ATMOSPHERIC REFRACTIVITY PROFILE FOR MICROWAVE COMMUNICATION IN BNAGLADESH

বাংলাদেশ প্রকৌশল বিশ্ববিদ্যালয়
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DECLARATION

I do hereby declare that neither this thesis nor any part thereof has been submitted or being concurrently submitted in candidature for the award of any degree or diploma at any other university.

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The thesis titled "Atmospheric Refractivity Profile for Microwave Communication in Bangladesh" is accepted as satisfactory in partial fulfilment of the requirements for the degree of Master of Science in Engineering (M.Sc.Engg.) in Electrical and Electronic Engineering of Md. Altaf Hossain, Roll.No. 871328F, Session:1985-86.

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ABSTRACT

Atmospheric refractivity or radio refractive index(RRI) plays an important role in microwave propagation. This refractivity is not a fixed factor at a particular place over a time. An extensive study is done in this thesis on radio refractive index for thirty locations of Bangladesh over four seasons of a year. Variations of RRI at different places of Bangladesh over a year and also the distribution of RRI for some places for a particular season are shown. Maximum and minimum RRI of each season over eleven years for thirty locations are presented through bargraphs and tables. Contours of RRI are drawn as RRI profiles for Bangladesh for the months of January, April, July and October representing the four seasons using average RRI of eleven years. RRI variations with height from the earths' surface is shown for the radiosonde stations like Dhaka, Chittagong and Bogra. Some empirical formulas of refractive index for four seasons are developed here from which refractivity gradients for the first kilometer from earth surface are found out.

A correlation between surface RRI and refractivity gradient for the first kilometer from earth surface is also established over a year. Such type of relations are also foundout for Bangladesh for different seasons and for some places over a year.

Finally, the bending of a radio ray is calculated using surface refractivity and its gradients for different launching angles.

LIST OF SYMBOLS AND ABBREVIATIONS

ENGLISH LETTERS

a	=	Radius of Earth
a'	=	Effective Earth Radius
C_p'	=	Specific heat of gas at constant pressure.
C_v'	=	Specific heat of gas at constant volume
d	=	Distance between two points
d'	=	Arc distance
e	=	Partial pressure due to water vapour
E_r	=	Pressure of water vapour which will saturate air at a given temperature
g	=	Acceleation due to gravity.
H	=	Absolute humidity
h	=	Height
K	=	a/a
M	=	Modified Radio Refractive Index
m	=	Mass of dry air
m'	=	Air mass
m''	=	Dipole-moment of molecules of water vapour $= 613 \times 10^{-30}$ coloumb-meter.

N	=	Radio Refractive Index or Refractivity.
n	=	Refractive Index
P	=	Atmospheric pressure (mbar)
R	=	Radius of curvature of ray
R'	=	Universal gas constant = 8.314×10^7 ergs/mole ^oK
r	=	Radial distance from the centre of the earth
R_H	=	Relative humidity
S	=	Specific humidity
T	=	Absolute temperature (^oK)
t	=	Atmospheric temperature (^oC)
V	=	Volume of air
Z	=	Ratio of reflected oscillation to the incident oscillation.

GREEK LETTERS

α	=	Relative phase shift
β	=	Phase of reflection
γ	=	Angle at the earth centre by the arc distance
δ	=	Path difference (between reflected and direct ray)
μ	=	Number of fresnel zone
θ	=	Elevation angle of ray
λ	=	Wave length
ρ	=	Gas density
ρ'	=	Modulous of reflection Co-efficient
τ	=	Amount of bending of radio ray
ϕ	=	Angle of incident ray

ABBREVIATIONS

LOS	-	Line of Sight
RRI	-	Radio Refractive Index
BGR	-	Bogra
BLA	-	Bhola
BSL	-	Barisal
CML	-	Comilla
CND	-	Chandpur
CTG	-	Chittagong
CXB	-	Cox-s-Bazar
DAK	-	Dhaka
DJP	-	Dinajpur
FNI	-	Feni
FRD	-	Faridpur
HTA	-	Hatia
ISD	-	Ishurdi
JSR	-	Jessore
KHL	-	Khulna
KHP	-	Khepupara
KTB	-	Kutubdia
MDR	-	Madaripur
MYM	-	Mymensingh

MZD - Maizde Court
PTK - Patuakhali
RNG - Rangpur
RJS - Rajshahi
RMT - Rangamati
SLT - Sylhet
SML - Shrimangal
SNP - Sandwip
STD - Sitakundu
STR - Satkhira
TNF - Teknaf
JA - January
FB - February
MR - March
AP - April
MA - May
JU - June
JL - July
AG - August
SP - September
OC - October
NO - November
DC - December

CONTENTS

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CHAPTER - 1

INTRODUCTION

1.1 Introduction

A major task for the radio communication system design is to be able to predict the behaviour of the radio signal from the point of transmission to the receiving point. Preliminary calculations, before the system design is embarked upon, involve the signal strength expected at the receiving point, its behaviour with time and the probability of interference between a given system and another system operating on the same or adjacent frequency channel. The parameters involved fall into two categories. The first category are parameters within the control of the design engineer, such as the transmitter power, frequency, type of signal modulation, type of antenna structure and the sites of transmitter and receiver. The second category are parameters that are usually not within the control of the designer such as the nature of the terrain over which the propagation is to be made and the nature of the propagation medium. A reliable communication system can only be obtained after all relevant parameters are calculated and this, therefore, calls for proper preliminary survey of the propagation path.

Communication links operating at frequencies within the VHF, UHF and upto microwaves depend very much on the propagation conditions at the earth's lower atmosphere i.e. the troposphere. The geometry of the path travelled by the radio wave depends mostly on the vertical distribution of the atmospheric refractive index. Standard field strength prediction methods therefore depend on an accurate knowledge of the time and spatial variations in the value of this refractive index.

The radio refractive index (RRI) is central to all theories of radio wave propagation through the lower atmosphere ie. the troposphere. At shorter distances the propagation is controlled by the variability of the RRI of the medium. It is not a fixed factor for the atmosphere i.e. this refractivity value is different at different places in different seasons depending upon the weather condition at that location and time. The main weather constituents which affect the atmospheric refractivity are the atmospheric pressure, temperature and humidity. Consequently the radio refractive index changes from season to season and also the wave propagation characteristics of the atmosphere. Thus for an efficient communication link, a thorough knowledge of RRI of the atmosphere is extremely important and a detailed RRI profile is usually available with CCIR for assisting the designer.

1.2 Necessity of Atmospheric Refractivity Study for Bangladesh

In Bangladesh,telecommunication links have been established between inter-districts using Line-of-sight (LOS) microwave communication system. The LOS microwave communication takes place through propagation within troposphere, and thus the RRI of the troposphere has a definite bearing on microwave transmission. The conditions in the troposphere in the tropical countries vary in different ways over the year. The changes in pressure, temperature and relative humidity take place in different seasons which directly affect the atmospheric refractivity. This directly affects the microwave propagation causing serious signal fading or distortion. To eleminate the signal distortion and to have a good and efficient communication link we should have a clear picture of the atmospheric refractivity and its varation over the year, so that during the design of a communication link we can easily calculate signal variations due to the weather changes over the year and preventive measures can be taken to remove the microwave communication difficulties and have an efficient communication link. In most developed countries atmospheric refractivity studies have already been done and used for design of microwave communication systems. In Bangladesh no such study was carried out before and as such the LOS microwave links have been installed on the basis of general 'thumb-rule' atmospheric conditions. In this thesis an extensive study has been carried out to find out the atmospheric radio refractive index and its varaiations over the year for Bangladesh.

1.3 Brief Discussion on Relevant Studies

Evaluation of atmospheric refraction effects on VHF - UHF radio propagation has long been accomplished with the convenient four-thirds earth concept of Schelling, Burrows and Ferrel [1]. This method has proven particularly useful in evaluating performance of point -to-point radio communication systems. However, relatively new long-range applications have demanded a model of atmospheric radio refractive index more representitive of observed refractive index profiles than the simple linear decay inherent in the four-thirds earth approach. Before that, however, Smyth and Trolese in 1947 investigated the effect of tropospheric layers on the propagation of high frequency radiowaves and proposed a theory which is in agreement with salient propagation characterstics observed on a non optical link. Fields beyond the optical horizon are governed by the layer height and the refractive index change through the layer [2].

Schulkin in 1952 [3] presented a scheme for calculating atmospheric refraction of radio-frequency rays numerically from radiosonde data. He computed ray bending for a range of climatological conditions for rays passing entirely through the atmosphere and arriving or departing tangentially at the earth's surface.

Crain, Deam and Gerhardt [4] measured the fluctuations of radio refractive index with a direct reading microwave refractometer over the Atlantic Ocean and coastal areas near Lakehurst N.J. in April 1951 and over vicinity of wright patterson Field, Dayton Ohio in June 1951 and published profiles of these in 1953.

Smith and Weintraub in 1953 [5] made improvement of the constants of the radio refractive index equation and developed the most widely used equation in their paper.

Bean and Meaney in 1955 [6] had found a consistent correlation between the monthly median values of 100 mc transmission loss and refractivity gradient, determined from standard radiosonde observations.

George H. Millman in 1958 showed [7] the effects of the troposphere and ionosphere on the propagation of VHF and UHF radio waves. He presented tropospheric refractive index profiles and ionospheric electron density models representative of average atmospheric condition and developed mathematical relationship for calculating refraction effects, time delay, attenuation experienced by radio waves traversing the entire atmosphere.

In 1959, Bean and Thayer introduced [8] two models of atmospheric radiorefractive index which can be used to predict refraction effects from the value of the refractive index at the transmitting point. Both models offer considerable improvement over the four-thirds earth model, particularly for applications at long distances and high elevations in the atmosphere. Further, both models may be adjusted to represent mean conditions at different times of year and in different geographical locations.

Weisbrod and Anderson [9] developed some methods for computing the bending of Radio waves due to atmospheric refractivity assuming that the refractive gradient is radial and the refractive index profile was approximated by a finite number of linear segments whose thickness is small compared with the earth´s radius.

In 1962 Bean [10] reviewed the derivation of the classical Debye expression for the radiorefractive index. Constants in this expression were reviewed and made a conclusion that differences between constants are small compared with the error in using standard meterorological data in the formula.

Kazarian, Gurvich, Manucharian and Vartanian [11] in 1970 developed an expression called "structure constant of the refractive index" to characterise the turbulence -induced fluctuations of the refractive index that plays an important role in many problems related to propagation through the atmosphere.

Robertshaw [12] calculated the refraction of radio and microwave propagation paths within 1 Km of the earth's surface, using his effective earth radius model. With the help of this model approximate determinations of grazing angle, ground range and slant range for higher altitude paths can be done. Kolawole [13] showed radio refractivity and atmospheric absorption of centimeter and millimeter waves in different climates of Africa. He also explained seasonal variations of the surface refractivity and developed a relation between surface refractivity and refractivity gradient for that continent.

1.4 Objective and Methodology of the Present Study

The objective of this study is to find out the radio refractive index of lower atmosphere i.e troposphere for Bangladesh in different time of the year and its variations as weather changes. The maximum and minimum values of radio refractive index at a particular place over a month or the average value over the year as well as the changing characterstic of it from season to season will also be studied.

In addition to the surface refractivity, the refractivity at different heights from the earth surface will also be calculated. From these values of Radio Refractive Index (RRI) the refractivity gradient for the first Kilometer from the earth surface will be determined to investigate if there exists any emperical relation between the surface radio refractive index and the refractivity gradient. If any relation is found out between these two values then an emperical equation showing their relationship will be developed for a particular place or for whole of Bangladesh for a particular time of the year or whole.

Finally, it will be investigated how the radio ray refraction takes place due to the radio refractive index and its variation at different places in Bangladesh in different seasons.

The methods adopted here to find radio refractive index, its variations and its effects on microwave communication is described chronologically :-

For the calculation of radio refractive index one requires the values of pressure, temperature and relative humidity at different places and time. In this study the whole year is devided into four seasons depending on the climatic condition of Bangladesh: i) winter or north-east-monsoon (ii) summer or premonsoon (iii) south-west monsoon or monsoon and (iv) Autumn or post monsoon. The pressure, temperature and relative humidity data is collected from Bangladesh Meteorological Department for the months of January, April, July and October, representing the four seasons - winter, summer, monsoon and autumn respectively over a year. The data is collected over a period of eleven years. i.e from 1977 to 1987 as is available at Bangladesh Meteorological Department to have a wide distribution of radio refractive index. Thirty locations of Bangladesh were selected depending on availability of pressure, temperature and relative humidity data to calculate the radio refractive index distribution in each season and variation of maximum, minimum and average radio refractive index over a month and a year.

After obtaining the necessary surface data, the surface refractivity will be computed. The radiosonde data gives the variation of pressure, temperature, relative humidity with the height.Based on these values an empirical relation will be established for the refractive gradient with the surface refractivity for various places at different times of the year. This would generate a refractivity profile of Bangladesh.

Summary

In chapter 2, of this thesis a brief description of the atmosphere and its different layers is given. Also this chapter shows how the atmospheric pressure, temperature and partial pressure due to water vapour change with heights.

Chapter 3 deals with propagation of radiowaves and their classifications, also discussed about the attenuation of radiowave by different constituents of atmospehre.

In chapter 4, a mathematical expression for the radio refractive index is developed in terms of pressure, temperature and water vapour pressure. A calculation is made to find the amount of bending of radio ray in terms of refractivity, refractivity gradient and launching angle.

In chapter 5, variation of radio refractive index is shown by variation of pressure, temperature and relative humidity by simulation method. Radio refractive index is calculated for different locations of Bangladesh using the pressure, temperature and relative humidity data of different seasons and figures are drawn to show variation of RRI.

In chapter 6, RRI is calculated from radiosonde data at different heights from earth surface and several expressions are developed using the surface RRI and refractivity gradient. Also using these values amount of bending of radio wave is calculated.

Conclusions on the present work are presented in chapter 7.

CHAPTER 2

STRUCTURE OF ATMOSPHERE AND VARIATIONS OF DIFFERENT ATMOSPHERIC PARAMETERS

2.1 Introduction

This chapter deals with the structure of the atmosphere and its classification into different layers and their compositions and properties. A detail description of the lowest atmospheric layer i.e. troposphere is depicted in this chapter. Through this layer microwave communication takes place and our main goal is to find the refractivity of the atmosphere for microwave propagation. The pressure, temperature and relative humidity of the atmosphere are related with the atmospheric refractivity and thus their variations have definite effect upon the refractivity of the atmosphere.

2.2 The Atmospheric Regions

In a general description of its physical Constitution and chemical composition, the earth's atmosphere may be considered as a perfect gas composed of molecules and atoms of which only a small fraction is represented by charged particles, ions and electrons, influenced by the geomagnetic field. This gaseous volume, called the atmosphere, is divided into some regions about which a brief description is followed.

The lower region, called the troposphere (trops = turn or change), can be defined in a static atmosphere by the pressure and temperature if the molecular mass is assumed to be constant. Meteorological soundings (a typical method of measurements) have shown that the temperature decreases with altitude in the troposphere, reaching a temperature of about 200^{o}K in the polar regions and about 190^{o}K at the equator. The general properties of the troposphere will be discussed in details in the next sections and will be shown how the pressure, temperature and humidity affect the microwave propagation in this region by varying the atmospheric refractivity. The lower limits of the temperature of the troposphere are representative of the tropopause (pausis = end, cessation). The latter, however, varies in height as a function of latitude, from below 10 km in the polar regions to more than 15 km in the equatorial belt. The variations in the level of the tropopause (about 5 km) in the middle latitudes show that the changes in its structure are dependent on such atmospheric phenomena as high and low pressures. One of the essential characters of the troposphere is that the geographic equator is to a certain extent, a 'barrier' differentiating and separating the northern and southern hemispheres.

The next region, called the stratosphere, is essentially that region where the temperature increases or at least does not decrease with altitude. The stratosphere extends from the tropopause to an altitude of about 50 km (stratopause) where the temperature reaches a peak of the order of 270°K.

The mesosphere (mesos = middle) is a region situated above the stratopause (50 ± 5 km) where the temperature decreases rapidly with altitude. The temperature may reach a minimum, as low as 150° ± 10°K, at about 85 ± 5 km, where the mesosphere ends at a level called the mesopause. Photochemical action plays an important role in the mesosphere, where the chemical reactions affect minor constituents in the air.

The upper part of the atmosphere commonly called the ionosphere, consists of several ionized layers. Conventional definition of the ionosphere include that part of the atmosphere which comprises the D,E and F regions, that is to say, roughly the atmospheric region between 80 and 400 km. Accordingly, ionospheric region starts from part of mesosphere and is spread over upto major part of thermosphere. Above the mesopause there is a change in the composition and the structure of the air concurrent with the large height gradient of temperature. Because the composition of the atmosphere changes with height, this region is called the heterosphere (heteros = other). This variation is due, first to the partial dissociation of oxygen and second to diffusion.

If, however, the temperature, which is an important parameter in this region is considered, then this region above mesopause is called the thermosphere, because the temperature in the thermosphere increases with altitude. The height at which this temperature gradient should cease could be called the thermopause.

The outermost part of the atmosphere, which is almost fully ionized and where protons are more abundant than neutral hydrogen, is called protosphere. Originally this region was called the exosphere (exo=outside) because it was thought that

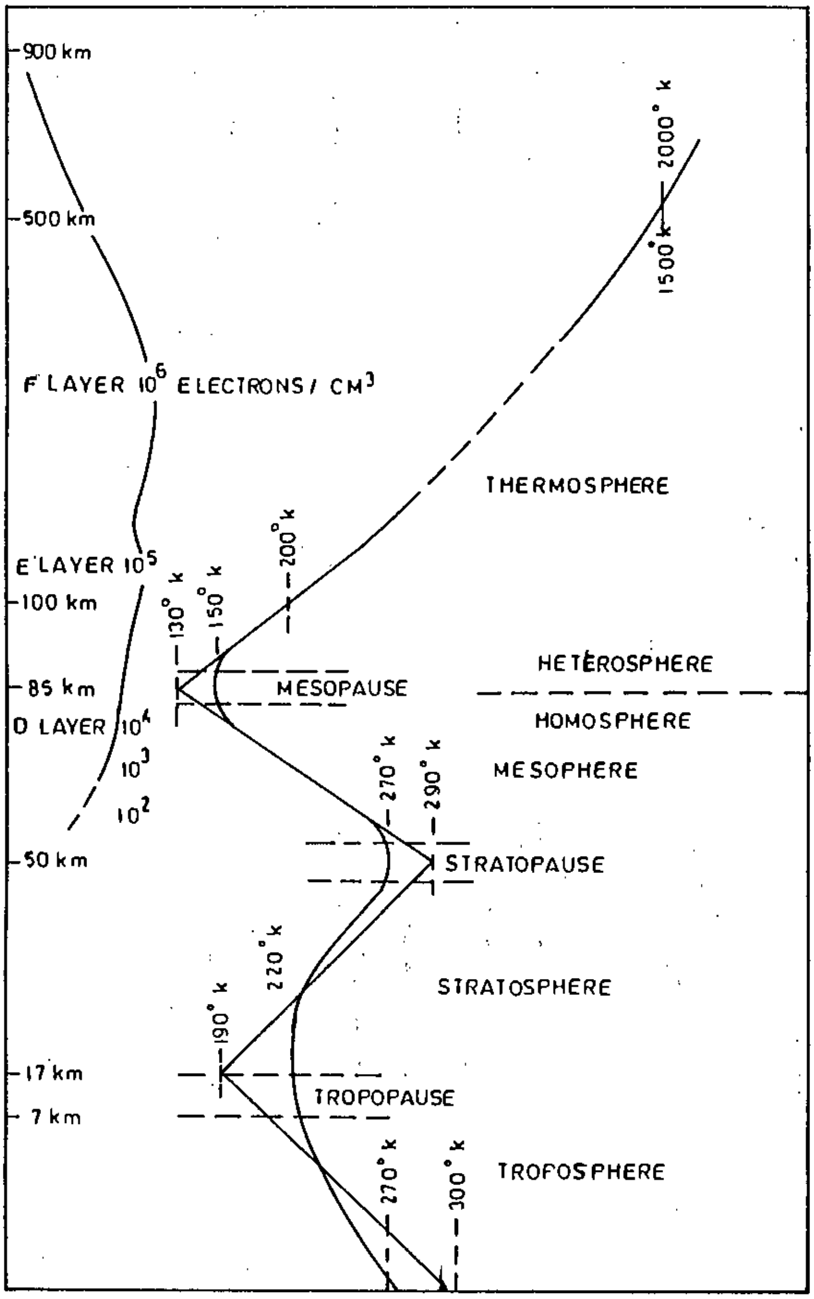

Fig.2.2.1: The regions of atmosphere from troposphere to thermosphere based on a thermal classification.

in this region the laws of gas kinetics can no longer be applied. In fig(2.2.1) a qualitative graphical representation is given showing the temperature gradients in the atmospheric regions [14].

2.3 <u>Composition and Structure of the Troposphere</u>

The troposphere is the region of the atmosphere extending from the surface of the earth upto a height of 8 to 10 kilometres at polar latitudes, 10 to 12 kilometres at the moderate latitudes (mid latitudes) and upto 16 to 18 kilometres at the equator.

In the troposphere, the percentage of the gas components does not vary with height, remaining practically the same as it is at the surface. The only exception is the water-vapour content which is strongly dependent on the weather conditions sharply decreasing with height [15].

The thermal strurcture of the troposphere is important not only from considerations of atmospheric dynamics and heat exchange but also from radio propagation point of view. The temperature in the troposphere gradually decreases from ground level upwards with height [16]. The average vertical temperature gradient of the troposphere is 6°C per kilometer (about 5°C per kilometer in the lower atmosphere and 7°C per kilometer in the upper atmosphere). The annual average temperature of the air in the upper troposphere is -55°C in the polar regions, and -80°C at the equator. The upper boundary of the troposphere is called the tropopause which is a narrow region of constant temperature.

The cause of the gradual decrease in the temperature of air with height lies in the fact that the troposphere is almost transparent to sun rays which, on passing through it, heat it very little, if at all. The bulk of the solar energy is absorbed by the earth's surface. The heated earth surface is in turn, a source of thermal radiation which heats the troposphere in an upward direction. Convective air movements also contribute to the heating of the troposphere-the air adjacent to the ground rises in temperature and moves upwards to give way to a colder air which is in turn heated and moves upwards and so on. The non-uniform heating of ground areas produces ascending and descending air currents which result in turbulences and the mixing of air masses vertically, and this decides the temperature conditions in the troposphere [15].

There are a number of occasions when the standard temperature lapse rate is modified in such a way that the temperature increase with height. These are known as temperature inversions which increase the stability of the atmosphere and inhibit vertical mixing. As a consequence air pollution problems intensify; such inversions also modify radar and radio communications in a major way. Several situations may cause temperature inversions, one of the most obvious being radiation cooling. On a typical warm and cloudless day, the ground cools rapidly after sunset, cooling the air in its vicinity. The air higher up remains warm with consequent positive temperature gradient. Yet another typical process is advection, which means the movement of a mass of air over another mass of air. Hot dry air from land, for example may blow over cold wet air causing in temperature inversion [16].

Although the troposphere extends out to a relatively low height; it accounts for four fifths of the entire mass. The average pressure at the earth's surface is 1014 millibars (1 millibar=1/1000 th bar. 1 bar = 10^6 newtons per square metre

= 1.019 kilograms per square centimetre, which is very close to one atmosphere. 1 millimetre Hg = 1.332 millibars). At an altitude of 5 kilometres, it is nearly halved, at 11 kilometres it is 225 millibars, while at an altitude of 17 kilometres (the upper boundary of the troposphere at the equator), the atmospheric pressure is a mere 90 millibars [15].

The ubiquitous water vapour in the lower atmosphere plays a very important role in modulating the thermal structure. In the most simple terms, the water vapour generated from ocean surfaces, seas and other large bodies of water rises up due to buoyancy and condenses due to cooling at some height and releases the latent heat of evaporation and produces local heating at different levels [16].

The troposphere over an ocean carries more moisture than it does over a desert. The water-vapour content rapidly decreases with height. At an altitude of 1.5 kilometres, the water-vapor content is about one-half and at the upper boundary of the troposphere it is a few thousandths of what it is at the earth's surface.

The key characterstics of the troposphere are pressure P(in millibars), absolute temperature T (in degrees Kelvin, such that $T = t^{o}C+273$), and absolute humidity H (also in millibar). Sometimes, the water-vapour content of air is expressed in terms of specific humidity S (which is the mass of water vapour in grams per kilogram of air) or relative humidity R_H, expressed in percent. Absolute humidity H is related to S and R_H as follows [15],

$$H = (S_{g/kg} P_{mbar}/623 - 0.377 S_{g/kg}) \text{ mb} \qquad (2.3.1)$$

and $$e = (E_{rmbar} \; R_H/100) \text{ mb} \qquad (2.3.2)$$

where E_r is the pressure, found from charts, of water vapour which will saturate the air at a given temperature.

2.4 Variation of Pressure, Temperature and Partial Pressure due to water vapour

The troposphere is affected by the variations of pressure (P), partial pressure due to water vapor (e) and the absolute temperature (T). These variations, however, can themselves display many forms, depending upon the thermodynamic conditions prevailing in the local air mass.

The particular atmospheric conditions with which we shall deal are those which characterize an air mass which has been thoroughly mixed by convection, eddy turbulence and molecular diffusion while tending at all elevations towards a state of mechanical equillibrium indicative of a balance between gravitational and buoyant forces. This is the state toward which we should expect an air mass to evolve when mixing is brought about through convective forces resulting from absorption of heat from the ground by the air layers lying nearest to the ground. An atmosphere in this state is known as a well-mixed atmosphere. The variation of P, e and T with elevation in the portion of a well-mixed atmosphere high enough above the ground to be unaffected by proximity of the ground is the fact that air is such a poor conductor of heat that we may regard heat transfer between neighbouring parcels of air as practically nonexistent. We may thus regard a movement of air parcel from one elevation to a slightly different elevation as an adiabatic process. From consideration of the thermodynamics of such a process, we shall now determine the desired variations of P, e and T with elevation.

2.4.1 Variation of Temperature With Elevation

Let a small parcel of air mass m be in mechanical equillibrium with neighbouring parcels in a well-mixed atmosphere, its elevation above the ground being great enough to prevent it from exchanging heat with the ground at an appreciable rate via radiation. Let its volume be v, its total pressure against its surrounding p′, and its temperature T. To the extent that we can treat it as an ideal gas, we can express its equation of state as [17],

$$P'V' = (m'/m'_o) = R'T, \qquad (2.4.1)$$

in which R' is the universal gas constant, with the same numerical value 8.314×10^7 ergs/mole ^{o}k for all gases, and m'/m'_o is a dimensionless ratio equal numerically to the effective molecular weight of the gas. If m' is expressed in grams, for example, the m'_o is the gram molecular weight.

Let us now suppose the gas parcel to be displaced upward through an infinitesimal distance dh, as might come about through a random convective or turbulent process. The pressure exerted on the gas parcel by the surrounding gases in its new environment is less than that exerted by the gases in its original environment by an amount given by the hydrostatic pressure relation

$$dp' = -(m'/v)\, g\, dh, \qquad (2.4.2)$$

in which g is the acceleration due to gravity. This reduction in pressure allows the gas parcel to expand, thereby allowing the pressure that it exerts against the surrounding gases to remain in balance with those exerted on it by the surrounding gases.

In expanding against the surrounding gases, the gas parcel expends an amount $p'dv$ of energy in mechanical work against these gases, dv representing the change in volume of the parcel. Since the expansion is essentially adiabatic, this energy must be supplied in its entirety from the internal energy of the gas parcel, thereby resulting in a lowering of its temperature. We can calculate the amount by which its temperature is lowered from the first law of thermodynamics, expressible in general through the relation,

$$dQ = m'C_v'dT + P'dv, \qquad (2.4.3)$$

in which dQ is the amount of thermal energy absorbed by the gas parcel from its surroundings in the course of an expansion dv and temperature increase dT. Cv' denotes its specific heat at constant volume. For equation (2.4.3) to be dimensionally correct with P' in mechanical units, we must also express both dQ and Cv' in mechanical units. That is if P' and dv are in dynes/cm^2 and cm^3, respectively, dQ must be in erges and Cv' in ergs/gm ^oK, assuming m' and dT to be in grams and degrees kelvin, respectively.

Since we are concerned with an adiabatic process, we set dQ=0, whereupon equation (2.4.3) yields

$$dT = - (p'/m' C_v')dv \qquad (2.4.4)$$

To eliminate dv from equation (2.4.4) and introduce dh so that we can find the functional relation between T and h requires a certain amount of manipulation among equation (2.4.1), (2.4.2) and (2.4.4) along with introduction of the specific heat Cp' at constant pressure. Details are given in Appendix (A); The resulting expression for T is simply

$$T = T_o - (g/C_p')h, \qquad (2.4.5)$$

in which T_o is the temperature at the reference elevation from which h is measured. Evidently, h=0 can be taken as ground level only if the mixing process is adiabatic all the way down to ground level. Since radiative transfer of heat between the air and the ground is usually present near ground level, it is seldom safe to fix h=o at ground level [17].

2.4.2 Variation of Pressure with Elevation

To obtain an expression for P' as a function of h, we can substitute equation (2.4.5) in equation (2.4.1) and solving the latter for v, substitute this expression in equation (2.4.2) and then integrating equation (2.4.2). The integration is straight forward and yields [17],

$$P' = P_o \{(1 - g/C_p' T_o) h\}^{m_o' C_p'/R'} \qquad (2.4.6)$$

in which P_o represents the pressure at elevation h=0.

2.4.3 Variation of Partial Pressure Due to Water Vapour with Elevation

In this case it will be useful to regard the air parcel as containing a mass m of dry air with specific heat C_p and effective molecular weight m/m_o together with a mass m_w of water vapor with specific heat C_{pw} and molecular weight

m_w/m_{ow}. In terms of m/m_o and m_w/m_{ow}, we may express the equations of state of the dry air and of the water vapor in the air parcel as [17],

$$pV = (m/m_o)\ RT \qquad (2.4.7)$$

$$\text{and} \quad eV = (m_w/m_{ow})RT \qquad (2.4.8)$$

respectively. It is also useful to introduce specific humidity S, defined as

$$S = m_w/(m + m_w) \qquad (2.4.9)$$

we can then calculate C_p' and m_o interm of S from

$$C_p' = (1 - S)\ C_p + S\ C_{pw} \qquad (2.4.10)$$

$$\text{and} \quad m_o = 1/\{(1-S)/m_o + (S/m_{ow})\} \qquad (2.4.11)$$

derivation of which are given in Appendix (B).

Finally, dividing Equation (2.4.8) by equation (2.4.1), substituting for m_o' from equation (2.4.11), replacing m' by ($m + m_w$), and introducing S through equation (2.4.9) yields

$$e = m_o\ P'\ S/\{m_{ow}\ (1 - S) + m_o\ S\} \qquad (2.4.12)$$

In evaluating e from equation (2.4.12) for any given elevation, we must substitute for P' from equation (2.4.6) and for S from equation (2.4.9). In using equation (2.4.6), we must evaluate C_p' through use of Equation (2.4.10).

In our next chapter we discuss the propagation properties of radio waves.

CHAPTER 3

PROPAGATION AND CLASSIFICATION OF RADIO WAVES AND THEIR ATTENUATION DUE TO DIFFERENT FACTORS

3.1 Introduction

This chapter deals with the propagation of radio waves and their classification. Depending on the mechanism of propagation, the radio waves are classified as ground wave space wave and sky wave. Different characterstics of these waves are discussed in details. Terrain effects on microwave radio system which cause propagation loss (blockage of microwave beam by hills, trees etc., beam reflection from water or smooth surface) are also discussed in this chapter.

The random fluctuation of radio signal called fading, types of fading and the causes of fading and also the ways by adopting which the fluctuation level of the signal can be reduced is described in this chapter. The radio waves while passing through the atmosphere are attenuated by the different constituents of the atmosphere. In the last portion of this chapter, attenuation of radio waves by Oxygen, Nitrogen, Hydrogen, Argon, water vapour and also by rains and fogs are discussed briefly.

3.2 Propagation of Waves and Their Classifications

The propagation of electromagnetic waves around the earth is influenced by the properties of the earth and its atmosphere. The atmosphere over the earth is a dynamic medium; its properties change with the variation of pressure, temperature and humidity as discussed earlier. When a radio wave is radiated from a transmitting antenna it spreads out in all directions, decreasing in amplitude with increasing distance because of the spreading of the electromagnetic energy through larger and larger surface areas. The portion of the energy arriving at a distant receiving antenna may have travelled over any of the several possible propagation paths designated by the terms ground waves, sky waves and space or tropospheric waves.

At frequencies below about 30 mega hertz, where vertical antennas erected are close to the surface of the earth, the transmission from transmitter T_1 to R_1 may be by means of a ground wave or surface wave which is guided along the surface

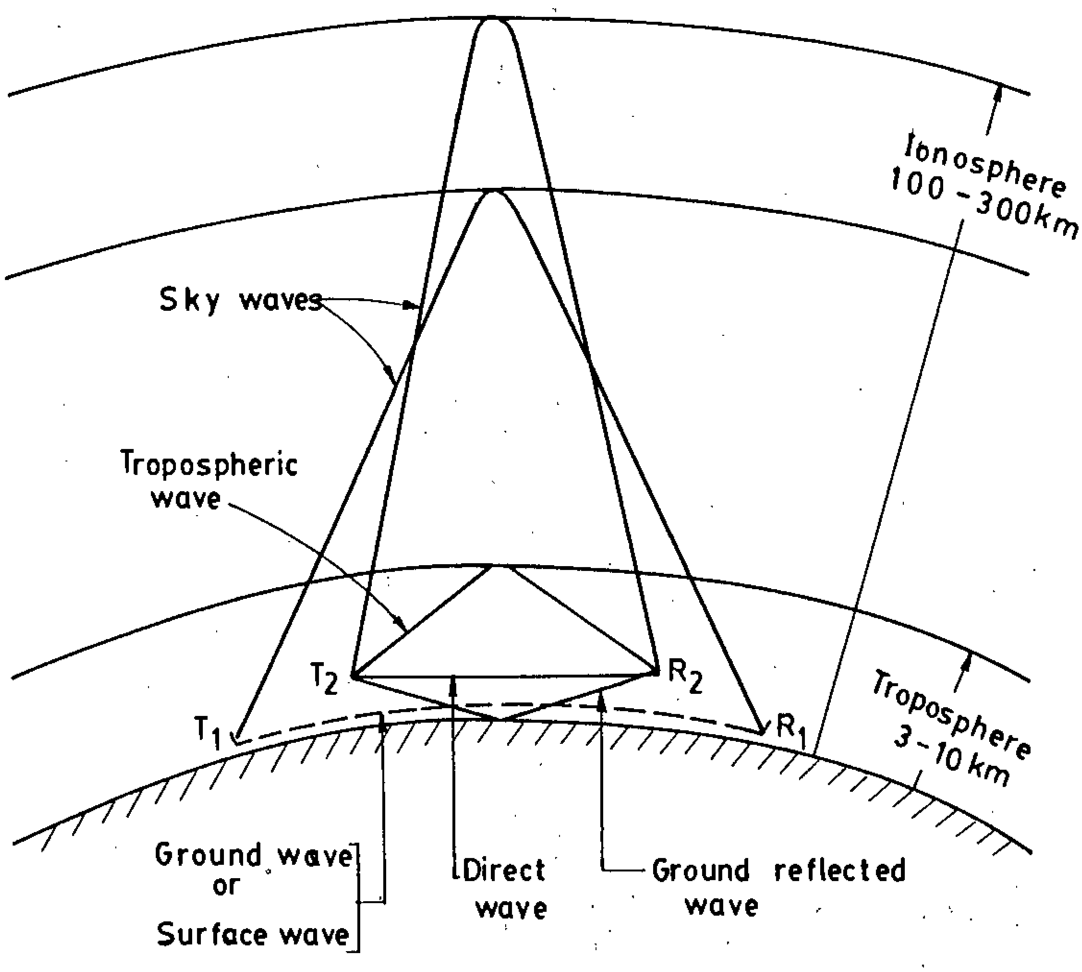

Fig.3.2.1: Possible propagation paths from transmitter to receiver.

of the earth (fig 3.2.1) [19]. Some portion of it (specially frequencies from 2 to 30 megahertz) may also propagate by means of a sky wave or space wave which is radiated up into space. This is reflected back to the earth i.e to the receiving antenna from a layer of ions and electrons called the ionosphere. This layer is about 80 km above the earth's surface.

At higher frequencies,(VHF,UHF and above) when elevated antennas are used (indicated by T_2 and R_2 as in fig (3.2.1)) the space wave represents energy that travels from the transmitting to the receiving antenna in the earth's troposphere or travels straight into the deep space depending on the launching angle. The space wave commonly consists of at least two components. One of these is a ray that travels directly from the transmitter to the receiver, while the other is a ray that reaches the receiver as a result of reflection from the surface of the earth. Space-wave energy may also reach the receiver as a result of reflection or refraction produced by variations in the electrical characteristics of the troposphere and by diffraction around the curvature of the earth, hills etc.

Which of the several possible paths are operative in any particular instance depends upon the frequency, the separation between transmitter and receiver, and the conditions of the ionosphere and troposphere. While there are cases where several of these paths are operative simultaneously, it will usually be found that propagation is restricted to only one or two paths or at any rate, that the signal received over a particular path is very much stronger than those received over other paths [19].

We shall now discuss in details the various aspects of ground wave, sky wave and space wave here.

3.2.1 Ground Wave

A radio wave propagated close to the earth's surface and partly following the curvature of the globe due to diffraction is called a ground or surface wave [15].The surface wave is guided along and around the surface of the earth somewhat as a wave is guided along a transmission line. In this guiding process voltages and currents are induced in the ground, and energy is abstracted from the wave. If the ground were a perfect conductor, these ground currents could flow without any losses and the wave could not be affected. However, the ground does have resistance, or a finite conductivity, so the energy is required to make these ground currents flow and this energy is absorbed from the wave. The result is that the ground wave is thus attenuated or decreased in strength. The amount by which the wave is attenuated due to an imperfectly conducting ground is important in determining how far the wave will travel before the signal becomes too weak to be of any use.

The attenuation caused by the ground depends both upon the conductivity (or resistivity) of the ground and upon the frequency being used. A high-frequency wave is attenuated much more than a low-frequency wave over the same ground. Because the ground wave is attenuated so much at the higher frequencies its chief usefulness lies in the long-wave (or lower frequencies) and broadcast bands. Daytime reception of broadcast stations is entirely by means of the ground wave.

The ground wave is always vertically polarized because any horizontal component of electric field would be shorted out by the ground. For this reason vertical antennas must be used for ground-wave transmission.

3.2.2 Sky Wave

The ionosphere consists of several ionized layers. These layers exist at high altitudes, in the upper parts of the earth's atmosphere, extending out from 60 to 600 kilometres. Radio waves that strike these layers have their paths changed while passing through the layers. Sometimes the waves penetrate all the layers and are lost, but more often the waves are bent in their paths so much that they return to the earth at distant points. With respect to radio waves, the layers act as imperfectly conducting surfaces which reflect radio waves. The wave radiated in the directions above the horizon will travel through space until it reaches the ionized layers i.e.the ionosphere, then the path of the wave will be bent earthward. This reflection from the ionosphere, however happens only to waves longer than 10 metres. In otherwords, the ionosphere is opaque to waves longer than about 10 metres and they cannot ordinarily leave the atmosphere. To the shorter waves, including those in the radio-optical band, the ionosphere is a transparent medium.

After a single reflection from the ionosphere, radio waves usually can cover distances not exceeding 4000 kilometres. However, the waves reflected from the ionosphere can bounce off the imperfectly conducting surface of the earth to be again reflected from the ionosphere. Owing to these multiple reflections from the ionosphere and earth, radio waves can reach localities at any distance from the transmitter and even girdle the earth more than once.

Apart from reflection, the ionosphere can cause the scattering of radio waves owing to minute inhomogeneities in the layers. Further more, meteors impinging on the terrestrial atmosphere produce meteor trails which can also cause scattering of radio waves. Ionospheric and meteor-trail scattering occur only to waves shorter than 10 metres, that is, the waves which can not be reflected from the ionosphere in a regular fashion. On wave-lengths longer than 10 metres, the effect of ionospheric and meteor-trail scattering is masked by the regular reflection from the ionosphere which produces stronger fields at the point of reception [15].

3.2.3 Space or Tropospheric Wave

At radio frequencies above about 30 MHz, the ionosphere is not able to refract or reflect energy to earth, while the ground wave attenuates to negligible amplitude in a relatively few hundred feet. Useful propagation can , however, be achieved at these frequencies by means of the space wave travelling between elevated transmitting and receiving antennas.

The atmosphere through which the space wave travels is able to influence the propagation to a significant degree. This arises from the fact that the presence of gas molecules, particularly of water vapor (which has a high dielectric constant), causes the air of the troposphere to have a dielectric constant slightly greater than unity [20].

The troposphere is an inhomogeneous medium with time-varying properties due to the weather conditions. Its refractive index gradually decreases with height. Gradual variations in the refractive index resutls in a bending of paths taken by radio waves. The curvature of bending depends on the type of variations of the refractive index. Changes in temperature and moisture content result in changes in the gradient of the index of refraction. Conditions may result in an increase in index with height and a bending of rays away from the earth.

Sometimes meteorological conditions can produce areas having a steeper decrease of refractive index with height in the lower troposphere such that the rays are bent toward the earth more strongly. This condition arises when a body of warm air is over water, resulting in a high density of water vapour over the surface. Under such conditions the atmosphere forms a duct or waveguide, that guides the waves over the surface. Abnormally large ranges beyond the line of sight are then obtained. The effect is significant in microwave region (In previous chapter, the variations of RRI were discussed). Different types of bending of radio waves due to the variation of RRI will be discussed later elaborately.

The troposphere affects waves shorter than 10 metres, i.e, only metric, decimetric and centimetric waves (popularly known as microwave) will be propagated by the troposphere mode.

3.3 Terrain Effects on Microwave Frequencies

Under normal atmospheric conditions, terrain has two effects on the propagation loss of a microwave:

i) Trees, buildings, hills or the earth can block a portion of the microwave beam to cause an obstruction loss (in addtition to the free space attenuation).

ii) A very smooth section of terrain or water can reflect a second signal to the receiving antenna. The reflected signal may arrive out of phase with the direct signal, resulting in additional attenuation from signal cancellation (interference).

3.3.1 Effect of Obstacles-Fresnel Zone Clearance

The phenomena produced by ground interception of part of the direct radiation, can be analysed by applying the notions introduced by Fresnel in optics. Let a broad ridge be situated at distances d_1 and d_2 from the transmitter T and the receiver R, respectively at a height h below or above the optical line of sight as shown in figs.(3.3.1.1a) and (3.3.1.1b) [21].

Regions of space corresponding to increased path lengths of $\lambda/2$, $2\lambda/2$, $3\lambda/2$ etc. with respect to $TR = d_1 + d_2 = d$, are ellipsoids with foci T and R. The μth Fresnel surface is that for which the sum of distances between the transmitter and receiver and a point on the surface of the ellipsoid of revolution (dotted line in fig. 3.3.1.1a) exceeds by δ i.e. $\mu(/2)$ the distance between the transmitter and the receiver.

$$\delta = (r_1 + r_2) - (d_1 + d_2) = \mu \lambda/2 \qquad (3.3.1.1)$$

$$l_1=(d_1{}^2+h^2)^{\frac{1}{2}}=d_1\{1+(h/d_1)^2\}^{\frac{1}{2}}$$
$$= \quad d_1 [1 + 1/2 (h/d_1)^2] \text{ for } h/d_1 << 1 \qquad (3.3.1.2)$$

Similarly,

$$l_2 = d_2 [1 + 1/2 (h/d_2)^2] \qquad (3.3.1.3)$$

Hence, $\delta = h^2/2 [1/d_1 + 1/d_2] =\mu \lambda/2$ (3.3.1.4)

It is customary to express this result in terms of Fresnel zones. The necessary clearance for the first Fresnel-Zone is therefore given by

$$h_1 =[\lambda/(1/d_1 + 1/d_2)]^{\frac{1}{2}} \qquad (3.3.1.5)$$

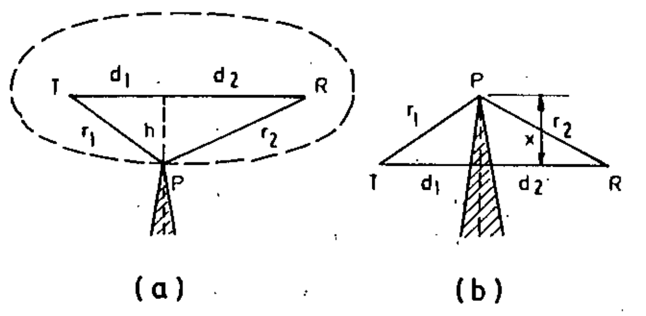

Fig.3.3.1.1: Effect of wide ridge.

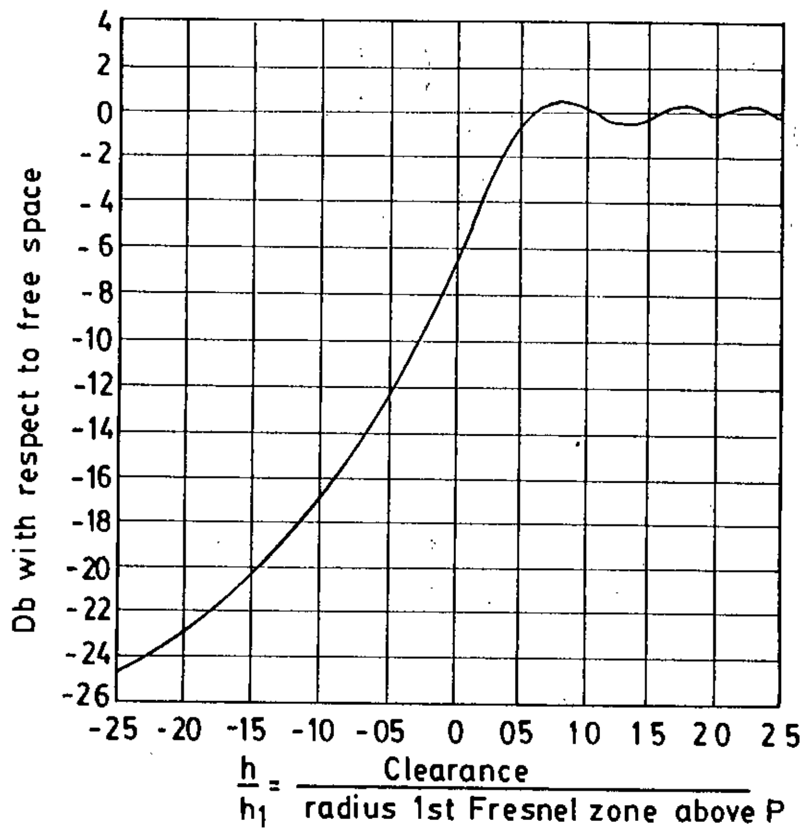

Fig.3.3.1.2: Attenuation Vs.Fresnel clearance.

and generally the clearances for the μth Fresnel zone are given by

$$h\mu = [\mu \lambda/(1/d_1 + 1/d_2)]^{1/2} \quad (3.3.1.6)$$

It is seen from analysis that when the ridge top is on the line of sight, there is a loss of 6 dB. As the ridge goes above the line of sight, the loss increases rapidly; but as the ridge goes below the line of sight, the loss drops rapidly to zero and oscillates about ± 1 dB. The received wave has a magnitude nearly equal to the free space value if the ridge is below the line of sight by an amount such as $\delta/\lambda > 0.5$. Thus the main feature is to put the transmitter and receiver at such heights that there is at least clearance for the first Fresnel zone.

3.3.2 Ground Reflections

Reflections from the earth can cause very important effects upon the received wave. The simplest case is the reflection from a plane earth as shown in fig.(3.3.2.1). The resultant wave at the receiver R consists of the direct ray TR and the reflected ray OR. Reflection causes attenuation and phase shift

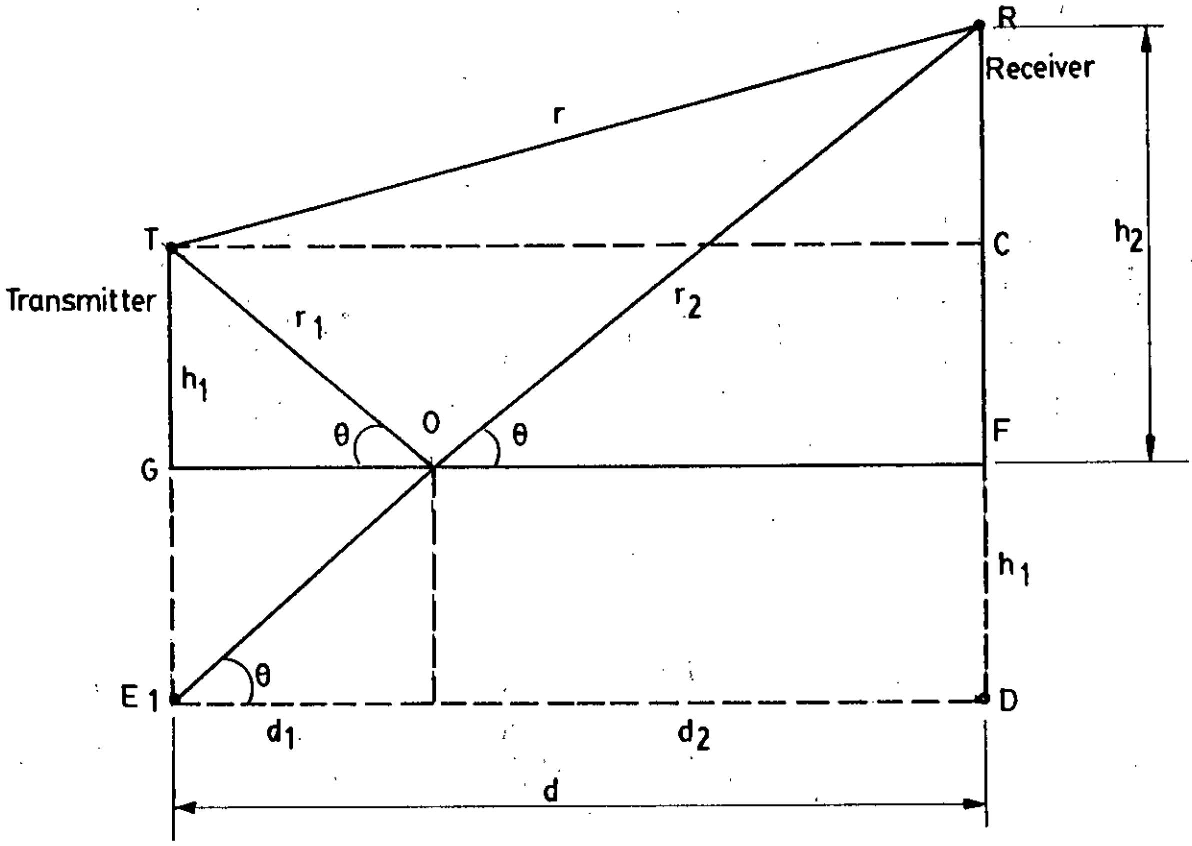

Fig.3.3.2.1: Reflection by plane earth.

along the indirect ray, which may be accounted for by the reflection co-efficient expressing the ratio of the reflected oscillation to the incident oscillation [21].

$Z = \rho' e J\beta$

where ρ' is the modulus of the reflection co-efficient and β is the phase of the reflection. The path difference between the reflected and the direct ray is given by

$\delta = (TO + OR) - TR$

In practice, h_1 and h_2 are small compared to d so that

$\delta = d\{[1+ 1/2 ((h_2 + h_1)/d)^2] - [1 + 1/2((h_2-h_1)/d)^2]\}$

$= 2h_1h_2/d$ (3.3.2.1)

Thus the receiver recieves, in addition to the direct wave, a reflected wave of the relative amplitude ρ' and of relative phase shift α which is the result of the delay due to the path difference δ , together with the pahse shift β due to reflection. The total phase shift is thus

$= \beta - 2\pi\ \delta/\lambda = \beta - 4\pi h_1h_2/\lambda d$ (3.3.2.2)

β is normally negative and much less than 180^o. The negative sign for the reflection co-efficient accounts for the fact that a wave undergoes a 180^o phase reversal when reflected.

It is well known [21] that multipath transmission causes amplitude and phase distortion in FM waves. The amplitude of the resultant wave at the receiver input will vary, as either h_1 or h_2 is varied, between $1-\rho'$ and $1+\rho'$.

If ρ' is near unity, there may be almost complete cancellation of the direct wave by the reflected wave. By using diversity reception on two antennas stepped in height, it is possible to obtain a suitable reception level on one of the two antennas.

3.4 Fading

Radio fading refers to random fluctuation of radio signal level. It is a fundamental problem in considering reliability of relevant radiopaths.

Radio signals on line of sight paths are stable under normal refraction conditions. When sub-refraction occurs and grows, direct ray gradually closes in upon the earth and even be obstructed by it, giving rise to so-called diffraction fading. On the contrary, when super-refraction occurs and grows, the direct ray path will be far from the earth, the effects of ground reflection could emerge and as result of interference between the two paths, the received signal could change with varying relative phase shift between the paths, forming ground reflection fading. Both diffraction fading and ground reflection fading are caused by k-factor, and is known as k-type fading.

It is worth noting that refraction from layers could affect radio paths in the aspect of fading. A refracting layer with a constant refractivity gradient above a radio path could cause upto four multipaths between terminals, depending on the height, thickness and lapse of refractivity across the layer and the difference between the two antenna heights. If the antennas are at the same height, the multipath number is reduced to one or two. The layer-caused fading is often called multipath fading. When k-type fading is limited to be negligible, multipath fading could become a main threat [16].

So various types of disturbances to propagation may be encountered. Almost invariably, these include a loss in received signal strength. Several mechanisms capable of causing fading are:

i) Decreased Fresnel-Zone clearance of the line of-sight propagation path over the terrain as a result of reduced effective earth radius.

ii) Interference between waves reaching the receiving antenna via two or more different paths,

and

iii) Deflection of radiation from the line of sight path by a duct associated with a region of temperature inversion [17]. Turbulence in the troposphere causes additional radiowave components which under normal conditions are not strong enough to eliminate the direct ray component and hence, can only cause slight fluctuation of radio level, i.e. scintillation, when the direct ray component is weakened to a certain extent, however, the turbulent components can also reinforce radio fading to be deep [16].

There is no commonly accepted nomenclature in use for distinguishing between different types of fading phenomena. Most authors use names based on the way in which the fading varies with time. By far the most widespread usage is one which classifies all fading as fast fading and slow fading, which are elaborately discussed below.

3.4.1 Slow Fading

When the effective earth radius factor k is temporarily smaller than its standard value of 4/3 because of the presence of an unusually small vertical refractivity of gradient along the propagation path, the microwave path joining the antennas possesses less curvature than normal. The normal curvature causes the path to be an arc of a circle convex upward; reducing the curvature of this arc allows its clearance over the underlying terrain to become less than normal. The Fresnel-zone clearnce of the path is thus decreased. In an extreme case, the path may actually be intercepted by the ground. The transmitting antenna becomes no longer "visible" to the receiving antenna, and the received signal may become too small to use.

This type of fading, developes slowly, and it subsides slowly, for gross changes in the refractivity gradient can not take place rapidly since they involve large-scale modifications in the thermodynamic state of the atmosphere. Because of its slow time variation, it is called slow fading. It typically developes on a microwave path which passes relatively close to the ground in a region where the ground is intensely heated by the sun so that a region is formed in which the temperature of the air decreases unusually rapidly with elevation. The propagation velocity of microwaves in this region thus decreases more rapidly with elevation that it does in a well-mixed atmosphere in neutral mechanical equillibrium, thereby leading to a change in path curvature of the type described above.

Slow fading is most effectively avoided by locating the antennas so as to provide more Fresnel-zone clearance than is needed for free space transmission under normal atmospheric conditions. Adverse refractive conditions then need not reduce the clearance to the point at which fading begins to become appreciable [17].

3.4.2 Fast Fading

When the atmosphere is turbulent and not well-mixed, the received signal is not a single ray but a number of separate and distinct rays, each arriving via a slightly different path. Each of these paths is continually changing its shape by small amounts, but such changes can correspond to many wavelengths at microwave frequencies. The result is that the rays combine with constantly changing phases, thereby leading through constructive interference to large resultant amplitudes at some instants and through destructive interference to very small ones at others. The fluctuations in the amplitude of the resultant occur at random and are generally quite rapid.

At any given wavelength, the most effective way to minimize the effects due to this type of fading is to keep the effective radiated power at the transmitting antenna high enough and the length of the transmission path to the receiving antenna short enough to permit the received signal to remain of usable magnitude in the presence of the most severe fade likely to occur and, in addition, to employ one or more of the methods of diversity operation.

A sceond type of fast fading is caused by multipath interference between line-of-sight ray and a ray reflected from the ground. This fast fading takes place only when the difference between the lengths of these paths is changing, which can happen only in the presence of the mechanism responsible for slow fading. Thus, this type of fast fading always appears superimposed upon a background of slow fading which, however, may itself be of such slight magnitude as to escape detection. More frequently, fast and slow fading are both of significant magnitude at the same time. Moreover, it often happens, that fast fading increases in severity when a slow fade is deepening and vice versa. There are two reasons for this:

1) As the direct ray is deflected closer to the ground during a deepening slow fade, it enters a region in which the air is likely to be both inhomogeneous and turbulent and therefore suffers increased multipath fading;

and

2) as its amplitude decreases due to loss of Fresnel-zone clearance, the amplitude of the reflected wave increases as its incidence becomes more glancing, thereby causing the direct and reflected waves to become more nearly

comparable in magnitude, so that their destructive interfence leads more nearly to complete extinction [17].

3.5 Attenuation of Microwave by Atmosphere

The concept of free space transmission assumes that the atmosphere is perfectly uniform and nonabsorbing and that the earth is either infinitely far away or that its reflection co-efficient is negligble. In a practical line-of-sight microwave communication system, the received signal will be near the free space value. When the wave is propagated in the atmosphere and near the ground, the free space transmission equivalent is modified due to various causes such as atmospheric refraction, reflection etc. It is observed that the received signal level fluctuates with time and sometimes undergoes fade-outs. This condition of course, depends on the carrier frequency and certain meteorological conditions, both seasonal and local. These phenomena constitute fading, the intensity of which generally increases with the carrier frequency and with the length of path, which is discussed elaborately in the previous section.

Atmospheric absorption may also cause attenuation, especially in the case of very short wavelengths [21].

Each constituent of the atmosphere is capable of interfering, either by absorption or scattering, with the propagation of microwaves.

At sea level in the absence of moisture, the atmosphere has the composition of Nitrogen, Oxygen, Argon, Carbondioxide, Neon, Helium, Methane, Krypton, Nitrous Oxide, Xenon and Hydrogen [17]. Nitrogen, Oxygen and Argon are by far its most important constituents. These gases are primarily responsible for any microwave absorption that can occur in the dry atmosphere, at least to the extent that their molecules possess mechanisms for absorbing microwave. Water vapour is also an important constituent of the atmosphere. We shall discuss the attenuation to microwave propagation due to these atmospheric constituents.

