MICROWAVES ABSORPTION BY OXYGEN AND WATER VAPOUR AT TROPICAL LATITUDES

ADENUGBA DAVID

A THESIS SUBMITTED IN PARTIAL

FULFILMENT OF THE REQUIREMENTS

FOR THE AWARD OF THE DEGREE OF

MASTER OF TECHNOLOGY (M.TECH.)

IN

COMMUNICATION PHYSICS

DEPARTMENT OF PHYSICS

FEDERAL UNIVERSITY OF TECHNOLOGY,

AKURE, NIGERIA.

OCTOBER, 1998.

TABLE OF CONTENTS

PAGE

CHAPTER ONE

CHAPTER TWO

CHAPTER THREE

CHAPTER FOUR

CHAPTER FIVE

ABSTRACT

The total atmospheric absorption due to oxygen and water vapour in the frequency range, 10-350GHz was evaluated employing Liebe's empirical model. The basic data include monthly mean meteorological parameters of pressure, temperature and relative humidity obtained from four tropical sites, namely Akure (Lat.07°17'N,Long.05°14'E),Kano(Lat.03°12'N, Long.08° 32'E), Lagos (Lat. 06° N, Long.03° 21'E) and Minna (Lat. 09° 57'N, Long.06° 32'E). All the four stations are in Nigeria.

The specific attenuations by oxygen and water vapour are presented together with the graphical illustrations of the results for the two principal seasons in Nigeria, dry and wet seasons The wet season has a greater attenuation than the dry season. An exception to this takes place at Akure site in 1991 when the attenuation during the dry season exceeds that of wet season. In addition to this seasonal variation, the specific attenuation also exhibits geographical variations. Lagos, a coastal station, has the highest attenuation; Kano a far inland station, has the least attenuation value. The water vapour three resonant absorption lines are obtained at 22,184 and 326GHz. The weakest spectrum line being at 22GHz,while the strongest is at 326GHz. Oxygen has an isolated resonant absorption at 118GHz and a series of close lines at 54-66GHz, the peak of this is at 60GHz.

Using typical International Telecommunication Union (ITU) temperate climatic parameters of pressure, temperature and water vapour pressure, the specific attenuation for a temperate region is computed which, in turn, is compared with those from tropical sites. Attenuation is higher in the tropical sites than in the temperate zone. The tropical sites attenuation at 326GHz for wet season is about two times the attenuation for the temperate region.

ACKNOWLEDGEMENTS

I thank the Almighty God for making this research work possible. He granted me good health strength and wisdom.

My profound gratitude goes to my able supervisor,Professor L.B.Kolawole, the Vice Chancellor, Federal University of Technology, Akure. He suggested the topic and instructed tha I learn Word Perfect and FORTRAN 77. My proficiency in Microsoft Words besides th aforementioned was to his credit. I have the full statisfaction from imbibing from his researc and academic knowledge.

I thankfully acknowledge the suggestions, discussions and assistance of Dr.M.O.Ajewole an Brother Gbenga Orunto in the development of the FORTRAN 77 program used for the work Dr. Ajewole 's ready assistance in making the current reports and materials of the ITU availabl is recognised and appreciated.

I am grateful to the Acting Head of Department of Physics, Dr.(Mrs)L.A.Fuwape,and Dr. M.T Babalola for their encouragement and assistance.

Special thanks go to Mr.B.O.G.Mella and other members of the Department for their variou assistance.

Indeed, I treasure very highly the patience, understanding and unequal love of my amiabl spouse during this period of study.

CERTIFICATION BY SUPERVISOR

I Certify that this work has been

carried out by D.A Adenugba

in the Department of Physics,

Federal University of Technology, Akure.

....

Professor L.B.KOLAWOLE,BSc.,Ph.D(Ibadan),*fnip,fsan.*

Department of Physics,

Federal University of Technology,

Akure, Nigeria.

OCTOBER,1998.

DEDICATION

This work is dedicated to my loving parents-----

Mr ATEREMONIWON PHILIPS ADENUGBA

and

Mrs FAKUROLIE JULIANAH ADENUGBA

INDEX OF FIGURES

PAGE

INDEX OF TABLES

CHAPTER ONE

1.0 INTRODUCTION

1.1 MICROWAVES

Electromagnetic waves cover a very broad spectrum of wavelengths and frequencies. Included in the spectrum ,as shown in figure (1.1), are microwave , radio and television bands.

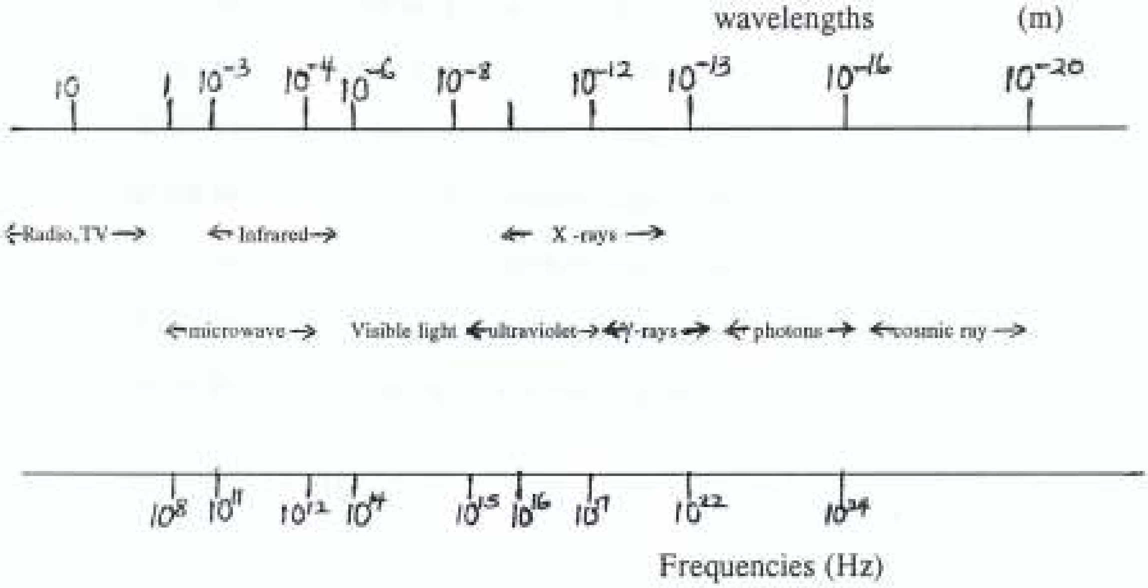


Figure (1.1) : ELECTROMAGNETIC SPECTRUM

Radiowaves, according to the International Telecommunication Union ITU, are electromagnetic waves with frequencies lower than 3000 GHz. Part of the radio spectrum is shown in Table (1.1).

Table(1.1): A PORTION OF THE ELECTROMAGNETIC SPECTRUM

FREQUENCY BAND	WAVELENGTH	DESCRIPTIVE DESIGNATION	
30-300 Hz	10000-1000 km		ELF
3-30 kHz	100-10 km	Myriametric waves	VLF
30-300 kHz	10-1 km	Kilometric waves	LF
300-3000 kHz	1000-100 m	Hectometric waves	MF
3-30 MHz	100- 10 m	Decametric waves	HF
30-300 MHz	10-1 m	Metric waves	VHF
300-3000 MHz	100-10 cm	Decimetric waves	UHF
3-30 GHz	10-1 cm	Centimetric waves	SHF
30-300 GHz	10-1 mm	Millimetric waves	EHF
300-3000 GHz	1-0.1 mm	Submillimetric waves	

Source: Hall,M.P.M (1989).

Microwaves are very short waves. The shortest wavelengths of the radio spectrum are in the microwaves' region but the boundaries are not well defined. The ultra-high frequency, UHF and Super-high-frequency, SHF constitute the microwave frequency range with wavelengths extending from 1 to 100 cm.[Table 1.2]. The microwave band was put into extensive use following the invention of the magnetron in 1940. The second world war further witnessed rapid advancement in the applications of microwaves both theoretically and practically. The mostly used microwave frequencies are those below 10 GHz.

With the growing use of this frequency band for military ,commercial and experimental purposes, it soon became overcrowded ; thus necessitating the use of higher frequency bands. The uses of the frequency band include line-of -sight microwave relay systems and earth-space communications. Satellites as well as terrestrial links, for instance, make use of the frequency bands11-18 GHz and 35-50 GHz . Besides, microwaves are utilised in radio astronomy, microwave oven and radar.

Microwaves are highly indispensable in modern communication systems. The broad use to which microwaves are put is due to a good number of reasons. First, in the microwave frequency range, large numbers of wideband of channels can be accommodated . Apart from enhanced bandwidth, there is the advantage of improved directivity with an antenna array. At the microwaves frequencies, directivity can be substantially boosted by using an array of dipoles or by using a reflector at focal plane.

In the microwave bands, there is reduced fading since radiation transmission is by line-of -sight propagation. Receptions of signals are greatly enhanced with increasing frequency in the microwaves ranges. Foggy weather has little effects on propagation in this frequency band. In addition to the reliability of microwave bands, the power requirement of both transmitter and receiver is very small. As a result of the use of microwaves our understanding and knowledge of the solar system and celestial bodies are enhanced.

While it is enough to use waveguides or coaxial cables for short distances, microwave transmission through the atmosphere over very long distances requires the use of several repeaters.

1.2 CLASSIFICATION OF THE MICROWAVE SPECTRUM

The microwave spectrum classification dated back to the second world war. The world war II radar security subdivided microwave spectrum into bands. This designation never received official sanction from any quarter [Samuel ,1989]. It was in August 1969 that the new microwave band became operational by the United States Department of Defence [see Table 1.2]. This classification was short-lived as it was replaced with another one on May 24,1970 [see Table1.3].

The current microwave band designation in Table [1.4] came as a result of the recommendations of the Institute of Electrical Electronics Engineers [IEEE].

Table (1.2) 1969 US Military microwave Band.

Band	Frequency (GHz)
p	0.225-0.390
L	0.390-1.550
S	1.550-3.900
C	3.900-6.200
X	6.200-10.900
K	10.900-36.000
Q	36.000-46.000
V	46.000-56.000
W	56.000-100.00

Table (1.3) : 1970 US Military microwave Bands

Band	Frequency Range (GHz)
A	0.100-0.250
B	0.250-0.500
C	0.500-1.000
D	1.000-2.000
E	2.000-3.000
F	3.000-4.000
G	4.000-6.000
H	6.000-8.000
I	8.000-10.000
J	10.000-20.000
K	20.000-40.000
L	40.000-60.000
M	60.000-100.000

Table (1.4) IEEE microwave Bands.

Band	Frequency Range (GHz)
HF	0.003-0.030
VHF	0.030-0.300
UHF	0.300-1.000
L	1.000-2.000
S	2.000-4.000
C	4.000-8.000
X	8.000-12.000
KU	12.000-18.000
K	18.000-27.000
Ka	27.000-40.000
Millimeter	40.000-300.000
Submillimeter	> 300.000

1.3 ATTENUATION OF MICROWAVES

Attenuation is the reduction in intensity or flux density quantity passing through a given medium, resulting from absorption and/or scattering of the transmitted radiations. It is not only a function of distance but also of frequencies and climatic conditions.

In the practical operation of radio links, it has been observed that radio waves shorter than 10 cm do experience appreciable attenuation that may cause serious impairment to radio signals. However , radiowaves longer than 10 cm do not experience marked attenuation. Radiowaves propagating in the millimeter and submillimeter ranges through the troposphere are attenuated by absorption and dispersion . The dispersion may be caused by hydrometeors and molecules. Also atmospheric absorption may result due to solids ,such as dust and smoke , which are present in the troposphere as dry haze. Precipitation particles like rain, fog, hail and snow, apart from molecules of various gases equally cause absorption . Water vapour and oxygen , for instance , are two major absorbers of radiation in the troposphere. The absorptive effect of trace gases , however, becomes significant above a certain frequency. Indeed, both the dispersive and absorptive effects of the atmosphere are as a result of the changes in tropospheric pressure ,temperature and relative humidity and , in turn , the refractive index of the troposphere.

1.4 PHYSICAL PROPERTIES OF THE ATMOSPHERE

The atmosphere consists of different particles. The principal constituents of the atmosphere and their percentage composition by volume are: Nitrogen , 78.09% , Oxygen, 20.95% , Argon , 0.93%. Present also in the atmosphere are several measurable trace gases like Carbon-monoxide, Nitrous oxide, Nitric oxide and Sulphur dioxide. The percentage composition of the dry air does not vary with height but remains practically the same as it is at the surface. Moreso, the gases do not have permanent electric dipole moment.

Hence, they exhibit no resonant absorption. Oxygen, however, shows resonant absorption at certain frequencies because of its paramagnetic nature with magnetic dipole moment.

Another significant but highly varying constituent of the atmosphere is water vapour

Besides, there are suspended particles or impurities such as sodium ,chloride, smoke particles, dust, pollens, fungus spores and so on in the atmosphere. Their presence is due to large-scale vertical mixing process that transports them to the various layers of the atmosphere.

The atmosphere is divided into several distinct regions starting from the earth's surface. As in figure (1.2),these regions, going by the recommendations of International Union of Geodesy and Geophysics of 1951, are: the troposphere ,the stratosphere ,the mesosphere and the thermosphere. The neutral region of the atmosphere is the troposphere where microwaves propagation takes place.

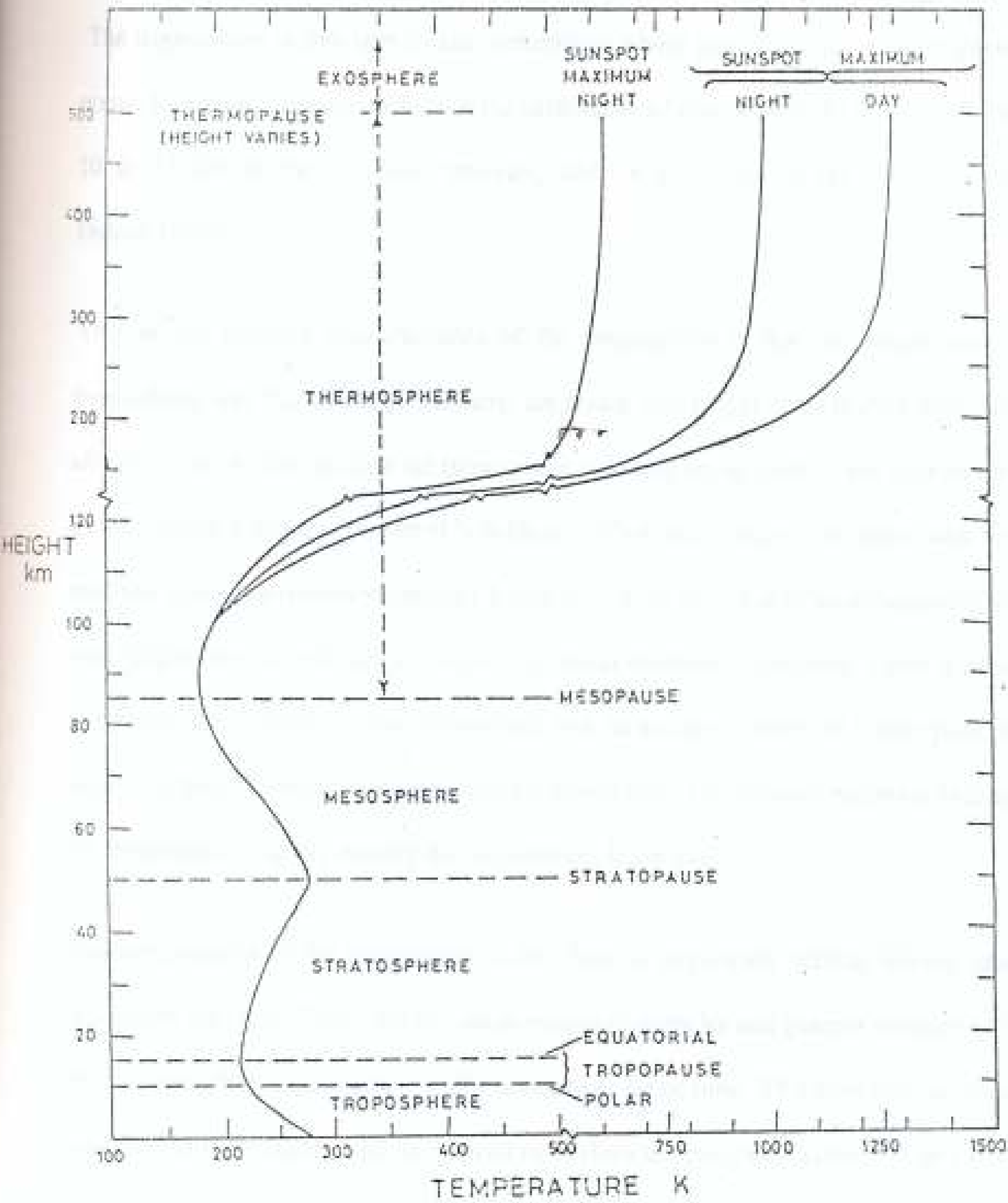


Fig 1.2 Atmospheric regions with average temperatures

1.4.1 THE TROPOSPHERE

The troposphere is that part of the atmosphere where practically all weather phenomena occur. It extends from the surface of the earth up to a height of 8 to 10 km at polar latitudes, 10 to 12 km at the moderate latitudes, and 16 to 18 km at the equator [Bean and Dutton,1968].

One of the primary characteristics of the troposphere is that the temperature of the troposphere, like that of the mesosphere, decreases with height. This decline with increasing altitude is due to the fact that the troposphere is almost transparent to sun rays and also due to the uneven heating of the earth's surface . When temperature decreases with height, a positive lapse rate condition occurs.(Lapse rate is the decrease of an atmospheric variable with height, the variable being temperature unless otherwise specified). There is an average lapse rate of 6.5 Kkm^{-1} in the troposphere with an exception near the winter pole where a strong surface inversion extends to several kilometres. The infrared radiation exchanges in the troposphere slightly modify the temperature lapse rate

Another property of the troposphere is that there is large-scale vertical mixing caused by convection currents. Consequently transportation of particles and gaseous products to the top of the troposphere is actualised within a short period of time. This atmospheric circulation is enhanced by frictional effects induced by surface irregularities within 1.5 to 2 km of the atmosphere. In the absence of large-scale vertical mixing ,diffusive equilibrium occurs, that is, lighter gases would be present in greater ratio at higher altitudes and heavier gases at lower altitudes; and the molecular weight would decrease with height. Again, when there is no large-scale vertical mixing, the partial pressure, p (in kPa) of each constituent gas decreases at a separate rate according to the hydrostatic equation

$$1 / p (\partial p / \partial z) = -g M / R^* T \qquad (1.1)$$

where $\partial p / \partial z$ is the vertical pressure gradient, M is the molecular weight, R^* is the universal gas constant, T is the temperature, g is the acceleration due to gravity.

1.5 REVIEW OF PREVIOUS WORK

This section deals with the review of some relevant work done elsewhere . In the literature, it has been established that at the centimetre and millimetre wavelengths, water vapour and oxygen are the principal absorbers of radiation , and that above 70 GHz and in the absence of water vapour, trace gases absorption becomes significant.

1.5.1 RESONANT ABSORPTION OF OXYGEN

Oxygen ,a diatomic molecule, is electrically non-polar. Therefore, oxygen molecules do not interact with the applied field. Therefore, no absorption occurs due to electric dipole resonance. However, oxygen, being a paramagnetic molecule possesses a permanent magnetic moment that causes resonant absorption at particular frequencies.

It has been well established that oxygen has an isolated absorption line at 118.74 GHz and a host of very close lines between about 50 and 70 GHz [Ajayi et. al. (1996)], Brussard et. al. (1995)] . These series of lines act as a continuous absorption band in the lower altitudes. Upwards of 15 km above the sea-level, the spectral lines are resolvable as the pressure is reduced.

The magnetic moment of the oxygen also produces a line at zero frequency in the absorption spectrum . This non-resonant or Debye spectrum accounts for practically all of the dry air attenuation at 1 GHz, about 9% at 10 GHz, falling to less than 1% above 30 GHz . Moreover, there are higher frequency absorption lines at 367 GHz and above. At the sea-level, pressure collision-induced nitrogen absorption becomes noticeable at frequency above about 150 GHz[ITU-R 719-3, (1990)].

Barbaliscia et. al. (1994) evaluated the absorption of oxygen and water vapour for clear atmosphere with a large data-base of meteorological parameters for the Italian climatology. The computed oxygen effects using radiosonde profile of temperature and pressure and / or ITU algorithms shows that oxygen presents a complex resonance centred at 60 GHz. Apart from an isolated weaker line at 118.8 GHz, several resonant spectral lines surfaced between the frequency range 50 GHz and 69 GHz. Due to its constant concentration in the atmosphere ,oxygen shows low absorption up to 40 GHz, far away from the resonant lines. Relatively high specific attenuation values of 2dB and 5dB for 50 GHz and 53 GHz respectively were reported.

The resonant absorption by oxygen is relatively constant because the atmospheric temperature profiles are slowly changing with altitude. Ajayi and Kolawole [1984] have shown that there exist 'windows' in the troposphere which are transparent to radio waves. In the window regions, w_1,-w_3 they unveiled that molecular absorption is pronounced at lower angles of elevation (23^0) than at higher elevation angles (55^0). Thus very small absorption occurs at zenith path as against the marked absorption at the slant path. Further, the total atmospheric attenuation of oxygen and water-vapour in comparison with rainfall attenuation up to about 150 GHz is negligible, but above 190 GHz their contributions become significant.

