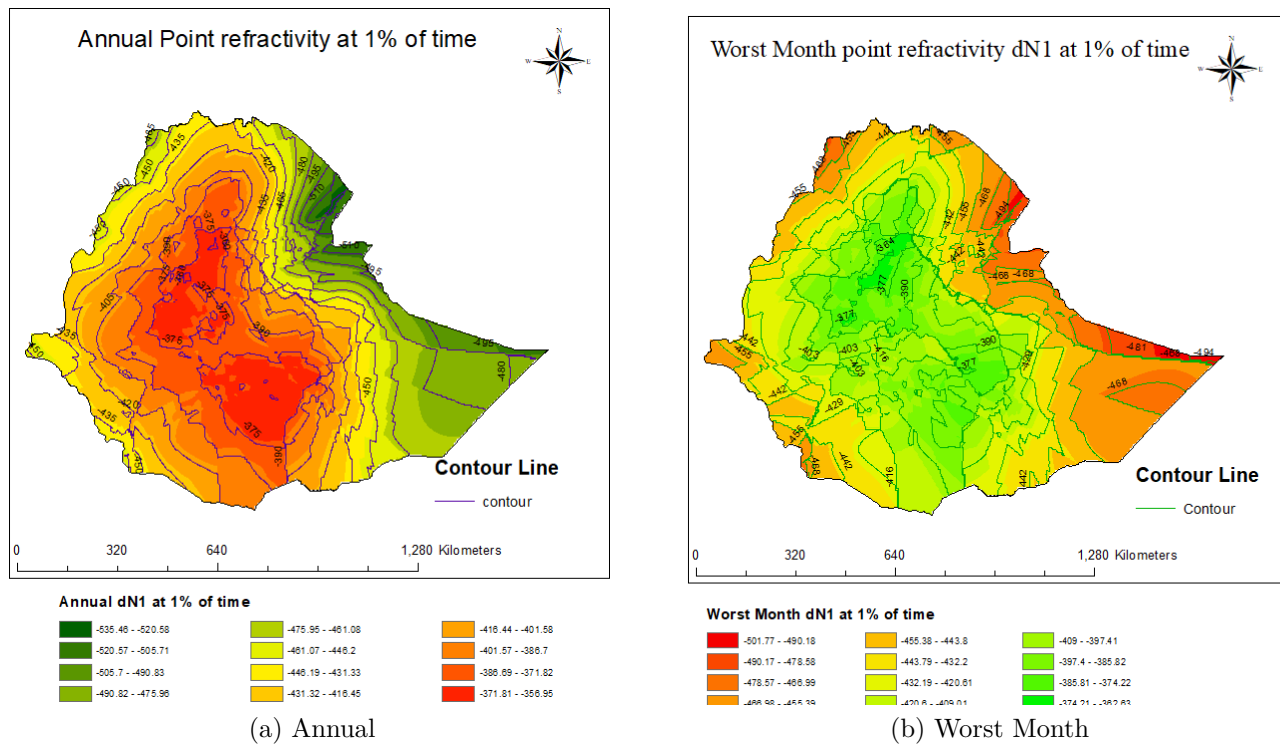


Figure 6.25: Worst month and Annual Point refractivity at 1% of time map of Ethiopia