3.5.1 Nitrogen

Although comprising close to 80 percent of the entire atmosphere, nitrogen plays no part at all in absorption of microwaves, for the nitrogen molecule possesses no permanent dipole moment, either electric or magnetic.

3.5.2 Oxygen

Since oxygen possesses no permanent electric moment, Oxygen is incapable of responding in any way to the electric component of a microwave field. On the other hand, it possesses a small magnetic moment which enables it to display a group of weak absorption lines between 54 GHz and 120 GHz. They consist of a group of lines lying between 54 and 66 GHz together with one isolated line at 120 GHz. Due to collisions between oxygen molecules, the lines clustered around 60 GHz are quite broad, their "wings" extending to low enough frequencies to cause significant absorption in the frequency range from 2 to 13 GHz. Oxygen absorption in this range increases slowly with frequency due to presence of these wings.

In addition to the resonant absorption, oxygen also displays a non-resonant absorption extending continuously throughout the entire spectrum. In the frequency range from 2 to 13 GHz, this absorption is practically independent of frequency. Although it accounts for more than 80 percent of the total absorption due to oxygen in this range, the small increase in absorption that may be observed with incrasing frequency is due almost entirely to the resonant component.

A plot of the absorption characterstic for oxygen between 2 and 13 GHz appears in Fig.(3.5.1), which is adapted from a curve computed from quantum-mechanical theory.

3.5.3 **Argon**

Since argon possesses no detectable absorption at 9.4 GHz. we can reasonably surmise that it would exhibit negligible absorption at any other frequency in the 2 to 13 GHz range, since lines with frequencies in or near this range should be sufficiently wide due to collision - broadening that their wings would be at least detectable at 9.4 GHz.

3.5.4 **Trace Gases**

With atmospheric abundance less than 0.1 percent, gases such as carbondioxide, Neon, Helium, Methane Krypton, Xenon, Hydrogen and Nitrousoxide can not produce appreciable absorption since the absorption capability of any gas is proportional to its density.

3.5.5 Moisture

In both gaseous and droplet form, moisture possesses significant absorption capability throughout the 2 to 13 GHz band. The mechanisms and the characterstics of the absorption they produce are sufficiently dissimilar that we must discuss water vapour and water droplets separately.

a) Water Vapour

Water vapour is a molecular gas and absorbs microwaves in the same manner as does oxygen,that is through transitions between different molecular energy state. Since, unlike oxygen, it's molecule possesses a permanent electric dipole moment, it is more responsive to excitation by an electromagnetic field than is oxygen. Thus, it absorbs relatively heavily in the atmosphere even at quite low concentrations. Its absorption in the microwave range is due to transitions with resonant frequencies at and above 22 GHz.

A plot of the absorption predicted by theory in the frequency range from 2 to 13 GHz due to water vapour in an atmosphere in which water molecules comprise one percent of all

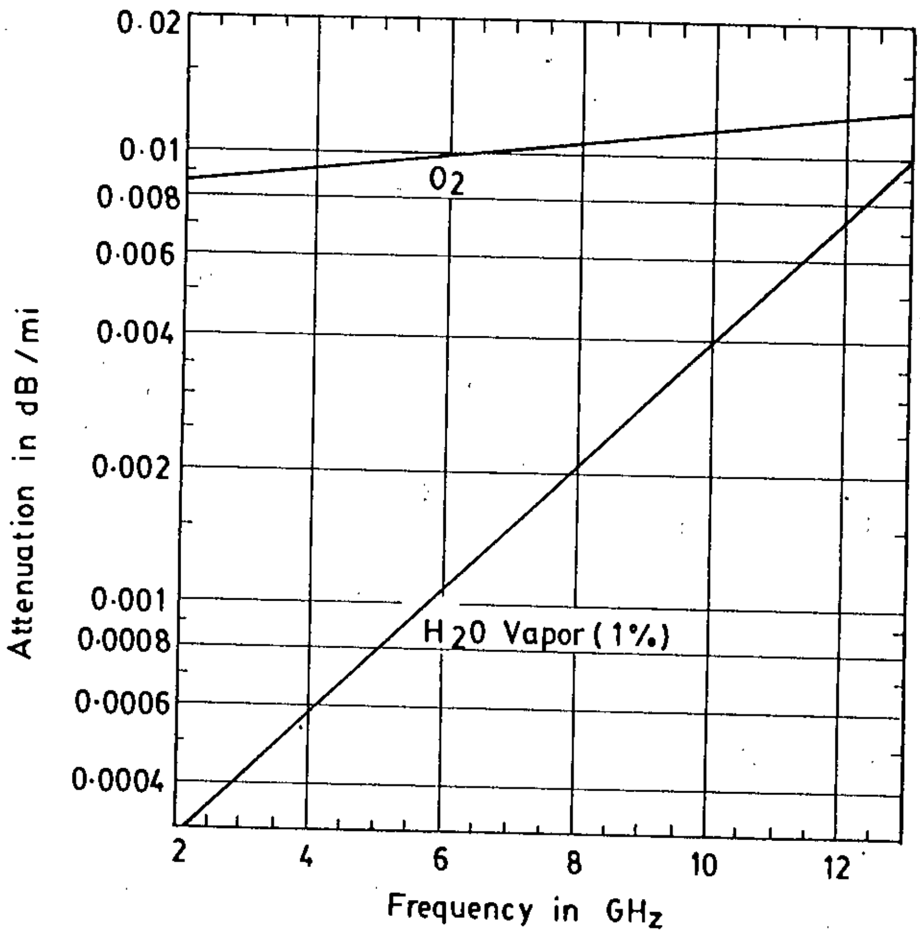

Fig.3.5.1: Microwave absorption due to atmospheric oxygen and water vapour. Curve for water vapour assumes 1 percent of molecules present are H_2O molecules.

gas molecules present is shown in fig.(3.5.1). Although the curve should be drawn concave upward to conform rigorously to theory, the indicated attenuation at 10 GHz being lowered from 0.040 dB/mi to more nearly 0.037 dB/mi, the error due to plotting it as a straight line is negligible compared to that which must evidently be assigned to the theory itself changing the concentration changes the widths of the absorption lines in a manner not calculable from theory and not deducible from the available experimental data.

b) **Water Droplet**

Water droplets cause attenuation of microwave fields through both absorption and scattering. Since water droplets are small compared to the radiation wavelength when the latter is in the 2 to 13 GHz band of frequencies, the Rayleigh fourth power law of scattering is applicable [17]. In accordance with this law, the power density in the scatterd radiation field varies, for scattering particles of given size, as the fourth power of the frequency. Thus, the attenuation in decibels at 13 GHz due to scattering is more than 1700 times the corresponding attenuation at 2 GHz, all other conditions remaining the same. On the other hand, the attenuation in decibels due to absorption within water droplets has been found to vary linearly with the square of frequency. The actual variation with frequency therefore depends upon how the attenuation is devided between that caused by scattering and that caused by absorption. We may distinguish two separate cases, depending upon whether absorption is or is not the dominant process. One case concerns clouds and fogs; the other concerns rains.

c) **Clouds and Fogs**

For the very small droplets which comprise clouds and fogs, absorption is dominant. Under this condition, the attenuation is independent of droplet size as long as the total mass of water droplets in a given volume of the atmosphere is fixed. With the attenuation in decibels then varying linearly with the square of frequecny as well as with the mass of water droplets per unit volume, we must expect log-log plots of attenuation in decibels/mile against frequency in clouds and fogs of various densities to yield straight lines with slopes of 2. Fig.(3.5.2).

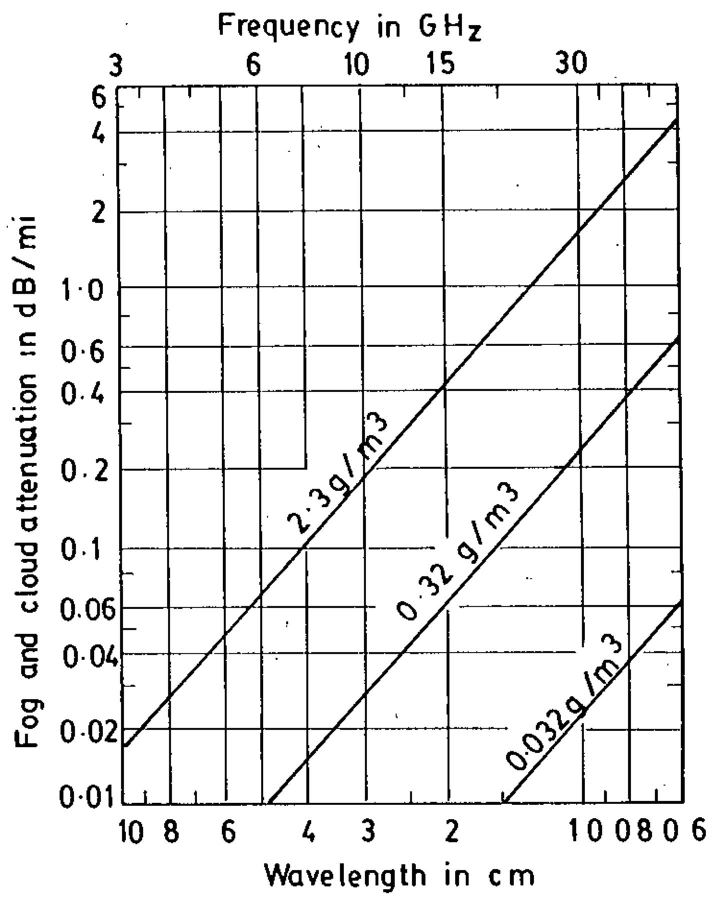

Fig.3.5.2: Attenuation due to fogs and clouds of various densities as function of a radiation wavelength.

d) **Rains**

Even in light drizzles, the droplets are large enough so that the contribution due to scattering is no longer negligible, and a different form of attenuation characterstic results. Several attenuation curves obtained theoretically and practically are shown in fig.(3.5.3) by solid and dotted lines respectively.

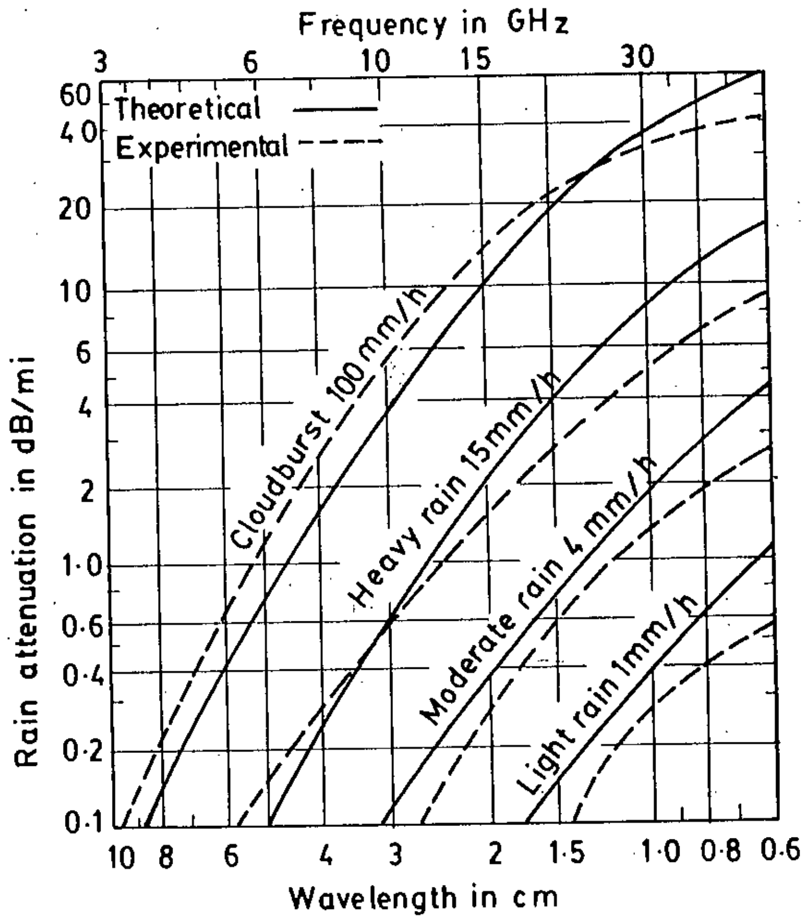

Fig.3.5.3: Attenuation due to rainfall of various intensities as function of radiation wavelength. Theoretical curves are solid, experimental are dashed.

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CHAPTER 4

ATMOSPHERIC REFRACTIVITY AND ITS EFFECT ON TROPOSPHERIC RADIO WAVE PROPAGATION

4.1 Introduction

A brief discussion of the radio refractive index (RRI) is given at the begining of this chapter and an equation for radio refractive index is developed in terms of three parameters i.e. atmospheric pressure (p), temperature (T) and water vapour pressure(e). The way in which the refraction of a radio ray takes place due to the variation of refractivity is shown in this chapter and the concept of effective earth radius factor(k) is introduced in this chapter. Different types of radio ray refraction takes place due to non-uniform radio refractive index variation with height for the various meteorological conditions in the atmosphere. Some special type of low loss propagation of radio ray over long distances called ducting is discussed here. Radio ray bending occurs while transmitted wave reaches the receiving station. A mathematical treatment is presented here calculating the amount of bending of radio ray in terms of refractivity of the atmosphere, the refractivity gradient and the angle at which it is radiated (launched) from the transmitting antenna.

4.2 Radio Refractive Index(RRI) in the Troposphere

Propagation of radio waves in VHF, UHF and SHF (microwave) bands are effected by meteorological conditions in the troposphere. The refractive index which affects the microwave communication in the troposphere depends upon the pressure, temperature and water vapour pressure in the atmosphere. For all practical purposes, the atmosphere may be considered to consist of dry air and water vapour from refractive index considerations. Molecules of dry air do not have a significant permanent dipole moment, that is the displacement between the effective positive and negative charges in the molecule is essentially zero. However, under the influence of an external electromagnetic field (due to a passing radiowave) a small dipole moment is induced. The net effect of all such induced dipoles in the sphere of influence of radio waves is to increase the dielectric permittivity of the medium and hence the radio refractive index [5]. Since the density of a gas is directly proportional to its partial pressure and inversely to its temperature, the radio refractive index contribution of any gas is proportional to its partial pressure divided by its temperature. Water vapour in the atmosphere profoundly influences the tropospheric radio refractive index. The water molecule possesses a permanent dipole moment and these permanent dipoles normally are randomly distributed. However, in response to the magnetic field associated with a passing radiowave, the permanent dipoles (water vapour molecules) partially align with such magnetic field adding to the polarization of the medium. This effect is obviously proportional to the number density of water molecules. But with increasing temperature, the random thermal motions make it difficult to discipline the dipoles to fall in line with the imposed magnetic field, thus the polarization is inversely proportional to temperature. A clear description of the dry and wet parts of the refractivity with the help of radio refractive index expression is given in the next section.

4.3 Radio Refractive Index Equation

In wave propagation the radio refractive index plays a vital role. The bending of porpagating wave, fading factors, scatter angle, scatter volume all these factors are effected by the change of refractive index. In designing a communication system the study and calculation of radio refractive index is thus of prime importance.

The refractive index n of the troposphere at the surface of the earth is only 0.000325 percent greater than unity [15]; it is more convenient to refer to variations in the refractive index in N units

$$N = (n-1) \times 10^6 \qquad (4.3.1)$$

where N is the excess index of refraction. It is the excess over unity of the refractive index, expressed in millionths. Thus , at the surface, where n=1.000325, there is a value of 325 N units.

The excess refractive index is known as Radio Refractive Index or Refractivity.

From the view-point of the refractive index, the troposphere may be treated as a mixture of dry air and water vapour. The refractive index of the mixture can therefore be found from the known water-vapour content in the atmosphere,the partial pressure P_d of dry air, and the partial pressure e of water vapour, knowing that the refractivity of a mixture is the sum of the refractivities of the parts.

From physics it is known that the refractive index of a gas [15] is

$$n=1+\rho(A+B/T) \quad (4.3.2)$$

where ρ is the gas density in kilograms per cubic meter, A is the constant (expressed in cubic metres per kilogram) dependent on the polarization of the gas molecules in an external field, and B is the constant (expressed in cubic metres x degrees per kilogram) decided by the permanent molecular dipole moment.

Since, by Clapeyrons's law, the density of a gas is directly proportional to its partial pressure and inversely proportional to its temperature in degrees absolute,

equation (4.3.2) may be re-written

as $$N = (C_{p\ part}/T)(A+B/T) \quad (4.3.3)$$

where C is the proportionality factor, expressed in kilograms-degrees per cubic metres-millibars.

The gases making up dry air do not possess a permanent dipole moment. In contrast, the molecules of water vapour have a permanent dipole moment, m"=6.13 x 10^{-30} coulombs-metre. The total refractivity is the sum of the refractivities of the parts, and thus the excess refractive index for moist air may be written as

$$N = (C/T)\ A_d\ P_d + (C_e/T)(A_w + B_w/T) \qquad (4.3.4)$$

where A_d is the respective constant for dry air, while A_w and B_w are the constants for water vapour.

From experiments it is known that for dry air the product CA_d is 77.6 degrees per millibar. This seems to be true also of the product CA_w for water vapour. The ratio B_w/A_w has been measured fairly accurately and is assumed to be 4810. Substituting the numerical values of CA_d and B_w/A_w in equation (4.3.4) gives [15],

$$N = (CA_d/T)(P_d + e + B_w e/A_w T)$$

$$= 77.6/\ T_{deg}\ (P_{mb} + 4810\ e_{mb}/T_{deg}) \qquad (4.3.5)$$

where P is the total atmospheric pressure in millibars, T is the absolute temperature in degrees kelvin (such that $T=t^{o}c+273$) and e is the (absolute humidity) partial pressure of water vapour. Sometimes, the water-vapour content of air is expressed in terms of specific humidity S (which is the mass of water vapour in grams per kilogram of air) or relative humidity R_H expressed in percent.

Absolute humidity H is related to S and R_H as follows

$$H = (S_{g/kg}\ P_{mbar})/(623-0.377\ S) \qquad (4.3.6)$$

and $$H = (E_{r\ mbar}\ \ R_H/100)\ mb \qquad (4.3.7)$$

where E_r is the pressure found from charts of water vapour which will saturate the air at a given temperature.

It is obvious from the equation (4.3.4) that the water vapour plays a dominant role in tropospheric refractivity. It should be noted however that with increasing temperatures the wet part of refractivity steeply increases because for a given relative humidity, the water vapour pressure incrases rapidly with increasing temperature. The portion by volume of water vapour at ground level varies from near zero levels at the poles to more than 6% in the tropics. It is also interesting to note that the mass of water vapour in tropics may exceed 30 grams per cubic meter while even during torrential rains the atmosphere has less than 10 grams of liquid water per cubic meter.

The water vapour distribution especially in tropics, assumes great significance because of its role in modifying turbulence-related refractivity fluctuations, in causing attenuation at frequencies above 15 GHz and in producing large refractivity gradients leading to anomalous propagation conditions [16]. Different types of anomalous propagation will be discussed later.

4.4 Atmospheric Refraction and Refraction of Waves Through Troposphere

In the troposphere, because of the inhomogeneity of refractive index, radio phase velocity varies with position and different portions of a wave front pass through paths of different length during a period, forming a new and tilted wave front i.e. the radio propagation direction changes. This phenomena is known as atmospheric refraction [16].

Inhomogeneities in the troposphere have a direct bearing on the atmospheric refraction. Atmospheric refraction consists in that a ray of light (and, similarly radio ray) encounters variations in the atmospheric refractive index along its trajectory that cause the ray path to become curved.

We derive an expression for the radius of curvature of the ray path in the troposphere. For simplicity, we neglect the effect of the curvature of the earth's surface and assume that the troposphere consists of strata, or planes, each with a constant value of N and parallel to the flat earth. We consider two such planes (Fig.4.4.1) spaced at a distance dh apart. The refractive index of the lower plane or surface is n and that of the upper surface, n+dn.

A ray, incident upon the lower surface at an angle ø and refracted along the distance dh, will fall upon the upper surface at an angle ø+dø. Since at point b the element of the ray path is turned through the angle dø relative to the element of the ray path at point a, the same angle is obtained between the normals to these path elements, that is, the angle at the centre 0 of the curavature.

The sought radius of curavature R is given [15] by

$$R = (ab/d\phi)\ m \tag{4.4.1}$$

From the triangle abc we get

$$ab = dh/\cos(\phi+d\phi) \approx dh/\cos\phi\ \ m$$

whence,

$$R = dh/\cos\phi d\phi\ m \tag{4.4.2}$$

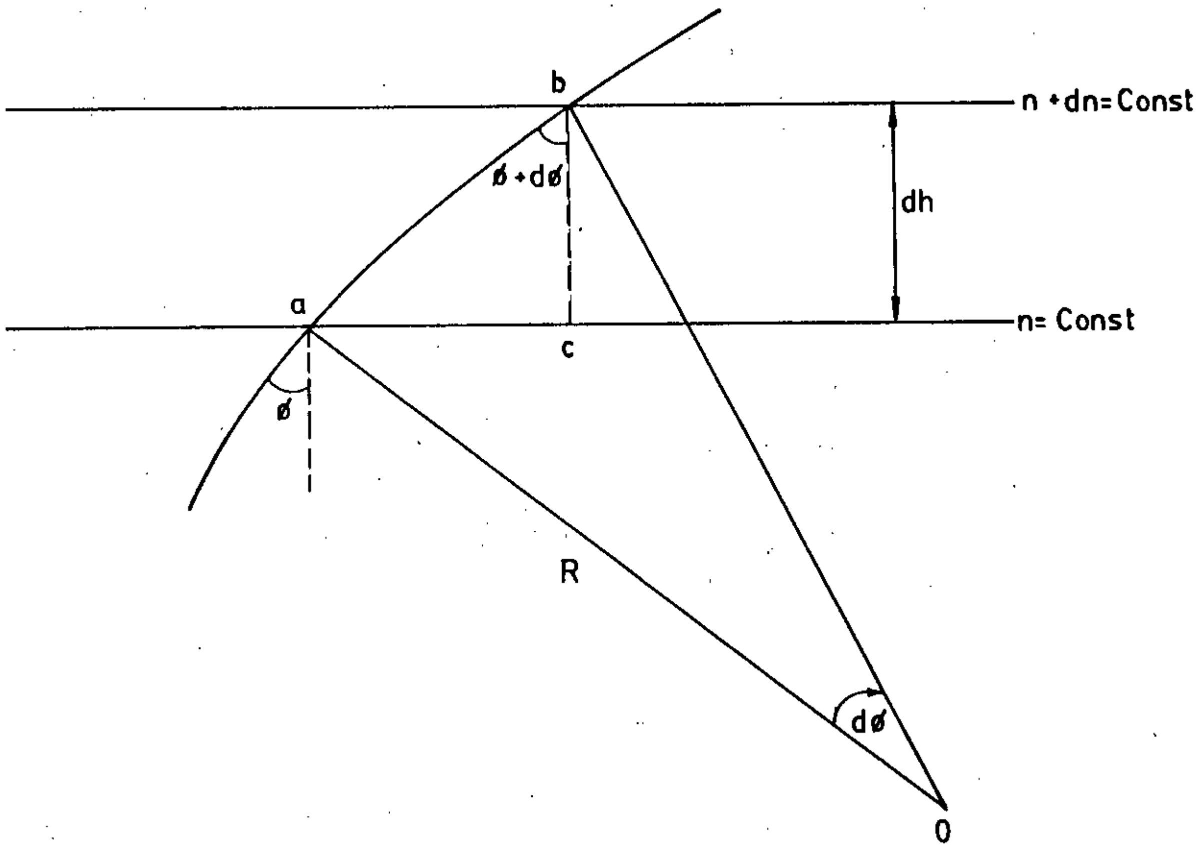


Fig.4.4.1: Determining the radius of curvature of the wave path.

In media with a gradually varying refractive index the law of refraction must hold at any point along the propagation path including points a and b in our example. Therefore, we may write

$$n \sin\phi = (n + dn)\sin(\phi + d\phi).$$

Writing out the right hand side and neglecting the second order infinitesimals, we get

$$n \sin\phi = n \sin\phi + n \cos\phi \, d\phi + \sin\phi \, dn$$

or, $\cos\phi \, d\phi = - \sin\phi \, dn/n$

substituting it in equation (4.4.2) gives

$$R = n/\sin\phi(-dn/dh) \text{ m} \qquad (4.4.3)$$

In the earth's atmosphere, n only differs from unity by a few parts in 10,000. However, we usually always deal with links between points at altitude which are much smaller than the length of the trajectory [22]. The electromagnetic rays following this trajectory are only slightly inclined to the horizon. Thus without any detriment to the accuracy of calculation, we may set

$$n \approx 1 \text{ and}$$

$$\sin\phi \approx 1$$

very nearly in the expression (4.4.3) just derived.

As a result, the expression for the radius of curvature of the ray path may be further simplifed as follows

$$R = 1/-dn/dh \quad =(10^6/dN/dh) \qquad (4.4.4)$$

From (4.4.4) it is seen that in the lower troposphere the radius of curvature of the ray path is decided by the lapse rate of refractive index with height and not by its absolute value. The minus sign of the derivative implies that the radius of curvature will be positive, i.e. the propagation path will be convex only when the refractive index decreases with height [15]. Different types of refraction may occur depending on the different refractive index gradient which is discussed later.

4.5 Effective Earth's Radius

In the microwave frequency range, transmission is accomplished largely over optical distances by the direct and ground reflected waves. Transmission occurs almost exclusively within the troposphere. The troposphere is not homogeneous and thus due to the variations, as discussed earlier, the troposphere causes a very gentle refraction of the direct wave. To a small extent, the wave follows the curvature of the earth and causes transmission to occur over larger distances than would be predicted by ordinary line of sight calculations. Calculations of station coverage are usually and more easily, made by assuming straight line transmission. The effect of atmospheric refraction is then accounted for by assuming the earth to have a larger radius than it actually does. The specification of this effective radius depends upon the character of the troposphere.

Assuming a standard atmosphere the fictitious radius of the earth is selected in such a way that the straight line drawn from the transmitter is tangent to this hypothetical earth at the same distance from the transmitter as the actual refracted signal is tangent to the actual earth.

Fig.(4.5.1a) and (4.5.1b) show the relationship between the actual curved ray over the true earth and the assumed straight line over the fictitious earth.

In fig (4.5.1b) an earth appropriately larger than the actual earth is assumed so that the curvature of the radio ray may be absorbed in the curvature of the effective earth, thus leaving the relative curvature of the two the same and allowing radio rays to be drawn as straight lines over this effective earth rather than curved lines over the true earth.

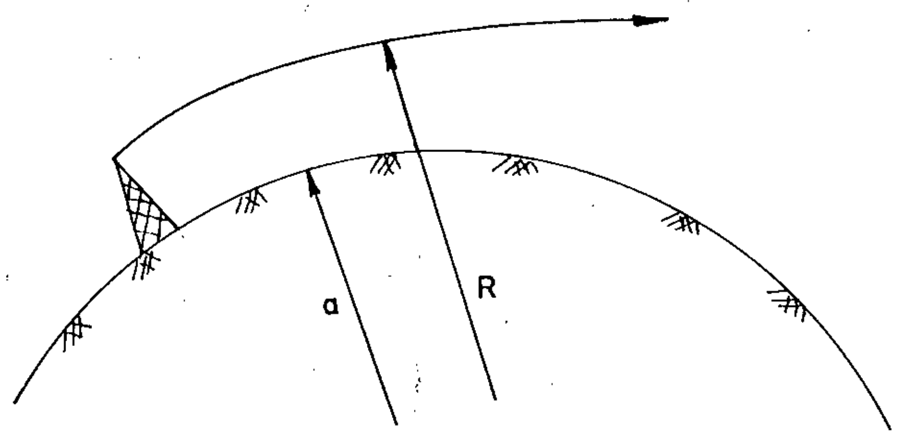


Fig.4.5.1a: Curved ray over actual earth.

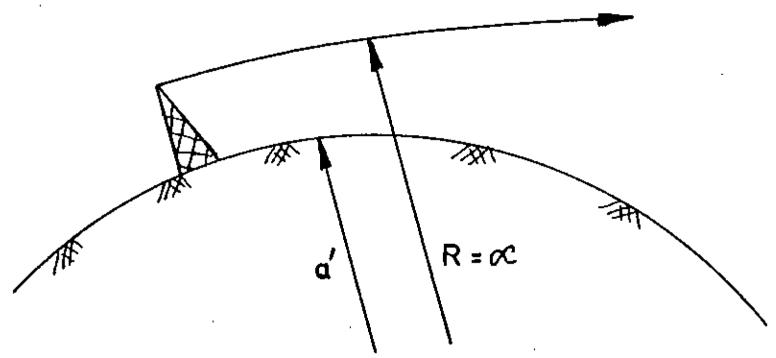


Fig.4.5.1b:Assumed straight ray over fictitous earth.

In analytical geometry, the relative curvature is defined as the difference $1/a - 1/R$.

Equating the relative curvatures for the situations shown in fig. (4.5.1a) and (4.5.1b), we get

$$1/a-1/R = 1/a' - 1/\infty$$

whence the effective earth radius is

$$a' = a/(1-a/R)m \qquad (4.5.1)$$

Substituting equation (4.5.1) in equation (4.4.4) gives

$$a' = a/ \{1+ a(dN/dh)10^{-6}\} \; m \qquad (4.5.2)$$

The effective earth's radius factor k, which is defined as the ratio of the effective earth's radius to the true earth's radius, is given by

$$k = a'/a = 1/\{1 + a\,(dN/dh)10^{-6}\} \qquad (4.5.3)$$

For standard atmospheric refraction, $dN/dh = -4 \times 10^{2}\ m^{-1}$. Substituting it and the numerical value of the true earth's radius [15]

$a = 6.37 \times 10^{6}$ in equation (4.5.2) and equation (4.5.3) gives

$a' = 8500$ Km

$k = 4/3$

A strong tendency is seen for k-value to lie in the neighborhood of 1.3 or 1.4 over much of the country, particularly during the winter months. k can assume numerical values covering a considerable range [17].

A great variability is observed in the median value of k near the equator. For example median values of k in the range 1.3 - 1.8 have been observed in the equatorial region of India [16] and a mean value of k=1.5 has been observed for the equatorial region of Africa. Kolawole and Owonubi [16] also found mean k= 1.43 and 1.22 for the rainy and dry seasons of tropical Africa respectively and k=1.20 for the desert.

From equation (4.5.3), we compute some of the typical values of k for different values of refractivity gradient dN/dh, shown in table (4.5.1) and this variation is plotted in Fig.(4.5.2).

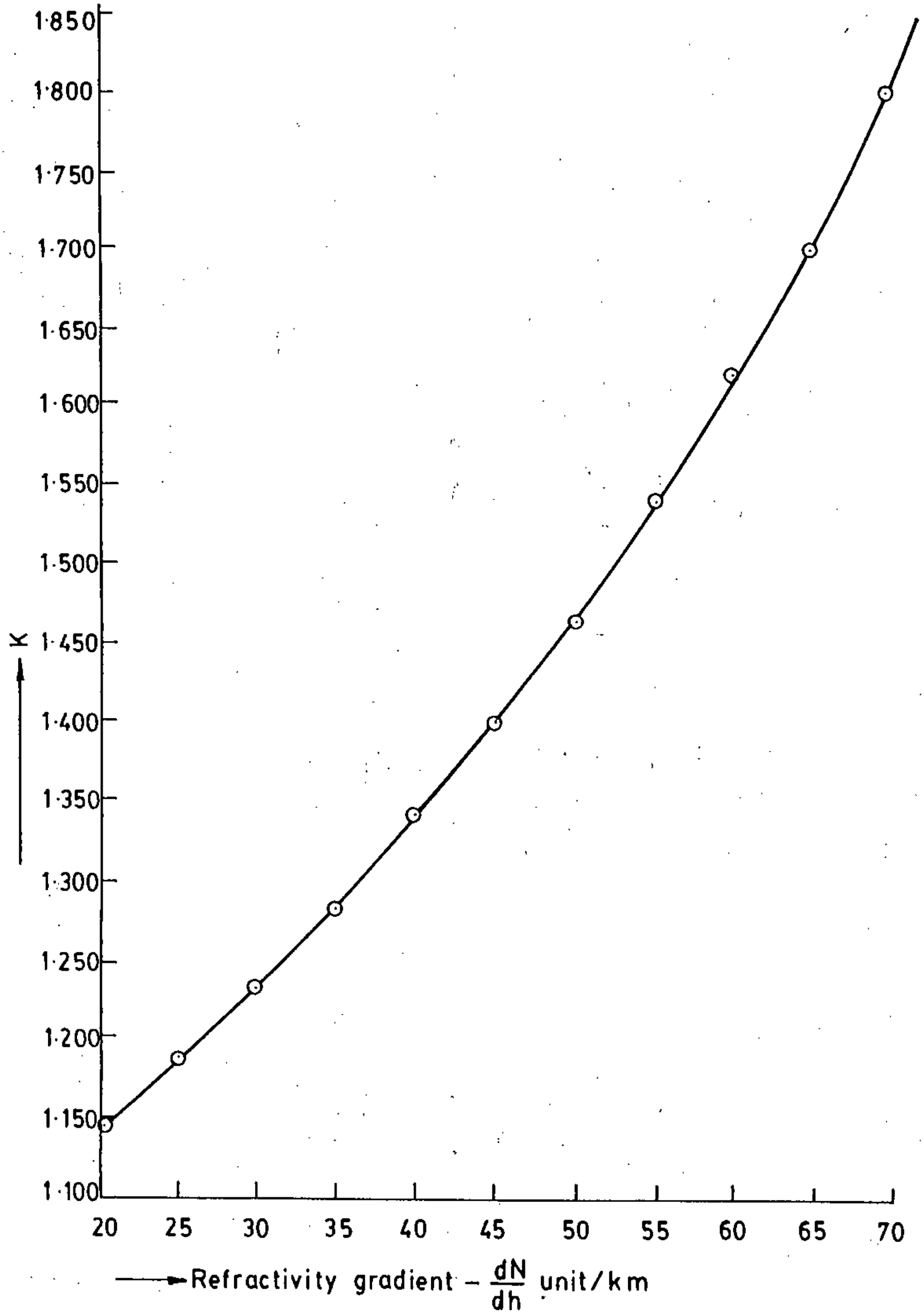


Fig.4.5.2: Variation of effective earth's radius factor 'K' with refractivity gradient.

TABLE (4.5.1)

Values of K for different refractivity gradients.

No. of obs.	-dN/dh (in N/Km)	K(=a'/a)	a' km	a km
1	20	1.146	7300	
2	25	1.1894	7577	
3	30	1.236	7875	
4	35	1.287	8198	
5	40	1.342	8548	
6	45	1.402	8930	6370
7	50	1.467	9347	
8	55	1.54	9805	
9	60	1.62	10310	
10	65	1.707	10871	
11	70	1.805	11496	

Where,

Earth Radius, a=6370 km

Refractivity Gradient, (dN/dh)=-40 N/KM (STANDARD)

Effective Earth Radius, a'=8500 km

This shows the great importance of having clear knowledge of refractivity of troposphere over a particular region for various periods of the year. Without this, the design of a microwave link would not be true to the actual scenario.

4.6 Forms of Atmospheric Refraction

Meteorological condition in the atmosphere may lead to a refractive index distribution with height materially differing from that of standard atmospheric state. Obviously the effect of refraction will likewise be different. Several forms of refraction will be considered here based on the equations for N, dN/dh, R, a and k. For convenience, three of these equations are written again;

$$R = 10^6/(-dN/dh) \text{ in metre} \qquad (4.4.4)$$

$$a' = a/(1-a/R) = a/\{1+a(dN/dh)10^{-6}\} \text{ in metres} \qquad (4.5.1) \,\&\, (4.5.2)$$

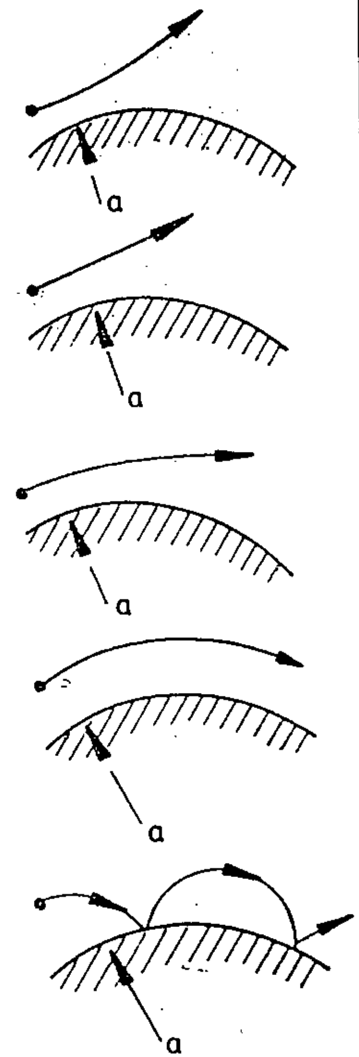
$$K = a'/a \qquad (4.5.3)$$

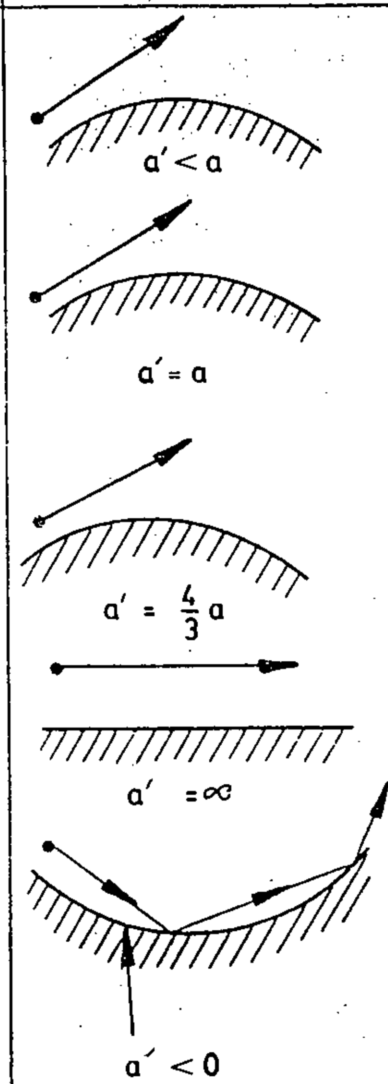
Above all, atmospheric refraction may be negative, zero or positive.

For each of these three forms, Table (4.6.1) gives either numerical values of dN/dh, R, a and k or their limits [15]. The last but one column presents sketches of ray path for the various forms of refraction and the last column illustrates propagation over the effective earth (that is over the 4/3 earth). In the latter case, the ray paths are straight line segments.

Table: 4.6.1: Various forms of atmospheric refraction.

No.	Form of refraction	$\frac{dN}{dh}$, m^{-1}	R,m	a′ m	k	Actual path	Equivalent path
A	**Negative**	>0	<0	$<6.37 X 10^6$	<1		
B	Zero	0	∞	$6.37 X 10^6$	1		
C	Positive						
C1	Sub-refraction	0 to 0.04	∞ to 2.5 X 10^7	$6.37 X 10^6$ to 8.5 X 10^6	1 to 4/3		
C2	Standard	-0.04	2.5 X 10^7	8.5 X 10^6	4/3		
C3	Augmented	-0.04 to -0.157	2.5 X 10^7 to 6.37 X 10^6	8.5 X 10^6 to ∞	4/3 to ∞		
C4	Critical	-0.157	6.37 X 10^6	∞	∞		
C5	Super-refraction	<-0.157	<6.37 X 10^6	<0	<0		





Negative refraction

Refraction is referred to as negative when $dN/dh > 0$, that is, when instead of decreasing, N increases with height. As follows from equation (4.4.4) in this case $R<0$, that is the ray paths are curved upwards. In other words, the radio wave moves away from the earth's surface and the line-of-sight range and the range of propagation decreases accordingly. Negative refraction is an infrequent occurrence.

Zero Refraction:

Sometimes weather conditions may be such that N will remain fixed in an interval of altitudes hence $dN/dh = 0$. This will be zero refraction, dealt with in the second line of Table (4.6.1)

Positive refraction:

Refraction is referred to as positive when $dN/dh < 0$, that is when N decreases with height. The ray paths are now curved toward the earth and there is an increase in the range of propagation.

Positive refraction may be devided into -

- Subrefraction (when the bending of rays is smaller than in standard refraction.)
- Standard refraction (already discussed) and described in line C2 of the table (4.6.1)
- Augmented (In which the bending of rays is greater than in standard refraction, but stops short of the critical one).
- Critical refraction (In which the radius of curvature of the ray path is equal to the earth's radius).

By definition, with critical refraction R=a, substituting the numerical value of the earth's radius for R in equation

$R = 10^6/-dN/dh$ gives

$dN/dh = -10^6/6.37 \times 10^6 = -0.157\ m^{-1}$ (Line C4 in table (4.6.1

It follows from the equation (4.5.1) that the effective earth's radius takes infinitely large values, that is, the earth reduces to a plane. Under condition of critical refraction a horizontally directed ray will be propagated at a fixed height above the earth's surface. That is, it will travel all the way around it.

- Superrefraction (in which the bending of rays is more pronounced than in critical refraction).

With super-refraction, the radius of curvature of the ray path is smaller than the earth's radius, and the rays leaving the transmitting aerial at small angles of elevation will undergo total internal reflection in the troposphere and return to the earth at some distance from the transmitter (C5 in table 4.6.1). On reaching the earth's surface and being reflected from it, the waves can skip large distances, thereby giving abnormally large range beyond the line of sight due to multiple reflections. It is interesting to consider the respective ray path over the 4/3 earth. According to equation (4.5.1), when $R<a$, the effective earth's radius is a negative quantity. That is, the earth must be approximated by a concave surface. It is seen from the last heading of line C5 in Table (4.6.1), the straight rays, after multiple reflections from a concave surface, may reach extremely remote points.

Super-refraction may occur in a limited height interval in the troposphere where

$$dN/dh < -0.157 \ m^{-1}$$

With super-refraction, the refractive index decreases at a rate which is four times the lapse rate of standard refraction.

Let us consider the weather conditions that are conducive to super-refraction. By differentiating equation (4.3.5) for N with respect to height we get,

$$dN/dh = 77.6 \; [1/T \; dP/dh - (P/T^2 + 9620e/T^3) \; dT/dh + 4810/T^2 \; de/dh] \; m^{-1} \qquad (4.6.1)$$

From the above equation, it follows that the vertical gradient of refractive index, dN/dh at a height h and the lapse rate of this gradient, are mainly determined by the gradients of pressure, temperature and humidity. Although P,T and e vary with height, their numerical values have a much smaller effect on the gradient of refractive index.

The pressure of the air decreases with height always, and its gradient is dependent on weather conditions only slightly. Therefore, the first term in equation (4.6.1) is nearly constant and always negative. In contrast, the gradients of temperature and humidity are subject to strong variation - they are markedly dependent on weather conditions and may even change sign. In the standard atmosphere the temperature and humidity always decrease with height, for which reason the two derivatives dT/dh and de/dh are negative. Therefore, the absolute value of dN/dh, which always takes a minus sign, is obtained by subtracting the absolute value of the second term from the sum of the absolute values of the first and third terms in the (-) - (-) + (-) sequence.

Obviously, with temperature inversion, dT/dh > 0, and the second term in equation (4.6.1) takes a minus sign. Now the absolute value of dN/dh is obtained by adding together three negative terms in the (-)-(+)+(-) sequence.

Thus, among the conditions conducive to super-refraction, that is abnormally high negative values of dN/dh, are above all temperature inversions and an extremely high lapse rate of humidity with height. Of the two factors, temperature inversion is the decisive one. Temperature inversions may be caused by advection process, cooling of the earth's surface through radiation and compression of air masses [15].

4.7 Ducting

In meteorological conditions where over a large horizontal area the atmospheric refractive index decreases sharply with height, radiowaves can be trapped and experience low-loss propagation over long distances. This condition is known as tropospheric ducting. Although it is a frequent phenomena in some places and under certain meteorological conditions, it is not sufficiently reliable mode for communication purpose. However it can cause strong interference fields well beyond the horizon and can also cause severe fading on line of sight paths [24].

The first necessary condition for a duct to occur is that the radio refractive index gradient shall be equal to or more negative than -157 N/Km. This causes the rays to reamin close to the earth's surface beyond the normal horizon (even if the radio refractive index gradient is not quite sufficiently negative to produce a duct, some radio energy will pass beyond the normal radio horizon).

The second necessary condition is that the gradient should be maintained over a height of many wavelengths [24].

To understand ducting, the concept of modified radio refractive index M, when the refractivity gradient is no longer constant with height is introduced here.

The actual refractive index in terms of a modified radio refractive index M is defined by the relation

$$M = (n - 1 + h/a) \times 10^6 \qquad (4.7.1)$$

where, n = refractive index

h = height above ground

a = radius of earth = 6.37×10^6 m

$$M = (N + h/a \times 10^6) \qquad (4.7.2)$$

The aspect of M that is of importance in radio propagation is the variation dM/dh of M with height [20].

Then $dM/dh = dN/dh + 157$ N/Km (4.7.3)

i.e. dM/dh is positive for N-gradients less negative than -157 N/Km, for which rays are refracted away from the flat earth, and negative for N gradients more negative than -157 N/Km, for which refraction is towards the flat earth and which can therefore cause ducting. The gradient of M is consequently a useful indicator as to whether ducting may occur [24].

When n is independent of height, as is always the case at quite high altitudes then M increases by 0.048 unit per feet i.e. 157 N/Km. However near the surface of the earth n over land usually decreases linearly with increasing height. The value of M near the earth's surface then increases linearly at a constant rate that is less than 0.048 units per feet. For typical conditions of this type the value of dM/dh approximates 0.036 units per feet;this condition is termed the standard atmosphere and result in M curve shown in Fig. (4.7.1a).

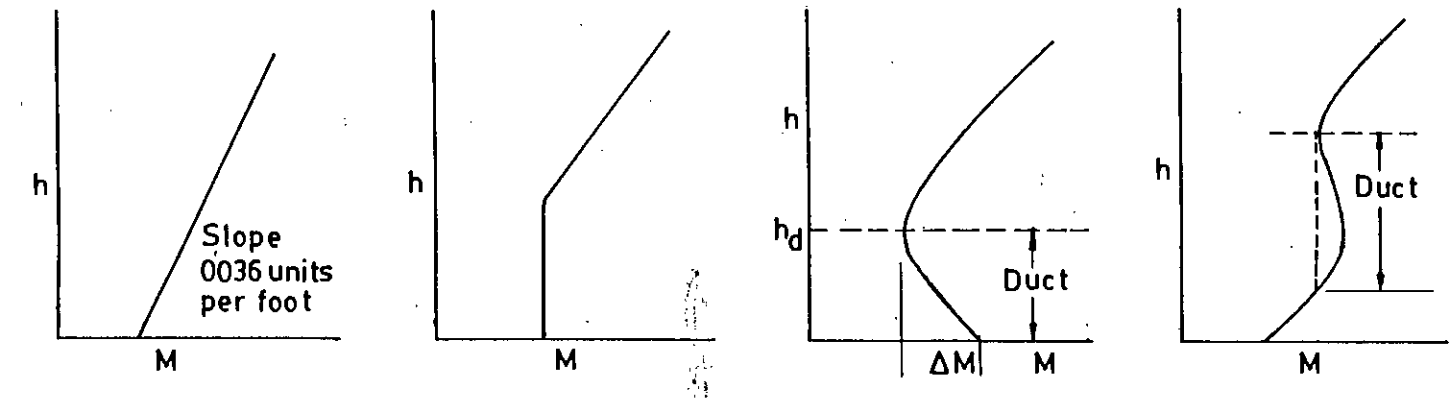
When air masses that differ in temperature and moisture content overlay each other, the M curve will no longer vary linearly with height. Various types of situations that may result are illustrated in Fig.(4.7.1c) & (4.7.1 d). However, at heights much greater than in Fig. (4.7.1) the M curve will settle down in all cases (including) to a steady increase of 0.048 unit per feet.

When the decrease to refractive index with height is at such a rate that M remains unchanged with height as in Fig. (4.7.1b) then the curvature of the ray is the same as that of the earth.

On the other hand, if n increases with height the ray path will be bent away from the earth.

An M curve of the type illustrated in fig.(4.7.1.c) occurs when the moisture content of the air at the surface of the ground is very high but decreases rapidly with increasing height. In the region where dM/dh is negative as in Fig.(4.7.1 c) the curvature of the rays passing through the atmosphere is greater than that of the earth. As a result, energy originating in this region and initially directed approximately parallel to the earth's surface, tends to be trapped and to propagate around the curved surface of the earth in a series of hops involving successive earth reflection as illustrated in fig.(4.7.2) by rays a,b and c.

When duct propagation exists, energy will travel great distances around the curvature of the earth with relative low attenuation. Here the energy represented by rays a, b & c lying within the angular range ψ about the horizontal is trapped within the duct, while rays such as d and e that are outside of this angular range ultimately pass out of the duct to the space above.



(a) Standard atmosphere (b) Refraction at lower heights equals earth's curvature (c) Simple surface duct (d) Elevated duct

Fig.4.7.1: Variation of modified refractive index M with height for typical cases. The examples shown are for conditions near the surface of the earth, at great heights the M curve always assumes a slope of 0.048 units per feet, corresponding to a constant refractive index.

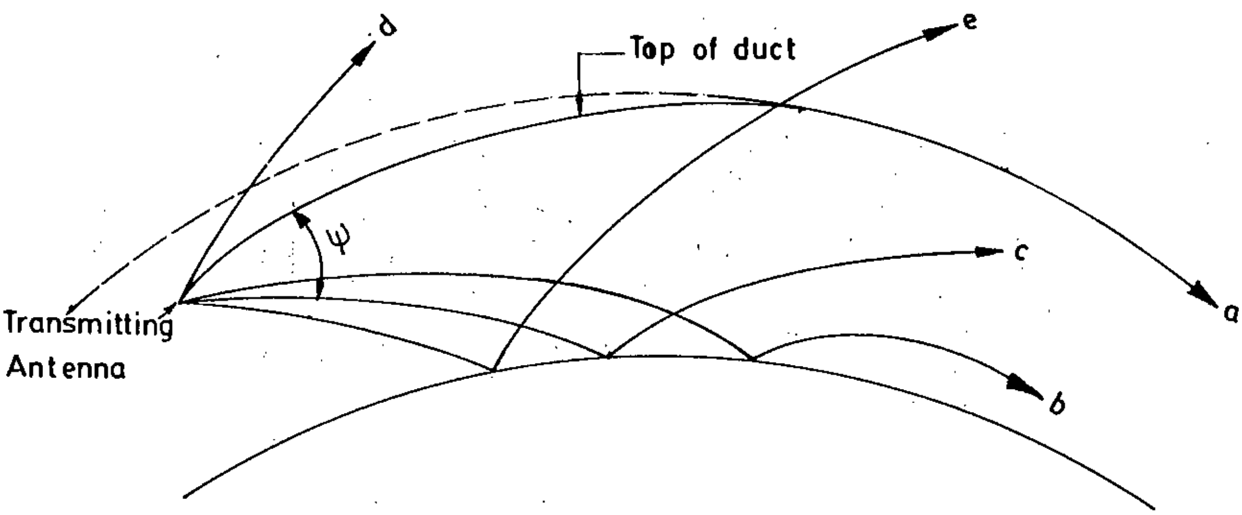


Fig.4.7.2: Ray concept of duct propation.

Under certain meteorological conditions the M curve will have the character as in fig.(4.7.1d). This results in the formation of an elevated duct. When the transmitting antenna is such as to place it within such a duct, energy will propagate in the duct to points well beyond the normal horizon with surprisingly low attenuation. By locating a receiving antenna within the duct, it is then possible to obtain a strong signal at distances such that the received field would be extremely weak in the absence of the duct [20].

Some charts showing anomalous radio propagation due to different meteorological conditions are shown in Appendix (C).

4.8 Calculation of Atmospheric Bending of Radio Rays

When a radio wave passes through the different layers of atmosphere it experiences a bending due to the variation of refractive index at different height from the earth surface. Most of the bending of a radio ray takes place at low elevations. To calculate the bending of ray transmitted from point(1) and passing through the atmosphere to the point (2) we have the geometry as in Fig.(4.8.1). If it is assumed that the refractive

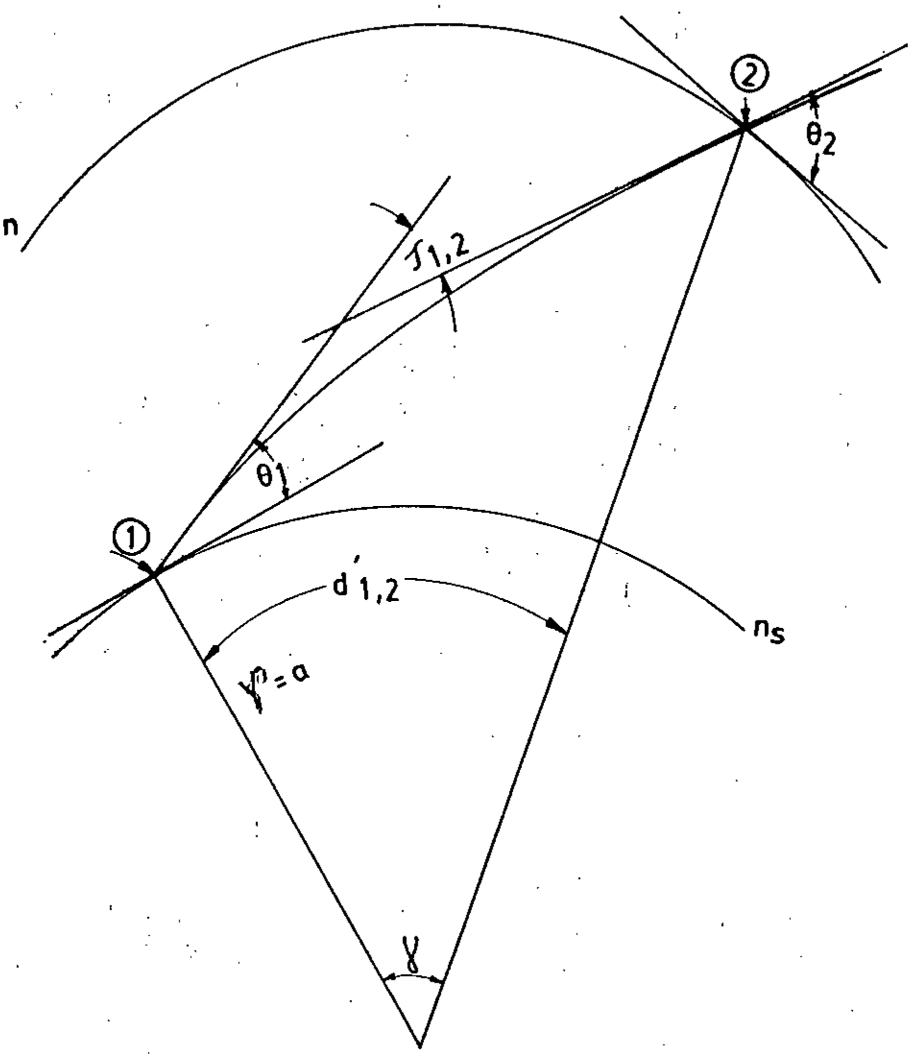


Fig.4.8.1: Geometry of radio ray refraction.

index is spherically stratified with respect to the earth, then Snell's law may be expressed in cylindrical co-ordiantes as [2];

$$nr\ \cos\theta = n_o\ r_o\ \cos\theta_o = \text{Constant.}$$

$$\text{or, } (1+N \times 10^{-6})(a+h)\ \cos\theta$$

$$= (1+ N_s \times 10^{-6})\ (a+h_s)\ \cos\theta_o \qquad (4.8.1)$$

where the radial distance from the centre of the earth r equals (a+h). The zero or s subscript refer to the initial values at the earth's surface. Equation (4.8.1) may be used to calculate the local elevation angle, θ at any point along the ray and thus affords a complete description of the ray path.

In fig (4.8.1) arc distance $d_{1,2}$ subtends an angle γ at the earth's centre. The ray makes an angle θ_1 with the horizontal at one end and another angle θ_2 of the horizontal at the other end, bending through an angle $\tau_{1,2}$. If we denote by n_1 and n_2 the values of the refractive indexes corresponding to r_1 and r_2 and h_1 and h_2 the heights above sea levels, respectively, we have

$$n_2 r_2 \cos\theta_2 = n_1 r_1 \cos\theta_1$$

and

$$n_2 = n_1 + \Delta n$$

$$r_2 = r_1 + \Delta r$$

$$\text{and } \theta_2 = \theta_1 + \Delta\theta$$

where Δn, Δr and $\Delta\theta$ are infinitesimals.

Then $n_1 r_1 \cos\theta_1 = (n_1 + \quad n)(r_1 + \quad r)\cos(\theta_1 + \theta)$

and in the limit as r approaches zero, this becomes

$$n_1 r_1 \cos\theta_1 = (n_1 + dn)(r_1 + dr)(\cos\theta_1 - d\theta \sin\theta_1)$$

Expanding the above equation and omitting the products of differential we get -

$$n_1 r_1 \cos\theta_1 = n_1 r_1 \cos\theta_1 + n_1 dr \cos\theta_1 + r_1\, dn \cos\theta_1 - n_1 r_1\, d\theta \sin\theta_1$$

$$n_1 r_1 d\theta \sin\theta_1 = n_1\, dr \cos\theta + r_1\, dn \cos\theta_1$$

$$n_1 r_1 d\theta \tan\theta_1 = n_1 dr + r_1\, dn$$

$$\tan\theta_1 d\theta = dr/r_1 + dn/n_1$$

Finally we have the differential equation

$$\tan\theta\, d\theta = dn/n + dr/r$$

$$d\theta = (dn/n)\cot\theta + (dr/r)\cot\theta$$

Noting that $dr \cot\theta / r = rd / r = d$ and, from geometry, $d\theta = d - d\tau$, the expression for the bending of a radio ray

$$d\tau = -(dn/n)\cot\theta$$

$$\text{or, } \tau_{12} = -\int_{n_1}^{n_2} \cot\theta\, dn/n \qquad (4.8.2)$$

Equation (4.8.2) defines downward bending as a positive qunatity.

This equation (4.8.2) provides a convenient means for calculating the bending of a radio ray that is simply the angle formed by the intersection of the tangents to the ray at the two points being considered. The bending of radio rays is obtained by numerical evaluation of equation (4.8.2).

In the next chapter we obtain the surface refractivity for different periods of the year i.e. winter, pre-monsoon, monsoon and autumn for different regions of Bangladesh.

CHAPTER 5

ATMOSPHERIC REFRACTIVITY OF BANGLADESH IN DIFFERENT SEASONS AND ITS VARIATIONS

5.1 Introduction

This chapter deals with radio refractive indices for regions of Bangladesh and its variations during different seasons. Different types of variations of Radio Refractive Index is considered here and these variations are shown by graphical representations over different seasons at different places. The maximum and minimum RRI is shown in the form of bar-graph over eleven years i.e. from 1977 to 1987 for the months of January, April, July and October.

