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NAME OF AUTHOR/NOM DE L'AUTEUR Hassan Nadir Kheirallah
TITLE OF THESIS/TITRE DE LA THÈSE Prediction techniques of rain and multipath
outage statistics for line of sight radio com-
munication systems.
UNIVERSITY/UNIVERSITÉ Carleton
DEGREE FOR WHICH THESIS WAS PRESENTED/
GRADE POUR LEQUEL CETTE THÈSE FUT PRÉSENTÉE Ph. D
YEAR THIS DEGREE CONFERRED/ANNÉE D'OBTENTION DE CE GRADE 1980
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LA THÈSE A ÉTÉ
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PREDICTION TECHNIQUES OF RAIN AND
MULTIPATH OUTAGE STATISTICS FOR LINE OF
SIGHT RADIO COMMUNICATION SYSTEMS

by

(C)

Hassan N. Kheirallah, B.Sc.Eng.; M.Eng.

A thesis submitted to the Faculty of Graduate
Studies and Research in partial fulfillment of
the requirements for the degree of

Doctor of Philosophy

Department of Electronics
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June 1980

The undersigned recommend to the Faculty of Graduate Studies and Research the acceptance of the thesis:

"Prediction techniques of rain and multipath outage statistics
for line of sight radio communication systems"

submitted by Hassan N. Kheirallah in partial fulfillment of the
requirements for the degree of Doctor of Philosophy.

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June-1980

ABSTRACT

The near saturation of the frequency bands below 10GHz, currently used for line of sight radio communication systems, and the anticipated growth in demands have resulted in an increased interest for the use of higher frequency bands allocated for such services. Furthermore, because of the advantages presented by digital techniques and the advancement in this technology, it is expected that digital systems will dominate in any future expansion.

The electromagnetic wave propagation at these frequencies is affected by rain and multipath. In addition to varying the received signal level, multipath, due to its frequency selectivity, also degrades digital signals operating well above the thermal noise limit. Therefore, it is increasingly important to be able to predict accurately the performance reliability of systems operating under these conditions.

The first part of the work deals with different techniques for predicting rain attenuation statistics. The frequency dependence of the effective path length, used in frequency scaling of rain attenuation, is demonstrated. This is then used to derive the theory behind Hogg's graphical method. The new approach of the "normalized effective path length" for combining attenuation measurements at different frequencies is introduced. Based on this approach, a more accurate single-frequency scaling technique, at small percentages of time, is outlined. Moreover, the concept of using the synthetic storm technique to evaluate simpler prediction techniques based on rainfall rate statistics is presented. As a result, the universality of several

reduction coefficient models, employed in path average rain rate techniques, is tested, and improvements in these techniques are suggested.

The second part of the work deals with the multipath effects, especially on digital systems. The design steps of a 37GHz experimental digital radio link, built and installed in Ottawa, Canada, are outlined. Preliminary statistical results for the different signal characteristics are also presented. Finally, in order to gain a better understanding of the process involved, an attempt to correlate propagation and weather data is made.

ACKNOWLEDGEMENTS

The author would like to acknowledge the efforts of his thesis supervisors Prof. J.P. Knight and Drs. R.L. Olsen and K.S. McCormick. He also would like to emphasize the special role of Dr. R.L. Olsen in the form of guidance, discussions and criticism.

He also deeply appreciates the technical assistance provided by the Radio Propagation Laboratory of the Communications Research Centre, Ottawa. The exceptional help and assistance of Mr. W. Mather in building and setting the radio link is warmly recognized. The author would like also to mention the technical assistance of Misterys G. Phillips, W. Rolfe, N. Reed, R. Bérubé and R. Charron. He also would like to thank Dr. B. Segal for the synthetic storm calculations and Mr. J. Schlesak for his assistance in the data recording.

He finally would like to express appreciation to Ms. Saull for her superb typing and the Communications Research Centre for its financial assistance during the course of his research.

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LIST OF SYMBOLS AND ABBREVIATIONS

a	multiplicative factor for the aR^b relation
a_i	amplitude of the i^{th} component
b	exponent of the aR^b relation
$b(t)$	binary sequence
$b'(t)$	auxiliary binary sequence
c	velocity of light
c_ϕ	quadratic phase nonlinear coefficient
d	path length
d_0	short path length
e	water vapour pressure
f	frequency
$f(x,y)$	joint probability density function
j	$\sqrt{-1}$
l	effective path length
l_a	apparent path length
l_0	measure of the extent of the rainfall
m	complex index of refraction of water
n	index of refraction of air
p	total atmospheric pressure
$p\%$	percentage of time
r	amplitude of secondary ray
r	reduction coefficient
$\bar{t}$	integration time
$\bar{t}(L)$	average fade duration

v	terminal raindrop velocity
$V_{\text{DPSK}}(t)$	differential phase shift keying signal
x	distance
x	real part
y	imaginary part
z	height
A	attenuation
A	carrier magnitude
A_P	peak fade
B_N	noise bandwidth
B_R	bit rate
C	terrain factor
D	raindrop diameter
D	antenna diameter
DPSK	differential phase shift keying
E_O	energy per bit
FSL	free space loss
G_T	transmitting antenna gain
G_R	receiving antenna gain
$H(\omega)$	channel transfer function
K	factor for climatic conditions
L	path length
L	signal level
LOS	line of sight
N	refractivity
N	noise power

$N(D)$	drop-size distribution
$N(L)$	total number of fades
N_o	noise power density
P	total outage time per month
$P()$	probability
P_e	bit error rate
P_r	Rayleigh distribution
P_R	received power
P_T	transmitted power
Q	factor for terrain condition
Q_E	extinction cross section
R	rainfall rate
R	amplitude of interfering signal
R	radius of curvature of the ray inside the inversion layer
$\bar{R}$	path average rainfall rate
$R(x)$	path profile of rainfall rate
R_a	apparent rainfall rate
R_i	spatial distribution of rainfall rate
R_j	average rainfall rate
R_o	peak rainfall rate
R_o	radius of curvature of the ray
R_p	point rainfall rate
S	signal power
T	temperature
$T(\omega)$	envelope delay distortion
T_M	total fade duration during heavy fading month

V	signal envelope
L	normalized effective path length
α	specific attenuation
β	differential phase
θ	phase of interfering signal
θ	departure angle of the refracted ray
θ_i	phase shift of i^{th} component
λ	wavelength
τ	relative delay
τ_{max}	maximum echo delay
ϕ	signal phase
ω	angular frequency
ω_c	carrier angular frequency
ω_0	angular frequency of the fade minimum
ΔA	linear amplitude distortion
$\frac{\Delta^2 A}{2}$	quadratic amplitude distortion
ΔL	unit cell distance

CHAPTER ONE

INTRODUCTION

1.1 Introduction

Currently the world is undergoing what some experts term "Information Revolution". Increasing amounts of information are being transferred between different locations around the globe. Information that used to be carried by cables is increasingly using terrestrial or satellite radio systems. The competition between these last two systems is governed by cost, accessibility, reliability and efficiency. Terrestrial systems are almost exclusively used for short-haul applications and are even becoming more attractive for some over-land long distance communication systems.

At the present time, most line of sight (LOS) microwave systems use analogue modulation techniques and operate below 10GHz. However, because of their increasing economic advantage and anticipated high performance reliability, digital modulation techniques are being introduced in several countries. The first microwave digital radio-relay system was built in Japan in 1969. This system was capable of carrying 240 telephone channels using QPSK and a carrier frequency of about 2GHz. Since then, medium and small capacity digital systems using 2, 6, 8, 11, 13, 15 and 20GHz bands have become operational in Canada, France, Italy, Japan, UK and USA.

The increasing demands for high capacity microwave LOS systems, have necessitated the exploration of frequency bands higher than those presently used. Previous international agreements resulted in allocating for this purpose the bands 14.5-15.35, 17.7-19.7, 21-23.6,

25.5-31.3, and 36-40GHz. The recent 1979 World Administrative Radio Conference (WARC) has modified some of these allocations and added a number of new allocations for terrestrial services above 40GHz.

At these high frequencies, the troposphere plays a dominant role in determining the reliability of communication systems. This is manifested through molecular absorption by atmospheric gases, absorption and scattering by hydrometeors (rain, hail, sleet, etc.) or focussing loss caused by the vertical gradient of refractive index.

Molecular absorption constitutes a background attenuation more or less independent of the weather conditions but highly dependent on frequency. Both water vapour and oxygen have well defined absorption bands in the lower centimetre and the millimetre regions of the spectrum. Therefore, their effects can be avoided or at least taken into consideration in any link design.

Rain is by far the most important hydrometeor affecting the electromagnetic wave propagation in the frequency bands of interest. Its effects increase with frequency and are highly variable with both time and space. It causes a constant fading of the signal across a given frequency band and therefore influences both digital and analog systems equally.

Atmospheric multipath is a propagation phenomenon caused by the vertical variation in the refractive index gradient in the lower troposphere. It is, by definition, the arrival of the transmitted signal, at the receiving antenna, through two or more paths. The resulting interference causes the signal to fluctuate around its normal level. Moreover, multipath may be a highly frequency selective phenomenon. Therefore its effects differ with the type of modulation and bandwidth used.

1.2 Thesis objectives and principal results

The purpose of this work is to investigate the behaviour of signals, in the proposed frequency bands, when propagation is hampered by influence of either rain or multipath with special emphasis on systems using digital modulation techniques in the millimetre wave band 36-40GHz. The ultimate objective is to clarify and improve present techniques for predicting the outage probabilities due to propagation effects.

The first part of the work is concerned with the estimation of rain induced attenuation statistics. Because of the lack of reliable long term attenuation measurements at the proposed frequencies, several techniques have been developed previously to either extrapolate measured statistics at other frequencies (frequency scaling) or predict these statistics from point-rain rate data. A detailed theoretical and numerical study of methods using these two approaches is carried out. The theory behind the two-frequency scaling technique by Hogg is derived and a new single-frequency scaling technique is presented. Finally, a comparative evaluation of the synthetic storm and the path average rain rate techniques is given.

The second part of the work involves the establishment of a LOS radio link in Ottawa to study the effects of multipath on digital systems. According to the author's knowledge, this is the first such experiment to be conducted at a carrier frequency in the band 36-40GHz. The purpose of this experiment is to confirm or challenge the present belief that multipath effects are negligible at these high frequencies compared to rain effects.

1.3 Thesis Format

Chapter 2 represents a brief general overview of the effect of rain on electromagnetic wave propagation. A general formula that relates the different characteristics of rain to the signal attenuation is given. The effects of the nonspherical shape of raindrops, their temperatures and size distributions are discussed briefly along with models of rain rate statistics.

Chapter 3 is concerned with the frequency scaling of rain attenuation. Several single and two-frequency scaling techniques are outlined. Theoretical and numerical arguments for the frequency dependence of the effective path length are given. The theory behind Hogg's graphical method is also presented and a new single-frequency scaling technique proposed.

Chapter 4 gives a theoretical and numerical comparison between the path average rain rate and the synthetic storm techniques for predicting attenuation statistics from rain rate measurements. A new concept of employing synthetic storm data to evaluate techniques based on rainfall statistics is introduced. As a consequence, modifications in the path average rain rate model given by Crane [1] are suggested.

Chapter 5 is a brief discussion of the multipath phenomenon. The effects of both flat and frequency selective fading on system performance are outlined. Several models for the multipath propagation are compared. Throughout, special emphasis is given to the behaviour of digital systems under multipath.

Chapter 6 describes the experimental project undertaken to investigate the performance of LOS digital radio systems in the band 36-40GHz under multipath conditions. Basic path calculations and

application of some prediction techniques are given. Also, laboratory results for the performance of the system under thermal noise and simulated multipath conditions are presented.

Chapter 7 presents the results obtained from the field experiment. Several statistical properties for the fading and enhancement of the signal are given. In particular, bit error rate distributions are discussed. Also, an attempt to correlate weather and propagation data is made.

Finally, chapter 8 gives a summary and the conclusions derived from this study.

CHAPTER TWO

RAIN ATTENUATION

2.1 Introduction

Rain plays a dominant role in affecting electromagnetic wave propagation in the centimetre and millimetre wavelength bands. It causes absorption and scattering of radio waves resulting in a reduction of the received signal level and the possibility of interference with adjacent systems. The rain attenuation is a complicated function of many time varying parameters of the propagation medium [2]: the total number of rain drops in the path, the drop-size distribution, the fine grain spatial characteristics of the rain density along the path, wind velocity, the presence of up or down drafts, raindrop shape, the storm cell shapes and sizes, raindrop temperature, etc.

In this chapter, a brief discussion of some basic information on rain attenuation that is relevant to the prediction techniques in the subsequent chapters, is presented.

2.2 Theoretical evaluation of rain attenuation

The simplest theoretical approach for evaluating rain attenuation assumes the raindrops to be spheres of homogeneous complex dielectric constant, randomly distributed in space with uniform density. Results from this approach are commonly used in the prediction techniques in spite of the fact that models accounting for the non-spherical nature of the raindrops have been developed.

Based on the classical Mie scattering theory, the specific attenuation α (dB/km) due to rain at a given frequency, can be related

to the rainfall rate R (mm/h) from the knowledge of the complex index of refraction of water m , the terminal velocity v (m/s) and the size distribution of the raindrops [3-6]. It can be expressed by

$$\alpha = 4.343 \times 10^{-3} \int_0^{\infty} N(D) Q_E(m, \lambda, D) dD \quad (2.1)$$

where $N(D) dD$ (m^{-3}) is the number of drops per unit volume of space with diameter in the interval between D and $(D+dD)$, and $Q_E(m, \lambda, D)$ (mm^2), the extinction cross section of a drop of diameter D (mm) at a wavelength λ (mm), is the summation of both absorption and scattering cross sections.

On the other hand the rainfall rate can be expressed by [4]

$$R = 1.885 \times 10^{-3} \int_0^{\infty} N(D) v(D) D^3 dD \quad (2.2)$$

It can be seen from Eqns. (2.1) and (2.2) that, given a drop-size distribution, the specific attenuation and rainfall rate can be related. However, since typically the rainfall rate is the measured quantity and not the drop-size distribution, a direct relation between α and R is required. One early approach, proposed by Ryde and Ryde [7], assumed the entire rain medium to be composed of drops of the same size, and then superimposed a number of such fictitious rains, each having raindrops of a different diameter, weighted according to their respective probability of occurrence in a certain rain rate. This approach amounts to a numerical integration of Eqn. (2.1). A more recent approach is to fit regression curves for the α - R relation.

2.2.1 The aR^b approximation

Ryde pointed out, based on his early Mie scattering calculations, the approximate validity of a near linear relation between α and R given by [8]

$$\alpha = aR \quad (2.3)$$

However, later, Gunn and East proposed the more general nonlinear relation of the form

$$\alpha = aR^b \quad (2.4)$$

Values for a and b were obtained either by fitting the results of Mie calculations at several frequencies or by evaluating Eqn. (2.4) experimentally [8]. Olsen et al. [8] were able to demonstrate the theoretical basis of Eqn. (2.4). They showed that both a and b are dependent on frequency, drop-size distribution and temperature. They, also, concluded that values of a and b determined by an empirical fit of Eqn. (2.4) give, in general, the best approximation to the full Mie solution. Accordingly, they compiled sets of a and b for frequencies up to 1000GHz for raindrop temperatures of -10 , 0 and 20°C and different drop-size distributions. Additional values for a and b at rain temperatures of 10°C were calculated using their computer program and are given in Appendix A.

The choice of a rain drop temperature is only important for evaluating α at frequencies below 20GHz [8,9] causing a difference of up to 20%.

2.2.2 Drop-size distribution (DSD)

The knowledge of the DSD in rain of given intensity is essential in order to determine the corresponding specific attenuation. Therefore it is important to understand the processes which determine the sizes of raindrops near or above ground.

After their initial formation within a cloud system, the drops are affected by their presence within the cloud, by coalescence and collisions between drops and coalescence between the drops and the water vapour of the cloud. Then, in falling to the ground, the drops may be influenced by evaporation, by droplet interaction and by atmospheric turbulence. At each stage, the drop size depends on many variables, the drop concentration, air temperature, aerosol concentration, humidity, etc., and the change in the size of a particular drop at any time will depend on its existing size [10].

It is therefore not unreasonable to expect that the drop size may have different distributions on a storm by storm basis or even within the same storm [11,12]. However, several attempts have been made to deduce long term average distributions for raindrop sizes.

1. Laws and Parsons distribution (L-P)

This tabular distribution, which is also the most commonly used, has been found to be a reasonable choice for continental temperate rainfall.

It was based on measurements for rain rates up to 50mm/h and then extrapolated to 150mm/h [3]. Olsen et al. [8] fitted two regressions to the L-P distribution, for low and high rain rates, to obtain better accuracy for the values of a and b .

2. Marshall and Palmer distribution (M-P)

This is the first of several analytic distributions that uses a negative exponential function to represent $N(D)$ ($m^{-3} mm^{-1}$)

$$N(D) = N_0 \exp(-BDR^{0.21}) \quad (2.5)$$

$$\text{where } N_0 = 8 \times 10^3 \text{ (m}^{-3} \text{mm}^{-1}) \text{ and } B = 4.1 \text{ (mm}^{-1})$$

This distribution has been found to closely fit the L-P distribution except for small D where it overestimates their number.

3. Joss et al. distributions

Joss et al. proposed three negative exponential distributions of the form of Eqn. (2.5), the thunderstorm distribution (J-T) for convective rain for which $N_0 = 1.4 \times 10^3$ and $B = 3.0$, the drizzle distribution (J-D) for very light widespread rain for which $N_0 = 3 \times 10^4$ and $B = 5.7$ and finally the widespread distribution (J-W) with $N_0 = 7 \times 10^3$ and $B = 4.1$.

It has been pointed out [8,10] that the values of R used in these three distribution versions of Eqn. (2.5) do not agree with the calculated values of R from Eqn. (2.2). Olsen et al. [8] suggested, as a means to solve this discrepancy, a normalization of N_0 of the form

$$\text{For J-T} \quad N_0 \approx 1.31 \times 10^3 R^{0.084} \quad 25 \leq R \leq 150 \quad (2.6)$$

$$\text{For J-W} \quad N_0 \approx 6.62 \times 10^3 R^{0.021} \quad 1 \leq R \leq 50 \quad (2.7)$$

$$\text{For J-D} \quad N_0 \approx 3.38 \times 10^4 R^{-0.03} \quad 0.25 \leq R \leq 5 \quad (2.8)$$

Other attempts to fit log normal or gamma distributions to the raindrop sizes have been made [10]. However they are not commonly used.

Therefore, all calculations in the next two chapters will be restricted to the three major distributions mentioned before.

2.2.3 Effects of the non-spherical shape of water droplets

The assumption of spherical raindrop shape used in the Mie calculation is only a first-order approximation. Close examination by photography reveals that many of the larger drops are better represented by oblate spheroids [13]. As a result, vertically polarized waves are attenuated less than those which are horizontally polarized with the differential increasing with carrier frequency and rainfall rate. In some climates it may reach values as high as 35% [9].

Following the initial analysis conducted by Oguchi in 1960 [13], several researchers have published sets of attenuation coefficients for vertical and horizontal polarizations [9,39,125-128]. Moreover, Nowland et al. [39] generalized the aR^b relation to include the effect of non-spherical drops.

2.3 Rainfall rate distribution

In order to compare the theoretical and experimental results and also to predict the attenuation at any site, rainfall rate distributions must be employed. Rain gauges are used to collect and measure the water from the rain and the data is normally tabulated over a certain time period, such as 1 minute, 5 minutes, an hour or more. Graphs representing the cumulative distribution of rainfall are then drawn. The statistics become more accurate as the period of data gathering increases. Unfortunately these statistics are not made for all regions on the earth. An attempt has been made to determine the cumulative

distribution of rainfall rate at any point using the total annual rainfall. This method is unreliable, since when comparing between two regions having the same total annual rainfall, one may have heavy rain for short periods of time while the other may have light rain for longer periods. The effect of the rain on attenuation is completely different between the two cases.

2.3.1 Types of rain

It is important to consider the different kinds of rain when estimating rain attenuations. In general, rain can be classified into two types [14]:

1. Homogeneous rain, which usually extends widely in the horizontal direction with a constant thickness. It has a rate of 10 to 20mm/h at its maximum and is continuous for a relatively long time.
2. Convective rain, which has horizontal and vertical dimensions ranging from about several to ten or more kilometres. This type of rain is usually accompanied by strong ascending air currents and occasionally brings localized heavy rain for short periods with rates varying rapidly with time. A thunderstorm is an example of this sort of rain.

However, other strong rain, like those associated with typhoons, may extend over large regions. For example, the maximum horizontal extent of such rain observed in Japan was 144km.

2.3.2 Models of rainfall rate distributions

Attempts have been made to generate local and global models for rain rate distributions. On a local basis, several sets of rain rate data indicate that rain rate distributions can be closely approximated

by a log normal distribution [15,16]. However, in the absence of specific information for any location, global rainfall rate prediction models have been proposed.

Rice and Holmberg were the first to present such a model to predict point rain rate distributions. Their model contains three basic parameters: the annual rainfall, the ratio of thunderstorm rain to total rain, and the annual number of days for which precipitation is greater than 0.25mm. This model has been extended by Dougherty and Dutton [17,18], for Europe and the USA, to include spatial and temporal (year to year) variability of rainfall rate which had previously limited the consistency of the model [19].

Furthermore, based on a preliminary version of this model, the OCIR introduced five global rain rate climate types and a corresponding surface point rain rate distribution for each. However, it was pointed out that the model failed to adequately represent the rainfall rate distribution in several parts of the world [20,21]. Recently, a modified version presented by Crane [1,20] divided the world into eight climatic regions and provided a rain rate distribution for each. It also stipulated that the possible variation of the rain rate distribution for a region, either in time (at a point) or in space (within the region) is bounded by the distributions for adjacent regions.

Segal [57] used a new approach to generate a rainfall rate model for Canada based directly on measurements of rainfall rate distributions rather than Rice and Holmberg rain model. This was made possible due to a unique data base from rain gauges spread across the country. This new model shows that both the OCIR and Crane's model do not adequately

represent the Canadian rain climate. It is believed that this approach leads to a more accurate division of the rain climate. However, the adaptation of this approach to generate a global model is hampered by the fact that only few countries possess such a long term data base.

Finally, it should be pointed out that the assumption of the steadiness of climates has not been yet verified. Even after some 20 years, variations in the rain pattern have been noticed. It is not yet clear whether this is due to the use of nonstandard raingauges or to random variations in decennial measurements [16].

2.3.3 Other important rainfall rate characteristics

The cumulative distribution of rainfall rate is not the only quantity of interest to radio engineers. Statistics for worst month, spacial extent of rain cells, space and time autocorrelation functions, average durations, etc., are important quantities required to determine the outage time for any radio systems. Unfortunately, these are not commonly available. Attempts have been made to generate them by using dense networks of raingauges, radar observations, and synthetic storm techniques [23-25,128].