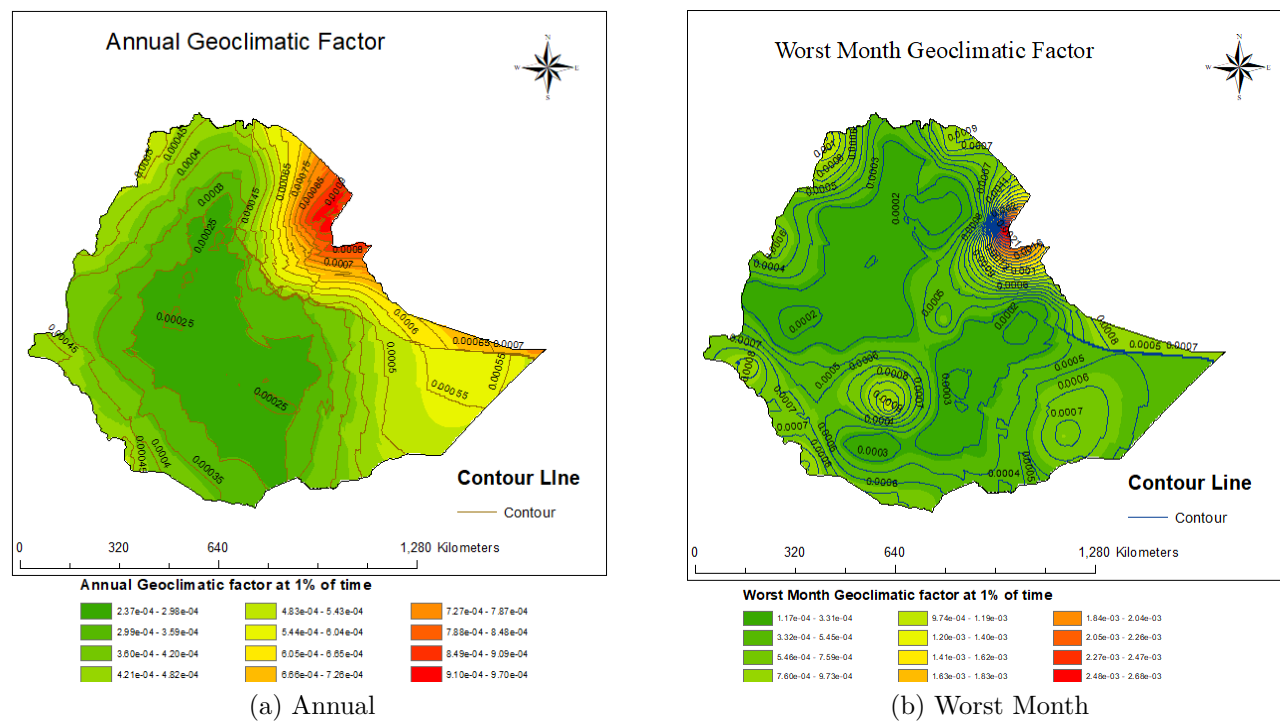


Figure 6.26: Worst month geoclimatic factor map of Ethiopia

6.8 Outage probability and Fade depth analysis

In terrestrial link design, the fade caused by multipath is important parameter. Since, the occurrence of this multipath fade is not continues, it is important also to find the probability of happening in the link design the randomness of the fade nature can be expressed statistically[62]. The value of geoclimatic factor K as it was calculated in equation(4.20), the prediction of outage probability and fade depth are calculated from the equation (6.11).

$$P_0 = Kd^{3.1} (1 + |\epsilon_p|)^{-1.29} f^{0.8} x 10^{-0.00089h_L} \quad (6.11)$$

$$|\epsilon_p| = \frac{h_r - h_t}{d} \quad (6.12)$$

h_r and h_t are altitude in meter above sea level. For this paper, the microwave link found between Addis Ababa (Furi) to Adama (Adama-West) link was taken to analyse. The following table(6.25) summarises the value of the link parameters found between the two point.

Table 6.25: Summery of link configuration

Parameters	description
Path-Length	70.47Km
Height-of-TX a.g.l	40m
Altitude-of-Tx a.s.l	1885m
Height-of-Tx a.g.l	35m
Altitude-of-rx a.s.l	2833m
Carrier-frequency	7GHz
Transmitting-power	30dB
Tx-loss: cable loss(4.3dB/100), and other	8.61dB
Trx/RX antenna-gain	45.2dB
Freespace-loss	146.3dB
Atmospheric-loss	0.54
Recieved-signal	-38.68

In our case given parameters are,

$$f = 7GHz, h_e = 2837m, h_r = 1923m \text{ and } d = 70.47km$$

The approximation of the generated graph for distance verses fade depth is given on the figure(6.27). The curve of fade depth vs frequency is given on the figure(6.28). At different outage probability the fade depth vs distance is given in figure(6.29). Outage probability vs fade depth at different months given with frequency of 7GHz in figure (6.30).