5.2 Change of Radio Refractive Index With Variations of Pressure, Temperature and Relative Humidity

To find the change of theoretical values of the radio refractive index for different combinations of pressure, temperature and relative humidity, we use the generally accepted relationship -

$$N = 77.6/T\ (P + 4810e/T) \qquad (5.2.1)$$

where

P = Atmospheric pressure (mb)

T = Atmospheric temperature (^{o}k)

e = Water vapour pressure (mb)

For calculating the radio refractive index by using this formula, there are three variables as mentioned above. So the radio refractive index is calculated here in different ways keeping one variable constant and varying the second variable rapidly for each step up value of the third variable. Again keeping the first variable cosntant the next two variables are varied by interchanging their positions i.e. one of these two variable which was varied rapidly, it is now varied step by step and for the third variable it's rapid variation is considered. For each set of combinations the figures are drawn showing the variation of refractivity in relation to the rapid changing variable. Different cases are considered for different combinations of these three variables below -

CASE - 1: Temperature Constant

Here, the atmospheric temperature is kept constant at an average value 20^{o}C and by rapid variation of relative humidity and pressure two sets of curves are drawn.

For the rapid variation of one parameter (say, atmospheric pressure) the other parameter (relative humidity) is varied step by step. One set of curves (Fig. (5.2.1a)) for refractivity is obtained with this variation. Similarly varying relative humidity rapidly and the atmospheric pressure step by step, another set of curves (Fig. (5.2.1b)) for refractivity is obtained.

From the first set of curves it is seen that the refractivity varies linearly with the variation of pressure for a fixed value of relative humidity. Similar type of variation is observed from the second set of curves when the relative humidity is varied rapidly with a fixed value of pressure.

CASE - II: Relative Humidity Constant

Here the relative humidity is kept constant at an average value of 70% and pressure and temperature are varied rapidly increasing temperature and pressure step by step respectively. Two cases considered here shows very interesting results.

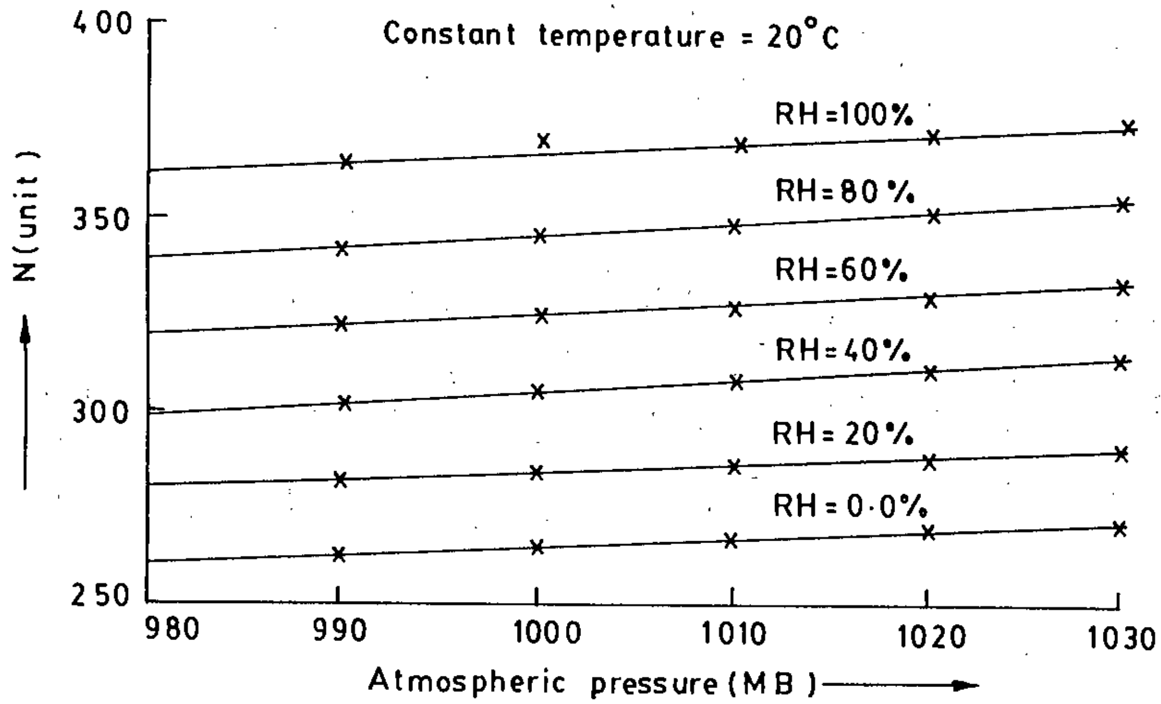


Fig.5.2.1a:Calculated values of RRI plotted against atmospheric pressure at different relative humidity.

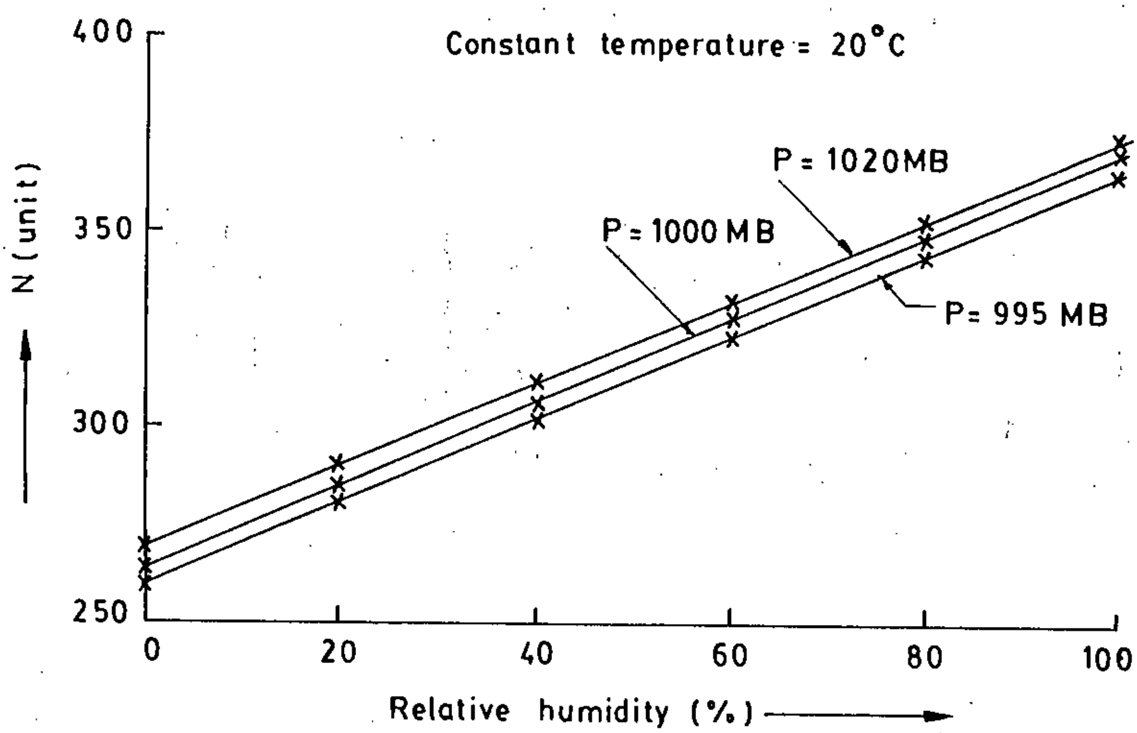


Fig.5.2.1b: Calculated values of RRI plotted against relative humidity at different atmospheric pressure.

When the temperature is increased by $10^{o}C$ at each step and for each step of temperature increment, the pressure is varied rapidly; the ploting of the refractivity obtained here (Fig.(5.2.2a)) shows a linear variation of refractivity. Also the spacing between the linear curves increases more and more for the same increment of temperature ($10^{o}C$) step by step; though it seems that the curves should have equal spacing for equal increment of temperature at each step. The reason behind this is as the temperature increases linearly the saturated vapour pressure increases more rapidly and the increment becomes more prominent as the temperature increases. So as the temperature increases linearly their corresponding saturated vapour pressure increases rapidly and it has the dominating effect upon temperature.

Again, when the pressure is varied step by step (10 mb) by keeping the relative humidity constant the refractivity increases rapidly as the temperature increases linearly as in Fig (5.2.2.b)

Also, for the increase of pressure step by step the curves are shifted upwards and are almost equally spaced for equal increment of pressure.

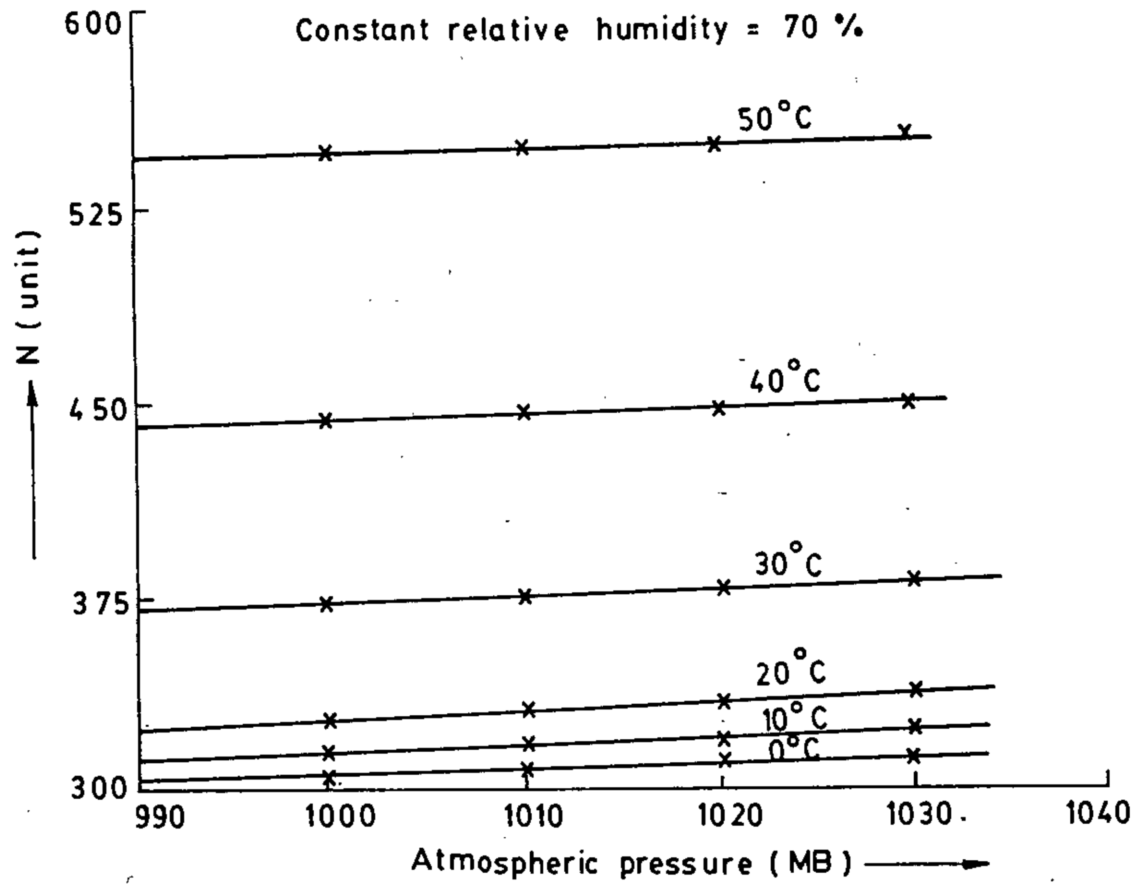


Fig.5.2.2a: Calculated values of RRI plotted against atmospheric pressure at different temperatures.

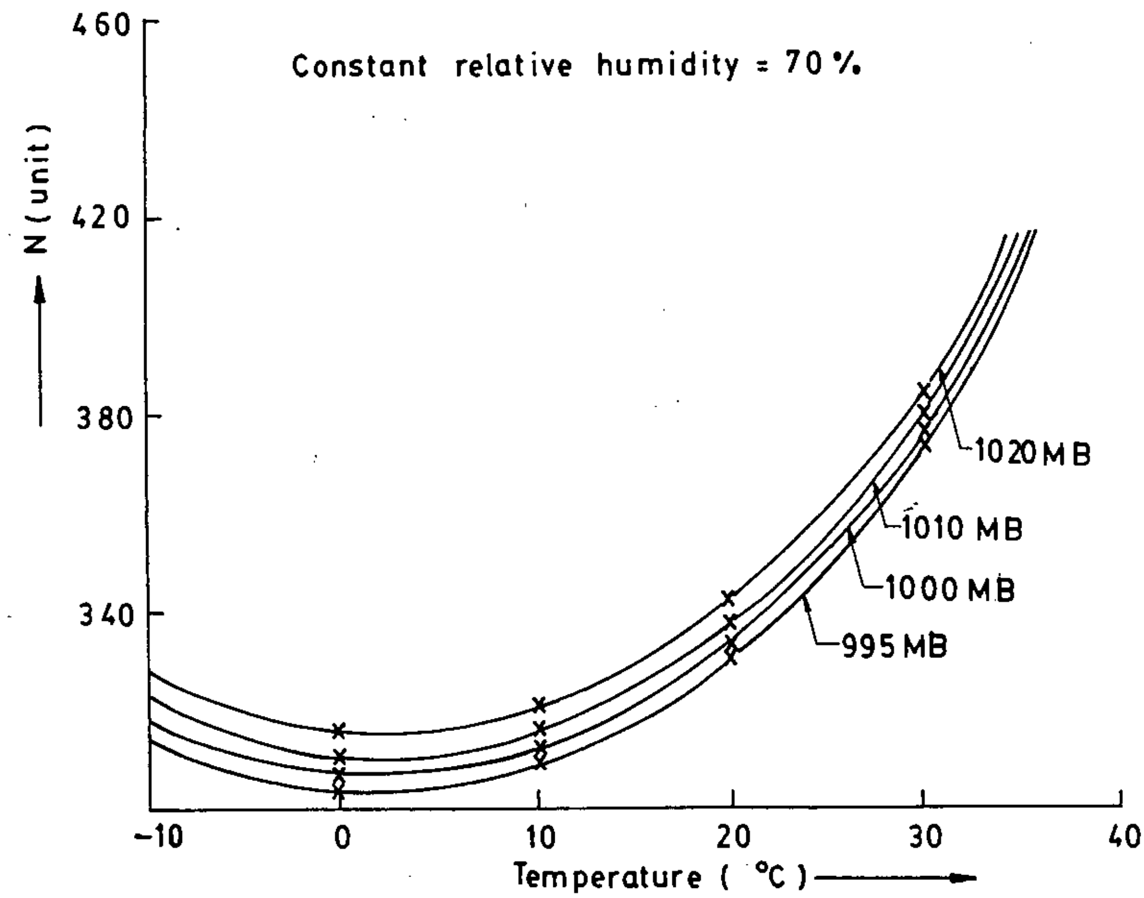


Fig.5.2.2b: Calculated values of RRI plotted against temperature at different atmospheric pressure.

CASE - III: Atmospheric Pressure Constant

Here,the atmospheric pressure is kept constant at an average value of 1010.0 mb and the temperature and relative humidity are varied rapidly for the step by step increase of relative humidity and temperature respectively. Here also two interesting cases occur.

For step by step increase of relative humidity, the temperature is varied rapdidly and the refractivity also increase rapidly. For the same increment of temperature the variation of refractivity is smaller at low temperature zone than that at high temperature zone as seen in Fig. (5.2.3a).This is due to the fact that as the temperature increases, the corresponding increase in the saturated vapour pressur is more which cause the rapid increase in the radio refractive index in the higher temperature zone. Again when the temperature is varied step by step by 10^{o}C keeping pressure (1010.0 mb) constant, the refractivity varied linearly as in Fig. (5.2.2.b). But an interesting phenomenon occurs at lower relative humidity described below. Above 20% relative humidity as the relative humidity increases, the refractivity also increases linearly and at high temperature it

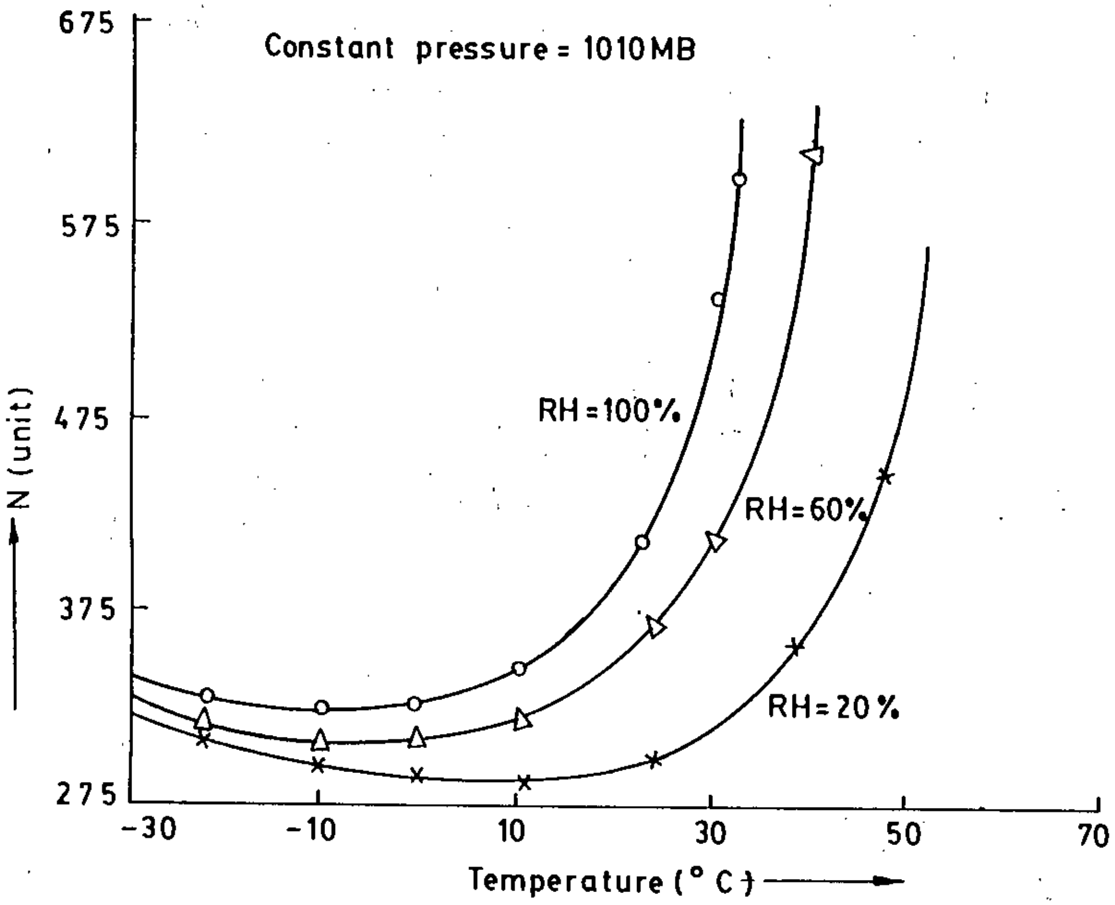


Fig. 5.2.3a: Calculated values of RRI plotted against temperature a different relative humidity.

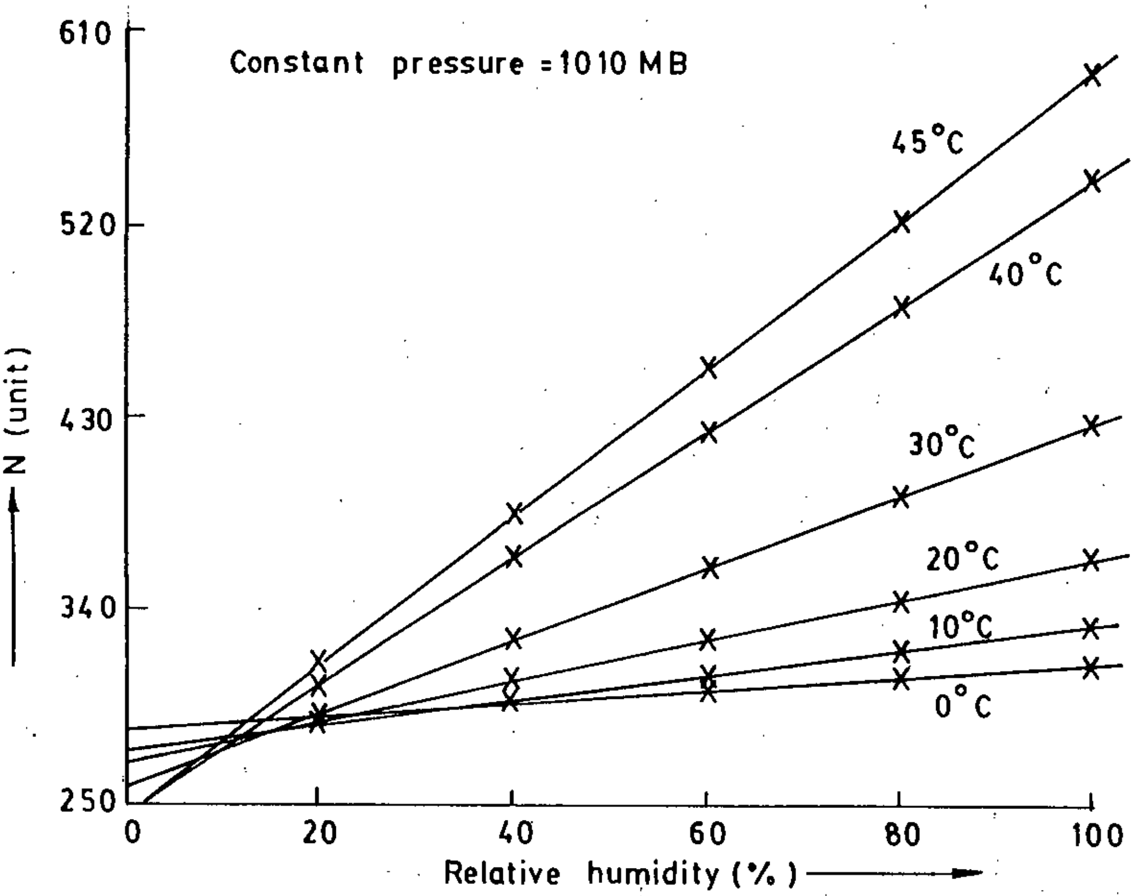


Fig.5.2.3b: Calculated values of RRI plotted against relative humidity at different temperatures.

increases more as the saturated vapour pressure is larger at higher temperature.

At about 20% below the relative humidity, the refractivity is more at lower temperature than at higher temperature for the same relative humidity. This is an exceptional case, becasue normally at higher temperature the refractivity is higher. To understand this anomalous behaviour, first we consider the behaviour of the two terms of the radio refractive index expression i.e. $N = (77.6\ P/T) + 3.73 \times 10^5\ e/T^2$.

The terms $77.6P/T$ and $3.73 \times 10^5\ e/T^2$ are sometimes referred to as N_{dry} and N_{wet} respectively and the refractivity N is the summation of the two above terms and their variation with temperature and relative humidity is given in Fig.(5.2.4) for an atmospheric pressure of 1010 mb. At very low temperatures, N_{wet} becomes very small even for saturated air and so N is almost independent of relative humidity i.e. N_{wet}, thus N consists mainly of N_{dry} which is higher at lower temperature and vice versa. As the temperature rises, there is a slow decrease in N_{dry} but a rapid increase in the value of N_{wet}. At high temperatures N_{wet} can become somewhat larger than N_{dry} and N varies considerably with relative humidity. At high temperature

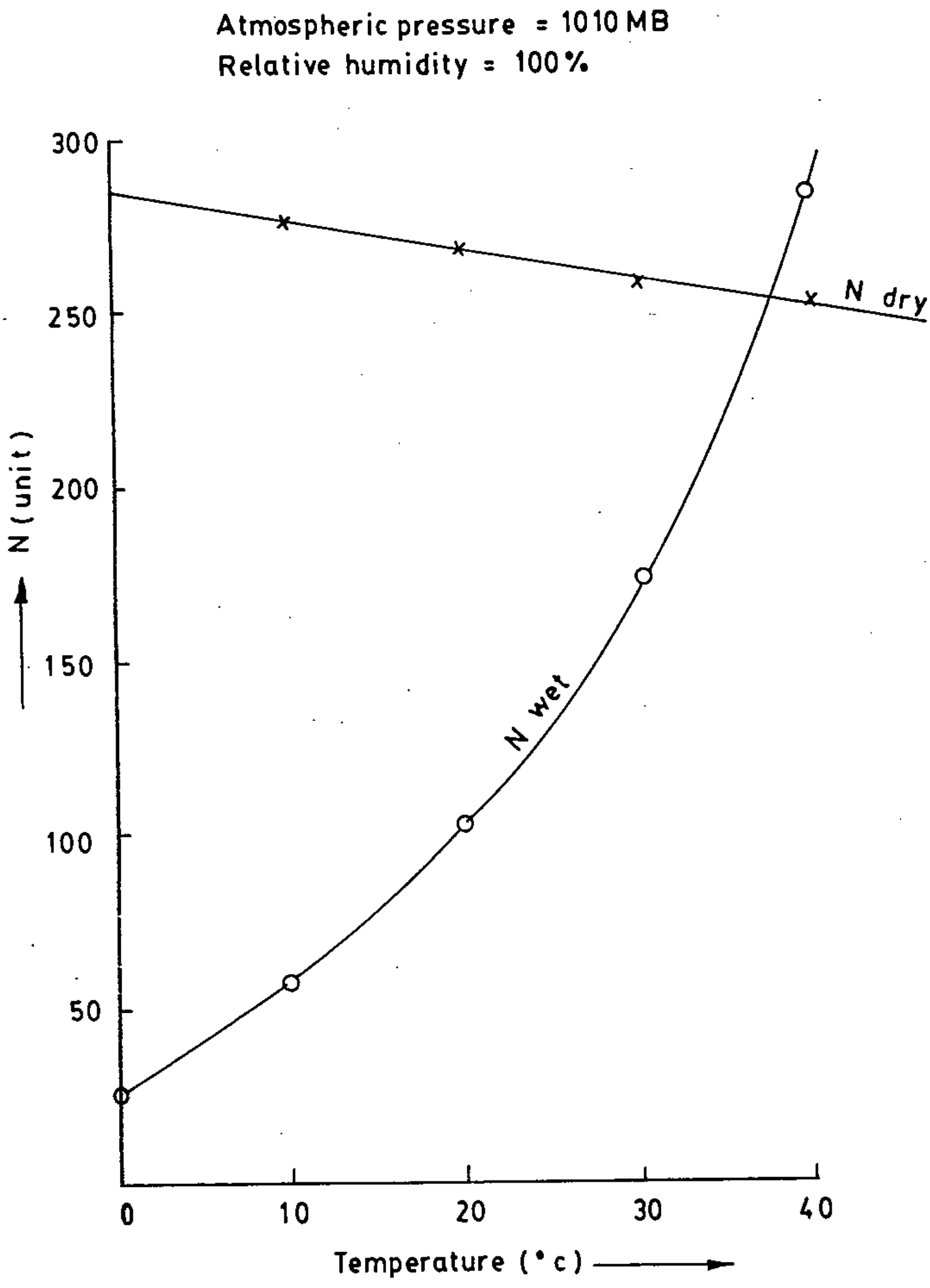


Fig.5.2.4: Variations of N_{dry} and N_{wet} with temperature.

and high relative humidity, N is very sensitive to small changes in temperature and relative humidity. Consequently, the variability of refractivity in tropical areas is greater than that of cold climates.

When the relative humidity is zero then the only dry part (77.6P/T) of the refractivity exists and the wet part ($3.73 \times 10^5 \times e/T^2$) of the refractivity reduces to zero. So at zero relative humidity, as the temperature increases the refractivity decreases. As the relative humidity increases slowly then the wet terms of radio refractive comes into effect and increases the refractivity. As the temperature increases the saturated vapour pressure increases and ultimately at high temperature and high relative humidity the refractivity is also higher.

5.3 Seasons of Bangladesh

Based on pressure, rainfall and temperature the climate of Bangladesh can be described (according to Bangladesh Meteorological Department (BMD) Annual Weather Report) under the following four seasons -

1) Winter or north-east monsoon: December, January and February.

2) Summer or pre-monsoon: March, April and May
3) South-west monsoon or monsoon: June, July, August and September
4) Autumn or postmonsoon: October and November.

5.3.1 **Winter Season**

The winter season is characterised mainly by an anticyclonic pressure system dominating the country except in February when a shallow trough of low makes its appearance over the northern districts. During this season, Very light northerly winds, mild temperature and dry weather with clear to occassionally cloudy skies prevail over the country.

The mean temperature is in the range of $18^{o}C$ to $21^{o}C$ in the northern and the central districts. The lowest temperature at times comes down occassionally to $4^{o}c$ to $5^{o}c$ over these districts. In the south-western and the coastal districts the mean temperature ranges between $22^{o}c$ to $23^{o}c$ with its lowest ranging between $6^{o}c$ to $10^{o}c$.

The prevailing air mass is dry as will be evident from the low humidities during 0900 to 1500 hours local time. The dryness of air is not evident from the morning and late afternoon humidity trends. This is due to the reason that continuous evaporation takes place from numerous rivers, lakes and natural water-sheds during clear sunny day and the evaporated moisture showes up in the form of high humidity during the cool hours of late evening and morning. This ultimately helps in the formation of mists/fogs during late night and early morning. The effect is more pronounced in the gangetic central districts and the coastal districts.

Rainfall over the country during winter is very scanty. The driest month of the season is December when the northern and the western districts get hardly 3-10 mm of rainfall, the coastal districts of Barisal, Noakhali, Chittagong and Chittagong Hill tracts get 15-30 mm of rain. With the progress of the season the rainfall increases over the whole of the country.

5.3.2 **Summer Season(Pre-monsoon)**

The winter anticyclonic pressure regime starts changing to a summer heat low from March onwards. The heat low develops over Behar and the adjoining central India when the pressure system over Bangladesh forms part of the resultant trough. In the northern and the central districts the surface wind changes from northerly in winter to southwesterly and it becomes southerly south-easterly over rest of the areas.

The mean temperature during Summer months remains within $23^{o}c$ to $30^{o}c$. April and May are the hottest months. The highest temperature ranging from $44^{o}c$ to $45^{o}c$ is attained in the northern and north-western districts. Over rest of the country it ranges from $41^{o}c$ to $43^{o}c$.

The southerly low level circulation brings in considerable moisture from the Bay of Bengal over the region causing sultry weather towards afternoon and evening. Such in flow of moisture gives rise to local thunderstorms in the late afternoon and early night. These local severe storms are usually called nor´westers as because they move across the country mainly from the north-westerly to northerly direction. The nor´westers are locally known as Kalbaishakhis after the name of the Bengali month, "Baishakh" in which they occur frequently. These stroms are often associated with strong squalls and occassionally with hailstorms.

These local severe storms are however, responsible for the welcome rain over the country that lies perchid under the hot summer sun. In march the rainfall is 20-40 mm in the districts west of $90^{o}E$ longitude and also over south-eastern tip, Cox's Bazar and Teknaf. Over rest of the country,, the rainfall is between 40-80 mm with the progress of the season the rainfall increases and in May it is 150-300 mm except in the district of Sylhet where the amount is about 600 mm. There are on the average 2.5 to 3.5 days of rainfall in March throughout the country, increasing to 10 to 13 days in May over most parts of the country except the western districts i.e. Dinajpur, Rajshahi, Pabna, Jessore and Khulna where there are 6.5 to 9 rainy days. In the district of Sylhet the number of rainy days is 21 in May.

5.3.3 Monsoon Season

The summer low over the north-west India and Pakistan intensifies in June and extends its trough to Bangladesh and adjoining North Bay. The surface wind changes to southerly direction over the southern and the central districts and to south-easterly over the northern districts of the country, wind speed is light to moderate.

Monsoon normally reaches the coastal districts of the country by the last week of May to first week of June and progressively engulfs the whole country through June. Generally heavy to very heavy rain with overcast skies characterizes the season. On the average there are 20-25 rainy days per month during June to August, decreasing to 12-15 days in September. More than 75 percent of the total annual rainfall is greater over the north-eastern, the southern and the southeastern districts than over the central, western and north-western districts. During the first two months of the season the rainfall is between 450-600 mm per month over the northern and the southern-districts and it is 700-850 mm per month over the district of Sylhet and the South-eastern districts of Chittagong and Chittagong Hill Tracts. Over the cental districts, the rainfall is 250-380 mm per month in these two months. As the season advances, the rainfall over the country decreases generally. In September the rainfall is 200-250 mm over the country except in the districts of Sylhet and the coastal districts of Barisal, Noakhali, Chittagong and Chittagong Hill Tracts, where the rain-fall is 300-450 mm.

With the advent of monsoon the summer extreme temperatures fall appreciably throughout the country. Although the mean temperature falls hardly by one degree, the maximum temperature falls by $2^{o}c$-$5^{o}c$ over most of the country except the coastal districts where the fall is by $5^{o}c$-$6^{o}c$.

5.3.4 Post-Monsoon Season

This is the transitional season from summer monsoon to the winter.

South-west monsoon starts to withdraw in early October and its withdrawal from the country is complete through October.

There is generally rise of pressure and the monsoon pressure structure breaks down over the country. The monsoon low over the central India weakens and shifts towards the Bay of Bengal with its trough extending over the coastal Bangladesh.

Rainfall decreases considerably in October and in November the dry period starts setting in over the country. The district of Sylhet gets 200-250 mm of rain in October and the rest of the country gets about 100-170 mm. In November the amount of rainfall over the south-eastern coastal districts amount to 25-65 mm whereas the rest of the country gets only about 10-20 mm of rain in October there are 4-10 days of rainfall over the country and only 1-3 days in the month of November. The mean temperature falls from $28^{o}c$-$29^{o}c$ in September to $26^{o}c$-$27^{o}c$ in October and to $23^{o}c$ to $25^{o}C$ in November. The highest maximum temperature hardly exceeds $29^{o}c$ and the lowest minimum does not fall below $10^{o}c$ throughout the country. Meansea level pressure, temperature and relative humidity distributions for Bangladesh over the period 1951-80 for the month of July are shown in Appendix (D).

5.4 Radio Refractive Index for Bangladesh in Different Seasons

The radio refractive index is central to all theories of radio propagation through the lower atmosphere. At shorter distances, however, the propagation is mainly through the troposphere. The propagation is controlled by the variability of the radio refractive index of the tropospheric medium. So to design a communication system we should have the knowledge about the radio refractive index.

To find the radio refractive index at different places in Bangladesh we chose thirty locations or stations where the parameters i.e. pressure, temperature and relative humidity which are needed for calculating the radio refractive index are available. These selected stations are Dhaka, Rajshahi, Chittagong, Khulna, Rangpur, Mymensingh, Sylhet, Comilla, Dinajpur, Ishurdi, Satkhira, Madaripur, Patuakhali, Khepupara, Srimangal, Chandpur, Maizde court, Feni, Bhola, Hatia, Sandwip, Sitakunda, Rangamati, Kutubdia, Cox's-Bazar, Barisal, Bogra, Jessore, Faridpur and Teknaf. The data of pressure, temperature and relative humidity for these places were collected for eleven years, from 1977 to 1987. But these data for some places were not available over few years for some stations. The data were collected from Bangladesh Meteorological Department". The climatological data collected were for the months January, April, July and October in each year. In these months, the pressure, temperature and relative humidity data in three forms were available. These are the highest value of pressure and temperature in each month also the lowest value of pressure and temperature in every month and the average relative humidity. For some places the annual average of pressure, temperature and relative humidity were also available. The maximum, minimum or average value of pressure, temperature and relative humidity as that of previous years were not available. But the raw data of these three parameters were available for the considered stations during the years 1986 and 1987. From these raw data the value of pressure, temperature and relative humidity were taken as required for calculation of radio refractive index for the years 1986 and 1987.

Refractive index at different locations are computed from these data using the radio refractive index evaluation formula -

$$N = \frac{77.6P}{T} + \frac{4810\ e}{T^2} \tag{5.4.1}$$

For three different form of data (maximum, minimum and average) three different forms of radio refractive index are found out for the four months of January, April, July and October in each year for the considered stations. These three forms are (i) The monthly maximum radio refractive index calculated using monthly maximum pressure, maximum temperature and the average relative humidity (ii) The monthly minimum radio refractive index calculated using montly minimum pressure, minimum temperature and the average relative humidity. iii) The monthly average radio refractive index calculated using the monthly average value of atmospheric pressure, temperature and relative humidity.

Here average relative humidity was used for calculating the maximum and minimum radio refractive index instead of maximum and minimum relative humidity as these were not available in Bangladesh Meteorological Department except the monthly average relative humidity.

The monthly maximum, minimum and average radio refractive index calculated for every stations considered from monthly data are plotted and described for some important places later. These curves show the variation of radio refractive index over the year at those stations.

To see the typical variation of radio refractive index over a year, the average values of the pressure, temperature and relative humidity were considered for the twelve months in a year of the four divisional-stations i.e. Dhaka, Chittagong, Khulna and Rajshahi for computing radio refractive index for the years 1978 and 1986.

From the plottings Fig. (5.4.1) of these radio refractive index it is seen that the shapes of the curves for the four places are almost same though they vary in their maxima and minima. The lowest refractivity occurs in the month of January and increases in value as the month passses and the highest value of radio refractive index is found in July over a year. After July refractivity begins to reduce and gradually decreases upto month of January. The underlying fact of this characteristic is described below.

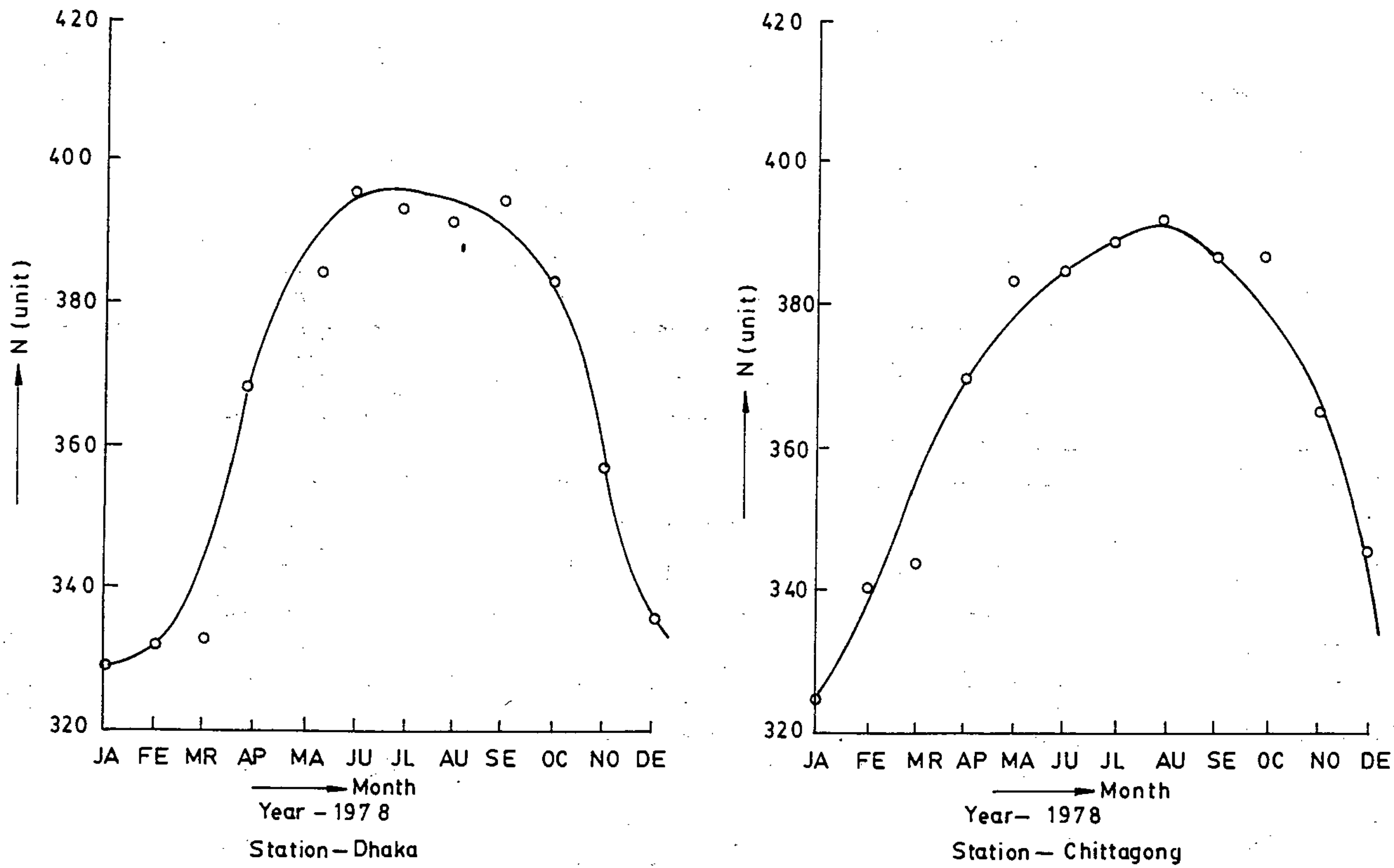


Fig.5.4.1: Surface refractivity on the basis of average temperature, pressure and relative humidity over a year.

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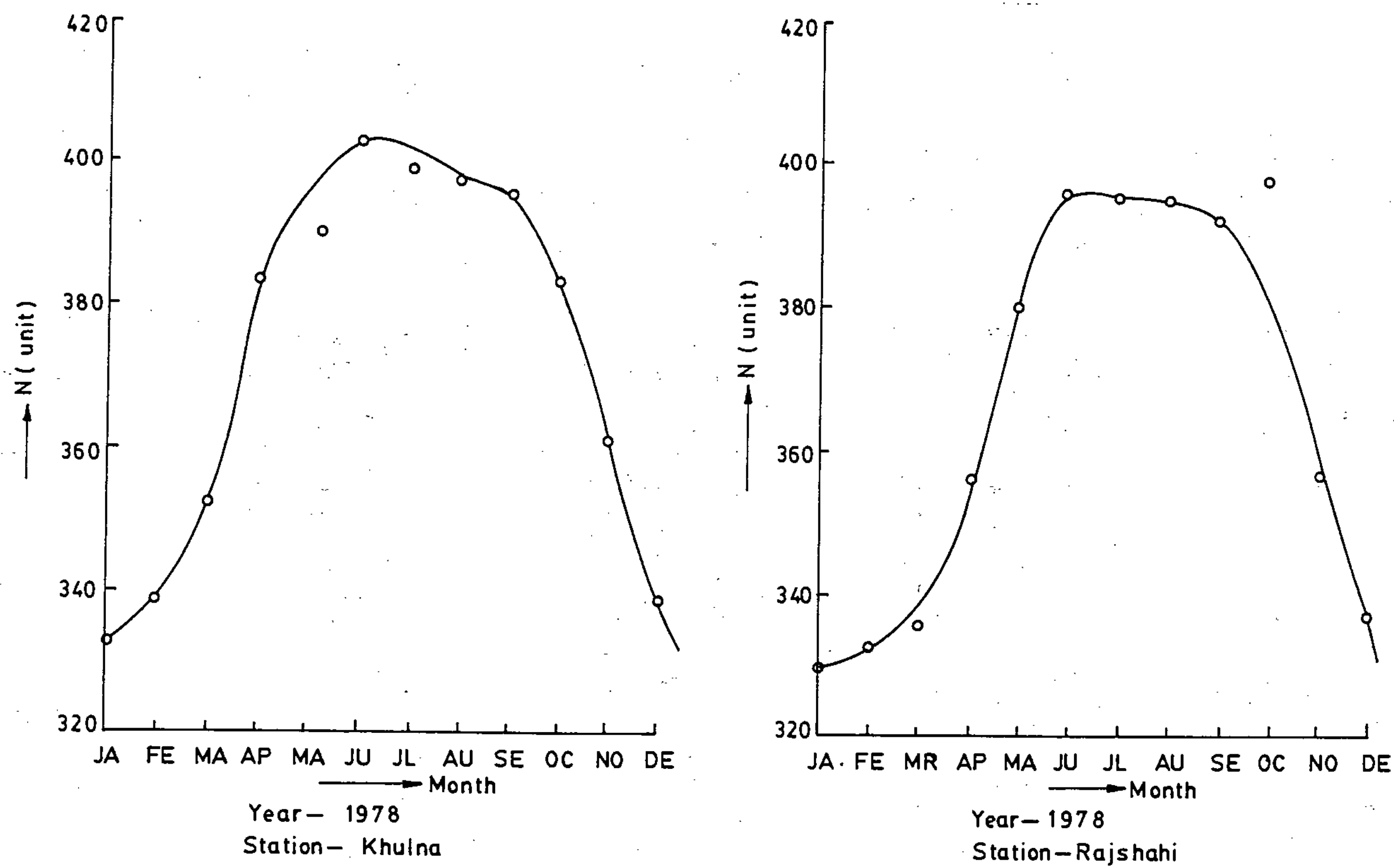
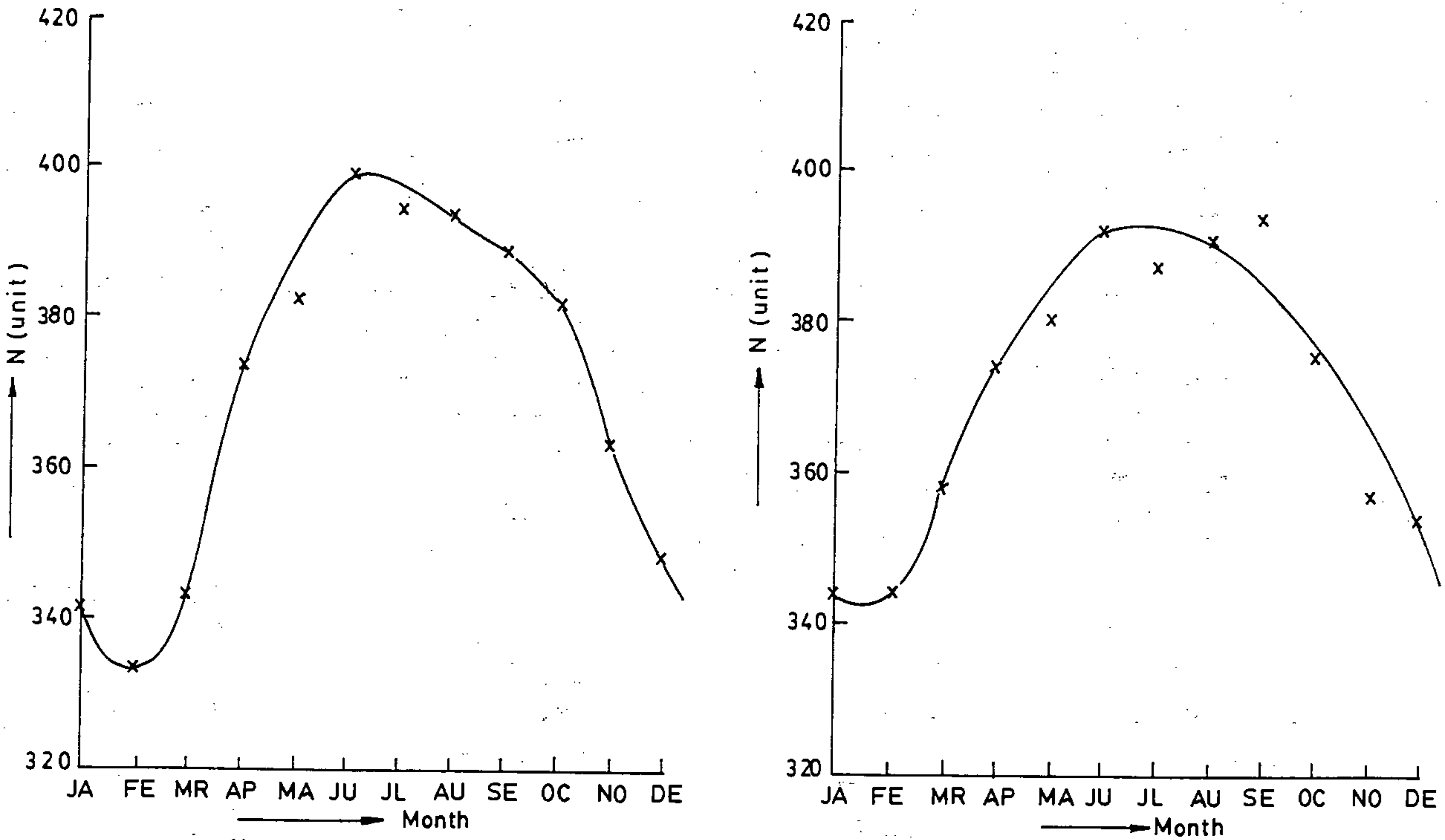


Fig.5.4.1:(Contd..)



Year – 1986
Station–Dhaka

Year - 1986
Station– Chittagong

Fig.5.4.1 (Contd..)

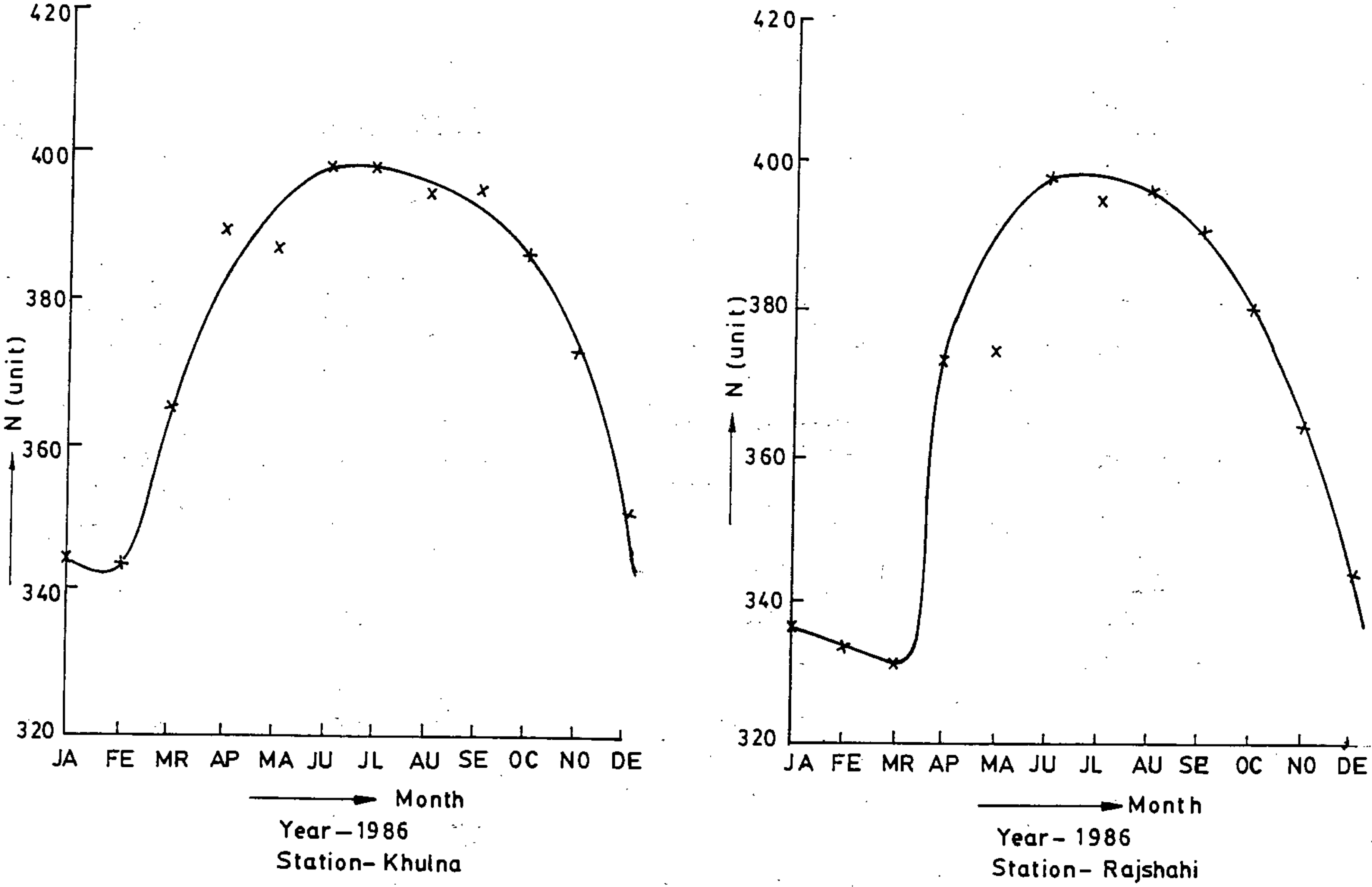

420
400
380
360
340
320
N (unit)
JA FE MR AP MA JU JL AU SE OC NO DE
Month
Year—1986
Station- Khulna
420
400
380
360
340
320
N (unit)
JA FE MR AP MA JU JL AU SE OC NO DE
Month
Year- 1986
Station- Rajshahi

Fig.5.4.1

Temperature is the most governing factor among the three parameters i.e. pressure, temperature and relative humidity contributing to the radio refractive index. As the temperature increases corresponding saturated vapour pressure also increases. The increment of saturated vapour pressure is relatively more than the increment of temperature and ultimately the radio refractive index increases.

From the data it is seen that the average temperature and relative humidity are the lowest in the month of January. So the lowest value of radio refractive index occurs in the month of January.

In the month of April the temperature is higher than that in January but lower than that of July. Again the relative humidity is slightly larger than that of January but the atmospheric pressure is lower. The variation of pressure effects the refractivity expression little than the other two factors ie temperature and relative humidity. So in April the radio refractive index is larger than that in January but lower than that of July.

The average temperature and relative humidity have the highest value in the month of July than those of any other month in the year but on the other hand the lowest atmospheric pressure occurs in this month. As the effect of temperature and relative humidity is pronounced on the radio refractivity expression. So it is obvious that the largest value of radio refractive index occurs in the month of July.

In the month of October, the temperature and relative humidity reduces to a smaller value than those of July but still higher than those of April. The atmospheric pressure is very near to that in April. As the temperature and relative humidity are higher than those in April, the radio refractive index in October is larger than in April but smaller than that of July.

Finally, we can say that the largest value of radio refractive index occurs in the month of July, next in October and April and the smallest value occurs in January.

Hardly, it is seen that the radio refractive index in April and October is greater than that of July. This is an exceptional case and may occur due to the anomalous change of temperature or relative humidity.

5.5 R.R.I Curves Over a Year for Different Places

Three forms of RRI i.e. maximum, minimum and average RRI were calculated for thirty different locations for different time as previously described. To find the trend of variation of RRI in Bangladesh, these three forms of RRI were plotted for the places Rangpur, Mymensingh, Comilla, Sylhet, Jessore, Ishurdi, Faridpur, Teknaf, Cox's-Bazar, Hatia, Kutubdia, Sandwip, Rangamati, Sitakundu and Feni for two different years in Fig. (5.5.1).

It is clearly observed from Fig. (5.5.1) that the maximum and minimum RRI over the year occurs in the months of July and January respectively at almost all the stations considered here. Again the maximum or minimum RRI observed in the month of October is slightly greater than that of April. The nature of variation of RRI can be described as the lowest RRI is observed in the month of January and it begins to increase as the time passes.In July RRI attains the highest value and then it begins to decrease towards the end of the year. This is the normal RRI variation for Bangladesh. The maximum and minimum curves differs from each other by about 40 units of RRI as observed from the Fig. (5.5.1).

Again some deviation is observed from the curves plotted as described above. Normally the RRI in the month of October is

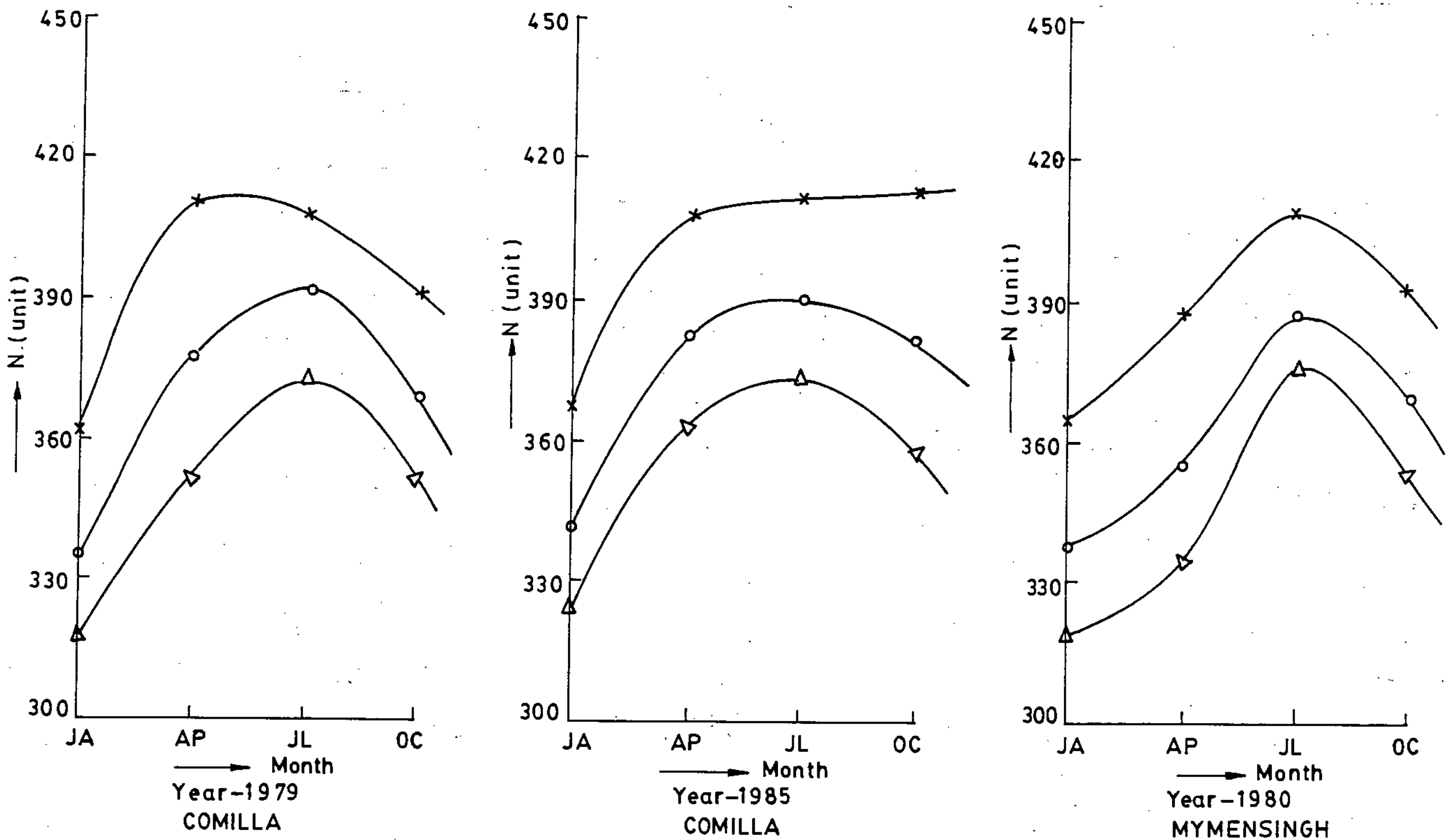


Fig.5.5.1: Variation of maximum, minimum, and average RRI over a year at different places. (Contd..).