Bean and Dutton [1968] ,found that the resonant absorption of oxygen at millimetre wave band occurs at 60GHz and 118 GHz . Thev , like Ajayi and Kolawole, (loc.cit.) reported that the resonant absorption by oxygen is relatively constant. The reason being that the atmospheric temperature profile are slowly changing with altitude. A peak attenuation of 15dB/km has been reported for oxygen absorption at 60 GHz ; while at 118.74 GHz it is 1.4dB/km.

1.5.2 WATER-VAPOUR ABSORPTION

Water, and hence water vapour ,is a polar molecule with a permanent dipole moment. Therefore, water vapour molecules interact with the applied electric field and so absorption occurs due to electric dipole resonance at critical frequencies

Water vapour has three resonant absorption lines. There is a weak absorption peak due to a rotational spectral line at about 22.3 GHz, and a much stronger line at 183.3 GHz and 325 GHz. Most of the transitions occur in the infrared region with very large number of lines whose low-frequency pressure-broadened wings combine to produce a substantial contribution to the absorption at millimetre frequency [Barbaliscia et al, 1994 ; Westwater et. al, 1994; ITU-R 719-3, 1990; Watson,1989; McEwan,1989] .

The resonant absorption of water vapour varies tremendously owing to the variation in the distribution of water vapour in the atmosphere both in time and space. Water vapour shows a strong seasonal variation , reaching maximum values in summer time but without particular diurnal variation. This non-diurnal variation implies that the total water content does not depend on a diurnal- cycle time . But the total content always exhibits monthly variations ranging from 0.4 to 3.5cm, with the peak value reached at summer. [Westwater et al ,1994]. The evaluated specific attenuation at 22.3 GHz is less than 0.2 dB/km. While at 183.3 and 325.8 GHz ,the attenuations are approximately 40 and 50 dB/km respectively.

There is a resonant absorption of water vapour at wavelengths of 1.35 cm, 1.5 mm and 0.75 mm. The daily variation of water vapour depends strongly the humidity of the air [Bean and Dutton,1968] .

1.6 THE SCOPE OF THE PRESENT WORK

One of the parameters of interest to the system designers is specific absorption. It determines the extent of the distortion to propagating signals. This parameter also determines the transmitted power and antenna gains.

Not much has been done in the developing countries to determine the absorption effects of oxygen ,water vapour and other atmospheric gases on microwaves. Therefore, there is insufficient information available to the system designers. Hitherto, radio meteorological data derived from temperate climates were used in planning radio services for Africa. Optimised planning in Africa ,would definitely require data which take account of the peculiar climatic conditions in Africa.

For effective, efficient and meaningful designing and operating of radio equipment in Africa, African-based data, reflecting performance-influencing meteorological factors, need to be acquired and utilised. The ITU fortunately has started off with 'Radio -wave propaga*tion* *measurement campaign for Africa'* in 1984. This campaign kicked off with two successful experiments, namely ,VHF field strength measurements and refractivity measurements in the clear atmosphere in Burkina Faso.

The current work addresses the molecular absorption by atmospheric gases in the frequency range of 10 to 350 GHz . It evaluates the specific attenuation by oxygen and water vapour, using meteorological input parameters of pressure ,temperature and relative humidity from four tropical meteorological stations in Nigeria. The stations are Akure, Lagos, Kano and Minna. The computed results are compared with previous ones from both tropical and temperate regions. The study is thus significant in providing information and data on tropical specific attenuation .The information and data can be employed by system designers in designing microwaves communication systems. The study ,no doubt , will provide a partial solution to the problem of dearth of information and data on radiowave propagation in Africa particularly in a tropical region like Nigeria.

CHAPTER TWO

2.0 RELEVANT THEORY

2.1 ELECTRIC FIELD APPLICATIONS

When an asymmetrical molecule is subjected to an electric field ,it is said to be polar with orientation in the direction of the imposed field .The polarisation of a molecule is the relative displacement of the positive and negative charges of the molecule, caused by an applied electric field , E. A plane radio wave propagating the distance r can be described by

$$E(r,t) = E_o \exp[-j\,(2\pi f/c)\, r.n] \tag{2.1}$$

where j is given by square root of -1 . The complex refractive index,

$$n = n' - jn'' \tag{2.2}$$

is responsible for electromagnetic wave absorption and bending of the electromagnetic rays. The index is a function of frequency, f .The imaginary part n'' reduces the initial amplitude E_o , while the real part n' causes the slowing of the propagating velocity to values less than the speed of light in vacuum, c.

At high altitude the refractive index is unity. But in the neutral tropospheric medium, it is greater than unity,typical value being 1.0003. This thus necessitated the use of a practical quantity, N to characterise the atmosphere. The complex refractivity, N (in units of ppm), is therefore, the practical measure of the atmosphere and is related to refractive index by

$$N = (n-1)\ 10^6 \qquad (2.3)$$

and to the meteorological parameters of pressure, temperature and relative humidity is given by Smith and Weintraub [1953].

$$N = 77.6/T\ (P + 4810\ e/T) = 77.6\ P/T + 3.73 \times 10^5\ e/T^2 \qquad (2.4)$$

The electric polarisation, p is directly proportional to both the applied field, E and the electric susceptibility,χ_e and is given by

$$p_e = \chi_e\ \varepsilon_o E \qquad (2.5)$$

where ε_o is the permittivity of free space. The induced polarisation P_i of the molecules, M per unit volume is given by

$$P_i = M\gamma_i\ E_{loc} = M\gamma_i\ g_r\ E \qquad (2.6)$$

where g_r is the ratio between the local electric field,E_{loc} acting on the molecule, and the applied electric field E; and it is given by $g_r = (2 + \varepsilon_r)/3$. The molecular polarisability, γ_i (Fm^2) is given by

$$\gamma_t = \gamma_e + \gamma_{ii} + \gamma_d \qquad (2.7)$$

with γ_e equal to the 'electronic' part, caused by the shift of the electron cloud in each atom relative to its positive nucleus; γ_{ii} is the 'ionic' part, caused by the displacement of positive and negative ions from their neutral positions while γ_d is the 'dipole' part, caused by permanent dipole moments of each molecule. The applied electric field tends to align these permanent dipoles against the randomising forces of molecular collision. This effect is strongly dependent on temperature because as the temperature increases so does the random motion.[Brussard et al, 1995]. While the frequency response of γ_d is given by

$$\gamma_d = p_d^2 / 3kT\,(1+jw\tau_r) \qquad (2.8)$$

that of γ_e and γ_{ii} is of the form

$$\gamma_j = S_j / (w_j^2 - w^2) + jw\Gamma_j \qquad (2.9)$$

where S_j measures the strength of the j^th resonance with damping constant Γ_j ; p_d is the permanent dipole moment, k ,Boltzmann's constant, and τ_r is the relaxation time,which is the time for the polarisation to fall to 1/e of the original value if the applied field is removed . The angular velocity, w is related to frequency ,ν by

$$\nu = w / 2\pi \qquad (2.10)$$

The angular velocity is related to the wavenumber , k_n and the speed of light, c by

$$w = k_n\, c \qquad (2.11)$$

k_s ,in turn, is related to the wavelength by

$$k_s = 2\pi / \lambda \qquad (2.12)$$

The relationship between molecular polarizability and permittivities is given by Clausius-Mossotti relation

$$(\varepsilon_r + 1)/(\varepsilon_r - 2) = M \gamma_t / 3 \qquad (2.13)$$

This relation turns out to be Debye equation when the frequency effects in γ_t are included. For a non-polar molecule the electric dipole moment due to polarisation is

$$p_m = \gamma_t E \qquad (2.14)$$

2.2 ABSORPTION MECHANISM

As the electromagnetic wave is propagated through the atmosphere,there exists interaction between the electric field,E and the atmospheric molecules,thereby inducing resonances. Molecular absorption of spectral lines takes place in the absence of precipitation particles and it depends very strongly on the permanent dipole moments of individual molecules. Atoms and molecules have dipole moments with a non-zero alignment. In the absence of a permanent dipole molecule, there is no interaction between molecules and radiation, hence no absorption of radiation.

Unlike water molecules, molecules of dry air gases, like oxygen and nitrogen, do not have a permanent dipole moment. Thus in the microwave region, non-polar nitrogen exhibits no resonance absorption, although it contributes to the refractivity of the air. On the other hand, oxygen being a paramagnetic molecule has a permanent magnetic moment responsible for resonant absorption at certain frequencies. Water and water vapour with electric dipole moment exhibit resonant absorption.

It should be noted that as the electromagnetic wave progresses through the linear, isotropic and lossy dielectric medium, its energy is either dispersed or absorbed by the atmospheric molecules. Upon acquiring thermal energy, the molecules and atoms are excited from a lower energy level to a higher energy level. The resultant effects of this transition is a selective absorption of radiation.

2.3 QUANTUM NUMBERS

Essentially, there are four quantum numbers that govern the energy, size and shape of orbitals. They also determine the electronic and spin angular momentum of atoms as well as the behaviour of electrons in a magnetic field. These quantum numbers are:

2.3.1 *Principal quantum number.*

It is designated by letter n_r, and the variable that led to its existence is r. This quantum number determines the complete energy and size of orbital angular momentum. Its allowed values are 1.2.3.4……; it is not limited by selection rules. When its value is greater than unity different quantum states with same energy result. This occurrence is referred to as degenerate states.

2.3.2 *Orbital angular momentum quantum number*

It is denoted by letter ℓ and the variable resulting in its appearance is θ. Not only does it determine the shape of the orbital, it also decides the angular momentum of the electron as it revolves around the nucleus in its orbital. The permitted values of the quantum number , ℓ are given by n-1, n-2, ... 0. Hence it is always less than principal quantum number. The quantum number is an integer, positive or zero, representing the state of an electron in an atom. The magnitude and z-component of ℓ are quantised according to these relations.

$$\ell = \sqrt{[\ell(\ell+1)]}\hbar \tag{2.15}$$

$$\ell_z = m_\ell \hbar \tag{2.16}$$

$$\text{where } \hbar = h / 2\pi \tag{2.17}$$

2.3.3 *Magnetic quantum number*

It is also called azimuthal quantum number ,or the component of orbital angular momentum. It is identified by the symbol m_ℓ,and its appearance is by the variable φ . Magnetic quantum number specifies the direction of a particular orbital and gives the behaviour of electrons in orbital when the atom is placed in a magnetic field. Its allowed values are given by ± l , ± (ℓ -1) -------0. For a given value of l, there are (2ℓ +1) possible values of m_ℓ . Like orbital quantum number it is limited by selection rules.

2.3.4 *Spin quantum number.*

This quantum number is denoted by letter s for electron spin quantum number or I for nuclear spin quantum number. Many atomic nuclei spin about an axis resulting in nuclear spin. The nuclear spin quantum number depends on the nucleus of the atom and its permitted values are zero, integer or half-integer. Its quantised magnitude is expressed by

$$I = \sqrt{[I(I+1)]}\hbar \qquad (2.18)$$

The quantum number determines spin angular momentum and nuclear angular momentum possessed by electron either in an atom or molecule in free space. The electron spin quantum number may take integral or half integral values. The magnitude and z-component of s are quantised and these are given by

$$s = \sqrt{[s(s+1)]}\hbar \qquad (2.19)$$

$$s_z = m_z\hbar \qquad (2.20)$$

2.4 ENERGY TRANSITION

An atom or molecule in the field of electromagnetic radiation experiences magnetic and electric interactions. The interactions between magnetic moment and the magnetic field are entirely negligible compared to the interactions between the electric charges and the electric field, E of the atom or molecule.

The electric field vector is independent of position. Subject to the field of the radiation , the atom or molecule will undergo quantum jump from either a lower energy level to a higher energy state in which case quantum absorption takes place or from a higher energy state to a lower energy level with stimulated or induced emission occurring. Spontaneous transition, in the absence of any external field, from an excited state to a state of lower energy may occur with the emission of photons. The resulting spectral lines due to the transitions vary greatly in intensity.

The important properties of spectral transition are intensity, line width and position given in terms of its frequency and wavelength or wave number.

2.4.1 THE TRANSITION RATE FOR ABSORPTION , STIMULATION AND SPONTANEOUS EMISSIONS

Assuming a non -degenerate stationary states, transition from one state of energy to another will be accompanied by the emission or absorption of radiation of frequency

$$\nu_{mn} = (E_m - E_n)/\hbar \qquad (2.21)$$

The probability per unit time that an atom or molecule from a lower energy level is found in a higher energy level is referred to as transition rate for absorption . The transition rate, R_{mn} is directly proportional to the average energy density $\rho(\nu_{mn})$ of the atom or molecule, and is given by the relation

$$R_{mn} = B_{mn}\,\rho(\nu_{mn}) \qquad (2.22)$$

The Einstein's coefficient of absorption, B_{mn} is given by

$$B_{mn} = 2\pi / 3h^2 [\mu^*_{xmn} \mu_{xmn} + \mu^*_{ymn} \mu_{ymn} + \mu^*_{zmn} \mu_{zmn}] \qquad (2.23)$$

The terms in the bracket is the electric dipole matrix elements for x,y and z components;their complex conjugates are indicated by *.

While the average energy density ρ is the time average of the energy content per unit volume of the electromagnetic radiation . The density is proportional to the average value of the square of the electric field strength, E^2 ; and for unit dielectric constant and magnetic permeability it is given by this expression

$$\rho (\nu_{mn}) = (1/4\pi) E^2 \qquad (2.24)$$

The transition rate for stimulated emission is, on the other hand, the probability per unit time that an atom or molecule in a higher energy state E_m will undergo a quantum jump to a lower energy level E_n .It is not inherent in the atom, but is induced by the application of electromagnetic radiations. All the expressions given for the transition rate for absorption apply to induced emission with the modification that all the subscripts have to be reversed except for ν_{mn} .

The transition rate for stimulated emission is equal to the transition rate for absorption . Accordingly their Einstein's coefficients are equal, that is

$$B_{mn} = B_{nm} \qquad (2.25)$$

The transition rate for spontaneous emission is an inherent property of the atom which is not influenced by electromagnetic radiation or by the environment where the atom is placed . It is proportional to the electric dipole matrix element as well as the cube of the frequency or cube of the energy of the emitted photon, and is given by

$$S_{nm} = 32\pi^3 \nu_{mn}^3 / 3\hbar c^3 \left[\mu^*_{xmn} \mu_{xmn} + \mu^*_{ymn} \mu_{ymn} + \mu^*_{zmn} \mu_{zmn} \right] \qquad (2.26)$$

The transition rate for spontaneous emission is related to stimulated emission by the relation

$$A_{nm} = (8\pi h \nu_{mn}^3 B_{nm}) / c^3 \qquad (2.27)$$

where A_{nm} is the Einstein's coefficient for spontaneous emission which is equal to the transition rate for spontaneous emission . That is

$$A_{nm} = S_{nm} \qquad (2.28)$$

From equation(26), we see that the transition rate for spontaneous emission is also related to transition rate for absorption.

2.4.2 THE INTENSITY OF SPECTRAL LINES

The intensity of spectral line is the average rate of energy flow through unit cross-sectional area normal to the direction of propagation of radiation . Three parameters are of basic interest in determining the intensity of spectral lines .These are: the transition probability , the population states and the concentration or path length of the sample.

(i) THE TRANSITION PROBABILITY

The probability of an atom radiating a quantum depends on what the atom does in the initial energy level before radiating and on its future behaviour in the final energy level after radiation. This is because when the atom radiates it is neither in the initial energy level nor the final state but in some linear combination of the two states.

The transition probability is the probability that an atom in one state of quantum energy will be found in another state. During atomic or molecular transition, radiation will be absorbed or emitted The probability that an atom will make a transition from an initial state of energy E_n to a higher energy level, E_m is given by

$$P_{xmn} \cong 1/h^2 \mu^*_{xmn} \mu_{xmn} E^o_x (\nu_{mn})^2 t \qquad (2.29)$$

The electric dipole matrix element of the x component μ_{xmn} is expressed by

$$\mu_{xmn} = \int \psi^*_m \Sigma ex_j \psi_n d\tau \qquad (2.30)$$

its complex conjugate is μ^*_{xmn}, ψ_n is a wavefunction and the complex conjugate of wavefunction

ψ_n is ψ^*_m . $d\tau$ is the volume element.

SELECTION RULE :

If the electric dipole matrix element, μ_{xmn} vanishes, no transition from initial to final state occurs. That is, for $\mu_{xmn} = 0$, transition is said to be forbidden. But if $\mu_{xmn} \neq 0$, transition is allowed . The set of rules that governs whether or not the matrix element is zero are known as selection rules. The selection rules are a set of conditions on the quantum numbers of the eigenfunction of the initial and final states such that the electric dipole matrix elements are zero when calculated with a pair of eigenfunctions whose quantum number violate these conditions. The set of electric dipole selection rules are

$$\Delta l = \pm 1 \qquad (2.31)$$

$$\Delta l \neq 1 \qquad (2.32)$$

$$\Delta m = 0 \text{ or } \pm 1 \qquad (2.33)$$

$$\Delta n = \text{anything} \qquad (2.34)$$

There is no selection rule limiting the principal quantum number,n, ;the spectrum consists of all frequencies. The magnetic quantum number,m changes by unity or zero. For the orbital quantum number, l it changes by unity . Transitions, generally are forbidden between even and even or odd and odd states. This is because the matrix elements are zero. The existence of forbidden transitions is indicated by observed faint spectral lines. Indeed, transitions with the emission or absorption of dipole radiation are allowed only between even and odd states. Odd number of electrons in orbitals with orbital quantum number, l odd, lead to odd states , otherwise to even states.

Selection rules never indicate that they represent the only transition permitted. They only indicate the most favoured ones.

(ii) THE POPULATION OF STATES

The population of state refers to the number of atoms or molecules initially in the state from which the transition occurs. Suppose N_k is the total number of atoms or molecules in the lower energy level. The total number of transitions per unit time from a lower energy level E_n to a higher energy state E_m equal the total number of transition in the reverse direction. This relation gives the required expression:

$$N_{mn} = N_n \; B_{mn} \; \rho(v_{mn}) \tag{2.35}$$

Again, if N_m is the total number of atoms of molecules in the higher energy state. The total number of transitions per unit time from the higher energy level to the lower energy level is given by

$$N_{nm} = N_m \; [B_{nm} \, \rho(v_{mn}) + A_{nm}] \tag{2.36}$$

At equilibrium when the temperature is T, the probability that an atom will have energy E_n and E_m is directly proportional to $\exp(-E_n / kT)$ and $\exp(-E_m / kT)$ respectively . This is the Boltzmann distribution law, with k as Boltzmann's constant and its value is 1.38×10^{-23} JK^{-1} .

The ratio of the number of atoms with E_n and E_m is given by

$$N_n / N_m = \exp[(E_m - E_n) / kT] = \exp(hv_{mn} / kT) \tag{2.37}$$

where $E_m - E_n = hv_{mn}$ .This is the Einstein's relation between the frequency v_{mn} and the energy of the quantum absorbed in the transition. After excitation of an atom from one energy level to another, the number of atoms remaining in the initial state decreases exponentially from the original value N(0) according to the relation

$$N(t) = N(0) \exp(-\lambda_p t) \qquad (2.38)$$

At time $t = 1 / \lambda_p$, the rest number of the atoms is reduced by a factor e^{-1} . For a population of N atoms, the mean radiated power is given by

$$P_{nr} = N w_0^4 / 3\pi c^3 [\mu^*_{xmn} \ \mu_{xmn} + \mu^*_{ymn} \ \mu_{ymn} + \mu^*_{zmn} \ \mu_{zmn}] \qquad (2.39)$$

The intensity, I_t for a given volume, v is proportional to the number of photons $N(\nu_{mn})$ by the relation

$$I_t = \rho(\nu_{mn}) c = h \nu_{mn} N(\nu_{mn}) c / v \qquad (2.40)$$

AKURE

2.4.3 LIFETIMES AND SPECTRAL LINE WIDTH

2.4.3.1 LIFETIMES

The lifetime or half-life of an atom is the average time the atom spend in its initial state before making a transition. This is expressed by

$$\tau = [\int_0^\infty t N(t) \, dt] \ / \ [\int_0^\infty N(t) \, dt] = 1 / \lambda_p = [\Sigma S_{nm}]^{-1} \qquad (2.41)$$

where λ_p is the probability per unit time that one of the atoms in the higher energy state E_m will under go a quantum jump to any of the states of lower energy, say E_n . S_{nm} is the sum of the spontaneous emission for all n for which $E_n < E_m$ .The life time of an excited electronic state is of the order of 10^{-8} s.

2.4.3.2 SPECTRAL LINE WIDTH

The inevitable consequence of molecular or atomic transition from one energy state to another is the production of spectral lines. Spectral lines are not perfectly sharp .They have measurable finite width . The observed spectral line width usually have greater width than the natural line width . The reason for this is because the mechanical slits in spectrometers are not infinitely narrow . As a result it permits a range of frequency instead of a single frequency , to fall on the detector , hence blurring the pattern . Therefore the radiating atoms involving in the chaotic thermal agitation travel at velocities that differ both in magnitude and direction from the measuring instrument .

Another reason is that the energy states of atomic and molecular systems are not exactly determined . They possess certain imprecision as a result of collision broadening, Doppler broadening and Heisenberg uncertainty principle[Bandwell , 1972 , Eiseberg , 1961].