2.4 Prediction methods of rain attenuation statistics

The main reason for radio engineers to be interested in studying rain is due to its effect on propagation. Statistics for rain induced attenuation are needed for the design of microwave communication systems. In general, there are four methods for establishing such statistics [4]:

1. Compilation of data from actual propagation experiments.
2. Determination of statistics from estimated attenuations based on indirect measurements, e.g., radar or radiometer.
3. Extrapolation or interpolation of existing statistics to other frequencies, path configurations, or climatic locations, using theoretical or empirical models.
4. Generation of attenuation statistics by simulation, using a statistical rainstorm model, e.g., the synthetic storm technique.

Statistics based on propagation experiments are available for only a limited number of frequencies, relatively few path configurations, and for time periods generally too short for statistical confidence. Therefore, it has been necessary to turn to indirect measurements, by radar, or radiometer, to extend the data base, and also to seek models that will permit extrapolation of existing data or direct generation of attenuation statistics from rain rate information.

A new extension to the extrapolation methods based on frequency scaling will be introduced in the next chapter. In chapter 4, a comparative evaluation of prediction methods based on rainfall rate statistics and the synthetic storm technique will be carried out.

CHAPTER THREE

FREQUENCY SCALING OF RAIN ATTENUATION

3.1 Introduction

Because of the limited amount of rain attenuation statistics, it is convenient to be able to scale attenuation statistics measured at one frequency to predict those at any other frequency. In general, frequency scaling techniques can be classified into two main groups: those which require attenuation statistics at one frequency, and those which, in addition, require either attenuation statistics at another frequency or point rainfall rate statistics. Usually, methods in the first group require a greater degree of approximation and are consequently less accurate.

In this chapter a brief comparison between several frequency scaling techniques is presented. Theoretical and numerical proof of the frequency dependence of the effective path length are given. This is then used to derive a theoretical basis for the graphical two-frequency scaling technique by Hogg [5,26]. Afterwards, the new concept of the "normalized effective path length" for combining data at various frequencies is introduced. Finally, a new single frequency scaling technique that gives better prediction results for the small percentages of time, is outlined.

3.2 Existing single frequency scaling techniques

One of the basic techniques to scale rain attenuation in frequency is according to the ratio of the multiplicative constants in the ar^b relation. The attenuation experienced in propagation through a homogeneous rainfall of extent L can be expressed as

$$A = aR^b L \quad (3.1)$$

Therefore, the ratio of attenuations at two different frequencies becomes

$$\frac{A_2}{A_1} = \frac{a_2}{a_1} R^{b_2 - b_1} \quad (3.2)$$

If the difference $(b_2 - b_1)$ is assumed very small, this reduces to

$$\frac{A_2}{A_1} \approx \frac{a_2}{a_1} \quad (3.3)$$

This result is strictly correct only for a homogeneous rainfall rate of 1mm/h. For higher rainfall rates, the approximation involved becomes increasingly inaccurate, especially since the exponents b_i vary from about 0.7 to 1.2 over the frequency range from 1 to 100GHz [8].

Since it is unlikely that the rainfall rate is homogeneous over any path other than an extremely short one, Hodge [27] suggested another technique in which he assumed that the rainfall along the propagation path was a Gaussian function of position, x , given by

$$R(x) = R_0 e^{-\left(\frac{x}{l_0}\right)^2} \quad (3.4)$$

where R_0 is the peak rainfall rate and l_0 is a measure of the extent of the rainfall. By integrating the value of the specific attenuation along the entire rainfall, the resultant attenuation becomes

$$A = aR_0^b l_0 \sqrt{\frac{\pi}{b}} \quad (3.5)$$

After some further approximations, the attenuation ratio at two frequencies can be expressed as

$$\frac{A_2}{A_1} = \frac{a_2}{a_1} \left(\frac{A_1}{a_1} \sqrt{\frac{b_1}{\pi}} \right) \left(\frac{b_2}{b_1} - 1 \right) \sqrt{\frac{b_1}{b_2}} \quad (3.6)$$

Although this technique takes into account the inhomogeneity of the rain along the path, the Gaussian distribution and the assumption of infinite path length cannot be always justified.

In spite of the fact that in the derivation of Eqns. (3.3) and (3.6), instantaneous attenuation values were assumed, the further approximation of their applicability to statistical values is usually made.

Other simplistic approaches, based on measured instantaneous attenuation or cumulative statistics, attempt to show that linear [28] or nonlinear [29-32] relationships exist between values of attenuation or their ratios for any two given frequencies. Drufuca [25] has found that, in the frequency range of approximately 11 to 18GHz, the following empirical relation between the attenuation events for the same probability $p\%$ at different frequencies for terrestrial links, exists

$$\frac{A_2(p\%)}{A_1(p\%)} = \left(\frac{f_2}{f_1} \right)^{1.72} \quad (3.7)$$

Furthermore, in the frequency range 10 to 15GHz, Flavin [33] shows a relation, for earth-space paths, of the form

$$A_f(p\%) = A_{11.075}(p\%) [1 + 0.237(f - 11.075)] \quad (3.8)$$

3.3 A two-frequency scaling technique

This is mainly a graphical technique that was developed by Hogg [5,26] to use cumulative attenuation distributions measured at any two frequencies to predict statistics at a third frequency. In this technique, he determines "apparent" rainfall rates at which the theoretical ratio of specific attenuations at any two given frequencies is equal to the measured ratio of attenuations at the same frequencies for given exceedence probabilities. A cumulative distribution of apparent rainfall rate thus obtained is then used in conjunction with the attenuation statistics at one of the frequencies to derive a curve for an "apparent" path length through rain. By multiplying this apparent path length with specific attenuation values, attenuation statistics at any third frequency can be obtained. This technique is applicable to terrestrial as well as earth-space paths.

The application of this technique by Henry [34] resulted in good agreement between measured and predicted attenuation values. However, when it was used in conjunction with data at 4 and 6GHz by the author [35], it failed to give any reasonable results. This prompted an investigation in the theoretical basis of this technique, the results of which is given in section 3.6.

3.4 The effective path length technique

In this technique, commonly used for earth-space paths, the statistics of rain attenuation $A(p\%)$ and point rain rate $R_p(p\%)$ are combined to obtain estimates of an effective path length $l(p\%)$

$$l(p\%) = \frac{A(p\%)}{aR_p(p\%)^b} \quad (3.9)$$

The effective path length can be defined as the extent of a hypothetical uniform rain that causes the same attenuation as that exceeded for a given percentage of time. Curves of effective path length are usually presented as a function of elevation angle [14,36] or rainfall rate [14,37,38]. Some empirical expressions of effective path length have also been given in the literature [12,19,32,39].

The values of effective path length, when combined with any point rain rate distribution and values for a and b for any frequency, can then generate a corresponding attenuation distribution. However, two assumptions are embedded in this technique. First, that the effective path length itself is independent of frequency, and, second that it is universally applicable to any climatic region. These two assumptions will be discussed in more detail in subsequent sections.

For the simpler situation of scaling statistics at the same location, equation (3.2) can be used. However, in this case, A_1 , A_2 and R assume statistical values.

Although the concept of effective path length has not been used for terrestrial paths, it is believed that it can be very helpful in case of long propagation paths along which the rainfall rate cannot be assumed uniform. As a matter of fact, as will be shown in the next chapter, this concept is implicit in some of the prediction techniques based on rainfall statistics.

3.5 Frequency dependence of the effective path length

One of the main assumptions in the effective path length technique is that l_e is independent of frequency. Recently, this assumption has been challenged by the author [35] who showed that the effective path

length may be indeed dependent on frequency. Since then, several researchers, independently, recognized that fact [14,19,32,40]. However, some of them assumed that its effect on the prediction values is insignificant [14].

The frequency dependence of the effective path length results from the nonuniformity of rain along the propagation path in combination with the nonlinear dependence of the specific attenuation on rain rate. This can be seen by substituting in Eqn. (3.9) the actual value of path attenuation for nonuniform rain on a link of length L given by

$$A(p\%) = \left[\lim_{n \rightarrow \infty} \sum_{i=1}^n a R_i^b \frac{L}{n} \right] (p\%) \quad (3.10)$$

to obtain

$$\ell(p\%) = \left\{ \lim_{n \rightarrow \infty} \sum_{i=1}^n \left[\frac{R_i}{R_p(p\%)} \right]^b \frac{L}{n} \right\} (p\%) \quad (3.11)$$

where R_i represents the spatial distribution of rain rate. Thus, since b varies with frequency [8], so does ℓ .

In the approximate frequency range 4 to 100GHz, with the limits depending slightly on the drop-size distribution, b decreases with increasing frequency. Unfortunately, the behaviour of $\ell(p\%)$ with frequency does not appear to be obvious from Eqn. (3.11). However, calculations [35,40] performed on four sets of multiple-frequency measurements for earth-space paths [5,32,37,41] are consistent with a hypothesis that the direction of variation of $\ell(p\%)$ with frequency follows that of b . This is illustrated in Fig. 3.1 and in Figs. 3.2 and 3.3 by curves (a) and (b), which plot $\ell(p\%)$ as a function of $R(p\%)$. The curves in Figs. 3.1 and 3.2 are based jointly on point rain-rate statistics and on path attenuation statistics measured at 13, 19 and

Fig. 3.1 Plots of effective path length versus rain rate for USA data [5]. Specific attenuation calculations based on a and b values for a Laws and Parsons drop-size distribution (LP_H regression) and a rain temperature of 10°C . Percentage of time for which l and R values at each data point exceeded shown in parentheses.

Fig. 3.2 Plots of effective path length versus rain rate for USA data [5,41]. (a) X__X 16GHz data, (b) O__O 30GHz data, (c) Δ__Δ 16GHz prediction from 30GHz data, (d) □__□ 30GHz prediction from 16GHz data. Specific attenuation calculations based on a and b values for a Laws and Parsons drop-size distribution (LP_H regression) and a rain temperature of 10°C . Percentage of time for which l and R values at each data point exceeded shown in parentheses.

Fig. 3.3 Plots of effective path length versus rain rate for Japanese data [37]. (a) X__X 4GHz data, (b) O__O 6GHz data, (c) Δ__Δ 4GHz prediction from 6 GHz data, (d) □__□ 6GHz prediction from 4GHz data. Specific attenuation calculations based on a and b values for a modified Joss-thunderstorm drop-size distribution and a rain temperature of 10°C. Percentages of time for which l and R values at each data point exceeded shown in parentheses.

30GHz [5] and 16 and 30GHz respectively in the USA [5,41], while those in Fig. 3.3 are based on point rain-rate statistics and on attenuation statistics obtained at 4 and 6GHz in Japan [37]. Additional extensive calculations for frequencies between 4 and 100GHz based on applying the "synthetic storm" technique to terrestrial paths of several lengths in two climatic regions also show the variation in ℓ to follow that of b .

3.6 Theoretical examination of Hogg's method

The graphical nature of this method [5,26], requires the tedious task of extracting points from different curves then using them to predict attenuation. Moreover, the lack of a theoretical analysis for the method made it difficult to appreciate the approximations and limitations involved. A thorough investigation was very helpful in gaining a better understanding of this technique in particular and of other scaling techniques in general.

Assuming that ℓ is dependent on frequency, the attenuations at two frequencies $f_1 < f_2$ can be given by

$$A_1(p\%) = a_1 R_p(p\%)^{b_1} \ell_1(p\%) = a_1 R_a(p\%)^{b_1} \ell_a(p\%) \quad (3.12)$$

$$A_2(p\%) = a_2 R_p(p\%)^{b_2} \ell_2(p\%) = a_2 R_a(p\%)^{b_2} \ell_a(p\%) \quad (3.13)$$

where R_a and ℓ_a are an "apparent" rain rate and path length for the equalities to apply. Manipulating these two equations leads to

$$R_a(p\%) = \left[\frac{a_2 A_1(p\%)}{a_1 A_2(p\%)} \right]^{\frac{1}{b_1 - b_2}} \quad (3.14)$$

and

$$\ell_a(p\%) = \frac{A_2(p\%)}{a_2} \left[\frac{a_2 A_1(p\%)}{a_1 A_2(p\%)} \right]^{\frac{b_2}{b_2 - b_1}} \quad (3.15)$$

From the above two equations, distributions for R_a and ℓ_a that corresponds to A_1 and A_2 for the same exceedence probability can be derived. According to Hogg, the attenuation statistics for any third frequency can be expressed as

$$A_3(p\%) = a_3 R_a(p\%)^{b_3} \ell_a(p\%)^{b_3} \quad (3.16)$$

The apparent rain rate and path length can also be expressed in terms of the effective path lengths and point rain rate. Suppressing the $p\%$ for simplicity gives

$$R_a = R_p \left(\frac{\ell_1}{\ell_2} \right)^{\frac{1}{b_1 - b_2}} \quad (3.17)$$

$$\ell_a = \ell_2 \left(\frac{\ell_1}{\ell_2} \right)^{\frac{1}{1 - b_1/b_2}} = \ell_1 \left(\frac{\ell_1}{\ell_2} \right)^{\frac{1}{b_2/b_1 - 1}} \quad (3.18)$$

Given that $b_1 > b_2$ (corresponding to $f_1 < f_2$), it can be shown that $R_a > R_p$ and $\ell_a < \ell_1 < \ell_2$ on the basis of the finding that the variation of ℓ with frequency is in the same direction as that of b .

Hogg showed numerically the same tendency for R_a with respect to R_p . He attributed this to the assumption that the former applies to occurrences on a path whereas the latter applies only at a point, in other words, that a shower is much more likely to intercept a long path than to include a point [5]. However, from Eqn. (3.17), it can be shown that the reason that $R_a > R_p$ is the fact that ℓ decreases with frequency rather than Hogg's explanation. Moreover, if one assumes that ℓ is independent of frequency, as in the effective path-length technique, R_a would be equal to R_p . As a matter of fact, if the frequency dependence of ℓ was in the opposite direction, R_a would be even less than R_p .

Additional calculations have shown that R_a can reach values of hundreds and sometimes thousands of mm/h while l_a can be as small as a few hundred meters for very small percentages of time. For these reasons, it is incorrect to try to give physical interpretations for these two quantities.

3.6.1 Approximations involved in Hogg's method

As in the effective path length technique, implicit in this method is the assumption that l_a is independent of frequency. However, as will be shown later, this is less critical than assuming that l itself is independent of frequency.

If $l_{a_{13}}$ is the apparent path length calculated from attenuation measurements at frequencies f_1 and f_3 , and $l_{a_{23}}$ is that corresponding to the frequencies f_2 and f_3 , then, from Eqn. (3.18) the ratio of $l_{a_{13}}$ and $l_{a_{23}}$ can be given by

$$\frac{l_{a_{13}}}{l_{a_{23}}} = l_3 \frac{b_3(b_2 - b_1)}{(b_1 - b_3)(b_2 - b_3)} \cdot l_1 \frac{b_3}{b_3 - b_1} \cdot l_2 \frac{b_3}{b_2 - b_3} \quad (3.19)$$

Consequently, the exact value of l_3 can be expressed as

$$l_3 = \left(\frac{l_{a_{13}}}{l_{a_{23}}} \right) \frac{(b_1 - b_3)(b_2 - b_3)}{b_3(b_2 - b_1)} \cdot l_1 \frac{b_2 - b_3}{b_2 - b_1} \cdot l_2 \frac{b_3 - b_1}{b_2 - b_1} \quad (3.20)$$

By assuming that $l_{a_{13}} = l_{a_{23}} = l_a$, Hogg implicitly approximates l_3 by

$$l_3 = l_1 \frac{b_2 - b_3}{b_2 - b_1} \cdot l_2 \frac{b_3 - b_1}{b_2 - b_1} \quad (3.21)$$

However, since the values of b are all near unity, one can obtain the same result as in Eqn. (3.21) with the much less restrictive approximation that

$$\left(\frac{\ell_{a_{13}}}{\ell_{a_{23}}} \right) \frac{(b_1 - b_3)(b_2 - b_3)}{b_3(b_2 - b_1)} = 1 \quad (3.22)$$

The effective use of the less restrictive approximation of Eqn. (3.22) is believed to be the main reason for the excellent performance of Hogg's method, as compared to what would be expected from assuming that ℓ_a is independent of frequency.

3.6.2 Dependence of the accuracy of A_3 on the accuracy of A_1 and A_2

It is expected that the accuracy in measuring the attenuation at frequencies f_1 and f_2 will reflect on the accuracy in predicting the attenuation at f_3 . Furthermore, the relative effect of errors in A_1 or in A_2 on the prediction of A_3 will depend on the relative position of f_3 with respect to f_1 and f_2 . Substituting in Eqn. (3.16) for the values of R_a and ℓ_a gives

$$A_3 = a_3 \left[\left(\frac{A_1}{a_1} \right)^{b_3 - b_2} - \left(\frac{A_2}{a_2} \right)^{b_1 - b_3} \right] \frac{1}{b_1 - b_2} \quad (3.23)$$

The variation in A_3 can be expressed by

$$\Delta A_3 = \frac{\partial A_3}{\partial A_1} \Delta A_1 + \frac{\partial A_3}{\partial A_2} \Delta A_2 \quad (3.24)$$

Upon substitution from Eqn. (3.23), it becomes

$$\frac{\Delta A_3}{A_3} = \frac{b_3 - b_2}{b_1 - b_2} \frac{\Delta A_1}{A_1} + \frac{b_1 - b_3}{b_1 - b_2} \frac{\Delta A_2}{A_2} \quad (3.25)$$

Now, if both A_1 and A_2 have the same relative error, then

$$\frac{\Delta A_3}{A_3} = \frac{\Delta A_1}{A_1} = \frac{\Delta A_2}{A_2} \quad (3.26)$$

while if $\frac{\Delta A_1}{A_1} = -\frac{\Delta A_2}{A_2}$, Eqn. (3.25) becomes

$$\frac{\Delta A_3}{A_3} = \left(1 + 2 \frac{b_2 - b_3}{b_1 - b_2}\right) \frac{\Delta A_2}{A_2} \quad (3.27)$$

In order to examine Eqn. (3.25), three situations have to be considered.

1. Prediction of a higher frequency ($f_1 < f_2 < f_3$). In this case $\left| \frac{b_1 - b_3}{b_1 - b_2} \right| > \left| \frac{b_3 - b_2}{b_1 - b_2} \right|$, and consequently a relative error in A_2 affects A_3 more than does a similar error in A_1 , and produces an error in A_3 of opposite sign. Moreover, as $b_3 \rightarrow b_2$, the effect of $\frac{\Delta A_1}{A_1}$ is reduced and $\frac{\Delta A_3}{A_3} \rightarrow \frac{\Delta A_2}{A_2}$.
2. Prediction of a lower frequency ($f_3 < f_1 < f_2$). In this case the same arguments can be applied to show the importance of the relative error in A_1 .
3. Prediction of a middle frequency ($f_1 < f_3 < f_2$). In this case the effect of the relative errors is additive with the contribution depending on how close f_3 is from each one.

3.7 Frequency scaling of the effective path length

It has been shown that the accuracy of the frequency scaling of rain attenuation using the effective path length technique may be affected by the neglect of the frequency dependence of ℓ . The theoretical investigation of Hogg's technique led to an expression relating the effective path length at different frequencies.

Rearranging Eqn. (3.18) gives

$$\ell_2 = \ell_1 \frac{b_2/b_1}{1 - b_2/b_1} \ell_a \quad (3.28)$$

and making the approximation that

$$l_a \frac{1 - b_2/b_1}{1} \approx 1 \quad (3.29)$$

results

$$l_2 \approx l_1 \frac{b_2/b_1}{1} \quad (3.30)$$

Given that $f_2 > f_1$ and consequently $b_2 < b_1$, Eqn. (3.30) shows that l decreases with frequency which is in agreement with experimental observations. Moreover, Eqn. (3.30) allows measurements at one frequency to be transformed into predictions at another frequency.

Application of Eqn. (3.30) is demonstrated in Fig. 3.2 using the 16 and 30GHz data [41], and in Fig. 3.3 using the 4 and 6GHz data [37]. In each case, curve (c) is a prediction of l at low frequency from measurements at the high frequency, curve (d) a prediction at the high frequency from measurements at the low frequency. As evident in Fig. 3.3, Eqn. (3.30) is a better approximation than the normal assumption that l is independent of frequency. This is true at all percentages of time for which attenuation statistics were measured. For example, at a percentage of time of approximately 0.06% where Eqn. (3.30) gives exact results, the error in predicting the path attenuation at 6GHz using the effective path length for 4GHz is 17%.

As seen in Fig. 3.2, Eqn. (3.30) is a better approximation than the "constant- l assumption" only for small percentages of time. The failure of Eqn. (3.30) for the largest percentages of time in Fig. 3.2 but not in Fig. 3.3, is believed to result, at least in part, from the presence of

significant cloud attenuation for these percentages of time at the higher frequencies. In general, however, the rain becomes more uniform at large percentages of time and consequently it is expected that Eqn. (3.30) would overestimate the frequency dependence of ℓ .

Unfortunately, because of the lack of multiple frequency attenuation measurements for long terrestrial paths, it was only possible to test Eqn. (3.30) for earth-space data. Nevertheless, extensive calculations of the effective path length for hypothetical terrestrial paths, using "synthetic-storm" data, have shown considerably less frequency dependence than predicted by Eqn. (3.30). Although, one should be cautious in interpreting these results, it is still possible that there exist a significant difference between terrestrial and earth-space paths in the amount of frequency dependence of ℓ .

3.7.1 The normalized effective path length

In the effort of predicting the rain attenuation at different locations, attempts have been made to develop universal curves for the effective path length from measurements at a number of different locations[42]. These attempts are hampered by the fact that these measurements were conducted at different frequencies. The concept involved in Eqn. (3.30) represents one possible way to solve this problem.

Eqn. (3.30) can be rewritten for N frequencies as

$$\ell_1^{1/b_1} = \ell_2^{1/b_2} = \dots = \ell_N^{1/b_N} \quad (3.31)$$

If this approximation is as accurate as it appears in the results of Figs. 3.2 and 3.3, then $\ell = \ell_i^{1/b_i}$ ($i=1, \dots, N$), defined as the "normalized effective path length", is a much less frequency dependent quantity than ℓ . Consequently, it is suggested that all effective path calculations for small percentages of time should be expressed in terms of ℓ before data at various frequencies are combined in order to seek universal relationships involving elevation angle and either rain rate or percentage of time.

3.7.2 A new single frequency scaling technique

From the previous discussion of the single frequency scaling techniques, it was argued that some of the approximations involved were inaccurate. The concept of the normalized effective path length offers an alternative prediction technique that compensates for some of these inaccuracies.

Eliminating R_p from Eqns. (3.12) and (3.13), the following relation between the attenuations at different frequencies can be obtained

$$A_2 = a_2 \left(\frac{A_1}{a_1} \right)^{b_2/b_1} \frac{\ell_2}{\ell_1^{b_2/b_1}} \quad (3.32)$$

Using the assumption in Eqn. (3.30) this reduces to

$$A_2 = a_2 \left(\frac{A_1}{a_1} \right)^{b_2/b_1} \quad (3.33)$$

Thus, for frequency scaling of rain attenuation statistics at the same location, point rain rate statistics are unnecessary. It is for predictions at other locations where the R_p statistics may be different that it is useful to calculate ℓ as an intermediate step.