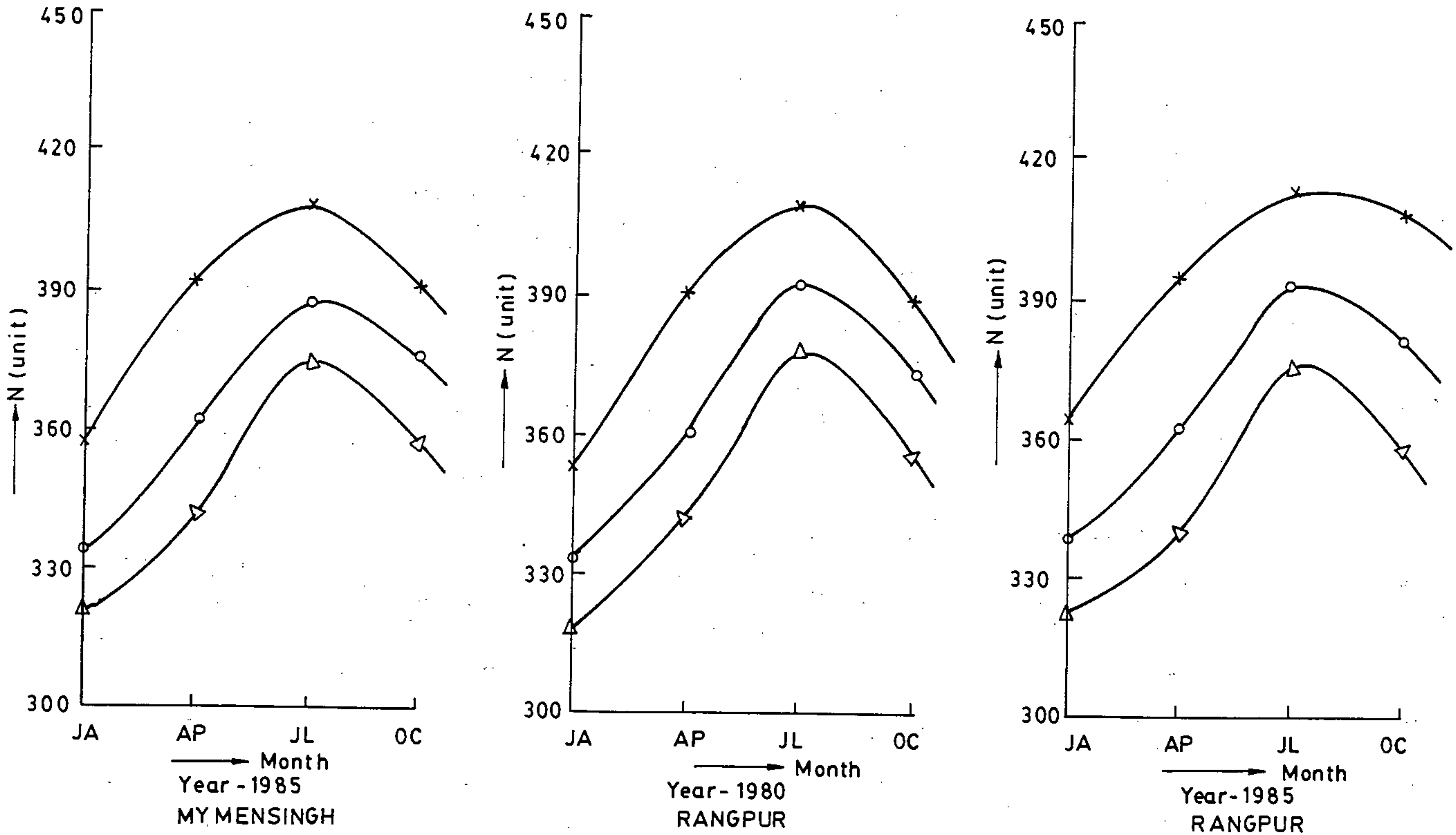


Fig.5.5.1 (Contd..)

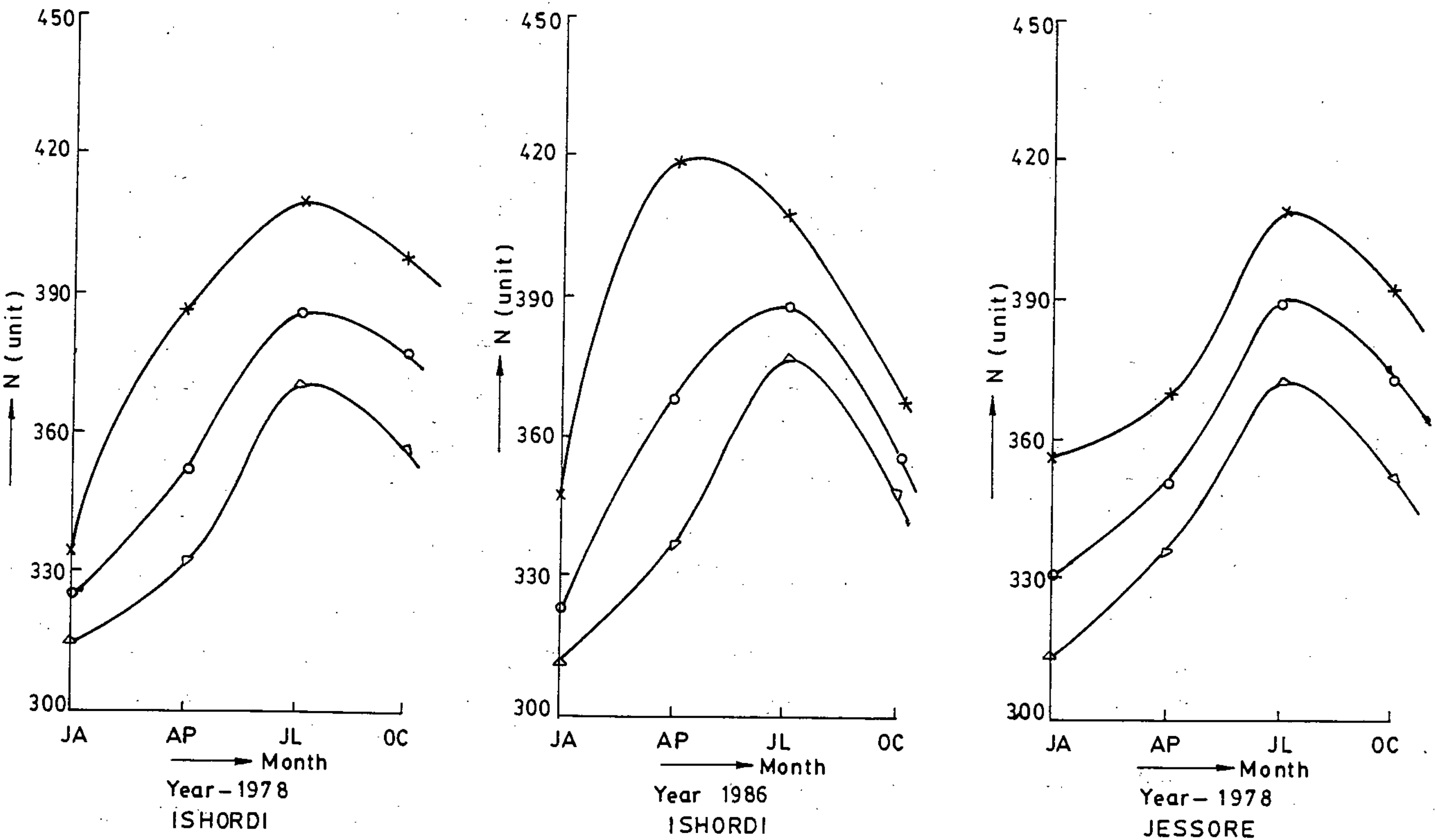


Fig.5.5.1 (Contd..)

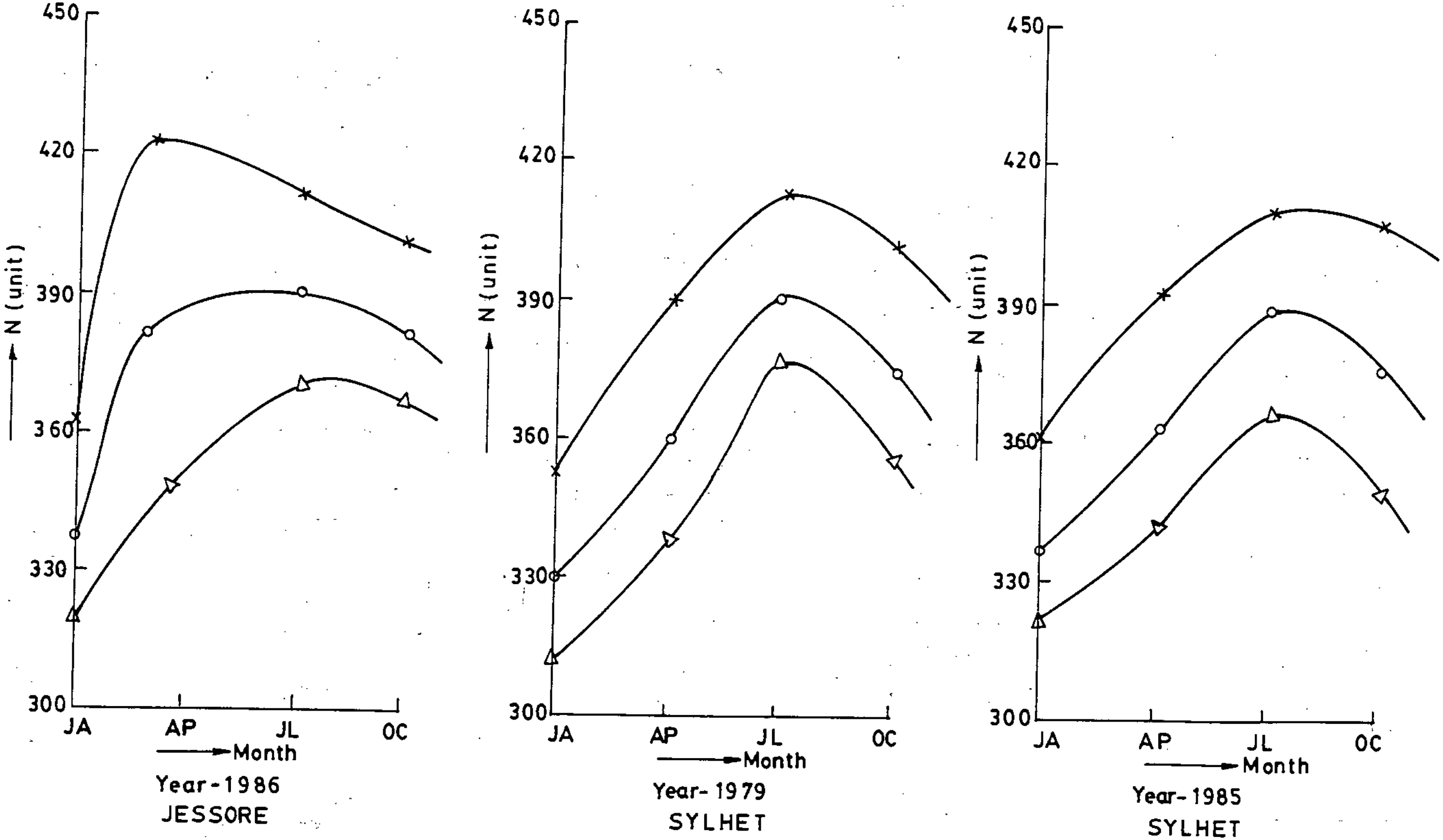


Fig.5.5.1 (Contd..)

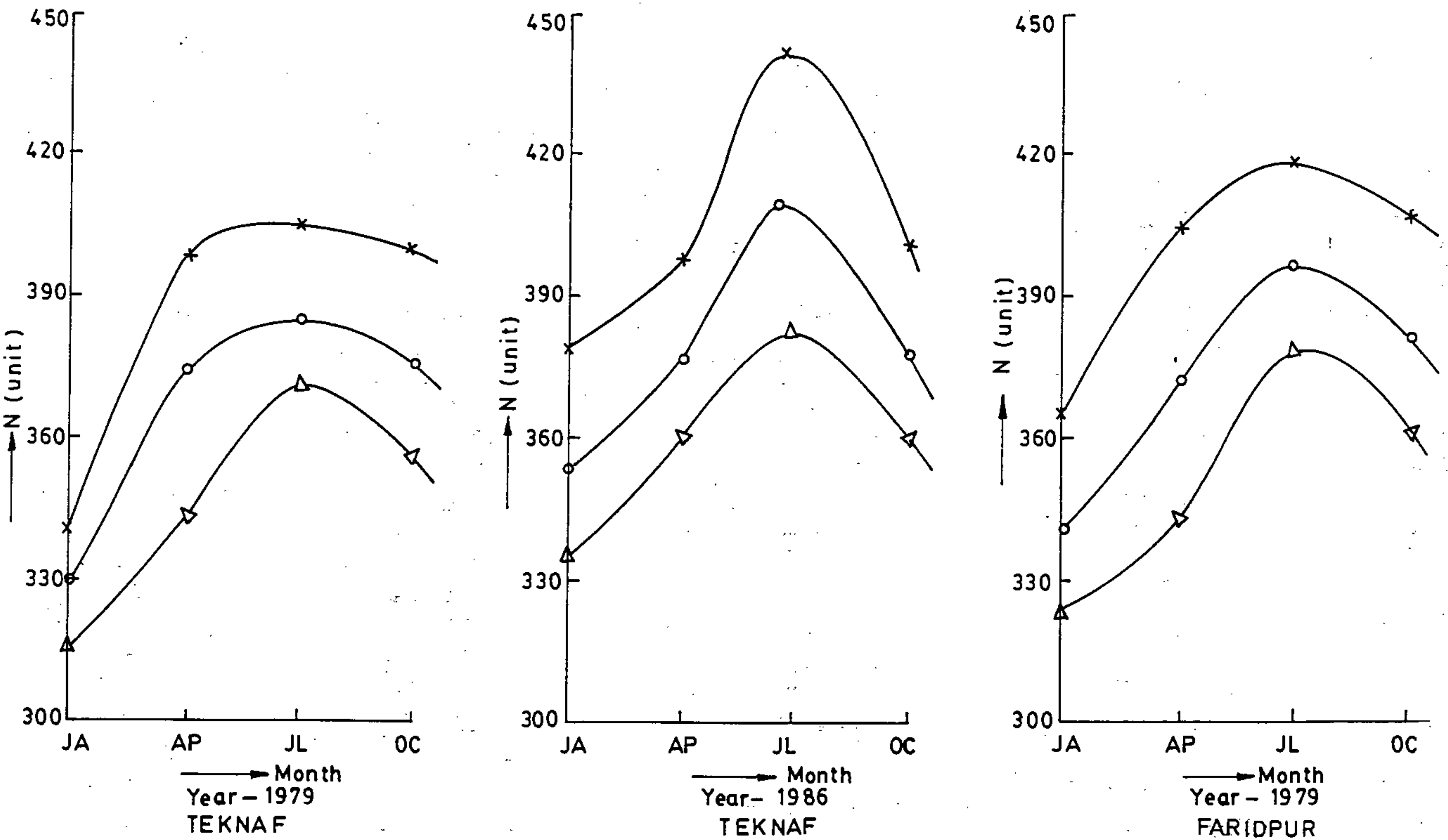


Fig.5.5.1 (Contd..)

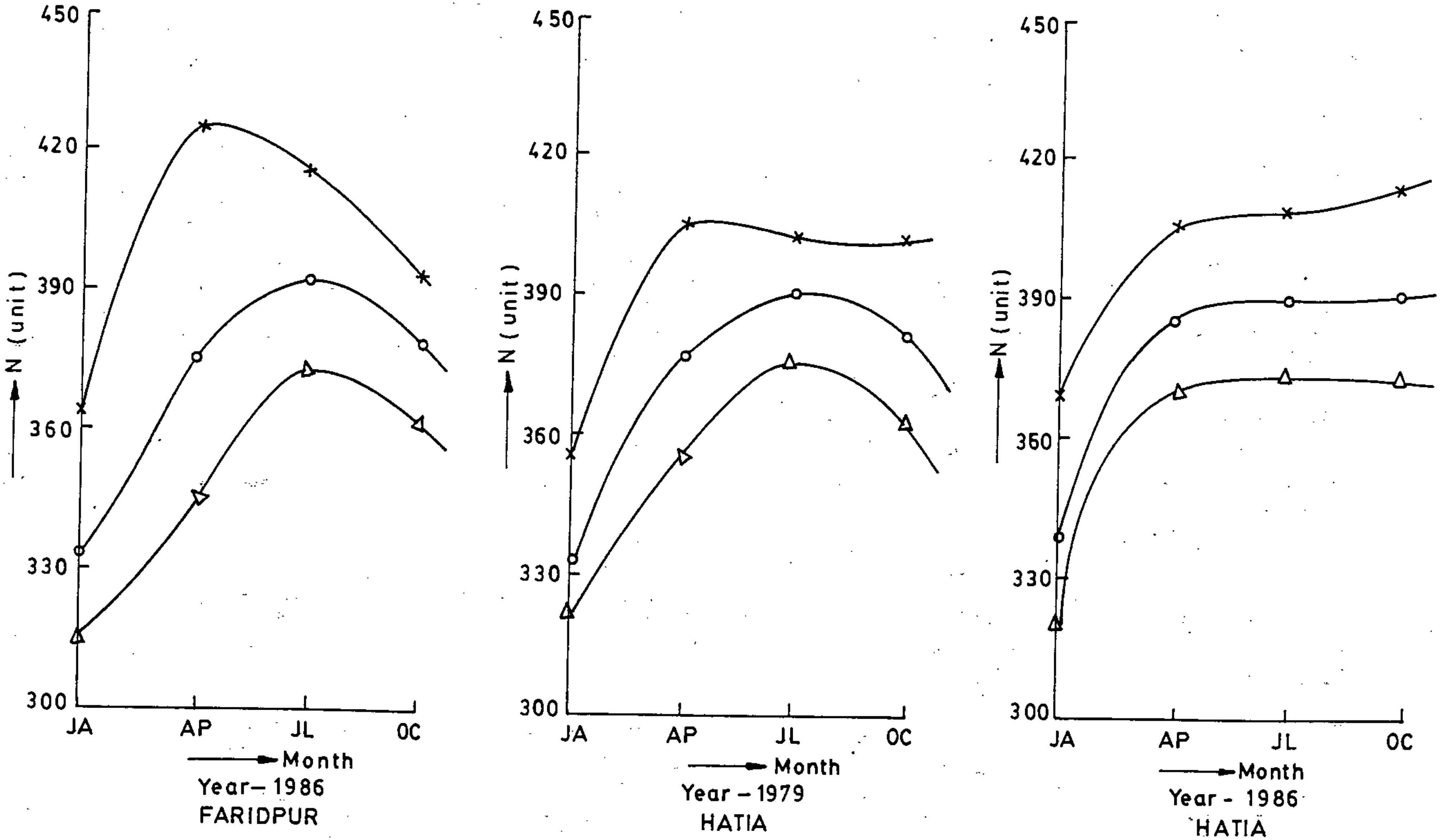


Fig.5.5.1 (Contd..)

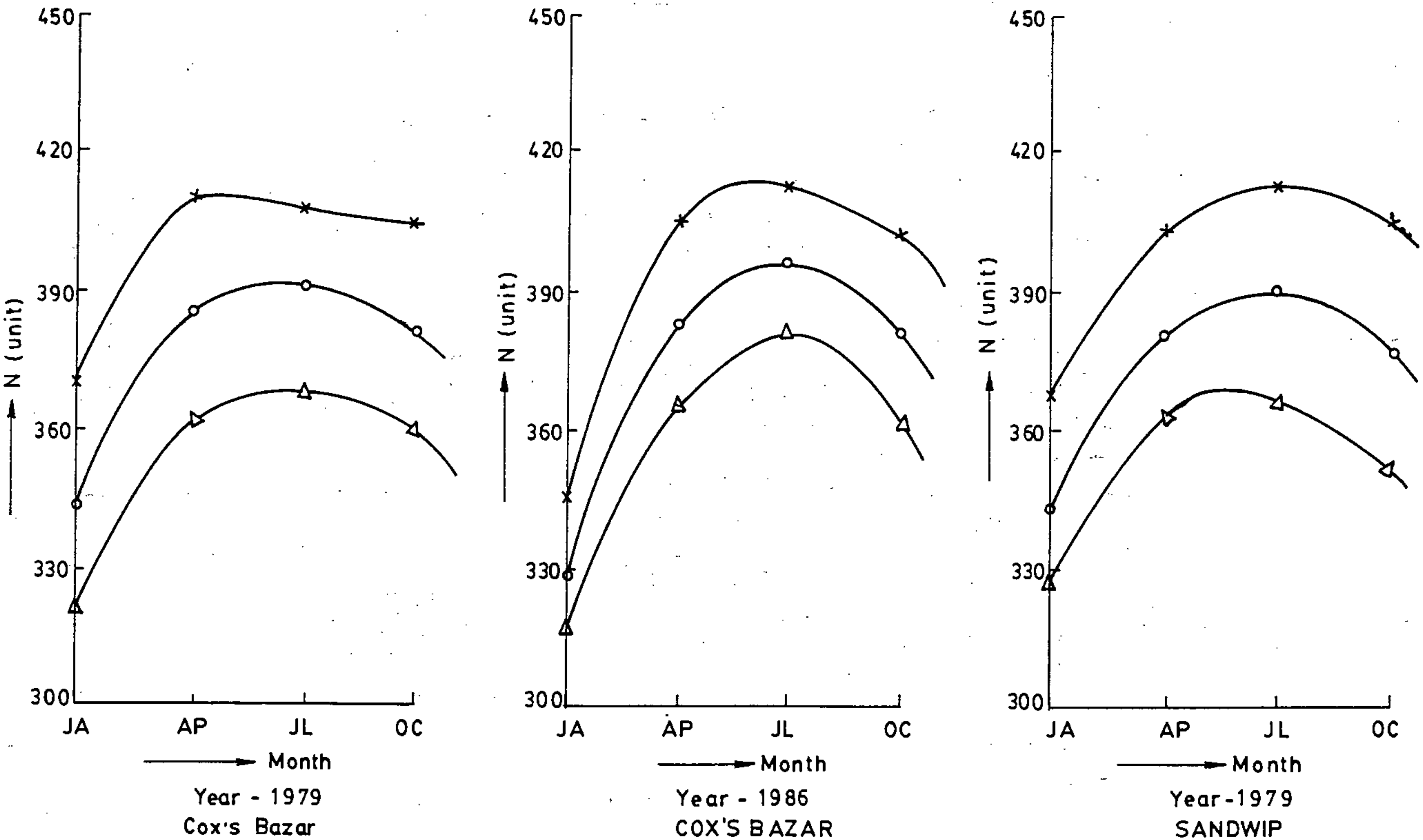


Fig.5.5.1 (Contd..)

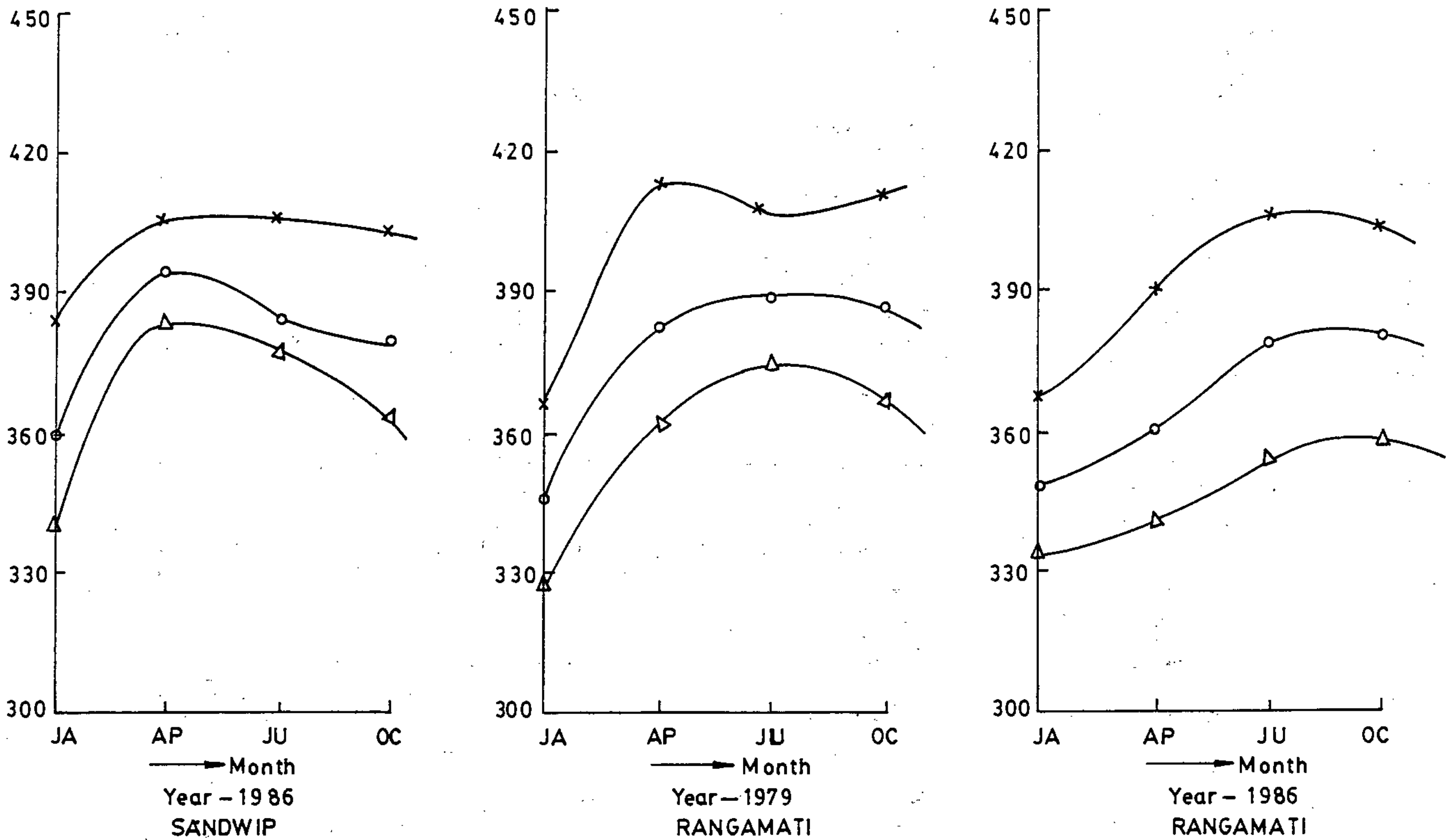


Fig.5.5.1 (Contd..)

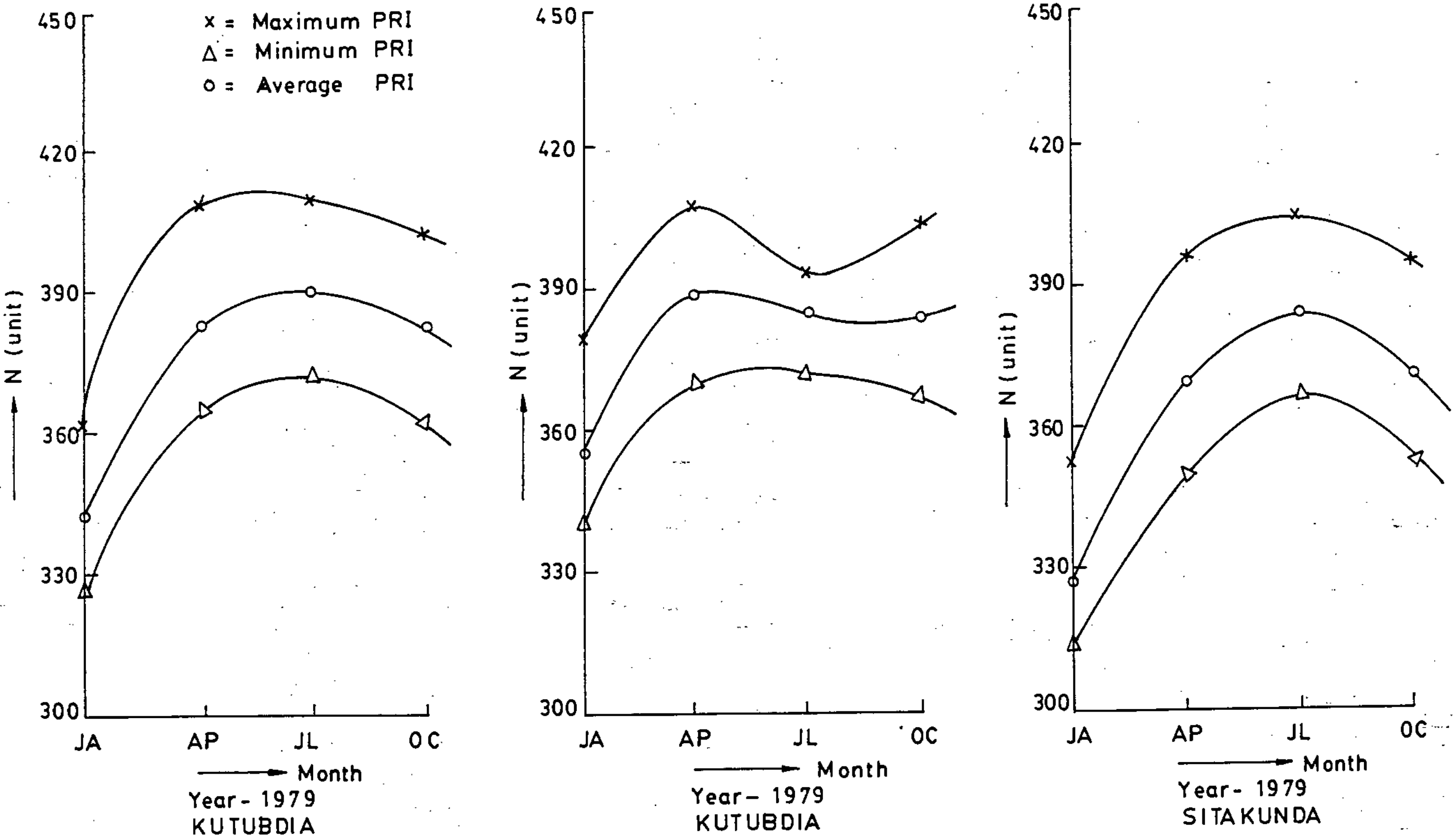
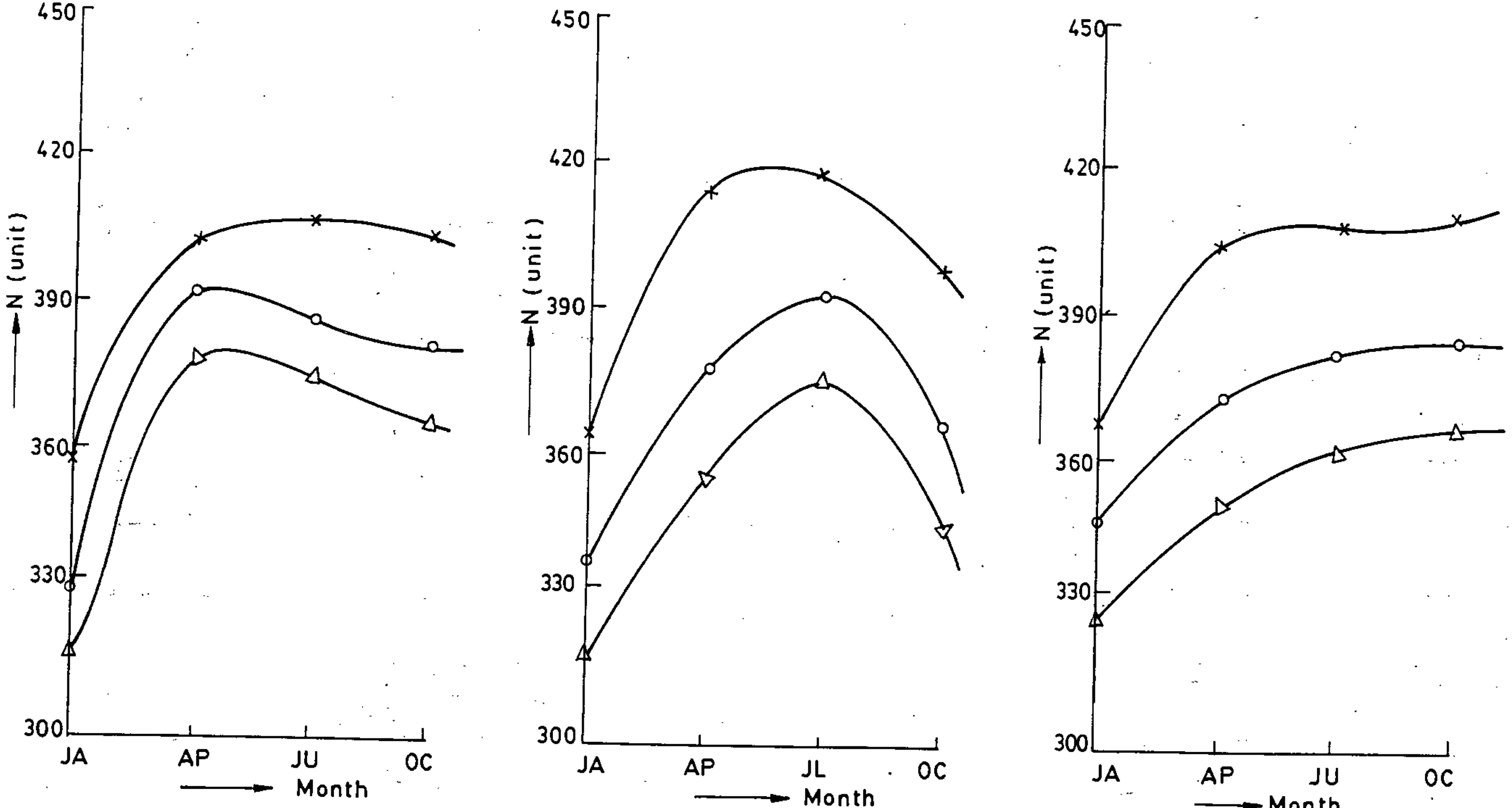


Fig.5.5.1 (Contd..)



Year – 1986
SITAKUNDA

Year–1979
FENI

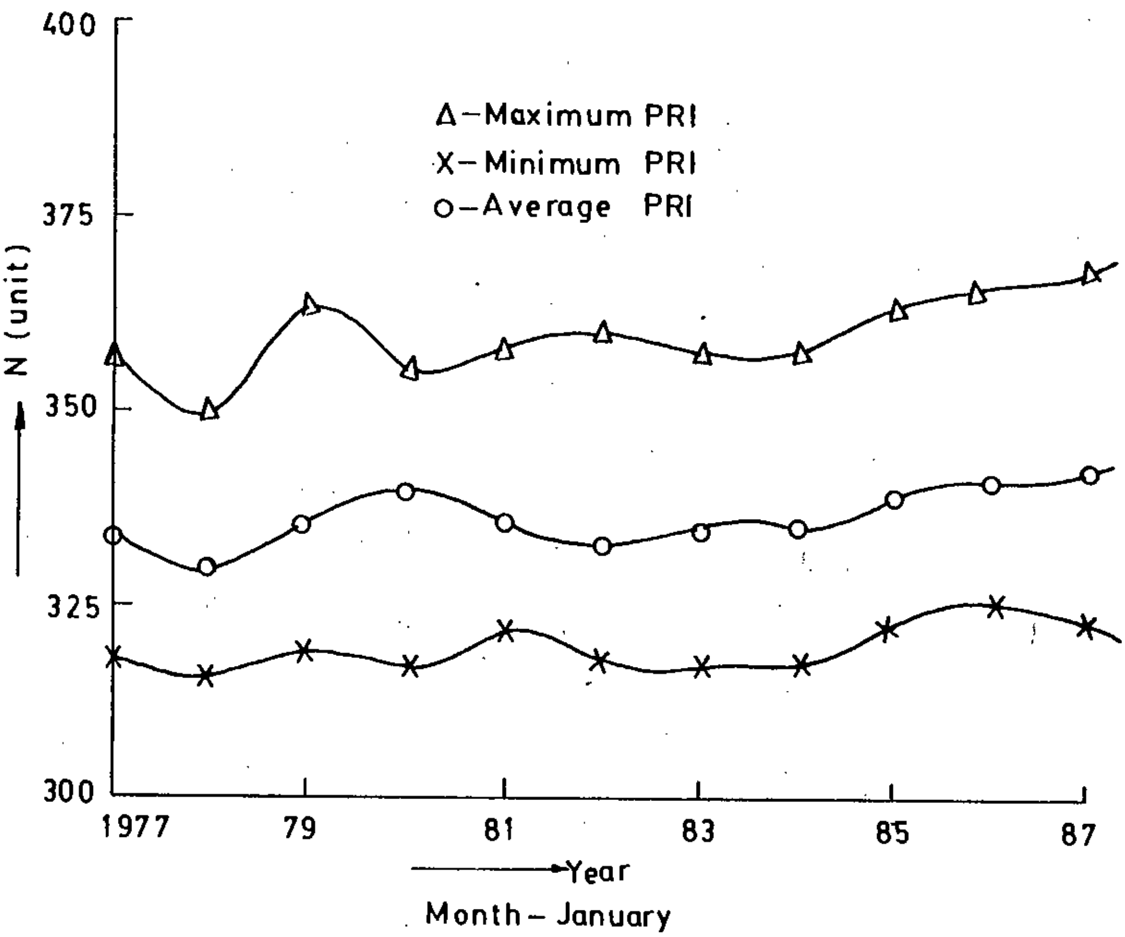
Year—1986
FENI

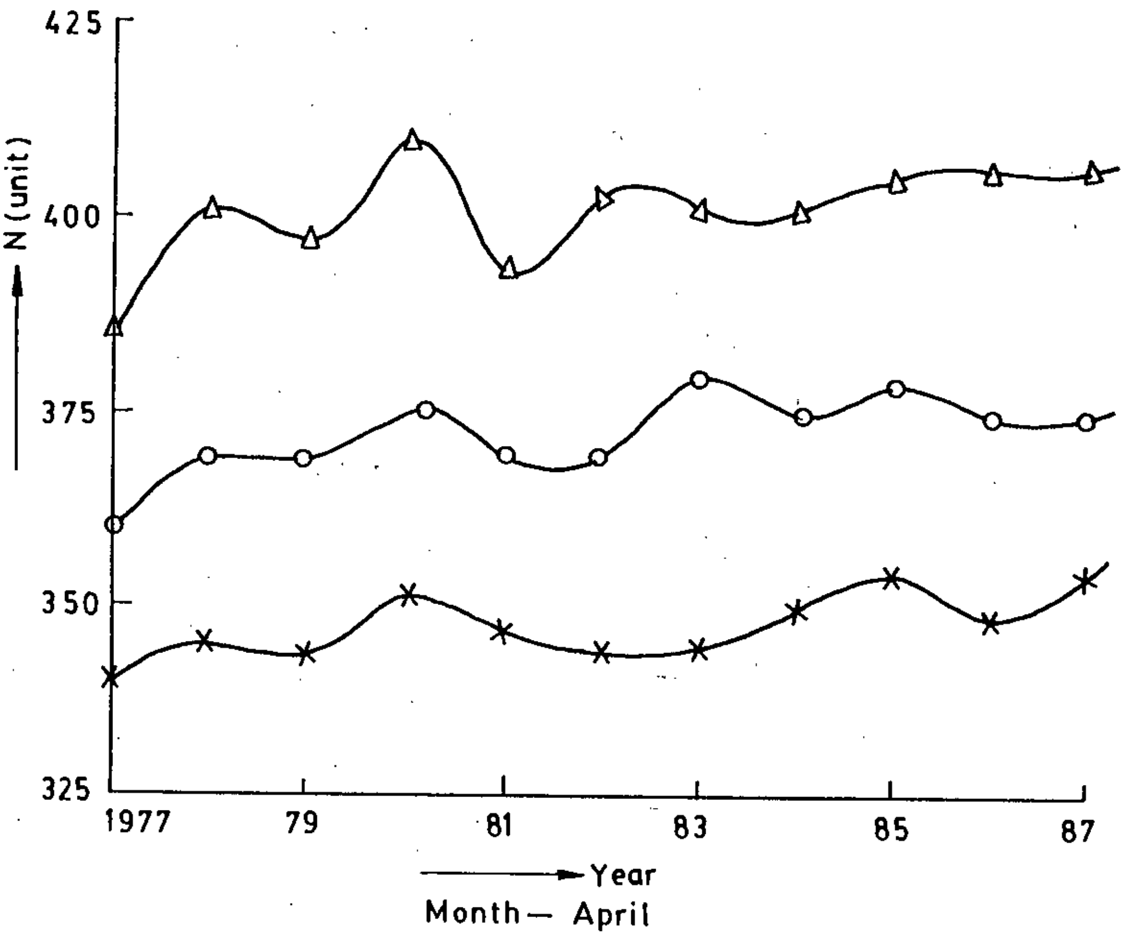
Fig.5.5.1

smaller than that of July but at some places over sometime opposite picture is observed. Mainly such type of abnormal situation is found at the coastal area such as Cox's-Bazar, Kutubdia and Sandwip. The reason of this phenomenon is that the weather at the coastal zone may deviate from that of normal places. As weather at any place may differ from year to year at the same season of the year this also causes abnormal variation of RRI. As is seen for sometimes the RRI in the months of April and October is higher than that of July, though normally the highest RRI occurs in the month of July at almost every places in Bangladesh.

5.6 RRI Distribution for a Particular Month at a Particular Place over Several Years

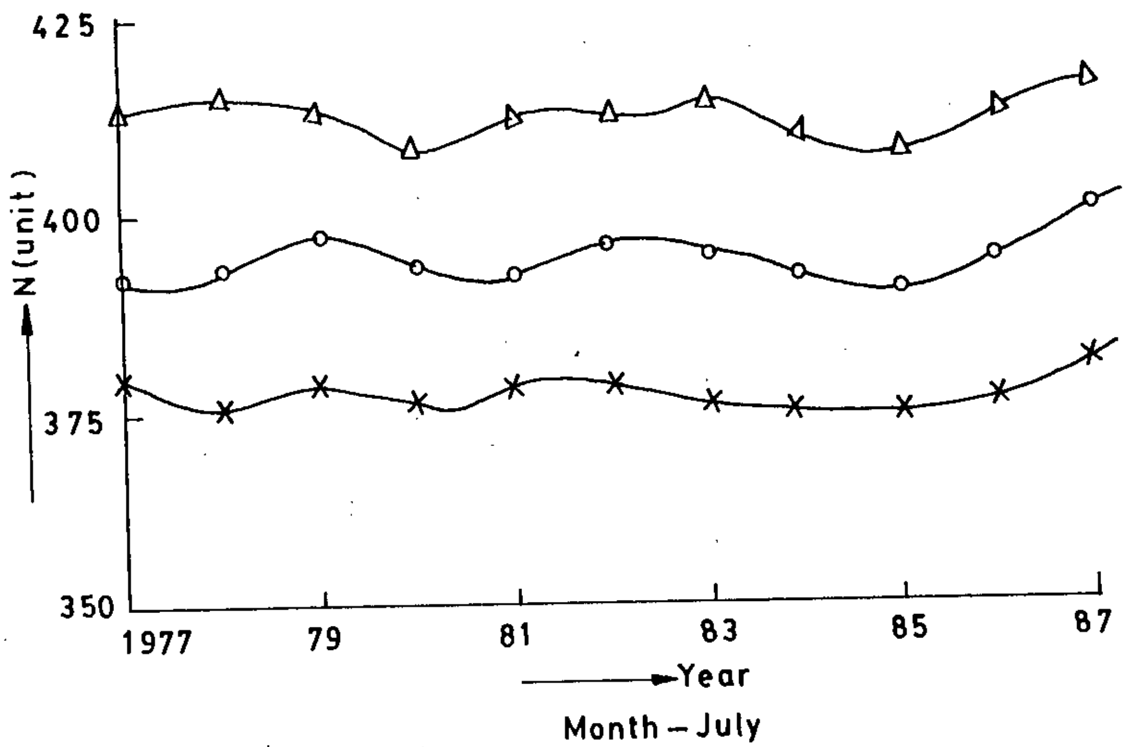
Radio Refractive index were calculated for the thirty locations over the eleven years from 1977 to 1987 as data available. Three forms of RRI ie maximum, minimum and average RRI for the four Districts, Dhaka, Chittagong, Rajshahi and Khulna among the thirty locations are plotted here to find the trend of variation as time passes by in Fig. (5.6.1).

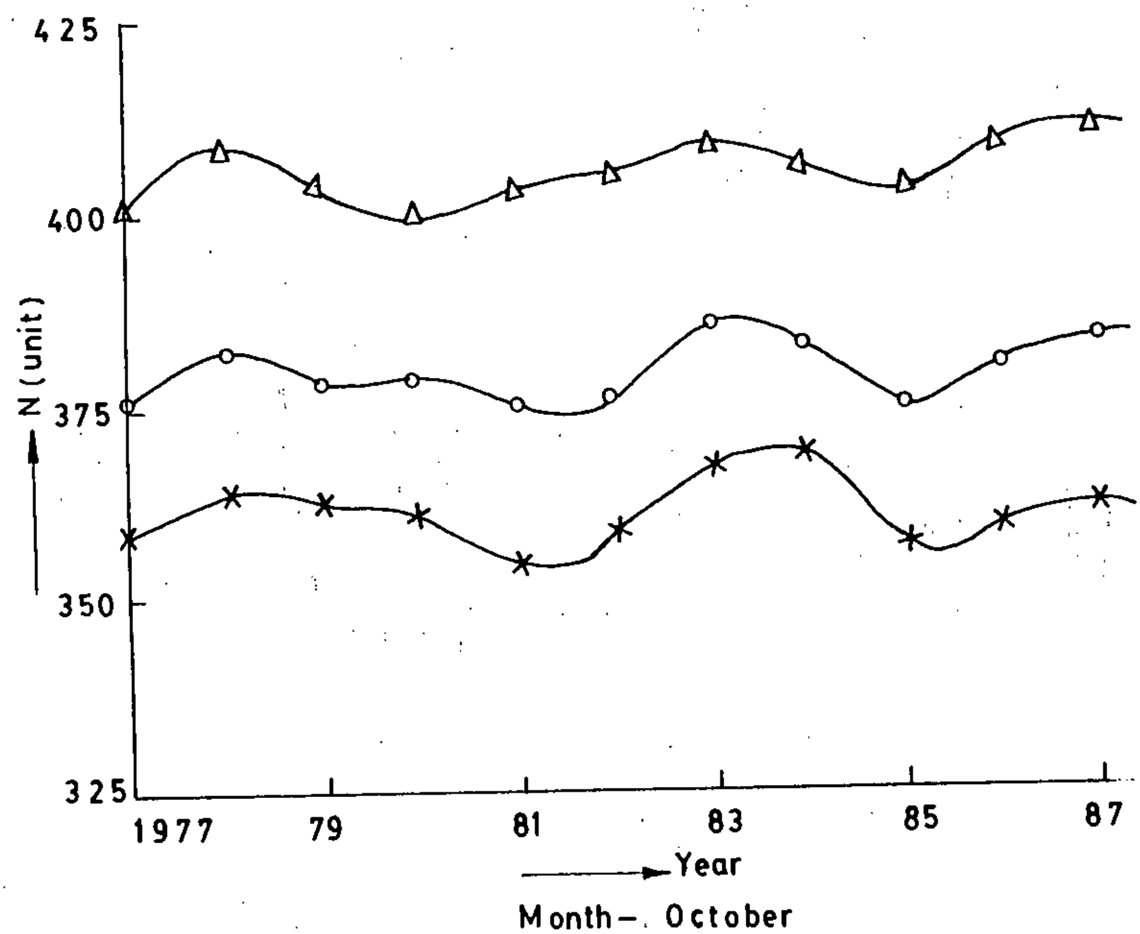




STATION − DHAKA

Fig.5.6.1: Variation of maximum minimum and average RRI over the observed years in each season. (Contd..)





STATION – DHAKA

Fig.5.6.1 (Contd..)

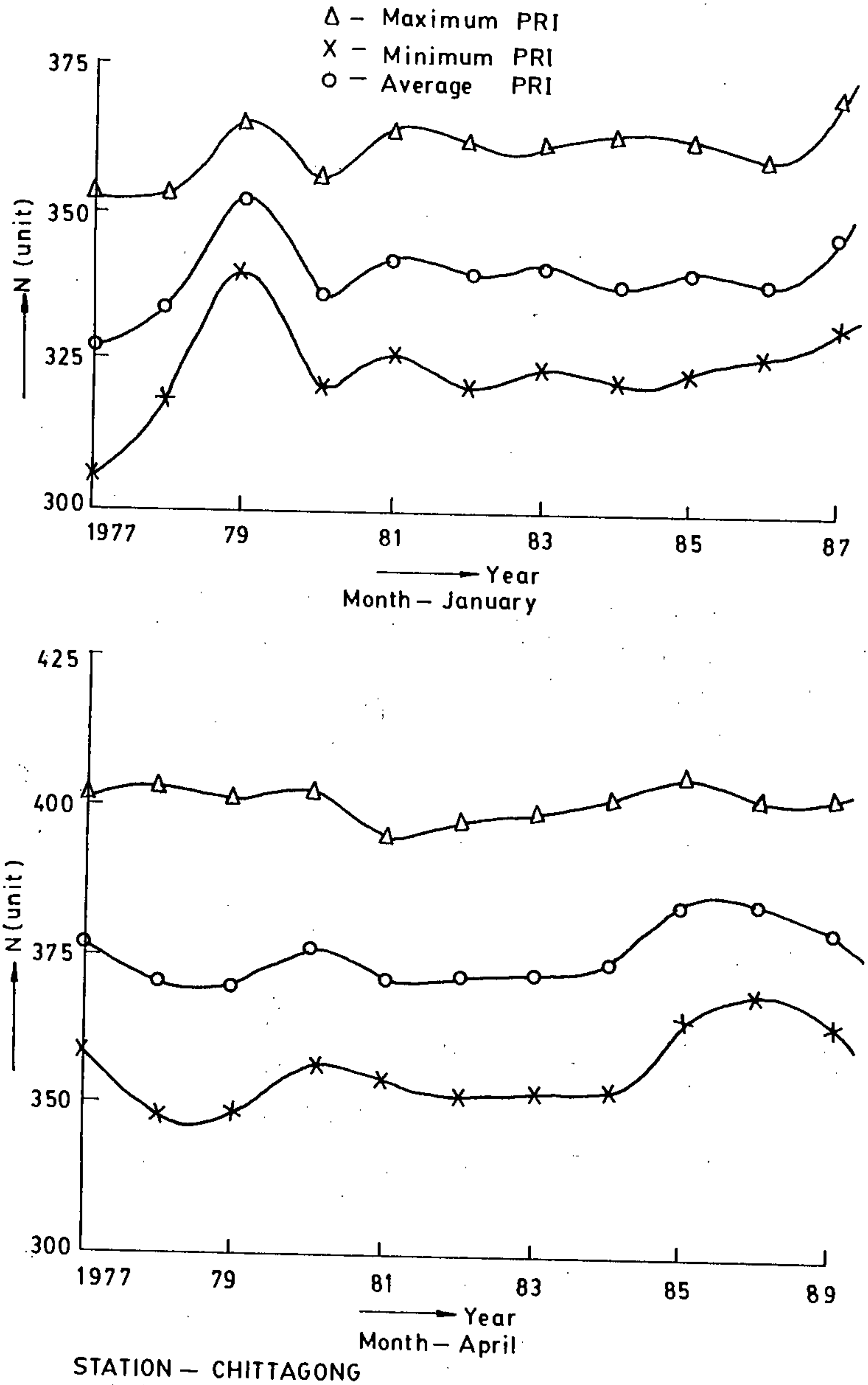
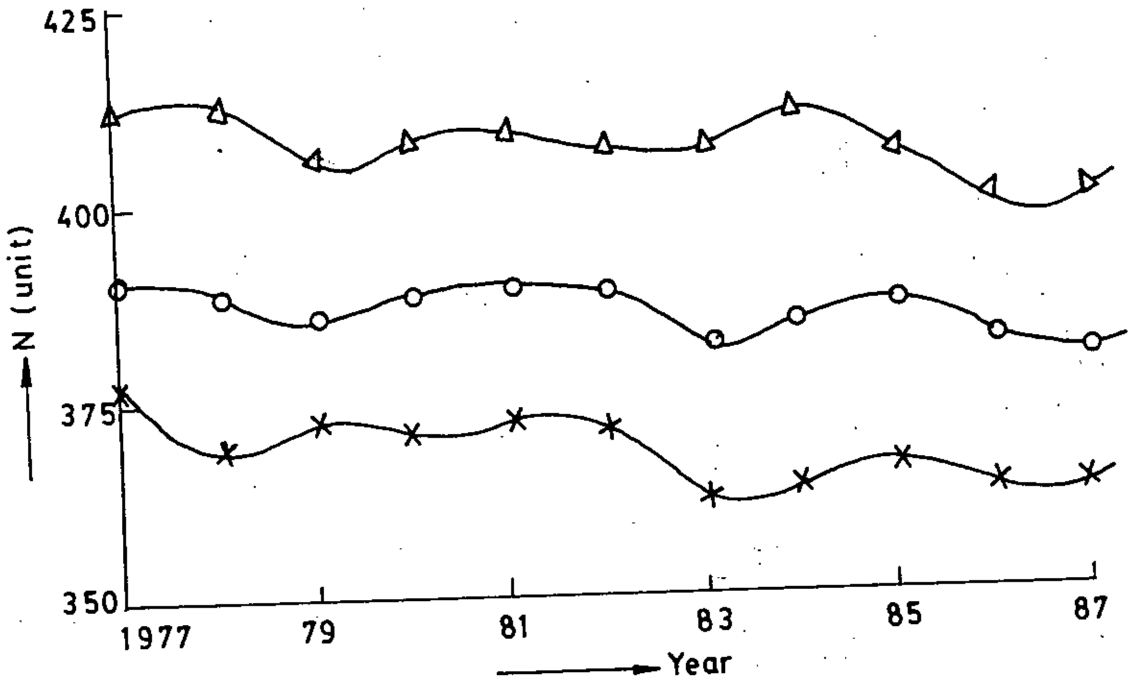
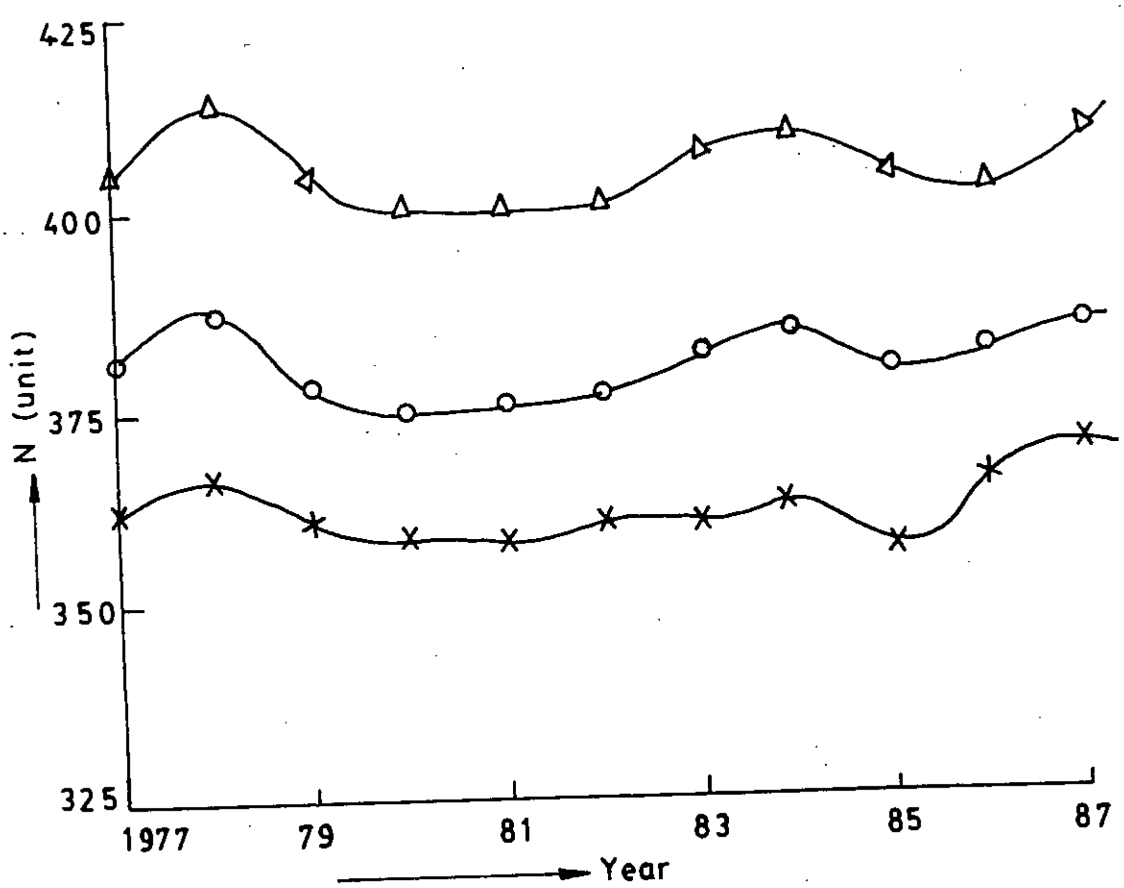


Fig.5.6.1: (Contd..)