2.5 LINE BROADENING MECHANISMS

Numerous spectral line widths exist, each with attributed physical cause. The line shapes can be classified according to their origins and assign different values characteristic of their physical causes. Some of this spectral lines are:

2.5.1 NATURAL LINE WIDTH

The natural line width is the frequency broadening due to uncertainty in the energy of an excited quantum level. If a system exists in an energy state for a limited time Δt seconds, then the energy of that state, according to Heisenberg uncertainty principle, must be uncertain by an amount ΔE, where

$$\Delta E \,.\, \Delta t \sim \hbar / \tau \qquad (2.42)$$

For a time comparable to the lifetime t of the excited state, the principle can have any value within the range

$$\Delta E \sim \hbar / t \qquad (2.43)$$

The corresponding uncertainty frequency , $\Delta\upsilon$ is given by

$$\Delta\nu = \Delta E \;/\; \hbar \sim \hbar / h\tau = 1 / 2\pi\tau \qquad (2.44)$$

The accompanied spectral line will have a corresponding width. The transition rate R for absorption, according to quantum theory, to a certain state depends on the energy $\Delta\nu$ of the quantum according to the relation

$$R\,(h\nu) \;\alpha\; 1 \;/\; [(h\nu - h\nu_0)^2 + (\,\Gamma / 2)^2\,] \qquad (2.45)$$

where $h\nu_0$ is the mean energy of the state and Γ is the full width at half maximum and is expressed by

$$\Gamma = \hbar\,\Delta\nu \qquad (2.46)$$

The full width is related to the life time;τ by

$$\tau = \hbar \;/\; \Gamma \qquad (2.47)$$

The intrinsic width, Γ of a spectral line is the same for both initial state and final state of much narrower width.

The frequency broadening associated with Heisenberg uncertainty principle is not considered in the computation of microwaves absorption due to its minute value [Brussaard et al,1991].

2.5.2 *DOPPLER BROADENING*

This is a frequency shift in the radiation received from a moving source. When a source emitting monochromatic radiation at frequency moves towards an observer, the emitted wave trains arrive at a higher frequency. This also affects the radiowave frequency, subject to absorption and dispersion by a gas molecule which is in a thermal motion. The more intensive the thermal agitation, the more the lines are broadened. The Doppler half-width is given by

$$\Delta f_d = 3.581 \times 10^{-7} f \sqrt{[(T/m)]} \qquad (2.48)$$

where m is the molecular weight (u) of the gas,T the absolute temperature(K) .Under conditions of gas discharges, Doppler broadening is greatest for light atoms . For visible light, it is of the order of 10^{10} to 10^{11} s^{-1} or 0.01 to 0.1 Å .Doppler effect is more pronounced in gases than in liquids. [Brussaard et al, 1991,Yavorsky B and Detlaf, 1975, Banwell].

2.5.3 *COLLISION OR PRESSURE BROADENING*

At high pressures, the time between collisions of the emitting atom with other atoms becomes smaller than the lifetime of the excited state. As a result, it is no linger possible to carry out an undisturbed measurement for a time comparable to the lifetime . The width of the line will be larger than its natural width. This effect is called collision broadening or pressure broadening [Eisberg,1961]. Among others,this effect depends on the type of interaction of the particles and their concentration .As the lifetime decreases the uncertainty collisional frequency Δf_d increases. Currently there is no single satisfactory formula for evaluation collision uncertainty frequency Δf_d, but the most popular in use being that given by Rosenkrantz [1975].

$$\Delta f_p = 1.16 \times 10^{-3} P(300 / T)^{0.85} \qquad (2.49)$$

2.5.4 ZEEMAN BROADENING [Liebe,1981].

The magnetic field influence on an atom or a molecule causes the splitting of the quantum energy levels. This effect is called Zeeman effect. Now the z-component, J_z of the rotational quantum momentum, J becomes essential in the energy quantum level computation.

The atmosphere, under the influence of weak earth's magnetic field, is capable of generating a splitting. Oxygen molecular level, for instance, characterised by a given J value results in (2J +1) sublevels splitting . The separation energy between such levels is very small (corresponding to 1-2 MHz)and does not affect the microwave region .

The splitting, all the same, causes a sort of broadening of the original unperturbed level known as Zeeman broadening . For all absorption lines we have

$$\Delta f_z \approx 25.2H \qquad (2.50)$$

where H is the earth's magnetic field strength (T)

The combined effects of the total broadening is given by [Liebe,1975,1977]

$$\Delta f = \sqrt{[(\Delta f_p)^2 + (\Delta f_d + \Delta f_z)^2]} \qquad (2.51)$$

2.6 GASEOUS ATTENUATION MODELS

In computing the specific attenuation for oxygen and water vapour we can employ the services of :

1 *The ITU semi-empirical model, (formerly CCIR Semi-empirical model)*

2 *Liebe's semi-empirical model, and*

3 *Otto-Thomson model*

2.6.1 THE ITU SEMI-EMPIRICAL MODELS

For practical applications, this model, as adopted in the ITU-R 719 [1990], uses an approximate technique based on the Van Vleck Weisskopf line shapes. The input spectroscopic coefficients are adjusted to fit the results of computer calculations on available measurements [Liebe,1985]. The model only evaluates the attenuation effects of oxygen and water vapour for frequency range up to 350 GHz and within a pressure range of 1013 ± 50 hPa.

The total gaseous absorption in the atmosphere, A_c (dB), over a path length r_o (km) is given by

$$A_c = \int_0^r \alpha_c(r)\,dr \quad \text{(dB)} \qquad (2.52)$$

where $\alpha_c = \alpha_o(r) + \alpha_w(r)$ (dB/km) (2.53)

a_c is the specific attenuation and α_o , α_w are the dry air and water vapour contribution respectively. The specific attenuation for oxygen at ground level pressure 1013 mb and at a temperature of 15°C is given by [Gibbins, 1986a]

$$\alpha_o = \{7.19 \times 10^{-3} + 6.09 / (f^2 + 0.227) + 4.81 / [(f-57)^2 + 1.50]\} f^2 \times 10^{-3} \quad (2.54)$$

for f < 57 GHz

$$\alpha_o = \{ 3.79 \times 10^{-7} f + 0.265 / [(f-63)^2 + 1.59] + 0.028 / [(f-118)^2 + 1.47]\}(f + 198)^2 \times 10^{-3}$$

for f >63 GHz (2.55)

The specific attenuation at sea-level for water vapour, also by Gibbins, at a temperature of 15°C, and including the effects of the quadratic dependence on water vapour density, is given by

$$\alpha_w = \{ 0.050 + 0.0021\rho + 3.00 / [(f-22.2)^2 + 8.5] + 10.6 / [(f-183.3)^2 + 9.0] + 8.9/ (f-325.4)^2 + 26.3]\} f^2 \rho \, 10^{-4} \quad \text{dB / km} \quad (2.56)$$

with f, being the frequency in GHz, and ρ, the water density in g/m^3 . We see from equations (55) , (56) and (57) that the absorption lines of oxygen and water vapour are modelled as poles in denominators. Besides, the far wing effects of absorption peaks at higher frequencies and various continuous spectra are modelled as constants and factors.

For temperature in excess of 15°C, temperature correction of -1.0% per °C from 15°C for dry air and -0.6% per °C from 15°C for water vapour, valid over the range -20°C to 40°C , is taken into account .This temperature correction has been confirmed in a field experiment as frequency dependence near resonance lines [Manabe et al .,1987].

2.6.1.1 MODEL MERITS

1.The ITU model requires no detail information about radio meteorological data, such as pressure, temperature and relative humidity .

2.It permits a rough, fast computation of specific attenuation .

2.6.1.2 MODEL DEMERITS

1. The evaluated attenuation by the model is not as accurate as that obtained from Liebe's model or Otto-Thomson model.

2. It cannot be used for frequency above 350 GHz.

2.6.2 LIEBE 'S SEMI-EMPIRICAL MODEL

This model is also referred to as millimetre wave propagation model [MPM] or Line -by -line method of gaseous attenuation .The specific attenuation is determined by Liebe model when the input parameters are known to a high degree of accuracy. This procedure uses a *reduced line base* for frequencies up to 350 GHz, and above this frequency, *full line base* is utilised [Liebe ,1985].

The atmospheric propagation medium is expressed in measurable quantities in the form of a complex refractivity, N expressed by

$$N(f) = N_o + N^{'}(f) + jN^{''}(f) \qquad \text{ppm} \tag{2.57}$$

The frequency independent part , N_o is given by [Liebe ,1981; Hill et al ., 1982]

$$N_o = (2.588p + 41.6et + 2.39e)t \qquad \text{ppm} \tag{2.58}$$

The real frequency dependent part $N^{'}$ (f) is the cause of dispersive effects; the imaginary part $N^{''}$(f) causes absorption. As recommended by the commission F working party of the international Union of Radio science (URSI), the specific gaseous attenuation is given by

$$\alpha_o = 0.1820f\, N^{''}(f) \qquad \text{dB/km} \tag{2.59}$$

The frequency dependence of the absorptive term is

$$N^{''}(f) = \Sigma\,(SF)_i + N_D^{''}(f) + N_W^{''}(f) \tag{2.60}$$

Where the summation is over all absorption lines, S_i (KHz) is the strength of the i^{th} line, F_i (GHz^{-1}) is the line shape factor ; $N_D^{''}$(f) and $N_W^{''}$(f) are dry and wet continuum spectra. The complex line shape factor for both oxygen and water vapour is given by

$$F_i = f\ /\ f_i \{[\gamma -(f_i -f)\, I_i\ ] / [(f_i -f)^2 + \gamma_i^2\ ]\ + [(\gamma_i\ -(f_i +f)\, I_i\,] /\ [(f_i +f)^2 + \gamma_i^2\ ]\} \tag{2.61}$$

Where f_i is the resonance frequency, γ_i (GHz) is the line width in GHz and I_i is the interference coefficient which arises owing to the interference effects in the oxygen lines [Rosenkranz,1975] .

The dependence of oxygen and water vapour on pressure, temperature and relative humidity is given by six spectroscopic coefficients each. For oxygen, the coefficients are a_1 to a_6 ;while b_1 to b_6 are for water vapour,as shown in table (2.1) and table (2.2).They are expressed thus for oxygen:

$$S_i = a_1 p\, t^3 \exp[a_2(1-t)]10^{-6} \qquad (2.62)$$

$$\gamma_i = a_3(p\, t^{(0.8-a4)} + 1.1et)10^{-3} \qquad (2.63)$$

$$I_i = p\, t^{0.8}(a_5 + a_6 t)\, 10^{-3} \qquad (2.64)$$

For water vapour,

$$S_i = b_1 e t^{3.5} \exp[b_2(1-t)] \qquad (2.65)$$

$$\gamma_i = b_3(p\, t^{b4} + b_5 e\, t^{b6})\, 10^{-3} \qquad (2.66)$$

$$I_i = 0 \qquad (2.67)$$

p is the dry air pressure ; e is the water vapour partial pressure both in mb. The measurable total barometric pressure, P_b and the relative inverse temperature,t are given by

$$P_b = p + e \qquad (2.68)$$

$$t = 300 / T \qquad (2.69)$$

The relative humidity, rh (%) is related to vapour concentration, v (g/m^3)and water vapour pressure, e by

$$v = 7.223et = 1.739.10^{9}\ rh\ t^{5} \exp(-22.64t) \qquad (2.70)$$

The relative humidity is the percentage ratio of water vapour pressure to water vapour saturation pressure, e_s . That is,

$$Rh = (e/e_s)100 \leq 100 \qquad (2.71)$$

The dry air continuum N_D'' arises from Debye spectrum of oxygen below 10 GHz and a pressure -induced nitrogen attenuation above 100 GHz. The nonresonant dry spectrum makes a small contribution at ground level and is expressed by

$$N_D''(f) = S_d\, f / \gamma_o [1 + (f / \gamma_o)^2] + a_p\, f\, p^2\, t^{3.5} \qquad (2.72)$$

where Debye strength and width are

$$S_d = 6.14.10^{-4}\ p\ t^2 \qquad (2.73)$$

$$\gamma_o = 5.6.10^{-3} (p + 1.1e)\ t \qquad (2.72)$$

The nitrogen coefficient is expressed by

$$a_p = 1.40(1 - 1.2.10^5\ f^{1.5})10^{-10} \qquad (2.74)$$

Table(2.1): SPECTROSCOPIC COEFFICIENTS FOR OXYGEN

fi	a1	a2	a3	a4	a5	a6
50.474238	0.94	9.694	8.60	0	1.600	5.520
50.987749	2.46	8.694	8.70	0	1.400	5.520
51.503350	6.08	7.744	8.90	0	1.165	5.520
52.021410	14.14	6.844	9.20	0	0.883	5.520
52.542394	31.02	6.004	9.40	0	0.579	5.520
53.066907	54.10	5.224	9.70	0	0.252	5.520
53.595749	124.70	4.484	10.00	0	-0.066	5.520
54.130000	228.00	3.814	10.20	0	-0.314	5.520
54.671159	391.80	3.194	10.50	0	-0.706	5.520
55.221367	631.60	2.624	10.79	0	-1.151	5.514
55.783802	953.50	2.119	11.10	0	-0.920	5.025
56.264775	546.90	0.015	16.46	0	2.881	-0.069
56.363389	1344.00	1.660	11.44	0	-0.596	4.750
56.968206	1763.00	1.260	11.81	0	-0.556	4.104
57.612484	2141.00	0.915	12.21	0	-2.414	3.536
58.323877	2386.00	0.626	12.66	0	-2.635	2.686
58.446590	1457.00	0.084	14.49	0	5.848	-0.647
59.164207	2404.00	0.391	13.19	0	-6.032	1.858
59.590983	2112.00	0.212	13.60	0	6.266	-1.413
60.306061	2124.00	0.212	13.82	0	-7.170	0.918
60.434776	2461.00	0.391	12.97	0	5.664	-2.323
61.150560	2504.00	0.626	12.48	0	1.731	-3.039
61.800154	2298.00	0.915	12.07	0	1.738	-3.797
62.411215	1933.00	1.260	11.71	0	-0.048	-4.277
62.486260	1517.00	0.083	14.68	0	-4.290	0.238
62.997977	1503.00	1.665	11.39	0	0.134	-4.860
63.568518	1087.00	2.115	11.08	0	0.541	-5.079
64.127767	733.50	2.620	10.78	0	0.814	-5.525
64.678903	463.50	3.195	10.50	0	0.415	-5.520
65.224071	274.80	3.815	10.20	0	0.069	-5.520
65.764772	153.00	4.485	10.00	0	-0.143	-5.520
66.302091	80.09	5.225	9.70	0	-0.428	-5.520
66.836830	39.46	6.005	9.40	0	-0.726	-5.520
67.369598	18.32	6.845	9.20	0	-1.002	-5.520
67.900867	8.01	7.745	8.90	0	-1.255	-5.520
68.431005	3.30	8.695	8.70	0	-1.500	-5.520
68.960311	1.28	9.695	8.60	0	-1.700	-5.520
118.750343	945.00	0.009	16.30	0	-0.247	0.003
368.498350	67.90	0.049	19.20	0.6	0	0
424.763124	638.00	0.044	19.16	0.6	0	0
487.249370	235.00	0.049	19.20	0.6	0	0
715.393150	99.60	0.145	18.10	0.6	0	0
773.839675	671.00	0.130	18.10	0.6	0	0
834.145330	180.00	0.147	18.10	0.6	0	0

Source: Liebe,H. (1989).

Table(2.2): SPECTROSCOPIC COEFFICIENTS FOR WATER VAPOUR

fi	b1	b2	b3	b4	b5	b6
22.235080	0.1090	2.143	28.10	0.69	4.80	1.00
67.813960	0.0011	8.735	28.58	0.69	4.93	0.82
119.995940	0.0007	8.356	29.48	0.70	4.78	0.79
183.310074	2.3000	0.668	28.13	0.64	5.30	0.85
321.225644	0.0464	6.181	23.03	0.67	4.69	0.54
325.152919	1.5400	1.540	27.83	0.68	4.85	0.74
336.187000	0.0010	9.829	26.93	0.69	4.74	0.61
380.197372	11.9000	1.048	28.73	0.69	5.38	0.84
390.134508	0.0044	7.350	21.52	0.63	4.81	0.55
437.346667	0.0637	5.050	18.45	0.60	4.23	0.48
439.150812	0.9210	3.596	21.00	0.63	4.29	0.52
443.018295	0.1940	5.050	18.60	0.60	4.23	0.50
448.001075	10.6000	1.405	26.32	0.66	4.84	0.67
470.888947	0.3300	3.599	21.52	0.66	4.57	0.65
474.689127	1.2800	2.381	23.55	0.65	4.65	0.64
488.491133	0.2530	2.853	26.02	0.69	5.04	0.72
503.568532	0.0374	6.733	16.12	0.61	3.98	0.43
504.482692	0.0125	6.733	16.12	0.61	4.01	0.45
556.936002	510.0000	0.159	32.10	0.69	4.11	1.00
620.700807	5.0900	2.200	24.38	0.71	4.68	0.68
658.015000	0.2740	7.820	32.10	0.69	4.14	1.00
752.033227	250.0000	0.396	30.60	0.68	4.09	0.84
841.073593	0.0130	8.180	15.90	0.33	5.76	0.45
859.865000	0.1330	7.989	30.60	0.68	4.09	0.84
899.407000	0.0550	7.917	29.85	0.68	4.53	0.90
902.555000	0.0380	8.432	28.65	0.70	5.10	0.95
906.205524	0.1830	5.111	24.08	0.70	4.70	0.53
916.171582	8.5600	1.442	26.70	0.70	4.78	0.78
970.315022	9.1600	1.920	25.50	0.64	4.94	0.67
987.926764	138.0000	0.258	29.85	0.68	4.55	0.90

Source: Liebe,H.(1989).

The wet continuum is included to take care of the measurements of water vapour attenuation in excess of those predicted. It is expressed by this formula

$$N_W''(f) = f(b_s e + b_f p)10^{-5} e t^3 \qquad (2.75)$$

where

$$b_s = 3.57t^{7.5} \qquad (2.76)$$

$$b_f = 0.113 \qquad (2.77)$$

The b_f - term is insensitive to specific shape function. Also the wet spectrum term b_s lacks satisfactory theoretical explanation. Attempt to explain its origin from far wing and water dimers, according to Liebe, is inconclusive. Therefore,the wet spectrum is still a major source of uncertainty in evaluating millimeter wave attenuation rates, especially in the four window ranges [waters,1976; Rice and Ade, 1979; Emery et al ,1980 ; Liebe ,1983].

2.6.2.1 SIGNIFICANCE OF THE MODEL

Among the merits of this model are the following :

1.The model reduces complicated microphysical methodology to simple radio engineering terms.

2.It takes into consideration all performance influencing factors of the atmosphere.

3.It provides therefore a cost effective means of predicting system performance.

4. Unlike the ITU model, it can be used above 350 GHz frequency range.

2.6.2.2 MODEL LIMITATIONS

The accuracy of this model is limited by a number of factors. Some of these factors are:

1. Lack of exact measurements of the atmospheric input parameters-temperature, pressure and relative humidity.There is marked spatial and time invariability observed for these quantities.Thus, the models often use averaged quantities as a practical step to providing answers for system designers.

2. The model fails to account convincingly for the empirical water continuum absorption , especially the e^2 -term of the water continuum. Thus modelling errors can be introduced when predicting transmission characteristic in atmospheric window ranges .

3. The model requires a great deal of computational time and efforts for each input parameter. Thus it is prone to error.

2.6.3 OTTO -THOMSON MODEL

This model treated the absorption spectrum of oxygen as a continuum due to the collision broadening mechanism. According to the model, the specific attenuation is given by

$$A = (-w / c)(s / \gamma)(1 / (1+ z^2))(p / 1013.25)(300 / T)^2 (20 \log_{10} e) \times 10^{-19} \qquad (2.78)$$

$$\text{with } z = f_0 - f / \gamma \qquad (2.79)$$

The line width, γ is the frequency difference for which the attenuation is maximum and half its maximum. Also f_0 and f are the line center frequency and the frequency of radiowave respectively. P is the pressure,T the temperature,S the line strength,w is the angular frequency and c is the velocity of light.

2.6.3.1 MERITS OF THE MODEL

1.Unlike Liebe's semi-empirical model, this model eliminates tedious computations involved in the evaluation of the interference for 44 individual resonance lines at low altitudes.

2.It is therefore less prone to error and not time consuming .

3.The model takes account of all the system performance influencing factors of the atmosphere . Hence, provides cost effectiveness for predicting system performance.

2.7 SUMMARY OF THE VARIABLES USED

S/N	SYMBOLS	MEANINGS
1.	a_p	Nitrogen coefficient.
2 .	a_1-a_6	Spectroscopic coefficients for oxygen.
3.	A_c	Total gaseous absorption in the atmosphere in dB.
4.	A_{mn}	Einstein coefficient for spontaneous emission.
5.	b_1-b_6	Spectroscopic coefficients for water vapour.
6.	B_{mn}	Einstein coefficient of absorption.
7.	c	Velocity of light in vacuum;valueis 3.0x10^8 m/s
8.	e	Water vapour presure in kPa.
9.	e_s	Water vapour saturation presure in kPa.
10.	E	Applied electric field in v/m.
11.	E_{loc}	Local electric field in v/m.
12.	E_m	Higher energy level of molecule.

13.	E_n	Lower energy level of molecule.
14.	ΔE	Uncertainty energy of an atom.
15.	f, ν, ν_{mn}	Frequency in Hz or GHz
16.	f_L, f_o	Resonance or center line frequency in GHz .
17.	F_i	Line shape factor in $(GHz)^{-1}$.
18.	Δf_d	Doppler half width.19
19.	Δf_p	Presssure or collision Uncertainty frequency.
20.	Δf_z	Zeeman broadening frequency in GHz.
21.	Δf	Total broadening frequency in GHz.
22.	g	Acceleration due to gravity;$g=9.8m/s^2$.
23.	g_r	Ratio beween local electric field and appliec electric field.
24.	h	Planck's constant,value is 6.63 x 10^{-34} Js.
25.	I	Nuclear spin quantum number.
26.	I_t	Intensity in NC^{-1}.
27.	I_i	Interference coefficient of oxygen line.
28.	k	Boltzmann's constant,value is $1.38x10^{-23}$J/k.
29.	k_n	Wave number.
30.	ℓ	Orbital angular momentum quantum number.
31.	ℓ_z	Quantised z-component of orbital quantum number.
32.	M	Molecular weight.
33.	m_ℓ	Magnetic quantum number
34.	n	Complex refractive index;typical valueis 1.0003.
35.	N	Complex refractivity in ppm.