3.7.3 Comparison with existing single frequency scaling techniques

In order to determine the prediction accuracy of the new method, a comparison was carried out with measurements and other prediction techniques. The expressions used for predicting attenuations in each of these techniques are

1. The exact value

$$A_2 = A_2' \cdot \ell_2 / (\ell_1^{b_2/b_1}) \quad (3.34)$$

2. New method

$$A_2 = A_2' \cdot 1 \quad (3.35)$$

3. Constant- ℓ method

$$A_2 = A_2' \cdot \ell_1^{1 - \left(\frac{b_2}{b_1}\right)} \quad (3.36)$$

4. Hodge's method

$$A_2 = A_2' \cdot \left[\left(\sqrt{\frac{b_1}{\pi}} \right)^{\frac{b_2}{b_1}} - 1 \sqrt{\frac{b_1}{b_2}} \right] \quad (3.37)$$

where $A_2' = a_2 \left(\frac{A_1}{a_1} \right)^{b_2/b_1}$

Basically, the only difference between these expressions is the multiplier at the right hand side. For predicting the attenuation at a higher frequency, the multipliers for the constant- ℓ and Hodge's method are greater than one, predicting more attenuation than the new method. And since from Figs. 3.2 and 3.3, $(\ell_2/\ell_1)^{b_2/b_1}$ is less than one for low percentages of time, the new method will give more accurate results. A similar argument will lead to the same conclusion for predictions at lower frequencies.

Figs. 3.4 and 3.5 represents numerical comparisons between these prediction techniques. As expected the new method gives better results at low percentages of time where rain is nonuniform. However, for high percentages of time, Hodge's method is the best. This can be explained by comparing Eqns. (3.35) and (3.37). The difference in their predicted attenuation is a constant factor for any two frequencies. This means that Hodge's method is equivalent to assuming a frequency dependence less than that given by Eqn. (3.30) which is probably more accurate at high percentages of time.

3.8 The effect of drop-size distribution on the scaling methods

In all the scaling techniques, the aR^b approximation for the specific attenuation is used. Since a and b are dependent on drop-size distribution and drop temperature it is to be expected that the values of the predicted attenuations will be influenced by their choice. The value of a is linearly proportional to N_0 in Eqn. (2.5) for the drop-size distribution and may vary by up to 60% from one drop-size distribution to another. Meanwhile the change in b is much more moderate.

If one assumes that the variation of a and b with drop-size distribution and temperature is given by $a \propto f_1(N(D), T)$ and $b \propto f_2(N(D), T)$ and that in any ratio of a (or b) at different frequencies, this dependence is either cancelled out or minimized, then the corresponding dependence of the predicted attenuation on these functions can be derived for each of the prediction techniques.

1. The new method

$$A_2 = K_1 [f_1(N(D), T)]^{1 - \frac{b_2}{b_1}} \quad (3.38)$$

Fig. 3.4 Comparison between predicted attenuations at 6GHz using measured data at 4GHz in Japan. Calculations based on a and b values for a modified Joss-thunderstorm drop-size distribution and a rain temperature of 10°C. Percentage of time for which A values at each data point exceeded shown in parentheses.

Fig. 3.5 Comparison between predicted attenuations at 16GHz using measured data at 30GHz in USA. Calculations based on a and b values for a Laws and Parsons drop-size distribution (LP_H regression) and a rain temperature of 10°C . Percentage of time for which A values at each data point exceeded shown in parentheses.

2. Hodge's method

$$A_2 = K_2 [f_1(N(D), T)]^{1 - \frac{b_2}{b_1}} [f_2(N(D), T)]^{\frac{b_2}{b_1} - 1} \quad (3.39)$$

3. Constant- k method

$$A_2 = K_3 R_p K_4 f_2(N(D), T) \quad (3.40)$$

It is obvious that all these methods are highly dependent on drop-size distribution and drop temperature. In comparison, by rewriting Eqn. (3.23), of Hogg's method, in the form

$$A_3 = A_1 \frac{b_3 - b_2}{b_1 - b_2} A_2 \frac{b_1 - b_3}{b_1 - b_2} \left\{ \left[\frac{a_3}{a_1} \right] \frac{b_3 - b_2}{b_1 - b_2} \left[\frac{a_3}{a_2} \right] \frac{b_1 - b_3}{b_1 - b_2} \right\} \quad (3.41)$$

it becomes clear that it is almost independent of drop-size distribution and drop temperature.

Table 3.1 represents the effect of drop temperature on the predicted attenuation at 6GHz from measurements at 4GHz [37] for the three single-frequency scaling techniques. The percentage error in some cases may exceed 40%. Table 3.2 is a sample of the calculations performed to study the effect of the drop-size distribution. The three frequency data presented in reference [5] was chosen in order to include results from Hogg's method. The calculations confirms the theoretical analysis. The predicted values from Hogg's method are almost independent of drop-size distribution while those from the other techniques have much wider variations.

It should be noted that all the above calculations and derivations are based on the assumption that b decreases with frequency which is

% of time	A_6	New Method			Constant- λ method			Hodge's method		
		0°C	10°C	20°C	0°C	10°C	20°C	0°C	10°C	20°C
.01	2.90	-1	12	33	10	29	53	7	23	44
.03	2.620	-5	7	27	8	26	50	2	17	38
.06	2.560	-14	-2	15	0	17	39	-7	7	25
.10	2.400	-18	-6	10	-2	15	36	-11	2	19
.20	2.080	-19	-7	18	-1	17	39	-12	0	17
.30	1.904	-21	-10	5	-1	17	39	-15	-1	14
.40	1.710	-19	-7	8	9	32	55	-12	1	18
.80	1.420	-24	-12	2	1	24	45	-17	-4	11

Table 3.1 Comparison between the effects of drop temperature variation on three prediction techniques. The entries are percent differences between values of attenuation measured at 6GHz and those predicted from measurements at 4GHz in Japan [37]. J-T drop-size distribution.

% of time	A ₁₉	New method		Constant-t method				Hodge's method			Hogg's method		
		J-T(10°C)	LP _H (10°C)	J-T(10°C)	LP _H (10°C)	J-T(10°C)	LP _H (10°C)	J-T(10°C)	LP _H (20°C)	LP _H (10°C)	J-T(10°C)		
		A _{19/19} A _{19/19}	A _{19/19} A _{19/19}	A _{19/19} A _{19/19}	A _{19/19} A _{19/19}	A _{19/19} A _{19/19}	A _{19/19} A _{19/19}	A _{19/19} A _{19/19}					
0.04	25.48	0 -10	9 -26	15 -32	23 -41	5 -23	14 -35	-9	-2	-4			
0.07	21.11	-11 0	-2 -18	4 -28	11 -37	-5 -15	2 -27	-10	-7	-8			
0.10	16.70	-11 15	-2 -5	4 -19	11 -28	-5 -1	1 -16	-5	-3	-4			
0.20	9.57	-14 49	-7 23	0 2	5 -8	-9 27	-3 9	1	0	0			
0.40	5.09	-16 41	-10 19	-2 -3	2 -12	-11 21	-5 5	-1	-2	-2			
0.70	3.15	-16 39	-11 18	- -	- -	-11 19	-6 5	-1	-3	-3			
1.00	2.22	-15 35	-10 16	- -	- -	-10 16	-5 3	0	-3	-2			

Table 3.2 Comparison between the effects of drop-size distribution on different prediction techniques. The entries are percent differences between values of attenuation measured at 19GHz and those predicted from measurements at 13 and 30GHz in the USA [5].

true for most of the frequencies of interest [8]. However, for frequencies below 8GHz, the b increases with frequency for some drop-size distributions. Consequently, caution is recommended when applying the above scaling techniques. For example, the application of Hogg's method using L-P drop-size distribution and 4 and 6GHz attenuation measurements results in values of R_a increasing with percentages of time, which is physically unrealistic. Table 3.3 represents values for R_a and L_a along with predicted attenuation at 12GHz which is much higher than one would expect.

3.9 Conclusions

The frequency dependence of the effective path length, presented in this chapter, was essential for the derivation of the theoretical basis of Hogg's method. This method has been demonstrated to be the best available frequency scaling technique.

The new single frequency scaling technique which is based on the concept of the normalized effective path length has been shown to have the following advantages:

1. It considers the nonuniformity of the rain rate.
2. No point rain rate statistics are needed.
3. No spatial distribution of rain rate is assumed.
4. Gives better results at the small percentages of time of greater interest.

However, it still has to be tested for long terrestrial paths to determine its applicability.

Finally, it should be remembered that, the accuracy of all frequency scaling techniques is affected by the lack of long term

% of time	R_a	l_a	A_{12}
.01	1.75	1258.0	55.5
.03	2.37	739.7	46.1
.06	4.65	248.5	38.3
.10	6.40	170.7	33.1
.20	7.60	116.1	27.4
.40	8.40	83.0	21.9
.80	13.80	34.5	16.1

Table 3.3 The application of Hogg's method to predict the 12GHz attenuation from data measured at 4 and 6GHz [37] using L-P_H drop-size distribution and drop temperature of 20°C.

attenuation statistics. Also, additional complications may arise, if it is required to scale the attenuation for a different path length and/or climatic region.

CHAPTER FOUR

ATTENUATION PREDICTION FROM RAIN RATE MEASUREMENTS

4.1 Introduction

Attenuation prediction techniques based on rain rate measurements are widely used because of the frequent availability of rain gauge records. Generally, they do not suffer from the same restrictions of the frequency scaling techniques. And therefore, constitute a quick and inexpensive way of estimating the outage probability of radio systems operating under a large variety of conditions, e.g., frequency, path length, climatic region, etc.

The rain attenuation along a path can be expressed as in Eqn. (3.10) by

$$A = \lim_{n \rightarrow \infty} \sum_{i=1}^n a R_i^b \frac{L}{n} = \overline{a R^b} L \quad (4.1)$$

The direct application of this equation to predict attenuation is impractical since a large number of rain gauges would be required to adequately measure the spatial distribution of rain. Consequently, all available prediction methods are based on an estimate of that distribution from rain gauge readings at one location on or near the path.

The prediction techniques based on rain gauge data can be classified into two main groups: (a) the synthetic storm technique, and (b) rainfall statistics techniques.

The first group, utilizing the synthetic storm concept, is basically a single technique with a few differences in implementation

procedure [25,43-45]. This technique generates attenuation statistics by using a storm translation velocity to convert time records of rain rate at a point to spatial distributions along a path. It does not in general give agreement with observed attenuation in individual cases, but it has been found to give good statistical agreement. Although the synthetic storm technique requires a more detailed analysis than the others, it has the advantage that it can be used also to investigate other attenuation characteristics such as duration and joint probability distributions for hops in tandem [25].

The second group of methods all make use of the cumulative distribution of rain rate measured at a point. Some of the methods in this group use a fitted theoretical distribution [46,47] while others employ a measured distribution directly [48]. In some methods, the problem of spatial inhomogeneity of rain is handled by integrating a statistical path profile of rain intensity [21,45-49], while in others a path average rain rate is employed [1,49-51]. In the latter, the path average rain rate statistics are normally derived from the point statistics by means of an empirical reduction coefficient. The chief advantage of all the methods of this group is that they are relatively simple to apply.

Because of the similarity of the synthetic storm approach to the actual process and its statistical accuracy, it offers a potential means of evaluating the approximations inherent in simpler techniques based on rainfall statistics [52]. Since path average rain rate statistics can be generated in addition to attenuation statistics [53], prediction methods based on a path average rain rate can be given particular attention. In this chapter, the assumptions underlying the synthetic

storm and the path average rain rate techniques are first examined, and several versions of the latter [1,21,49,51,54] are then singled out for evaluation with synthetic storm data from several locations across Canada.

4.2 The synthetic storm technique (SST)

In this technique, a storm translation velocity v is used to convert time records of rain rate measured by a rain gauge at a point into spatial distributions along a certain path. More specifically, the average rain rate R_j measured by a rain gauge having an integration time $\bar{t}$ is assumed to apply over a unit cell distance along the path

$$\Delta L = v\bar{t} \quad (4.2)$$

The total attenuation is then given by the summation of the contribution of n such cells

$$A = \sum_{j=1}^n a R_j^b \Delta L \quad (4.3)$$

where $n = L/\Delta L$. This value remains the same for an interval of time equal to $\bar{t}$. In the next time interval, R_1 assumes the value of the new rain gauge reading, and the R_j assumes the values of R_{j-1} in the present interval. The resulting values of attenuation are then compiled into statistics.

As evident from this procedure, the SST involves the following assumptions:

1. The spatial structure of the rain cell is maintained, not only until it has crossed the rain gauge, but also until it has passed beyond the limits of the hypothetical path. This hypothetical path length is bounded on the lower end by the length of the unit cell in Eqn. (4.2) and on the upper end by the validity of the time - space interchangeability assumption. A tentative length of 30km is usually regarded as upper limit [55].
2. The microwave-link coincides with the main direction of travel of the storms. Studies have shown that statistically the use of the windspeed, as opposed to the wind velocity component along a link, or indeed the use of long-term average windspeed during rain, appears to be acceptable [25,44,45]. The windspeed at the 700mb pressure level was found to best represent the storm translation velocity [45,56].
3. The drop-size distribution, drop temperature and inclusion of polarization effects are taken into consideration by the choice of the appropriate values of a and b in Eqn. (4.3).

The consequence of these assumptions is that individual attenuation calculations will not agree with detailed observations, but this is not an inherent limitation. The important result is that attenuation statistics agree with observations. Indeed, good statistical agreement has been found for most paths [25,43-45], including some in regions of orographic (mountainous) rain [43]. However, only a few comparisons have been carried out for long paths [43,45], and these were hampered by the limited length of the experimental data sample available.

4.3 The path average rain rate technique (PARRT)

In general, all versions of this technique, except the modified Crane's method in section 4.3.2, multiply specific attenuation values calculated from path average rain rate statistics $\bar{R}(p\%)$ by the actual path length L to obtain the statistics of attenuation $A(p\%)$. Expressed in terms of the approximate power-law relation for specific attenuation, this becomes

$$A(p\%) = a \bar{R} (p\%)^b L \quad (4.4)$$

where

$$\bar{R} = \sum_{i=1}^n \frac{R_i}{n} \quad (4.5)$$

In most versions of the PARRT, the path average rain rate statistics $\bar{R}(p\%)$ are related to the point rain rate statistics $R_p(p\%)$ by a reduction coefficient

$$r = \bar{R}(p\%) / R_p(p\%) \quad (4.6)$$

Curves of r have been proposed for different path lengths using either percentage of time [49,54] or rain rate [51] as parameter. Attempts have also been made to deduce empirical expressions for r [48]. More recently, Crane [1] has modelled r by the following power law approximation

$$r = \gamma R_p^{-\delta} \quad (4.7)$$

where γ and δ are coefficients dependent on path length given by

$$\gamma(L) = 1 + \left[\frac{L}{4.5} \right] - 0.23 \left[\frac{L}{4.5} \right]^2 + 0.0215 \left[\frac{L}{4.5} \right]^3 \quad (4.8)$$

$$\delta(L) = \left[\frac{L}{21.5} \right] - 0.98 \left[\frac{L}{21.5} \right]^2 + 0.446 \left[\frac{L}{21.5} \right]^3 \quad (4.9)$$

for path lengths less than 22.5km. In most instances, models for r have been based on the limited data available from dense rain gauge networks. In others, less reliable models have been deduced from attenuation and point rain rate statistics. However, in all cases the model is assumed to be universally applicable for all climatic regions.

4.3.1 The approximations in the PARRT

Previous investigators appear to have assumed that the approach expressed by Eqn (4.4) is valid. A comparison with Eqn. (4.1), however, demonstrates that the following approximation is inherent in this approach [52]:

$$\overline{R}^b(p\%) = \overline{R}(p\%)^b \quad (4.10)$$

Eqn. (4.4) is accurate at frequencies for which b is very close to unity, but as b departs from this value [8], the approximation becomes increasingly inaccurate. For $b < 1$, Eqn. (4.4) will overestimate and for $b > 1$, it will underestimate the actual attenuation.

Because the accuracy of Eqn. (4.10) depends on frequency it is useful to consider the approximation further. Substitution of Eqn. (4.6) in Eqn. (4.4) gives

$$A(p\%) = aR_p(p\%)^b r^b L \quad (4.11)$$

It is evident, therefore, that the PARPT employed by most investigators is equivalent to assuming an effective path length

$$l = r^b L \quad (4.12)$$

which is a function of frequency in addition to path length and rain rate. Furthermore, in the high rain rate range for which $r < 1$, and in the frequency band of interest where b decreases with increasing frequency [8], the l expressed by Eqn. (4.12) will increase with increasing frequency. This is in contradiction with the results obtained in the previous chapter. Only for low rain rates, where $r > 1$, is the sense of the frequency variation of Eqn. (4.12) correct.

In his version of the PARPT, Crane [1] made the additional simplification

$$r^b = r \quad (4.13)$$

which when substituted in Eqn. (4.12) results in an effective path length

$$l = rL \quad (4.14)$$

that is independent of frequency. When viewed in isolation, this approximation would appear to be unnecessary. However, when examined in a general context [52] it turns out to have a compensating effect to the incorrect frequency variation of l in Eqn. (4.12) caused by the approximation in Eqn. (4.10). Only for low rain rates where $r > 1$ do

the approximations of Eqns. (4.10) and (4.13) have a noncompensating effect.

Finally, in the versions of the PARRT of Crane [1] and Barsis and Samson [51], extrapolation in the rain attenuation statistics is required for path lengths longer than 22.5 and 22km, respectively. On the one hand Crane assumes that the occurrence probability of a given attenuation for path lengths longer than 22.5km is proportional to path length. On the other, Barsis and Samson assume that the attenuation for a given occurrence probability is proportional to path length. These assumptions are both reasonable, but in different ranges of the attenuation distribution. For large percentages of time where rain is more uniform, the assumption of Barsis and Samson is appropriate. However, for the low percentages of time which is of greatest interest, Crane's assumption would seem to be more appropriate.

4.3.2 Modified Crane's method

Recently, Crane [21] recognized the inaccuracy involved in the path average rain rate approach. He noted that although his path average model produced the desired relationship between the rain rate at a point and the rain rate averaged over a horizontal path of length L , it was not adequate for estimation of attenuation because of the nonlinear relation between rain rate and specific attenuation. He concluded that a statistical model of the profile of instantaneous rain rate along the path was required which then could be integrated to produce the desired attenuation value.

The path average rain rate can be expressed as a function of path length L by

$$\bar{R}(L) = \frac{1}{L} \int_0^L R(x) dx = r(L) R_p \quad (4.15)$$

where $R(x)$ is the desired path profile of rain rate. Upon rearranging Eqn. (4.15) and differentiating

$$\frac{d}{dL} \left[\int_0^L R(x) dx \right] = \frac{d}{dL} [Lr(L) R_p] \quad (4.16)$$

then

$$R(L) = R_p \frac{d}{dL} [Lr(L)] \quad (4.17)$$

Using values of $R(L)$ thus obtained, Crane derived a modified model for the predicted attenuation

$$\left. \begin{aligned} A &= aR_p^b \left(\frac{e^{ub} - 1}{ub} - \frac{w^b e^{cbd}}{cb} + \frac{w^b e^{cbL}}{cb} \right); \quad d \leq L \leq 22.5 \text{ km} \\ A &= aR_p^b \left(\frac{e^{ubL} - 1}{ub} \right); \quad 0 < L < d \end{aligned} \right\} \quad (4.18)$$

$$\text{where } u = \frac{\ln[we^{cd}]}{d}; \quad d \text{ in km} \quad (4.19)$$

$$w = 2.3R_p^{-0.17}; \quad R_p \text{ in mm/h} \quad (4.20)$$

$$c = 0.026 - 0.03 \ln R_p \quad (4.21)$$

$$d = 3.8 - 0.6 \ln R_p \quad (4.22)$$

Although Crane's modified method addresses the main problem in the PART, it has two potential draw backs. First, it incorporates his path average rain rate model which, as will be demonstrated in section 4.4, appears to be inadequate. Second, it assumes that the statistical rain rate profile along a path that corresponds to a statistical path average rain rate can be used to derive the exact rain attenuation statistics.

4.4 Numerical results

In order to investigate the various approximations inherent in the PARRT, synthetic storm calculations were carried out using the 10-year rain rate data bases [57] for Ottawa, Winnipeg, Regina and Vancouver. These cities are representative of at least three distinct climatic regions in Canada [22]. Both attenuation and path average rain rate statistics were obtained for path lengths of 5, 10, 15 and 20km. A one minute integration time was employed with the average 700mb wind speeds appropriate for these regions.

4.4.1 Test of the universality of r

The assumption of all versions of the PARRT that a universal relation for r exists in either rain rate or percentage of time is examined in Figs. 4.1 and 4.2. In Fig. 4.1, synthetic storm calculations for r are compared with the results for the models of Crane (CM) [1] and Barsis and Samson (BSM) [51] on a rain rate scale; in Fig. 4.2 the same calculations are compared with results for the models of Harden et al. [49] and the CCIR [54] on a percentage of time scale.

The comparison in Fig. 4.1 indicates that CM overestimates r for low rain rates. At the very lowest rain rates, the model predicts values of r that are much greater than unity, the occurrence of which is doubtful in reality. In contrast, the SST results show that the value of r remains close to unity up to at least 12mm/h for Ottawa, 10mm/h for Regina, and 7mm/h for Winnipeg, for path lengths of 20km or less. This agrees with previous results by Jones and Sims [58] that indicate that point and path average rain rates are the same on a 22km path at rates of 10-14mm/h or less. It may be significant that almost all data

(a)

(b)

Fig. 4.1 Reduction coefficient versus point rain rate, — Synthetic storm calculations for Ottawa (O), Regina (R), Vancouver (V), and Winnipeg (W); - - Crane's model [1]; X model of Barsis and Samson [51]. (a) $L = 5\text{km}$, (b) $L = 20\text{km}$.

Fig. 4.2 Reduction coefficient versus percentage of time. -- Synthetic storm calculations for Ottawa (O), Regina (R), Vancouver (V), and Winnipeg (W); • model of Harden et al. [49]; X C.C.I.R. model [54]. (a) $L = 5\text{km}$, (b) $L = 20\text{km}$.

employed by Crane showing values of r much greater than unity for low rain rates came from measurements in Florida.

For rain rates above 20mm/h and paths up to about 10km in length, both CM and BSM give a relatively good fit to the synthetic storm results for Ottawa and Regina. Above about 70mm/h the Winnipeg results deviate sharply from both models. This is believed to be due to one heavy storm that passed over the rain gauge. For paths longer than 10km both models underestimate r for the three locations. In the case of Vancouver, they overestimate r for all rain rates and path lengths. This suggests that the reduction coefficient cannot be assumed universal in terms of rain rate and that different models may be required for different climates.

The comparison on a p% scale in Fig. 4.2 indicates that the model of Harden et al. [49] fits the synthetic storm data better for short paths than does the CCIR model, whereas for long paths the CCIR model provides a better fit. The difference in these two models is understandable, however, in view of the differences in the synthetic storm data for different locations. In contrast to the situation in Fig. 4.1, the Vancouver data do not represent an extreme except at high percentages of time. This lends a further degree of support to the accuracy of the synthetic storm data for Vancouver in Fig. 4.1.