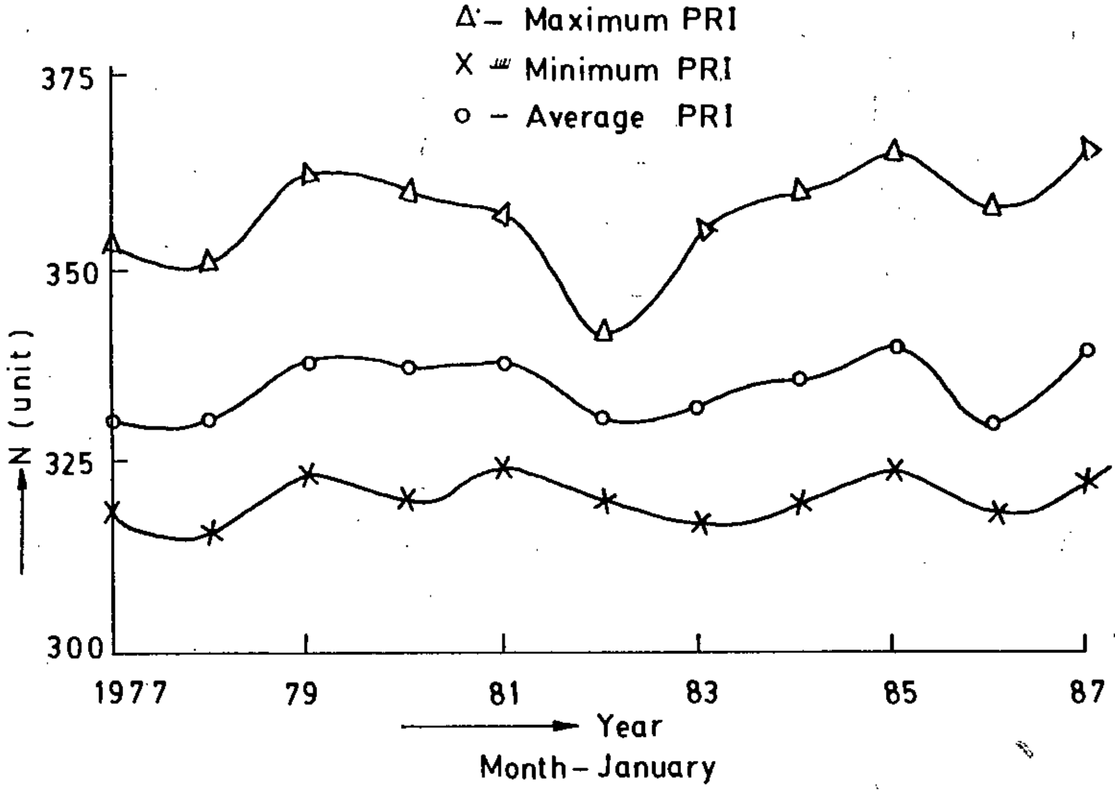
Month – July

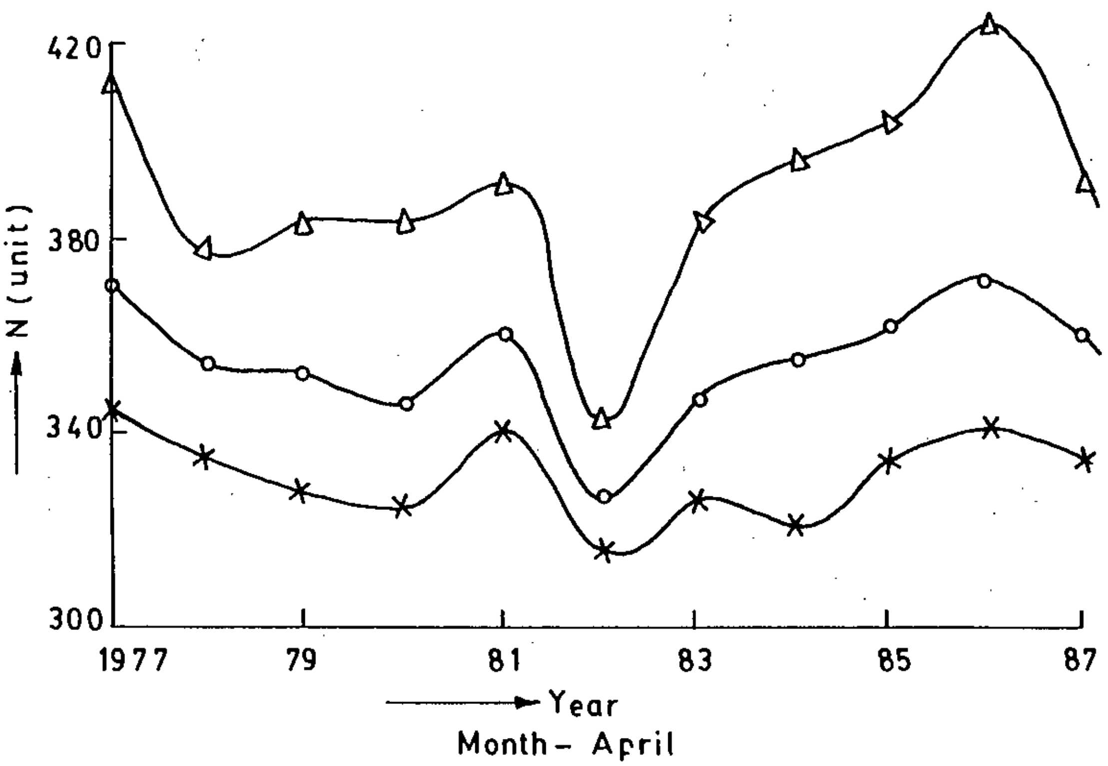


Month – October

STATION – CHITTAGONG

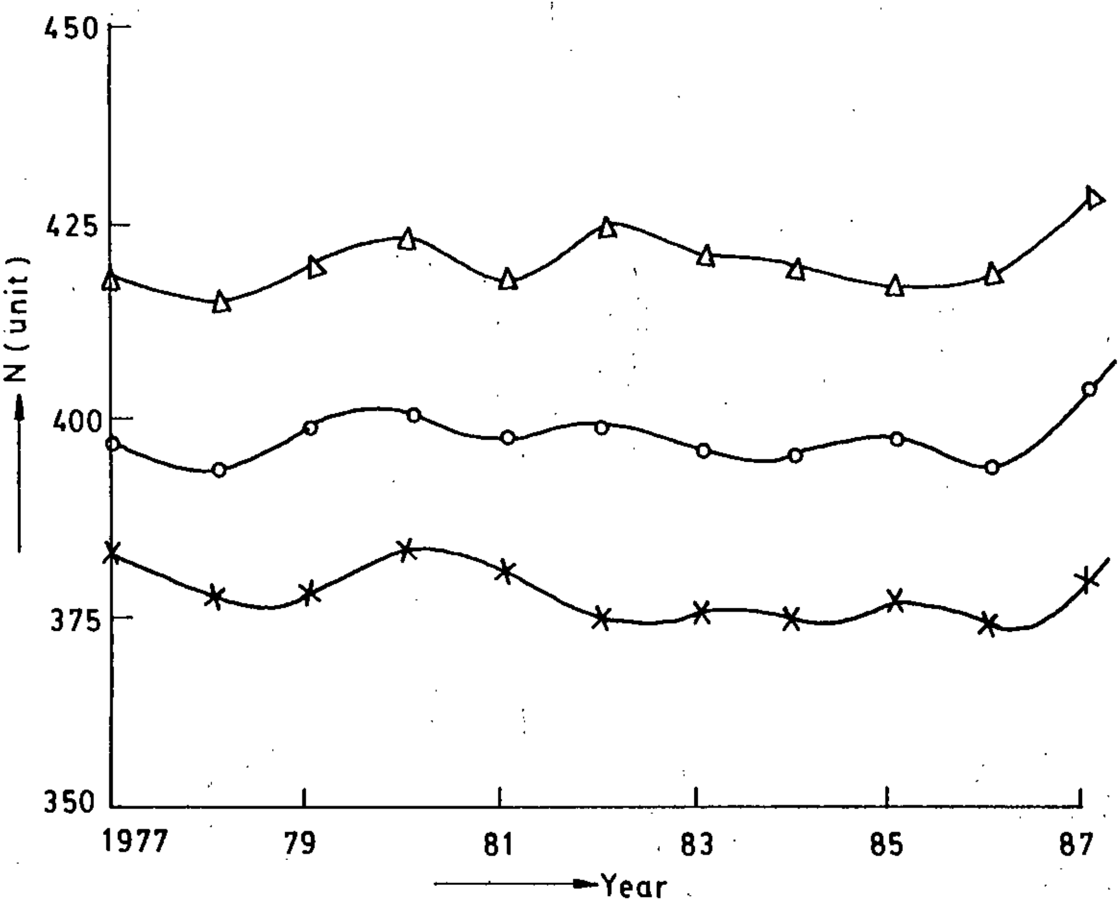
G Fig.5.6.1 (Contd..)



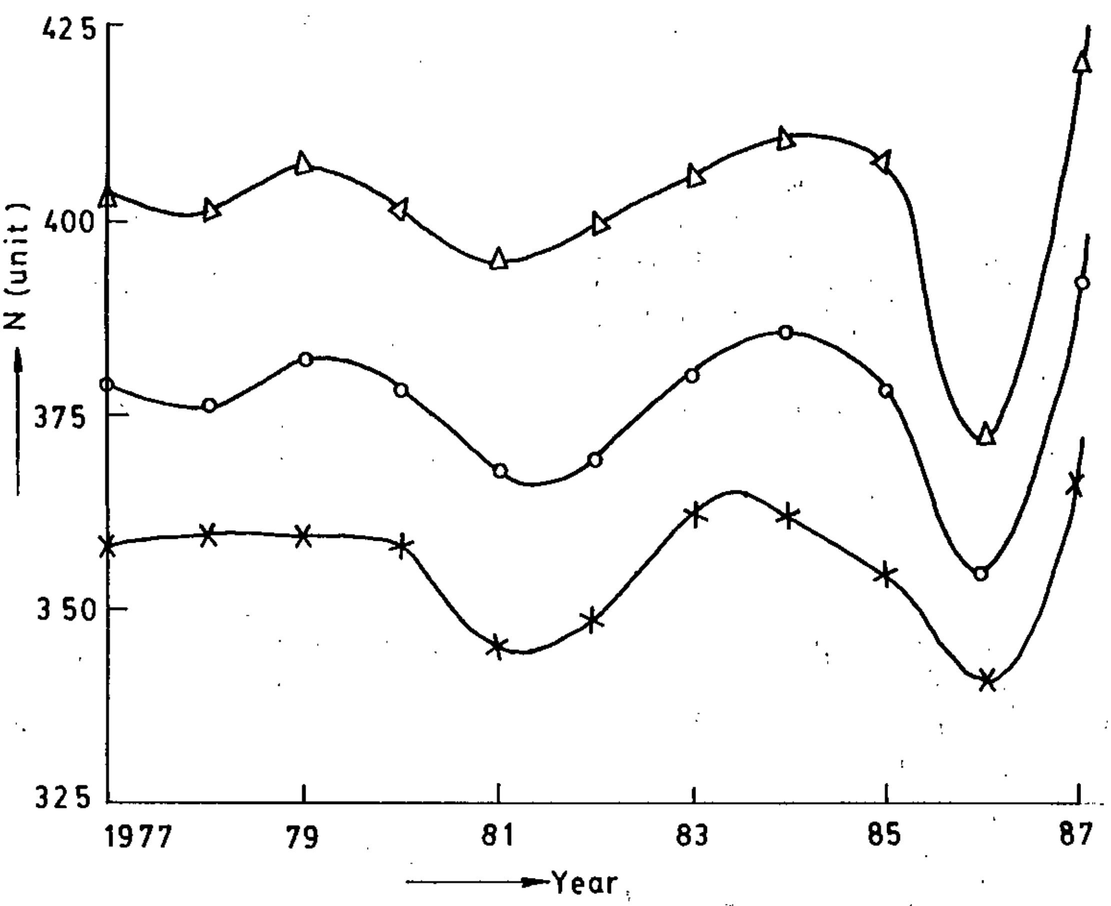


STATION - RAJSHAHI

Fig.5.6.1 (Cond..)



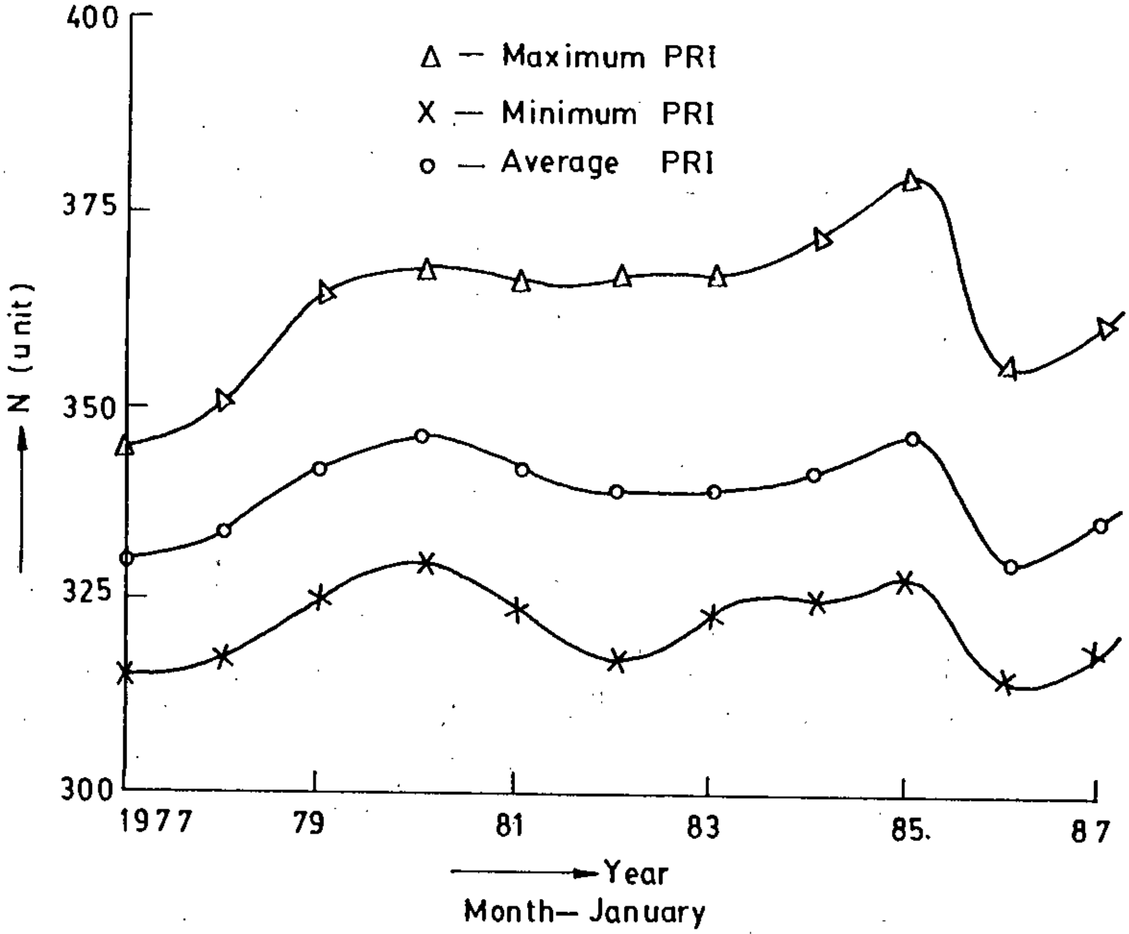
Month — July

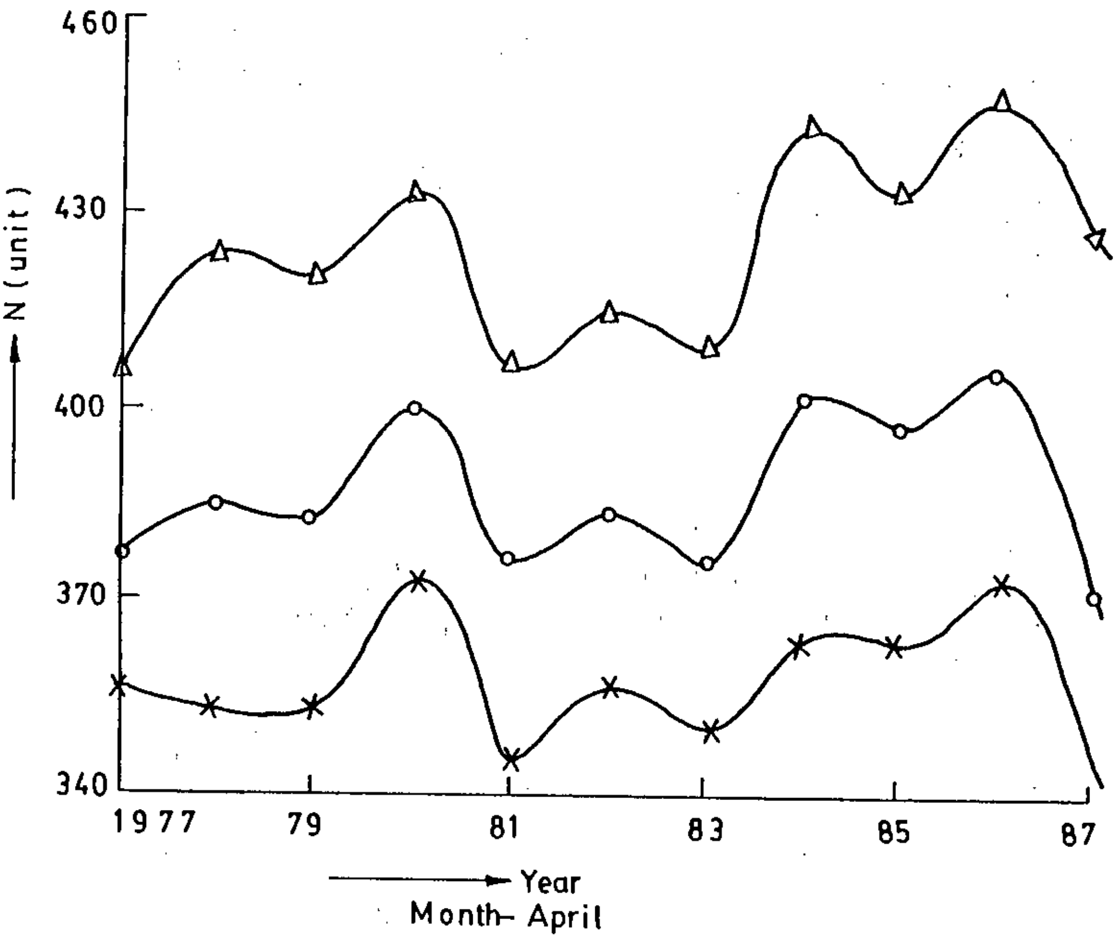


Month — October

Station — Rajshahi

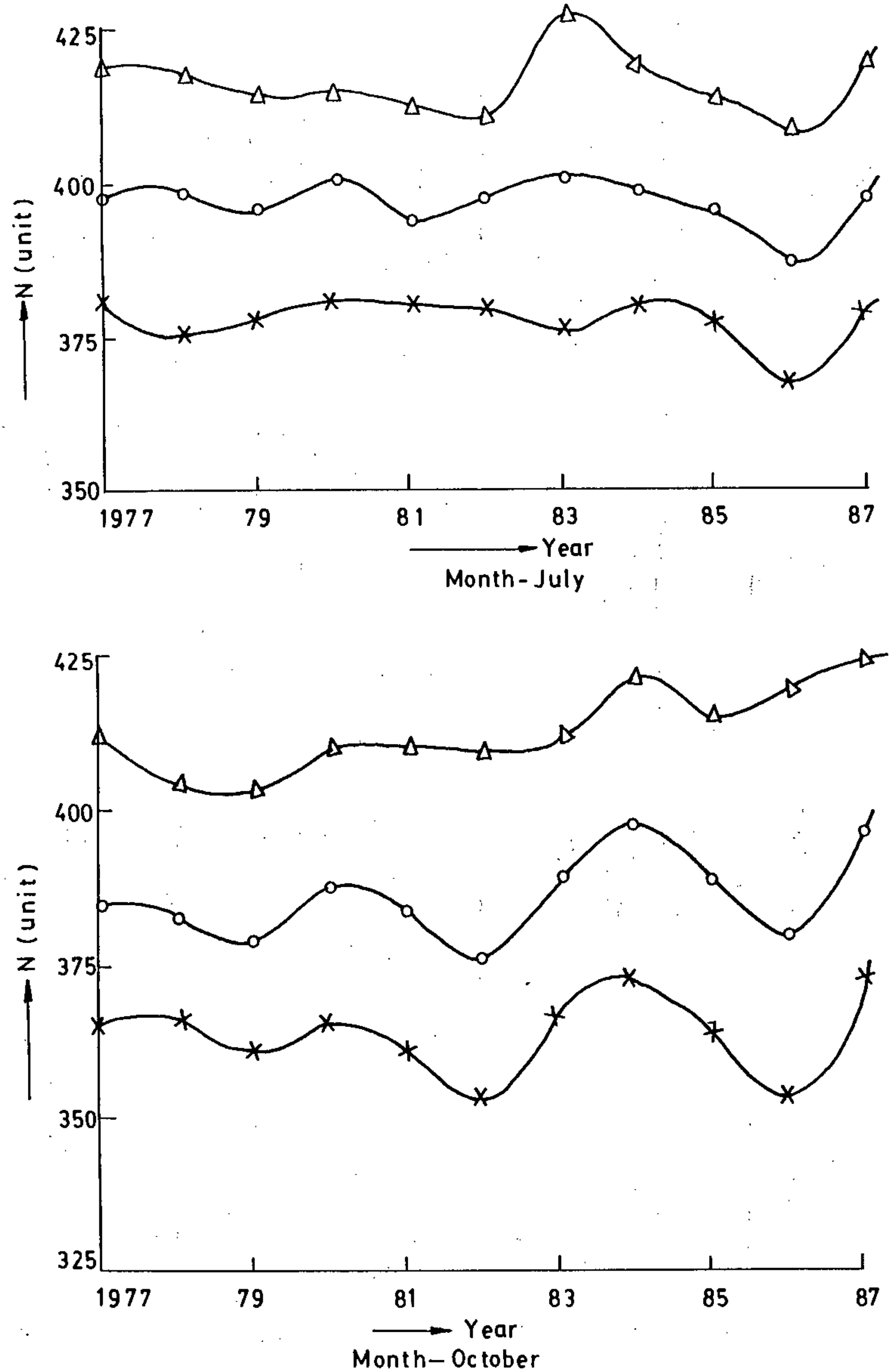
Fig.5.6.1 (Contd..)





STATION - KHULNA

Fig.5.6.1 (Contd..)



STATION- KHULNA

Fig.5.6.1

From Fig (5.6.1)the curves of Dhaka district for the months of January, April, July and October. Maximum R.R.I were 368 in 1987; 410 in 1980; 416 in 1987 and 410 in 1978 respectively. Again the minimum R.R.I observed from the curves over years 1977 to 1987 were 308 in 1980, 340 in 1977; 375 in 1978 and 353 in 1981 in the above four months respectively. The average RRI curve of any month though varies but average RRI is almost constant over years with little variations. The average RRI for Dhaka for the four months are respectively 335, 370, 395 and 380. The highest average value of RRI is observed in the month of July, then in October and next to October is in April and the lowest value is in January. Also the maximum and minimum RRI for Dhaka follows the same trend as avarage RRI value. The maximum and the minimum RRI curves for Dhaka for the four months differs by about 40 units RRI as is observed from plotting of RRI over eleven years.

From Fig(5.6.1) the curves of Chittagong district for the months of January, April, July and October maximum RRI were 370 in 1987, 406 in 1985, 413 in 1984 and 412 in 1978 respectively. Again the minimum RRI observed from the curves over the years 1977 to 1987 were 306 in 1977, 348 in 1978,361 in 1983 and 358 in 1980 above four months respectively. The averrage RRI curve of any month though varies but average RRI is almost constant over years with little varaitions. The average RRI for Chittagong for the four months are respectively 340, 375, 385 and 380. The highest average value of R.R.I is observed in the month of July, then in October and next to October is in April and the lowest value in January. Also the maximum and minimum R.R.I for Chittagong follows the same trend as average value. The maximum and the minimum R.R.I curves for Chittagong for the four months differs by about 44 units RRI as is observed from plottings of RRI over eleven years.

From Fig (5.6.1) the curves of Rajshahi district for the months of January, April, July and October maximum R.R.I were 366 in 1985, 425 in 1986; 428 in 1987 and 420 in 1987 respectively. Also the minimum RRI observed from the curves over year 1977 to 1987 were 315 in 1978, 314 in 1982, 374 in 1982 and 340 in 1986 in the above four months respectivly. The maximum, minimum and average RRI curves for Rajshahi show anomalous behaviour in the month of April. RRI decreases from the values it has in 1977 as time passes and in 1982. RRI drops suddenly to the lowest value than it has in any other years during 1977 to 1987, and starts incrasing as year passes after 1982 and attain the maximum value in 1986 and a decrasing tendency is observed in 1987 in April.On the other hand the average RRI in the months of January, July and October is almost constant though a small variation is observed and the values are 335, 398 and 380 respectively. The highest average value is observed in July and the lowest average value in the month of January and the maximum and minimum RRI curves differs by about 44 units over these three months though a slight anomaly is found in the month of October.

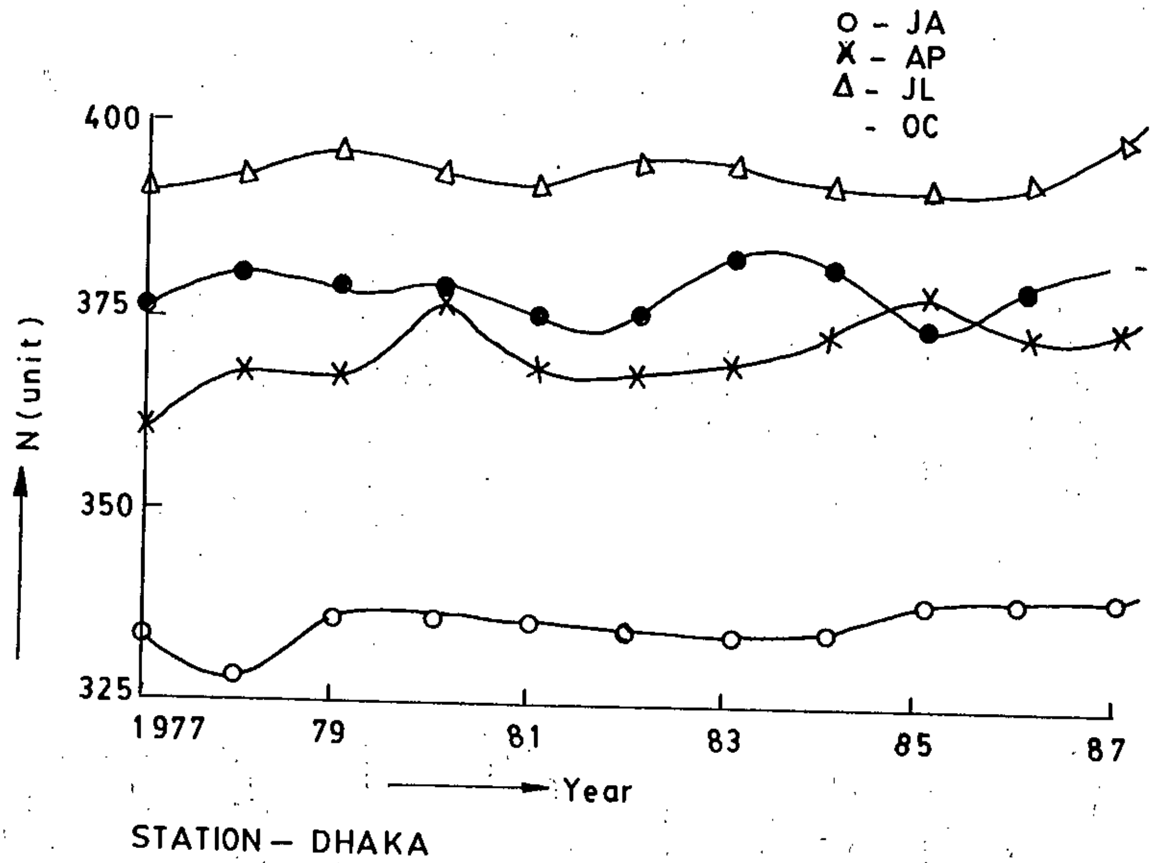
From Fig (5.6.1) the curves of Khulna district for the months of January, April, July and October maximum RRI observed were 380 in 1985, 440 in 1986, 427 in 1983 and 422 in 1984 respectively. Also the minimum RRI observed from the curves over the years from 1977 to 1987 were 314 in 1977, 336 in 1987, 308 in 1986 and 352 in 1982 in the above four months respectively. The maximum, minimum and average RRI curves for Khulna show anomalous behaviour in the month of April. RRI curves for the month of April show sudden increase and decrease over the years from 1977 to 1987.

On the other hand the average RRI in the months of January, July and October is almost constant though a small variation is observed and the average values are 340, 400 and 385 respectively. The highest average value is observed in July and the lowest value in the month of Junuary and the maximum and minimum RRI curves differs by about 42 units over these three months though a slight anomaly is observed in the month of October.

5.7 Monthly Average RRI for a Particular Place Over Several Years

Radio Refractive index were calculated for thirty locations as described previously for the months of January, April, July and October. To find the trend of variation of RRI over a long time for a particular place in a particular season, average RRI was plotted as in Fig (5.7.1) for the places Barisal,Chandpur, Bogra, Bhola, Dinajpur, Chittagong, Dhaka, Khulna, Srimangal and Patuakhali of the months of January, April, July and October of evelen years from 1977 to 1987 as data was available.

From Fig (5.7.1) it is seen that the maximum RRI occurs in the month of July and the lowest RRI occurs in the month of January normally in each year at the considered location during eleven years. The average RRI for the month of October is higher than that of April but the difference is very small.



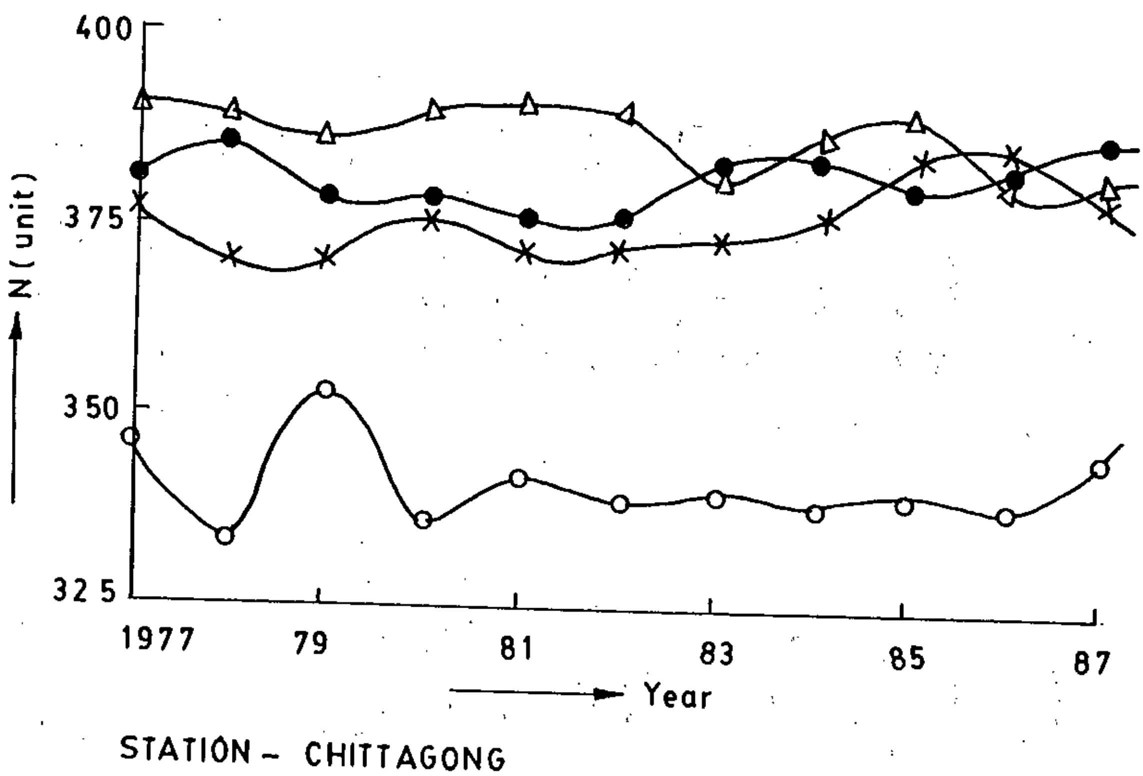
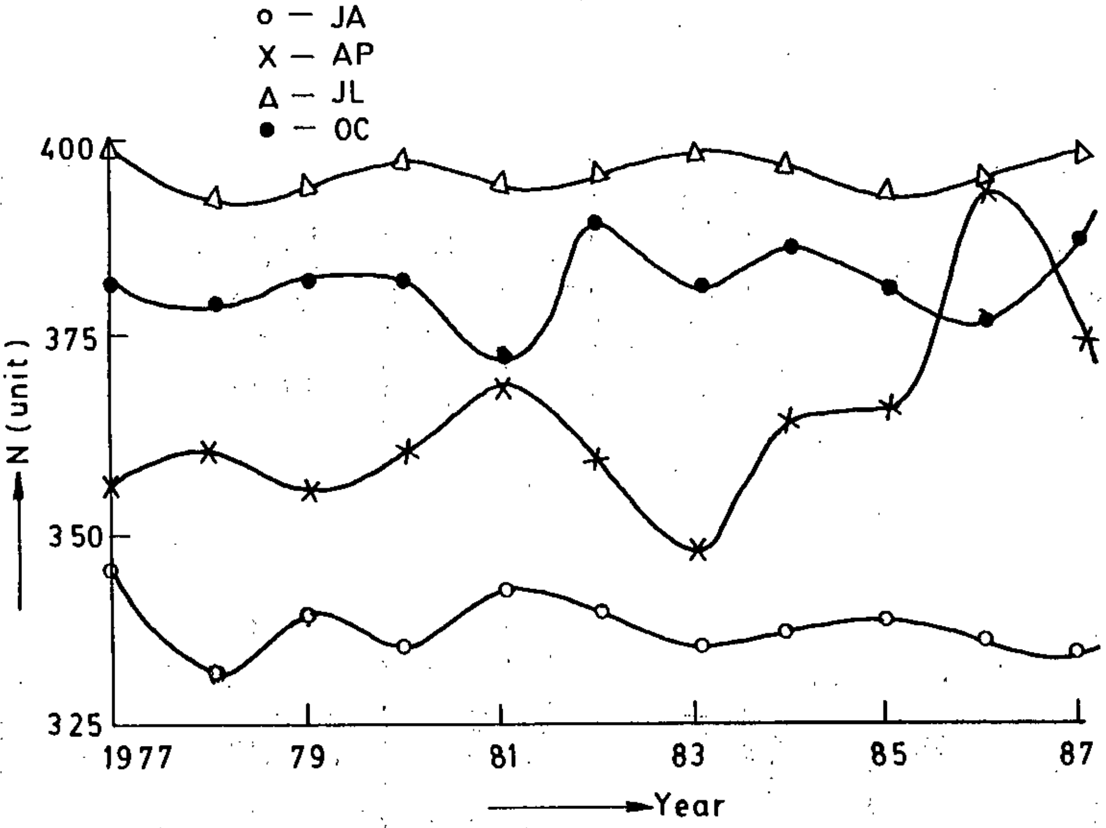
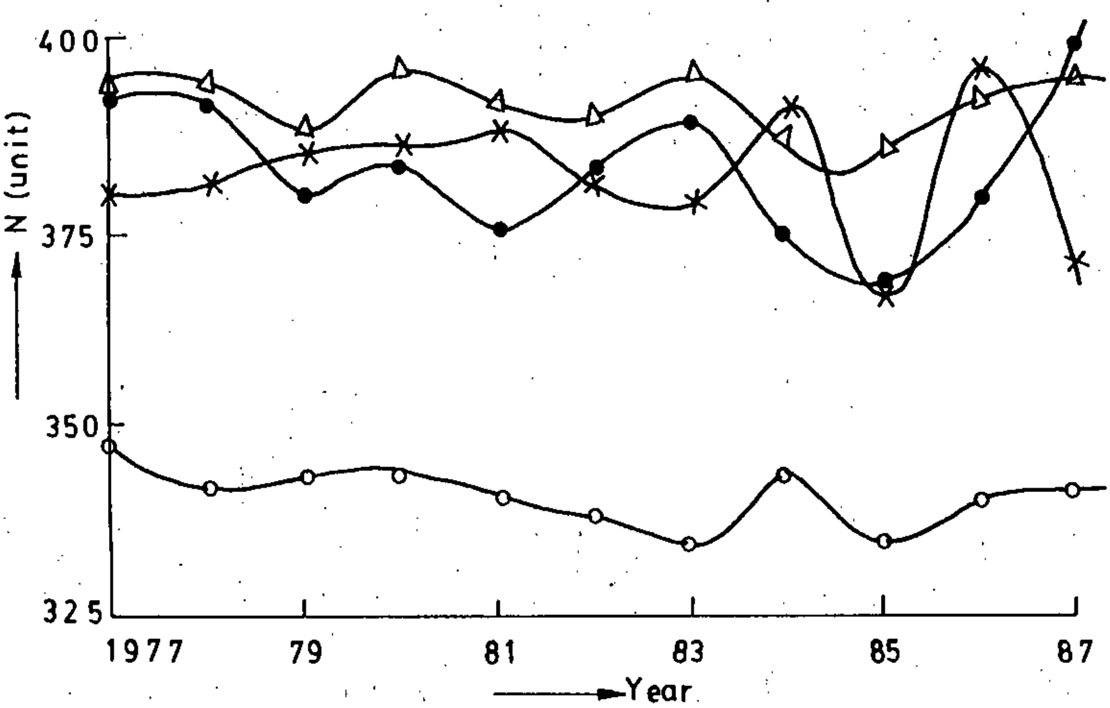


Fig.5.7.1: Variation of average RRI over the observed years (Contd..)

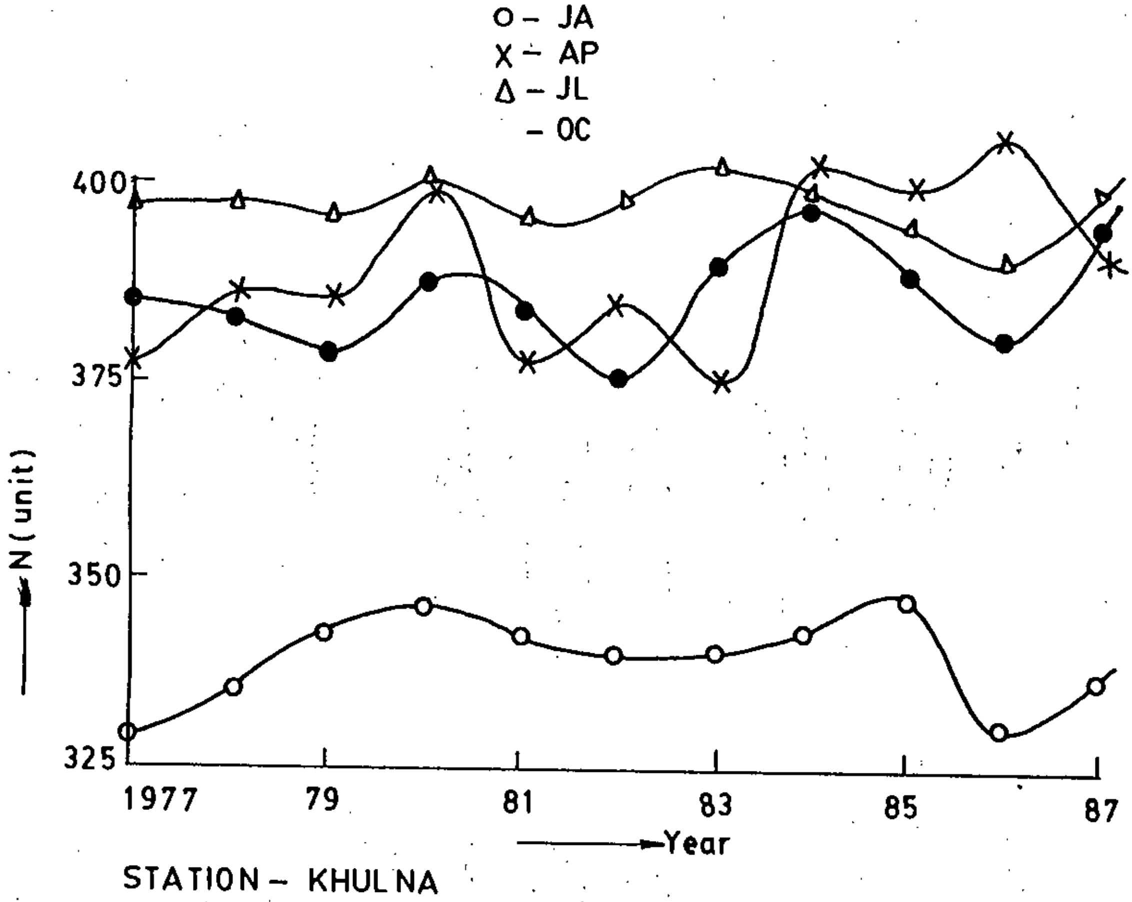


STATION – BOGRA



STATION – BHOLA

Fig.5.7.1 (Contd..)



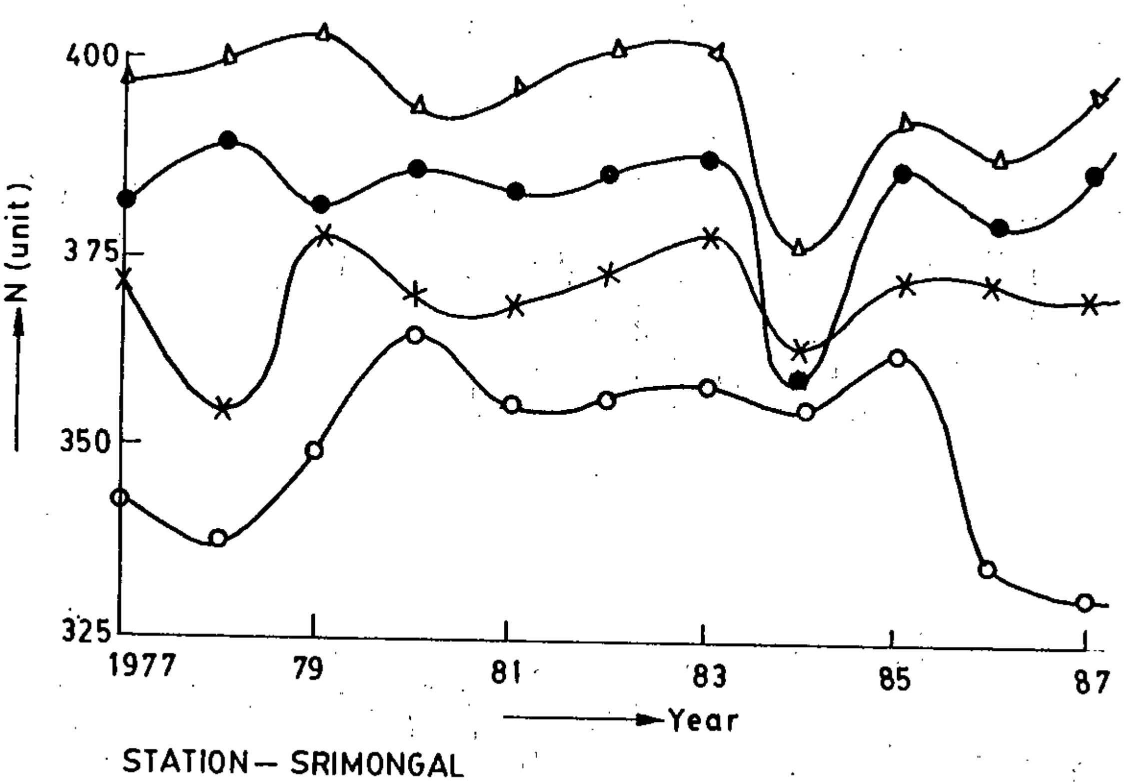
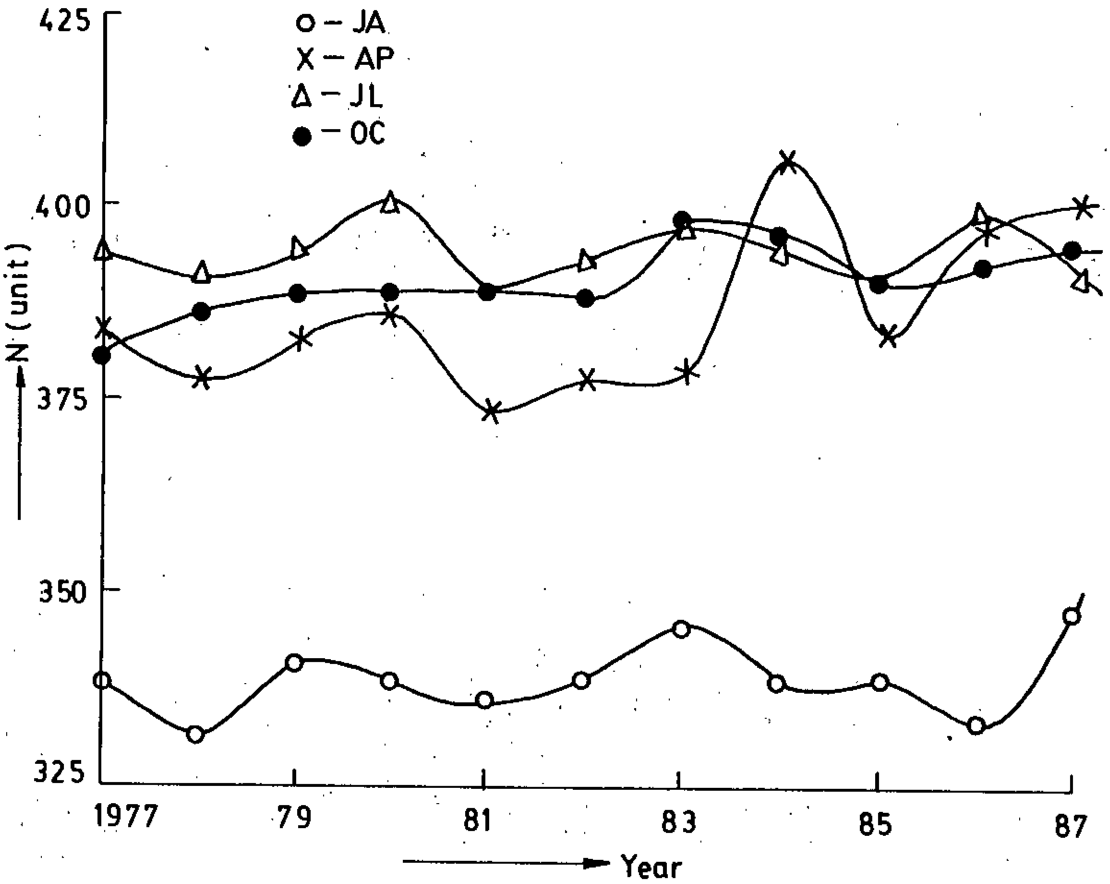
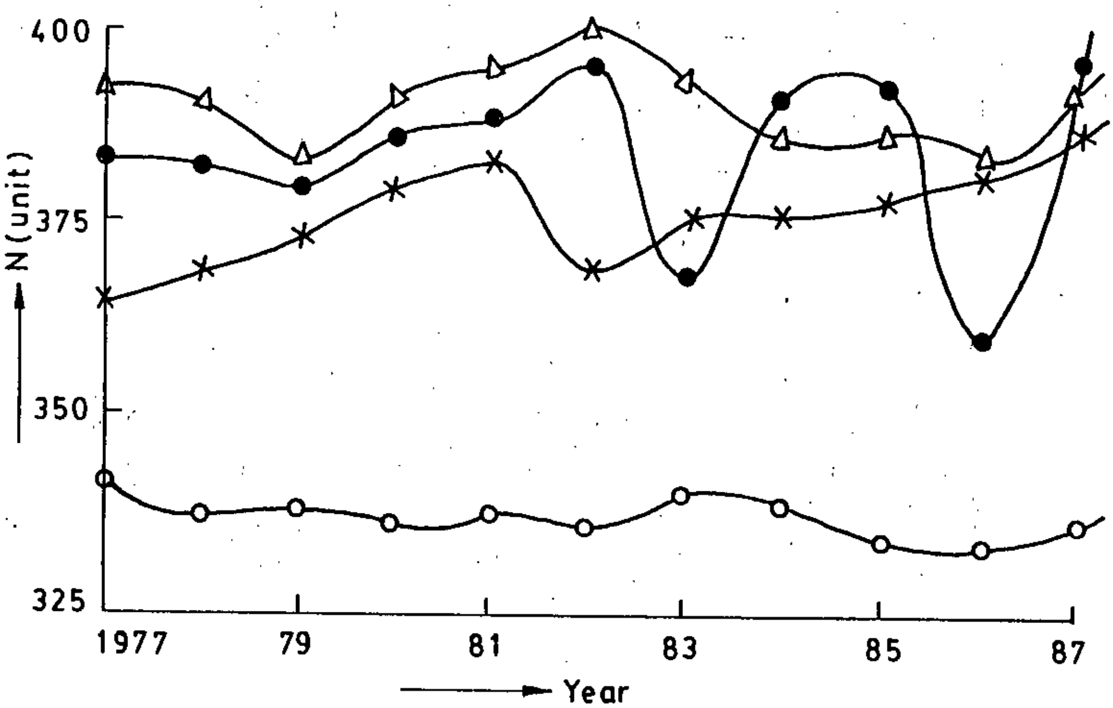


Fig.5.7.1 (Contd..)



STATION – BARISAL



STATION – CHANDPUR

Fig.5.7.1 (Contd..)

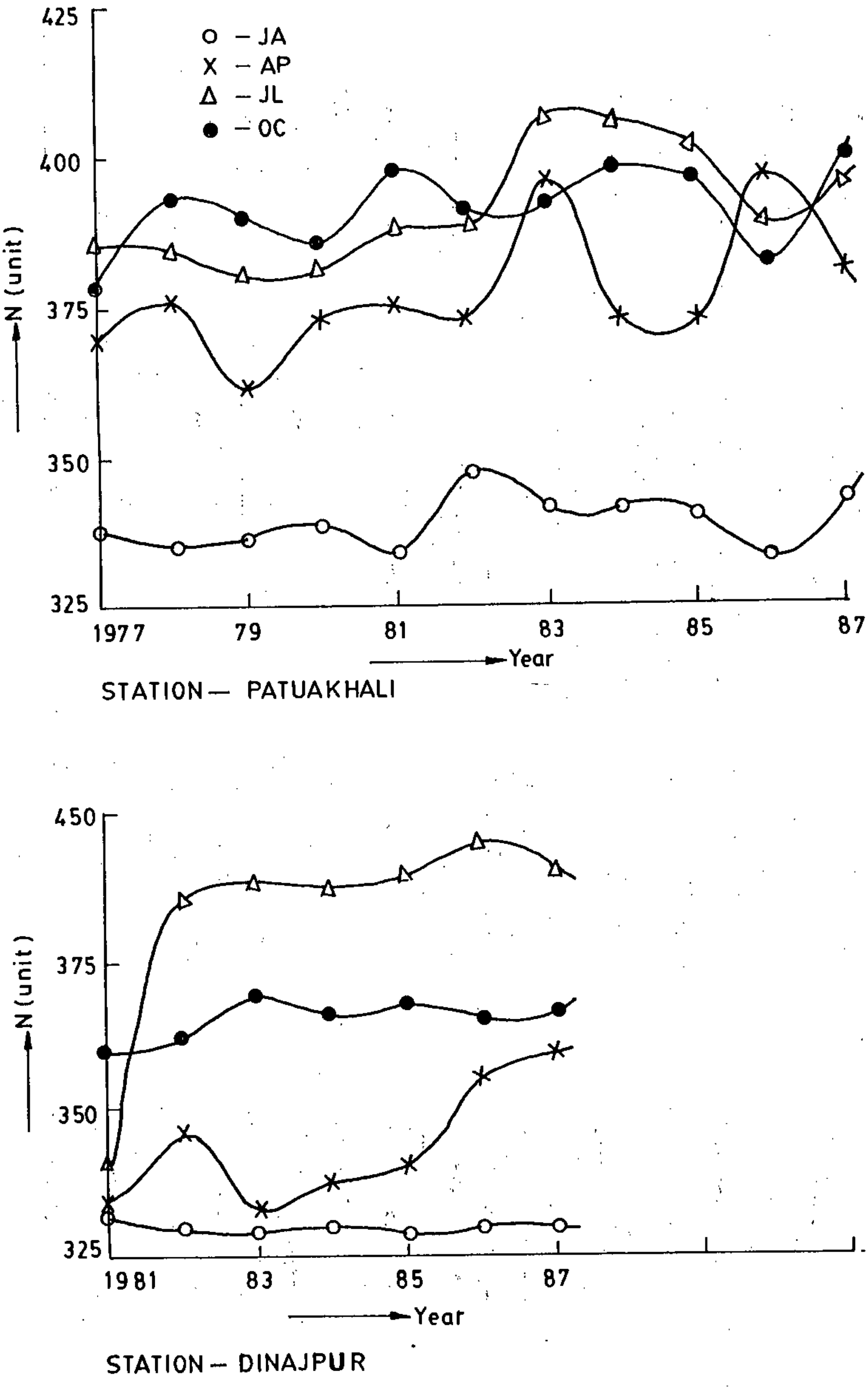

425
400
375
350
325
o – JA
X – AP
Δ – JL
● – OC
N (unit)
1977
79
81
83
85
87
Year
STATION — PATUAKHALI
450
375
350
325
N (unit)
1981
83
85
87
Year
STATION — DINAJPUR

Fig.5.7.1

Depending on weather condition RRI at a location may deviate from the normal variation as is observed in the other years. This type of phenomenon is observed for the RRI distribution over the month of April at Chandpur, Bogra and Srimangal during the period 1983 to 1987. Again though the average RRI in the month of October is normally higher than that of April but opposite phenomena is observed for some coastal places i.e. Bhola, Chittagong and Khulna some time during the period considered. This may occur due to the fact that the weather at the coastal area may vary markedly from the other places causing to abnormal variation at that time for these places.

5.8 Bar-Graph of Maximum and Minimum RRI in the Months of January, April, July and October for the Different Locations

Radio Refractive Index (RRI) were calculated for the thirty locations in Bangladesh over the eleven years from 1977 to 1987 as discussed previously for the four months ie January, April July and October over a year. To have an idea about the variation of RRI for a particular location over a month, the calculated RRI were investigated to find out the maximum and minimum RRI over these eleven years. The found RRI of each month are represented

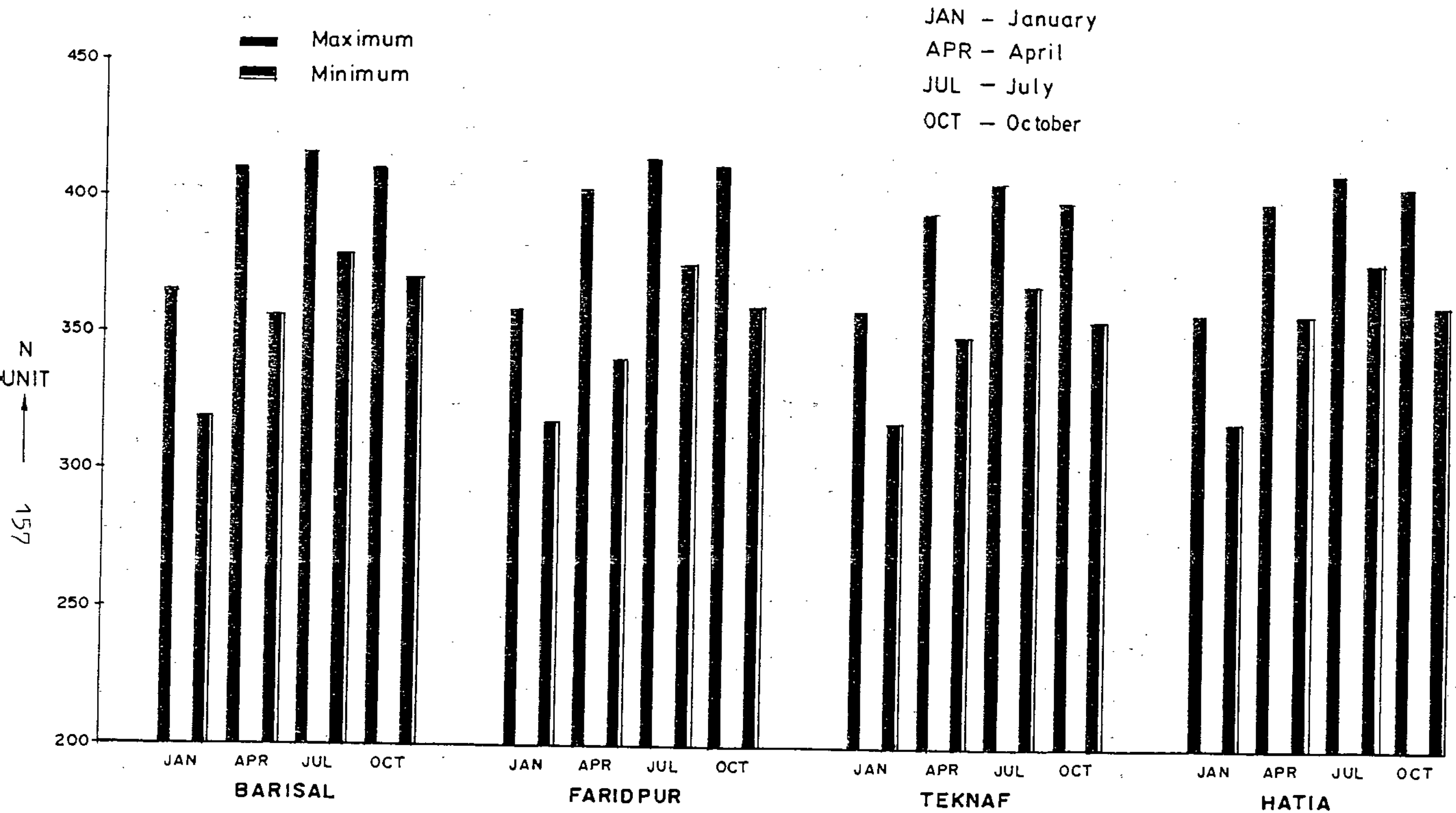


FIG.-5·8·1 MAXIMUM AND MINIMUM RADIO REFRACTIVE INDEX FOR THE MONTHS JANUARY, APRIL, JULY & OCTOBER FOR DIFFERENT STATIONS.

Contd...