36.	n_r	Principal quantum number.
37.	$N(t)$	Number of atoms at time,t.
38.	$N(0)$	Number of atoms at time,t= 0.
39.	$N(n_{mn})$	Number of photons .
40.	N_D''	Dry air continuum.
41.	N_W''	Wet continuum.
42.	N_o	Frequency independent refractivity in ppm.
43.	p	Pressure in kPa.
44.	p_i	Induced polarisation.
45.	p_e	Electric polarisation.
46.	p_d	Permanent dipole moment.
47.	p_{nm}	Non-polar electric dipole moment.
48.	p_{xmn}	Probability of higher energy level.
49.	p_{mr}	Mean radiated power.
50 .	p_b	Total barometric pressure in kPa.
51.	r_o	Path length in km.
52.	R_{nm}	Transition rate of absorption.
53.	rh	Relative humidity in %.
54.	S	Spin quantum number.
55.	S_j	Line strength in kHz.
56.	S_z	Quantised z-component of spin quantum number.
57.	S_{nm}	Spontaneous emission transition rate.
58.	S_d	Debye strength.
59.	T ,t	Temperature, relative inverse temperature in K.

60	Δt	Uncertainty time of an atom.
61.	t	Time in s.
62.	v	Vapour concentration in g/m^3.
63.	Δv	Uncertainty frequency .
64.	w	Angular frequency or angular velocity.
65.	ε_0	Permittivity of free space ,value is $8.85x10^{-12}F/m$.
66	ε_r	Relative permittivity.
67.	γ_t	Molecular polarisability in Fm^2.
68.	χ_e	Electric susceptibility.
69.	τ_r	Relaxation time.
70.	τ	Lifetime or half-life of an atom.
71.	γ_i ,γ	Line width in GHz.
72.	γ_e	Electron part of γ_t .
73.	γ_{ii}	Ionic part of γ_t .
74	γ_d	Dipole part of γ_t.
75	γ_0	Debye width.
76.	Γ_j	Damping constant.
77	Γ	Full width at half maximum.
78.	μ_{xmn}	Electric dipole matrix element for x-component.
79.	μ_{xmn}^*	Complex conjugate of μ_{xmn} .
80.	μ_{ymn}	Electric dipole matrix element for y-component.
81	μ_{ymn}^*	Complex conjugate of μ_{ymn} .
82	μ_{gmn}	Electric dipole matrix element for z-component.

83.	μ_{zmn}^{*}	Complex conjugate of μ_{zmn}.
84.	Ψ_n	Wave function.
85.	Ψ_n^{*}	Complex conjugate of Wave function Ψ_n.
86.	λ	Wavelength in m.
87.	λ_p	Probability per unit time.
88.	α	Specific attenuation in dB/km.
89.	α_o	Specific attenuation for oxygen in dB/km.
90.	α_w	Specific attenuation for water vapour in dB/km.

CHAPTER THREE

3.0 RESEARCH METHODOLOGY

3.1 DATA BASE

The study used monthly mean meteorological parameters of pressure, temperature and relative humidity collected from the meteorological station, Oshodi, Lagos for three meteorological sites in Nigeria. These meteorological stations are Lagos (Lat. 06° 32`N, Long. 03°21`), in the Southern Nigeria, Kano (Lat. 03°12`N, Long. 08°32`E) and Minna (Lat. 09°57`N, Long. 06°32E), both situated in Northern Nigeria. However, data are collected directly from Akure (FUTA) Lat. 07° 17`N, Long. 05°14E), a station in the Southern Nigeria, as shown in figure (3.1).

For Akure site data are collected for 5 years: 1990-1993 and 1995; for Minna 1981 to 1983, 1975 and 1990; Kano 1981-1983, 1985 and 1989 and Lagos 1966, 1968-1969 and 1990-1991. Typical values of the data used are shown in Table (3.1). The data values appear to increase with each successive year. All the data are for 1200 GMT and for peak dry and wet seasons. Nigeria has two principal seasons: dry and wet seasons. In the south, the dry season starts October and ends February, while the wet season commences and ends in March and September respectively. On the other hand, October and March mark the beginning and end of dry season in the North; wet season starts April and ends September. The typical representative months thus for dry and wet seasons are January and July respectively, being the peak dry and wet seasons.

3.2 DATA ANALYSIS

In analysing the data a FORTRAN 77 program was developed for the Liebe's semi-emprical model of section (2.6.2). There are two FORTRAN 77 programs employed. The first program, cheer.For, did the entire calculations and output the results. This program requested the user to specify the range of frequency to use. The range employed throughout in this work for each site is 10-350GHz. The line centre frequency ,f_i and permanent spectroscopic coefficients: 44 for oxygen a_1-a_6 and 30 for water vapour b_1-b_6 are stored in two files. These parameters are inherent to the Liebe's model as already pointed out in section (2.6.2).The program reads the two files: Gen2, for oxygen coefficients and Watv2, for water vapour coefficients and performs the computations. The results are stored in another file:Temm.dat.

The second program, cheer2.For, reads the results and output them in the required form for plot. A sample of the computed program is shown in the appendix 1.
To plot graphs, a Grapher package was utilized.

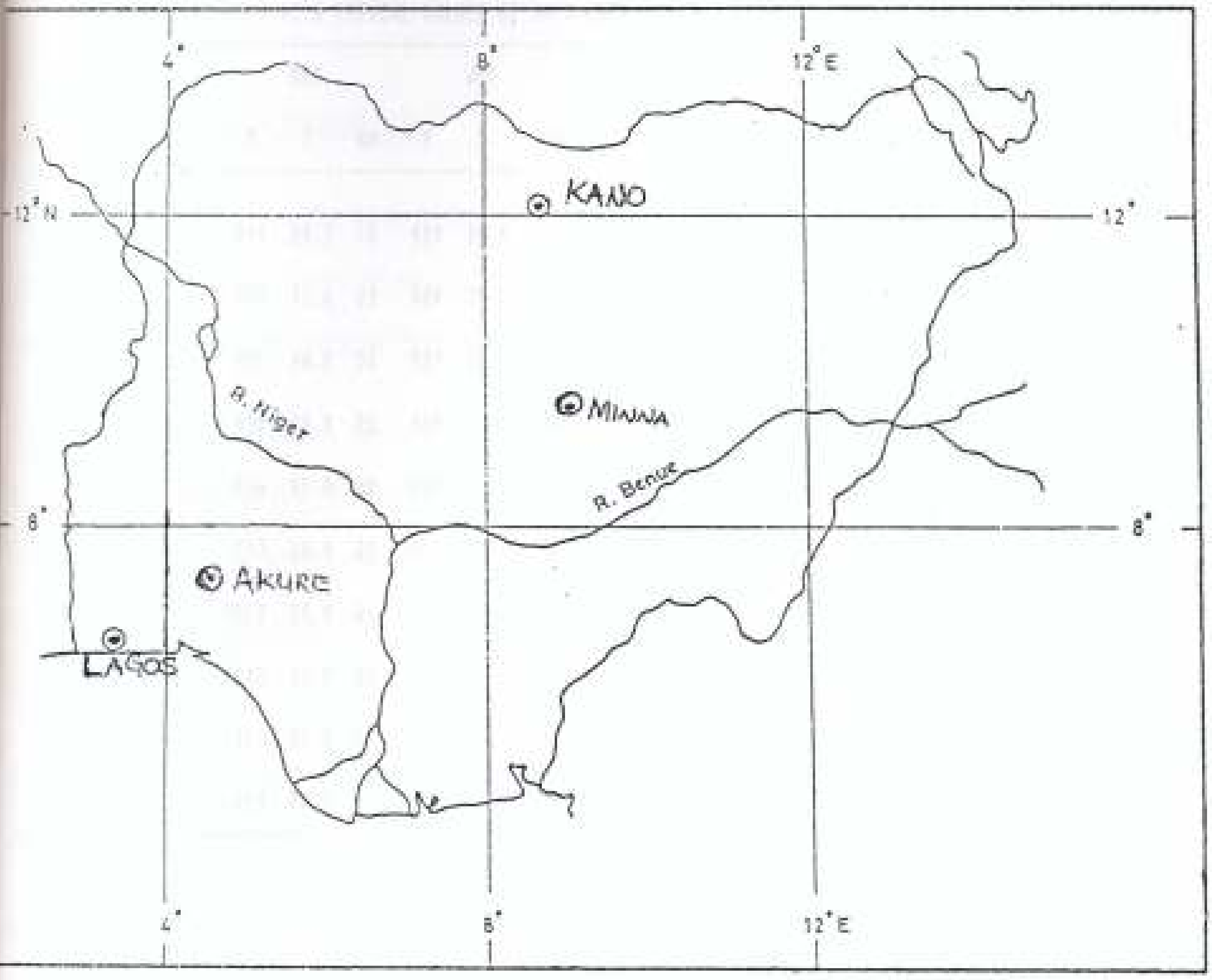


Fig 3.1 Location of the Stations in Nigeria

```
-------------------------------------------
TABLE (3.1):A TYPICAL VALUES OF DATA USED
-------------------------------------------
        DRY            WET

    P    T    RH    P    T    RH
-------------------------------------------

   959  29.2  16   959  28.4   66

   981  31.6  23   984  28.3   72

   982  34.0  26   984  27.1   78

   958  28.9  22   959  31.0   54

   956  31.6  38   957  30.7   59

  1013  26.5  83  1013  24.5   82

  1013  25.9  81  1013  24.0   76

  1013  24.0  28  1013  22.9   75

  1013  28.8  34  1013  25.1   81

  1013  24.0  31  1013  24.9   82
-------------------------------------------
```

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

4.1 ANALYSIS AND RESULTS

The specific attenuation for each of the four tropical sites was evaluated by employing Liebe's semi-empirical model given in section (2.6.2). The accuracy of the results is closely tied to the input elements that vary both in time and space.

Tables (4.1) to (4.4) show typical evaluated attenuation values for oxygen and water vapour (Moist air), while Tables (4.5) to (4.9) display typical attenuation values for oxygen (Dry air),and water vapour. The specific attenuation is higher in wet season than in dry season. The observed high values can be accounted for by high relative humidity and pressure that characterised the wet season.

Temperature is higher in dry season than in wet season. This fact underscores the low attenuation obtained during the dry season.

An obvious departure from the uniform trend of wet season attenuation being greater than that of dry season is noticed at Akure site for 1990 and 1991 for moist air. During this period attenuation is more for dry season. Observations show (See Table 4.1) that temperature and relative humidity for dry season exceed that of wet season. Since attenuation decreases with increasing temperature, one expects that temperature will offset the extra humidity of dry season, so as to bring the attenuation value low. But this is not the case. The clear indication therefore, is that attenuation has stronger dependence on relative humidity than on temperature.

This, in turn, indicates the variability of water vapour, not only in space, but also in time. The graphical illustrations of these results are presented in figures (4.1) to (4.13) for moist air. The peaks of these graphs indicate the peak of the resonant absorption. Water vapour shows resonant absorption at 22GHz, 184 GHz and 326 GHz. There is a maximum oxygen absorption at 60 and series of resonant absorptions occur between 54-66 GHz. The isolated oxygen absorption becomes observable at 118 GHz.

The computed specific attenuation shows both geographical and seasonal variations. Figures (4.14) and (4.15) depict the geographical variation of the attenuation . Lagos, a coastal station, has the highest attenuation values, while Kano, a far inland site, scores the least values. These differences in results are due to the variation in the atmospheric water vapour content . For the same reason , there are wide differences in the values of attenuation noticed at 22 GHz , 184GHz and 326 GHz .

In contrast, attenuation varies only slightly at 60 GHz and 118 GHz owing to the constant concentration of oxygen in the atmosphere.

Table(4.1): A TYPICAL COMPUTED ATTENUATION FOR MOIST AIR FOR DRY AND WET SEASONS AT AKURE

FREQ (GHz)	22		60		118		184		326	
YEAR	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
1990	.46	.41	14.31	14.48	2.86	2.71	70.26	62.94	96.99	85.91
1991	.44	.37	14.34	14.49	2.83	2.50	66.72	57.19	91.66	77.52
1992	.15	.35	14.29	14.59	1.48	2.38	22.06	53.39	28.86	71.93
1993	.23	.42	13.80	14.42	1.71	2.74	34.17	64.12	45.67	87.73
1995	.16	.42	14.30	14.44	1.53	2.75	24.35	64.21	31.92	87.83

Table(4.2): A TYPICAL COMPUTED ATTENUATION FOR MOIST AIR FOR DRY AND WET SEASONS AT KANO

FREQ (GHz)	22		60		118		184		326	
YEAR	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
1981	.12	.42	13.16	13.49	1.28	2.55	17.45	64.47	22.73	87.71
1982	.19	.46	13.21	13.83	1.49	2.80	27.52	68.87	36.57	94.78
1983	.24	.46	13.00	13.99	1.63	2.84	34.78	69.27	46.76	95.13
1985	.16	.40	13.20	13.18	1.40	2.37	23.42	60.72	30.66	82.70
1989	.31	.43	12.99	13.22	1.88	2.52	45.21	65.02	60.68	88.83

Table (4.3): A TYPICAL COMPUTED ATTENUATION FOR MOIST AIR FOR DRY AND WET SEASONS AT MINNA

FREQ (GHz)	22		60		118		184		326	
YEAR	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
1981	.31	.48	12.49	13.83	1.83	2.80	44.97	68.87	61.89	94.78
1982	.19	.47	13.21	14.07	1.49	2.93	27.52	71.21	36.57	97.89
1983	.24	.46	13.00	13.99	1.63	2.84	34.78	69.27	46.78	95.13
1975	.18	.43	13.35	14.12	1.42	2.75	23.47	66.20	30.99	90.40
1990	.22	.44	13.03	13.98	1.59	2.78	32.87	67.64	44.07	92.74

Table (4.4): A TYPICAL COMPUTED ATTENUATION FOR MOIST AIR FOR DRY AND WET SEASONS AT LAGOS

FREQ (GHz)	22		60		118		184		326	
YEAR	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
1986	.44	.47	13.95	14.36	2.72	3.04	65.61	71.59	90.79	99.27
1988	.44	.47	14.04	14.40	2.77	3.05	66.41	71.62	91.89	99.32
1989	.45	.51	13.98	13.96	2.78	3.14	67.14	75.94	93.03	106.33
1990	.49	.45	13.94	14.37	3.03	2.89	73.39	68.00	102.74	93.97
1991	.45	.45	13.91	14.33	2.78	2.92	66.78	66.81	92.67	95.28

Table(4-5): A TYPICAL COMPUTED ATTENUATION FOR OXYGEN AND WATER VAPOUR FOR DRY AND WET SEASONS AT AKURE

	OXYGEN				WATER VAPOUR					
FREQ (GHz)	60		118		22		184		326	
YEAR	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
1990	13.51	14.05	1.01	1.00	.45	.40	70.24	62.42	96.96	85.88
1991	13.88	14.12	1.04	1.06	.43	.36	66.70	57.17	91.63	77.49
1992	14.19	14.25	1.07	1.07	.14	.33	22.05	53.37	28.83	71.90
1993	13.62	13.98	1.02	1.05	.22	.41	34.16	64.11	45.64	87.70
1995	14.18	14.00	1.07	1.05	.15	.41	24.34	64.19	31.89	87.80

Table(4-6): A TYPICAL COMPUTED ATTENUATION FOR OXYGEN AND WATER VAPOUR FOR DRY AND WET SEASONS AT KANO

	OXYGEN				WATER VAPOUR					
FREQ (GHz)	60		118		22		184		326	
YEAR	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
1981	13.09	13.09	1.01	1.00	.11	.41	17.43	64.45	22.71	87.68
1982	13.08	13.36	0.99	1.01	.18	.44	17.51	68.86	34.54	94.76
1983	12.83	13.52	0.97	1.02	.23	.44	34.77	69.25	40.74	95.10
1985	13.10	12.82	1.01	0.98	.15	.39	23.41	66.71	30.63	82.67
1989	12.76	12.82	0.98	0.98	.29	.42	45.20	65.00	60.66	88.81

Table (4.7): A TYPICAL COMPUTED ATTENUATION FOR OXYGEN AND WATER VAPOUR FOR DRY AND WET SEASONS AT MINNA

	Oxygen				Water vapour					
FREQ (GHz)	60		118		22		184		326	
YEAR	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
1981	13.26	13.36	0.97	1.01	.30	.44	44.96	68.96	61.67	94.76
1982	13.08	13.58	0.99	1.02	.18	.46	27.51	71.19	36.54	97.86
1983	12.83	13.52	0.97	1.02	.23	.44	34.77	69.25	46.74	95.10
1975	13.24	13.68	1.01	1.03	.15	.42	23.46	66.19	30.96	90.37
1990	12.87	13.52	0.97	1.02	.21	.43	32.85	67.63	44.05	92.71

Table (4.8): A TYPICAL COMPUTED ATTENUATION FOR OXYGEN AND WATER VAPOUR FOR DRY AND WET SEASONS AT LAGOS

	Oxygen				Water vapour					
FREQ (GHz)	60		118		22		184		326	
YEAR	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
1966	13.51	13.84	1.01	1.03	.43	.46	65.60	71.57	90.76	99.24
1968	13.58	13.88	1.01	1.03	.43	.46	66.39	71.61	91.86	99.29
1969	13.52	13.42	1.01	1.00	.44	.50	67.12	75.93	93.00	106.30
1990	13.41	13.89	1.00	1.03	.48	.44	73.37	67.98	102.71	93.93
1991	13.45	13.84	1.00	1.03	.43	.44	66.76	68.80	92.64	95.25

Table (4.9):A TYPICAL COMPUTED SPECIFIC ATTENUATION VALUE FOR MOIST AIR

LOCATIONS	AKURE(1991)		KANO(1981)		LAGOS(1966)		MINNA(1981)	
FREQUENCY(GHz)	DRY	WET	DRY	WET	DRY	WET	DRY	WET
10	.03	.02	.01	.02	.02	.03	.02	.02
11	.03	.03	.01	.03	.03	.03	.02	.03
12	.04	.03	.01	.03	.03	.04	.02	.04
13	.05	.04	.01	.04	.04	.05	.03	.04
14	.06	.05	.02	.05	.05	.06	.03	.05
15	.07	.06	.02	.06	.06	.07	.04	.06
16	.09	.08	.02	.07	.08	.09	.05	.08
17	.11	.10	.03	.09	.10	.12	.06	.11
18	.15	.13	.03	.13	.14	.15	.09	.14
19	.20	.18	.05	.17	.19	.21	.12	.19
20	.28	.25	.07	.25	.26	.29	.18	.27
21	.38	.33	.09	.34	.36	.39	.25	.37
22	.48	.41	.12	.42	.44	.47	.31	.46
23	.48	.43	.12	.44	.46	.50	.32	.48
24	.44	.39	.11	.40	.42	.46	.28	.43
25	.38	.34	.09	.34	.36	.40	.24	.37
26	.33	.29	.07	.29	.31	.34	.20	.32
27	.29	.26	.07	.25	.27	.31	.17	.28
28	.27	.24	.06	.23	.25	.28	.15	.25
29	.25	.22	.06	.21	.23	.26	.14	.24
30	.24	.21	.05	.20	.22	.25	.13	.23
31	.24	.21	.05	.20	.22	.25	.13	.22
32	.24	.21	.05	.20	.22	.25	.13	.22
33	.24	.21	.05	.20	.22	.25	.13	.22
34	.24	.21	.06	.20	.22	.25	.13	.23
35	.25	.22	.06	.20	.23	.26	.13	.23
36	.26	.22	.06	.21	.23	.27	.14	.24
37	.26	.23	.06	.22	.24	.27	.14	.25
38	.27	.24	.07	.23	.25	.28	.15	.26
39	.29	.25	.07	.23	.26	.30	.15	.27
40	.30	.26	.08	.24	.27	.31	.16	.28
41	.31	.28	.08	.26	.28	.32	.17	.29
42	.33	.29	.09	.27	.30	.34	.18	.31
43	.35	.31	.10	.28	.31	.36	.19	.32
44	.37	.33	.11	.30	.33	.38	.20	.34
45	.39	.35	.12	.32	.35	.40	.22	.36
46	.42	.37	.13	.34	.38	.43	.23	.39
47	.45	.40	.15	.37	.41	.46	.26	.42
48	.49	.44	.18	.41	.45	.50	.29	.45
49	.54	.49	.22	.45	.50	.56	.33	.50
50	.61	.57	.27	.52	.57	.63	.39	.58