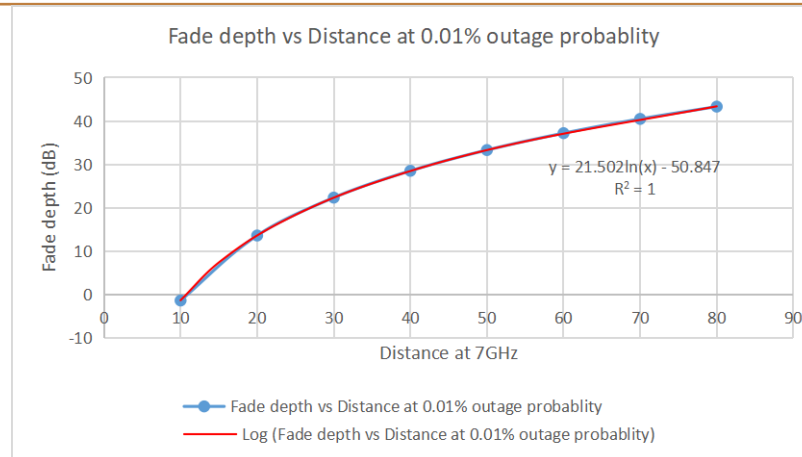


Figure 6.27: Fade depth vs Distance at 0.01% outage probability at Addis ababa

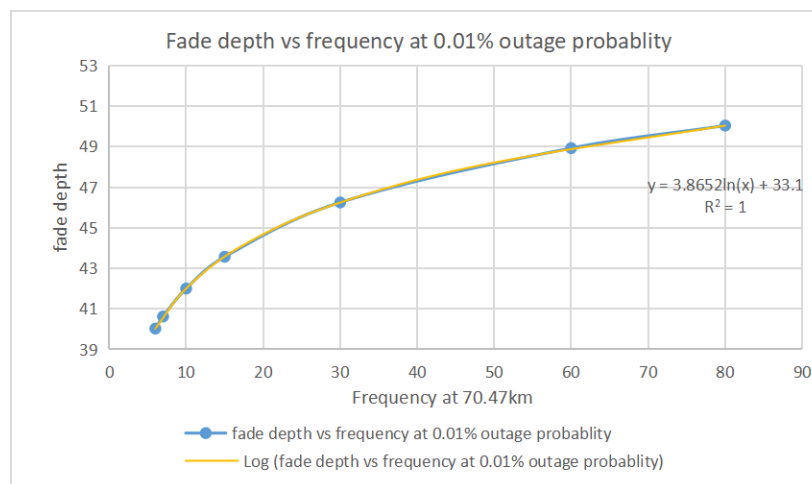


Figure 6.28: Fade depth vs frequency at 0.01% outage probability

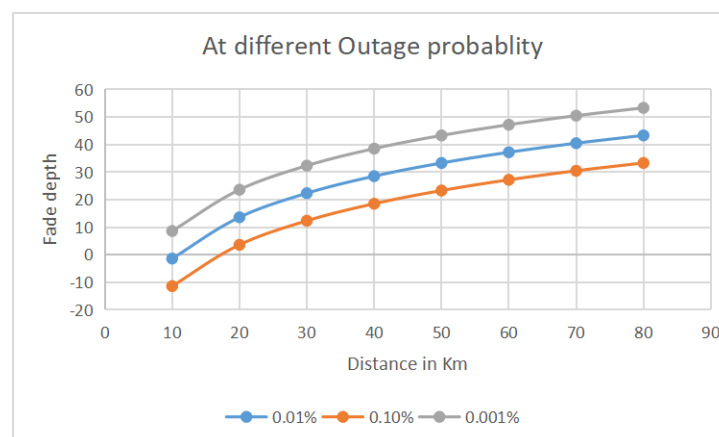


Figure 6.29: Fade depth vs distance different outage probability

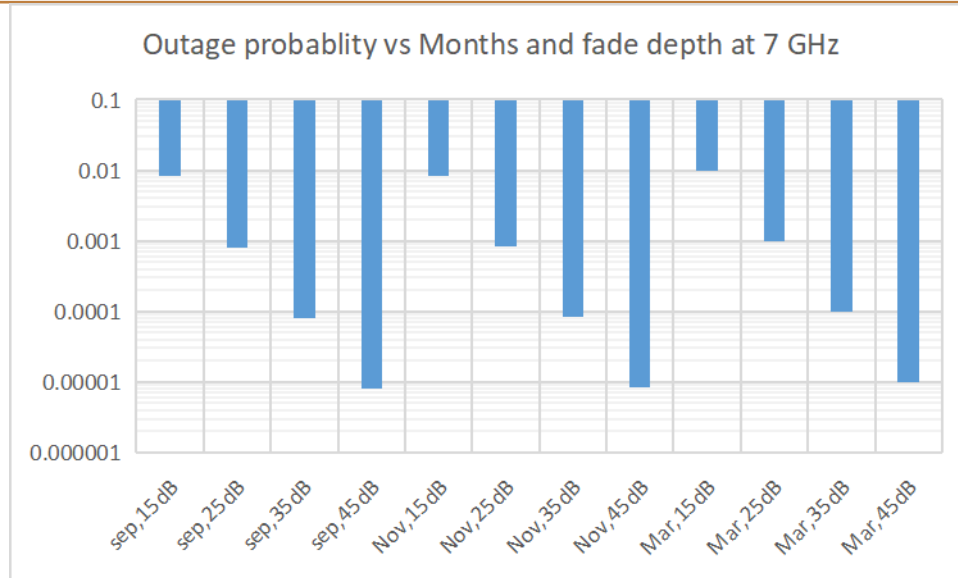


Figure 6.30: Fade depth vs outage probability at Addis ababa

Commonly, the target value of fade depth expected is found at 0.01% exceedance of time. The pattern of the curve created by the Fade depth vs distance is following natural logarithm. As the distance in kilometer increases, the fade depth increases with fixed outage probability. There is a similar pattern of curve fitting between Fade depth vs frequency. The outage probability versus fade depth have been also presented in different months and exceedance of time. Fade margin is estimated from the sum of long term and short term fading caused by multipath[68] also calculated from sum of receiver sensitivity and received signal[2]. In selected months, the