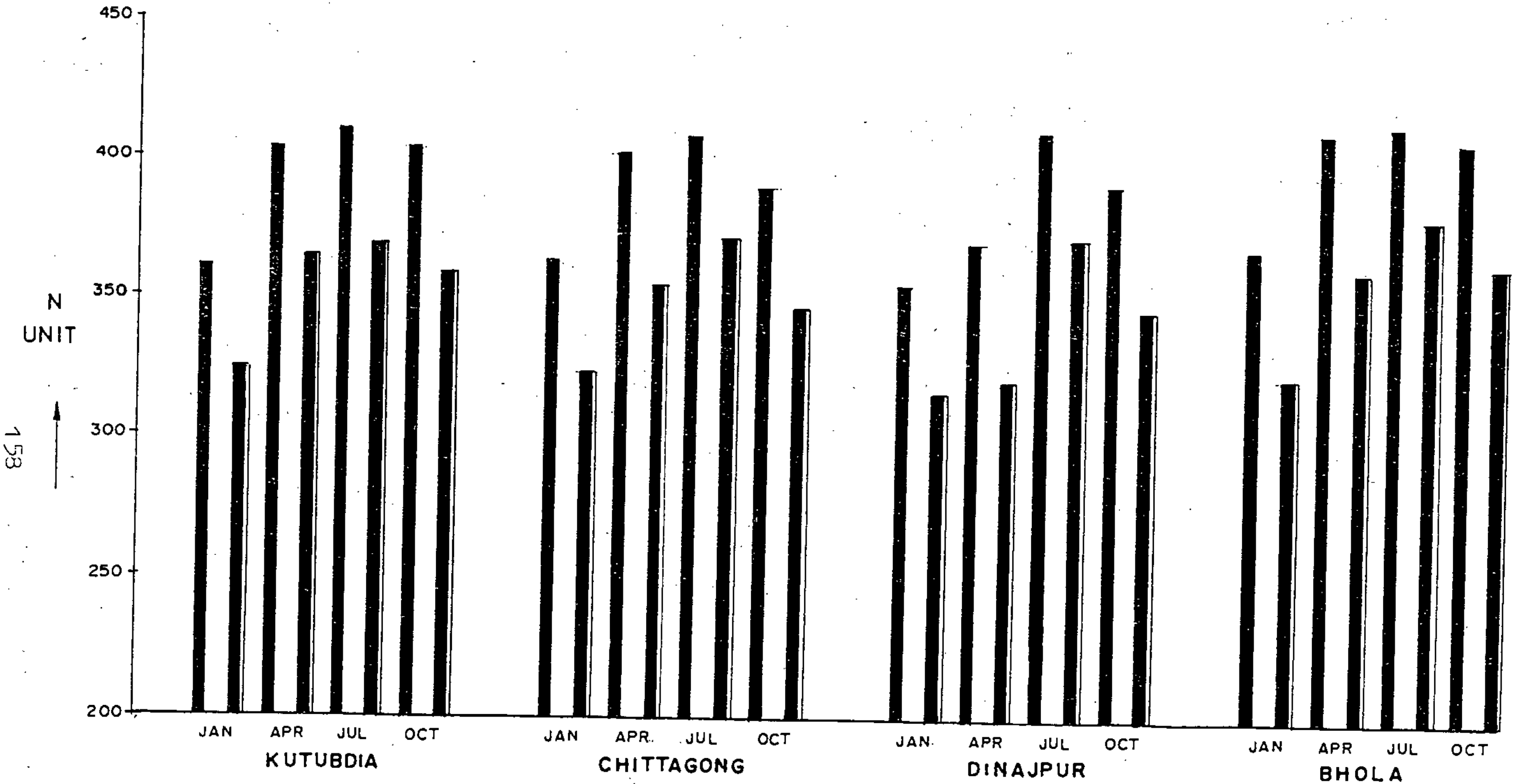


FIG.-5·8·1 MAXIMUM AND MINIMUM RADIO REFRACTIVE INDEX FOR THE MONTHS JANUARY, APRIL, JULY & OCTOBER FOR DIFFERENT STATIONS.

Contd..

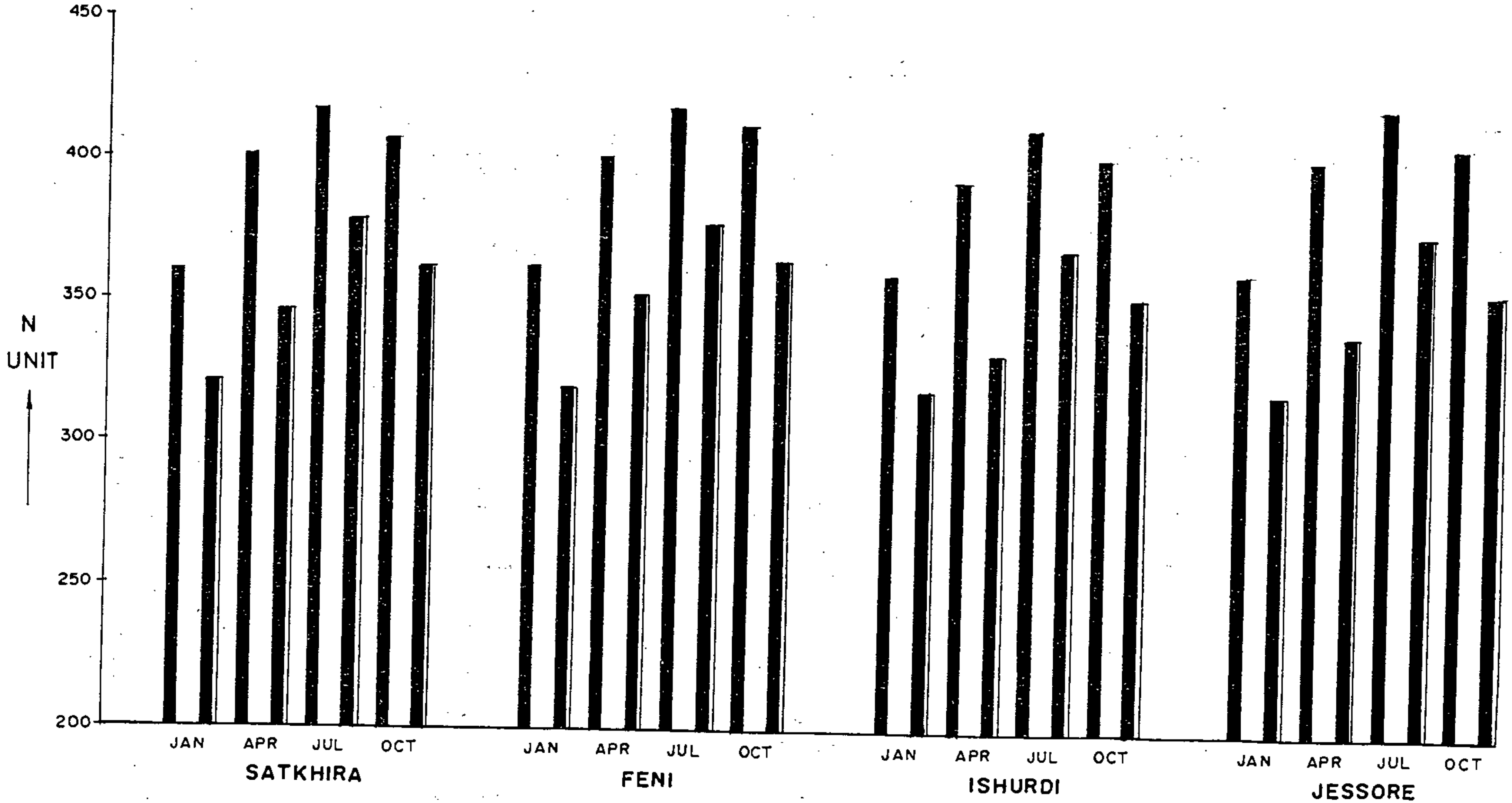


FIG.-5·8·1 MAXIMUM AND MINIMUM RADIO REFRACTIVE INDEX FOR THE MONTHS JANUARY, APRIL, JULY & OCTOBER FOR DIFFERENT STATIONS.

Contd...

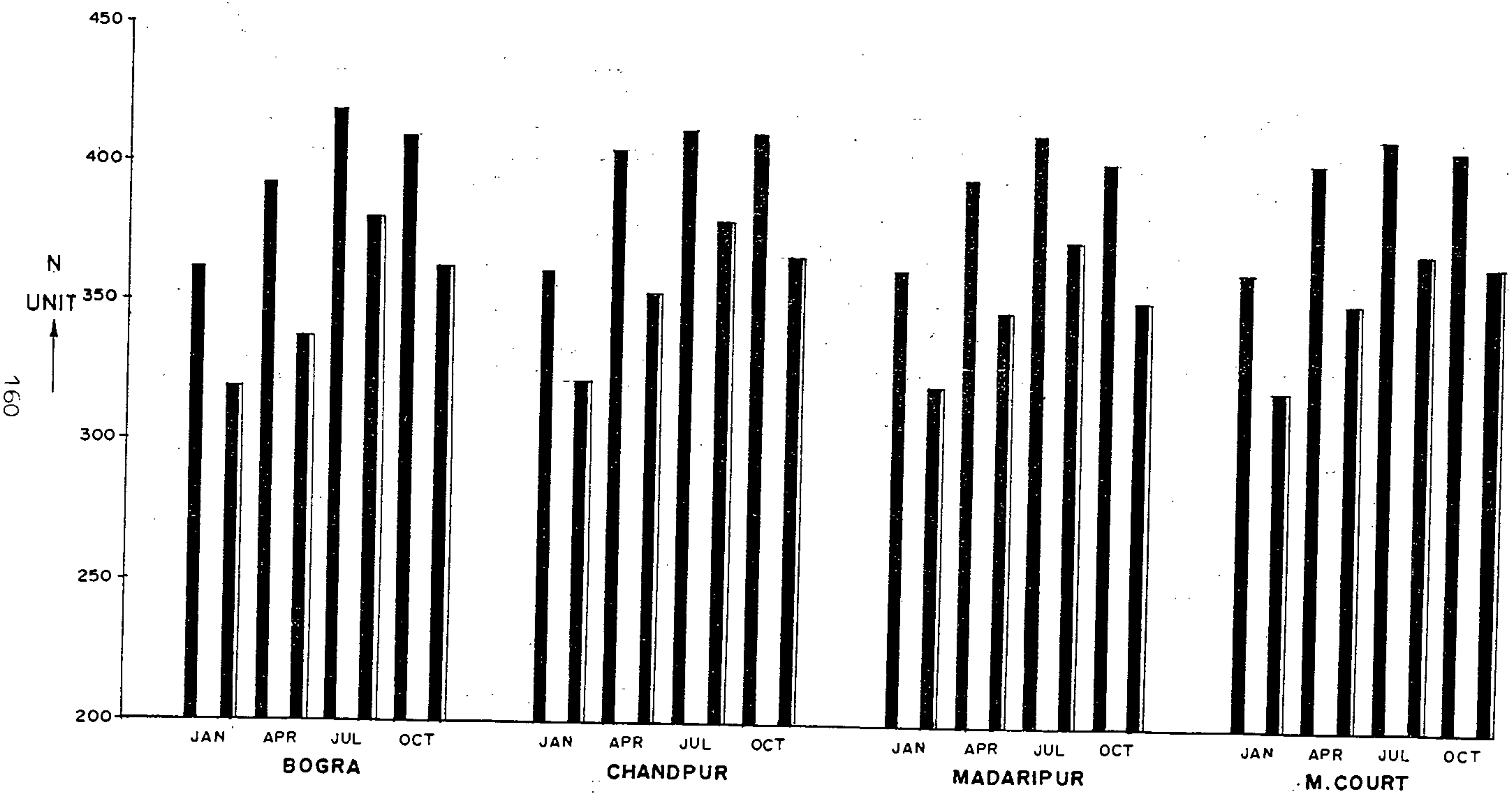


FIG.-5·8·1 MAXIMUM AND MINIMUM RADIO REFRACTIVE INDEX FOR THE MONTHS JANUARY, APRIL, JULY & OCTOBER FOR DIFFERENT STATIONS.

Contd..

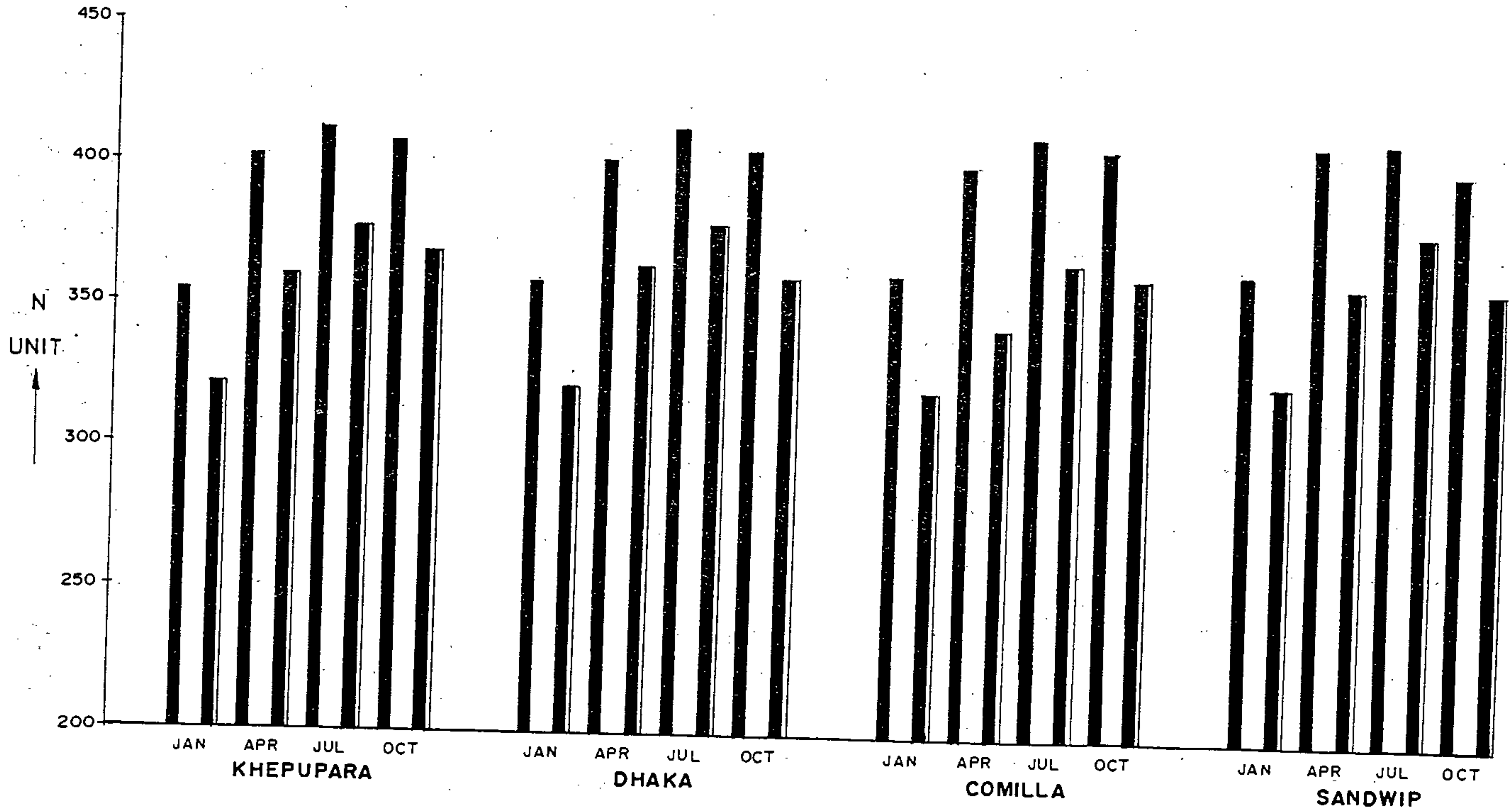


FIG.-5·8·1 MAXIMUM AND MINIMUM RADIO REFRACTIVE INDEX FOR THE MONTHS JANUARY, APRIL, JULY & OCTOBER FOR DIFFERENT STATIONS.

Contd..

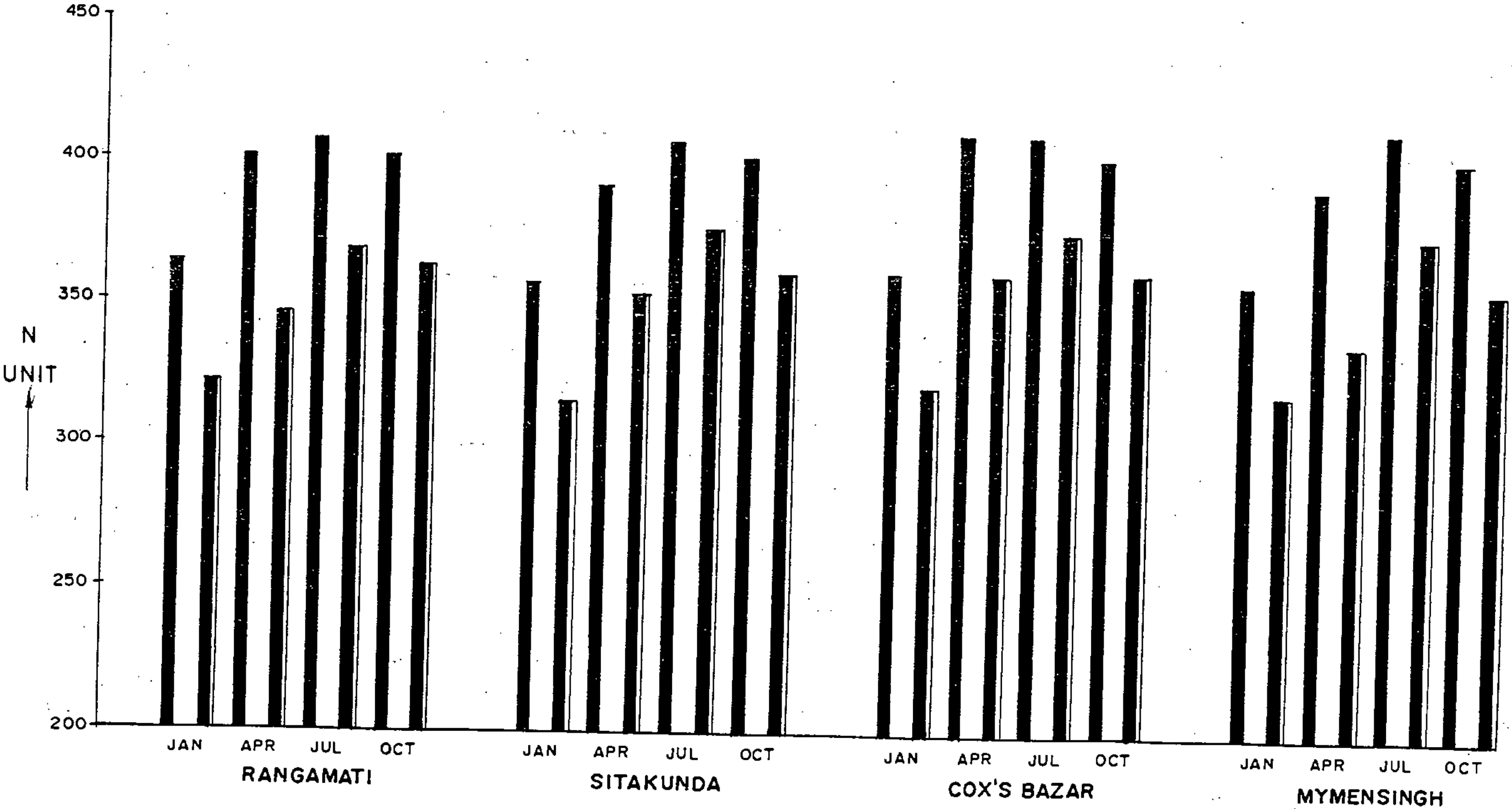


FIG.-5·8·1 MAXIMUM AND MINIMUM RADIO REFRACTIVE INDEX FOR THE MONTHS JANUARY, APRIL, JULY & OCTOBER FOR DIFFERENT STATIONS.

Contd..

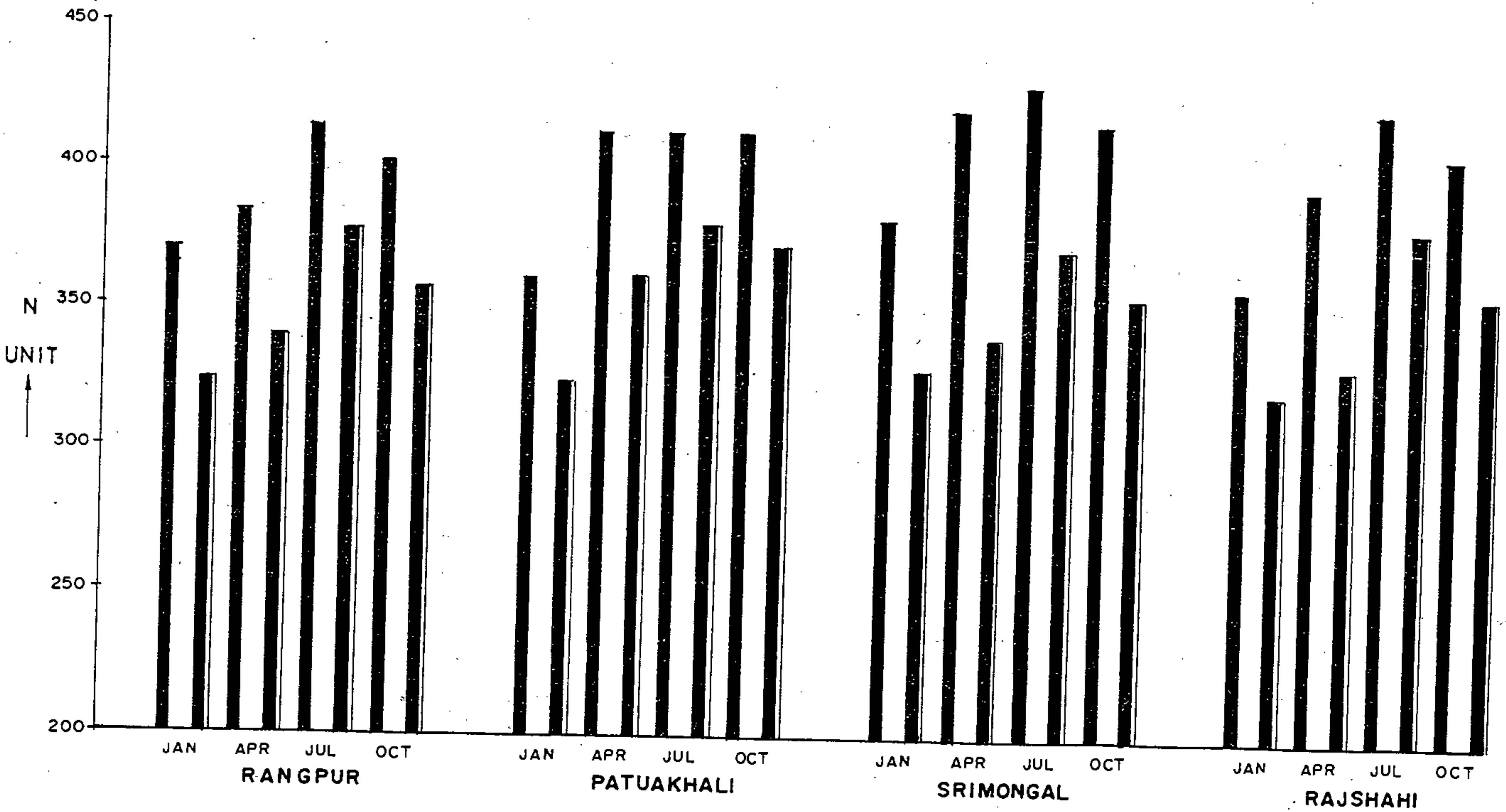


FIG.-5·8·1 MAXIMUM AND MINIMUM RADIO REFRACTIVE INDEX FOR THE MONTHS JANUARY, APRIL, JULY & OCTOBER FOR DIFFERENT STATIONS.

Contd..

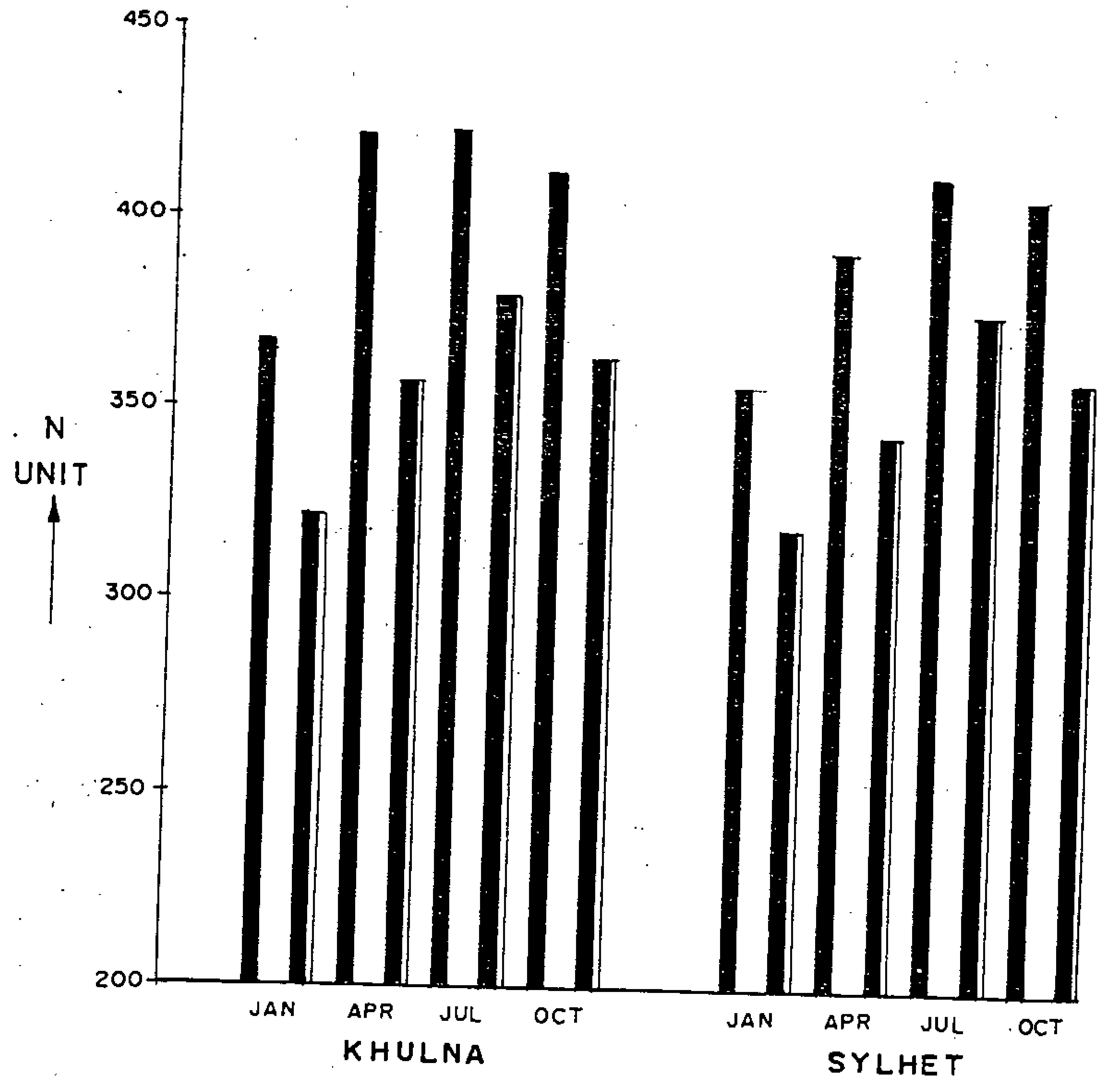


FIG.-5·8·1 MAXIMUM AND MINIMUM RADIO REFRACTIVE INDEX FOR THE MONTHS JANUARY, APRIL, JULY & OCTOBER FOR DIFFERENT STATIONS.

here in the form of bar-graph in fig (5.8.1) fof different locations Also the numerical values are presented in table form in Appendix-E. The variations of RRI at any locations over any month can be determined easily i.e. the bar-graph depicts a clear picture of the RRI variations over eleven years from 1977 to 1987 for the thirty locations. From the bar-graph it is seen that the highest RRI occurs in the month of July of each of the thirty stations and it is in the range of 375 to 430. Again lowest RRI is observed in the month of January for the thirty locations considered and it is situated in the range 325 to 370. Again the RRI observed in the months of April and October is almost the same though RRI in October is slightly higher than that in April but the value for both of these months is between the values of January and July. An approximate range of RRI for the months of April and October can be considered as 340 to 400 and 355 to 410 respectly for each station over eleven years from 1977 to 1987.

On the whole, we can say the bar-graph represents a quicker means to find the variation of RRI for the thirty stations considered here over the months of January, April, July and October.

5.9 RRI Profiles for Bangladesh

The refractivity profile of Bangladesh is shown through some refractivity contours as shown in fig (5.9.1).The variation of radio refractive index over whole of Bangladesh is depicted in these contour maps. Using the average radio refractive index of eleven years (1977 to 1987) four refractivity profiles are drawn to see the variation of RRI over the months January, April, July and October i.e. over the four seasons. Profiles are drawn by joining the places having almost equal refractivity. In four seasons, the refractivity profiles for the coastal area are similar. But for other parts of Bangladesh the refractivity profiles are different in different seasons.

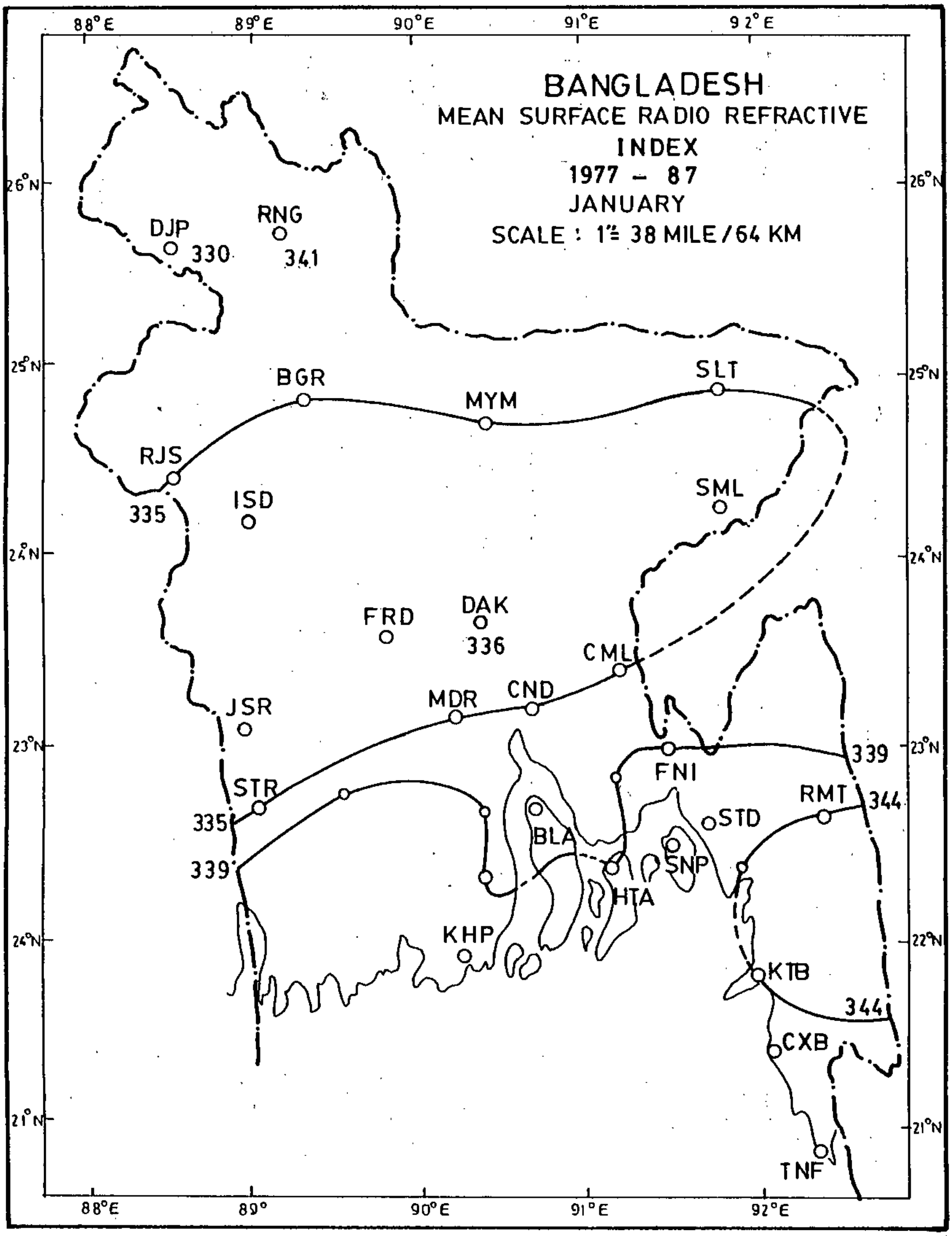


Fig.5.9.1a: Contours of surface RRI for the month of January of Bangladesh.

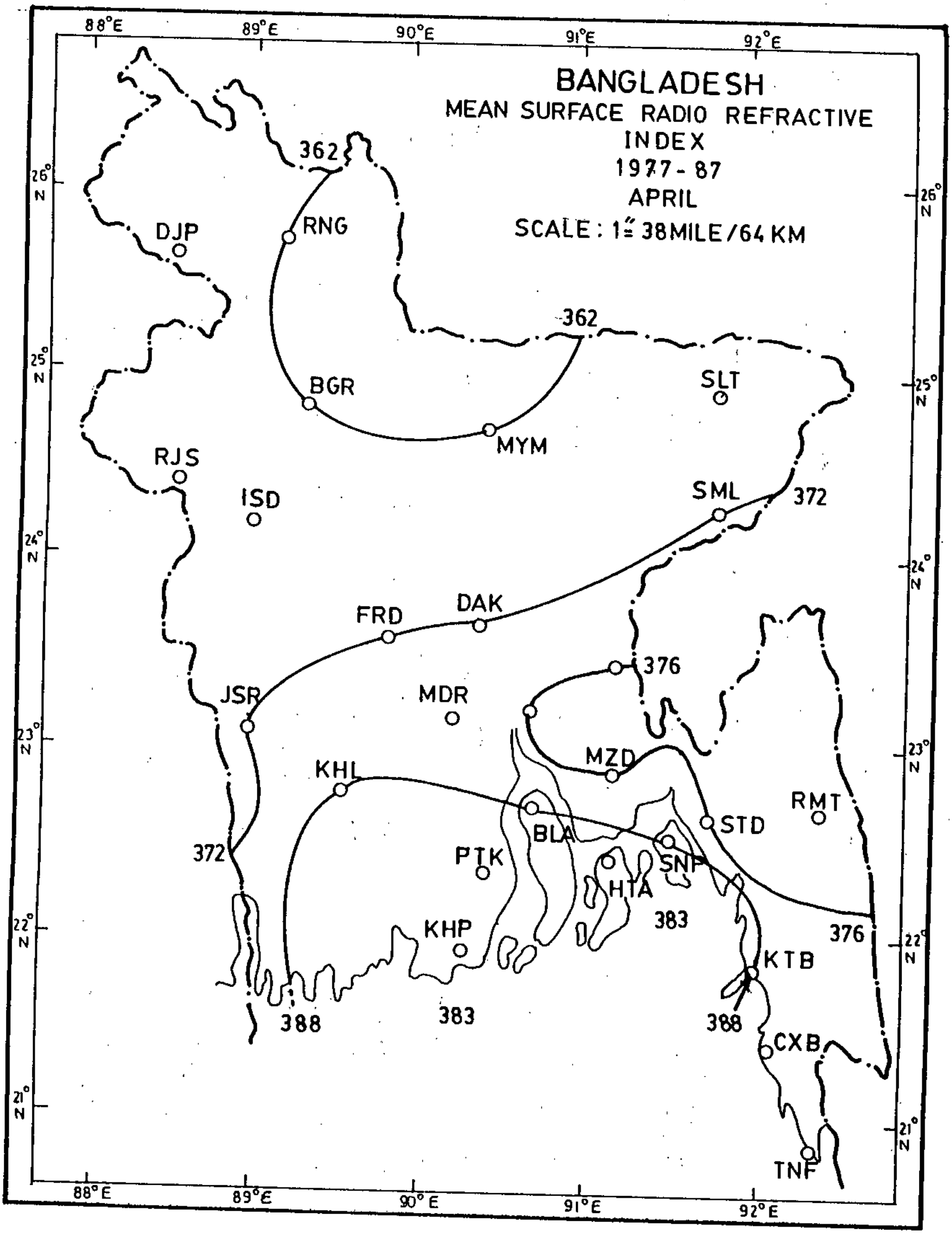


Fig.5.9.1b: Contours of surface RRI for the month of April of Bangladesh

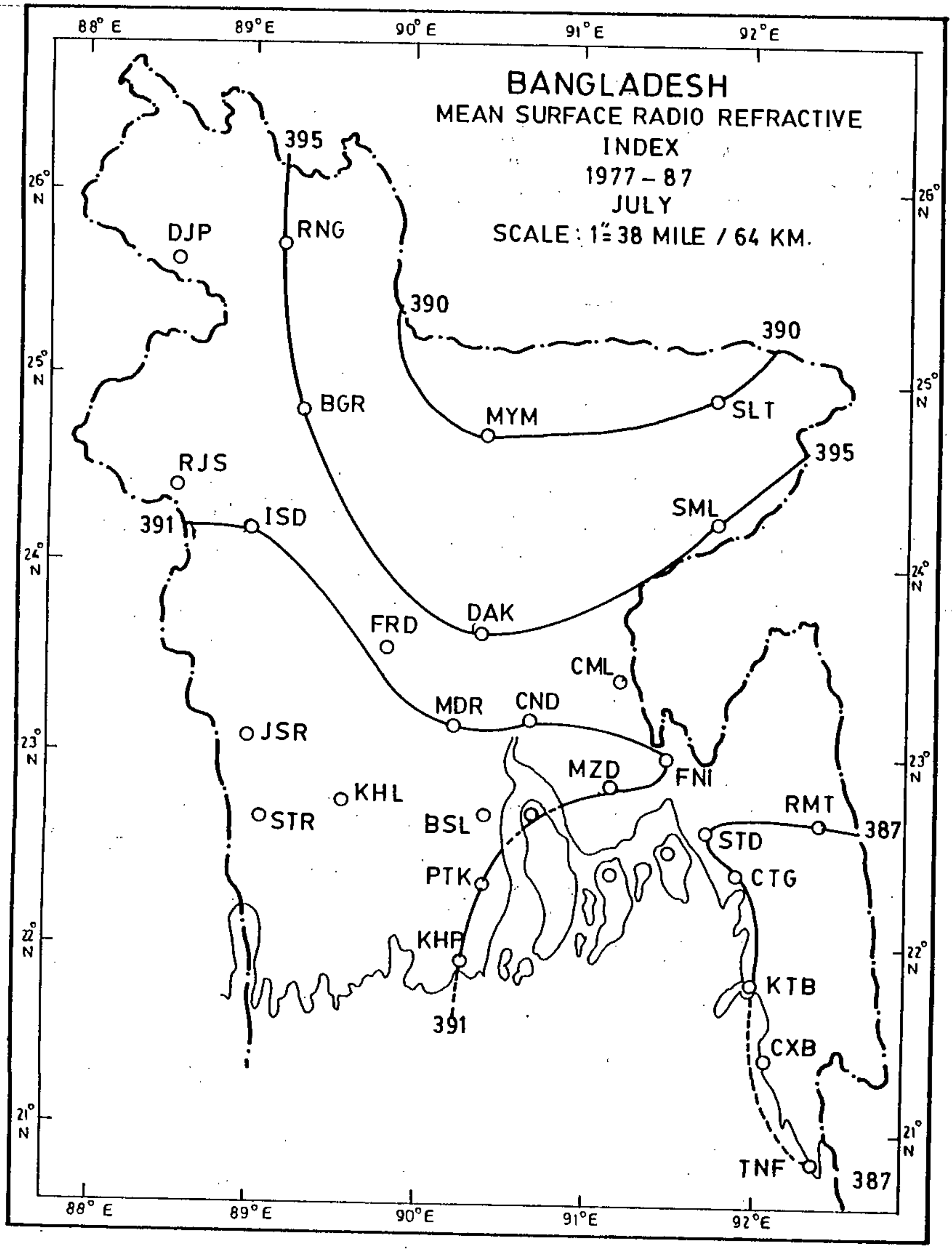


Fig.5.9.1c: Contours of surface RRI for the month of July of Bangladesh.

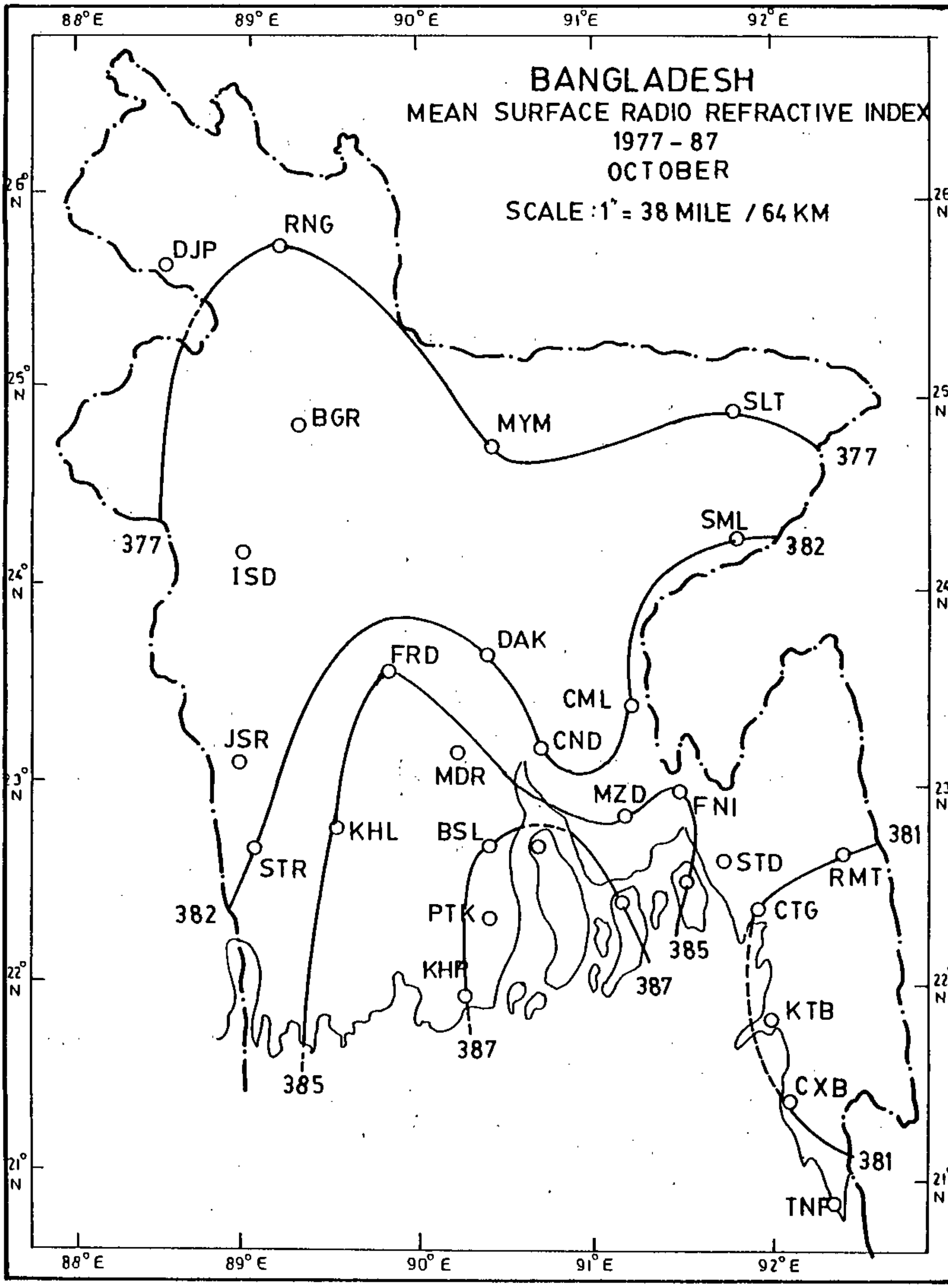


Fig.5.9.1d: Contours of surface RRI for the month of October of Bangladesh.

CHAPTER 6

RADIO REFRACTIVE INDEX AND ITS GRADIENT FROM RADIOSONDE DATA AND THEIR EFFECT ON RADIO WAVE PROPAGATION

6.1 Introduction

In this chapter we describe the radio-sonde data of temperature, pressure and relative humidity as collected by the Bangladesh Meteorological Department (BMD). The RRI is calculated from these data. These RRI values show their variation with height. From these values of RRI we calculate the refractivity gradient and an effort is made here to derive an emperical formula to show a relationship between the surface RRI and refractivity gradient for Bangladesh as a whole and also for some places considering separately. The variation of refractivity with height affects propagation of waves which causes bending of wave path as discusded earlier. In this chapter we calculate the bending of waves with the help of refractivity and its gradient.

6.2 Radio Refractive Index from Radiosonde Data

The radisonde data are obtained from the monthly climatic data for the regions Dhaka, Chittagong and Bogra only as available from Bangladesh Meteorological Department. The data includes the atmopsheric pressure, temperature and dew point temperature which are measured at different heights from the earth surface by sending meteorological balloons. Relative humidity is calculated from this dew point temperature. Thus using these atmospheric pressure, temperature and relative humidity the radio refractive index is calculated at different heights from the earth surface and the radio refractive index profile (Radio refractive index vs height) is drawn for the regions Dhaka, Chittagong and Bogra for the months of January, April, July and October showing variation of refractivity with heights in Figs.(6.2.1a,b and c).

From these profile it is seen that both the surface refractivity together with the slope of the refractivity profile for different regions vary as a function of time or season. In January the surface refractivity is low, about 340 and also the change in radio refractive index for the first kilometer i.e. the radio refractive index gradient is low and about -45/km.

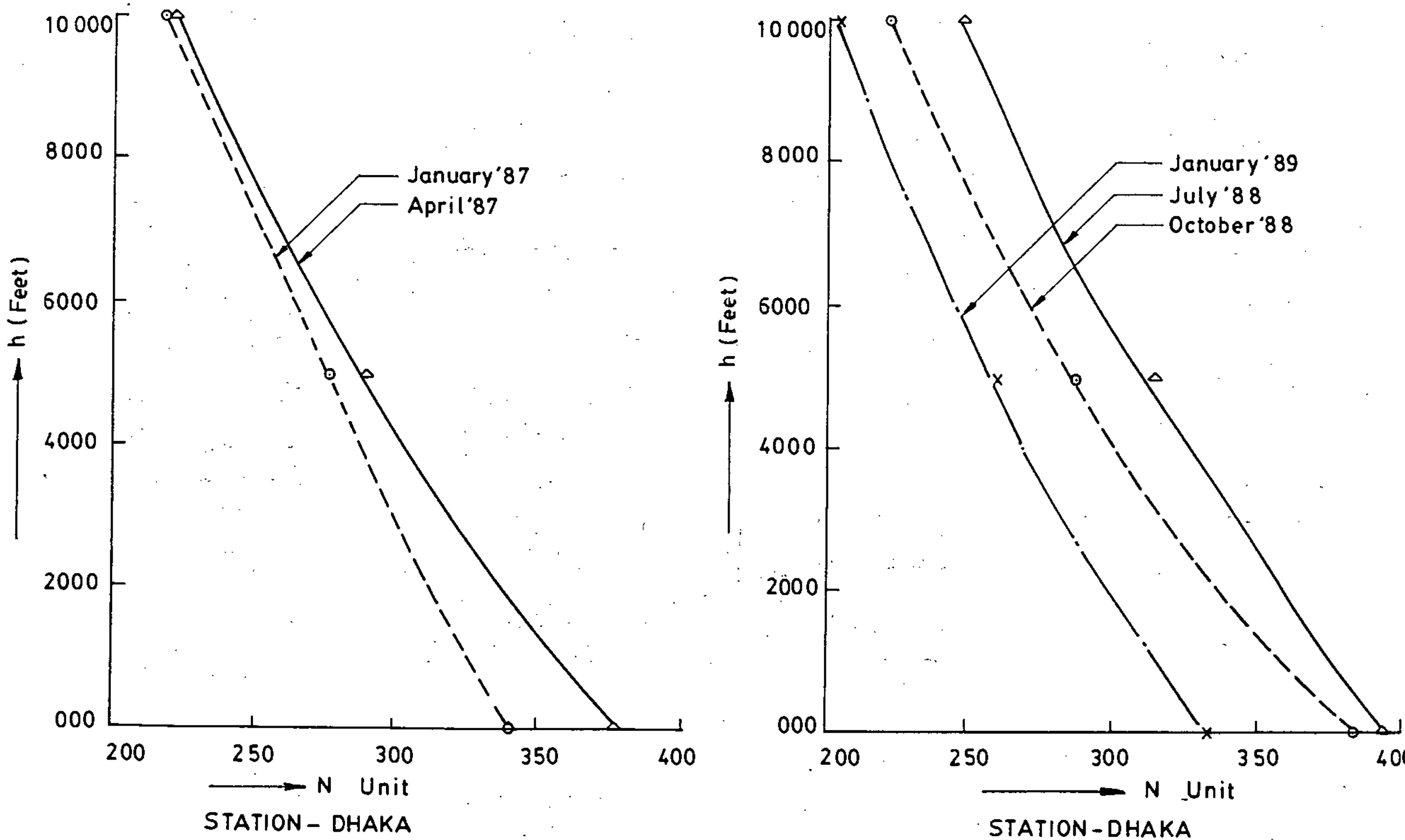


Fig.6.2.1a: Variations of RRI with height of radiosonde stations for different months.

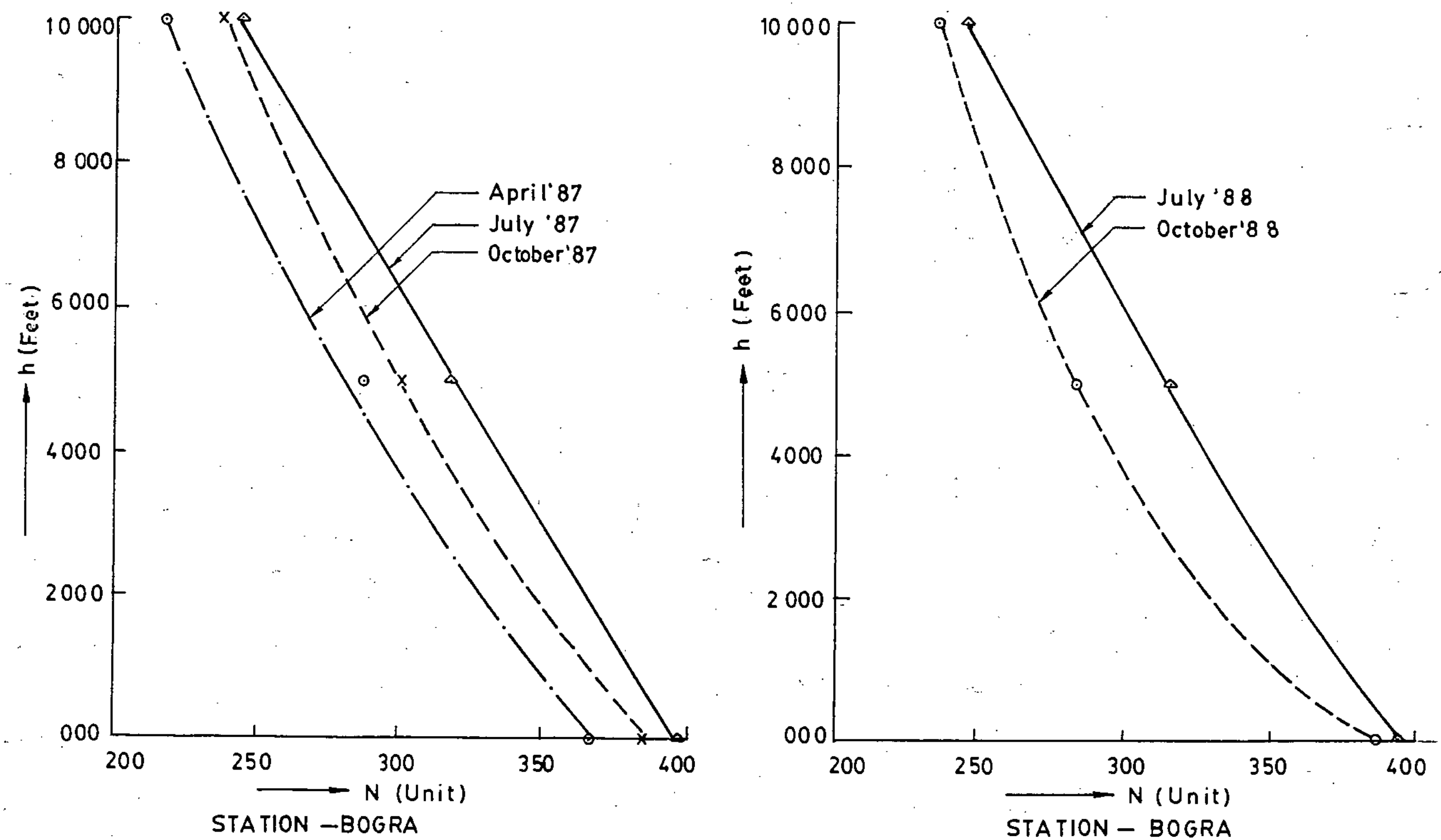


Fig.6.2.1b: Variations of RRI with height of radiosonde stations for different months.

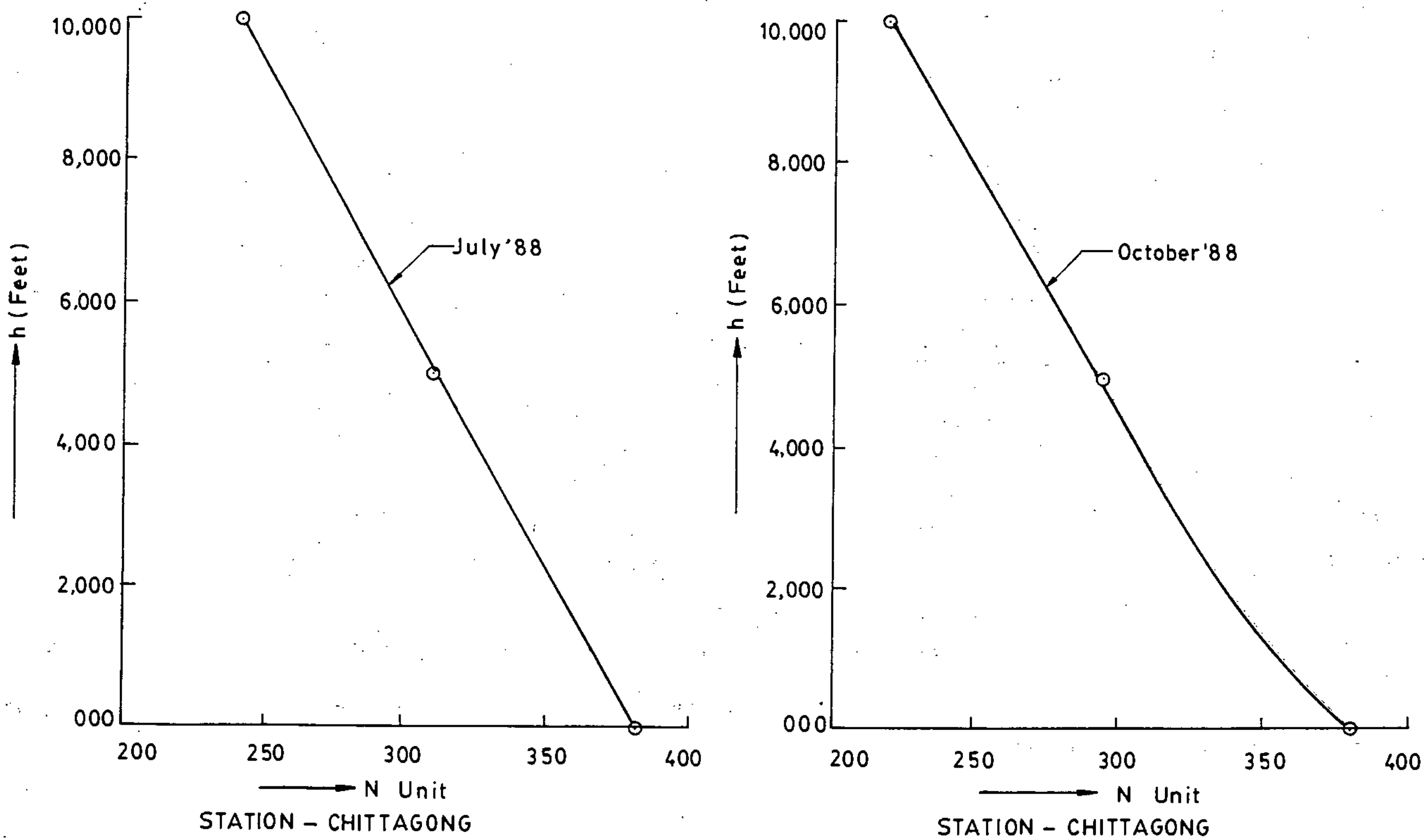


Fig.6.2.1c: Variations of RRI with height of radiosonde stations for different months.

In April as the temperature increases slightly the surface refractivity increases by about 30 unit than that of January and also the gradient of radio refractive index increases by 10 units than the gradient in the month of January.

In the month of July the highest temperature occurs in Bangladesh and the relative humidity increases due to the rainy-season. Both these conditions are favourable to increase the radio refractive index. Also the highest surface radio refractive index is observed from Figs.(6.2.1) and the value is about 400 units. But the radio refractive index gradient is smaller than that in April.

In October the temperature is reduced than that of July which causes a decrease in the radio refractive index. The decrease in radio refractive index is about -15 unit from the values of the radio refractive index in July. The surface radio refractive index in October is about 385 unit. But the radio refractive index gradient in the month of October is higher than that in any other month in the year.

On the whole we can say that the temperature at the earth surface is high and it decreases with increasing height. Again the quantity of water vapour present in the atmosphere is highly variable. This is important since the permanent dipole moment of the molecules of water vapour causes it to be very significant contributor to the variability of the atmospheric radio refractive index.

At about 40,000 feet elevation the dew point temperature is not available, so the measurement of relative humidity is not possible above this height. The relative humidity decreases rapidly with height and is highly dependent on local air temperature. Atmospheric temperature decreases with height and at about 18000 feet it becomes negative. Also the atmospheric pressure decreases with height.

So the three parameters i.e. atmospheric pressure, temperature and relative humidity decreases with height and ultimately the radio refractive index of the atmosphere decreases with increasing height from the earth surface.

6.3 Variability of Radio Refractive Index with Height

One of the most significant parameters in the influence of the troposphere on radio wave propagation is the large-scale variation of radio refractive index with height. With the increase of height the atmospehric pressure and the water vapour content in the atmosphere decreases. But these two factors are directly related to the atmospheric refractive index. Temperature also decreases with increasing height and it appears in the denumerator of the radio refractive index expression which seems to increase the radio refractive index. But the water vapour content has the more pronounced effect than the temperature. Ultimately, the radio refractive index decreases with increasing height.

The expression for the refractive index at different levels in atmosphere in terms of height from the earth surface and the mean surface refractivity is given as [8].

$$n(h) = 1 + N_S \exp(-bh) \times 10^{-6} \qquad (6.3.1)$$

Here suffix S refers to earth surface, h is in km and b is determined by the relation

$$\exp(-b) = 1 + \Delta N/N_S \qquad (6.3.2)$$

where ΔN is the difference in N values at a height of 1 km above the earth surface and N at the surface of the earth. ΔN is a negative quantity because it decreases with height. ΔN is called the refractivity gradient.

The variations of refractivity with height are determined for few places of Bangladesh. The surface refractivity N_s and the gradient ΔN for the first kilometer are found out for the stations Dhaka, Chittagong and Bogra for the months of January April, July and October from radiosonde data using weather balloon with transceiver that monitors temperature, pressure and humidity at different heights from the surface and sends back the data to the surface stations. Using these data the average surface refractivity N_s and the average refractivity gradient ΔN for the first kilometer are found out for the months of January, April, July and October. By using these values, the refractive index expression in terms of height i.e. n(h) expressions are found out for these months.