4.4.2 Test of the approximations in the PARRT

The effect of the various approximations in Crane's version of the PARRT, selected as an example, is illustrated in Fig. 4.3 using the synthetic storm data for a 20km path at Ottawa. The solid curves express the percent difference in calculations based on Crane's method

Fig. 4.3 The effect of various approximations in the PARRT at 10, 30 and 50GHz with respect to percentage of time. Rain rate data for Ottawa, 20km path length, modified Joss-widespread drop-size distribution (10°C rain temperature). — percent difference between SST and Crane's method; --- percent error caused by the approximation in Eqn. (4.10); percent error caused by combined effect of approximations in Eqns. (4.10) and (4.13).

from those based on the SST for a range of exceedance percentages $p\%$ on the cumulative distribution. The large percent differences at high $p\%$ is due to the large discrepancies in OM for r at low rain rates as indicated in Fig. 4.1b. The differences for different frequencies is due to the variable effect of the combination of approximations in Eqns. (4.10) and (4.13).

The effect of the fundamental approximation of Eqn. (4.10) is illustrated by the dashed curves, which are based entirely on synthetic storm data (including r). As noted in the previous section, the PARRT will underpredict the attenuation when $b > 1$ (e.g., 10 and 30GHz) and overpredict when $b < 1$ (e.g., 50GHz). Since b is near maximum at 10GHz for the modified Joss-widespread drop-size distribution employed, it is expected that the highest negative error of 18% is near maximum. Large positive errors can be expected at frequencies above 50GHz.

The combined effect of the fundamental approximation of Eqn. (4.10) and that of Eqn. (4.13) introduced by Crane is shown by the dotted curve in Fig. 4.3 for 10GHz. Again these results are based on synthetic storm data. As noted previously, there is a general tendency of Crane's approximation to offset the fundamental one. For the most important low percentages of time, the reduction in the error is considerable. For the large percentages of time for which the frequency dependence of $r^b L$ is in the same direction as the actual dependence of L , the error is increased as expected. Similar results were obtained for 30 and 50GHz. Thus, although the combined effect of the approximations of Eqns. (4.10) and (4.13) causes some error, the major limitation to the accuracy of Crane's method would appear to be the model for the reduction coefficient r .

Fig. 4.4 is a comparison between the modified Crane's method and the SST. In general, this new method gives better results than the old one. However, at large percentages of time the comparison is still poor. It gets even worse at frequencies for which $b > 1$ (e.g., 10 and 30GHz). Once more it is believed that CM for r , incorporated in the new method, is the main cause of most of the inaccuracies.

Figs. 4.5 and 4.6 represent comparisons between effective path lengths calculated using SST, Crane's method and the modified Crane's method. Both the SST and the modified Crane's method give values of l that decrease with frequency, except for the case of the SST at $L = 20\text{km}$ and very low percentages of time. This is probably due to insufficient amount of data. Although the frequency dependence of l in the modified Crane's model is much larger than in the SST, it is less than that predicted by Eqn. (3.30). Moreover, in both methods it decreases with decreasing percentage of time. Both Crane's method and the modified version give values of l that are much larger than the actual path length L for large percentages of time. This is due to the fact that CM predicts that $R > R_p$ at these percentages of time. Finally, it is to be noted that for low percentages of time, where the accuracy of CM improves especially for short path lengths, the differences in l from the three techniques is reduced.

4.4.3 The effect of drop-size distribution

As mentioned before the values of the predicted attenuation depends on the drop-size distribution chosen for the calculations. Even in the 30 to 50GHz range where differences in the drop-size distribution tend

Fig. 4.4 Percent difference between SST and the modified Crane's method for 10, 30 and 50GHz with respect to percentage of time. Rain rate data for Ottawa, 20km path length, modified Joss-widespread drop-size distribution (10°C-rain temperature).

Fig. 4.5 Plots for (l/L) versus frequency for different percentages of time for SST (1), Crane's method (2) and modified Crane's method (3). Rain rate data for Ottawa, 5km path length, modified Joss-widespread drop-size distribution (10°C rain temperature).
 — 1%, --- 0.1%, — 0.01%, - - - 0.001%.

Fig. 4.6 Plots for (l/L) versus frequency for different percentages of time for SST (1), Crane's method (2) and modified Crane's method (3). Rain rate data for Ottawa, 20km path length, modified Joss-widespread drop-size distribution (10°C rain temperature).
 — 1%, --- 0.1%, -.- 0.01%, .-. 0.001%.

to be least significant in their effect on attenuation [8], their effect can still be sizable. Fig. 4.7, for example, gives curves showing the percent difference in attenuation for the J-W and the J-T distributions using Crane's method and the cumulative rain rate distribution for Ottawa. Similar differences occur for the SST and other prediction techniques. Thus, while it is desirable to reduce the error inherent in the various techniques, these errors are not necessarily the greatest limitation to the accuracy of attenuation predictions.

4.5 Conclusions

On the basis of a comparison of the various assumptions underlying the path average rain rate technique and the synthetic storm technique for predicting rain attenuation statistics, the latter is believed to be more accurate. However, some suitable version of the PARRT could provide a viable alternative when detailed rain gauge records required for a synthetic storm prediction are unavailable. Crane's version of the PARRT, although containing the same fundamental approximation of Eqn. (4.10) as all other versions, is improved somewhat by the normally compensating approximation of Eqn. (4.13). It appears that all present versions may be limited, however, by the assumption that the reduction coefficient r is universal in its behaviour. The results presented in this chapter, although not conclusive, do not indicate a universal behaviour either in terms of rain rate or percentage of time. Crane's model for r , a power law in rain rate, gives a satisfactory fit to the synthetic storm results for rain rate above about 20mm/h and path lengths less than about 10km. The fit at low rain rates, and for long paths at high rain rates appear to be unsatisfactory. The data

Fig. 4.7 Percent difference between the attenuations calculated using the modified Joss-widespread and Joss-thunderstorm drop-size distribution (10°C rain temperature) with respect to percentage of time. Crane's method with rain rate distribution for Ottawa and a 20km path length.

presented here could be fitted more accurately with a model dividing the rain rate into two groups: a low rain rate range where $r = 1$ and a high rain rate range where r follows a power-law relation, with the "break point" dependent on path length. Some allowance could also be made for climatic variability. Additional synthetic storm data should be analyzed to obtain more conclusive results.

The idea involved in the modified Crane's method is definitely an improvement over the PARRT. However, the apparent inaccuracy of the CM for r causes a major source of errors. A modification in this method using an improved model for r is straight forward by substitution in Eqn. (4.17).

The concept, introduced in this chapter, of employing synthetic storm data to evaluate the PARRT, should also be useful for evaluating other techniques based on rainfall statistics [52]. There are three advantages that make it particularly attractive. One is that the same model of drop-size distribution can be used throughout, eliminating this as a factor in the evaluation. Another is that the evaluation can be carried out over a wide range of frequencies and path lengths. Thirdly, there is frequently more rain rate data available for use in a synthetic storm evaluation than there is actual attenuation data.

Finally, it is recognized that synthetic storm data cannot fully replace actual data for a complete evaluation of other prediction techniques. Indeed, such data must be used with caution, and a final evaluation must be based on actual data.

CHAPTER FIVE

MULTIPATH PROPAGATION

5.1 Introduction

Multipath propagation can be defined as the arrival, at the receiving antenna, of the transmitted signal via two or more propagation paths with different time delays and different relative amplitudes. These received signals may then add either constructively or destructively affecting the performance of the radio systems. Multipath propagation can be classified into two main types:

1. Discrete multipath; this type is characterized by relatively large differential path delays between the different components. It is caused by either reflection from the ground or water surface or by reflection or refraction from an elevated layer in the atmosphere. The rays reaching the receiving antenna have different angles of arrival which can be detected and identified using a very narrow beam scanning antenna.

2. Continuous multipath; this type is characterized by relatively small differential path delays between the different components. It is due to volume scattering caused by either atmospheric turbulence or by hydrometeors. Furthermore, the different rays cannot be distinguished from one another.

In addition to affecting the received signal level, multipath may be a highly frequency selective phenomenon causing inband amplitude and group delay distortions. These distortions can degrade wide-band systems operating well above the thermal noise limit. However, their effect on digital systems is thought to be more pronounced than on

analog systems [60,61]. This is due to two factors: first, the FM commonly used for analog transmission is inherently more resistant to inband distortion than the modulation systems which are suitable for bandwidth efficient digital transmission, and second, the susceptibility of analog systems to inband distortion decreases with the loading conditions. Since most multipath fading occurs during the night when the network is lightly loaded, the effect on analog systems is reduced. Digital modulation systems, however, transmit the same data rate continually whether or not information is being sent and consequently their susceptibility to distortion is not affected by the number of users.

Finally, multipath fading also affects systems using a dual-polarized-frequency radio channel by reducing the cross polarization discrimination between the two polarizations [62-64].

In this chapter, a general review of the multipath fading theory is presented. The frequency selectivity of this phenomenon is also outlined along with several models for predicting it. Special emphasis is given to its influence on digital microwave systems. Finally, techniques to minimize the multipath fading effects are summarized.

5.2 The refractive index in the lower atmosphere

The velocity of propagation of electromagnetic waves in a medium is controlled by its refractive index, the denser the medium the slower the velocity. In the troposphere the refractive index changes with height, and consequently different parts of the wavefront propagate at different velocities. This causes the wave to bend either towards or away from the earth according to the refractive index gradient. This situation

causes a wide range of anomalous propagation effects, e.g. ducting, antenna decoupling, blackout fading, multipath, etc. [65,66]. Multipath propagation is by far the most serious effect. In order to understand its causes a review of the refractive index in the troposphere is required.

The index of refraction, n , of air at microwave frequencies depends upon temperature, pressure and humidity. Since n is very close to unity, it is common to consider the refractivity N , which is given by

$$N = (n-1) \times 10^6 = \frac{77.6}{T} (p + 4810 \frac{e}{T}) \quad (5.1)$$

where p = total pressure in mb

e = water vapour pressure in mb

T = temperature in $^{\circ}K$

N typically has a value of 300

The form of Eqn. (5.1) suggests that the variables affecting N are independent of one another. In reality this is not true. For example, in tropical regions where T is high, one might expect values of N smaller than those in temperate regions. However, the effects of temperature on e considerably outweigh the corresponding effects of changes in T itself, resulting in higher values of N [67]. On the other hand, in Northern Canada, N is larger in winter than in summer due to the small values of e at all times. Taking typical conditions $p = 1000\text{mb}$, $T = 288^{\circ}K$, $e = 12\text{mb}$ (70% relative humidity) the change ΔN due to small changes Δp , ΔT and Δe becomes

$$\Delta N = 0.27 \Delta p - 1.40 \Delta T + 4.5 \Delta e \quad (N \text{ units}) \quad (5.2)$$

Thus water vapour makes a relatively important contribution. Molecules of water are easily polarized in the case of radio wavelengths so that the dielectric constant of water vapour assumes a high value [68].

In general, temperature, pressure and water vapour content in the troposphere decrease with height. On the average the index of refraction decreases with a linear gradient near the ground of about $-40N$ units/km in temperate climates.

During daytime hours, when the lower atmosphere is thoroughly mixed by rising convection currents and winds, and also during winter months when humidity content of the atmosphere is low, only small deviations from the linear gradient profile exist. Under these conditions, only volume scattering occurs due to continuous spatially random fluctuations in refractive index. The effects of this volume scattering are relatively unimportant for communication systems.

However, during summer nights with little or no winds, layers of different gradients may occur due to non-uniform distributions of temperature and humidity. These layers are characterized by steep humidity gradients and inversions in temperature gradients (from which they received the name of "inversion layers") resulting in a refractive index gradient steeper than normal. Electromagnetic waves reaching such layers will be either reflected at the interface or refracted downwards as it travels through it. Depending on the height of the layer above the antennas, its thickness, the refractive index gradient inside and outside the layer and the line of sight (LOS) direct path length, the reflected or refracted rays may reach the receiving antenna along with the direct ray causing discrete multipath.

Statistical distributions of layer thickness give average values of 66 meters in an arctic climate, 97 meters in a temperate climate and 106 meters in a tropical maritime climate [69]. The steepest gradient observed by Bean and Dutton was -420N units/km and the typical value was -300N units/km . It is also believed that gradients may be steeper than these values but only over shorter distances [70]. Usually these layers are nearly horizontal and may extend to several kilometres. Due to wind shear and frontal inversions, they may have a tilt angle of a few degrees. In the presence of multiple convective processes, there may be perturbations in the layered structure which manifest themselves as random wave like disturbances [69,71].

The reflection process has been studied by many authors [68,72-75] and it is believed that, for LOS propagation in the GHz frequency range, only under extreme conditions, such as extreme gradients and very small incident angles and layer thicknesses, will the reflected wave have any appreciable value compared to the direct wave [75]. Therefore, the attention from now on will be concentrated on the refraction mechanism from elevated layers.

5.3 Flat fading

If one transmits a continuous tone, due to multipath, several continuous sine waves will arrive sequentially at the receiver, but only the result of their superposition is actually seen. The several different signals may add either constructively or destructively, according to the values of the relative phase shifts introduced by the differential electrical-path delays.

Moreover, changes in the relative path lengths by amounts of the order of the radio frequency wavelength will change the relative phasing of the received signals. If such changes occur continually and randomly, the observed resultant carrier will correspondingly change randomly in envelope and radio frequency phase [76].

$$\sum_i a_i e^{j\theta_i} = V e^{j\phi} = x + jy \quad (5.3)$$

where a_i and θ_i are the relative amplitude and phase shift of the i^{th} component

V and ϕ are the envelope and phase of the resulting multipath signal

x and y are the real and imaginary parts of the received signal.

By the central limit theorem, the real and the imaginary parts of the sum of a large number of independent interfering signals will be approximately Gaussian. And provided that they are all of comparable magnitude one obtains a Rayleigh fading envelope and a uniformly distributed rf phase.

Recent experimental results and ray tracing models show that it is unlikely to obtain a large number of multipath interfering signals in LOS links [77]. Even in cases where it appears that four or six components are needed to synthesize satisfactorily the received signal [78], Ruthroff [79] indicates that if time variations were assumed in the height, thickness and index of refraction of the refractive layer,

only three distinct signals are required to model the experimental results.

Furthermore, in the case of a dominant ray, for example by reflection from water surface, the theoretical results of the complex Gaussian model do not agree well with experimental ones. This is not surprising since in the model it was assumed that all rays have comparable magnitudes.

It was clear that a new model was needed to explain the LOS multipath phenomenon. Lin [77] simply modelled the fading signal $V e^{j\phi}$ as a constant vector plus an interfering random vector, i.e.

$$V e^{j\phi} = 1 + R e^{j\theta} = 1 + x + jy \quad (5.4)$$

where R , θ , x and y are the amplitude, phase, real and imaginary parts respectively of the interfering vector. This interfering vector is described by the joint probability density function $f(x,y)$ and represents the resultant of all the received extraneous signals, echoes, rays and noise. His analysis applies for R and θ either dependent or independent, θ uniformly or non-uniformly distributed; x and y either Gaussian or non-Gaussian. Thus, the results of his analysis may be applied to a wide class of fading problems. He also proves that specifying the Rayleigh distribution for the magnitude of the fading signal does not necessarily imply that x and y are Gaussian nor does it necessarily imply a large number of interfering signals.

From his analysis Lin shows that $P(V \leq L)$, the probability of the envelope V to be less than or equal to a certain level L , is given by

$$P(V \leq L) \propto L^2 \quad \text{for small } L \quad (5.5)$$

where V and L are both relative to the unfaded value, provided that $f(x,y)$ is neither singular nor zero at the deep fade point ($x=-1, y=0$).

If one considers a Rayleigh distribution of the envelope V

$$P_r(V \leq L) = 1 - e^{-L^2} \quad (5.6)$$

$$\approx L^2 \quad \text{for } L < 0.1 \quad (5.7)$$

it becomes clear why some authors still refer to relation (5.5) as Rayleigh fading. Lin states that other distributions have also a square law dependence in the deep fade region.

Experimental results showed a very good agreement with Lin's conclusions [80-85]. They all showed a slope of a decade of probability per 10dB change in fade depth ($20 \log L$), which is the square law relation. However, Janes and Thompson [86] obtained a relation of the form $P(V \leq L) \propto L^{3.2}$.

The CCIR adopted a semi-empirical relation for the envelope distribution of the received signal given by [87]

$$P(V \leq L) = K Q L^2 f^B d^C \quad (5.8)$$

where K is a factor for climatic conditions, Q a factor for terrain conditions, f the frequency in GHz, d the path length in km, and B and C constants. These constants have the values of 1.2 and 3.5, 1 and 3.5, and 1 and 3 for Japan, N.W. Europe and the United States respectively.

Some experimental results [80,82,83] show that the distribution of the number of fades $N(L)$ below a level L is proportional to L . This confirms Lin's theoretical results. However, some other results show that

it is proportional to $L^{4/3}$ [85] and to $L^{2.4}$ [86]. Moreover, Barnett indicated that $N(L)$ increases linearly with frequency.

As for the distribution of the average fade duration time $\bar{t}(L)$, it was found to be proportional to L [77,80,82,83]. Once more results from [85] and [86] were different, showing that it was proportional to $L^{2/3}$ and $L^{0.6}$ respectively. Although Barnett [82] concluded that $\bar{t}(L)$ was independent of frequency, Bullington [80] indicated a frequency dependence of the form

$$\bar{t} \propto \sqrt{\frac{d}{f}} \quad (5.9)$$

Results in [85] indicated the presence of a certain frequency dependence that was different from that given by Eqn. (5.9).

It is interesting to note that Barnett [82] found that for fades of 40dB, 49% of the worst month multipath occurs in a single day with 20% in the worst hour.

Finally, only one set of statistics was reported in the literature for signal enhancements [85]. The results indicated that

$$P(v > L) \propto L^{-4.5} \quad 1.25 < L < 3.0 \quad (5.10)$$

$$\bar{t}(L) \propto L^{-0.75} \quad 1.4 < L < 3.2 \quad (5.11)$$

$$N(L) \propto L^{-3.75} \quad 1.2 < L < 3.5 \quad (5.12)$$

5.4 * Selective fading

In the previous section it was assumed that the multipath causes a flat fading across the entire frequency spectrum of the signal. This assumption may be valid for narrow band signals, but becomes inaccurate

as the bandwidth increases. It is important to investigate the frequency selectivity of multipath for two reasons:

1. To determine its effects on the received signal (for example bit-error rate in case of digital communication).
2. To determine the most efficient frequency spacing in frequency diversity schemes in order to reduce the effects of multipath fading.

Investigations of the frequency selectivity of multipath were carried out during the early fifties using frequency sweep experiments. Typical results are shown in Fig. 5.1 [88] and Fig. 5.2 [78]. Kaylor [78] and Crawford and Jakes [88] showed that severe fades are frequency selective. Kaylor also remarked that 95% of fades greater than 40dB showed a variation in path loss across the observed band of 400MHz of at least 17dB. He also remarked that frequencies separated by 160MHz or more show little correlation in their fading. They both agreed that when the received signal was a few dB above or below the mid-day level due to focussing or trapping phenomena (volume scattering and ducting) no frequency selectivity was evident. Similar results were obtained recently using the same technique by Meadows et al. [70].

An extensive study for the selective effect was conducted by the Bell Laboratories on a microwave link between Atlanta and Palmetto, Georgia. The results of this study were published by Babler [81,89] and by Subramanian et al. [90]. It shows that fades below 10dB can be divided into two categories. The majority of them are relatively shallow (<20dB), long lasting (minutes) events which show little amplitude and non-linear phase distortion across the frequency band used, although linear phase dispersion corresponding to path length variations may be observed. A second class of events are those that

Fig. 5.1 Representative frequency sweep patterns observed on the Murray-Crawford Hill path, New Jersey, by Crawford and Jakes. (a) Normal day; (b), (c) and (d) show the frequency selective effect of the multipath phenomenon. Ref. [88].

Fig. 5.2 Typical path-loss versus frequency curves observed on the Princeton-Lowden, Iowa, path during July and August 1950. Ref. [78].

exhibit deep and brief (seconds) fades showing substantial amplitude and non-linear phase dispersion.

Fig. 5.3 describes two selective fading events [81]. In event (a) the selectivity swept through the narrow frequency band suggesting the appearance of a small echo with rapidly changing delay (phase), which maintained, at least approximately, a constant amplitude. In contrast, in event (b) the selectivity develops and dissipates in band, suggesting a continual change in the relative amplitude of the echoes present. All of the highly selective fading events observed during that experiment exhibited activity somewhere between these two extremes.

Subramanian et al. [90] monitored the amplitude of 4 tones in the 6GHz range, spaced 6.6MHz apart as well as their phase differences as shown in Figs. 5.4 and 5.5. The nominal unfaded levels A_2 , A_3 and A_4 are displaced 20, 40 and 60 dB. Fig. 5.4 represents no appreciable amplitude or phase differences. However Fig. 5.5 shows significant phase nonlinearity during periods of deep fade. Unfortunately no other studies were conducted on the time delay distortion caused by multipath.

5.4.1 Effect of selective fading on digital systems

As mentioned above, digital systems are more vulnerable to inband amplitude and group delay distortions than their analog counterpart. These distortions produce intersymbol interference resulting in high bit-error rates. This resulting degradation in system performance depends on the type of modulation used [91,92] and increases with both bit rate [93,94] and the number of modulation levels [95].

Results from several studies differ on the relative importance of amplitude and delay distortions in degrading digital systems.

Fig. 5.3 Signal level of 62 different tones within a narrow band of 33.55 MHz centered at 6.0342 GHz. Each line represents the relative fading within the band while the number to the left represents the fading of tone 1. Each set of measurements is taken 0.2 seconds apart (vertical axis). In event (a) the selectivity swept through the band while in event (b) it develops and dissipates in band. Ref. [81].

2

Fig. 5.4 Fade depth and phase difference of 4 tones spaced 6.6MHz apart in the 6GHz range. Nondispersive fading. Ref. [90].

Fig. 5.5 Fade depth and phase difference of 4 tones spaced 6.6MHz apart in the 6GHz range. Dispersive fading. Ref. [90].

Hartman and Allen [60] found that for a given delay between the received signals and a given fade depth, the effect of amplitude slope on threshold degradation is more drastic than that due to delay slope or parabolic delay. They also concluded that the next most serious problem is a symmetrical null at the centre of the passband. Mathews [96], Barnett [61,97] and Komaki et al. [99] went as far as empirically relating the BER to the channel amplitude distortion. On the other hand, Horikawa et al. [98] and Sunde [100] pointed out that digital radio systems are more sensitive to delay dispersion than to amplitude dispersion. O'Kelly [101], Anderson et al. [102] and Barnett [61] acknowledged the important contribution of delay distortion to the system degradation. However, a comparative study on the effects of amplitude and delay distortions on several digital modulation techniques [91] showed different degrees of deterioration, with the relative importance changing with bandwidth and bit rate.

The problem of determining the relative importance of delay distortion in field experiments lies with the difficulty in devising proper instrumentation to monitor phase differences. In contrast, the amplitude distortion can be detected as simply as by recording the received signal spectrum.

5.5 Modelling of multipath propagation

The prediction of microwave radio system performance on LOS links requires accurate statistical models of the channel. Such models must be capable of duplicating the amplitude and phase (at least approximately) of all observed channel conditions. In order to facilitate laboratory measurements and computer simulations for

calculating outage, the model should be realizable as a practical test circuit and should have as few parameters as possible. Most important, the parameters should be statistically well behaved [103]. In order to derive these models, measurements of angles of arrivals, differential time delay and amplitude of the multipath signals are required [104].