51	.74	.69	.37	.63	.69	.76	.49	.63
52	.97	.92	.57	.84	.93	1.00	.71	.92
53	1.46	1.41	1.02	1.30	1.41	1.49	1.16	1.39
54	2.46	2.41	1.94	2.24	2.40	2.50	2.09	2.36
55	4.23	4.20	3.62	3.93	4.16	4.28	3.73	4.09
56	6.81	6.82	6.10	6.40	6.69	6.87	6.07	6.61
57	9.60	9.66	8.76	9.06	9.41	9.66	8.52	9.31
58	11.82	11.94	10.85	11.16	11.56	11.88	10.40	11.45
59	13.24	13.41	12.16	12.49	12.93	13.31	11.57	12.81
60	14.29	14.48	13.16	13.49	13.95	14.36	12.49	13.83
61	14.54	14.71	13.40	13.73	14.21	14.61	12.78	14.07
62	13.41	13.53	12.37	12.70	13.14	13.48	11.92	13.01
63	10.37	10.42	9.42	9.79	10.18	10.44	9.25	10.07
64	6.76	6.74	5.90	6.31	6.65	6.84	5.99	6.55
65	4.10	4.04	3.34	3.77	4.02	4.16	3.54	3.96
66	2.48	2.41	1.79	2.23	2.41	2.53	2.02	2.38
67	1.64	1.58	.99	1.44	1.57	1.68	1.22	1.56
68	1.25	1.18	.61	1.07	1.17	1.28	.84	1.17
69	1.07	.98	.44	.90	.99	1.10	.66	1.00
70	.96	.88	.35	.81	.90	1.01	.57	.91
71	.93	.83	.30	.77	.85	.96	.52	.87
72	.91	.81	.26	.74	.82	.94	.49	.84
73	.89	.79	.24	.73	.81	.92	.47	.83
74	.89	.78	.22	.72	.80	.92	.46	.83
108	1.64	1.42	.27	1.32	1.46	1.71	.78	1.52
109	1.68	1.45	.28	1.35	1.49	1.74	.80	1.56
110	1.72	1.48	.29	1.38	1.53	1.79	.82	1.59
111	1.76	1.52	.30	1.42	1.57	1.83	.84	1.63
112	1.81	1.57	.32	1.46	1.61	1.88	.87	1.68
113	1.87	1.62	.35	1.51	1.67	1.94	.91	1.73
114	1.94	1.69	.39	1.57	1.73	2.01	.95	1.80
115	2.04	1.79	.46	1.66	1.83	2.12	1.03	1.90
116	2.20	1.95	.58	1.81	1.99	2.28	1.15	2.05
117	2.49	2.24	.83	2.08	2.26	2.57	1.40	2.33
118	2.98	2.71	1.28	2.55	2.72	3.04	1.83	2.80
119	3.18	2.92	1.49	2.77	2.93	3.25	2.03	3.01
120	2.81	2.54	1.05	2.38	2.56	2.89	1.64	2.64
121	2.50	2.22	.71	2.06	2.26	2.58	1.34	2.33
122	2.35	2.08	.54	1.92	2.11	2.44	1.20	2.18
123	2.29	2.00	.48	1.86	2.05	2.38	1.13	2.13
124	2.26	1.98	.42	1.84	2.03	2.36	1.11	2.11
163	4.94	4.27	.78	4.00	4.43	5.13	2.41	4.60
179	27.91	24.59	5.59	23.84	25.73	28.79	15.78	26.58
180	36.66	32.42	7.69	31.79	33.90	37.70	21.32	35.13
181	46.80	43.18	10.84	43.02	45.11	49.79	29.29	46.95
182	62.29	55.82	14.91	56.45	58.03	63.55	39.07	60.74
183	71.86	64.38	19.06	66.16	67.10	73.11	46.28	70.51
184	70.31	62.94	17.45	64.47	65.81	71.59	44.97	68.87
185	59.30	52.88	13.83	53.27	55.17	60.80	36.64	57.63
186	46.26	41.11	10.09	40.70	42.97	47.57	27.54	44.64

199	8.77	7.60	1.43	7.14	7.90	9.11	4.37	8.17
200	8.49	7.35	1.37	6.90	7.64	8.81	4.20	7.91
201	8.26	7.15	1.33	6.71	7.42	8.58	4.07	7.69
202	8.07	6.98	1.29	6.55	7.25	8.38	3.96	7.51
203	7.92	6.85	1.25	6.42	7.11	8.23	3.87	7.37
204	7.79	6.74	1.23	6.31	6.99	8.10	3.80	7.25
205	7.68	6.65	1.21	6.23	6.90	8.00	3.74	7.16
206	7.61	6.58	1.19	6.16	6.82	7.91	3.69	7.08
207	7.55	6.52	1.17	6.11	6.76	7.85	3.65	7.02
208	7.50	6.48	1.16	6.06	6.71	7.80	3.62	6.97
209	7.47	6.44	1.15	6.03	6.68	7.76	3.59	6.94
210	7.44	6.42	1.14	6.01	6.65	7.73	3.57	6.91
211	7.43	6.40	1.14	5.99	6.63	7.72	3.56	6.90
212	7.42	6.40	1.13	5.99	6.62	7.71	3.55	6.89
213	7.42	6.40	1.13	5.98	6.62	7.71	3.54	6.89
227	7.86	6.77	1.16	6.32	7.00	8.17	3.71	7.29
228	7.91	6.81	1.18	6.37	7.04	8.22	3.74	7.33
229	7.96	6.86	1.19	6.41	7.09	8.28	3.76	7.38
230	8.02	6.90	1.20	6.45	7.14	8.34	3.79	7.43
231	8.07	6.95	1.21	6.50	7.19	8.39	3.81	7.49
232	8.13	7.00	1.21	6.54	7.24	8.45	3.84	7.54
233	8.19	7.05	1.22	6.59	7.29	8.52	3.87	7.60
234	8.25	7.11	1.23	6.64	7.35	8.58	3.89	7.65
235	8.32	7.16	1.24	6.69	7.40	8.64	3.92	7.71
236	8.38	7.21	1.25	6.74	7.46	8.71	3.95	7.77
237	8.44	7.27	1.26	6.79	7.52	8.78	3.98	7.83
238	8.51	7.33	1.27	6.85	7.58	8.85	4.01	7.89
239	8.58	7.38	1.28	6.90	7.63	8.92	4.04	7.95
240	8.65	7.44	1.29	6.96	7.70	8.99	4.08	8.02
241	8.72	7.50	1.30	7.01	7.76	9.06	4.11	8.08
242	8.79	7.56	1.31	7.07	7.82	9.13	4.14	8.15
243	8.86	7.63	1.32	7.13	7.88	9.21	4.18	8.21
244	8.93	7.69	1.33	7.19	7.95	9.29	4.21	8.28
245	9.01	7.75	1.34	7.24	8.02	9.36	4.24	8.35
246	9.08	7.82	1.35	7.31	8.08	9.44	4.28	8.42
247	9.16	7.88	1.36	7.37	8.15	9.52	4.32	8.49
248	9.23	7.95	1.38	7.43	8.22	9.60	4.35	8.56
249	9.31	8.02	1.39	7.49	8.29	9.68	4.39	8.63
250	9.39	8.09	1.40	7.56	8.36	9.76	4.43	8.71
251	9.47	8.15	1.41	7.62	8.43	9.85	4.47	8.78
252	9.55	8.22	1.42	7.69	8.50	9.93	4.50	8.86
253	9.64	8.30	1.44	7.75	8.58	10.02	4.54	8.93
254	9.72	8.37	1.45	7.82	8.65	10.10	4.58	9.01
255	9.80	8.44	1.46	7.89	8.73	10.19	4.62	9.09
256	9.89	8.51	1.48	7.96	8.80	10.28	4.67	9.17
257	9.98	8.59	1.49	8.03	8.88	10.37	4.71	9.25
258	10.06	8.66	1.50	8.10	8.96	10.46	4.75	9.33
259	10.15	8.74	1.52	8.17	9.04	10.55	4.79	9.41
260	10.24	8.82	1.53	8.24	9.12	10.65	4.84	9.50
261	10.33	8.90	1.54	8.32	9.20	10.74	4.88	9.58

264	9.16	3.63	1.12	.17	1.05	.17	10.52	3.63	13.52	4.74
265	9.25	3.68	1.14	.17	1.06	.17	10.63	3.69	13.66	4.81
266	9.35	3.73	1.15	.18	1.07	.18	10.74	3.74	13.79	4.87
267	9.44	3.79	1.16	.18	1.08	.18	10.85	3.79	13.93	4.94
268	9.54	3.84	1.18	.19	1.09	.19	10.96	3.85	14.07	5.01
269	9.64	3.90	1.19	.19	1.11	.19	11.07	3.90	14.21	5.08
270	9.74	3.96	1.20	.20	1.12	.20	11.18	3.96	14.35	5.15
271	9.84	4.01	1.22	.20	1.13	.20	11.29	4.02	14.49	5.22
272	9.94	4.07	1.23	.21	1.14	.21	11.41	4.08	14.63	5.29
273	10.05	4.13	1.25	.21	1.16	.21	11.53	4.14	14.78	5.37
274	10.15	4.20	1.26	.22	1.17	.22	11.64	4.20	14.93	5.44
275	10.26	4.26	1.28	.22	1.19	.22	11.76	4.26	15.08	5.52
276	10.36	4.32	1.29	.23	1.20	.23	11.88	4.33	15.23	5.60
277	10.47	4.39	1.31	.24	1.22	.24	12.01	4.39	15.38	5.68
278	10.58	4.45	1.33	.24	1.23	.24	12.13	4.46	15.53	5.76
279	10.69	4.52	1.34	.25	1.25	.25	12.25	4.53	15.68	5.84
280	10.81	4.59	1.36	.26	1.26	.26	12.38	4.59	15.84	5.92
281	10.92	4.66	1.38	.27	1.28	.27	12.51	4.66	16.00	6.00
282	11.03	4.73	1.40	.28	1.30	.28	12.63	4.73	16.16	6.09
283	11.15	4.80	1.42	.29	1.32	.29	12.76	4.81	16.32	6.18
284	11.27	4.87	1.44	.30	1.33	.30	12.90	4.88	16.48	6.26
285	11.39	4.95	1.46	.31	1.35	.31	13.03	4.95	16.65	6.35
286	11.51	5.02	1.48	.32	1.37	.32	13.16	5.03	16.81	6.44
287	11.63	5.10	1.50	.33	1.39	.33	13.30	5.10	16.98	6.54
288	11.75	5.17	1.52	.34	1.41	.34	13.44	5.18	17.15	6.63
289	11.87	5.25	1.54	.35	1.43	.35	13.57	5.26	17.32	6.72
290	12.00	5.33	1.57	.36	1.46	.36	13.71	5.34	17.49	6.82
291	12.13	5.41	1.59	.38	1.48	.38	13.86	5.42	17.67	6.92
292	12.25	5.50	1.62	.39	1.50	.39	14.00	5.50	17.84	7.02
293	12.38	5.58	1.64	.41	1.53	.41	14.14	5.59	18.02	7.12
294	12.51	5.66	1.67	.42	1.55	.42	14.29	5.67	18.20	7.22
295	12.64	5.75	1.70	.44	1.58	.44	14.43	5.76	18.38	7.32
296	12.78	5.84	1.72	.46	1.60	.46	14.58	5.84	18.56	7.42
297	12.91	5.92	1.75	.47	1.63	.47	14.73	5.93	18.75	7.53
298	13.05	6.01	1.78	.49	1.66	.49	14.88	6.02	18.93	7.64
299	13.19	6.10	1.81	.51	1.69	.51	15.04	6.11	19.12	7.75
300	13.32	6.20	1.84	.53	1.72	.53	15.19	6.21	19.31	7.86
301	13.46	6.29	1.88	.56	1.75	.56	15.35	6.30	19.50	7.97
302	13.61	6.38	1.91	.58	1.78	.58	15.51	6.39	19.70	8.08
303	13.75	6.48	1.94	.60	1.81	.60	15.66	6.49	19.89	8.19
304	13.89	6.58	1.98	.63	1.84	.63	15.83	6.59	20.09	8.31

313	15.25	7.50	2.33	.91	2.18	.91	17.34	7.51	21.94	9.42
314	15.41	7.61	2.37	.94	2.22	.94	17.51	7.62	22.16	9.55
315	15.57	7.72	2.41	.98	2.26	.98	17.69	7.73	22.38	9.68
316	15.73	7.83	2.45	1.02	2.30	1.02	17.87	7.84	22.60	9.81
317	15.89	7.94	2.49	1.05	2.34	1.05	18.05	7.95	22.82	9.95
318	16.05	8.05	2.53	1.08	2.38	1.08	18.23	8.07	23.04	10.09
319	16.22	8.17	2.57	1.12	2.41	1.12	18.41	8.18	23.26	10.22
320	16.38	8.28	2.61	1.15	2.45	1.15	18.60	8.30	23.49	10.36
321	16.55	8.40	2.64	1.18	2.48	1.18	18.79	8.41	23.72	10.50
322	16.72	8.52	2.68	1.21	2.52	1.21	18.97	8.53	23.95	10.65
323	16.89	8.64	2.71	1.23	2.55	1.23	19.16	8.65	24.18	10.79
324	17.06	8.76	2.74	1.25	2.58	1.25	19.35	8.77	24.42	10.94
325	17.24	8.88	2.77	1.27	2.60	1.27	19.55	8.89	24.66	11.09
326	17.41	9.01	2.79	1.29	2.63	1.29	19.74	9.02	24.90	11.24
327	17.59	9.13	2.82	1.30	2.65	1.30	19.94	9.14	25.14	11.39
328	17.76	9.26	2.84	1.31	2.67	1.31	20.14	9.27	25.38	11.54
329	17.94	9.38	2.86	1.31	2.69	1.31	20.34	9.40	25.63	11.69
330	18.13	9.51	2.88	1.31	2.71	1.31	20.54	9.53	25.87	11.85
331	18.31	9.64	2.90	1.31	2.72	1.31	20.74	9.66	26.12	12.01
332	18.49	9.78	2.91	1.31	2.73	1.31	20.95	9.79	26.38	12.17
333	18.68	9.91	2.92	1.31	2.75	1.31	21.16	9.92	26.63	12.33
334	18.87	10.05	2.94	1.30	2.75	1.30	21.37	10.06	26.89	12.49
335	19.05	10.18	2.95	1.29	2.76	1.29	21.58	10.20	27.14	12.66
336	19.25	10.32	2.96	1.28	2.77	1.28	21.79	10.33	27.40	12.83
337	19.44	10.46	2.97	1.27	2.78	1.27	22.00	10.47	27.67	13.00
338	19.63	10.60	2.98	1.26	2.78	1.26	22.22	10.62	27.93	13.17
339	19.83	10.75	2.98	1.25	2.79	1.25	22.44	10.76	28.20	13.34
340	20.03	10.89	2.99	1.24	2.80	1.24	22.66	10.90	28.47	13.52
341	20.23	11.04	3.00	1.23	2.80	1.23	22.88	11.05	28.74	13.69
342	20.43	11.19	3.01	1.22	2.81	1.22	23.11	11.20	29.01	13.87
343	20.63	11.34	3.02	1.21	2.81	1.21	23.33	11.35	29.29	14.05
344	20.84	11.49	3.03	1.20	2.82	1.20	23.56	11.51	29.57	14.24
345	21.05	11.65	3.04	1.19	2.83	1.19	23.79	11.66	29.85	14.42
346	21.26	11.80	3.05	1.18	2.84	1.18	24.03	11.82	30.13	14.61
347	21.47	11.96	3.06	1.18	2.85	1.17	24.26	11.98	30.42	14.80
348	21.68	12.12	3.08	1.17	2.86	1.17	24.50	12.14	30.70	14.99
349	21.90	12.28	3.09	1.17	2.87	1.17	24.73	12.30	30.99	15.18
350	22.12	12.45	3.11	1.17	2.89	1.16	24.98	12.46	31.28	15.38

Years/Curves	1981a	1982b	1983c
P hPa	95.9	98.1	98.2
RH %	16	23	26
T °c	29.2	31.6	34.0

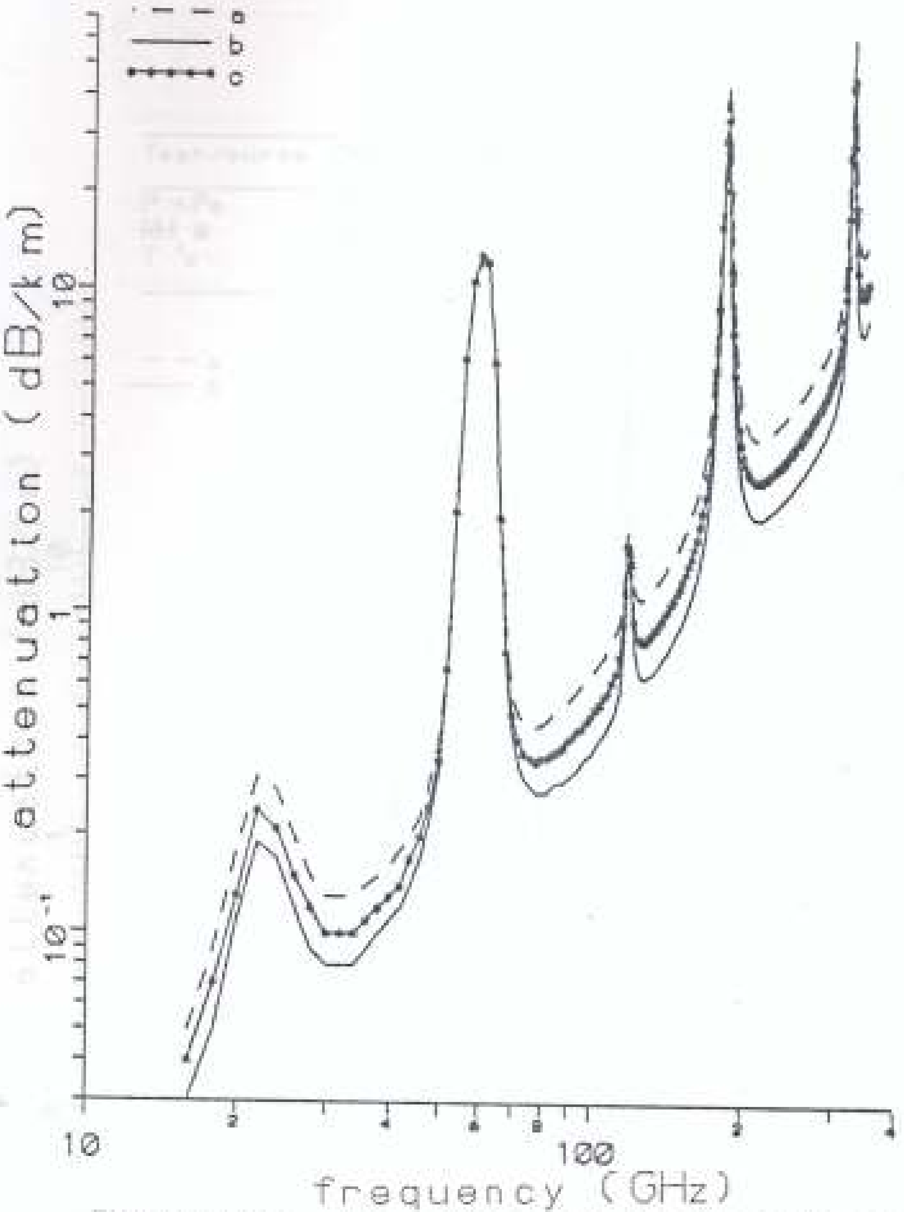


Figure (4.1): Specific attenuation due to Moist air for Dry season at Kano for the years indicated.

Year/curve	1981a	1982b
P hPa	96.9	98.1
RH %	16	23
T °c	29.2	31.6

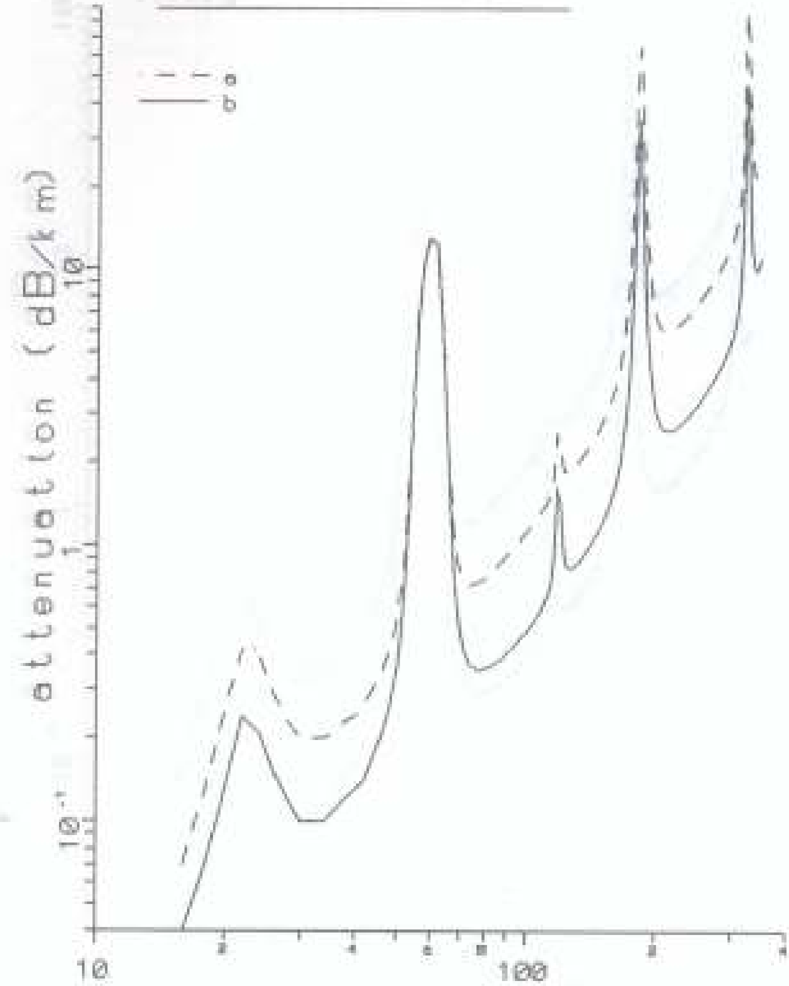


Figure (4.3): Specific attenuation due to Moist air for Wet season at Kano for the years indicate.