behaviors of outage probability and fade depth are more or less similar. But, at 0.01% outage probability, the month of worst month March has 15dB fade depth. For 99.999 network reliability (0.001% outage), the value will be 25dB.

6.9 Atmospheric Gas Loss

At Addis Ababa site the local surface temperature pressure and water vapor pressure were calculated to be $T=16.73^{\circ}$, $P=827.51\text{hPa}$ and $\rho=8.93\text{g}/\text{m}^3$. The graph given in figure(6.31) is the dry air atmospheric specific attenuation, figure(6.32) is the wet air atmospheric specific attenuation and figure(6.33) is total atmospheric specific attenuation. These figures have resulted from the procedure given by ITU-R p676-4[7].

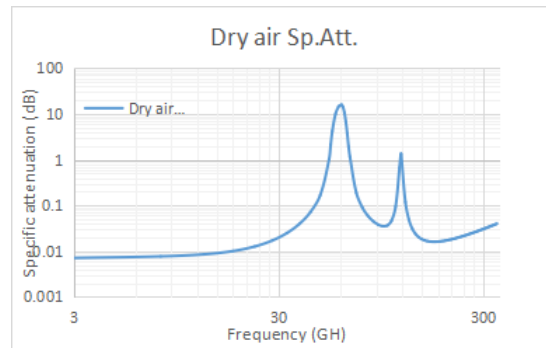


Figure 6.31: Dry air atmospheric specific attenuation vs frequency at Addis Ababa

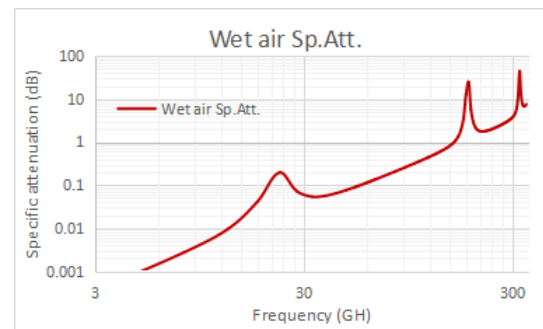


Figure 6.32: Wet air atmospheric specific attenuation vs frequency at Addis Ababa

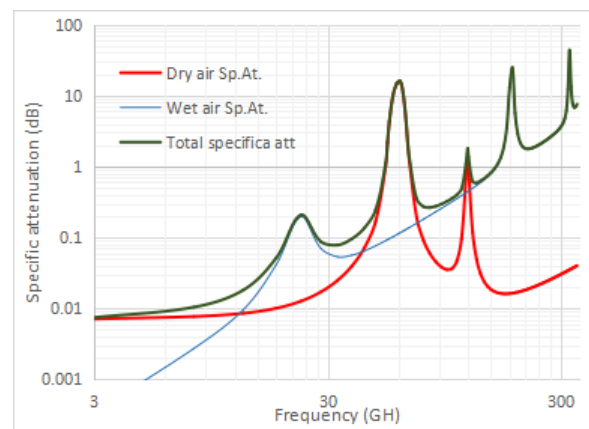


Figure 6.33: Total air atmospheric specific attenuation vs frequency at Addis Ababa