In general, two types of models have been considered for LOS microwave channels: power series type models and multipath models. Some of these models have been even extended to predict the performance of digital systems.

5.5.1 Power series models

The restriction on the number of terms in the power series in these models limit their usefulness to situations where the differential spread of delays is small relative to the reciprocal bandwidth of the communication channel.

By monitoring the amplitude of three reference tones symmetrically spaced by Δf , Babler [81,89] was able to represent the amplitude-frequency characteristics by two parameters, ΔA the linear amplitude distortion and $\frac{\Delta^2 A}{2}$ the quadratic amplitude distortion as given in Fig. 5.6. The amplitude of the sample at any frequency is then given by

$$A(f) = A(f_2) + \frac{\Delta A}{2\Delta f} (f-f_2) + \frac{\Delta^2 A}{2(\Delta f)^2} (f-f_2)^2 \quad (5.13)$$

He also found that ΔA and $\Delta^2 A$ exceeded 15 and 9dB respectively for 10^{-5} of the observed time. Subramanian et al. [90] represented the phase dispersion by a second order polynomial of the form

$$\phi(f) = a_\phi (f-f_3) + b_\phi (f-f_3) + c_\phi (f-f_3)^2 \quad (5.14)$$

Fig. 5.6 Linear and quadratic amplitude distortions due to frequency selectivity.
Ref. [81,89].

Their results show that $c\phi$, the quadratic phase nonlinear coefficient, increases with depth of fade. For fades deeper than 34dB, $c\phi$ exceeded an average value of 0.1 degree/(MHz) corresponding to a time delay distortion of 0.55 nanoseconds over 1MHz band. No simple relation between the quadratic amplitude and quadratic phase nonlinear coefficients was found. In concluding, Babler [81,89] and Subramanian et al. [90] indicated that in case of deep fades the amplitude and phase distortions exceeded second order.

Greenstein and Czekaj [105] suggested, based on earlier work by the former [106], a channel transfer function of the form

$$H(\omega) = A_0 + \sum_{n=1}^n C_n (j\omega)^n; \quad C_n = A_n + jB_n \quad (5.15)$$

where the A_n 's and the B_n 's change with time and multipath event.

Greenstein [106] speculated, by studying some typical fading responses, that a first order polynomial ($N=1$) is sufficient for the channelized common carrier bands below 15GHz. This reduces the transfer function to

$$H(\omega) = \begin{cases} 1 + j0 & \text{during non-fading periods} \\ A_0 + \omega B_1 + j\omega A_1 & \text{during } T_M \text{ seconds per heavy fading months} \end{cases} \quad (5.16)$$

The values of A_0 , A_1 and B_1 and their individual and joint distributions were obtained empirically by fitting measurement's results. However it is not clear whether these values are applicable to other paths, microwave frequencies, seasons, etc., and if not, the way to scale them.

5.5.2 Multipath models

The multipath models can be classified into two main groups:

1. Methods that use geometrical optics to determine the number, delays, amplitudes and arriving angles of the different multipath signals on LOS links [69,79,107-111]. These methods are based on the assumption of a certain refractive-index profile for the lower part of the troposphere and require the knowledge of the link geometry.
2. Methods that use two or more rays to synthesize a transfer function descriptive of the multipath medium [95,103,112-116]. This group also includes earlier studies [70,78,88] that tried to synthesize received signals from frequency-sweep measurements using a number of components with different amplitudes and delays.

A brief discussion of some of the methods in these two groups will be given. In the next chapter, they will be used to predict the performance of a radio LOS link installed to study the effect of multipath on digital systems.

1. Geometrical optics models:

- a) Ruthroff's model [79]: This model predicts that up to three rays can reach the receiver. Fig. 5.7 illustrates the path geometry for two rays with radii of curvature R_0 outside the inversion layer and R inside the layer, where

$$\frac{1}{R} \approx -\frac{d}{dz} n(z) = -10^{-6} \frac{d}{dz} N(z) \quad (5.17)$$

The largest phase difference, β , between a direct and refracted ray is found to be

$$\frac{\lambda \beta}{2\pi} \approx \frac{d^3}{24R^2} \frac{(1 - R/R_0)^4}{(1 - R/2R_0)^2} \quad (5.18)$$

Fig. 5.7 Refraction from a single layer. Ref. [79].

$$d_1 = R_f(\sin \theta_1 - \sin \theta_0^T)$$

$$d_2 = R \sin \theta_1$$

$$d_3 = 2(R + R_f) \sin \theta_1$$

$$d_4 = R \sin \theta_1$$

$$d_5 = R_f(\sin \theta_1 - \sin \theta_0^R)$$

Fig. 5.8 Link geometry with the terminals below layer surface. Modified refractive index and "earth flattening" coordinates used. Ref. [107].

Ruthroff defines a short path length d_0 , such that for any path length $d \leq d_0$, there is no deep fading. He computes values of d_0 based on angles of arrival measurements conducted by Crawford and Jakes [88] for New Jersey

$$d_0 = 4.8\lambda^{1/3} \quad (5.19)$$

where d_0 is in km and λ in cm, and then simplifies Eqn. (5.18) to

$$\beta = \frac{3\pi}{4} \left(\frac{d}{d_0} \right)^3 \quad (5.20)$$

This model has two major limitations. First, it assumes that the transmitter and receiver have equal height and are both below the inversion layer. Second, it does not predict the amplitudes of the received signals, although, it makes the "questionable" assumption that the relative amplitudes and phases of the received signals are statistically independent.

b) The CNR model [69,107-109]: This is the most comprehensive multipath model in the literature. It deals with a large variety of situations: equal or nonequal transmitting and receiving antenna heights, different antenna positions with respect to the inversion layer, horizontally stratified or tilted layers. As shown in Fig. 5.8, the model permits multiple reentry of the refracted rays into the layer. It predicts that according to the path geometry two or more rays can reach the receiver and gives their relative amplitudes and path delays. For equal height antennas below a layer, it reveals the existence of a minimum path

length, proportional to the separation of the antennas from the layer, and a maximum path length, proportional to the width of the layer, that define the range of path lengths over which multipath can occur. It is to be noted that this model uses the modified refractive index and the "earth flattening" coordinate transformation.

c) Ramadan's model [111]: This model assumes that the energy travels from the transmitter to the receiver via two paths only. The link geometry is similar to that in Fig. 5.7. This model has the advantage, over the two previous ones, of incorporating the effect of the transmit and receive antenna directivity pattern. This eliminates the need of assuming that the statistical distributions of echo delays and relative amplitude are independent, since it provides a means of relating them. It also leads to the interesting result that the maximum echo delay $\tau_{\max}$

$$\tau_{\max} = 2 \frac{d}{c} \left(\frac{\lambda}{\pi D} \right)^2 10^{-A_p/20}; \quad A_p > 5\text{dB} \quad (5.21)$$

decreases exponentially with the peak fade A_p . Here, D is the antenna diameter. Both the CNR and Ramadan's models were also applied to predict the performance of digital systems under multipath conditions.

2. Synthesis of transfer function

a) Jakes model [113]: This model is mainly intended to estimate the total outage time in a month, in digital systems, due to multipath. The model assumes that two rays reach the receiver, a direct ray with unity amplitude and a secondary ray with an

amplitude of $r(<1)$ and propagation delay τ relative to the direct ray

$$H(\omega) = (1 + re^{j\omega\tau}) \quad (5.22)$$

The envelope delay distortion $T(\omega)$ can be derived to be

$$T(\omega) = r\tau \frac{r + \cos\omega\tau}{1 + 2r\cos\omega\tau + r^2} \quad (5.23)$$

The derivation proceeds with the two following assumptions: first, that the system breaks down when the total peak-to-peak envelope delay distortion contained within the channel bandwidth is comparable to the symbol length of the digital signal, and second, that the fade depth and the time delays are statistically independent. This last assumption is questionable in light of Ramadan's model [111]. Finally, the total outage time per month is expressed by

$$P = \frac{1.6 mk^{0.85}}{uv} \left(1 + \frac{u}{v}\right) \quad (5.24)$$

where $m = 6.575Cfd^3$, k , u and v are dependent on the type of modulation, pulse width, and, fade depth and time delays distribution functions, and C is a terrain factor.

Prabhu and Greenstein [95] extended this model for application to any digital system.

b) Rummler's model [103,115,116]: This model assumes that the received signal is composed of three components. Two approximately

equal amplitude replicas of the transmitted signal with relatively small differential path delay, interfere with each other depressing the received signal level. The weak replica provided by the presence of a third path of relatively long delay causes selective fading within the channel. The resultant transfer function is given by

$$H(\omega) = a [1 - be^{-j(\omega - \omega_0)\tau}] \quad (5.25)$$

where the real positive parameters a and b control the scale and shape of the fade, respectively, and ω_0 is the radian frequency of the fade minimum. This model has been extended by Lundgren and Rummel [114,117] for application to digital systems.

c) Enshwiller's model [112]: This is again a two-ray model applicable to both analog and digital systems. By assuming that the fade depth and differential delay are statistically independent, it can predict the fractional time that a LOS radio hop will have unacceptable performance.

5.6 Diversity techniques

Since multipath propagation is inevitable, techniques have been suggested to reduce its effects on LOS systems. Three quantities characterize this phenomenon: the frequency of the transmitted signal, the angle of arrival of the received rays and their differential path delays. Only given combinations of these parameters can cause deep fading. Diversity techniques are based on the fact that a small variation in one or more of these parameters may improve the fading situation. They can be divided into three categories:

1. Angle diversity: This technique can be used with relatively narrow beam antennas, and uses the fact that rays reaching the receiving antenna off the main lobe are highly attenuated. Therefore, the two antennas are arranged so that one of them is pointed slightly upwards from the direct path [87]. This technique is the least expensive and the least reliable. It can also result in high attenuation in the direct path in case of superrefractive conditions.

2. Frequency diversity: One condition for deep fades is that the differential path length of the received rays be an odd multiple of half wave lengths. Consequently, given a certain multipath geometry, changing the carrier frequency will alter the previous condition. A change of 1 to 2% in the carrier frequency is usually sufficient to improve the system performance. However, at high carrier frequencies, the amount of fading increases and the improvement gained by frequency diversity decreases [118]. Also, fading due to radio ducting, which is frequency insensitive, cannot be eliminated by this technique [119]. Finally, for the conservation of the frequency spectrum the use of this technique has been restricted.

3. Space diversity: This is the most widely used diversity technique. It is based on using two vertically spaced antennas separated by a distance of approximately 150 wavelengths [87] (roughly 30 to 50 feet). Several versions of this technique exist that differ in the way the received signals from the two antennas are manipulated. In some versions, the receiver is switched between the two antennas [89]. This switching is done either to the antenna with the highest signal level, or whenever the signal at an antenna crosses a certain threshold [89,108]. In other versions, the received signals from the two antennas

are combined at the rf, if or base band levels [119]. Usually adaptive phase equalizers are used in these versions [102]. Several researchers have found out that a big improvement in signal performance can be achieved if an adaptive linear amplitude equalizer is also used in conjunction with space diversity [92,93,110,120-123].

CHAPTER SIX

THE PROPAGATION EXPERIMENT

6.1 Introduction

Experimental propagation information in the 36-40GHz band, proposed for fixed radio services, is virtually nonexistent. However, such information is essential in assessing the anticipated performance of systems using this band. An experimental project was initiated to investigate the effects of multipath propagation on digital radio communications. A carrier frequency of 37GHz was chosen for this task.

Although many researchers predicted that at these high frequencies the attenuation by rain far exceeds that of multipath [20,45,123], the sensitivity of high speed digital systems to the latter prompted the experiment. Moreover, since multipath fading does not occur simultaneously with rain attenuation, they have an additive effect on the total outage probability of any system. Finally, even the decision of neglecting the multipath effect compared to that of rain has to be substantiated by results from field experiments.

In this chapter, the design steps of the experiment are outlined. Some of the models discussed in the previous chapters are used to predict the system's performance. Results from laboratory back-to-back tests, to determine the signal degradation due to both thermal noise and simulated multipath conditions, are also presented. Finally, a technique for detecting temperature inversions using a set of temperature measuring devices, is outlined.

6.2 General description

As previously mentioned, an rf carrier frequency of 37GHz was chosen for the experiment. It was also decided to use binary differential-phase-shift keying (DPSK) as a modulation scheme, because of its simplicity, with a relatively high speed data rate of 65.5Mb/s and a bandwidth of 130MHz. It is believed that DPSK is less susceptible to multipath effects than higher level digital techniques. By monitoring the signal level, spectrum and bit-error rate (BER) at the receiver one can obtain an indication of the amount of degradation suffered by the signal due to multipath.

6.2.1 Differential-phase-shift keying (DPSK)

The DPSK avoids the necessity of providing a synchronous carrier at the receiver by differentially encoding the binary message to be transmitted. Fig. 6.1a represents a binary sequence $b(t)$ and the auxiliary (differentially encoded) sequence $b'(t)$. The first digit of $b'(t)$ is arbitrary and is assumed 1. Succeeding digits in $b'(t)$ are determined on the basis of the rule that when $b(t)$ is 1 in some bit interval, $b'(t)$ changes from its value in the preceeding interval. When $b(t)$ is 0, $b'(t)$ does not change. A method of generating the DPSK signal is shown in Fig. 6.1b. Thus,

$$v_{\text{DPSK}}(t) = v(t) A' \cos \omega_c t \quad (6.1)$$

where $v(t) = +V$ for $b'(t) = 1$ and $v(t) = -V$ for $b'(t) = 0$

$$A' = \frac{A}{V}$$

A and ω_c are the magnitude and angular frequency of the carrier.

(a) $b(t)$ is the message to be transmitted, $b'(t)$ is the auxiliary bit stream generated for DPSK transmission.

(b) a method for generating DPSK signal.

Fig. 6.1 DPSK Modulator.

(a) DPSK demodulator

(b) Operation of the demodulator

Fig. 6.2 DPSK Demodulator

At the receiver the signal is split and one path is delayed by exactly one bit period as shown in Fig. 6.2a. The two signals are then multiplied together and fed to a low pass filter (LPF).

$$v_o(t) = v(t) A' \cos \omega_c t \cdot v(t-T) A' \cos [\omega_c(t-T)] \quad (6.2)$$

$$= \frac{v(t) v(t-T)}{2} A'^2 [\cos \omega_c T + \cos 2\omega_c(t - \frac{T}{2})] \quad (6.3)$$

The LPF eliminates the high frequency component and the resulting signal becomes

$$v_o'(t) = \frac{v(t) v(t-T)}{2} A'^2 \cos \omega_c T \quad (6.4)$$

Whenever $v(t)$ and $v(t-T)$ are of the same sign, $v_o'(t)$ is positive and whenever they are of opposite sign, $v_o'(t)$ is negative. Fig. 6.2b shows that the result of such product is exactly the inverse of the binary sequence $b(t)$.

6.2.2 System block diagram

Fig. 6.3 represents a block diagram of the system built. A Tau-Tron MN-1 pseudorandom data generator provides a sequence of bits at 65.5Mb/s that, after being differentially encoded, phase modulates a 500MHz IF carrier, which, after band limitation and amplification, is upconverted to the carrier frequency of 37GHz. The signal is then amplified using a travelling-wave-tube amplifier (TWTA) and transmitted by a two foot diameter, 1° beamwidth, 44dB gain Cassegrain antenna.

After going through the receiving antenna, which has the same characteristics as the transmitting antenna, the received signal is down

Fig. 6.3 Block diagram of the system

converted to 500MHz, amplified, bandlimited and then demodulated. Part of the signal goes through a differentiator, high-Q filter, amplifier, low-pass filter and then to the clock recovery circuit. The demodulated signal is then sampled at the recovered clock frequency and fed to a Tau-Tron MB-1 BERT receiver. A sequence identical to that transmitted is generated in the BERT receiver at the recovered clock frequency, and then compared to the sampled signal. The number of bit-errors is displayed on a digital counter. Detailed schematic diagrams of the MODEM are presented in Appendix B. An M6800 microprocessor was assembled to control the data collecting process at the receiver.

6.3 Path calculations

It was decided to install the radio link along a 33.87 km path extending from the roof of the Journal Tower in downtown Ottawa to a microwave tower at Ashton, Ontario. Although this path may be unrealistically long for the frequency used (37GHz) it has been chosen for two reasons:

1. The probability of obtaining selective multipath fading increases with path length. This will permit the acquisition of enough data while being reasonably sure of experiencing multipath conditions in the experimental time available.
2. Two other microwave experiments at 7.4 and 14.5GHz are scheduled to use the same path. This would permit the future comparison between propagation results at three frequencies.

It was also decided to locate the transmitter at the Journal tower for reasons of accessibility and protection to the TWTA. At the receiver, in order to minimize the losses, the down converter was placed

directly behind the antenna. The if signal was brought down to a hut besides the microwave tower, where the rest of the equipment was located.

Fig. 6.4 represents a path profile of the radio link. It is worthwhile noting that the direct line of sight path between the transmit T_x and receive R_x antennas is almost horizontal (elevation angle of 4.5 minutes) and that the minimum clearance is about 28 Fresnel zones for standard atmospheric conditions ($K=4/3$).

The free space loss (FSL), assuming isotropic antennas is given by

$$\begin{aligned} \text{FSL} &= 92.4 + 20\log d + 20\log f \\ &= 154.36\text{dB} \end{aligned} \quad (6.5)$$

where d is in km and f in GHz.

The combined water vapour and oxygen absorptions at the proposed frequency is not expected to exceed 0.1dB/km even under the worst conditions of high humidity during the summer months [35]. This will cause an additional loss of approximately 3dB in signal power. Therefore, the expected received power, P_R , can be given by

$$\begin{aligned} P_R &= P_T - \text{FSL} + G_T + G_R - 3 \\ &= 26.4 - 154.36 + 44 + 44 - 3 \\ &= -42.96\text{dBm} \end{aligned} \quad (6.6)$$

where G_T and G_R are the transmitting and receiving antenna gains respectively and P_T is the transmitted power.

According to the specifications of the down converter, its noise figure is 4.2dB, and allowing for antenna temperature, the minimum

Fig. 6.4 Path profile for $K = 4/3$ and $2/3$. Clearance in terms of Fresnel zones indicates.

detectable signal for an if bandwidth of approximately 130MHz is -90.50dBm. In order to obtain a bit-error rate of 10^{-3} , a signal to noise ratio (S/N) of 5.5dB is required. This corresponds to a received signal of the order of -85.00dBm, giving an allowance of 42.04dB for other path attenuations. Calculations based on the synthetic storm technique show that this corresponds to an outage of approximate 0.24% or 21.02 hours/year due to rain in the Ottawa area.

6.3.1 Multipath calculations

Some preliminary calculations were carried on to investigate the behaviour expected of the signal under multipath conditions. The parameters of the suggested path were substituted in Rutherford's model [79], see Fig. 6.5. The refractive index gradient outside the layer was assumed to be -40N units/km and within the layer -300N units/km for typical conditions and -420N units/km for the steepest condition. Also, the maximum height of the direct path above the antennas was assumed to be equal to the inversion layer height, i.e., $h=h_p$. This is the condition under which, according to the model, the largest phase difference between the direct and refracted paths is obtained. The suffix t will represent the typical condition and the suffix s the steepest condition. Based on the model, the angles of departure θ of the refracted ray are calculated to be

$$\theta_t = 0.27^\circ \text{ and } \theta_s = 0.38^\circ$$

which are both within the beam angle of the antenna. The corresponding differential time delays are

$$\tau_t = 0.320\text{ns} \text{ and } \tau_s = 0.753\text{ns}$$

Fig. 6.5 Refraction from a single layer.
Ref. [79].

Fig. 6.6 Channel amplitude transfer
function for the two-ray
model.

$$H(\omega) = 1 + re^{-j\omega T}$$

$$|H(\omega)| = \sqrt{(1+r \cos \omega T)^2 + (r \sin \omega T)^2}$$

which are very small compared to the bit width of 15.25ns. The model also shows that for multipath to occur, the layer separation from the antennas should range between 5.73 and 31.51 meters for the steepest gradient, and 5.73 and 23.02 meters for the typical gradient.

However, if Eqn. (5.20), which is based on angle of arrival measurements by Crawford and Jakes, is used, the differential time delay becomes 4.39ns. This will definitely cause a large amount of intersymbol interference. However, this requires a refractive index gradient of $-1050N$ unit/km in the inversion layer and $-102N$ units/km outside it. Jakes [113] suggested that the atmospheric conditions, used in the derivation of Eqn. (5.20), were sometimes more complex than Ruthroff's model and therefore Eqn. (5.20) should be viewed only as a maximum possible limit.

As a means of verification, the maximum differential time delay was calculated using the CNR [69,107-109] and Ramadan [111] models. The CNR model predicts values not exceeding 0.3ns while Ramadan's model gives a formula that is dependent on the signal attenuation A

$$\tau = 4.047 \times 10^{-A/20} \text{ ns}, \quad A > 5\text{dB} \quad (6.7)$$

This formula gives differential delays of 0.4, 0.13 and 0.04ns for attenuations of 20, 30 and 40dB respectively.

These new calculations substantiate the argument that for the proposed bit-rate, little intersymbol interference should occur in the system.

According to any two-ray model, the frequency spacing between adjacent minima in signal level is equal to the reciprocal of the

differential time delay, Fig. 6.6. Therefore, in order to suffer two minima within a bandwidth of 130MHz, a differential time delay of 7.69ns would be required. Since this condition is not met, no more than one notch within the bandwidth will be expected. The question now is whether even one notch will be noticed within the band? Fig. 6.7 represents situations where complete cancellation of signal level, occurs at exactly the carrier frequency of 500MHz, 8.68GHz and 37GHz. Also presented is the corresponding attenuation, given by the model, within a bandwidth of 130MHz. The attenuations at the band edge in case of the three carrier frequencies are 7.77, 32.5 and 45.0dB respectively. This implies that, at 37GHz, before any deep notch can occur within the bandwidth, the whole signal would be below the noise level. The determining factor is therefore the ratio of the bandwidth to the carrier frequency. However, it should be remembered that the two-ray model is a very simplistic one. Nevertheless, it is not expected that more complicated atmospheric conditions would alter the conclusion drastically.

The predicted total outage time for the experiment, due to multipath was estimated from Jakes model [113] to be approximately 36.1 minutes/fading month which corresponds to an outage of 0.082%. The model, however, does not specify the way of extrapolating this to yearly statistics. But if the yearly outage due to rain, calculated previously using the synthetic storm technique, was divided equally over 12 months, the multipath outage would represent 34% of the rain outage.

Based on the previous discussion, it is expected that no large distortions in the signal spectrum will occur. Thus, the degradation in the system performance will result mainly from thermal noise. Moreover,

Fig. 6.7 Attenuation given by the two-ray model within a bandwidth of 130MHz when complete cancellation of signal level is assumed at the centre frequency.

if results in Jakes model [113], that show that multipath outage is proportional to d^9 (for $d \leq 24\text{km}$), is accurate, then its relative contribution to the total outage time will decrease much faster compared to that of rain when more realistic path lengths, for that frequency, are used.