6.3.1 <u>Refractivity Gradient of January</u>

In the month of January the Average value of N_s is 337 and average value of $\Delta N = -44.5$/km in Bangladesh.Putting these values in the equation (6.3.2), the value of the constant b is found out and it is equal to 0.1416 i.e. b=0.1416 (Appendix F.1). Then the expression (6.3.1) for refractive index in terms of height becomes:

$$n(h) = 1+N_s \exp(-0.1416h) \times 10^{-6} \quad (6.3.3)$$

From this expression, the refractive indices at different heights for the month of January is found as (Using , N_s = 337)

h = 1 km, n(1)=1.000292 i.e. N(1)=292

h = 2 km, n(2)=1.000253 i.e. N(2)=253

h = 3 km, n(3)=1.000220 i.e. N(3)=220

h = 4 km, n(4)=1.000191 i.e. N(4)=191

h = 5 km, n(5)=1.000166 i.e. N(5)=166

and the average radio refractive index gradient in the month of January for the first kilometer is - (337-292) = -45/km.

6.3.2 Refractivity Gradient of April

In the month of April the

Average value of N_s = 371

Average value of ΔN = -57

Putting these values in equation (6.3.2), the value of constant b is found out and b=0.1668 (Appendix F.2).

So the expression (6.3.1) for refractive index interms of height becomes-

$$n(h) = 1 + N_s \exp(-0.1668\ h) \times 10^{-6} \quad (6.3.4)$$

From this expression, the refractive index at different heights for the month of April are found as (Using , N_s = 371)

h	=	1	km,	n(1)=1.000314	i.e. N(1)=314
h	=	2	km,	n(2)=1.000265	i.e. N(2)=265
h	=	3	km,	n(3)=1.000224	i.e. N(3)=224
h	=	4	km,	n(4)=1.000190	i.e. N(4)=190
h	=	5	km,	n(5)=1.000161	i.e. N(5)=161

and the radio refractive index gradient in the month of April for the first kilometer is - (371-314) = -57

6.3.3 Refractivity Gradient of July

The average surface radio refractive index N_s = 392.5 and the average radio refractive index gradient for the first kilometer from the earth surface is ΔN=-51.5

The value of constant b is found out from the expression (6.3.2) by using above values and it is 0.1406 i.e. b=0.1406 (Appendix F.3).

So the expression (6.3.1) for refractive index in terms of height becomes-

$$n(h) = 1 + N_s \exp(-0.1406\ h) \times 10^{-6} \qquad (6.3.5)$$

From this expression the refractive index at different heights from earth surface in the month of July are found as (Using, N_s = 392.5)

h = 1 km, n(1)=1.000341 i.e. N(1)=341

h = 2 km, n(2)=1.000296 i.e. N(2)=296

h = 3 km, n(3)=1.000257 i.e. N(3)=257

h = 4 km, n(4)=1.000223 i.e. N(4)=223

h = 5 km, n(5)=1.000194 i.e. N(5)=194

and the radio refractive index gradient for the first kilometer for the month of July in Bangladesh is -51.5.

6.3.4 Refractivity Gradient of October

For the month of October, the average value of surface radio refractive index N_s = 383.25 and the average refractive index gradient for the first kilometer is ΔN=-66.

Now putting these values in the expression (6.3.2) the value of the constant b is found out and it is 0.1889 i.e. b=0.1889 (Appendix F.4).

Now the expression (6.3.1) of refractive index for the month of October in Bangladesh in terms of height is given by

$$n(h) = 1+N_s \exp(-0.1889\ h) \times 10^{-6} \qquad (6.3.6)$$

From the expression the refractive index at different height from the earth surface are given as (Using , N_s = 383.25)

h = 1 km, n(1)=1.000317 i.e. N(1)=317

h = 2 km, n(2)=1.000262 i.e. N(2)=262

h = 3 km, n(3)=1.000217 i.e. N(3)=217

h = 4 km, n(4)=1.000180 i.e. N(4)=180

h = 5 km, n(5)=1.000149 i.e. N(5)=149

and the radio refractive index gradient in the month of October for Bangladesh is given by ΔN=-66 for the first kilometer.

6.3.5 <u>Refractivity Curves of Bangladesh for Different Months</u>

For the months of January, April,July and October four expressions for refractivity index in terms of height from the earth surface are found out and at different heights the refractivities calculated from these four expressions are plotted with respect to height in Fig.(6.3.5.1).

From Fig.(6.3.5.1) of radio refractive index vs height, plotted from the generated expressions of n(h) for different months of January, April, July and October representing four seasons, it is seen that maximum RRI occurs in the month of July and minimum RRI occurs in the month of January. These two maximum and minimum RRI curves are separated by about 45 units N. The RRI curves for the months of October and April lie between these two curves and RRI in October is higher than that in April though some anomalous behaviour is observed at about 3 or 4 km height. It is clear from the curves as the height from the earth surface incrases the RRI decreases. These curves are almost similar with the curves drawn from actually obtained data as in Fig. (6.2.1).

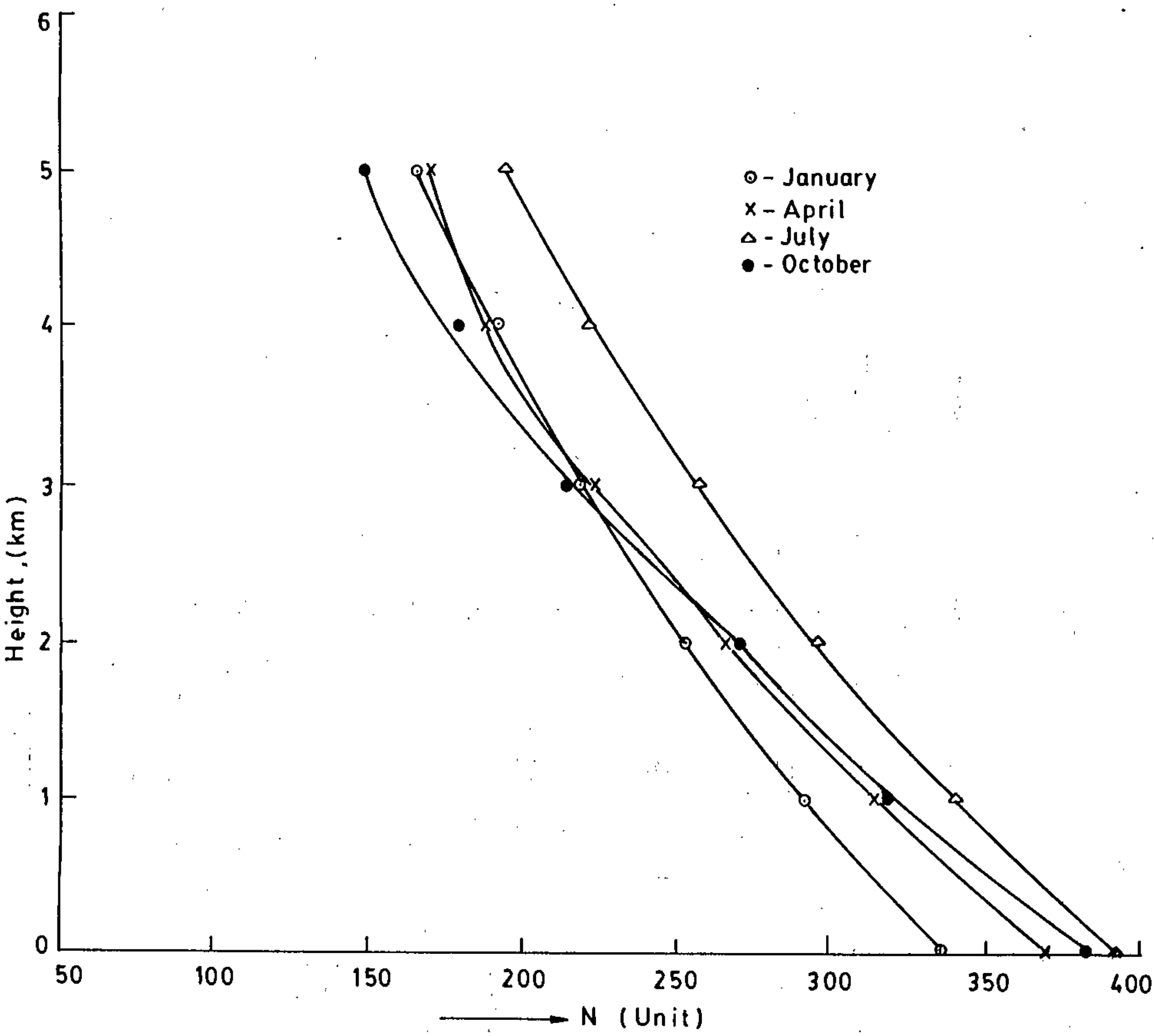


Fig.6.3.5.1: Theoretical variation of RRI with height for different seasons

6.4 Correlation of RRI Gradient (ΔN) with the Surface RRI (N_s)

The correlation between the mean refractivity gradient ΔN i.e. the decrease in refractivity N for the first kilometer and the surface refractivity N_s was first investigated by Bean and Thayer [8]. Similar analysis have since been carried out for different regions of the world.

In different regions of the world, the correlation between ΔN and N_s had been investigated, and an exponential relationship between N_s and ΔN of the form below

$$\Delta N = - A \exp (BN_s) \tag{6.4.1}$$

was obtained where the values of the parameters A and B vary with the climate. It must be pointed out that in order to derive the prediction formula from Equation (6.4.1) a necessary condition is that the meteorological data should span a fairly wide geographical region, thus taking into account the spatial variation of the surface refractivity. In addition, the determination of realistic values of A and B is inextricably bound up with good correlation between $\ln(-\Delta N)$ and N_s. If over a particular geographical region there is poor correlation between $\ln(-\Delta N)$ and N_s; it becomes unrealistic to derive a prediction formula.

Several studies have shown ΔN to be inversely corrletated with N_s and the general form [24] is

$$\Delta N = - A \exp(BN_s)$$

where

$2.1 < A < 9.3$ and

$0.0045 < B < 0.0094$

according to climate.

For Bangladesh such type of relations between ΔN and N_s are found out here with the help of radiosonde data which was obtained for the districts Dhaka, Chittagong and Bogra in different months of the year. For Bangladesh to establish relationships for specific months of January, April, July and October, the constants A and B are calculated by using the values of ΔN and N_s of the three radiosonde stations (Appendix G) are given in table (6.4.1).

Table (6.4.1)

Values of Constants A and B on the basis of refractivity and retractivity gradient of Bangladesh.

A	B	MONTH	REGION
2.65	0.008333	JANUARY	BANGLADESH
9.11	0.005	APRIL	BANGLADESH
2.147	0.008	JULY	BANGLADESH
2.4878	0.008571	OCTOBER	BANGLADESH

With the help of the radiosonde data the final relation between the average refractivity gradient ΔN and the surface refractivity N_s over a year for Bangladesh is found as (Appendix-G)

$$\Delta N = -4.572 \ \exp\ (0.006666\ N_s)$$

Again the relationships between N_s and ΔN are found from the data for the stations Dhaka, Chittagong and Bogra over the whole year which show the variation of ΔN all over the year for these three stations individually (Appendix -G). The values of the constants A and B are given in the Table (6.4.2) for these stations-

Table - (6.4.2)

Values of constants A and B on the basis of retractivity and refractivity gradient of different locations.

A	B	STATION
6.014	0.00588	DHAKA
2.405	0.008823	CHITTAGONG
4.461	0.006818	BOGRA

The correlation Co-efficients between $\ln(-\Delta N)$ and N_s determined for different sets of monthly values of ΔN and N_s from the three radiosonde stations in Bangladesh are within the ranges $2.1 < A < 9.3$ and $0.0045 < B < 0.0094$ as is suggested by several studies in [24].

Expressions showing relationships between N_s and ΔN for Bangladesh and other parts of the world and also the ΔN values obtained from these expressions and graphs are presented for comparison in Table 6.4.3.

Table 6.4.3

Comparision of refractivity gradient for different regions of the world calculated on the basis of surface refractivity.

(all gradients expressed here are negative quantities)

Station	Year	Month	Surface N_s	ΔN/KM From Graph	ΔN=-2.65 Exp (0.00833 N_s) January Bangladesh	ΔN=-9.11 Exp (0.005 N_s) April Bangladesh	ΔN=-2.147 Exp (0.008 N_s) July Bangladesh	ΔN=-2.48 Exp (0.008571 N_s) October Bangladesh	ΔN=-6.014 Exp (0.0058 N_s) Dhaka	ΔN=-2.405 Exp (0.008825 N_s) Chittagong	ΔN=-4.41 Exp (0.006818 N_s) Bogra	ΔN=-7.32 Exp (0.005577 N_s) USA	ΔN=-9.3 Exp (0.004565 N_s West Germany	ΔN=-3.95 Exp (0.0072 N_s) U.K.	ΔN=-3.42 Exp (0.007576 N_s) Japan	ΔN=-2.. Exp (0.008 N_s) Afric
Dhaka	1987	Jan-uary	340	42	45	50	31	46	44	48	45	49	44	46	45	43
		April	376	57	60.8	60	43	62	55	66	57	60	52	59	59	59
	1988	July	394	51	70	65	50	73	51	78	65	66	56	67	68	69
		Oct-ober	384	61	65	62	46	67	58	71	60	62	54	62	63	63
	1989	Jan-uary	334	47	42	48	31	44	43	45	43	47	43	44	43	41
Bogra	1987	April	366	57	56	57	40	57	52	61	53	56	49	55	55	54
		July	397	52	72	66	51	75	62	80	66	67	57	69	69	70
	1988	July	397	56	72	66	51	75	62	80	66	67	57	69	69	70
		Oct-ber	384	61	65	62	46	67	58	71	60	62	54	63	63	63
Chitt-agong	1988	July	382	47	64	61	45	66	57	70	60	62	53	62	62	62
		Oct-	384	71	65	62	46	67	58	71	60	62	54	63	63	63

6.5 Calculation of Radio Ray Refraction Using Surface RRI and it's Gradient

For computing the refraction of radio frequency rays through an atmosphere of known refractive-index distribution, assumptions are that surfaces of equal index are spherical and concentric with the earth. The expression for the refraction $\tau_{1,2}$ of a ray as in Fig.(6.5.1) below between heights h_1 and h_2 and making an angle θ with the spherical refracting surface at the height h is given by [3]

$$\tau_{1,2} = \int_{n_1}^{n_2} \frac{\cot\theta}{n}\, dn \tag{6.5.1}$$

Since n-varies from at most 1.0004 at the earth's surface to unity at the top of the atmosphere the factor 1/n may be taken as unity with an error of less than 4 parts in 10000 in the computed refraction. So the above equation is reduced to

$$\tau_{1,2} = -\int_{n_1}^{n_2} \cot\theta \; dn \tag{6.5.2}$$

Another form of the expression is

$$\tau_{1,2} = -\int_{n_1}^{n_2} \cot\theta \;\Delta n$$

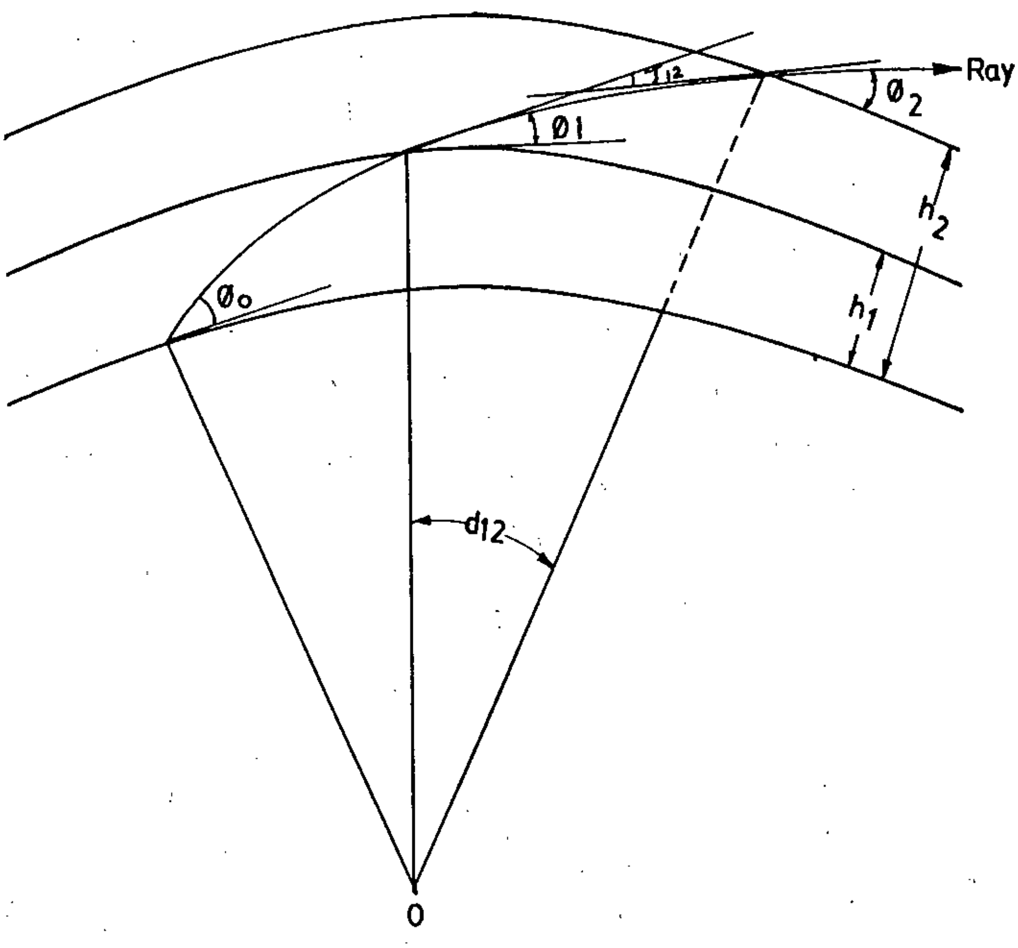


Fig.6.5.1: Propagation of a radio ray

$$= (\text{Cot}\theta)_{1,2} \ (\Delta n_1 - \Delta n_2) \text{ in radians} \qquad (6.5.3)$$

where, Δn is $(n-1)$ and $(\text{Cot}\theta)_{1,2}$ is the mean value of the constant function over the interval $\Delta n_1, \Delta n_2$. Here θ is a function of both Δn and h and Δn is only known empirically as a function of h and is given by a table of values computed from radiosonde data. According to Snell's law. The angle θ for a ray path through concentric spherical refracting surfaces are determined from the formula

$$nr \text{ Cos}\theta = n_o r_o \text{Cos}\theta_o = \text{Constant} \qquad (6.5.4)$$

where $r = a + h$ is the radius of spherical refracting surface at elevation h, a is the earth's radius and the subscript 'zero' refers to the ground level.

At small elevation angles, $\theta_o < 10^o$ and neglecting quantities of second and higher order terms equation (6.5.4) transforms into

$$\frac{\theta^2-\theta_o^2}{2} = (\Delta n+h/a)-(\Delta n_o+h_o/a_o) \qquad (6.5.5)$$

solving for θ

$$\theta = \{\theta_o^2 + 2\,(\Delta n + h/a) - 2\,(\Delta n_o + h_o/a_o)\}^{1/2} \qquad (6.5.6)$$

where h_o is the station elevation above mean sea level. The angle θ at any elevation may then be calculated for each station from a table of values of Δn against h, as is done later for the data obtained for Dhaka, Bogra, Chittagong.

It can be shown that $\cot\theta = 1/\theta_m$ where θ_m is the arithmatical mean of θ over an interval and for the interval $(\Delta n_1, \Delta n_2)$,

$$\theta_m = \frac{\theta_1 + \theta_2}{2} \tag{6.5.7}$$

Substituting this approximation into equation (6.5.3) with θ_m in radians, results

$$\tau_{1,2} = \frac{\Delta n_1 - \Delta n_2}{\theta_m} \text{ radian } (\theta^o < \theta_o < 10^o) \tag{6.5.8}$$

Above 18 km, the contribution to the total refraction is small and may be shown to be approximately as

$$\tau_{>18} = n_{18} \cot \theta_{18} \tag{6.5.9}$$

where the subscripts refers to the values of the quantities at 18 Km.

For angles of arrival or departure, θ_o greater than 10 degrees the total refraction through the entire atmosphere is small and may be approximated by the first term of the expression obtained by integrating (6.5.2) by parts -

$$\tau = -\int_{n_1}^{1} \text{Cot}\theta \, dn$$

$$= (n_o-1) \text{ Cot } \theta_o - \int_{o}^{\cot\theta_o} n \; d(\text{Cot } \theta) \qquad (6.5.10)$$

Here refraction has been computed from the actual refractive-index structure of the atmosphere as obtained from average meteorological data for locations, Dhaka, Chittagong and Bogra. for arrival angle θ_o=0°,5° and 10° as shown in Appendix-H. The assumption is made, as is usually done that the atmosphere is horizontally homogeneous. The results have been plotted as the Figs.(6.5.2a, 6.5.2b,6.5.2c, and 6.5.2d). These figures (6.5.2) represents the actual variation of refraction with height.

For Dhaka station refraction is calculated for the months of January, 1987, July 1988 and October, 1988 using the available data. From the Fig. (6.5.2a) curves we see that the refraction of radio-rays increases gradually as the height increases. But most of the refraction i.e. bending of the rays occurs below the height 1.5 Km. Above 1.5 Km height the increase in refraction occurs slowly.From the refraction calculation table in Appendix-H we can say that the refractive index decreases as the height increases from the earth surface and the largest value of refractive index occurs on the earth surface. The rate of change of refractive index gradually increases as the height increases upto 1.5 Km. And above 1.5 Km the rate of change of refractive index decreases. The rate of change of refractive index plays an important role in the ray bending i.e refraction. Thus it is clear that as the change of refractive index increases upto height 1.5 Km consequently the refraction of rays is large upto this height i.e. most of the bending of the ray takes place within this height. On the other hand the change of refractive index diminished above 1.5 Km. So the refraction of ray is relatively small. Above 2.5 Km the refraction is almost constant as we see from the figures (6.5.2) showing refraction with height.

Again from the Fig. (6.5.2.a) we see for the Dhaka station for different months for the angle of arrival 0^{o}, lowest refraction occurs in the month of January, 1987. In July, 1988 refraction is larger than that in January but lower than that of October, also the largest refraction occurs in the month of October 1988. This is becuase the change of refractive index for particular levels is different for different months. The change in refractive index is largest for the month of October than that of any other months as seen from table in Appendix-H. Also the change in refractive index in the month of July is larger than that of the month of January.

Thus we can conclude from above analysis that the change of refractive index of the atmospheric layers will determine the refraction of ray, which will be large for large change of refractive index i.e. ($\Delta n_i - \Delta n_{i-1}$) and small for small change or refractive index. Again, observing the Fig. (6.5.2a) and Fig. (6.5.2b) for the different stations in Bangladesh ie Dhaka, Chittagong and Bogra at an arrival angle $\theta = 0^o$, the nature of bending of ray is similar for these three locations. Most of the refraction of the ray occurs below height 1.5 Km and above this height rate of refraction is poor. The ray bends more than any other stations in Bogra as seen from the Fig.(6.5.2b) drawn for the month of October.The refraction is almost same at the stations Dhaka and Chittagong; though the refraction at Dhaka is slightly larger than that of Chittagong. From the refraction

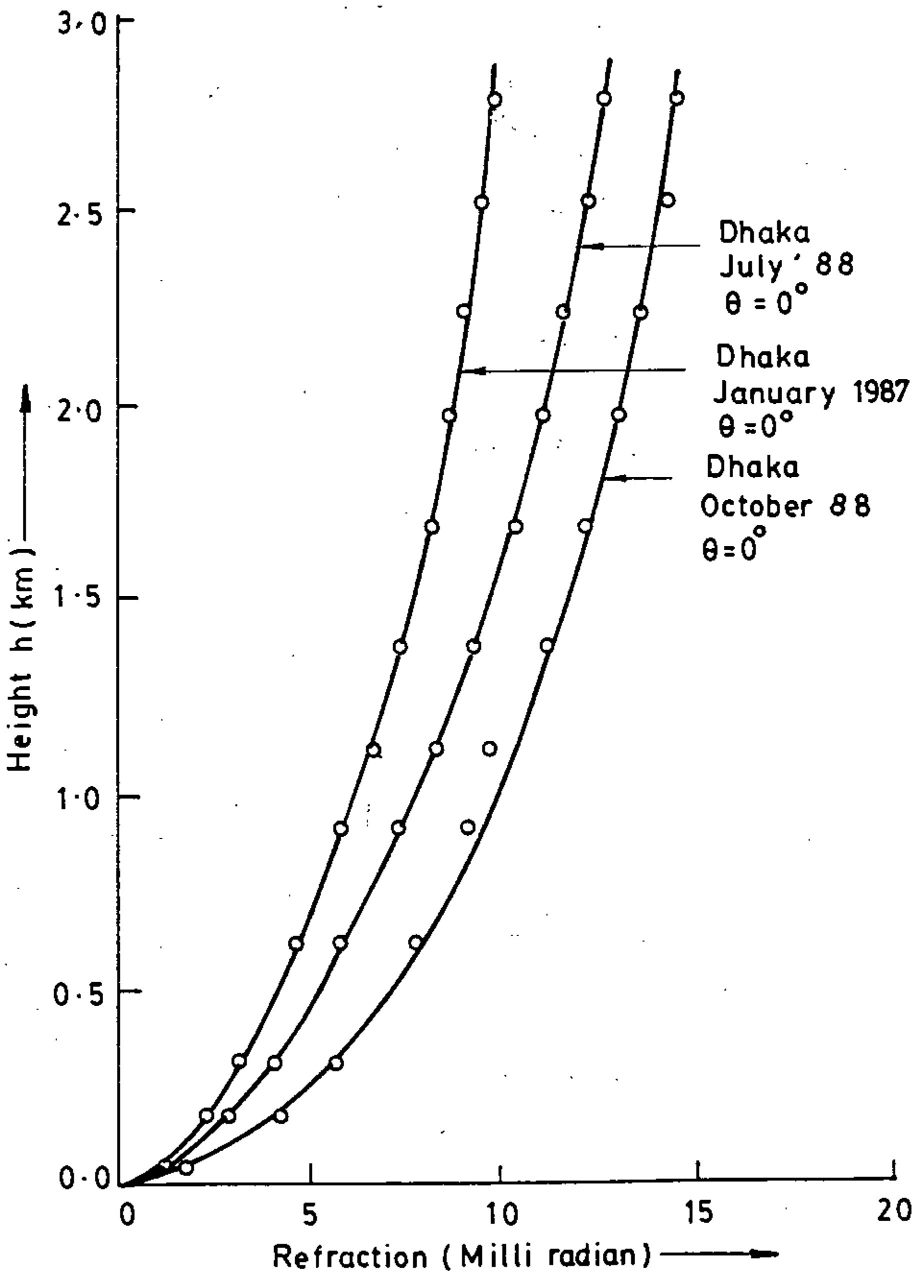


Fig.6.5.2a: Bending of a tangential radio ray.

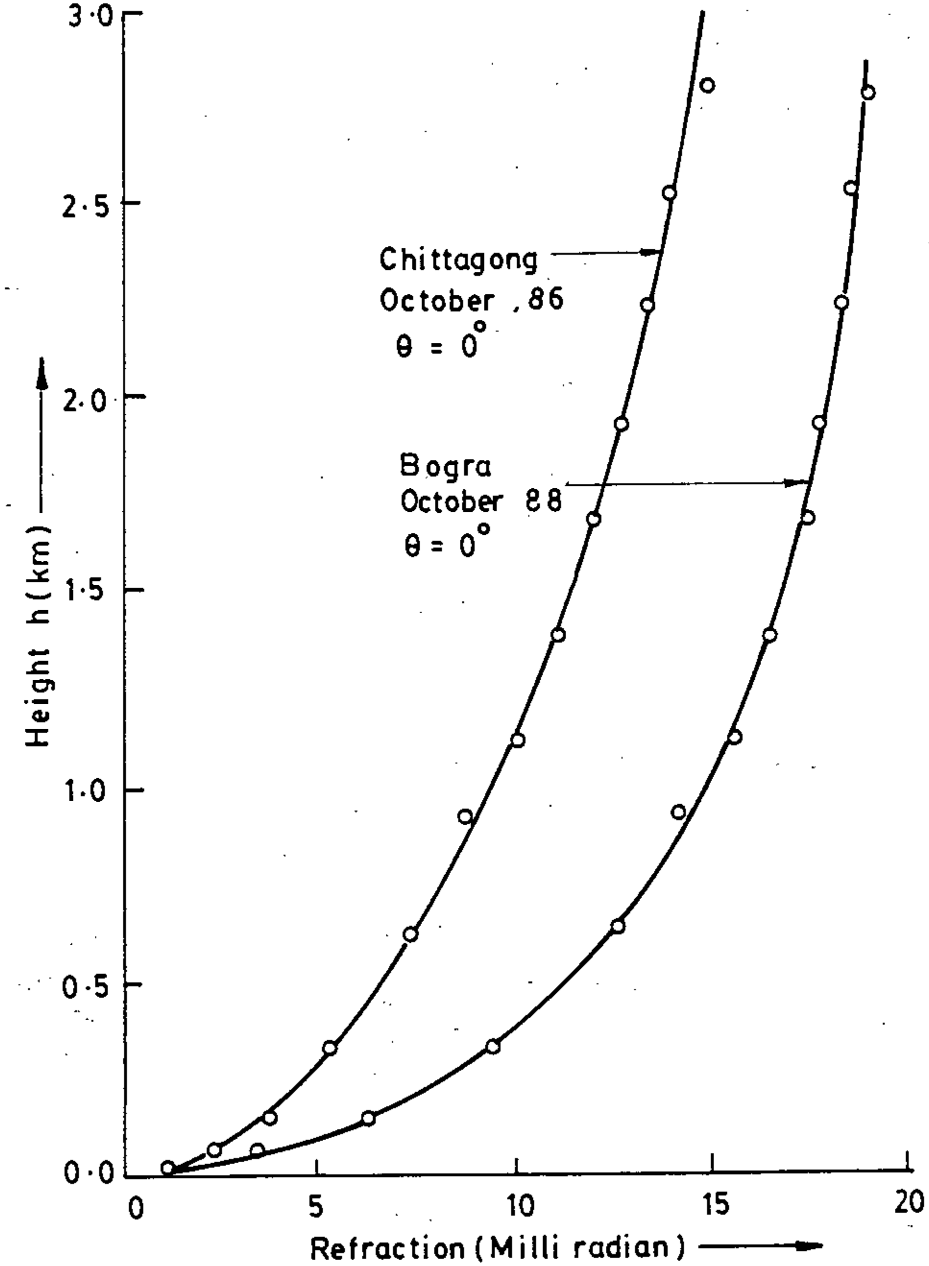


Fig.6.5.2b: Bending of a tangential radio ray.

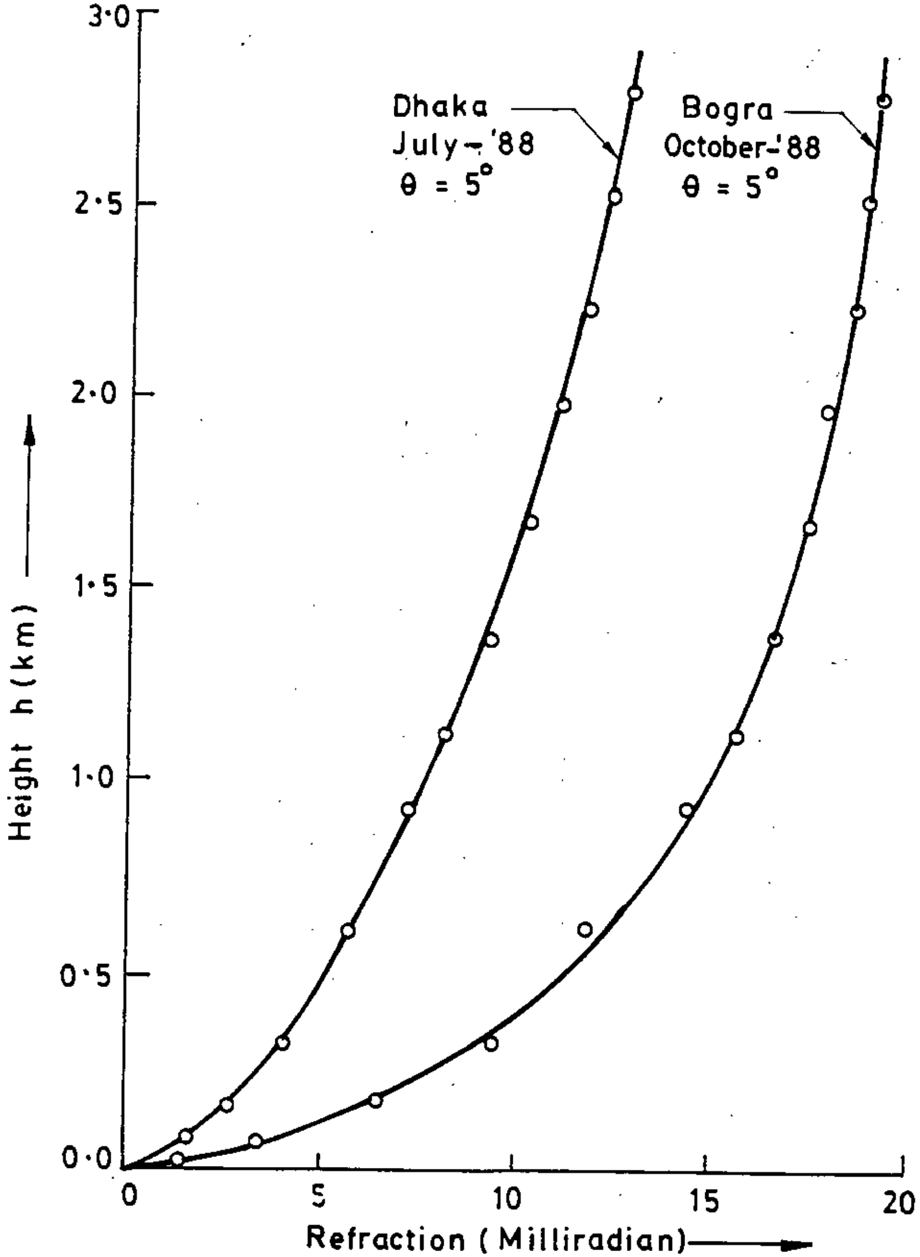


Fig.6.5.2c: Bending of a tangential radio ray.

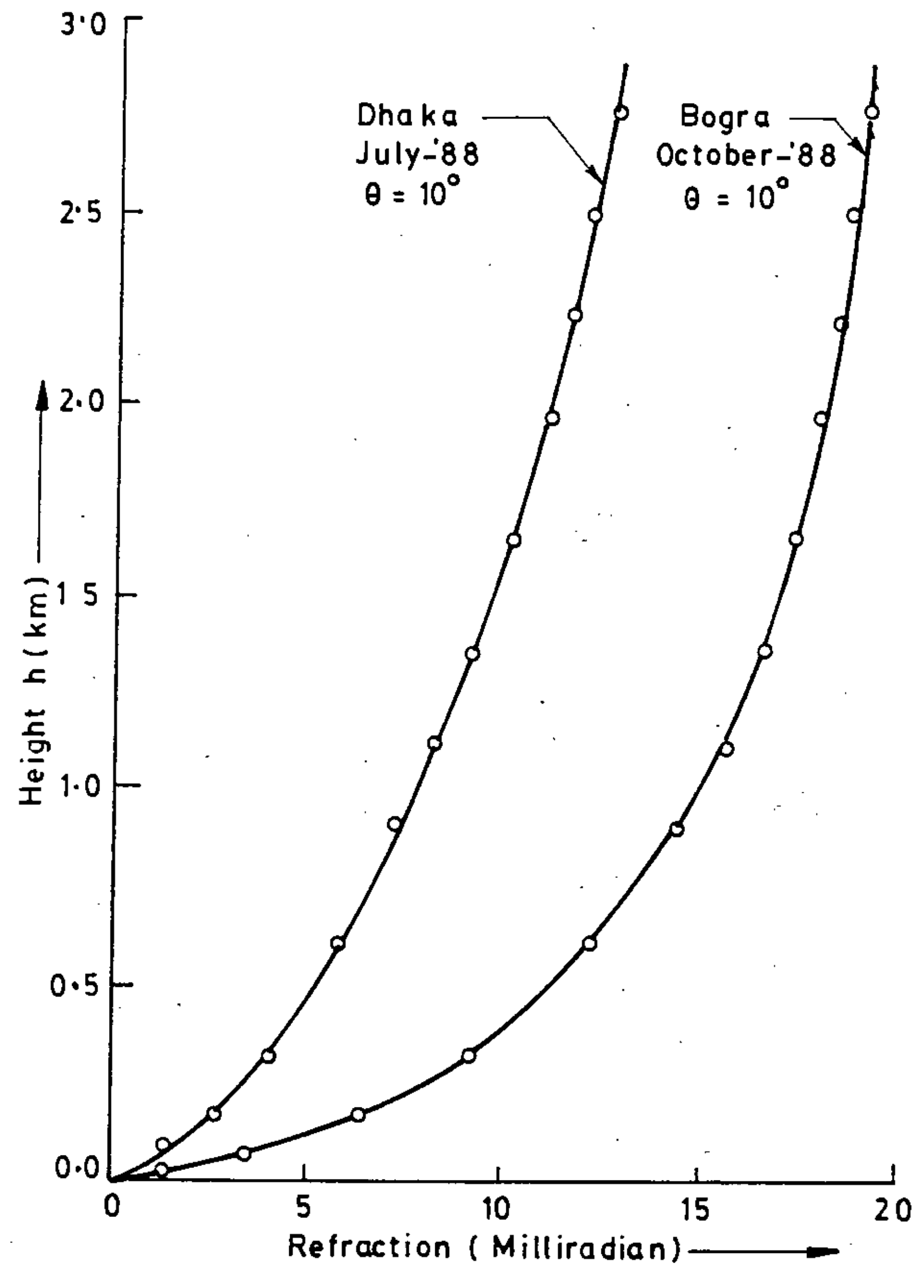


Fig.6.5.2d: Bending of a tangential radio ray.

calculation Table in Appendix-H. we can easily see the reason of largest refraction of ray at Bogra and the lowest refraction of ray at Chittagong. The change of refractive index between atmospheric layer increases from the surface upto a height 1.5 Km and decreases above 1.5 Km. This change in refractive index is more pronounced for Bogra than any other stations ie. Dhaka and Chittagong. For the three stations it can be said that the most of the refraction occurs below 1.5 Km and above this height refraction is almost constant though slight increase in refraction is observed.

CHAPTER 7

CONCLUSIONS

7.1 Conclusions

In this thesis we concentrated on the study of the atmospheric radio refractive index and its variation at different places of Bangladesh for the four seasons, winter or north-east-monsoon, summer or premonsoon, south-west monsoon or monsoon and Autumn or postmonsoon and also how it affects the radio ray propagation. Surface radio refractive index were calculated from the atmospheric pressure, temperature and relative humidity data for the thirty locations in Bangladesh for the above four considered seasons for the eleven years (from 1977 to 1987) on the basis of availability of data. Also the radio refractive indices were calculated at different heights from the earth surface using radiosonde data for three places i.e. Dhaka, Chittagong and Bogra as data were available, only for these stations.

In course of study of radio refractive index at different places it is seen from the plots of radio refractive index over a year the trend of variation is almost similar for the thirty locations though the numerical values are different at differnt locations. The minimum value of radio refractive index occurs in the month of January over a year and increases as time passes and the maximum value occurs normally in the month of July and then it begins to decrease. The RRI observed in the months of April and October is higher than that of January but lower than that of July. Also in some years RRI in April and October was not between the values of January and July due to the abnormal weather condition. Again from the plots of RRI for a particular month at a particular place for several years it is seen that the RRI varies from year to year as the weather changes from year to year. Normally the maximum RRI occurs in the month of July and the minimum RRI occurs in the month of January and the maximum and minimum curves are separated by about 40 units RRI. Also the variations of RRI at the coastal areas are different from other places due to the difference in weather.

Some refractivity profiles are drawn for four seasons using the average RRI of eleven years (1977-1987); which show the variation of RRI over Bangladesh in each season. Variation of RRI at coastal areas are similar in four seasons and are different at the other places of Bangladesh. From the plottings of atmospheric refractivity obtained from the radiosonde data it is seen that the RRI decreases with increasing height from the earth surface for all the radiosonde stations. This is because as the height increases from earth surface, atmospheric pressure, temperature and humidity decrease, which cause ultimately decreament of RRI. Refractivity gradients are different in different seasons.

Four expressions were developed in terms of average surface RRI and height from earth surface using the refractivity gradient and average RRI for calculating the refractive index at different height in four seasons for Bangladesh. Curves drawn from these four expressions for Bangladesh are almost similar to those curves of other locations drawn from actual data. Also some expressions are developed here calculating refractivity gradient in terms of surface refractivity for Bangladesh and for the places Dhaka, Chittagong and Bogra separtely.

Again using the RRI at different height the bending of a radio ray is calculated for different angles of incident. From these refraction curves it is seen that most of the refraction occurs below 1.5 km and above this refraction rate is low.

7.2 Suggestions for Further Work

A number of useful extensions of the works described in this thesis are possible. They are discussed in the following paragraph.

Radiosonde data was available only for three places ie Dhaka, Chittagong and Bogra. So radio rafractive index at different height was obtained only for the three places in Bangladesh. If it is possible to collect radiosonde data for other locations in Bangladesh then it would be possible to see the variation of RRI with height for Bangladesh.

Again some expressions were developed for refractivity gradient using average RRI obtained from radiosonde data only for the above three locations. But for this case we need a fairly wide range of data. So by using a large number of data for other locations, the obtained expressions can be reviewed and such type of expressions for these locations can be developed.

Again using the RRI for these three locaitons refractions of radio ray were calculated only for these stations for different incident angles due to the unavailability of radiosonde data. Such type of refraction can be calculated if a large number of radiosonde data are available for different locations in Bangladesh.

APPENDICES

APPENDIX - A

Derivation of the expression for variation of temperature with elevation in well-mixed atmosphere

Differentiating equation (2.4.1) yields [17]

$$P' \, dv = (m'/m'_o) \, R' \, dT - v dp' \qquad (A.1)$$

substituting this expression for P' dv into equation (2.4.4) and solving for dT yields

$$dT = -v \, dp' / \{m' c'_v + (m'/m'_o) R'\} \qquad (A.2)$$

To convert this result into the desired form shown in equation (2.4.5), we must establish a relation between the specific heats c'_v and c'_p. We may do this through equation (2.4.1) and (2.4.3) along with the definition

$$C'_p = (\delta Q/\delta T)p \qquad (A.3)$$

for specific heat at constant pressure. Differentiating equation (2.4.3) at constant pressure and using equation (A.3) yields

$$m' c'_p = m' C'_p + P' (\delta v/\delta T)p \,, \qquad (A.4)$$

while differntiating equation (2.4.1) at constant pressure yields

$$P'(\delta v/\delta T)_P = m'/m'_o\ R' \quad (A.5)$$

Substituting this expression into equation (A.4) and substituting the result into equation (A.2) and integrating the latter yields equation (2.4.5) [17]

APPENDIX-B

Derivations of the expression for effective specific heat and molecular weight of moist air

To raise the temperature of the air parcel one degree kelvin at constant pressure requires the addition of an amount $m' C_p'$ of heat to the parcel. On the other hand, the amount of heat absorbed by the water vapour is $m_w C_{pw}$, and that absorbed by all other gases in the parcel is $m C_p$ [17].

Thus,

$$m'C_p' = mC_p + m_w C_{pw} \tag{B.1}$$

Dividing by m' and substituting from equation (2.4.7) & (2.4.8) and

$$m' = m + m_w \tag{B.2}$$

yields equation (2.4.10). Combining equations (2.4.7), (2.4.8) and using

$$P' = P+e \tag{B.3}$$

yields

$$P V = (m/m_o + m_w/m_{ow}) R'T \tag{B.4}$$

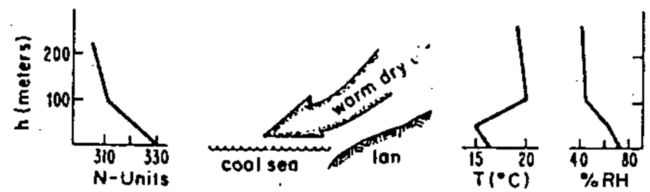
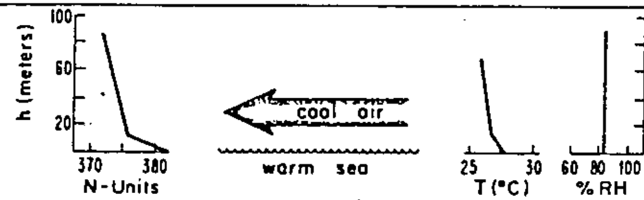
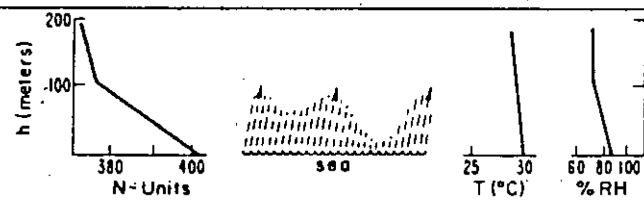
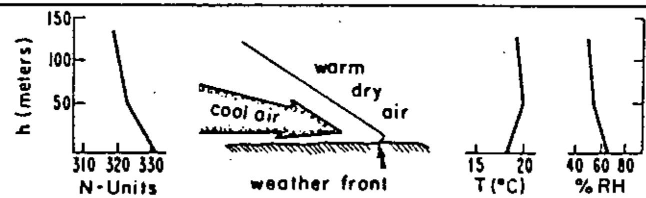
which, upon comparison with equation (2.4.1) yields

$$m'/m_o' = m/m_o + m_w/m_{ow} \tag{B.5}$$

Substitution from equation (2.4.9) and (B.2) and solution for m_o' yields equation (2.4.11) [17]

SOME METEOROLOGICAL CONDITIONS FAVORABLE FOR ANOMALOUS RADIO PROPAGATION

Chart I Surface Superrefractive Layers (ΔN/Δh < −100 N-units/km) (Reference-27)

	CAUSATIVE PROCESS	DESCRIPTION (N-Profile, T-Profile, RH-Profile)	OCCURRENCE
A	**ADVECTION** Horizontal motion of warm dry air across a cool moist surface (sea or moist ground). The warmer and drier the air, the stronger the gradient.		(1) Over large bodies of water such as lakes, bays, gulfs and seas; particularly along desert coastal regions (e.g., in the Mediterranean and Red seas, the Gulf of Arabia or in the English Channel during summers). The layers have been observed to extend up to 70 meters above the sea surface and out to 20 km from the shore. (2) Over cool irrigated valleys, below hot dry mountain slopes, just after sunset.
B	**QUASI-ADVECTION** Horizontal motion of cool air across a warm moist surface (sea or moist ground). The stronger the wind, the stronger the gradient.		(1) Over the poleward portions of temperate-zone seas in the winter (e.g., the North Atlantic). (2) Over moist land areas near the tropics. (e.g., Florida) during early winter. (3) In temperate-zones following a cold front passage.
C	**EVAPORATION** Evaporation from wet surfaces (sea or moist ground) to air at the same or higher temperatures. The less the wind speed, the stronger the gradient. The warmer the air, the weaker the gradient.		(1) Over land in moist tropical regions, particularly with vegetation and foliage cover and more commonly in the daytime. (2) Over the sea when the air is as warm as or warmer than the sea and in the absence of strong winds. (3) Over the sea in the tradewind regions as a "semi-permanent" layer extending up to 6 to 20 meters.
D	**FRONTAL WEATHER PROCESSES** The advance of cool air along the surface, lifting a stable warm air mass.		Over land in the near vicinity of the front (the junction of the two air masses at the surface)
E	**RADIATION** The radiation of heat from the warmer ground to the colder sky.		Clear skies and light surface winds, at night, result in considerable cooling of the earth causing the formation of a temperature inversion (an increase of temperature with height). Of major importance in the polar regions and during the winter at temperate latitudes where solar heating is confined to a limited surface depth. Probably unusual in tropical regions or in humid regions during the summer.

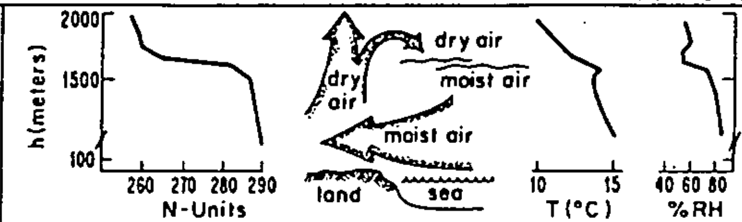
SOME METEOROLOGICAL CONDITIONS FAVORABLE FOR ANOMALOUS RADIO PROPAGATION

Chart II Elevated Superfractive Layers ($\Delta N/\Delta h < -100$ N-Units/km) (Reference-27)

CAUSATIVE PROCESS | **DESCRIPTION** (N-Profile, T-Profile, RH-Profile) | **OCCURRENCE**

A ADVECTION

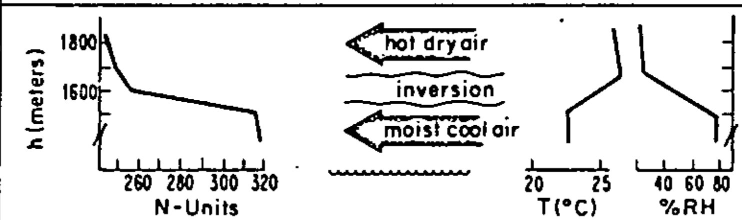
Horizontal motion of dry air over moist air.



Over land and water near the coast, the subsidence of the dry land air over moist sea air may occur. Daytime solar heating of land surfaces causes a rising of warm dry air near the land and a horizontal motion of moist air from sea to land (sea breeze).

B SUBSIDENCE

The flow of air from a high pressure cell such that hot, dry air flows out (subsiding) over cool moist air.

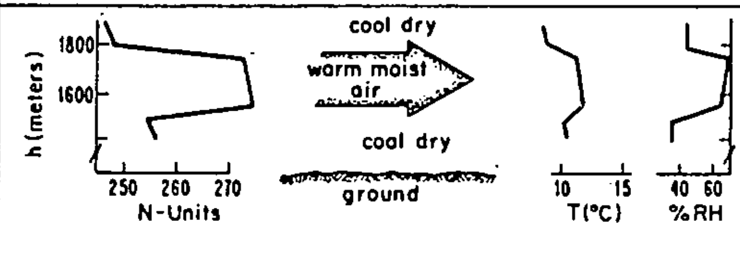


Over water roughly between 5° and 25° North and South latitude, elevated layers occur which are known as the Tradewind Inversion. These are due to subsidence of dry air from high altitudes which subsides over moist cool air over the sea.

Over land, the subsidence can occur due to a large slow moving high pressure system associated with the afore-mentioned over-water highs.

C ADVECTIVE INTRUSION

The horizontal motion of air, such that one air mass intrudes into another, can produce multiple elevated layers.

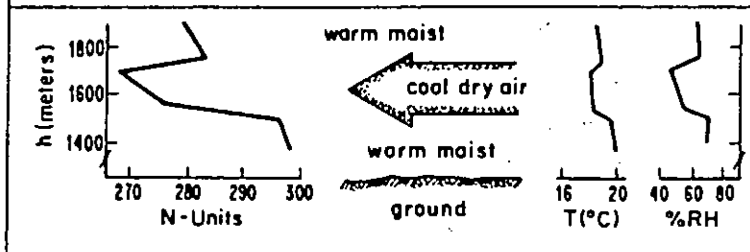


WARM MOIST INTRUSION

A tongue of warm moist air intruding into a cool dry air mass results in the combination of a superrefractive layer positioned above a subrefractive layer. Observed mainly over land in the temperate zone. Fairly common occurance.

COOL MOIST INTRUSION

A tongue of cool moist air intruding into warm dry air produces a similar super/sub type of N profile. Uncommon except possibly in some warm desert areas near cold water coasts.



COOL DRY INTRUSION

A tongue of cool dry air intruding into a warm moist air mass results in the combination of a subrefractive layer positioned above a superrefractive layer. Observed mainly over land in the temperate zone. Fairly common.

WARM DRY INTRUSION

A tongue of warm dry air intruding into a cooler moist air mass produces the same sub/super N profile. Common in tropical and subtropic areas.

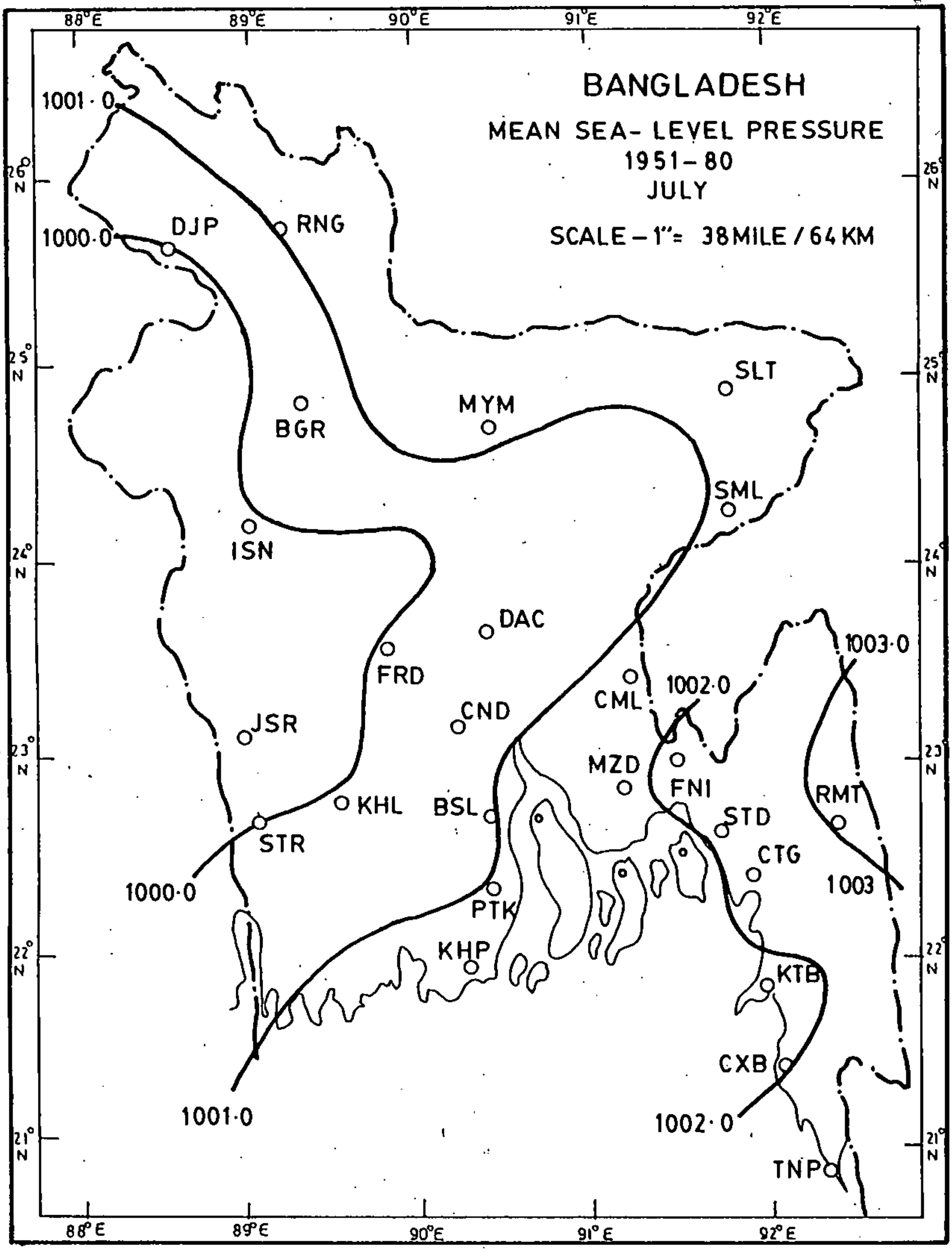


Fig.D-1: Contours of mean sea level pressure for the month of July of Bangladesh.
(Annual weather report,BMD).