Chapter 7

Conclusion and Future work

Consideration of clear-air losses during microwave radio-link is so crucial in order to avoid the effect caused by clear-air losses. Multipath fading caused by geoclimatic factor K, diffraction fading caused by effective earth radius factor (k-factor) and atmospheric gas absorption are some of the main losses considered in this thesis work, which are the main parameters used in design of terrestrial radio-link. The values of geoclimatic factor K is depending on point refractivity of the first 65m above the ground. Since, the value of k-factor is depending on the vertical refractivity gradient of the first kilometer above the ground, high refractivity gradient will result to low k-factor signal. On contrary, when the value of refractivity is highly negative value the signal will bend upward. Which will result to highly bending of the radio wave signal toward the surface of the earth.

Data from Radiosonde is used for modeling the vertical behavior of atmospheric parameters so that the resulting equation has been used to calculate the vertical atmospheric parameters for the rest of selected 58 sites in Ethiopia. At the selected sites, five to ten years 15 minute interval of humidity and temperature data were collected from NMA and ten years of satellite surface pressure data were combined and used for processing and analysis using selected model. ITU-R 530, ITU-R 453 and ITU-R 835 are used for processing and resulting of refractivity, k-factor, geoclimatic factor K, outage probability and fade depth. ITU-R 676 method is used for atmospheric gas attenuation.

The average values of k-factor discovered, for Ethiopia territory in this thesis, is 1.22 at 50% of time and 1.44 at 99.9% of time. The curve fitting for values of one selected site at Addis Ababa of the k-factor is found to be belly shaped. The resulting graph was almost symmetric around the center median value. Which was presented as monthly, season and annual curves. The month August has the highest value of k-factor, which is 1.39. And 1.23 is the lowest k-factor in month of January observed at Addis Ababa. For the rest of 58 sites annual curve fitting is given in table 6.13. The highest recorded of k-factor was observed at Dilla site with value of 1.446 at 50% of time and 2.478 at 99.9% of time. Assita site has the highest worst-month geoclimatic factor K, which is 0.00292 at 1 percentage time of point refractivity. Kriging spatial interpolation technique is found to be the best among available spatial interpolation for this work. It was applied for the rest of points at the place where no sample data was taken in Ethiopian territory with 0.0458x0.0458 degree resolution.

Recommendation and Future work

Since, the research subject is at its early stage in Ethiopia, encouraging researches to work more on the field will help. Devices like Radiosonde need to be installed to get more accurate data in geographical representative area of the country. More locations are needed for the data collection at meteorological sites to help for better accuracy. In addition, dedicated microwave radio-link need to be installed for similar study. Telecom operators need to cooperate accessing live data for authorized researchers and microwave network designers to work together on the subject to utilize the benefit of research results. The following points can be taken as title of future work.

- Clear-air radio-climatic determination using neural network
- k-factor and Geoclimatic factor determination in Arid region, Semi-Arid region, Rift valley region and plateau region of Ethiopia.
- Characterization and modeling of k-factor in Ethiopia
- k-factor investigation from point refractivity in Ethiopia