6.4 Back-to-back test

In order to characterize the performance of the MODEM under thermal noise conditions, a back-to-back test was conducted. The experimental layout is shown in Fig. 6.8. Unfortunately it was not possible to add the thermal noise at the rf level because of the lack of a noise source at that frequency. That eliminated the noise contributions of the up and down converters in addition to the TWTA nonlinearities on the system degradation. Thus, the results obtained should be considered to be on the optimistic side.

An Aventek amplifier with a bandwidth larger than 500MHz was used as a noise source at the receiver side. The signal level was held constant, while the noise level was increased in steps of 1dB. For each value of S/N one hundred error readings were obtained. The average, maximum and minimum values of the BER along with the corresponding standard deviations are given in Table 6.1. Usually results are given not for S/N but for the ratio of the energy per bit (E_o) to the noise power density (N_o), where

$$E_o = \frac{S}{B_R} \quad (6.8)$$

$$N_o = \frac{N}{B_N} \quad (6.9)$$

Fig. 6.8 Block diagram for the back-to-back test.

Step	N	S	S/N	E_o/N_o	AV BER	Max BER	Min BER	SD
0	-23.8 dBm	-25.3 dBm	-1.5	1.5	2.22×10^{-1}	4.15×10^{-1}	1.79×10^{-1}	6.36×10^{-2}
1	-24.25		-1.05	1.95	1.37×10^{-1}	2.73×10^{-1}	1.34×10^{-1}	1.38×10^{-2}
2	-25.10		-0.2	2.8	1.03×10^{-1}	1.96×10^{-1}	1.01×10^{-1}	9.49×10^{-3}
3	-26.35		1.05	4.05	5.80×10^{-2}	5.88×10^{-2}	5.74×10^{-2}	2.83×10^{-4}
4	-27.25		1.95	4.95	3.10×10^{-2}	3.16×10^{-2}	3.05×10^{-2}	2.27×10^{-4}
5	-28.45		3.15	6.15	1.26×10^{-2}	1.29×10^{-2}	1.23×10^{-2}	1.38×10^{-4}
6	-29.40		4.1	7.1	5.16×10^{-3}	5.41×10^{-3}	4.96×10^{-3}	8.50×10^{-5}
7	-30.50		5.2	8.2	1.88×10^{-3}	2.02×10^{-3}	1.77×10^{-3}	5.00×10^{-5}
8	-31.20		5.9	8.9	7.91×10^{-4}	8.65×10^{-4}	7.17×10^{-4}	2.80×10^{-5}
9	-32.41		7.11	10.11	7.00×10^{-5}	9.20×10^{-5}	4.90×10^{-5}	9.00×10^{-6}
10	-33.45		8.15	11.15	3.00×10^{-5}	1.33×10^{-5}	7.50×10^{-6}	1.10×10^{-6}
11	-34.30		9.0	12.0	1.14×10^{-6}	1.45×10^{-6}	9.00×10^{-7}	1.10×10^{-7}
12	-35.80		10.5	13.5	8.10×10^{-8}	1.03×10^{-7}	6.10×10^{-8}	9.00×10^{-9}
13	-36.90		11.6	14.6	2.10×10^{-9}	3.10×10^{-9}	1.10×10^{-9}	4.10×10^{-10}
14	-37.80	-25.3	12.5	15.5	1.80×10^{-10}	5.00×10^{-10}	0	1.71×10^{-10}
15	-38.74		13.45	16.45	1.00×10^{-11}	2.00×10^{-10}	0	3.70×10^{-11}
16	-39.80		14.5	17.5	0	0	0	0
17	-40.85		15.55	18.55	0	0	0	0

Table 6.1 Results of the Back to Back Test

B_R and B_N being the bit rate and the noise bandwidth respectively.

Therefore

$$\frac{E_O}{N_O} = \frac{S}{N} + \frac{B_N}{B_R} \quad (\text{in dB}) \quad (6.10)$$

Fig. 6.9 shows the average BER along with the theoretical one given by [76]

$$P_e = \frac{1}{2} \exp [-E_O / N_O] \quad (6.11)$$

A multipath situation, where two rays reach the receiver, was simulated in the laboratory at if. The experimental layout is given in Fig. 6.10. It was noticed that no errors occurred when the signal level in the second path was 5dB below that in the first one. Pictures of the if signal and its spectrum are given in Figs. 6.11 to 6.13 for different relative amplitudes (r) and time delays (τ). In Fig. 6.11, for which $r=1$, although a notch appears within the spectrum for $\tau=0.9\text{ns}$, no errors were recorded. Only, within a range of delays $\tau=(1\pm0.1)\text{ns}$, which corresponds to a phase shift of $(1\pm0.1)\pi$, were errors accumulated. That range decreased as the level of the interfering signal decreased. It should also be noted that the transition in phase of the DPSK signal, under multipath conditions, is no longer equal to 180° as in the ideal case. This means that the uncertainty of determining whether the incoming bit is a 1 or a 0 increases causing decision errors.

The same experiment was repeated at the rf level, with a carrier frequency of 8.68GHz (the 37GHz system being unavailable at that time). More deterioration in the performance was noticed due to the fact that,

Fig. 6.9 Results of the back-to-back error performance test.

Fig. 6.10 Block diagram for the multipath simulation test.

a) $r = 1$, $\tau = 0$, BER = 0 b) $r = 1$, $\tau = 0.9\text{ns}$, BER = 0 c) $r = 1$, $\tau = 1\text{ns}$, BER = overflow

Fig. 6.11 Results from the two-ray multipath simulation. DPSK signal and its spectrum for 2 equal amplitudes and different relative delays. Horizontal and vertical scale for LHS figures are 50ns and 20mv per division respectively and for RHS figures 20MHz and 10dB per division respectively.

a) $r = 0.707$, $\tau = 0$, BER = 0

b) $r = 0.707$, $\tau = 0.7\text{ns}$, BER = 0

c) $r = 0.707$, $\tau = 1.066\text{ns}$, BER = overflow

Fig. 6.12 Results from the two-ray multipath simulation. DPSK signal and its spectrum for the case of an interfering signal 3dB down and different relative delays. Horizontal and vertical scale for LHS figures are 50ns and 20mv per division respectively and for RHS figures 20MHz and 10dB per division respectively.

a). $r = 0.1, \tau = 0, \text{BER} = 0$

$r = 0.1, \tau = 0.7\text{ns}, \text{BER} = 0$

$r = 0.1, \tau = 0.93\text{ns}, \text{BER} = 0$

Fig. 6.13 Results from the two-ray multipath simulation. DPSK signal and its spectrum for the case of an interfering signal 10dB down and different relative delays. Horizontal and vertical scale for LHS figures are 50ns and 20mv per division respectively and for RHS figures 20MHz and 10dB per division respectively.

in this case the signal as a whole was much more attenuated, see Fig. 6.7. It is expected that the same trend will apply at 37GHz.

6.5 Temperature measuring devices

One technique to detect the presence of inversion layers, is to monitor the temperature profile of the lower troposphere. For that purpose, five temperature measuring devices were built and installed along a microwave tower at the CRC site at Shirley Bay. That tower is approximately eight km away from the middle of the radio path and almost perpendicular to it. A sketch of the tower with the location of the thermistors alongside it, is given in Fig. 6.14. A comparison between those heights and the path profile of Fig. 6.4 indicates that the height of the direct path is about 170 meters above sea level, i.e., about 60 meters above the highest thermistor. So if it is assumed that the inversion layers are formed near the ground after sunset and then rise upwards due to the earth's radiation, thus a certain delay will take place between the time an inversion is noticed in the thermistors readings and occurrence of multipath.

Each of these temperature measuring devices is composed of a bridge configuration, having thermistors in one of its branches. They were designed to give a linear output voltage with change in temperature. Their circuit diagram is given in Appendix C. For better accuracy, a calibration curve was obtained for each individual device. The maximum absolute error was found to be 0.6°C in the range 0 to 30°C . However, it is believed that the relative error is smaller than that.

Fig. 6.14 Positions of the temperature measuring devices along the microwave tower at the CRC site at Shirley Bay.

6.6 Conclusions

Preliminary calculations on the system proposed indicate that the outage due to multipath in a fading month may amount to up to 34% of that due to rain in the Ottawa region. However, this relative contribution to the outage time should decrease rapidly with reduction of the path length. Moreover, calculations of differential time delays suggest that the system would suffer very little from intersymbol interference under the present conditions. Finally, no deep notch in the spectrum of the signal is expected to occur before it falls below the thermal noise limit.

Therefore, it can be concluded that digital systems working at the frequency band 36-40GHz are not expected to suffer strongly from multipath. Nevertheless, experimental verification of these theoretical predictions is necessary. In the following chapter, some field measurements on the radio link will be presented.

CHAPTER SEVEN

EXPERIMENTAL RESULTS

7.1 Introduction

The radio link between Ottawa and Ashton was ready and operational during the summer of 1979. However, the data gathering process was hampered by interference at the receiver site. The origin of this interference was traced to three sources. The first source was a defective log-periodic antenna using the same tower. That antenna was used as a hf sounder for the ionosphere, and had one of its wires broken. Attempts to isolate the microwave system failed, and the hf system had to be switched to an alternate antenna. The other two sources of interference, a flashing light on top of the tower and the compressor of an air conditioner, shared the same power lines as the receiver's equipments. Power line filters and isolating transformers had to be used to eliminate their effects.

Before the elimination of the interference problem, bit-errors were accumulated continuously in the system and only chart recording of the received signal level was done. However, during August, after the interference problems were solved, a complete set of data (bit-error rate (BER) and signal level) was recorded for three fading days. Unfortunately due to a failure of the travelling-wave-tube amplifier (TWTA), the data gathering process was brought to a halt.

Two common approaches are usually followed to present and interpret the propagation results:

1. The generation of statistics for the signal level, number of fades, average fade duration, BER, etc., which requires a large data base taken over several months.

2. The study of individual events by comparing both weather and propagation data to try to come up with a better understanding of the multipath mechanism and its effects on the digital signal.

Although our data base was limited to only three days, an attempt was made to generate some of the previously mentioned statistics to compare them with theory. Moreover, in spite of the fact that the weather data was limited to the thermistors readings and the fact that the thermistors were much below the propagation path, it was still possible to correlate the occurrence of multipath propagation with the presence of inversion layers.

7.2 General discussion

Before discussing in detail the results of the experiment, some general comments on the performance of the system are necessary. Fig. 7.1 is a block diagram showing the rf connections with the signal and noise levels indicated at different stages.

Although the received signal level at the antenna was calculated in the design to be about -43dBm , from Fig. 7.1 it is estimated to be only -48dBm , i.e., a loss of 5dB . This may be due to:

- a) non ideal alignment of the antennas (This seems unlikely since the alignment was readjusted several times with no increase in signal level),
- b) antenna gains less than those specified,
- c) more losses in the waveguide and flexible waveguide, connecting the TWTA to the transmitting antenna, than anticipated (less probable since these losses were measured in the lab) or,

d) more losses in the cable connecting the down-converter box to the hut at Ashton (this may explain the loss of only two or three more dB).

The noise power at the output of the down-converter box was measured to be -41dBm , which is about 7dB higher than anticipated. This was caused by a defect in the mixer-preamp that raised its noise temperature to $2.79 \times 10^3\text{°K}$ corresponding to a noise figure of 10.2dB and reduced its gain by 7dB (from 25 to 18). The resulting extremely high noise power of -51dBm at the input of the logarithmic amplifier, which lies within its dynamic range (-65dBm to -5dBm), would have caused a further deterioration in the S/N of the system. To improve the situation a 15dB attenuator was added before the log amp to insure that the noise level is completely outside its dynamic range.

After this modification, the mid day signal level before the log amp was measured to be -32dBm with a S/N of about 35dB . It was also noticed that the signal could be reduced by a further 20dB without any errors being counted (i.e., $\text{BER} < 10^{-7}$). This means that for a bit error rate of 10^{-7} , the S/N required is approximately 15dB , which represents a deterioration of about 4.7dB from the if back to back test (10.3dB).

7.3 Data collecting procedure

The data collected at the receiver site is basically: signal level and bit-error-rate. Fig. 7.2 represents a block diagram of the receiver with the connection of the data display and recording equipment. The M6800 microprocessor controls the data collecting process. It samples the video output of the log amp, which is linearly proportional to the input power in dB, and then channels it, along with both the

Fig. 7.2 Block diagram of the receiver with the data recording equipment.

bit-error-rate reading from the demodulator and the real time, to a tape recorder and a video terminal. The BER reading represents the accumulated errors at the end of a block of 10^7 bits. Since each of these blocks lasts for about 0.15 seconds, the sampling rate was restricted to five times per second. Because of this high data density and the type of recorder available, 17 tapes were required for each night of recording. During periods of changing tapes, some data was lost. These periods are removed from the statistics. The tapes were later read into a Sigma 9 computer for data processing.

The video output of the log amp was also recorded on two chart recorders with different speeds. Finally, the if signal spectrum was monitored on a spectrum analyzer whose display was recorded by a movie camera whenever distortions occurred.

7.4 Propagation results

The experimental results obtained are composed of three fading days in July and three in August. The chart recordings of the signal level in July show many more fluctuations than the corresponding ones during August. This is believed to be caused by the fact that July was much warmer and more humid than August.

Fig. 7.3a represents a typical chart recording of signal level propagating under multipath conditions that occurred on the night of the 13th of July. For a comparison, Fig. 7.3b shows the recording under a rainy day on the 23rd of August. It can be noticed that, under multipath conditions, the signal level fluctuates rapidly while in case of rain the variation is smooth and longer lasting. Also, the presence of signal enhancements is a typical characteristic of multipath

(a)

(b)

Fig. 7.3 Chart recording for typical signal level variation.
(a) under multipath conditions, (b) under rain.
Horizontal scale is an hour per eight divisions.

propagation. It should also be pointed out that the duration of signal enhancements is much longer than that for signal fadings.

Fig. 7.4 shows the effect of variations in the angle of arrival of the received signal. Under super-refractive conditions, the direct-ray may reach the receiving antenna at an angle outside the antenna main beam, causing a partial loss of signal. The recording in Fig. 7.4 indicate that, in addition to fluctuations, the signal level was depressed, in general, during a period of about an hour. Complete chart recording for August are given in Appendix D.

7.4.1 Cumulative distribution of signal level

The cumulative distribution of signal fading was obtained by dividing the sum of all the sampling points at which the signal level was equal to or below a certain level L by the total number of sampling points. A similar technique was used for signal enhancements.

Fig. 7.5 represents the distribution of fades for the three days in August. For deep fades ($L \leq 0.1$) the individual distributions do not follow the theory. However, the combined distribution for the three days, given by the dashed line, does, which is encouraging for this very limited data base.

As for enhancements, Fig. 7.6 represents the individual and combined distributions. The latter is given by

$$P(V \geq L) \propto L^{-6.35}; \quad 1 \leq L \leq 2.23 \quad (7.1)$$

which is different from the Stephansen and Mogensen results [85]. The enhancements reached values of up to 9dB. The two-ray theory cannot explain such big enhancements. However, if three rays reach the

Fig. 7.4 Chart recording the typical signal level variations due to change in the angle of arrival.

Fig. 7.5 Cumulative probability distributions of multipath fades for the nights of the 16th, 21st and 22nd of August. Combined distribution given in dashed line.

Fig. 7.6 Cumulative probability distributions for multipath enhancements for the nights of the 16th, 21st and 22nd of August. Combined distribution given in dashed line.

receiver with equal phases and amplitudes, an increase in signal level of 9.54dB can be obtained. The probability that this situation occurred is small. Other logical explanations are that either the signal was trapped in a duct, or a tilt in the inversion layer, acting as a lens, focussed the signal at the receiver. Two such large enhancements, shown in Fig. 7.7, occurred after 10 O'clock p.m. on the 16th of August. One persisted for 3 minutes and the other for 6 minutes. During these two periods no bit errors were noticed, which can be explained by the fact that the received signal was probably composed of a bunch of rays with very small relative delays. However, during the same night another enhancement that occurred at 2:11 a.m. and lasted for approximately 90 seconds, produced most of the errors during enhancement in that day.

7.4.2 Total number of fades

The total number of fades of depth $20 \log L$ dB is equal, by definition, to the number of times an envelope crosses the level L in an upward direction. Fig. 7.8 represents the distributions obtained. The oscillations at the end of these distributions is believed to be due to the small sample sizes. The combined distribution for the three days shows a relation of the form

$$N(L) \propto L^2; \quad L \leq 0.1 \quad (7.2)$$

compared to theoretical and experimental results that show exponents of unity [77,80,82,83], $4/3$ [85] and 2.4 [86].

The combined distribution for the number of enhancements is given in Fig. 7.9. It has a relation of the form

$$N(L) \propto L^{-5.22}; \quad 1.12 \leq L \leq 2.24 \quad (7.3)$$

Fig. 7.7 Chart recording showing enhancements lasting for 3 minutes at 10:04 p.m. and 6 minutes at 10:16 p.m. during the night of the 16th of August.

Fig. 7.8 Total number of fades for the nights of the 16th, 21st and 22nd of August. Combined numbers are given in dashed line.

Fig. 7.9 Total number of enhancements for the nights of the 16th, 21st and 22nd of August. Combined numbers given in dashed line.

7.4.3 Average fade duration

The average time $\bar{t}$ below a certain fade is equal to the ratio of the total time spent in that fade to the total number of fades N . Fig. 7.10 shows the distributions obtained. As can be seen, a large fluctuation in values exist. The fact that $\bar{t}$ for large fades is sometimes greater than the corresponding one at smaller fades can probably be explained by the insufficiency of data.

The main point to emphasize in these results is that $\bar{t}$ is much less than those reported in the literature. Table 7.1 compiles results from different experiments. The comparison supports the argument that the tendency for $\bar{t}$ is to decrease with increasing frequency. Barnett [82] had previously concluded that $\bar{t}$ was independent of frequency, while Bullington [80] suggested a dependence of the form $1/\sqrt{f}$. Physically speaking, a frequency dependence in the form of decreasing $\bar{t}$ with increasing f is reasonable, since as the frequency increases and the wavelength decreases, small variations in differential path length can produce large fluctuations in signal level. More experimental and theoretical investigations are required to determine quantitatively the form of this dependence in addition to the influence of path length variations.

Fig. 7.11 represents the results for the average duration of enhancements.

7.5 Bit-error-rate

The real criterion on which the performance of any digital system can be judged is the amount of bit-error-rate (BER) generated. The attenuation in the signal or the distortion in its spectrum are of no importance as long as no bit errors result.

Fig. 7.10 Average fade duration for the nights of the 16th, 21st and 22nd of August. Combined duration given by the dashed line.

	f	d	Average fade duration (sec.) at level L		
	GHz	km	-20dB	-30dB	-40dB
Bullington [80]	4	48.3	40.0	12.6	4.0
Vigants [83]	4	45.8	40.8	12.9	4.1
	6	-	49.0	15.5	4.9
Barnett [82]	11	45.8	30.0	10.4	3.0
Stephanson and Mogensen [85]	14	44.7	5.3	2.5	1.1
This experiment	37	33.87	2.17	1.51	-
			1.04	.65	-

Table 7.1 Comparison between average fade duration
results from several experiments

Fig. 7.11 Average enhancement duration for the nights of the 16th, 21st and 22nd of August. Combined duration given by the dashed line.

The system was set up to measure BER ranging from 1×10^{-7} to 999999×10^{-7} which corresponds to six decimal digits. Whenever an overflow of errors occurred, the reading of the counter was ignored and a BER of 999999×10^{-7} was recorded instead. The distribution of BER as a function of the signal level is given in Tables 7.2, 7.3 and 7.4 for the three days of recording. The entries in the tables indicate the number of sampling points with errors in the range specified. The corresponding S/N can be obtained by subtracting from the signal level in column S the noise level of -67dBm .

In general the errors in the tables can be divided into two categories:

1. Errors occurring when the signal level was below -49dBm corresponding to a S/N of 18dB or less. These errors are mainly due to degradation of the S/N caused by destructive interference. However, intersymbol interference may have added to the errors since no error rate greater than 10^{-7} should have occurred before the S/N dipped below 15dB . In this category the BER ranged from 1×10^{-7} to overflow, which indicates that the events may have lasted from as little as tens of nanoseconds to as much as tens of milliseconds.
2. Errors occurring during shallow fadings and enhancements. Neither present multipath models nor ducting theory predict such a behaviour. The malfunction of the system was ruled out as a cause for these errors since they were not consistent with given signal levels and also they did not occur during preliminary testings of the link. Only two possibilities remain. First, that these errors were due to interference and, second, that they were due to propagation effects. The former reason is substantiated by the fact that some of these errors followed a

log (BER)		less than 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	Over-flow
S dBm	Gain dB	Number of samples with error						
-23	+ 9					2		
	+ 8					5	1	
	+ 7					4	2	
	+ 6					4		
	+ 5					1		
	+ 4					8	2	
	+ 3					5	1	
	+ 2					2	1	
-32	+ 1					2		
	0		1			2	2	
	- 1					1	1	
	- 2					2	1	
	- 3					2	1	
	- 4					1	1	
	- 5					3		
	- 6					1	2	
-42	- 7							
	- 8						1	
	- 9					3		
	-10						1	
	-11							
	-12							
	-13							
	-14							
-52	-15							
	-16							
	-17							
	-18						1	
	-19	8						
	-20	6	4					
	-21	10	2					
	-22	6	2	2				
-62	-23	1	5	1		1	1	
	-24	3	6	3	2	3	1	
	-25		1	2	2		5	2
	-26				6	2	9	3
	-27				1		3	5
	-28					1	2	7
	-29							5
	-30							5
-67	-31					1		7
	-32					1		11
	-33							5
	-34							4
	-35							16

Table 7.2 Distribution of BER for the night of the 16th of August

log (BER)		less than 1	1-2	2-3	3-4	4-5	5-6	Over-flow
S dBm	Gain dB	Number of samples with error						
-29	+ 3	1						
	+ 2	1						
	+ 1	1				1	1	
-32	0	1				2		
	- 1					1		
	- 2	1				1	1	
	- 3						1	
	- 4					1	2	
	- 5	1						
	- 6					1		
	- 7							
-42	- 8							
	- 9							
	-10							
	-11							
-45	-12			1				
	-13					1		

Table 7.3 Distribution of BER for the night of the 21st of August.

log (BER)		less than 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	Over- flow
S dBm	Gain dB	Number of samples with error						
-31	+ 1	1			1	1	1	
-32	0					3	2	
	- 1	1					2	
	- 2	1					3	
	- 3	1					2	
	- 4	1	1			1	2	
	- 5	1					1	
	- 6					1		
	- 7	1						
	- 8							
	- 9							
-42	-10							
	-11							
	-12							
	-13							
	-14							
	-15							
	-16							
	-17	4						
	-18	14						
	-19	34	10	1				
-52	-20	38	18	4	1			
	-21	33	21	5	2			
	-22	17	26	15	4			
	-23	6	14	15	8	1		
	-24		6	8	6	1		
	-25			7	9	3		
	-26			2	3	6		
	-27			1	4	2		
	-28				2	3		
	-29						1	
-62	-30					1	2	
	-31						1	
	-32							
	-33							
-66	-34						1	

Table 7.4 Distribution of BER for the night of the 22nd of August.

certain time pattern of occurring twice each hour. Moreover, since the majority of these errors lasted only during one single sampling period, the source of interference should be due to a pulsed signals rather than a continuous one. Nevertheless, this does not explain the presence of the rest of the errors that do not follow any time pattern and in particular, those which occurred at 02:11 a.m. on the 17th of August. During that enhancement, errors in 26 sampling periods occurred within 58 seconds. Fig. 7.12 shows signal variation that include this particular enhancement. Table 7.5 gives the corresponding distribution of BER as a function of signal level. The events that caused these errors were relatively slow, lasting at least for periods of 0.3 ms. This suggests that their cause may be other than interference.