Seasons	Dry	Wet	Dry	Wet
Years/curves	1981a	1981b	1982c	1982d
P hPa	96.9	96.9	98.1	98.4
RH %	16	66	23	72
T °c	29.2	28.4	31.6	28.5

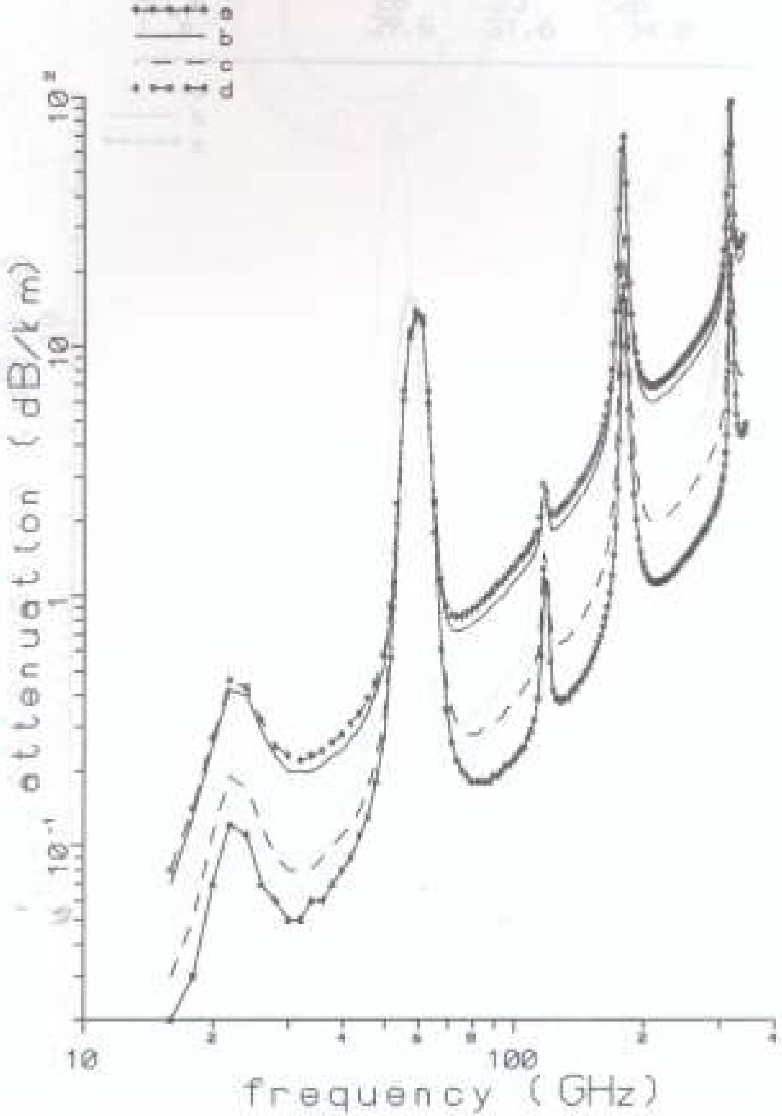
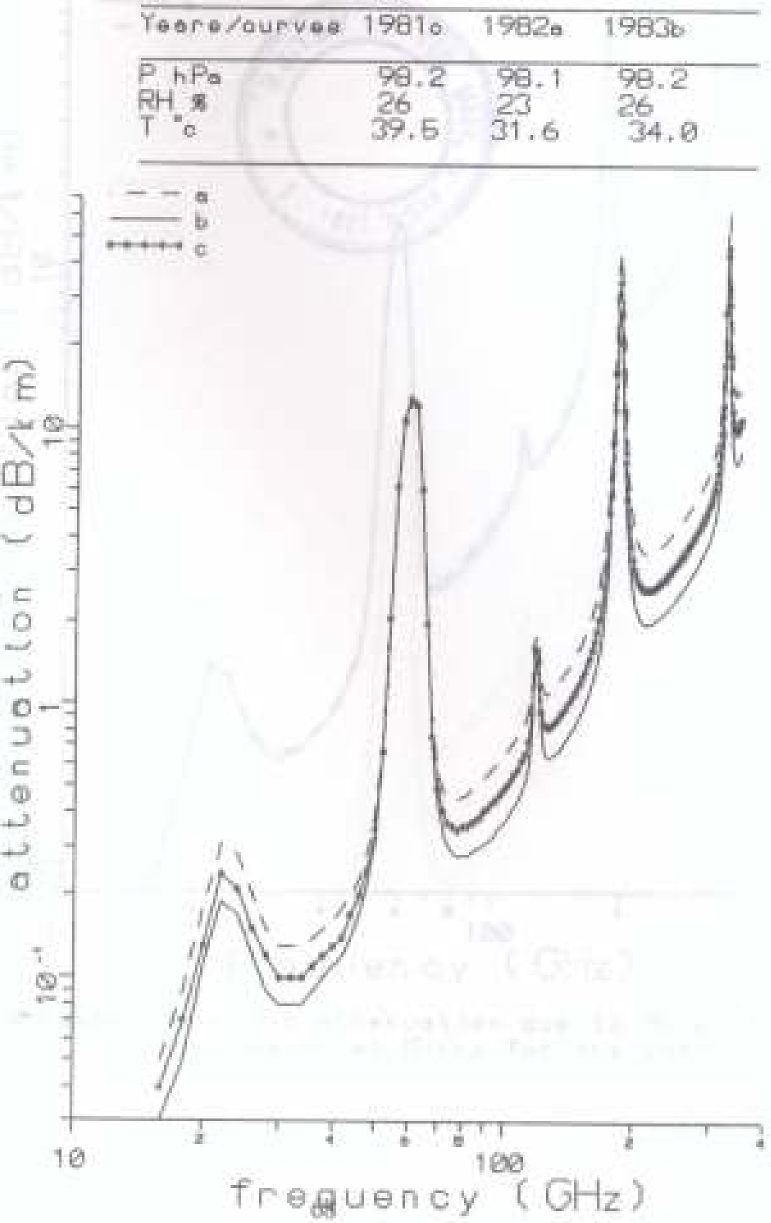


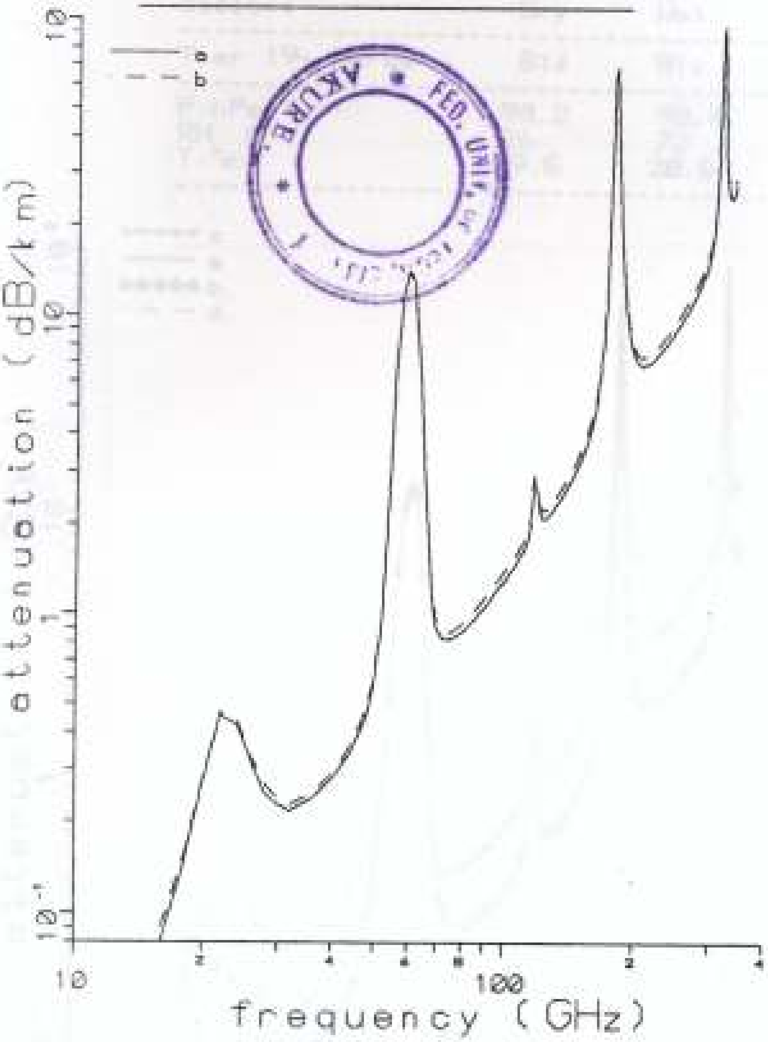
Figure (4.4): Specific attenuation due to Moist air for Dry and Wet seasons at Kano for the years indicated.



Years/curves	1981c	1982a	1983b
P hPa	98.2	98.1	98.2
RH %	26	23	26
T °c	39.5	31.6	34.0

Figure(4.5): Specific attenuation due to Moist air for Dry season at Minna for the years indicated.

Years/curves	1981b	1982a
P hPa	98.2	98.1
RH %	26	23
T °c	39.5	31.6



AKURE * FED. UNIV. OF TECH. *

Figure (4.6): Specific attenuation due to Moist air for Wet season at Minna for the years indicated.

Seasons	Dry	Wet	Dry	Wet
Year 19-/Curve	81d	81c	82a	82b
P hPa	98.2	98.4	98.1	98.4
RH %	26	72	23	83
T °c	39.5	28.5	31.6	26.5

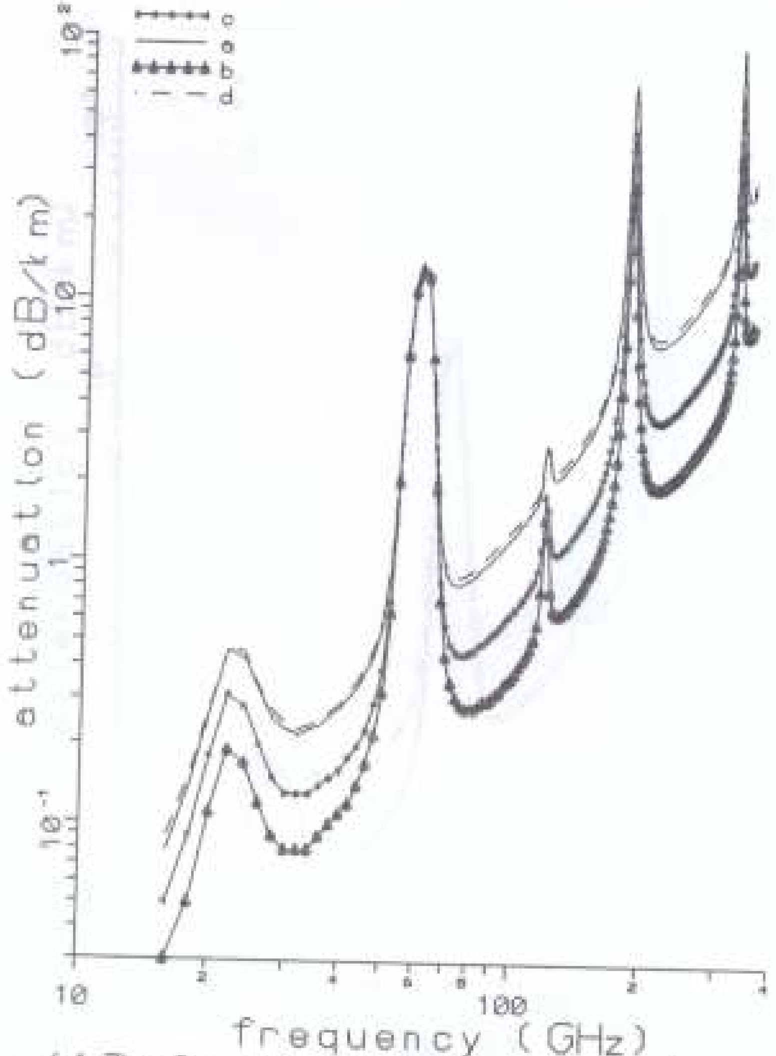


Figure (4.7): Specific attenuation due to Moist air for Dry and Wet seasons at Minna for the years indicated.

Years/curves	1966a	1990b
P hPa	100.8	101.3
RH %	65	69
T °c	29.8	31.1

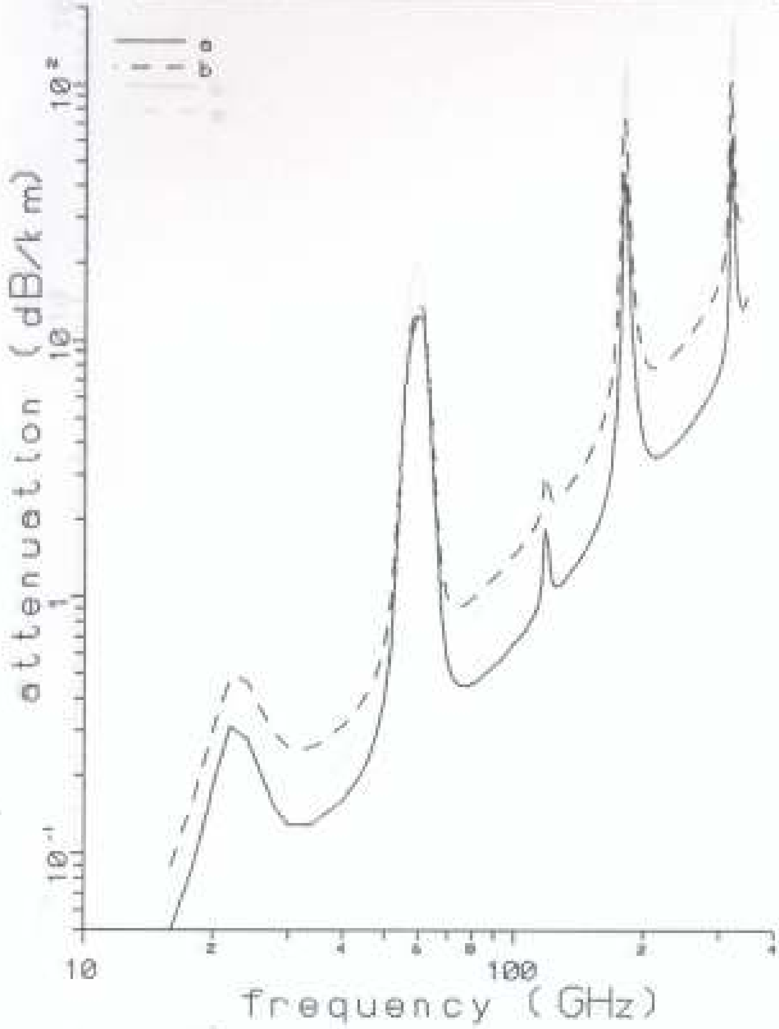


Figure (4.8) : Specific attenuation due Moist air for Dry season at Lagos for the years indicated.

Year/curve	1966a	1990b
P hPa	100.8	101.3
RH %	65	69
T °c	29.8	31.1

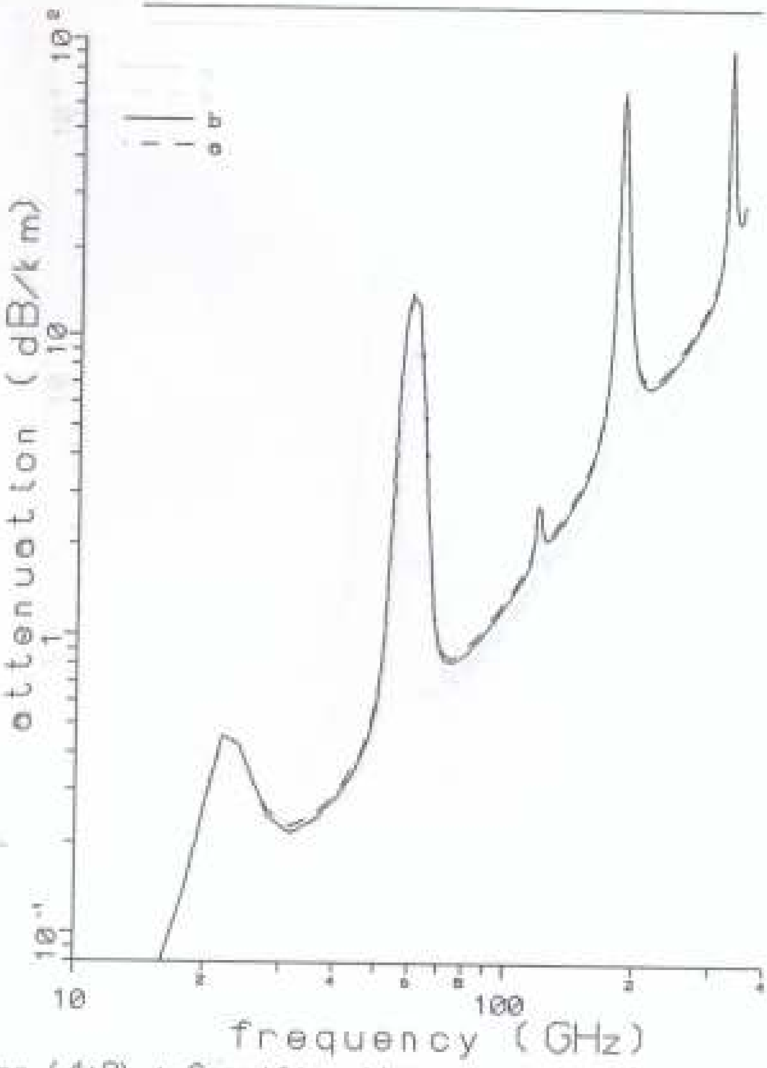


Figure (4:9) : Specific attenuation due Moist air for Wet season at Lagos for the years indicated.

Season	Dry	Wet
Year/curves	1990a	1990b
P hPa	101.3	103.3
RH %	69	79
T °c	31.1	26.9

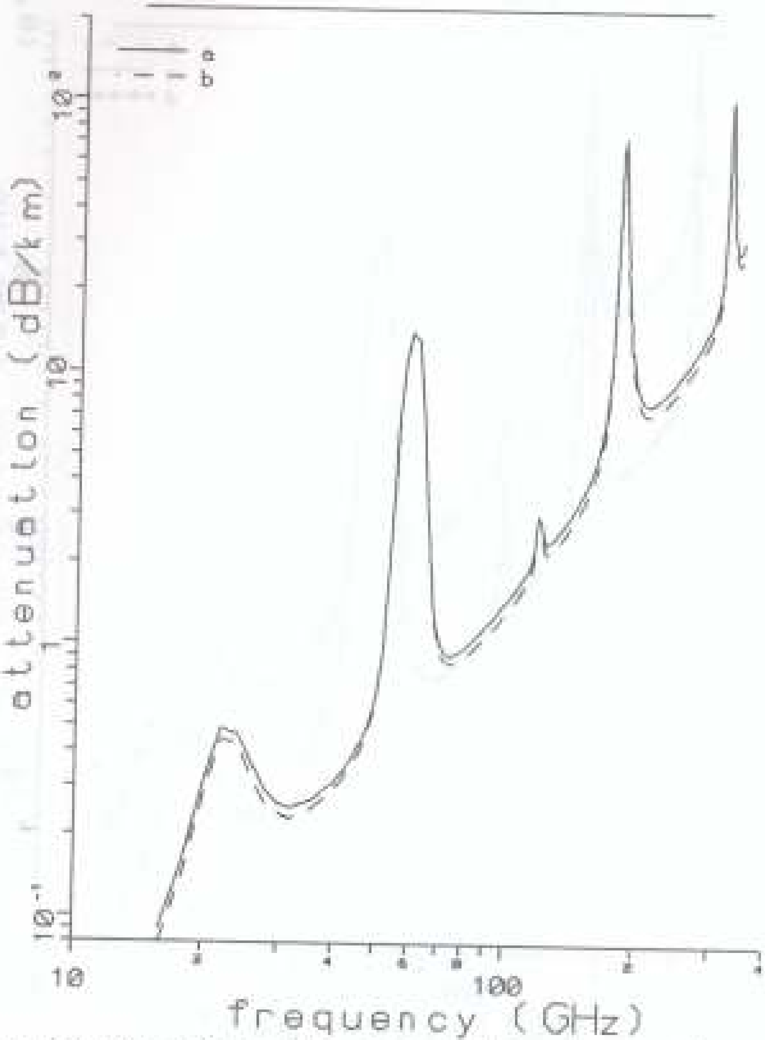
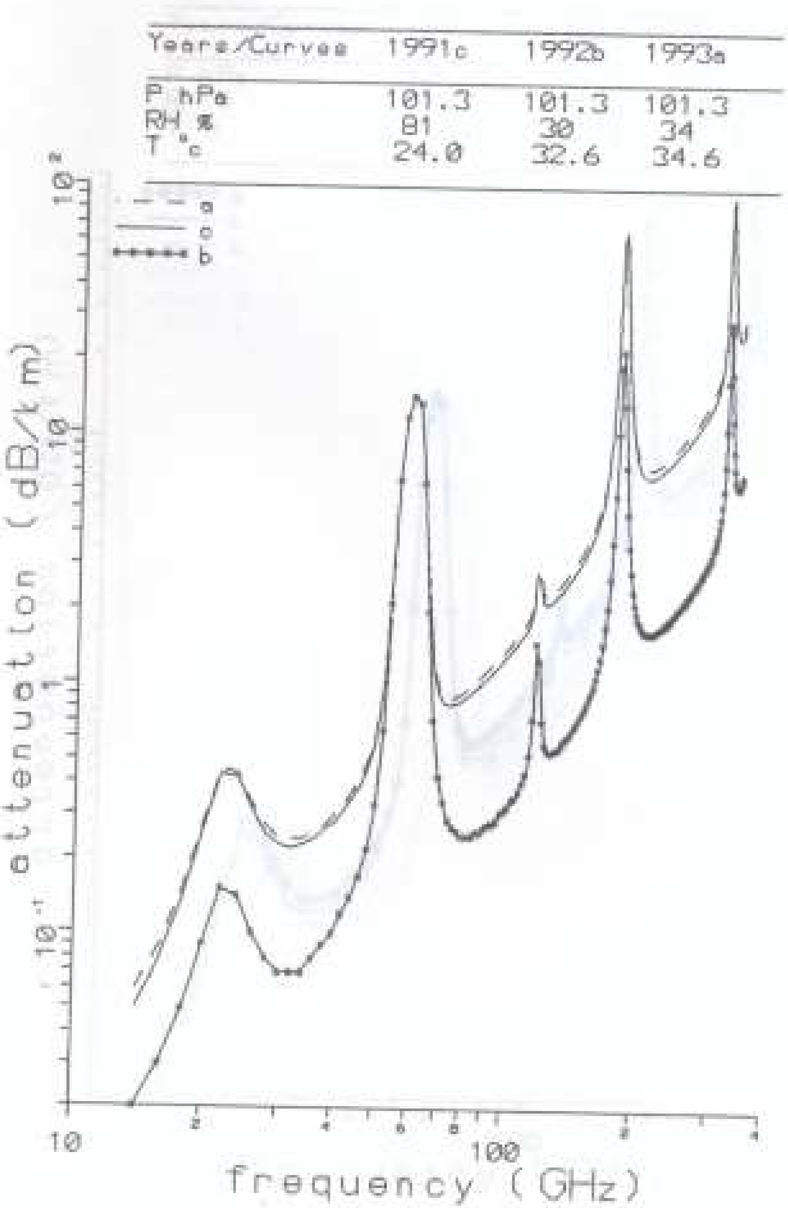


Figure (4.10) : Specific attenuation due to Moist air for Dry and Wet season at Lagos for the years indicated.