Bibliography

- [1] World Conservation Monitoring Centre. *Biodiversity Guide to Ethiopia*. Ed. by UK World Conservation Monitoring Centre Cambridge. GEMS, 1991.
- [2] Harvey Lehpamer. *Microwave transmission networks: planning, design, and deployment*. McGraw-Hill Education, 2010.
- [3] Jari Luomala and Ismo Hakala. “Effects of temperature and humidity on radio signal strength in outdoor wireless sensor networks”. In: *2015 Federated Conference on Computer Science and Information Systems (FedCSIS)*. IEEE. 2015, pp. 1247–1255.
- [4] Congzheng Han and Shu Duan. “Impact of atmospheric parameters on the propagated signal power of millimeter-wave bands based on real measurement data”. In: *IEEE Access* 7 (2019), pp. 113626–113641.
- [5] ITU-R. *The radio refractive index: its formula and refractivity data*. Geneva: International Telecom Union for Radio-communication Study Group III, 2019.
- [6] ITU-R. *Propagation data and prediction methods required for the design of terrestrial line-of-sight systems*. Geneva: International Telecom Union for Radio-communication Study Group III, 2017.
- [7] ITU-R. *Attenuation by atmospheric gases and related effects*. Geneva: International Telecom Union for Radio-communication Study Group III, 2019.
- [8] ITU-R. *effects of multipath propagation on the design and operation of line-of-sight digital radio-relay systems*. Geneva: International Telecom Union for Radio-communication Fixed Service, 199.
- [9] ITU-R. *Propagation by diffraction*. Geneva: International Telecom Union for Radio-communication Study Group III, 2012.
- [10] Joseph Ojo, Elijah Olurotimi, Obiseye Obiyemi, et al. “Assessment of Total Attenuation and Adaptive Scheme for Quality of Service Enhancement in Tropical Weather for Satellite Networks and 5G Applications in Nigeria”. In: *Journal of Microwaves, Optoelectronics and Electromagnetic Applications* 20 (2021), pp. 228–247.
- [11] Feyisa Debo Diba. “Radio wave propagation modeling under precipitation and clear-air at microwave and millimetric bands over wireless links in the horn of Africa.” In: 2017.
- [12] Andreas F Molisch. *Wireless communications*. Vol. 34. John Wiley & Sons, 2012.
- [13] LAR Silva Mello et al. “Radioclimatic parameters for the prediction of multipath fading in radio links in Brazil”. In: *1997 SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference. 'Linking to the Next Century'. Proceedings*. Vol. 2. IEEE. 1997, pp. 734–738.
- [14] Odedina Peter Kemi. “Clear-air radioclimatological modeling for terrestrial line of sight links in Southern Africa.” PhD thesis. 2010.
- [15] Peter K Odedina and Thomas J Afullo. “A simplified statistical modeling of radioclimatological parameters for los links in south africa”. In: *Proceedings of Progress In Electromagnetic Research Symposium (PIERS) ISBN*. 2008, pp. 978–1.
- [16] Agbo Udoka Jonas and Ugbor Desmond Okechukwu. “Investigation of the impact in variation of secondary radioclimatic variables on microwave at the lower atmosphere”. In: *Meteorology and Atmospheric Physics* 120.1 (2013), pp. 83–86.