There is one other experiment in which errors during shallow fading were noted. These errors lasted continuously for several seconds [59]. Unfortunately, signal enhancements could not be monitored in that experiment. Additional experimental investigations are required to verify the presence of these errors and determine their exact cause.

Fig. 7.13 is a scattergram of the BER showing the presence of both degradation in S/N and intersymbol interference. Once more, the two distinct regions are present, one following the theoretical and experimental curves and the second, forming a cluster of points at high BER and S/N. The presence of two points on the experimental curve and two below the theoretical curve cannot be explained.

Table 7.6 gives the total time spent in error during the 3 nights. A bit-error-rate of 10^{-3} corresponds to service failure in the telephone systems.

Fig. 7.12 Signal level fluctuation showing the enhancement at 02:11 a.m. on the 17th of August.

log (BER)		4 - 5	5 - 6
s dBm	Gain dB	Number of samples with errors	
-23	+9	2	-
-24	+8	5	1
-25	+7	4	2
-26	+6	4	-
-27	+5	1	-
-28	+4	6	1

Table 7.5 Distribution of BER during the enhancement at 02:11 a.m. on the 17th of August.

Energy per bit

Fig. 7.13 Scattergram of BER during the three days of August: Theoretical and experimental curves also shown.

	night of the 16 th	night of the 21 st	night of the 23 rd
Total time BER > 10^{-7} .	50.93 s.	5.09 s.	80.95 s.
Total time BER > 10^{-3}	37.56 s.	3.61 s.	16.73 s.
Total time BER > 10^{-7} continuously	12.31 s.	-	12.55 s.
Total time BER > 10^{-3} continuously	11.25 s.	-	1.46 s.

Table 7:6 Total time spent in error

7.6 Results of the temperature measuring devices

The task of correlating the thermistor results with the propagation data is not easy, especially since the propagation path is about 60 meters above the highest thermistor, and these are located about 8 km away from the mid path. Therefore, the presence and magnitude of a temperature inversion detected by the thermistors does not necessitate the presence of a similar inversion 60 meters above. Also, the absence of an inversion at the thermistors height does not mean that no inversions existed 60 meters above.

In order to interpret the results, the following reasonable assumption will be made. The formation of inversion layers occurs after sunset adjacent to the earth's surface due to radiation from the earth and as its surface cools down, the air adjacent to it also loses temperature and the inversion layer appears to rise. Therefore, an inversion detected by the thermistors will rise and affect the propagation after a certain time delay.

Due to data collecting problems, only results from three thermistors were recorded, namely 1, 3 and 5 in Fig. 6.14. These are approximately 12 meters apart. The voltage output from each thermistor box is sampled twice a second. This is a requirement imposed by data gathering from other experiments using the same multiplexer. The average reading of 120 points, corresponding to one minute, is taken and, using the calibration curve for each thermistor, the corresponding temperature is calculated. The resulting time records for the temperature variations are shown in Figs. 7.14, 7.15 and 7.16 for the three days in August. The points included in the graphs are for 5 minute intervals, since it was noticed that in general no rapid fluctuation occurred within that time period.

Fig. 7.14 Time record of temperature variations for the night of the 16th of August recorded by temperature boxes #1, 3 and 5. Sunset 20:09 and sunrise 06:05 (EDT)

Fig. 7.15 Time record of temperature variations for the night of the 21st of August recorded by temperature boxes #1, 3 and 5. Sunset 20:04 and sunrise 06:10 (EDT).

Fig. 7.16 Time record of temperature variations for the night of the 22nd of August recorded by temperature boxes #1, 3 and 5. Sunset 20:03 and sunrise 06:11 (EDT).

For the night of the 16th of August, Fig. 7.14, the inversion started around 6 p.m., and lasted until 7 a.m. The maximum temperature inversion detected was 5°C within 24 meters. A large temperature fluctuation occurred between 8 and 10:30 p.m. This probably caused the signal fluctuations between 10 p.m. and midnight. The steady inversion of about 3°C (in 24 meters) between 2 and 3 a.m., may have caused what appears to be an angle of arrival problem during the period between 3 and 4 a.m. After 8 a.m., when the inversion disappeared, only small scintillation in the signal level persisted.

During the night of the 21st of August, Fig. 7.15, the inversion detected was very small and also the fluctuation in the signal level was minimum. No deep fadings or large enhancements took place. A 1.5°C inversion at 10 p.m. may have caused the 16dB fading one hour and 13 minutes later. The signal fluctuations between 5 and 7 a.m. cannot be explained.

Finally, during the night of the 22nd of August, Fig. 7.16, a 1.5°C inversion between 10 and 10:30 p.m. may have caused the angle of arrival problem between 11:30 and 12:30 p.m. It is also to be noted that the signal level became steady after 5 a.m. when the inversion disappeared.

7.7 Conclusions

It was unfortunate that the data gathering process was limited by equipment breakdown and interference. Nevertheless, the experience achieved in building and operating such a high-data-rate digital radio link at a carrier frequency as high as 37GHz is very valuable. The limited results from this experiment cannot be taken as a basis to judge the performance of such systems. Nevertheless, they constitute a good

starting point for future design. It is hoped that if and when the TWTA is fixed, that a more complete set of results will be obtained. Of great importance is the investigation of the presence of bit errors during shallow fadings and enhancements. If it can be proven that they are caused by a propagation phenomena, then this will have a far reaching effect on the design of digital radio systems.

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary and conclusions

This work has been an attempt to tackle a major concern that faces radio engineers, namely, the prediction of performance reliability of systems using the lower troposphere as transmission medium for the centimetre and millimetre wave bands. It dealt, in general, with two principal sources of concern: rain attenuation and multipath propagation. A theoretical and numerical approach was employed in addressing the former, while a more experimental approach was chosen for the latter.

The realization of the fact that the effective path length, used in frequency scaling of rain attenuation, is dependent on frequency resulted in a better understanding of the scaling techniques. A new single-frequency scaling technique, based on the concept of the "normalized effective path length", which gives an estimate for this dependence, was developed. This new technique has been shown to have the following advantages:

1. It considers the nonuniformity of the rain rate along the propagation path.
2. No point rain rate statistics are needed.
3. No spatial distribution of rain rate is assumed.
4. Gives better results at values of attenuation which are exceeded only a small percentages of the time.

This technique has been tested for earth-space paths, but its applicability to terrestrial paths has still to be verified.

The detailed theoretical examination of Hogg's graphical two-frequency scaling technique has shown its superior accuracy compared to single-frequency techniques. In contrast with these techniques, it proved to be almost independent of the size distribution and temperature of the raindrops. The mathematical derivation of this technique eliminated the original requirement of plotting and extracting points from different curves in order to predict the attenuation.

The flexibility and relative accuracy of the synthetic storm technique were the reasons behind the new concept, introduced in this work, to employ this technique in the theoretical and numerical evaluation of simpler methods that use rain rate data to predict attenuation statistics. Based on path-average rain rate calculations using this technique, some modifications on Crane's model for the reduction coefficients were suggested. Moreover, these results, although not conclusive, did not indicate a universal behaviour of these coefficients either in terms of rain rate or percentage of time. Finally, this study showed that prediction methods in this category are highly dependent on the choice of drop size distribution.

In order to investigate the effects of multipath propagation on line of sight digital radio systems, an experimental link was installed along a 33km path extending from downtown Ottawa to Ashton. A carrier frequency of 37GHz was employed. Binary differential-phase-shift keying was chosen as a modulation scheme with a data rate of 65.5Mb/s.

In spite of the equipment failures that limited the amount of data collected in the propagation experiment, some interesting results were obtained. Most important was the presence of BER during enhancement and shallow fading. If it can be proven that this is indeed due to propagation effects, then it will constitute an important shift from the

accepted beliefs. Furthermore, the hypothesis that the average fade duration decreases with frequency was confirmed. However, the relative importance of selective multipath fading, compared to rain attenuation, in affecting digital systems could not be evaluated from such a limited data base.

8.2 Recommendations for further research

Because of the large scope of this work, it was not possible to pursue all aspects to a final conclusion. Nevertheless, some definite suggestions can be given for further research:

1. The possibility of using the "normalized effective path length" concept to combine attenuation measurements at different frequencies in the form of universal curves should be investigated. Currently, this can only be done for earth-space data, until the applicability of this concept is proven for long terrestrial paths.
2. The extension of the path-average rain rate calculations based on the synthetic storm technique to generate either local, regional or, if possible, universal models for the reduction coefficient should be attempted. Consequently, the modification of Crane's new method [21] to include these models should be done.
3. Further experimental investigations on the digital radio link to determine the exact cause of the bit errors during enhancement and shallow fading should be conducted. If proven to be due to propagation, modifications in the theoretical models become necessary. This further experimentation should also be used in the compilation of a large data base to generate more reliable statistics for the different characteristics of the signal during both fading and enhancement conditions.

LIST OF REFERENCES

1. Crane, R.K., "A global model for rain attenuation prediction", IEEE Eastcon Record, pp. 391-395, 1978.
2. Lin, S.H., "Statistical behaviour of rain attenuation", BSTJ, Vol. 52, No. 4, pp. 557-581, April 1973.
3. Medhurst, R.G., "Rainfall attenuation of centimeter waves: comparison of theory and measurement", IEEE Trans. Antennas Propagat., Vol. AP-13, pp. 550-564, July 1965.
4. Rogers, R.R., "Statistical rainstorm models: their theoretical and physical foundations", IEEE Trans. Antennas Propagat., Vol. AP-24, pp. 547-566, July 1976.
5. Hogg, D.C. and Chu, T., "The role of rain in satellite communications", Proc. IEEE, Vol. 63, No. 9, pp. 1308-1331, Sept. 1975.
6. Gaut, N.E. and Reifenstein, E.C., "Interaction of microwave energy with the atmosphere", Proc. AIAA Conference on Earth Resources, Annapolis, 2-4 March 1970.
7. Ryde, J.W. and Ryde, D., "Attenuation of centimeter and millimeter wave by rain, hail, fogs and clouds", Rept. 8670, General Electric Co. Research Labs., Wembley, England, May 1945.
8. Olsen, R.L., Rogers, D.V. and Hodge, D.B., "The aR^b relation in the calculation of rain attenuation", IEEE Trans. Antennas Propagat., Vol. AP-26, pp. 318-329, March 1978.
9. CCIR Report 721, "Attenuation and scattering by precipitation and other atmospheric particles", XIVth Plenary Assembly, Vol. V, International Telecommunication Union, Geneva, 1978.
10. Harden, B.N., Norbury, J.R. and White, W.J.K., "Use of a lognormal distribution of raindrop sizes in millimetric radio attenuation studies", IEE Conference Proceedings 169, Part 2, pp. 87-91, 1978.
11. Currie, N.C., Dyer, F.B. and Hayes, R.D., "Some properties of radar returns from rain at 9.375, 35, 70 and 95GHz", IEEE International Radar Conference, pp. 215-220.
12. Lin, S.H., "Empirical rain attenuation model for earth-satellite paths", IEEE Trans. on Com., Vol. COM-27, No. 5, pp. 812-817, May 1979.
13. Ogushi, T., "Attenuation of electromagnetic waves due to rain with distorted raindrops", J. Radio Research Labs (Tokyo), Vol. 7, pp. 467-485, September 1960.

14. CCIR Doc. 5/191 (Japan), 1974-1978, "Effective distance of a radiowave passing through rain in earth space path", May 1977.
15. Lin, S.H., "More on rain rate distributions and extreme value statistics", BSTJ, Vol. 57, No. 5, pp. 1545-1569, May 1978.
16. Misme, P., "Experimental results about rain induced attenuation and improvement of calculation methods", IEE Conference Proceedings 169, Part 2, pp. 102-106, 1978.
17. Dougherty, H.T. and Dutton, E.J., "Estimating year to year variability of rainfall for microwave applications", IEEE Trans. on Com., Vol. COM-26, No. 8, pp. 1321-1324, August 1978.
18. Dutton, E.J. and Dougherty, H.T., "Year to year variability of rainfall for microwave applications in the USA", IEEE Trans. on Com., Vol. COM-27, No. 5, pp. 829-832, May 1979.
19. Fang, D.J. and Harris, J.H., "Precipitation attenuation studies based on measurements of ATS-6 20/30-GHz beacon signals at Clarksburg, MD", IEEE Trans. Antennas Propagat., Vol. AP-27, No. 1, pp. 1-11, January 1979.
20. CCIR Doc. P/103 (USA), "Rain attenuation prediction", June 1978.
21. Crane, R.K., "Prediction of attenuation by rain", Environmental Research and Technology, INC., January 1980.
22. Segal, B., "An objective procedure for the classification of rainfall rate climatic zones", URSI Symposium, Lennoxville, Canada, May 1980.
23. Zawadzki, I.I., "Statistical properties of precipitation patterns", J. Applied Meteor., Vol. 12, pp. 459-472, April 1973.
24. Rogers, R.R. and Zawadzki, I.I., "Rainfall statistics for application to plume rainout models", Atmospheric Environment, Vol. 13, pp. 279-286, 1979.
25. Drufuca, G., "Rain attenuation studies", Stormy Weather Group Scientific Report MW-77, McGill University, Montreal, Canada, 1973.
26. Hogg, D.C., "Intensity and extent of rain on earth-space paths", Nature, Vol. 243, pp. 337-338, June 1973.
27. Hodge, D.B., "Frequency scaling of rain attenuation", IEEE Trans. Antennas Propagat., Vol. AP-25, pp. 446-447, 1977.
28. Turner, J.W. and Turner, D., "Attenuation due to rainfall on a 24km microwave link working at 11, 18 and 36GHz", Electron. Lett., Vol. 6, No. 10, pp. 297-298, May 1970.

29. Davies, P.G., "Radiometer measurements of atmospheric attenuation at 19 and 37GHz along sun-earth paths", Proc. IEEE, Vol. 120, No. 2, pp. 159-163, February 1973.
30. Ho, K.L., Mavrokowkoulakis, N.D. and Cole, R.S., "Rain induced attenuation at 36GHz and 110GHz", IEEE Trans. Antennas Propagat., Vol. AP-26, No. 6, pp. 873-875, November 1978.
31. Harden, B.N., Norbury, J.R., Tracey, M.A. and White, W.J.K., "Attenuation ratios and path-diversity gains observed in rain on a network of short terrestrial links at frequencies near 11, 20 and 36GHz", IEEE Conference Proceedings 169, Part 2, pp. 68-71, 1978.
32. Harris, J.M. and Hyde, G., "Preliminary results of COMSTAR 19/29GHz beacon measurements at Clarksburg, Maryland", COMSTAT Tech. Rev., Vol. 7, No. 2, pp. 599-623, Fall 1977.
33. Flavin, R.K., "Earth-space path rain attenuation at 11 and 14GHz, Darwin, Australia", A.T.R., Vol. 12, No. 2, 1978.
34. Henry, P., "Measurement and frequency extrapolation of microwave attenuation statistics on the earth-space path at 13, 19 and 30GHz", IEEE Trans. Antennas Propagat., Vol. AP-23, pp. 271-274, March 1975.
35. Kheirallah, H.N., "A study of tropospheric effects on satellite communications at 40GHz", M.Eng. Thesis, Department of Electronics, Carleton University, Ottawa, Canada, March 1976.
36. CCIR Doc. 5/1043, "Propagation data required for space telecommunication systems", Geneva, April 1974.
37. Yokoi, H., Yamada, M. and Ogawa, A., "Measurement of precipitation attenuation for satellite communications at low elevation angles", J. Rech. Atmos., Vol. 8, pp. 329-338, 1974.
38. Goldhirsh, J. and Robinson, F.L., "Attenuation and space diversity statistics calculated from radar reflectivity data of rain", IEEE Trans. Antennas Propagat., Vol. AP-23, pp. 221-227, March 1975.
39. Nowland, W.L., Olsen, R.L. and Shkarofsky, I.P., "Theoretical relationship between rain depolarization and attenuation", Electron. Lett., Vol. 13, No. 22, pp. 676-678, October 1977.
40. Kheirallah, H.N. and Olsen, R.L., "Effective path length and the frequency scaling of rain attenuation", USNC/URSI Meeting, Seattle, Washington, USA, June 1979.
41. Wilson, R.W., "Sun tracker measurements of attenuation by rain at 16 and 30GHz", BSTJ, Vol. 48, pp. 1383-1404, May 1969.

42. Yokoi, H., Yamada, M., Ogawa, A. and Futura, O., "Study of the effective path length through rain in earth-space path", Report URSI-F No. 222, Research and Development Laboratories, Kokusai Denshin Denwa Co. Ltd., Tokyo, Japan, April 1976.
43. Bertok, E., DeRenzis, G. and Drufuca, G., "Estimate of attenuation due to rain at 11GHz from raingauge data", URSI Commission-F, open symposium, La Baule, France, pp. 295-300, April-May 1977.
44. Drufuca, G., "Rain attenuation statistics for frequencies above 10GHz from raingauges observations", J. Recherches Atmospheriques, Vol. 8, No. 1-2, pp. 399-412, 1974.
45. Watson, P.A., Ahmed, H.J. and Papaioannou, G., "Long term prediction of attenuation on terrestrial radio links from rainfall data", IEE Conference Proceedings 169, Part 2, pp. 92-96, 1978.
46. D'Alessio, T. and Merlo, U., "Synthesis of models for rain induced attenuation", IEE Conference Proceedings 169, Part 2, pp. 172-176, 1978.
47. Lin, S.H., "A method for calculating rain attenuation distributions on microwave paths", BSTJ, Vol. 54, No. 6, pp. 1051-1086, July 1975.
48. Mogensen, G. and Stephansen, E., "An estimation of methods for prediction of rain induced attenuation on LOS paths", IEE Conference Proceedings 169, Part 2, pp. 97-101, 1978.
49. Harden, B.N., Norbury, J.R. and White, W.J.K., "Estimation of attenuation by rain on terrestrial radio links in the UK at frequencies from 10 to 100GHz", IEE J. Microwave, Opt. and Acoust., Vol. 2, No. 4, pp. 97-104, July 1978.
50. Semplak, R.A., "The influence of heavy rainfall on attenuation at 18.5 and 30.9GHz", IEEE Trans. Antennas and Propagat., Vol. AP-18, No. 4, pp. 507-511, July 1970.
51. Barsis, A.P. and Samson, C.A., "Performance estimation for 15GHz microwave links as a function of rain attenuation", IEEE Trans. on Com., Vol. COM-24, pp. 462-470, April 1976.
52. Kheirallah, H.N., Segal, B. and Olsen, R.L., "Application of synthetic storm data to evaluate path average rain rate techniques for predicting rain attenuation statistics", URSI Symposium, Lennoxville, Canada, May 1980.
53. Drufuca, G. and Rogers, R.R., "Statistics of rainfall over paths from 1 to 50km", Atmospheric Environment, Vol. 12, pp. 2333-2342, 1978.
54. CCIR Report 233-3, "Influence of the non-ionized atmosphere on wave propagation, ground-ground propagation", International Telecommunication Union, Geneva, Switzerland, 1975.

55. Segal, B., Private Communication.
56. Bussey, H.E., "Microwave attenuation statistics estimated from rainfall and water vapour statistics", Proc. IRE, Vol. 38, pp. 781-785, 1950.
57. Segal, B., "High-intensity rainfall rate statistics for Canada", CRC Report 1329-E, Department of Communications, Ottawa, Canada, 1979.
58. Jones, D.M.A. and Sims, A.L., "Climatology of instantaneous precipitation rates", Report AFCRL-TR-73-0171 (prepared by the Illinois state water survey). Rome Air Development Center, Bedford, USA, 1971.
59. McCormick, K.S., Private Communication.
60. Hartmann, P.R., and Allen, E.W., "An adaptive equalizer for correction of multipath distortion in a 90Mb/s 8 PSK system", IEEE Conference on Communications, pp. 5.6.1 - 5.6.4, June 1979.
61. Barnett, W.T., "Multipath fading effects on digital radio", IEEE Trans. on Com., Vol. COM-27, No. 12, pp. 1842-1848, December 1979.
62. Lin, S.H., "Impact of microwave depolarization during multipath fading on digital radio performance", BSTJ, Vol. 56, No. 5, pp. 645-673, May 1977.
63. Mottl, T.O., "Dual-polarized channel outages during multipath fading", BSTJ, Vol. 56, No. 6, pp. 675-701, May 1977.
64. Shkarofsky, I.P. and Nickerson, S.B., "Depolarization due to multipath propagation in radio relay systems", MPB Technologies Inc., Research Report No. MPB-124-1, October 1978.
65. "Anomalous propagation", Demodulator, Lenkurt, July-August 1975.
66. Dougherty, H.T. and Hart, B.A., "Anomalous propagation and interference fields", US Department of Commerce, OT Report 76-107, December 1976.
67. Flavell, R.G., "Refractive index gradients in lower troposphere - A fresh approach", IEE Conference Proceedings 160, Part 2, pp. 182-186, 1978.
68. Du Castel, F., "Tropospheric radiowave propagation beyond the horizon", Pergamon, 1966.
69. Bello, P.A., Derosa, J.K. and Boardman, C.J., "Line-of-sight wideband propagation", CNR, Inc., Technical Report, May 1973.

70. Meadows, R.W., Lindgren, R.E. and Samuel, J.C., "Measurement of multipath propagation over a line of sight radio link at 4 Gc/s using frequency sweep technique", Proc. IEE, Vol. 113, No. 1, January 1966.
71. Strickland, J.L., "Site diversity measurements of low angle fading and comparison with a theoretical model", URSI Symposium, Lennoxville, Canada, May 1980.
72. Bean, B.R., Frank, V.R. and Lane, J.A., "An analysis of VHF field strength variations and refractive index profiles", J. of Research NBS, Vol. 67D, No. 6, November-December 1963.
73. Lane, J.A., "Radar echoes from clear air in relation to refractive-index variations in the troposphere", Proc. IEE, Vol. 116, No. 10, October 1969.
74. Wait, "Electromagnetic waves in stratified media", Pergamon Press, pp. 477-479, 1970.
75. Paltridge, G.W., "Reflection from elevated layers in the troposphere", Proc. IEE, Vol. 117, No. 1, January 1972.
76. Schwartz, Bennett and Stein, "Statistical communication", McGraw-Hill, 1966.
77. Lin, S.H., "Statistical behavior of a fading signal", BSTJ, Vol. 50, No. 10, pp. 3211-3270, December 1971.
78. Kaylor, R.L., "Statistical study of selective fading of super-high frequency radio signals", BSTJ, Vol. 32, No. 5, pp. 1187-1202, September 1953.
79. Ruthroff, C.L., "Multi-path fading on line of sight microwave radio systems as a function of path length and frequency", BSTJ, Vol. 50, No. 7, pp. 2375-2398, September 1971.
80. Bullington, K., "Phase and amplitude variations in multipath fading of microwave signals", BSTJ, Vol. 50, No. 6, pp. 2039-2053, July 1971.
81. Babler, G.M., "A study of frequency selective fading for a microwave line of sight narrowband channel", BSTJ, Vol. 51, No. 3, pp. 731-757, March 1972.
82. Barnett, W.J., "Multipath propagation at 4, 6, and 11GHz", BSTJ, Vol. 51, No. 2, pp. 321-361, February 1972.
83. Vigants, A., "Number and duration of fades at 6 and 4GHz", BSTJ, Vol. 50, No. 3, pp. 815-841, March 1971.
84. Pearson, K.W., "Method for the prediction of the fading performance of a multisection microwave link", Proc. IEE, Vol. 112, No. 7, July 1965.