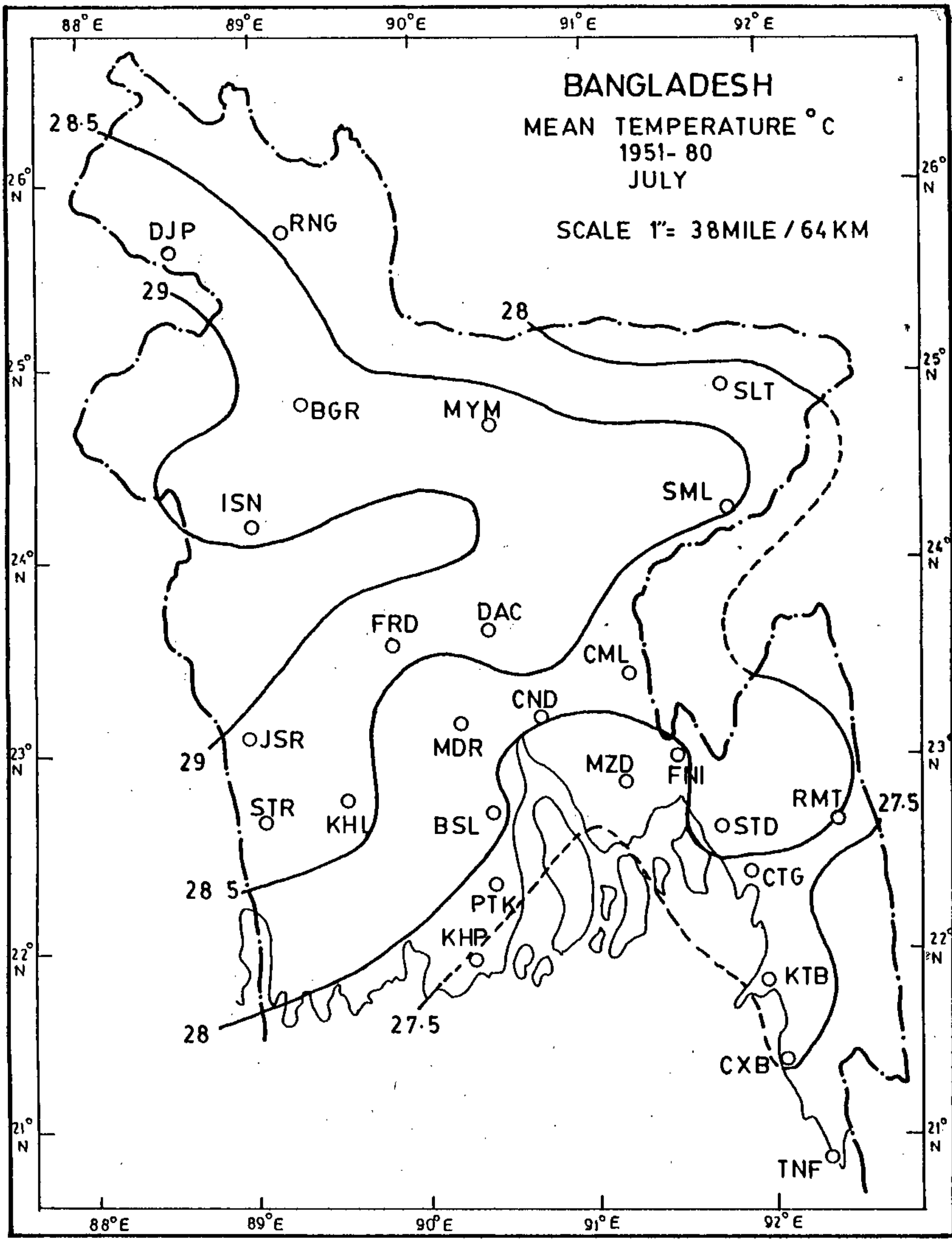


Fig.D-2:Contours of mean temperature for the month of July of Bangladesh.
(Annual weather report,BMD)

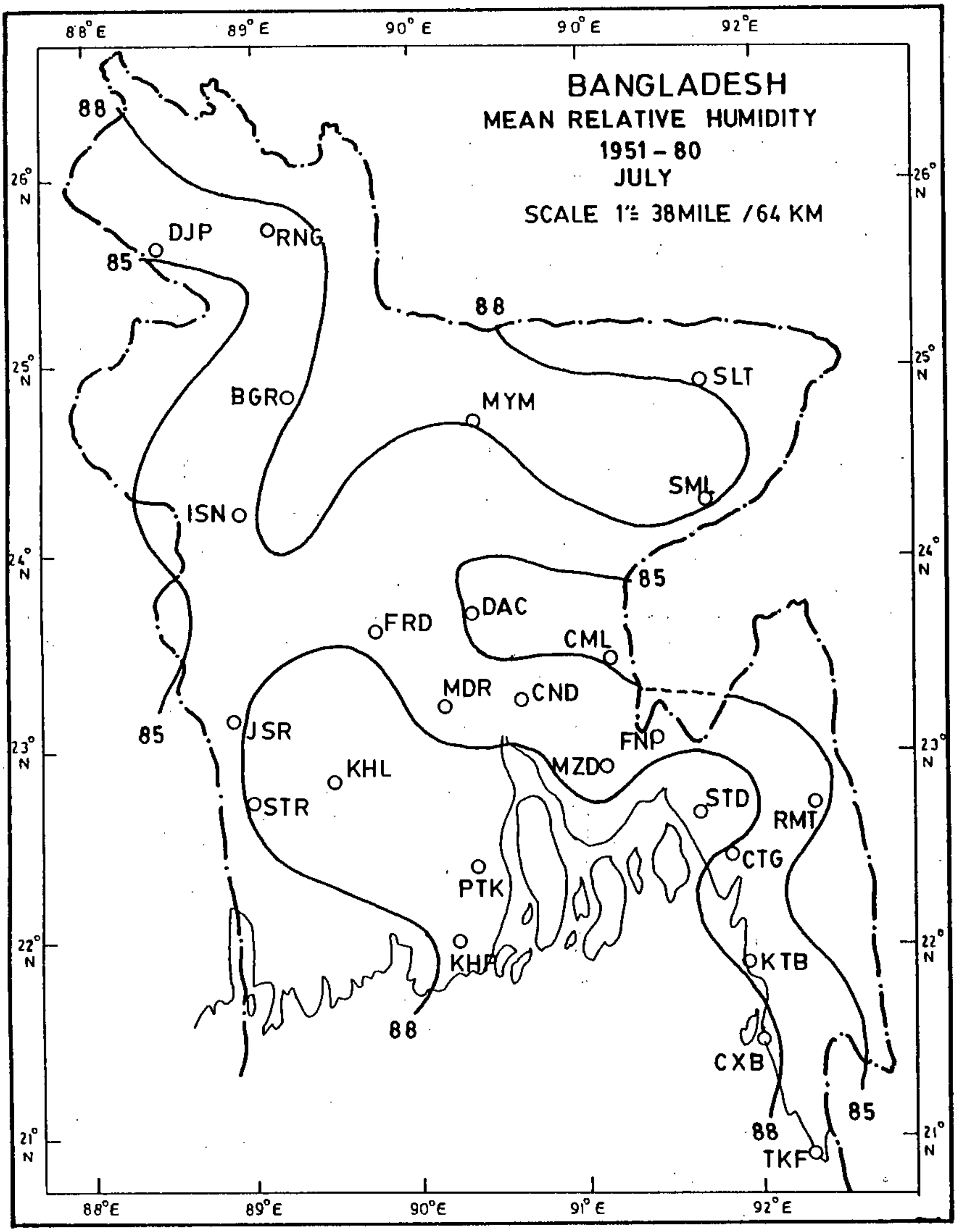


Fig.D-3: Contours of mean relative humidity for the month of July of Bangladesh. (Annual weather report, BMD).

Appendix E

Table E

Maximum and minimum Radio Refractive Indices of all stations of four seasons.

Month / Station	January		April		July		October	
	N_{max}	N_{min}	N_{max}	N_{min}	N_{max}	N_{min}	N_{max}	N_{min}
Rangpur	370	324	384	340	412	376	400	356
Patuakhali	360	322	410	360	410	376	410	370
Srimangal	380	334	420	340	430	372	415	355
Mymensingh	355	320	390	335	410	375	400	355
Rajshahi	358	320	395	330	420	378	405	356
Satkhira	360	320	400	345	415	376	405	360
Feni	362	320	400	350	415	377	410	362
Ishurdi	358	318	393	332	410	370	400	350
Jessore	360	320	400	340	420	376	405	355
Khulna	367	322	420	355	422	380	410	364
Sylhet	355	320	390	342	410	375	405	358
Madaripur	360	320	395	346	410	372	400	350
M.Court	360	320	400	352	410	370	405	365
Khepupara	352	320	400	358	410	376	405	367

Station \ Month	January		April		July		October	
	N_{max}	N_{min}	N_{max}	N_{min}	N_{max}	N_{min}	N_{max}	N_{min}
Dhaka	358	320	400	364	412	377	404	360
Comilla	360	320	400	342	410	365	405	360
Chittagong	362	323	400	352	408	370	402	360
Dinajpur	352	315	370	320	408	370	390	345
Bhola	367	322	410	360	414	378	406	362
Bogra	362	320	390	335	417	378	406	360
Chandpur	360	320	403	350	410	377	408	365
Barisal	365	320	410	355	415	378	410	370
Faridpur	357	317	400	340	415	375	410	360
Teknaf	360	320	395	350	405	370	400	355
Cox's Bazar	360	320	410	360	410	375	400	360
Hatia	358	320	400	357	410	377	405	361
Kutubdia	363	325	405	365	410	370	403	360
Sandwip	365	325	410	360	412	380	400	360
Rangamati	362	322	400	345	405	367	400	363
Sitakunda	355	315	390	350	405	375	400	360

Appendix - F

Determination of empirical formula for the variation of refractive index with height

Appendix F.1

$n(h) = 1 + N_s \exp(-bh) \times 10^{-6}$

where h in km.

b is determined from

$$\exp(-b) = 1 + \frac{N}{N_s}$$

For Bangladesh, Month January

$$\text{Average, } N_s = \frac{340 + 334}{2} = 337$$

$$\text{Average, } N = -\frac{42 + 47}{2} = -44.5$$

$$\exp(-b) = 1 - \frac{44.5}{337}$$

$$\exp(-b) = 0.8679$$

$$-b = -0.1416$$

$$b = 0.1416$$

N_s = 337

$n(h) = 1 + N_s \exp(-0.1416\ h) \times 10^{-6}$

n(1) = 1.000292

n(2) = 1.000253

n(3) = 1.000220

n(4) = 1.000191

n(5) = 1.000166

Appendix F.2

For Bangladesh - month April

$$\text{Average } N_s = \frac{376+366}{2} = 371$$

$$\text{Average } \Delta N = -\frac{57+57}{2} = -57$$

$$\exp(-b) = 1 - \frac{57}{371}$$

$$\exp(-b) = 0.846$$

$$-b = -0.1668$$

$$b = 0.1668$$

$$n(h) = 1 + N_s \exp(-0.1668\ h) \times 10^{-6}$$

$N_s = 371$

$n(1) = 1.000314$

$n(2) = 1.000265$

$n(3) = 1.000224$

$n(4) = 1.000190$

$n(5) = 1.000161$

Appendix F-3

For, Bangladesh, Month July,

$$\text{Average } N_s = \frac{394 + 397 + 397 + 382}{4} = 392.5$$

$$\text{Average } \Delta N = \frac{51 + 52 + 56 + 47}{4} = -51.5$$

$$\exp(-b) = 1 - \frac{51.5}{392.5}$$

$$\exp(-b) = 0.86878$$

$$-b = -0.1406$$

$$b = 0.1406$$

$$n(h) = 1 + N_s \exp(-0.1406\ h) \times 10^{-6}$$

n(1) = 1.000341

n(2) = 1.000296

n(3) = 1.000257

n(4) = 1.000223

n(5) = 1.000194

Appendix F.4

For Bangladesh, Month October

$$\text{Average } N_s = \frac{384 + 385 + 380 + 384}{4} = 383.25$$

$$\text{Average } \Delta N \quad \frac{61 + 56 + 76 + 71}{4} = -66$$

$$\exp(-b) = 1 - \frac{66}{383.25} = 0.8278$$

$$-b = -0.1889$$

$$b = 0.1889$$

$$n(h) = 1 + N_s \exp(-0.1889\, h) \times 10^{-6}$$

$N_S = 383.25$

$n(1) = 1.000317$

$n(2) = 1.000262$

$n(3) = 1.000217$

$n(4) = 1.000180$

$n(5) = 1.000149$

Appendix G

Derivation of constants A and B

In this section subscript `1´ is used after ΔN to indicate refractivity gradient for first kilometer from earth surface.

Appendix G.1

Month-January (Bangladesh)

$\Delta N_1 = -A \exp(BN_s)$

So $\ln(-\Delta N_1) = BN_s + \ln(A)$

A and B are constants. They are to be found.

From graph - G1

$N_s = 339 = x_1$ $\quad$ $N_s = 387 = x_2$

$\ln(-\Delta N_1) = 3.8 = y_1$ $\quad$ $\ln(-\Delta N_1) = 4.2 = y_2$

So the equation of this straight line is-

$$y - y_1 = \frac{y_1 - y_2}{x_1 - x_2}(x - x_1)$$

$$\text{So, } y - 3.8 = \frac{3.8 - 4.2}{339 - 387}(x - 339)$$

So $y = 0.008333x + 0.975$

So, $B = 0.008333$ and $\ln(A) = 0.975$

$A = 2.65$

$\Delta N_1 = -2.65 \exp(0.008333\ N_s)$

Appendix G.2

Month-April (Bangladesh)

$\Delta N_1 = -A\ \exp(BN_s)$

So $\ln(-\Delta N_1) = BN_s + \ln(A)$

A & B are constant. They are to be found.

From graph - G2:

$N_s = 338 = x_1$ $\quad$ $N_s = 378 = x_2$

$\ln(-\Delta N_1) = 3.9 = y_1$ $\quad$ $\ln(-\Delta N_1) = 4.1 = y_2$

So the equation of the straight line is

$$y - y_1 = \frac{y_1 - y_2}{x_1 - x_2}(x - x_1)$$

$$\text{So, } y - 3.9 = \frac{3.9 - 4.1}{338 - 378}(x - 338)$$

So, $y = 0.005x + 2.21$

So, $B = 0.005$ and $\ln(A) = 2.21$

$A = 9.11$

$\Delta N_1 = -9.11\ \exp\ (0.005\ N_s)$

Appendix G3

Month-July (Bangladesh)

$\Delta N_1 = -A \exp(BN_s)$

So $\ln(-\Delta N_1) = BN_s + \ln(A)$

A & B are constant

We have to find A & B

From graph - G3:

$N_s = 342 = y_1$ $\quad$ $N_s = 367 = y_2$

$\ln(-\Delta N_1) = 3.9 = y_1$ $\quad$ $\ln(-\Delta N_1) = 3.7 = y_2$

So the equation of the straight line is -

$$y - y_1 = \frac{y_1 - y_2}{x_1 - x_2}(x - x_1)$$

$$\text{So } y - 3.5 = \frac{3.5 - 3.7}{342 - 367}(x - 342)$$

So $y - 3.5 = 0.008(x - 342)$

So $y = 0.008x + 0.764$

So $B = 0.008$ and $\ln(A) = 0.764$

$A = 2.147$

$\Delta N_1 = -2.147 \exp(0.008\ N_s)$

Appendix G.4

Month-October, (Bangladesh)

$\Delta N_1 = -A \exp(BN_s)$

So $\ln(-\Delta N_1) = BN_s + \ln(A)$

A and B are constants. They are to be found.

From graph - G4:

$N_s = 337 = x_1$ Also, $N_s = 372 = x_2$

$\ln(-\Delta N_1) = 3.8 = y_1$ $\ln(-\Delta N_1) = 4.1 = y_2$

So the equation of this straight line is

$$y - y_1 = \frac{y_1 - y_2}{x_1 - x_2}(x - x_1)$$

$$\text{So, } y - 3.8 = \frac{3.8 - 4.1}{337 - 372}(x - 337)$$

So $y = 0.008571x + 0.9114$

$B = 0.008571$ and $\ln(A) = 0.9114$

$A = 2.4878$

$\Delta N_1 = -2.4878 \exp(0.008571 \ N_s)$

Appendix G.5

Whole year (Jan.App. July. Oct) (Bangladesh)

$\Delta N_1 = -A \exp(BN_s)$

So $\ln(-\Delta N_1) = BN_s + \ln(A)$

A and B are constant. We hve to find A and B.

From graph - G5

$N_s = 342 = x_1$ also $N_s = 372 = x_2$

$\ln(-\Delta N_1) = 3.8 = y_1$ $\ln(-\Delta N_1) = 4.0 = y_2$

So equation of this straight line is -

$$y - y_1 = \frac{y_1 - y_2}{x_1 - x_2}(x - x_1)$$

$$\text{So } y - 3.8 = \frac{3.8 - 4}{342 - 372}(x - 342)$$

So $y = 0.006666x + 1.52$

So $B = 0.006666$ and $\ln(A) = 1.52$

$A = 4.572$

$$\Delta N_1 = -4.572 \exp(0.006666 N_s)$$

Appendix G.6

Dhaka (over year)

$\Delta N_1=-A\ exp(BN_s)$

So $\ln(-\Delta N_1)=\ln(A)+BN_s$

A and B are constant. We have to find A and B.

From graph - G6:

$N_s=341=x_1$ also $N_s=375=x_2$

$\ln(-\Delta N_1)=3.8=y_1$ $\ln(-\Delta N_1)=4=y_2$

So equation of the straight line is -

$$y-y_1=\frac{y_1-y_2}{x_1-x_2}(x-x_1)$$

$$\text{So } y-3.8=\frac{3.8-4}{341-375}(x-341)$$

So $y=0.00588x+1.794$

So $B=0.00588$ and $\ln(A)=1.794$

$A=6.014$

$$\Delta N_1=-6.014\ exp\ (0.00588\ N_s)$$

Appendix G.7

Chittagong(over year)

$\Delta N_1 = -A \exp(BN_s)$

So $\ln(-\Delta N_1) = \ln(A) + BN_s$

A and B are constant. We have to find A and B.

From graph - G7:

$\ln(-\Delta N_1) = 3.7 = y_1$ $\quad$ $\ln(-\Delta N_1) = 4 = y_2$

$N_s = 338 = x_1$ $\quad$ $N_s = 372 = x_2$

So equation of this straight line is -

$$y - y_1 = \frac{y_1 - y_2}{x_1 - x_2}(x - x_1)$$

$$\text{So } y - 3.7 = \frac{3.7 - 4}{338 - 372}(x - 338)$$

So $y = 0.008823x + 0.7176$

So $B = 0.008823$ and $\ln(A) = 0.7176$

$A = 2.405$

$$\Delta N_1 = -2.405 \exp(0.008823 N_s)$$

Appendix G.8

Bogra(over year)

$\Delta N_1 = -A \exp(BN_s)$

$\ln(-\Delta N_1) = BN_s + \ln(A)$

A and B are constant. We have to find A and B.

From graph - G8:

$N_s = 338$ also $N_s = 382$

$\ln(-\Delta N_1) = 3.8$ and $\ln(-\Delta N_1) = 4.1$

So equation of this straight line is-

$$y - y_1 = \frac{y_1 - y_2}{x_1 - x_2}(x - x_1)$$

$$\text{So } y - 3.8 = \frac{3.8 - 4.1}{338 - 382}(x - 338)$$

So $y = 0.006818x + 1.4954$

So $B = 0.006818$ and $\ln(A) = 1.4954$

$A = 4.461$

$$\Delta N_1 = -4.461 \exp(0.006818\ N_s)$$

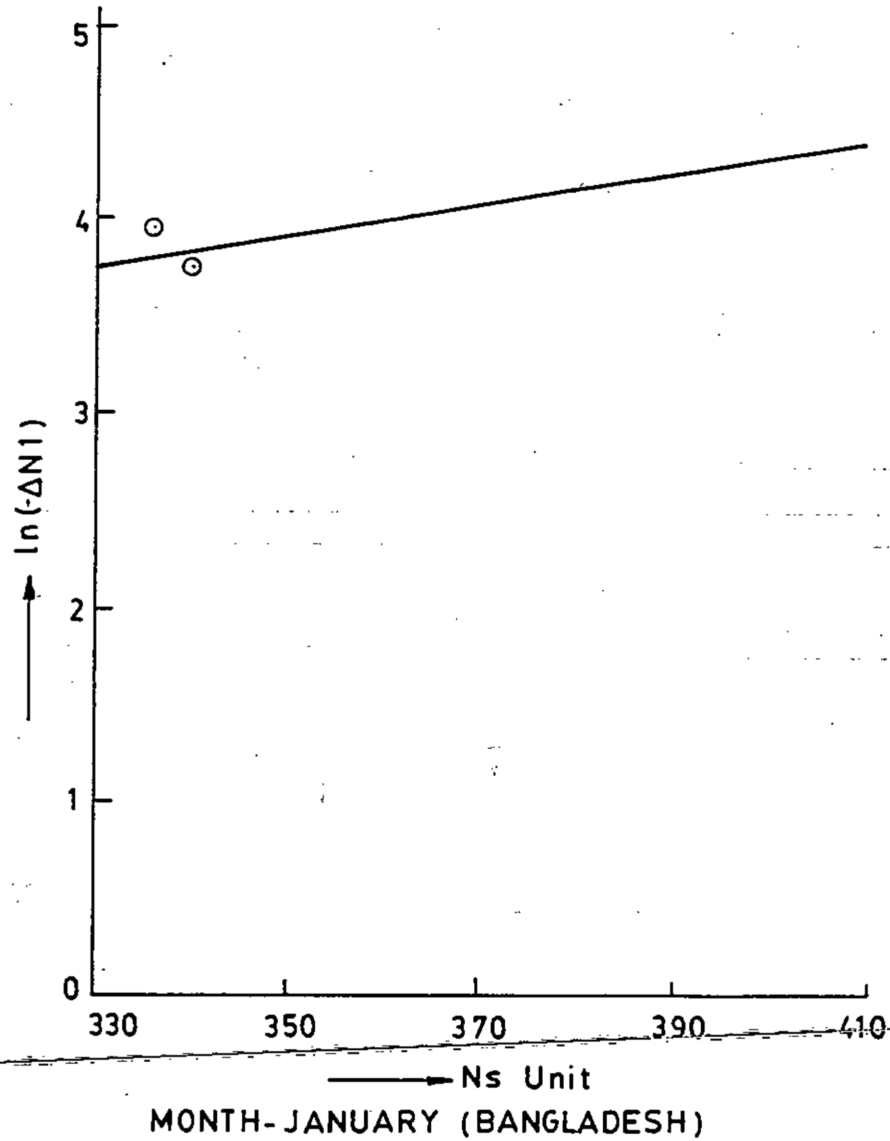


Fig.G1: Correlation of N_s with ΔN.

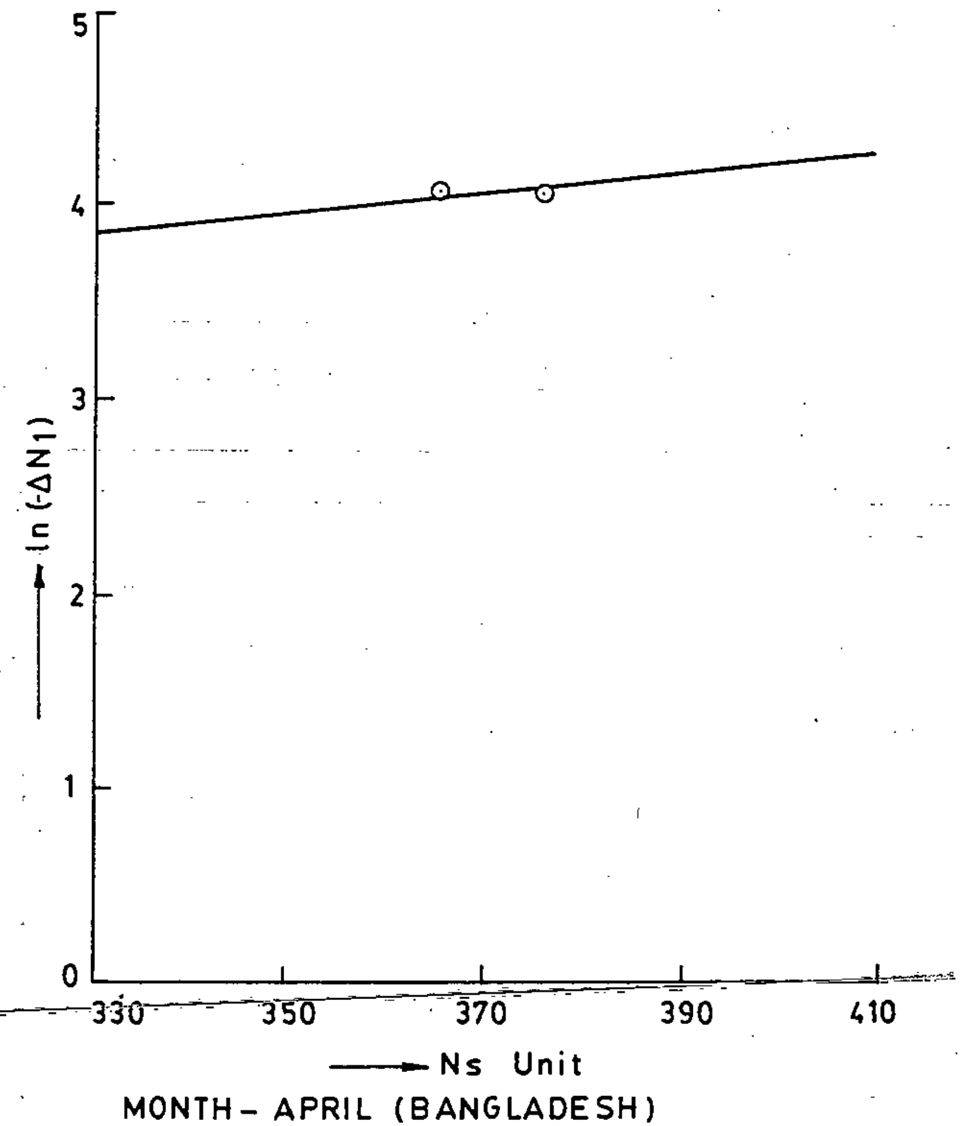
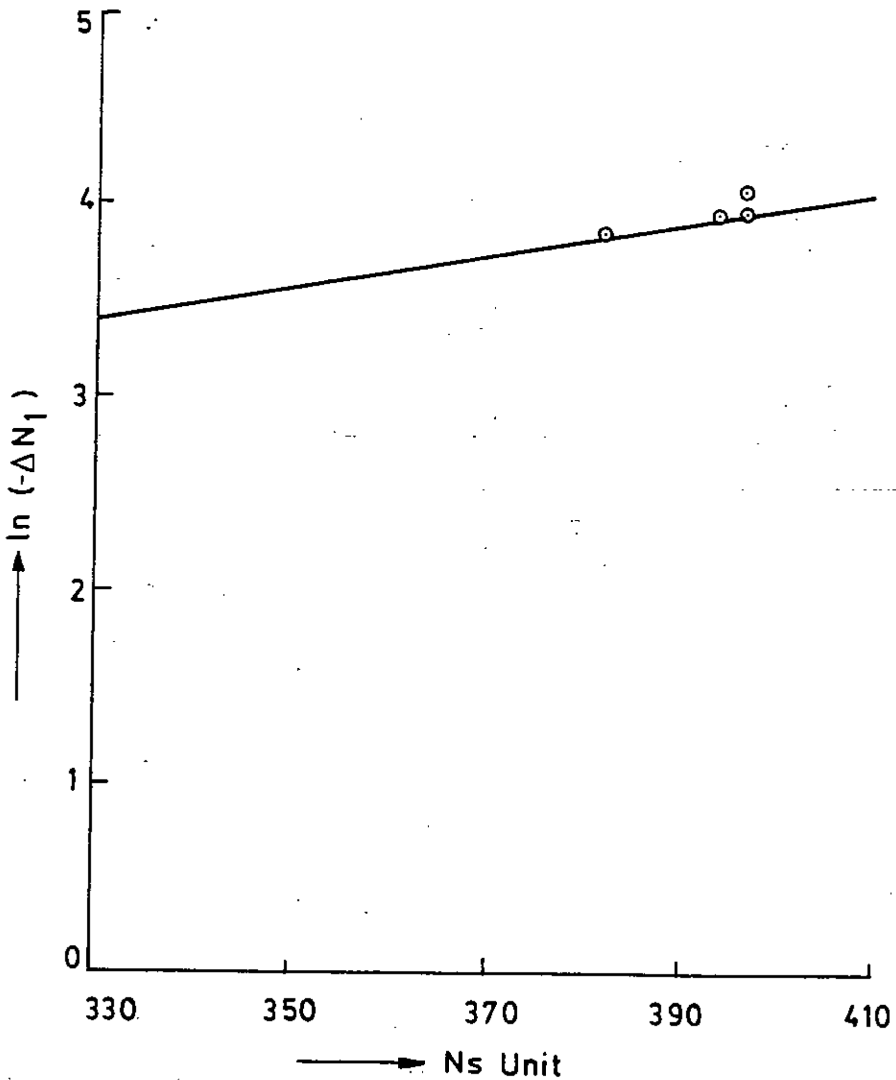
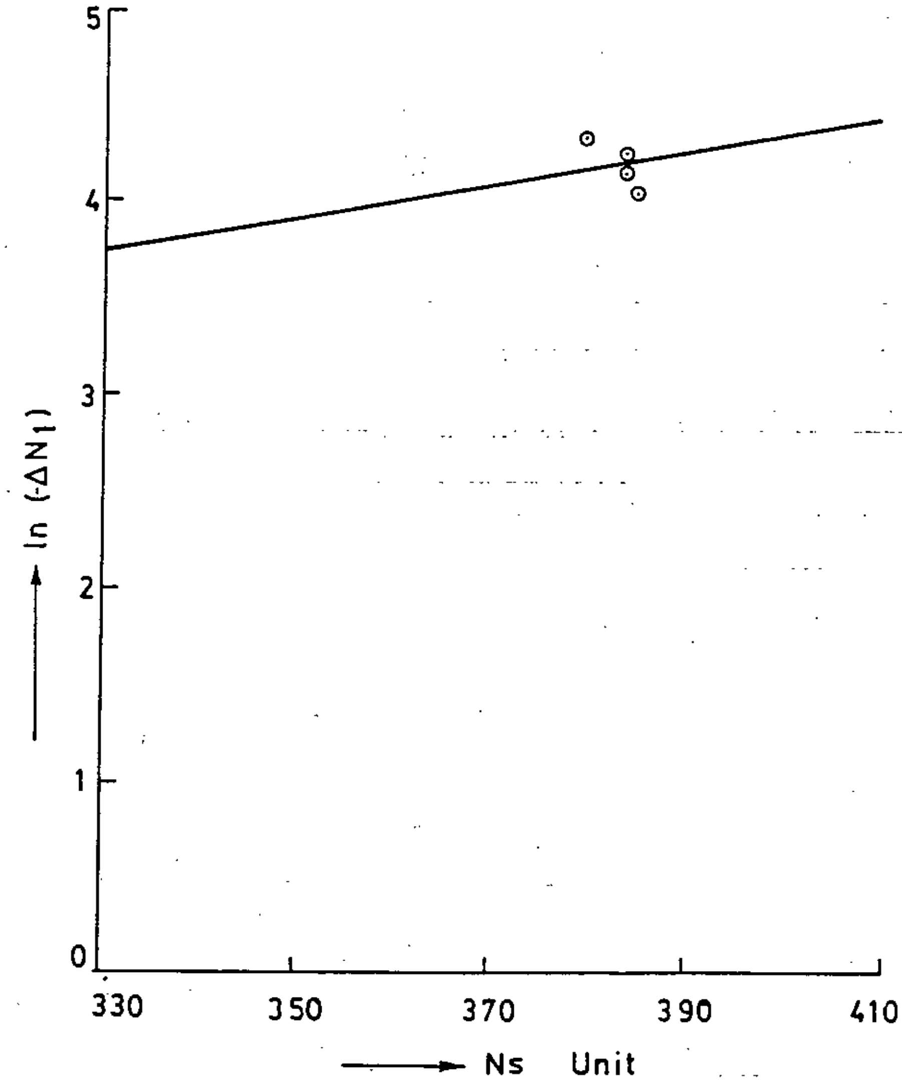


Fig.G2: Correlation of N_s with ΔN.



MONTH – JULY (BANGLADESH)

Fig.G3: Cprrelation of N_s with ΔN.



MONTH – OCTOBER (BANGLADESH)

Fig.G4: Correlation of N_s with ΔN.

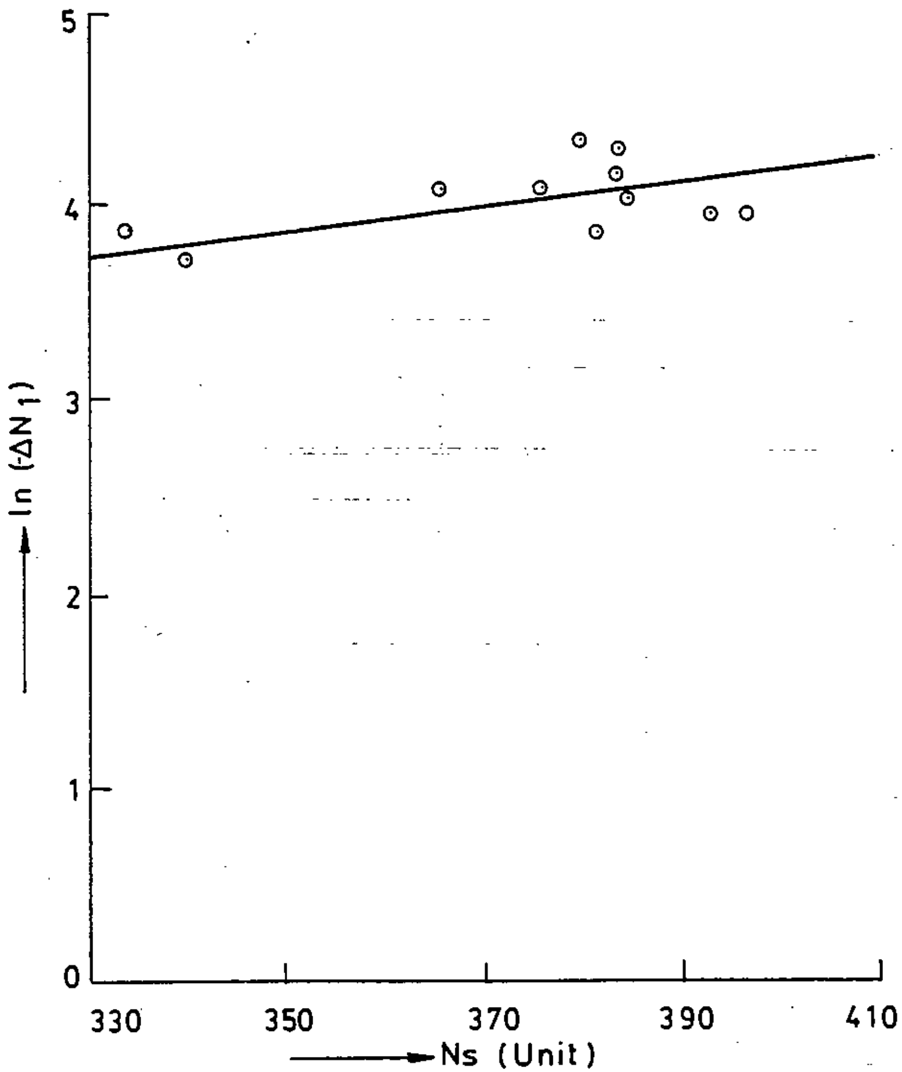


Fig.G5: Correlation of N_s with ΔN.

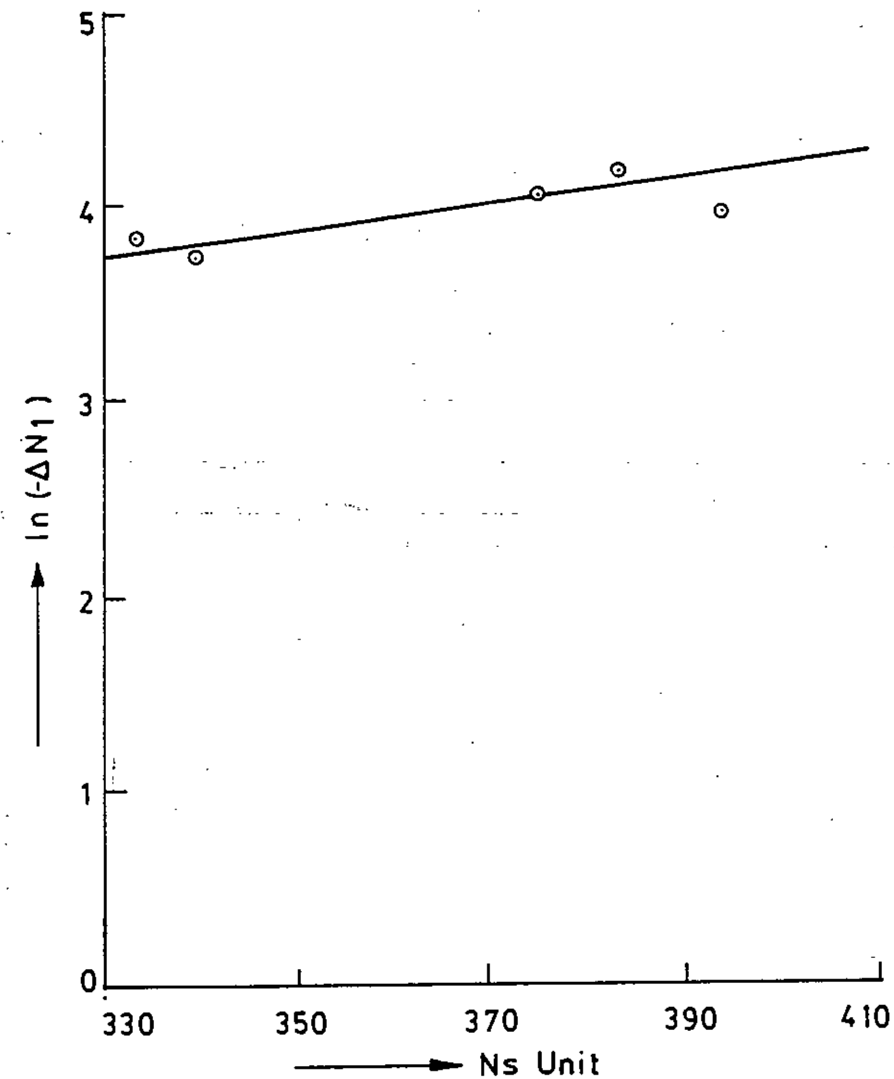


Fig.G6: Correlation of N_s with ΔN.

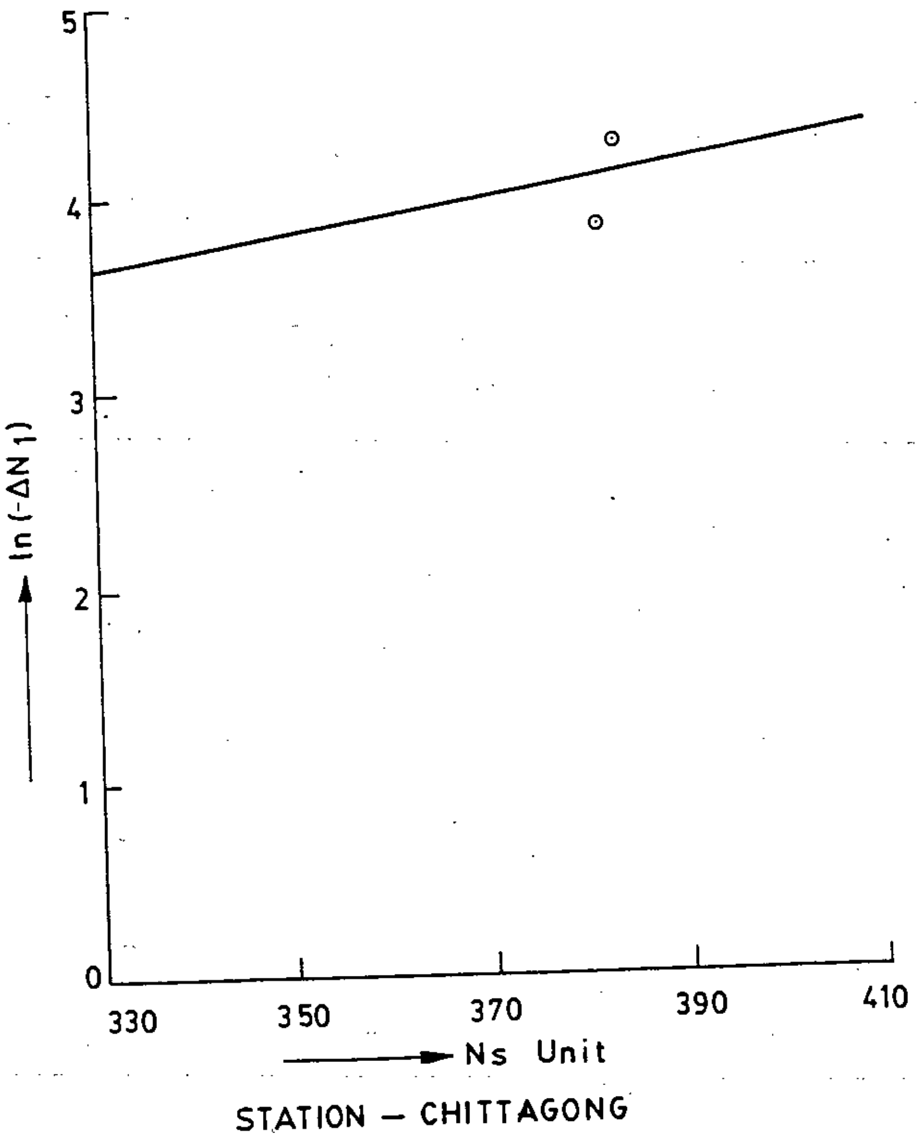


Fig.G7: Correlation of N_s with ΔN.

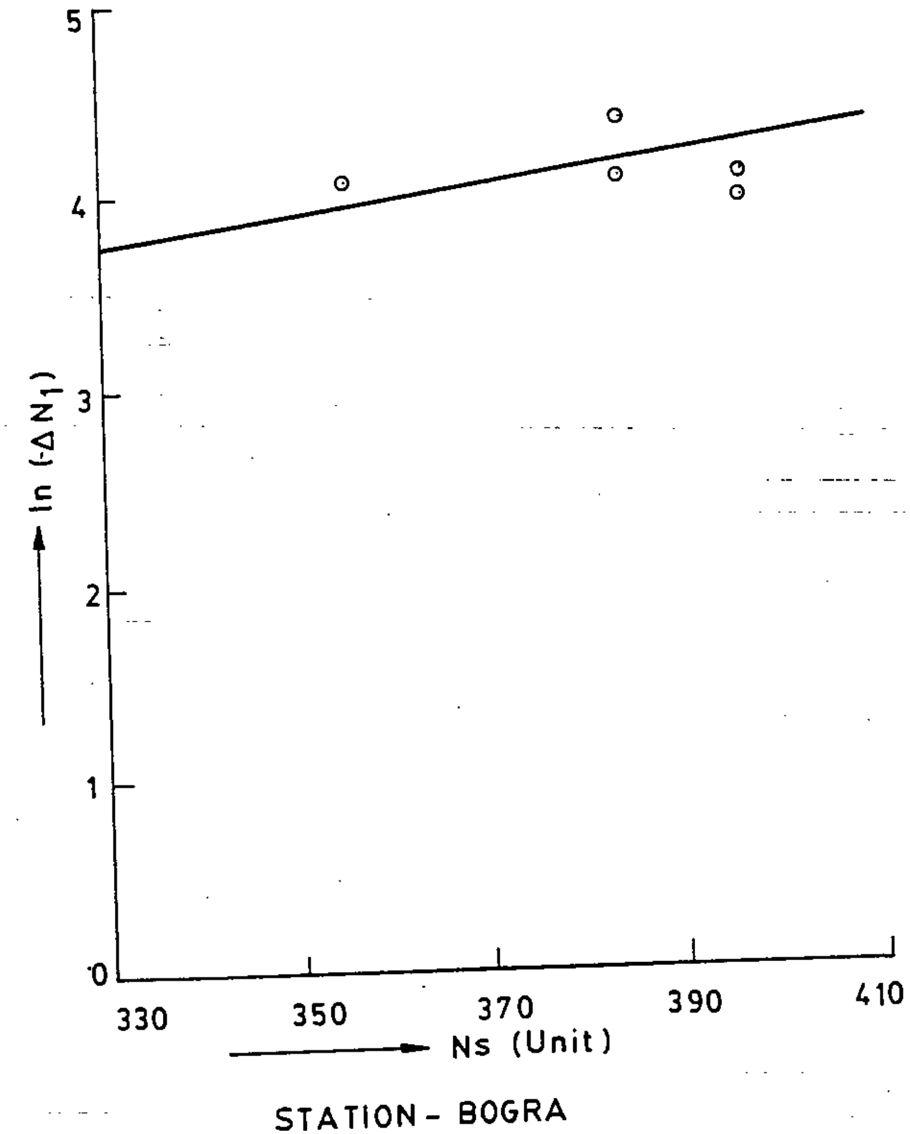


Fig.G8: Correlation of N_s with ΔN

Appendix - H

Determination of Radio Ray Bending

Table H.1

Refraction Calculation
of Dhaka for July 1988
when $\theta_o = 0^o$

h km	$\frac{h \times 10^6}{a}$	$\Delta n \times 10^6$	$M = (\Delta n + h/a) 10^6$	$M - M_o = \theta i^2/2$	θi^2 $(mr)^2$	θ_i mr	$\frac{\theta_{i-1} + \theta_i}{2}$	$(\Delta n_{i-1} - \Delta n_i) \times 10^6$	$\Delta \tau_i$ mr	$\Sigma \Delta \tau$ mr
0.0152	2.38	394	396.38	0	0	0	0	0	0	0
0.0304	4.77	393	397.77	1.39	2.78	1.667	0.833	1	1.1995	1.1995
0.0609	9.56	392	403.46	7.08	14.17	3.765	2.7159	1	0.368	1.5676
0.152	23.86	387	410.86	14.48	28.96	5.38	4.519	5	1.106	2.673
0.3048	47.8	379	426.8	30.42	60.84	7.8	6.59	10	1.517	4.1904
0.6096	95.7	363	458.7	62.32	124.64	11.164	9.482	16	1.687	5.877
0.914	143.5	346	489.5	93.12	186.24	13.464	12.405	17	1.37	7.248
1.1148	175	331	506	109.62	219.2	14.81	14.226	15	1.054	8.3023
1.3935	218.8	314	532.8	136.42	272.84	16.517	15.66	17	1.085	9.387
1.672	262.5	298	560.5	164.12	328.24	18.117	17.317	16	0.923	10.3109
1.954	306.32	282	588.32	191.94	383.88	19.59	18.854	16	0.848	11.159
2.229	349.97	268	617.97	221.59	443.18	21.05	20.32	14	0.6889	11.847
2.508	393.78	255	648.78	252.4	504.8	22.467	21.75	13	0.597	12.444
2.787	437.5	245	682.5	286.12	572.24	23.92	23.19	10	0.431	12.875

Table H.2

Refraction calculation
of Dhaka for July 1988
when, $\theta_o = 5^o = 0.0872$-radian

h km	$\frac{h \times 10^6}{a}$	$\Delta n \times 10^6$	$M = (\Delta n + h/a)10^6$	$M - M_o = Y$ (say)	$\theta i^2 = 2Y + \theta_o^2$	θ_i mr	$\frac{\theta_{i-1} + \theta_i}{2}$	$(\Delta n_{i-1} - \Delta n_i) \times 10^6$	$\Delta \tau_i$ mr	$\Sigma \Delta \tau$ mr
0.0152	2.38	394	396.38	0	0.0076	0.0872	0.0436	0	0	0
0.0304	4.77	393	397.77	1.39	2.787	1.6696	0.878	1	1.138	1.138
0.0609	9.56	392	403.46	7.08	14.16	3.7639	2.716	1	0.368	1.506
0.152	23.86	387	410.86	14.48	28.96	5.38	4.573	5	1.093	2.599
0.3048	47.8	379	426.8	30.42	60.847	7.8	6.59	10	1.517	4.116
0.6096	95.7	363	458.7	62.32	124.64	11.164	9.48	16	1.687	5.803
0.914	143.5	346	489.5	93.12	186.24	13.647	12.405	17	1.37	7.173
1.2192	175	331	506	109.62	219.24	14.807	14.227	15	1.054	8.227
1.5240	218.8	314	532.8	136.42	272.84	16.518	15.66	17	1.085	9.312
1.828	262.5	298	560.5	164.12	328.24	18.117	17.317	16	0.923	10.235
2.13360	306.32	282	588.32	192.59	385.18	19.626	18.87	16	0.847	11.082
2.438	349.97	268	617.97	221.59	443.18	21.05	20.339	14	0.688	11.77
2.743	393.78	255	648.78	252.4	504.8	22.467	21.758	13	0.597	12.367
3.048	437.5	245	682.5	286	572	23.916	23.191	10	0.431	12.798

Table H.3
Refraction calculation
of Dhaka for July 1988
when $\theta_o = 10^o = 0.745$ radian

h km	$\frac{hx10^6}{a}$	$\Delta n x 10^6$	$M=(\Delta n + h/a)10^6$	$M-M_o$ =Y(say)	$\theta i^2 = 2Y + \theta_o^2$	θ_i mr	$\frac{\theta_{i-1}+\theta_i}{2}$	$(\Delta n_{i-1} - \Delta n_i) x10^6$	$\Delta\tau_i$ mr	$\Sigma\Delta\tau$ mr
0.0152	2.38	394	396.38	0	0.03046	0.174	0.0872	0	0	0
0.0304	4.77	393	397.77	1.39	2.81	1.676	0.925	1	1.080	1.080
0.0609	9.56	392	403.46	7.08	14.19	3.767	2.72	1	0.367	1.447
0.152	23.86	387	410.86	14.48	28.99	5.384	4.575	5	1.092	2.539
0.3048	47.8	379	426.8	30.42	60.87	7.801	6.59	10	1.516	4.055
0.6096	95.7	363	458.7	62.32	124.67	11.165	9.483	16	1.687	5.742
0.914	143.5	346	489.5	93.12	186.27	13.648	12.406	17	1.37	7.112
1.1148	175	331	506	109.62	219.27	14.807	14.227	15	1.054	8.166
1.3935	218.8	314	532.8	136.42	272.87	16.518	15.66	17	1.137	9.303
1.672	262.5	298	560.5	164.12	328.2	18.118	17.318	16	0.923	10.226
1.951	306.32	282	588.32	192.59	385.2	19.626	18.87	16	0.847	11.073
2.229	349.97	268	617.97	221.59	443.21	21.052	20.339	14	0.688	11.76
2.508	393.78	255	648.78	252.4	504.83	22.468	21.76	13	0.597	12.357
2.787	437.5	245	682.5	286	572.03	23.917	23.19	10	0.431	12.788

Table H.4

Refraction calculation
of Dhaka for October 1988
when $\theta_o = 0^o$

h km	$\frac{h\times10^6}{a}$	$\Delta n \times 10^6$	$M=(\Delta n + h/a) 10^6$	$M-M_o = \theta i^2/2$	θi^2 $(mr)^2$	θ_i mr	$\frac{\theta_{i-1}+\theta_i}{2}$	$(\Delta n_{i-1} - \Delta n_i) \times 10^6$	ΔT_i mr	$\Sigma\Delta T$ mr
0.0304	4.77	382	386.77	0	0	0	0	0	0	0
0.0609	9.56	380	389.56	2.79	5.58	2.36	1.18	2	1.692	1.692
0.152	23.86	372	395.86	9.095	18.19	4.26	3.31	8	2.41	4.107
0.3048	47.8	364	411.8	25.1	50.2	7.08	5.67	8	1.41	5.517
0.6096	95.7	346	441.7	54.94	109.88	10.48	8.78	18	2.049	7.56
0.914	143.5	326	469.5	82.73	165.4	12.86	11.67	20	1.71	9.27
1.1148	175	307	482	95.26	190.5	13.80	26.66	19	0.712	9.98
1.3935	218.8	287	505.79	119	238	15.43	14.6	20	1.3685	11.34
1.672	262.5	270	532.5	145.75	291.5	17.07	16.25	17	1.046	12.386
1.951	306.32	254	560.3	173.55	347.1	18.63	17.85	16	0.896	13.28
2.229	349.97	242	591.9	205.2	410.4	20.25	19.44	12	0.617	13.897
2.508	393.78	229	622.78	236	472	21.72	20.98	13	0.619	14.516
2.787	437.5	220	657.58	270.8	541.6	23.27	22.49	9	0.4	14.916

Table H.5

Refraction calculation
of Dhaka for January 1987
when $\theta_o = 0^o$

h km	$\frac{h \times 10^6}{a}$	$\Delta n \times 10^6$	$M = (\Delta n + h/a) 10^6$	$M - M_o = \theta i^2/2$	θi^2 $(mr)^2$	θ_i mr	$\frac{\theta_{i-1} + \theta_i}{2}$	$(\Delta n_{i-1} - \Delta n_i) \times 10^6$	ΔT_i mr	$\Sigma \Delta T$ mr
0.0152	2.38	339	341.38	0	0	0	0	0	0	0
0.0304	4.77	338	342.77	1.39	2.78	1.667	0.83	1	1.199	1.199
0.0609	9.56	337	346.56	5.18	10.36	3.218	2.44	1	0.409	1.608
0.152	23.86	333	356.86	15.48	30.96	5.564	4.39	4	0.911	2.518
0.3048	47.8	327	374.8	33.42	66.84	8.175	6.869	6	0.873	3.39
0.6096	95.7	314	409.7	68.32	132.64	11.689	9.93	13	1.308	4.698
0.914	143.5	301	444.5	103.1	206.24	14.36	13.025	13	0.998	5.696
1.1148	175	284	459	117.62	235.24	15.33	14.848	17	1.144	6.841
1.3935	218.8	275	493.8	152.42	304.84	17.459	16.39	9	0.548	7.389
1.672	262.5	262	524.5	183.12	366.24	19.13	18.298	13	0.710	8.1
1.951	306.32	249	555.32	213.94	427.88	20.68	19.9	13	0.653	8.753
2.229	349.97	237	586.97	245.59	491.18	22.16	21.42	12	0.56	9.313
2.508	393.78	226	619.78	278.4	556.8	23.59	22.878	11	0.48	9.793
2.787	437.5	216	653.5	312.12	624.24	24.98	24.28	10	0.411	10.204

Table H.6
Refraction calculation
of Chittagong for October 1988
when $\theta_o = 0^o$

h km	$\frac{h\times10^6}{a}$	$\Delta n\times10^6$	$N=(\Delta n+h/a)10^6$	$N-N_o=\theta i^2/2$	θi^2 $(mr)^2$	θ_i mr	$\frac{\theta_{i-1}+\theta_i}{2}$	$(\Delta n_{i-1}-\Delta n_i)\times10^6$	$\Delta\tau_i$ mr	$\Sigma\Delta\tau$ mr
0.0152	2.38	383	385.38	0	0	0	0	0	0	0
0.0304	4.77	382	386.77	1.39	2.78	1.667	0.833	1	1.199	1.199
0.0609	9.56	380	389.56	4.18	8.36	2.891	2.279	2	0.877	2.076
0.152	23.86	374	397.86	12.48	24.96	4.995	3.943	6	1.521	3.597
0.3048	47.8	364	411.8	26.42	52.84	7.269	6.132	10	1.630	5.228
0.6096	95.7	346	441.7	56.32	112.64	10.613	8.94	18	2.013	7.241
0.914	143.5	327	470.5	85.12	170.24	13.047	11.83	19	1.606	8.847
1.1148	175	311	486	100.62	201.24	14.185	13.616	16	1.175	10.022
1.3935	218.8	295	513.8	128.42	256.84	16.026	15.105	16	1.059	11.081
1.672	262.5	278	540.5	155.12	310.24	17.61	16.819	17	1.010	12.091
1.951	306.32	263	569.32	183.94	367.88	19.18	18.395	15	0.815	12.906
2.229	349.97	247	596.97	211.59	423.18	20.57	19.875	16	0.836	13.742
2.508	393.78	232	625.78	240.4	480.8	21.927	21.248	15	0.705	14.447
2.787	437.5	218	655.78	270.4	540.8	23.255	22.59	14	0.619	15.066

Table H.7
Refraction calculation
of Bogra for October 1988
when $\theta_o = 0^o$

h km	$\frac{h \times 10^6}{a}$	$\Delta n \times 10^6$	$M = (\Delta n + h/a)\ 10^6$	$M - M_o = \theta i^2/2$	θi^2 $(mr)^2$	θ_i mr	$\frac{\theta_{i-1} + \theta_i}{2}$	$(\Delta n_{i-1} - \Delta n_i) \times 10^6$	$\Delta\tau_i$ mr	$\Sigma\Delta\tau$ mr
0.0152	2.38	385	387.38	0	0	0	0	0	0	0
0.0304	4.77	384	388.77	1.39	2.78	1.667	0.833	1	1.199	1.199
0.0609	9.56	380	389.56	2.18	4.35	2.088	1.877	4	2.13	3.329
0.152	23.86	371	394.86	7.48	14.96	3.867	2.977	9	3.022	6.351
0.3048	47.8	356	403.6	16.42	32.84	5.7306	4.798	15	3.125	9.476
0.6096	95.7	333	428.7	41.32	82.64	9.09	7.410	23	3.103	12.579
0.914	143.5	314	457.5	70.12	140.24	11.84	10.466	19	1.815	14.394
1.1148	175	298	473	85.62	171.24	13.085	12.46	16	1.283	15.677
1.3935	218.8	283	501.3	114.42	228.84	15.127	14.106	15	1.063	16.74
1.672	262.5	270	532.5	145.12	290.24	17.036	16.081	13	0.808	17.548
1.951	305.32	260	565.32	177.94	355.88	18.864	17.95	10	0.557	18.105
2.229	349.97	250	599.97	212.55	425.18	20.619	19.74	10	0.506	18.611
2.508	393.78	241	634.78	247.4	494.8	22.24	21.43	9	0.419	19.031
2.787	437.5	233	670	283.12	566.24	23.795	23.017	8	0.347	19.378

Table H.8
Refraction calculation
of Bogra for October 1988
when $\theta_o = 0^o = 0.087266$ radian

h km	$\frac{h \times 10^6}{a}$	$\Delta n \times 10^6$	$M = (\Delta n + h/a) 10^6$	$M - M_o = Y$ (say)	$\theta_i^2 = 2Y + \theta_o^2$	θ_i mr	$\frac{\theta_{i-1} + \theta_i}{2}$	$(\Delta n_{i-1} - \Delta n_i) \times 10^6$	$\Delta\tau_i$ mr	$\Sigma\Delta\tau$ mr
0.0152	2.38	385	387.38	0	0.0076	0.087	0.043	0	0	0
0.0304	4.77	384	388.77	1.39	2.787	1.669	0.878	1	1.138	1.138
0.0609	9.56	380	389.56	2.18	4.367	2.089	1.879	4	2.127	3.265
0.152	23.86	371	394.86	7.48	14.967	3.868	2.979	9	3.020	6.285
0.3048	47.8	356	403.6	16.22	32.447	5.696	4.782	15	3.136	9.422
0.6096	95.7	333	428.7	41.32	82.647	9.091	7.393	23	3.11	12.533
0.914	143.5	314	457.5	70.12	140.247	11.84	10.466	19	1.815	14.348
1.1148	175	298	473	85.62	171.247	13.086	12.463	16	1.283	15.63
1.3935	218.8	283	501.3	113.92	227.84	15.094	14.090	15	1.064	16.694
1.672	262.5	270	532.5	145.12	290.24	17.036	16.065	13	0.809	17.503
1.951	305.32	260	565.32	177.94	355.88	18.864	17.95	10	0.557	18.06
2.229	349.97	250	599.97	212.59	425.187	20.62	19.742	10	0.506	18.566
2.508	393.78	241	634.78	247.4	494.8	22.24	21.432	9	0.419	18.985
2.787	437.5	233	670.5	283.12	566.24	23.795	23.017	8	0.347	19.332

Table H.9
Refraction calculation
of Bogra for October 1988
when $\theta_o = 5^o = 0.1745$ Radian

h km	$\frac{h \times 10^6}{a}$	$\Delta n \times 10^6$	$M = (\Delta n + h/a) 10^6$	$M - M_o$ =Y(say)	$\theta i^2 = 2Y + \theta_o^2$	θ_i mr	$\frac{\theta_{i-1} + \theta_i}{2}$	$(\Delta n_{i-1} - \Delta n_i) \times 10^6$	$\Delta\tau_i$ mr	$\Sigma\Delta\tau$ mr
0.0152	2.38	385	387.38	0	0.03046	0.1745	0.087	0	0	0
0.0304	4.77	384	388.77	1.39	2.81	1.676	0.925	1	1.0805	1.080
0.0609	9.56	380	389.56	2.18	4.39	2.095	1.885	4	2.121	3.201
0.152	23.86	371	394.86	7.48	14.99	3.89	2.983	9	3.016	6.218
0.3048	47.8	356	403.6	16.22	32.47	5.698	4.784	15	3.135	9.353
0.6096	95.7	333	428.7	41.32	82.67	9.092	7.395	23	3.11	12.463
0.914	143.5	314	457.5	70.12	140.27	11.84	10.467	19	1.815	14.278
1.1148	175	298	473	85.62	171.27	13.087	12.46	16	1.283	15.56
1.3935	218.8	283	501.3	113.92	227.87	15.095	14.091	15	1.064	16.624
1.672	262.5	270	532.5	145.12	290.27	17.037	16.066	13	0.809	17.433
1.951	305.32	260	565.32	177.94	355.91	18.865	17.951	10	0.557	17.99
2.229	349.97	250	599.97	212.59	425.21	20.62	19.742	10	0.506	18.496
2.508	393.78	241	634.78	247,4	494.83	22.24	21.43	9	0.419	18.915
2.787	437.5	233	670.5	283.12	566.27	23.796	23.018	8	0.347	19.262

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