- [17] Abdulhadi AbouAlmal et al. "Seasonal statistics of anomalous propagation in United Arab Emirates". In: *2014 Loughborough Antennas and Propagation Conference (LAPC)*. IEEE. 2014, pp. 663–666.
- [18] Thomas J Afullo and Peter K Odedina. "On the K-factor distribution and diffraction fading for southern Africa". In: *Trans. SAIEE* 97.2 (2006), pp. 172–181.
- [19] Yamina Bettouche, Basile L Agba, and Ammar B Kouki. "Geoclimatic factor and point refractivity evaluation in Quebec-Canada". In: *2014 XXXIth URSI General Assembly and Scientific Symposium (URSI GASS)*. IEEE. 2014, pp. 1–4.
- [20] Abraham Mutunga Nyete. "Clear-air analytical and empirical K-Factor determination and characterization for terrestrial microwave LOS link applications." PhD thesis. 2013.
- [21] A Adediji, M Ajewole, and S Falodun. "Distribution of radio refractivity gradient and effective earth radius factor (k-factor) over Akure, South Western Nigeria". In: *Journal of atmospheric and solar-Terrestrial physics* 73.16 (2011), pp. 2300–2304.
- [22] Thomas J Afullo and Peter K Odedina. "Effective earth radius factor characterization for line of sight paths in Botswana". In: *2004 IEEE Africon. 7th Africon Conference in Africa (IEEE Cat. No. 04CH37590)*. Vol. 1. IEEE. 2004, pp. 227–231.
- [23] Andrew J Palmer and Duncan C Baker. "Predicting the long-term average of the effective earth radius factor for South Africa using ground-based observations". In: *2004 IEEE Africon. 7th Africon Conference in Africa (IEEE Cat. No. 04CH37590)*. Vol. 2. IEEE. 2004, pp. 1003–1006.
- [24] Andrew J Palmer et al. "A novel empirical model of the k-factor for radiowave propagation in Southern Africa for communication planning applications". PhD thesis. University of Pretoria, 2005.
- [25] Abdulhadi Abu-Almal and Kifah Al-Ansari. "Calculation of effective earth radius and point refractivity gradient in UAE". In: *International Journal of Antennas and Propagation* 2010 (2010).
- [26] Olalekan L Ojo, Joseph S Ojo, and Pelumi Akinyemi. "Characterization of secondary radioclimatic variables for microwave and millimeter wave link design in Nigeria". In: (2017).
- [27] Hans J Liebe. "A contribution to modeling atmospheric millimeter-wave properties". In: *Frequenz* 41.1-2 (1987), pp. 31–36.
- [28] Hans J Liebe. "MPM—An atmospheric millimeter-wave propagation model". In: *International Journal of Infrared and millimeter waves* 10.6 (1989), pp. 631–650.
- [29] Yunir Gataullin and Rolf Kozlowski. "Implementation of rain and gaseous attenuation models for 26-30 GHz Ka-Band Communication". In: (2009).
- [30] Juan R Pardo, Jose Cernicharo, and Eugene Serabyn. "Atmospheric transmission at microwaves (ATM): an improved model for millimeter/submillimeter applications". In: *IEEE Transactions on antennas and propagation* 49.12 (2001), pp. 1683–1694.
- [31] Jose Miguel Garcia-Rubia et al. "Attenuation measurements and propagation modeling in the W-band". In: *IEEE transactions on antennas and propagation* 61.4 (2012), pp. 1860–1867.
- [32] Hans J Liebe, Takeshi Manabe, and George A Hufford. "Millimeter-wave attenuation and delay rates due to fog/cloud conditions". In: *IEEE transactions on antennas and propagation* 37.12 (1989), pp. 1617–1612.
- [33] S Falodun, Joseph S. Ojo, and S Aboyeji. "Modeling of atmospheric primary radioclimatic variables in Nigeria for microwave radio propagation applications". In: *SN Applied Sciences* 3.1 (2021), pp. 1–15.

- [34] Abdulhadi AbouAlmal et al. “New approach for predicting vertical refractivity profile in low troposphere in a subtropical region”. In: *9th IET International Conference on Computation in Electromagnetics (CEM 2014)*. IET. 2014, pp. 1–2.
- [35] Egbe Jesam Nna, Ozuomba Simeon, and Enyenih Henry Johnson. “Modelling and Application of Vertical Refractivity Profile for Cross River State”. In: *World Journal of Applied Physics* 2.1 (2017), pp. 19–26.
- [36] Martin Grabner, Pavel Pechac, and Pavel Valtr. “On horizontal distribution of vertical gradient of atmospheric refractivity”. In: *Atmospheric Science Letters* 18.7 (2017), pp. 294–299.
- [37] Robin C Cherrett. *Capturing characteristics of atmospheric refractivity using observations and modeling approaches*. Tech. rep. NAVAL POSTGRADUATE SCHOOL MONTEREY CA, 2015.
- [38] NASA GSFC Hydrological Sciences Laboratory (HSL). *FLDAS Noah Land Surface Model L4 Global Monthly 0.1 x 0.1 degree (MERRA-2 and CHIRPS) V001*. 2020. DOI: 10.5067/5NHC22T9375G.
- [39] Hervé Sizun and Pierre de Fornel. *Radio wave propagation for telecommunication applications*. Springer, 2005.
- [40] Roger L Freeman. *Radio system design for telecommunications*. Vol. 98. John Wiley & Sons, 2006.
- [41] Barsocchi P. “Channel models for terrestrial wireless communications”. In: *National Research Council – ISTI Institute Technical Report (Pisa: CNR-ISTI)* (2006).
- [42] M. Younis and L. Zwirello. *Advanced Radio Communication*. Ed. by Radio Wave Propagation-Fundamentals. Karlsruhe Institute of Technology, 2012.
- [43] Fritz Albregtsen and Bent Nyboe Andersen. *Solar Physics* 95, 1985.
- [44] Bernard Sklar et al. *Digital communications: fundamentals and applications*. 2001.
- [45] VR Antti and Arto Lehto. *Radio engineering for wireless communication and sensor applications*. Artech house, 2003.
- [46] David G Andrews. *An introduction to atmospheric physics*. Cambridge University Press, 2010.
- [47] Sumbiri Djuma. “Microwave and millimetre radio wave propagation modelling for terrestrial line-of-sight links in Central Africa.” PhD thesis. 2018.
- [48] Trevor Manning. *Microwave radio transmission design guide*. Artech house, 2009.
- [49] John David Parsons. *The mobile radio propagation channel*. Wiley, 2000.
- [50] Basile L Agba et al. “Recent evolution of ITU method for prediction of multipath fading on terrestrial microwave links”. In: *Session 3P7 RF and Wireless Communication, Multipath* 857 (2011).
- [51] HIDE Makino and K Morita. “Design of space diversity receiving and transmitting systems for line-of-sight microwave links”. In: *IEEE Transactions on Communication Technology* 15.4 (1967), pp. 603–614.
- [52] Andrew J Palmer and Duncan C Baker. “A novel simple semi-empirical model for the effective earth radius factor”. In: *IEEE transactions on broadcasting* 52.4 (2006), pp. 557–565.
- [53] Steven M Babin. “A case study of subrefractive conditions at Wallops Island, Virginia”. In: *Journal of Applied Meteorology* 34.5 (1995), pp. 1028–1038.
- [54] Luigi Moreno. “Point-to-Point Radio Link Engineering”. In: (2001).