85. Stephansen, E.T. and Mogensen, G.E., "Experimental investigation of some effects of multipath propagation on line-of-sight path at 14GHz", IEEE Trans. on Com., Vol. COM-27, No. 3, pp. 643-647, March 1979.
86. James, H.B. and Thompson, JR., M.C., "Fading at 9.6GHz on an experimentally simulated aircraft-to-ground path", IEEE Trans. Antennas Propagat., Vol. AP-26, No. 5, September 1978.
87. CCIR Doc. 5/1043 (Kyoto, 1978), "Propagation data required for line-of-sight radio-relay systems", November 1977.
88. Crawford, A.B. and Jakes, JR., W.C., "Selective fading of microwaves", BSTJ, Vol. 31, pp. 68-90, January 1952.
89. Babler, G.M., "Selectivity faded nondiversity and space diversity narrowband microwave radio channels", BSTJ, Vol. 52, No. 2, pp. 239-261, February 1973.
90. Subramanian, M., O'Brien, K.C. and Puglis, P.J., "Phase dispersion characteristics during fade in a microwave line-of-sight radio channel", BSTJ, Vol. 52, No. 10, pp. 1877-1902, December 1973.
91. Morais, D.H., Sewerson, A. and Feher, K., "The effects of the amplitude and delay slope components of frequency selective fading on QPSK, Offset QPSK and 8 PSK systems", IEEE Trans. on Com., Vol. COM-27, No. 12, pp. 1849-1853, December 1979.
92. Dupuis, P., Joindot, M., Leclert, A. and Rooryck, M., "Fade margin of high capacity digital radio system", International Conference on Communication, pp. 48.6.1-48.6.5, June 1979.
93. Salwen, H., "Differential phase-shift keying performance under time-selective multipath fading", IEEE Trans. on Comm., Vol. COM-23, No. 3, pp. 383-385, March 1975.
94. Ott, R.H., Thompson, JR., M.C., Violette, E.J. and Allen, K.C., "Experimental and theoretical assessment of multipath effects on QPSK", IEEE Trans. on Com., Vol. COM-26, No. 10, pp. 1475-1477, October 1978.
95. Greenstein, L.J. and Prabhu, V.K., "Analysis of multipath outage with applications to 90-Mbit/s PSK systems at 6 and 11GHz", IEEE Trans. on Com., Vol. COM-27, No. 1, pp. 68-75, January 1979.
96. Mathews, R.C., "44.736Mb/s on 4GHz radio field experiment results", International Conference on Communication, pp. 48.5.1-48.5.6, June 1979.
97. Barnett, W.T., "Measured performance of a high capacity 6GHz digital radio system", International Conference on Communication, pp. 47.4.1-47.4.6, August 1978.

98. Horikawa, I., Okamoto, Y. and Morita, K., "Characteristics of a high capacity-16 QAM digital radio system on a multipath fading channel", International Conference on Communication, pp. 48.4.1-48.4.6, June 1979.
99. Komaki, S., Horikawa, I., Morita, K. and Okamoto, Y., "Characteristics of a high capacity 16 QAM digital radio system in multipath fading", IEEE Trans., on Com., Vol. COM-27, No. 12, pp. 1854-1861, December 1979.
100. Sunde, E.D., "Digital troposcatter transmission and modulation theory", BSTJ, Vol. 40, No. 2, pp. 353-422, March 1961.
101. O'Kelly, P., "Multipath fading simulation for evaluation of a digital microwave channel", IEEE Conference on Com., pp. 21.1-21.4, June 1975.
102. Anderson, C.W., Barber, S.G. and Patel, R.N., "The effects of selective fading on digital radio", IEEE Trans. on Com., Vol. COM-27, No. 12, December 1979.
103. Rummler, W.D., "A new selective fading model: application to propagation data", BSTJ, Vol. 58, No. 5, pp. 1037-1071, May 1979.
104. Webster, A.R., "A field test of a newly developed microwave diagnostic system", Centre for radio science, University of Western Ontario, October 1978.
105. Greenstein, L.J. and Czekaj, B.A., "A statistical model for multipath fading channel responses", International Conference on Communication, pp. 32.1.1-32.1.5, June 1979.
106. Greenstein, L.J., "A multipath fading channel model for terrestrial digital radio systems", IEEE Trans. on Com., Vol. COM-26, No. 8, pp. 1247-1250, August 1978.
107. Pickering, L.W. and DeRosa, J.K., "Refractive multipath model for line-of-sight microwave relay links", IEEE Trans. on Com., Vol. COM-27, No. 8, pp. 1174-1182, August 1979.
108. Pickering, L.W. and Bello, P.A., "Refractive multipath on microwave LOS links", National Telecommunication Conference, pp. 38:2-1-38:2-7, December 1977.
109. Bello, P.A., Pickering, L.W. and Boardman, C.J., "Multipath over LOS channels study", Final Report, Contract No. F30602-76-C-0419, RADC, CNR Inc., Needham Heights, MA, July 1977.
110. Sasaki, O. and Akiyama, T., "Multipath delay characteristics on line-of-sight microwave radio system", IEEE Trans. on Com., Vol. COM-27, No. 12, pp. 1876-1886, December 1979.

111. Ramadan, M., "Availability prediction of 8 PSK digital microwave systems during multipath propagation", IEEE Trans. on Com., Vol. COM-27, No. 12, pp. 1862-1869, December 1979.
112. Enshwiller, M., "Characterization of the performance of PSK digital radio transmission in the presence of multipath fading", International Conference on Communication, pp. 47.3.1-47.3.6, August 1978.
113. Jakes, W.C., "An approximate method to estimate an upper bound on the effect of multipath delay distortion on digital transmission", IEEE Trans. on Com., Vol. COM-27, No. 1, pp. 76-81, January 1979.
114. Lundgren, C.W. and Rummler, W.D., "Digital radio outage due to selective fading, observation vs prediction from laboratory simulation", BSTJ, Vol. 58, No. 5, pp. 1073-1100, May 1979.
115. Rummler, W.D., "Extensions of the multipath fading channel model", International Conference on Communication, pp. 32.2.1-32.2.5, June 1979.
116. Rummler, W.D., "A multipath channel model for line-of-sight digital radio systems", International Conference on Communication, pp. 47.5.1-47.5.4, June 1978.
117. Lundgren, C.W., "A methodology for predicting nondiversity outage of high capacity digital radio systems", International Conference on Communication, pp. 32.3.1-32.3.6, June 1979.
118. Vigants, A., "Space diversity engineering", BSTJ, Vol. 54, No. 1, pp. 103-142, January 1975.
119. Makino, H. and Morita, K., "Design of space diversity receiving and transmitting systems for line-of-sight microwave links", IEEE Trans. on Com. Technology, Vol. COM-15, No. 4, pp. 603-614, August 1967.
120. Guiffrida, T.S., "Measurements of the effect of propagation on digital radio systems equipped with space diversity and adaptive equalization", International Conference on Communication, pp. 48.1.1-48.1.6, June 1979.
121. Dinn, N.F., "In-service performance of 6GHz digital radio", International Conference on Communication, pp. 48.3.1-48.3.5, June 1979.
122. Morgan, D.R., "Adaptive multipath cancellation for digital data communications", IEEE Trans. on Com., Vol. COM-26, No. 9, pp. 1380-1390, September 1978.
123. Wang, Y.Y., "Space diversity combining for 6GHz digital radio", International Conference on Communication, pp. 48.2.1-48.2.6, June 1979.

124. Abel, N., "Statistics of multipath fading and rain attenuation on terrestrial radio links operating in the 7 to 15GHz range", IEE Conference Proceedings 169, Part 2, pp. 64-67, 1978.
125. Chu, T.S., "Rain-induced cross-polarization at centimeter and millimeter wavelengths", BSTJ, Vol. 53, No. 8, pp. 1557-1579, October 1974.
126. Oguchi, T. and Hosaya, Y., "Scattering properties of oblate raindrops and cross polarization of radio waves due to rain (part two): calculations at microwave and millimeter wave regions", J. Radio Research Labs (Tokyo), Vol. 21, No. 105, pp. 191-259, 1974.
127. Oguchi, T., "Scattering properties of Purppacher-and-Pitter from raindrops and cross polarization due to rain: calculations at 11, 13, 19.3, 34.8GHz", Radio Science, Vol. 12, No. 1, pp. 41-51, January-February 1977.
128. Fedi, F., "Attenuation due to rain on a terrestrial path", Alta Frequenza, Vol. LXVI, No. 4, pp. 167-184, April 1979.
129. Segal, B., "An examination of the worst-month rainfall criteria for radio system design", URSI Symposium, Lennoxville, Canada, May 1980.

APPENDIX A

Regression calculations for a and b in $A = aR^b$ (dB/km) as functions of frequency and drop-size distribution*, Rain temperature = 10°C.

FREQ. (GHz)	b					a				
	LP _L	LP _H	MP	J-T	J-D	LP _L	LP _H	MP	J-T	J-D
2.0	4.89x10 ⁻⁴	4.03x10 ⁻⁴	6.56x10 ⁻⁴	3.39x10 ⁻³	6.38x10 ⁻³	0.890	0.946	0.853	0.897	0.843
2.5	1.09x10 ⁻³	8.66x10 ⁻⁴	1.46x10 ⁻³	7.08x10 ⁻³	1.47x10 ⁻²	0.906	0.974	0.868	0.963	0.846
3.0	1.97x10 ⁻³	1.48x10 ⁻³	2.61x10 ⁻³	1.02x10 ⁻²	2.62x10 ⁻²	0.926	1.010	0.889	1.068	0.851
3.5	3.13x10 ⁻³	2.23x10 ⁻³	4.12x10 ⁻³	1.22x10 ⁻²	4.13x10 ⁻²	0.953	1.053	0.925	1.226	0.856
4.0	4.62x10 ⁻³	3.10x10 ⁻³	6.01x10 ⁻³	1.39x10 ⁻²	6.04x10 ⁻²	0.983	1.099	0.946	1.342	0.863
4.5	6.48x10 ⁻³	4.04x10 ⁻³	8.30x10 ⁻³	1.82x10 ⁻²	8.36x10 ⁻²	1.016	1.154	0.983	1.435	0.871
5.0	8.74x10 ⁻³	4.97x10 ⁻³	1.10x10 ⁻²	2.39x10 ⁻²	1.11x10 ⁻¹	1.053	1.217	1.024	1.413	0.880
5.5	1.47x10 ⁻²	7.63x10 ⁻³	1.81x10 ⁻²	3.04x10 ⁻²	1.82x10 ⁻¹	1.137	1.328	1.106	1.348	0.898
6.0	2.33x10 ⁻²	1.46x10 ⁻²	2.80x10 ⁻²	2.60x10 ⁻²	2.74x10 ⁻¹	1.203	1.342	1.170	1.265	0.919
7.0	3.60x10 ⁻²	2.65x10 ⁻²	4.21x10 ⁻²	5.23x10 ⁻²	3.92x10 ⁻¹	1.235	1.327	1.205	1.196	0.940
8.0	5.13x10 ⁻²	4.59x10 ⁻²	6.23x10 ⁻²	9.69x10 ⁻²	5.39x10 ⁻¹	1.245	1.292	1.219	1.116	0.962
9.0	7.64x10 ⁻²	7.52x10 ⁻²	8.64x10 ⁻²	1.43x10 ⁻¹	7.16x10 ⁻¹	1.241	1.248	1.214	1.083	0.982
10.0	1.05x10 ⁻¹	1.14x10 ⁻¹	1.18x10 ⁻¹	1.83x10 ⁻¹	9.25x10 ⁻¹	1.230	1.207	1.206	1.072	1.000
11.0	1.39x10 ⁻¹	1.62x10 ⁻¹	1.55x10 ⁻¹	2.31x10 ⁻¹	1.17x10 ⁻¹	1.215	1.171	1.193	1.057	1.015
12.0	1.78x10 ⁻¹	2.16x10 ⁻¹	1.98x10 ⁻¹	2.93x10 ⁻¹	1.44x10 ⁻¹	1.199	1.144	1.180	1.036	1.029
13.0	2.22x10 ⁻¹	2.78x10 ⁻¹	2.47x10 ⁻¹	3.65x10 ⁻¹	1.75x10 ⁻¹	1.184	1.124	1.165	1.016	1.039
14.0	2.70x10 ⁻¹	3.25x10 ⁻¹	3.01x10 ⁻¹	4.43x10 ⁻¹	2.10x10 ⁻¹	1.170	1.109	1.152	1.000	1.048
15.0	3.23x10 ⁻¹	3.99x10 ⁻¹	3.60x10 ⁻¹	5.22x10 ⁻¹	2.47x10 ⁻¹	1.158	1.098	1.140	0.988	1.055
16.0	3.80x10 ⁻¹	4.63x10 ⁻¹	4.24x10 ⁻¹	6.03x10 ⁻¹	2.88x10 ⁻¹	1.148	1.085	1.130	0.979	1.066
17.0	4.41x10 ⁻¹	5.34x10 ⁻¹	4.93x10 ⁻¹	6.90x10 ⁻¹	3.32x10 ⁻¹	1.138	1.083	1.115	0.970	1.064
18.0	5.05x10 ⁻¹	6.08x10 ⁻¹	5.65x10 ⁻¹	7.84x10 ⁻¹	3.80x10 ⁻¹	1.130	1.077	1.115	0.961	1.067
19.0	5.74x10 ⁻¹	6.88x10 ⁻¹	6.43x10 ⁻¹	8.90x10 ⁻¹	4.30x10 ⁻¹	1.123	1.071	1.108	0.951	1.070
20.0	6.47x10 ⁻¹	7.76x10 ⁻¹	7.28x10 ⁻¹	1.010	4.84x10 ⁻¹	1.117	1.064	1.102	0.939	1.072
21.0	7.24x10 ⁻¹	8.73x10 ⁻¹	8.13x10 ⁻¹	1.133	5.41x10 ⁻¹	1.111	1.056	1.096	0.927	1.073
22.0	8.05x10 ⁻¹	9.78x10 ⁻¹	9.05x10 ⁻¹	1.277	6.01x10 ⁻¹	1.105	1.048	1.090	0.915	1.074
23.0	8.91x10 ⁻¹	1.10	1.00	1.42	6.65x10 ⁻¹	1.099	1.039	1.084	0.903	1.076
24.0	9.82x10 ⁻¹	1.23	1.11	1.58	7.32x10 ⁻¹	1.093	1.029	1.078	0.890	1.076
25.0	1.08	1.37	1.22	1.75	8.02x10 ⁻¹	1.087	1.018	1.072	0.878	1.077
26.0	1.18	1.52	1.33	1.94	8.76x10 ⁻¹	1.081	1.007	1.066	0.865	1.078
27.0	1.29	1.69	1.46	2.13	9.53x10 ⁻¹	1.075	0.995	1.060	0.853	1.079
28.0	1.40	1.87	1.59	2.32	1.03	1.068	0.983	1.053	0.841	1.080
29.0	1.51	2.07	1.72	2.52	0.112	1.061	0.971	1.047	0.830	1.080
30.0	1.63	2.27	1.86	2.72	0.121	1.054	0.960	1.040	0.820	1.081
31.0	1.76	2.48	2.01	2.93	0.130	1.047	0.948	1.033	0.810	1.082
32.0	1.89	2.71	2.16	3.12	0.139	1.040	0.937	1.026	0.802	1.082
33.0	2.03	2.94	2.32	3.32	0.149	1.032	0.926	1.019	0.795	1.083
34.0	2.17	3.17	2.49	3.49	0.160	1.025	0.915	1.012	0.788	1.083
35.0	2.32	3.41	2.66	3.66	0.170	1.017	0.905	1.005	0.782	1.084
36.0	2.47	3.65	2.83	3.82	0.181	1.009	0.896	0.998	0.777	1.084
37.0	2.62	3.89	3.01	3.99	0.193	1.001	0.887	0.991	0.772	1.084
38.0	2.78	4.13	3.20	4.14	0.205	0.993	0.878	0.984	0.768	1.084
39.0	2.95	4.37	3.39	4.30	0.217	0.986	0.871	0.977	0.763	1.084
40.0	3.11	4.61	3.59	4.46	0.230	0.978	0.863	0.971	0.758	1.084
41.0	3.28	4.82	3.79	4.62	0.242	0.970	0.857	0.964	0.754	1.083
42.0	3.45	5.04	3.99	4.78	0.256	0.962	0.851	0.957	0.749	1.082
43.0	3.62	5.29	4.20	4.94	0.269	0.954	0.845	0.950	0.744	1.082
44.0	3.80	5.49	4.41	5.12	0.283	0.947	0.839	0.943	0.739	1.080
45.0	3.98	5.69	4.63	5.29	0.298	0.939	0.834	0.936	0.734	1.079
46.0	4.16	5.89	4.85	5.47	0.313	0.932	0.830	0.929	0.729	1.078
47.0	4.34	6.08	5.07	5.66	0.328	0.927	0.826	0.923	0.723	1.077
48.0	4.52	6.26	5.30	5.84	0.343	0.918	0.823	0.916	0.718	1.075
49.0	4.70	6.44	5.52	6.04	0.359	0.911	0.818	0.909	0.713	1.073
50.0	4.88	6.62	5.75	6.23	0.375	0.904	0.815	0.903	0.707	1.072

*In order to satisfy the rain rate integral equation (see Chapter 2) the values of a for the J-T, MP and J-D distributions must be multiplied by the factors 0.938, 0.828, and 1.13 respectively. The factors 0.084, 0.021, and -0.30, respectively, must be added to the corresponding values of b. No change has to be done for both LP_L and LP_H distributions.

APPENDIX B

Detailed schematic diagrams of the MODEM

This appendix gives detailed schematic diagrams for the different parts of the MODEM that has been built. The overall block diagram of the system is given in Fig. 6.3.

Fig. B.1 shows the block diagram of the two-phase differential-phase-shift keying modulator. A 65.5MHz sinusoidal wave from the precision frequency source (YH 859 XD) is fed to a clock shaping circuit, Fig. B.2a, to produce a square signal which is TTL compatible. This signal is used to clock the TAU-TRON pseudorandom (PR) data generator. The J-K flip-flop in Fig. B.2b, connected to the output of the PR generator, is used to produce the auxiliary binary sequence for the DPSK modulation. The dc component of this sequence is eliminated by the 1 μ F capacitance. Afterwards the output of this differential encoder is mixed with a 500MHz signal to produce the DPSK signal which is then channelled to the rf section.

At the receiver, after down conversion, the signal is fed to the demodulator, Figs. B.3 and B.4. In Fig. B.4, the if signal is split and one path is delayed by exactly one bit width using 11 feet of cable (RG.174/U) as a delay line. After being mixed with the signal from the other path, the original PR sequence is recovered. Undesired mixing products are eliminated by filtering and a differential comparator is used to boost the level. The subsequent D flip-flop is used to synchronize the PR sequence with the recovered clock. The connection at the bottom of Fig. B.4 acts as a differentiator, giving a narrow pulse whenever a transition occurs in the PR sequence. On the other hand, it

fails to give any pulse whenever two or more consecutive bits of the same type occur. This results in the bit stream out having periods of no pulses. The purpose of the high Q filter in Fig. B.4 is to maintain the oscillation during these periods for the proper functioning of the clock recovery circuit.

Figs. B.5 and B.6 show block and circuit diagrams, respectively, for the clock recovery circuit. Since the maximum frequency of the phase locked loop employed was 30MHz, the 65.5MHz signal had to be mixed with a 58MHz output from a crystal oscillator, Fig. B.7, to obtain a 7.5MHz signal. This signal, after amplification in a tuned amplifier, goes to the phase locked loop (561). Its output is fed to a voltage comparator and then to a bunch of buffer and delay gates. These delay gates are so arranged as to increase the duty cycle of the pulses. Two successive monostable multivibrators are used to adjust the phase of these pulses. Pulse triggering occurs at a particular voltage level and is not directly related to the transition time of the input pulse. The duration of the output pulses depends only on the external timing components. Finally, the signal is mixed up again to 65.5MHz and constitute the recovered clock. Both the recovered clock and PR sequence are then fed to the TAU-TRON BERT receiver.

Fig. B.1 Two phase differential phase shift keying modulator

Fig. B.2 Two phase modulator

- a) Clock shaping circuit
b) Differential encoder

Locking Range

55.6981 MHz max
65.4064 MHz min
2919 MHz Tracking Range

Fluctuation of 65.5 MHz Oscillator

$$65.5 \times 10^6 \frac{.0005}{100} = 327.5 \text{ Hz}$$

Fig. B.4 Two phase demodulator (Part II)

Fig. B.5 Block diagram of clock recovery circuit.

$Q_1 = 2N\ 3563$

$Q_2 = 2N\ 3646$

Fig. B.7 Circuit diagram of the 58MHz oscillator

APPENDIX C

Temperature measuring devices

The circuit diagram of the temperature measuring bridge is shown in Fig. C.1, where T1 and T2 are precision thermistors. Five of these bridges are built and each is installed in a sealed box with the thermistors hanging out. These are protected by a double perforated shield against direct sun rays, rain, snow etc. For better accuracy, an individual calibration curve was obtained for each box. The following calibration formulae are straight line fits to these curves.

- 1) $t = -0.2005011 + 8.765125V$
- 2) $t = -0.1986404 + 8.931592V$
- 3) $t = 0.5480104 + 8.987828V$
- 4) $t = 0.9138315 + 8.612319V$
- 5) $t = 0.4375234 + 8.764667V$

where t is in $^{\circ}\text{C}$ and V , the output voltage of the thermistor box, is in volt. These results are valid between zero and 30°C with an absolute accuracy of about 0.6°C .

Fig. C.1 Circuit diagram of temperature measuring device. T_1 and T_2 are YSI precision thermistors (4420A). The operational amplifiers are AD504J low temperature drift (Analog Devices).

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APPENDIX D

Chart recordings of signal level

- D.1 Signal level for the night of the 16th of August. Horizontal axis is time of day (EDT).
- D.2 Signal level for the night of the 21st of August. Horizontal axis is time of day (EDT).
- D.3 Signal level for the night of the 22nd of August. Horizontal axis is time of day (EDT).

(a)

(b)

(c)

D.1 Signal level for the night of the 16th of August. Horizontal axis is time of day (EDT).

(a)

(b)

D.2 Signal level for the night of the 21st of August. Horizontal axis is time of day (EDT).

(a)

(b)

D.3 Signal level for the night of the 22nd of August. Horizontal axis is time of day (EDT).

END

1 8 1 2 8 1 1

FIN