Years/Curves	1991c	1992b	1993a
P hPa	101.3	101.3	101.3
RH %	81	30	34
T °c	24.0	32.6	34.6

Figure (4.11): Specific attenuation due to Oxygen and Water vapour for Dry season at Akure for the years indicated.

Years/Curves	1991a	1992b	1993c
P hPa	101.3	101.3	101.3
RH %	73	78	85
T °c	12.0	27.3	28.8

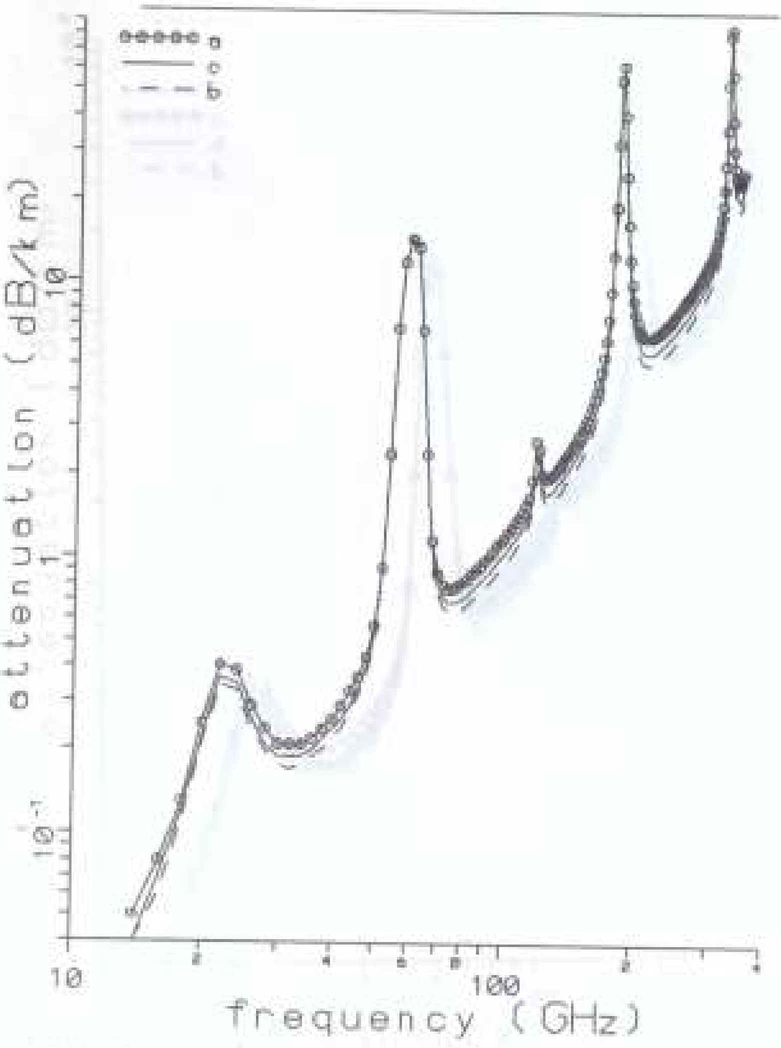


Figure (4.12): Specific attenuation due to Moist air for Wet season at Akure for the years indicated.

Seasons	Dry	Wet	Dry	Wet
Years/Curves	1991d	1991b	1992a	1992c
P hPa	101.3	101.3	101.3	101.3
RH %	81	73	30	78
T °c	24.0	12.0	32.6	27.3

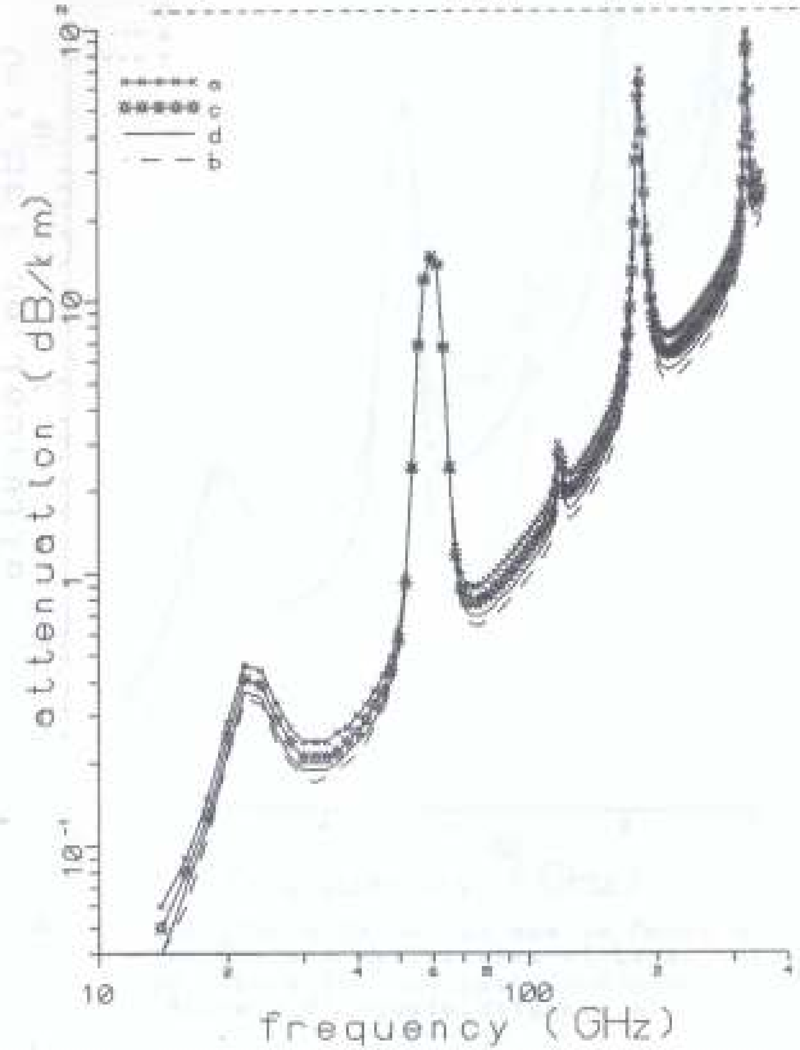


Figure (4.13): Specific attenuation due to Moist air for Dry and Wet seasons at Akure for the years indicated.

Seasons	Dry	Wet	Dry	Wet	Dry	Wet
Years/Curves	1990a	1990f	1966b	1966d	1981c	1981e
P hPa	100.2	100.3	100.2	100.3	95.9	95.9
RH %	81	73	30	78	16	66
T °c	24.0	12.0	32.6	27.3	29.2	28.4

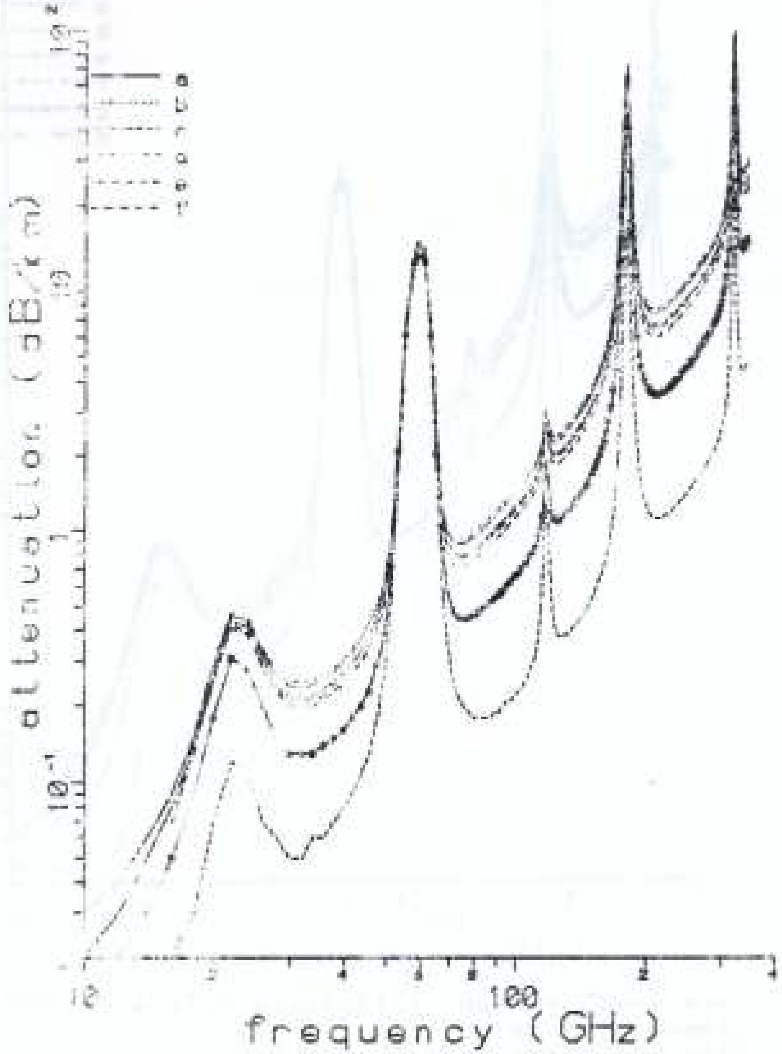
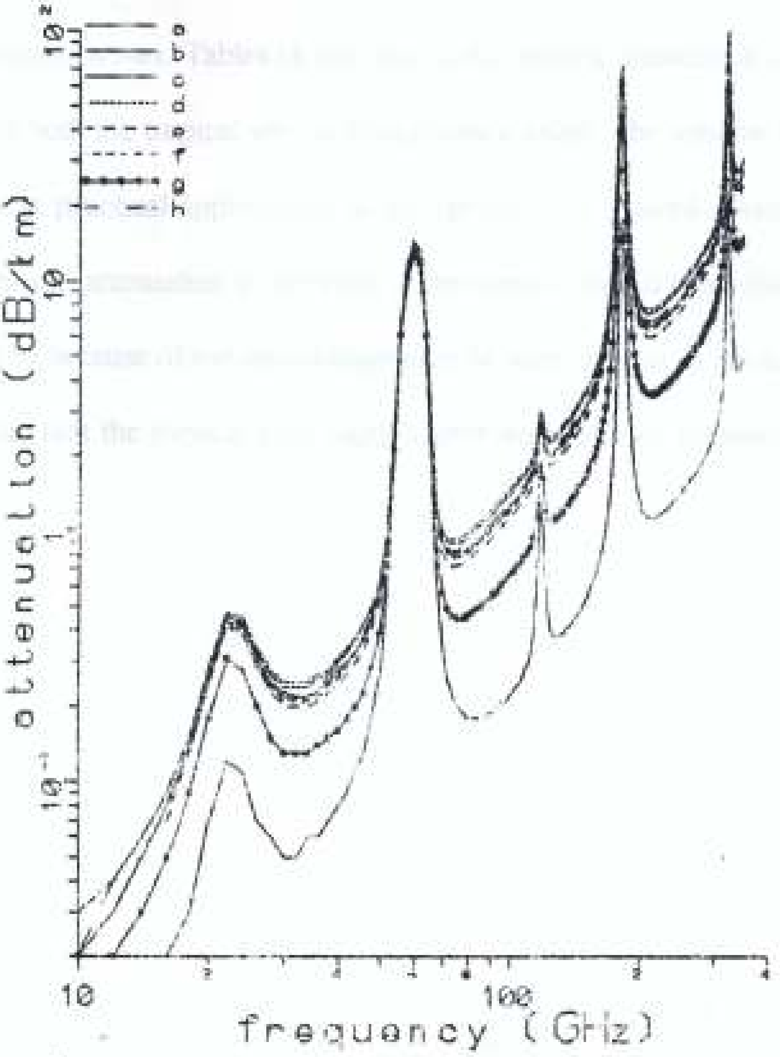


Figure (4.14): Specific attenuation due to Moist air for Dry and Wet seasons at Lagos, Kano and Azure for the years indicated. (Azure:a,f:Lagos:b,d:Kano:c,e)

Seasons	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Years/Curves	1990a	1990f	1966b	1966d	1981c	1981e	1981g	1981
P hPa	100.2	100.3	100.2	100.3	96.9	96.9	98.2	98.2
RH %	81	73	30	78	16	66	26	72
T °c	24.0	12.0	32.6	27.3	29.2	28.4	37.6	28.1



igure (4.15) : Specific attenuation due to Moist air for Dry and Wet seasons at Lagos,Kano, Akure and Minna for the years indicated. (Akure:a,f;Lagos:b,d;Kano:c,e;Minna:g,h)

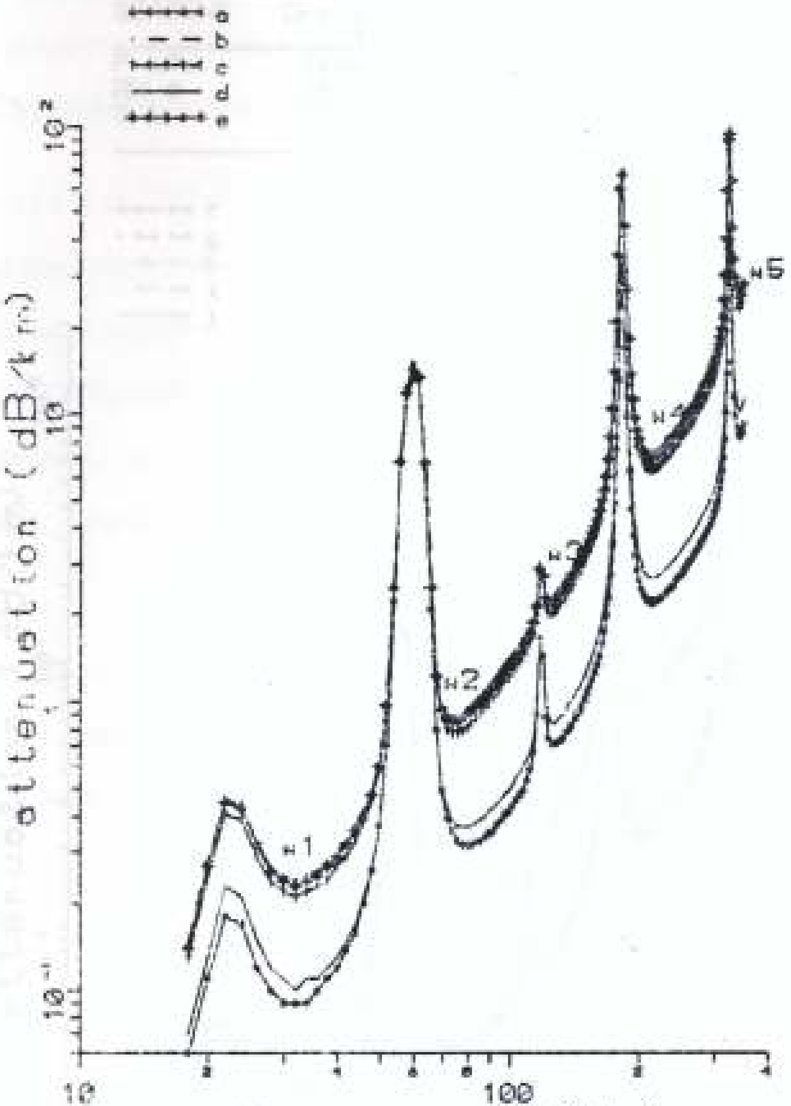
4.2 COMPARATIVE ANALYSIS

A typical ITU meteorological parameters of pressure (101.3 hPa), temperature (20.0 ° C) and water vapour pressure (10mb) for temperate climate were employed to compute specific attenuation. Graphical presentations of this together with that from the tropical sites are shown in figures (4.16) and (4.17). From these graphs, one can see the atmospheric window ranges, w_1-w_4. Tables (4.10) depicts the specific attenuation at the nearly transparent bands for both the tropical sites and temperate climate. The window regions frequency find use for most practical applications in the operation of ground -based systems.Generally, for wet season, attenuation at 326 GHz in the tropical sites is twice that from temperate region. This is so because of uneven concentration of water vapour in the atmosphere. Observations show also that the tropical sites enjoy higher water vapour pressure than the temperate climate.

TABLE (4.10) : RANGES OF SPECIFIC ATTENUATION AT THE WINDOWS

WINDOW	WINDOW RANGE FREQUENCY (GHz)	ATTENUATION RANGE (dB/Km)				
		TROPICAL				TEMPERATE
		AKURE	LAGOS	MINNA	KANO	
W1	24-52	0.44-0.99	0.47-0.99	0.20-0.69	0.21-0.70	0.18-0.71
W2	68-116	1.27-2.22	1.28-2.29	0.78-0.93	0.80-0.97	0.80-0.91
W3	122-180	2.37-36.69	2.45-38.66	0.93-15.36	0.98-16.31	0.89-13.24
W4	192-316	14.33-25.98	15.09-27.46	5.39-9.49	5.75-10.14	4.71-8.15
W5	338-350	28.74-29.60	30.31-31.14	10.40-28.40	11.12-11.29	9.01-9.23

SITES	TROPICAL				TEMPERATE
	AKURE		KANO		
SEASONS	Dry(d)	Wet(e)	Dry(f)	Wet(g)	(a)
	1990		1983		
P hPa	1atm	1atm	1 atm	1atm	1atm
RH %	83	82	26	78	44
T °c	26.5	24.5	34.0	27.1	20.0



Figure(4.16): Specific attenuation due to Moist air for both temperate and tropical sites.

SITES	TROPICAL				TEMPERATE
	MINNA		LAGOS		
SEASONS	Dry(g)	Wet(h)	Dry(i)	Wet(j)	(f)
	1990		1990		
P hPa	1atm	1atm	1 atm	1atm	1atm
RH %	25	76	69	79	44
T °c	33.6	27.1	31.1	26.9	20.0

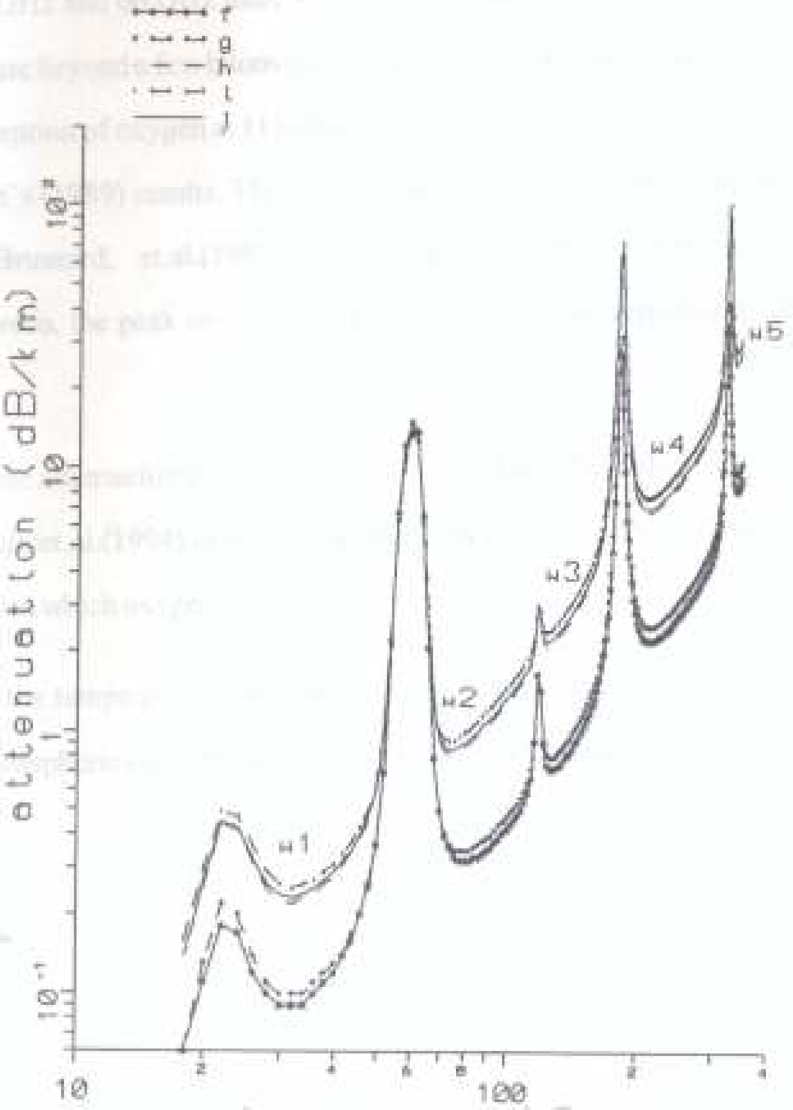


Figure (4.17): Specific attenuation due to Moist air for both temperate and tropical sites.