- [55] Harold T Dougherty. *The role of elevated ducting for radio service and interference fields*. Vol. 81. 69. US Department of Commerce, National Telecommunications and Information ..., 1981.
- [56] John S Seybold. *Introduction to RF propagation*. John Wiley & Sons, 2005.
- [57] Y Yan. “A model for millimeter wave attenuation by atmospheric gases in China area”. In: *International Journal of Infrared and Millimeter Waves* 24.9 (2003), pp. 1525–1530.
- [58] Abraham M Nyete and Thomas Joachim Odhiambo Afullo. “Seasonal distribution modeling and mapping of the effective earth radius factor for microwave link design in South Africa”. In: *Progress In Electromagnetics Research* 51 (2013), pp. 1–32.
- [59] Pierre Goovaerts and. “Kriging Interpolation”. In: *Geographic Information Science & Technology Body of Knowledge* 2019.Q4 (2019). DOI: 10.22224/gistbok/2019.4.4.
- [60] Geoffrey Bohling and Brownie Wilson. “Kansas Geological Survey”. In: *Kriging*. Accessed July 16 (2005), p. 2013.
- [61] Jon Barry Cherrie, Richard Keith Beatson, and Garry Neil Newsam. “Fast Evaluation of Radial Basis Functions: Methods for Generalized Multiquadrics in $\mathbb{R}^n$ ”. In: *SIAM Journal on Scientific Computing* 23.5 (2002), pp. 1549–1571.
- [62] Jan Bogucki and Ewa Wielowieyska. “Empirical season’s fadings in radio communication at 6 GHz band”. In: *Journal of telecommunications and information technology* (2009), pp. 48–52.
- [63] Tianfeng Chai and Roland R Draxler. “Root mean square error (RMSE) or mean absolute error (MAE)”. In: *Geoscientific Model Development Discussions* 7.1 (2014), pp. 1525–1534.
- [64] Mohammad Ahsanullah, B. M. Golam Kibria, and Mohammad Shakil. “Normal Distribution”. In: *Normal and Student’s t Distributions and Their Applications*. Atlantis Press, 2014, pp. 7–50. DOI: 10.2991/978-94-6239-061-4_2.
- [65] Kevin Johnston et al. *Using ArcGIS geostatistical analyst*. Vol. 380. Esri Redlands, 2001.
- [66] Yi-Hwa Wu and Ming-Chih Hung. “Comparison of spatial interpolation techniques using visualization and quantitative assessment”. In: *Applications of Spatial Statistics* (2016), pp. 17–34.
- [67] ITU-R. *Reference standard atmospheres*. Geneva: International Telecom Union for Radio-communication Study Group III, 2017.
- [68] Sergey Loyka, A Kouki, and François Gagnon. “Fade depth prediction on wireless microwave links using two-ray multipath model”. In: *Canadian Conference on Electrical and Computer Engineering 2001. Conference Proceedings (Cat. No. 01TH8555)*. Vol. 1. IEEE. 2001, pp. 493–498.