4.3 : DISCUSSIONS AND CONCLUSIONS

4.3.1 OXYGEN ABSORPTION

The absorption of oxygen up to 52 GHz is small. This is due to the constant concentration of oxygen in the atmosphere. This observation is in agreement with what was obtained for the Italian climate by Barbaliscia et.al. (1994).

Between 54 GHz and 66 GHz there are series of resonant absorption lines which can guarantee frequency reuse beyond a few kilometres without the risk of co-channel interference . The observed isolated absorption of oxygen at 118 GHz (0.93-1.03dB/km) agrees perfectly with Liebe's (1989) and McEwan's (1989) results. The result obtained by other authors are in line with the current evaluation.[Brussard, et.al.(1995) Barbaliscia et.al. (1994) , Watson, (1989) , ITU-R,719-3 (1990)]. Moreso, the peak oxygen attenuation at 60GHz corresponds to approximately 13- 14 dB/km.

At 50 GHz the attenuation is approximately 0.3 dB/km . This value is smaller than that obtained by Barbaliscia et.al.(1994) as a result of the differences in climatic conditions of pressure and temperature on which oxygen attenuation depends.

At 60 GHz the temperate climatic attenuation is approximately the same for the tropical sites since the atmospheric concentration of oxygen is more or less constant.

4.3.2 : WATER-VAPOUR ABSORPTION

There are water vapour resonant absorption lines at 22 GHz ,184 GHz ,326 GHz . The first of these has the weakest absorption spectrum ranges between 0.11dB/km and 0.48dB/km, 0.41dB/km and 0.50dB/km for dry and wet seasons respectively. Water vapour presents a weaker spectrum at 184 GHz. At this frequency the dispersion is about 17-73 dB/km for dry season and 64 -76 dB/km for wet season. The strongest line at 326 GHz exhibits variations between 23- 94 dB/km and 88 -106 dB/km for both dry and wet seasons respectively .

For the temperate climate, specific attenuation is 0.18 dB/km at 22 GHz, while at 184GHz and 326 GHz it is respectively about 27dB/km and 36 dB/km. Therefore it is concluded that tropical attenuation is greater than that of typical ITU temperate climate.

Water vapour spectrum has been reported at 325GHz ,183 GHz , 183.3 GHz and 22.3 GHz. [Ajayi, et.al.,1996, Liebe, 1989 , Barbaliscia et.al. ,1994 , McEwan, 1989 , Brussard, et.al.,1995 , Westwater, 1994].

Specific attenuation at 183.3, 325 and 22.3 GHz has been found to correspond to 40 dB/km, 50 dB/km and to less than 0.2 dB/km in that order. Any differences in results, however, could be blamed on the variability of atmospheric water vapour content.

CHAPTER FIVE

5.1 SUMMARY

The main results from the present work are as follows:

* Oxygen has an isolated resonant absorption line at 118 GHz together with series of absorption spectral lines between 54-66 GHz, the peak of this is at 60 GHz.

* Attenuation by oxygen varies slightly consequent upon constant concentration of oxygen in the atmosphere.

* Water vapour has three resonant absorption lines; these are 22,184,326 GHz . The weakest and the strongest lines are 22 GHz and 326 GHz respectively.

* Attenuation during wet season is higher than that of the dry season .This is largely due to the strong dependence of attenuation on humidity.

* Attenuation at tropical latitudes is generally higher than at temperate latitudes . For the wet season, at 326 GHz, attenuation is two times smaller in the temperate region than in the tropical sites.

* Attenuation exhibits direct dependence on relative humidity ,pressure and frequency, while it shows an inverse relationship with temperature.

5.2 CONCLUSION

The knowledge of gaseous attenuation engendered by oxygen and water vapour is of ultimate importance in planning and predicting transmission and reception of radiowave signals. The results of the present study indicate the significance of local climatic influences on microwave signals.

For a complete characterisation of atmospheric attenuation , however, there is the need to know the influence of cloud and rain on transmitted signals. This is a fertile area of research work in the tropical region yet to receive adequate research attention.

REFERENCES

1. Ajayi,G.O.,Feng.S,Radicella S.M,and Reddy B.M(1996),Handbook on Radio propagation related to satellite in Tropical and Subtropical Countries. pp.1-72.

2. Ajayi,G.O. and Kolawole, L.B. (1984), Centimeter and Millimeter wave attenuation by atmospheric gases and rainfall at a tropical station, International journal of infrared and millimetre waves, vol.5,no. 7. pp.919-935.

3. Barbaliscia,F., Mascullo.P., Carlo C. and Ada B.(1994), Modelling the atmospheric attenuation by means of meteorological parameters, Alta Frequenza Rivista Di Elettronica Vol.6, no.6. pp.101 -105.

4. Barbaliscia,F., Mascullo.P., Carlo C. and Ada B.(1994), Meteorology Parameters of the non-rainy atmosphere, Alta Frequenza Rivista Di Elettronica Vol.6, no.6; pp.76-80.

5. Banwell,C.N. (1972), Fundamentals of molecular spectroscopy, McGraw-Hill Book company (U.K) Ltd., 2nd.ed. pp.23-27,158-161.

6. Bean,B.R. (1962), The radio refractive index of air. Proc. IRE,50 no.3, pp. 260-273.

7. Bean,B.R.and Dutton, E.J. (1968), Radio Meteorology, Dover Publications Inc. N.Y, pp. 269-309.

8. Bransden,B.H. and Joachain, C.J. (1988), Introduction to Quantum Mechanics, Longman scientific and Technical N.Y, pp. 490- 514.

9. Brussard,G.,Watson,P.A.,Leyten,L.,Paptsoris,A.,Van de Kamp,M.M.J.L. and Herben,M.(1995),Atmospheric Modelling and Millimetre Wave Propagation (Final report):Education Eindhoven.

10. Eisberg, R.M. (1961), Fundamentals of modern Physics . John Wiley & Sons Inc.N.Y. pp. 453- 472.

11. Emery,R.J.,Zavody,A.M.andGibbie,H.A.(1980),Measurementsof atmospheric absorption in the range 5-17cm and its temperature dependence, Journal Atmospheric Terrestrial Physics, 42,pp.801-807.

12. Encyclopaedia Americana (1989), Inc. Ed.Grolier Incorporated vol.10 & 19, pp. 55,159.

13. Hall,M.P.M.(1989),Overview of radiowave propagation, Radiowave Propagation edited by Hall, M.P.M & Barclay, L.W. IEEE series.pp.1-21.

14. Hill,R.J.,Lawrence,R.S.and Priestley,J.T.(1982),Theoretical and calculational aspects of the radio refractive index of water vapour,Radio Science. vol.17, no.5,pp.1251-1257.

15. ITU-R 719-1(1982), Attenuation by atmospheric gases.

16. ITU- R 719-3(1990), Attenuation by atmospheric gases.

17. Karl,L.and Zouli, B., (1993), Radio wave propagation measurements in Burkina- Faso. SMK.ICTP,Trieste, Italy.pp.1-12.

18. Kolawole,L.B.(1993), Radiowave Propagation in Tropical Regions,S.M.K. ICTP,Trieste,Italy.

19. Liebe,H.J.(1981),Modeling Attenuation and phase of Radio waves in air at frequencies below 1000GHz, Radio Science, vol. No.6,pp.1183-1199.

20. Liebe, H.J. (1983), An Atmospheric Millimetre wave propagation model, NTIA-R 83-137.

21. Liebe,H .J. (1989), M.P.M -An Atmospheric Millimeter - Wave Propagation Model, International Journal of infrared and millimeter waves, vol.10,no.6.

22. Linus,P.and Bright,E.W. (1935), Introduction to Quantum Mechanics. McGraw -Hill Book Company, pp.299-314.

23. Lucien,B.(1987), Radio wave Propagation, McGraw Hill Book Company; Montreal Toronto.

24. McEwan, N.J. (1989), Nature of Precipitation, cloud and atmospheric gases and their effects on propagation mechanisms from VHF to millimeter waves , Radiowave Propagation, edited by Hall, M.P.M & Barclay , L.W. IEEE series.

25. McIntosh,D.H. and Thom, A.S. (1983), Essentials of Meteorology, Taylor and Francis Ltd. London, 6th. ed.,pp. 1-40.

26. Rice,D.P and Ade,P.A.(1979), Absolute Measurements of the Atmospheric Transparency at short Millimetre wavelengths, Infrared Physics, 12, pp.575-584.

27. Rosenkranz,P.W.(1975), Shape of the 5mm Oxygen Band in the Atmosphere, IEEE Trans. Ant. Prop. AP-23,no.4,pp.498-506.

28. Rotheram, S. (1989), Clear air aspects of the troposphere and their effects on propagation mechanisms from VHF to millimetre waves, Radiowave Propagation, edited by Hall, M.P.M & Barclay , L.W. IEEE series.pp.150-153.

29. Samuel Liao.Y. (1989), Microwave Devices and Circuits, Prentice-Hall Inc. 2nd.ed.,pp.1-4.

30. Savelyev.I.V.(1979), Electricity and magnetism waves optics. Physics: A General Course, Mir Publishers ,pp.304-310.

31. Semat, H. and Albright, J.R. (1971), Introduction to Atomic and nuclear Physics. 5th. ed., London Chapman and Hall, pp. 205-269.

32. Smith, E.K. and Weintraub, S. (1953), The Constants in the equation for atmospheric Refractive index at radio frequencies. Proc. IRE 41, pp.1033-1037.

33. Thewlis, J.(1979),Concise Dictionary of Physics. Pergamon Press Oxford 2nd.ed.pp.50-96.

34. The Oxford Reference Dictionary (1986), Oxford University Press, pp.529.

35. The Encyclopaedia of Physics (1974), Edited by Robert, M.B . Litton Education Publishing Inc. 2nd.ed. pp. 575-600.

36. Vakser I.KH ,Malyshenko Yu.I.and Kopilovich L.E.(1970), The effect of rain on the millimetre and submillimetre radio wave distribution. Journal of Atmospheric and oceanic Physics ,vol.6, no.1. pp.123-230.

37. Waters,J.R.(1976), Absorption and Emission by Atmospheric Gases, Methods of Experimental Physics 12B, edited by M.L.Meeks, chapter 2.3,Academic Press, New York.

38. Watson,P.A. (1989), Earth-space Propagation Path Predictions from VHF to Millimeter Waves , Radiowave Propagation edited by Hall, M.P.M & Barclay , L.W. IEEE series. pp.211-215.

39. Westwater, R., Ermanno,F. and Martellucci,A. (1994), Duration analysis of radiometric measurements at 20.6, 31.6, 52.8 GHz, Alta Frequenza Rivista Di Elettronica. Vol.6, No 6, pp. 81-85.

40. Yavorsky, B. and Detlaf,A. (1975), Handbook of Physics, Mir Publisher.

APPENDICES

APPENDIX A

```
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c                                                                               c
c       CHEER.FOR: A PROGRAM TO COMPUTE SPECIFIC ATTENUATION                    c
c                                                                               c
c       AUTHOR: ADENUGBA,DAVID                                                  c
c                                                                               c
c       PURPOSE: THIS PROGRAM COMPUTES AND OUTPUTS SPECIFIC ATTENUATION         c
c                                                                               c
c       FILE FORMAT:                                                            c
c                  GEN2=OXYGEN SPECTROSCOPY                                     c
c                  WATV2=WATER VAPOUR SPECTROSCOPY                              c
c                  TEM11.DAT=METEOROLOGY PARAMETER OF PRESSURE,TEMPERATURE      c
c                            AND RELATIVE HUMIDITY                              c
c                  TEMM.DAT=OUTPUT FILE                                         c
c       VARIABLES USED: These are some of the important variables used.         c
c                  s=Line Strength for Oxygen,KHz.                              c
c                  p=Pressure,kPa                                               c
c                  xt2=Temperature,oC                                           c
c                  rh=Relative Humidity,%                                       c
c                  sw=Line Strength for water vapour                            c
c                  wl=Line width for water vapour                               c
c                  ey=water vapour partial pressure,kPa                         c
c                  vcon=vapour concentration                                    c
c                  xul=Line width for Oxygen                                    c
c                  xf1 & xf2=Centre line frequency                              c
c                  xnt=Interference for Oxygen                                  c
c                  xnp=Dry air continuum                                        c
c                  xne=Wet continuum                                            c
c                  xt3=Relative Inverse Temperature,K                           c
c                  pro=Specific Attenuation,dB/km                               c
c                  zd=Specific attenuation for dry air,dB/km                   c
c                  zw=Specific attenuation for water vapour,dB/km               c
c                  zo=Specific attenuation for moist air,dB/km                  c
c                  a11-a66=Permanent spectroscopic coefficient for Oxygen       c
c                  b11-b66=Permanent spectroscopic coefficient for water vapour c
c                                                                               c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

       real rho,rh1,rh2,u1,u2,u3,u4
       intrinsic exp
      dimension s(44),sw(30),xul(44),wl(30),xf1(44),xf2(30),xnt(44)
      dimension a11(44),a22(44),a33(44),a44(44),a55(44),a66(44)
      dimension b11(30),b22(30),b33(30),b44(30),b55(30),b66(30),
     *xt2(10),rh(10),p(10)
      open(1,file='tem1',status='new')
      open(3,file='gen2',status='old')
      open(5,file='watv2',status='old')
      open(8,file='tempe.dat',status='old')

      write(*,*)'RANGE OF FREQUENCY TO READ'
       write(*,*)'nc,  nb,  nx '
       read(*,*)nc,nb,nx
```

```
c        cccccccccccccccccccccccc
c        c                      c
c        c    READING IN DATA   c
c        c                      c
c        c ccccccccccccccccccccc

          do 30 nk=1,10
          read(8,88)P(nk),rh(nk),xt2(nk)
 30         continue

           do 10 i=1,44
      read(3,33)xf1(i),a11(i),a22(i),a33(i),a44(i),a55(i),a66(i)
 10         continue

           do 70 m=1,30
      read(5,55)xf2(m),b11(m),b22(m),b33(m),b44(m),b55(m),b66(m)
 70              continue

c      ccccccccccccccccccccccccccccc
c      c                           c
c      c  PRELIMINARY CALCULATIONS c
c      c                           c
c      ccccccccccccccccccccccccccccc

          do 50 np=1,10
         xt1=xt2(np)+273.15
         xt3=300.0/xt1
         q1=-22.64*xt3
         q2=exp(q1)
         q3=10**9
         eu=(1.739/7.223)*rh(np)*(xt3**4)*q2*q3
         vu=eu
         x2=p(np)
         x1=x2/10.0
       vcon=7.223*vu*xt3
         s1=xt3**3
         s2=1.0-xt3
         y2=xt3**3.5
         u1=1.1*vu*xt3
         u2=xt3**0.8
         u3=x1*u2

c       cccccccccccccccccccc
c       c                  c
c       c   DRY CONTINUUM  c
c       c                  c
c       cccccccccccccccccccc

         ad=6.14*1.0E-4
         an=1.4*1.0E-10
         ao=(x1+(1.1*vu))*xt3
         am=5.6*1.0E-3
         ax=1.2*1.0E-5
```

```
         q6=x1*xt3*xt3
        qam=qm*qc
        qaq=qam*qam
         ad=ao*q6
         qt=x1*x1*y2

c       cccccccccccccccccccccc
c       c                    c
c       c   WET CONTINUUM    c
c       c                    c
c       cccccccccccccccccccccc

          b6=0.113
         baa=xt3**1.5
          ba=3.57*baa
         bv1=yu*x1*1.0E-5
         bv2=ba*yu
         bv3=b6*x1
         bv4=bv2+bv3
          xc=xt3-1.0
         xct=xc*xc
          6o=20.09-(142.0*xc)+(294.0*xct)
          6a=590.0-(1500.0*xc)
         xao=77.66+(103.3*xc)
         xe1=5.48
         xe2=3.51

           do 90 j6neq=nc,nb,nx
         xne=j6neq*bv4*bv1
            qn=j6neq**1.5
            qd=qa*qn
            ap=aa*(1.0-qd)
            qu=ap*j6neq*qt
            qp=(j6neq*j6neq)/qaq
            qq=qam*(1.0+qp)
            qg=(ad*j6neq)/qq
           xnp=qg+qu
           cx=xnp+xne

c          cccccccccccccccccccccccccccccccccc
c          c                                c
c          c   SUMMING  FOR OXYGEN STARTS   c
c          c                                c
c          cccccccccccccccccccccccccccccccccc

            aum=0.0
         do 60 j=1,44
        xc3=a11(j)*x1*x1
        xc4=a22(j)*x2
        xc5=exp(xc4)
       a(j)=xc3*xc5*1.0E-6
        xu5=a33(j)*1.0E-3
         u4=x1*(xt3**(0.8-a44(j)))
      xut(j)=xu5*(u4+u1)
        xv1=u3*1E-3
```

```
      xnt(j)=(a55(j)+(a66(j)*xt3))*xv1

c        cccccccccccccccccccccccccccccc
c        c                            c
c        c   SHAPE FACTOR FOR OXYGEN  c
c        c                            c
c        cccccccccccccccccccccccccccccc

                  go=x61(j)-j6xeq
                  g1=go*go
                  g2=x61(j)+j6xeq
                  g3=g2*g2
                  g8=j6xeq/x61(j)

c        cccccccccccccccccccccc
c        c                    c
c        c   INTERFERENCE XNT c
c        c                    c
c        cccccccccccccccccccccc
                 g10=xnt(j)*g8
              a1=(xut(j)*j6xeq)/x61(j)
                u4q=xut(j)*xut(j)
                 g14=g1+u4q
                 g15=g3+u4q
                 g12=go/g14
                 g13=g2/g15
                 g16=a1/g14
                 g17=a1/g15
                 g18=g16+g17
                dg19=g18-(g10*(g12+g13))
                yeo=a(j)*dg19
                dum=dum+yeo
 10             continue

c        cccccccccccccccccccccccccccccccccccccc
c        c                                    c
c        c   SUMMING FOR WATER VAPOUR STARTS  c
c        c                                    c
c        cccccccccccccccccccccccccccccccccccccc

              sud=0.0
             do 20 k=1,30
             y3=b11(k)*ya*y2
             y4=b22(k)*x2
             y5=exp(y4)
          sw(k)=y3*y5
             w1=b33(k)*1E-3
             w2=a1*(xt3**b44(k))
             w3=b55(k)*ya*(xt3**b66(k))
          wt(k)=w1*(w2+w3)

c        cccccccccccccccccccccccccccccccccccccc
c        c                                    c
c        c   SHAPE FACTOR FOR WATER VAPOUR    c
c        c                                    c
c        cccccccccccccccccccccccccccccccccccccc
```

```
                  q4=xf2(k)-jfreq
                  q5=q4*q4
                  q6=xf2(k)+jfreq
                  q7=q6*q6
                a2=(w1(k)*jfreq)/xf2(k)
                 q20=q5+(w1(k)*w1(k))
                 q21=q7+(w1(k)*w1(k))
                 q22=a2/q20
                 q23=a2/q21
                 fq24=q22+q23
                 yes=sw(k)*fq24
                 sud=sud+yes
  20            continue

c         cccccccccccccccccccccccccccc
c         c                          c
c         c   COMPUTING ATTENUATION  c
c         c                          c
c         cccccccccccccccccccccccccccc

              pro=0.1820*jfreq
               zd=(sum+xnp)*pro
               zw=(sud+xne)*pro
               za=zd+zw

c         cccccccccccccccccccccccccccccccccc
c         c                                c
c         c      OUTPUTTING FREQUENCY      c
c         c     AND SPECIFIC ATTENUATION   c
c         c                                c
c         cccccccccccccccccccccccccccccccccc

               write(1,66)jfreq,za,zd,zw
  90           continue
  50            continue

  33      format(f11.6,f16.2,f9.3,f8.2,f8.1,2f7.3)
  55      format(f15.6,f11.4,f10.3,f10.2,f7.2,f6.2,f7.2)
  88      format(f4.0,f3.0,f5.1)
  66      format(f5.0,2x,3f8.2)

                  stop
                  end
```

```
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c      CHEER2.FOR: PROGRAM TO OUTPUT SPECIFIC ATTENUATION    c
c                       IN THE FORM REQUIRED                 c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

       integer f(1710)
       Dimension ay(1710),xd(1710),xw(1710)

       open(1,file='sow',status='old')
       open(2,file='tdry.dat',status='new')
       open(3,file='twet.dat',status='new')

               do 70 kb =1,1710
          read(1,88)f(kb),ay(kb),xd(kb)
 70                 continue

           do 90 jc=1,171
              jx=jc+171
              jy=jx+171
              ju=jy+171
              jr=ju+171
              jq=jr+171
              jz=jq+171
              jm=jz+171
              jf=jm+171
              jt=jf+171

      write(2,89)f(jc),ay(jc),ay(jx),ay(jy),ay(ju),ay(jr),ay(jq),
     *ay(jz),ay(jm),ay(jf),ay(jt)
       write(3,89)f(jc),xd(jc),xd(jx),xd(jy),xd(ju),xd(jr),xd(jq),
     *xd(jz),xd(jm),xd(jf),xd(jt)

  90          continue
  88        format(I5.0,2x,3f8.2)
  89        format(I5.0,2x,10f8.2)

                      stop
                      end
```