ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 2, Issue 12, June 2013

Tropospheric Influences on Satellite Communications in Tropical Environment: A Case Study of Nigeria

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Abstract* – Among other atmospheric regions, ionosphere, which is ionized region of the atmosphere, is considered to impose serious limitations on satellite communication while the effect of other layers, more especially, the troposphere is often treated as negligible. At higher frequencies, radio waves pass through the ionosphere and are attenuated due to the free electrons present in ionosphere. However, recent studies have shown that while the ionospheric disturbance can be predicted on global scale, tropospheric disturbances is depend on geographic location due to dependence of local meteorology on surface topography and other location specific weather forcing. This paper discusses the tropospheric effects on high frequency radio waves, especially, microwave band, illustrating the attenuation and losses it may come across like attenuation due to atmospheric gases, rain, clouds, beam spreading loss (radio refractivity) and noise temperature. Results from some previous studies over Nigeria was used to illustrated location dependence of tropospheric effects such as attenuation due to atmospheric gases, rain, clouds, beam spreading loss (radio refractivity) and noise temperature. Data used to summarize the influence of atmospheric phenomena was obtained using Vantage Pro 2 automatic weather station. ITU-R models were employed to processed data using MATLAB and Microsoft Excel. Results from the studies shows that tropospheric influence on satellite communication is very significant and more research should be carried out in this field.

I. INTRODUCTION

Satellite communication is normally thought of as a robust means of communication, not sensitive to environmental impacts. This perception is not totally accurate. Satellite communication can be and is affected by the environment in which it operates. Space environmental effects on satellite communication can be separated into (1) effects on the space element (ie the satellite), (2) effects on the ground element (ie the Earth station), and (3) effects on the signals propagating through the Earth's lower and upper atmosphere. The propagating signal may be affected by its passage through the ionosphere (upper atmosphere) or the troposphere (lower atmosphere). These effects depend significantly on frequency, but include signal absorption, scintillation, Faraday rotation and bandwidth decoherence. Geographic location and signal propagation path can also determine the extent to which the signal is affected. The ionosphere is a region of the upper atmosphere that extends from about 70 to 500 km in altitude. It is a region where some of the atoms have had their outer electrons removed by extreme ultra-violet (EUV) and X-ray radiation coming from the sun. The atmosphere is thus said to be partially ionised - hence the name, ionosphere. The ionosphere usually consists of four layers but two layers are more important in radio propagation: the E layer which is about 80 to 113 km above the earth's surface and reflects radio waves of lower frequency. Above E layer is F layer which reflects higher frequency radio waves. The F layer is further sub divided into F1 and F2 layers. The F1 layer is lower portion of F layer and exists from 150 to 200 km above the earth's surface, whereas F2 layer is the upper portion and exists at a height of 200 to 500 km. F2 layer is mainly responsible for reflection of (High Frequency) HF waves during day and night. Since the ionization is mainly caused by solar radiations, it is dependent on location, time of the day, season and sunspots [1]. Radio waves propagating through ionosphere experience different attenuation mechanisms such as absorption, reflection, refraction, scattering, polarization, group delay and fading/scintillation. Tropospheric weather conditions, occurring in the lower 10 km of the atmosphere, can also cause losses in signals propagating between satellite and ground stations. Beam spreading is more pronounce at (Very High Frequency) VHF and (Ultra High Frequency) UHF. Water vapour is particularly damaging to signals above about 2 GHz, causing absorption of signals which becomes greater as the frequency increases. K-band signals (10-20 GHz) are particularly susceptible, and precipitation in the vicinity of satellite ground stations can cause total loss of signal. Again, signals with low elevations are more affected than those propagating near the zenith, because the wave has to follow a longer path through the atmosphere. At frequencies above 20 GHz we start to encounter resonant absorption at specific frequencies. Oxygen, in particular, will absorb electromagnetic energy only at certain well-defined frequencies. These frequencies correspond exactly to the energies required to lift the Oxygen atoms into higher energy states. Satellite communication links are designed to avoid these well known frequency bands.

II. ATTENUATION DUE TO ATMOSPHERIC GASES

Attenuation by atmospheric gases at microwave and millimetric frequencies is mainly due to oxygen and water vapour absorption. Oxygen possesses a permanent magnetic moment which cause absorption of wave energy due to its interaction with the wave's magnetic field[1]. At frequencies below 3 GHz, path attenuation due to

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ISO 9001:2008 Certified
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atmospheric gases, rain and clouds is small and is often neglected. It however becomes significant at higher frequencies. As the effect is highly frequency dependent so the attenuation due to atmospheric absorption in some frequency bands is much greater than in others. In most countries (Nigeria, inclusive), water vapour density is not available for propagation interest; hence it is often calculated from concurrent measurements of temperature and relative humidity using:

$$\rho = \left(\frac{H}{5.752}\right) \qquad (1)$$

where H is the relative humidity in percent, θ is the inverse temperature constant, given by:

$$\theta = \frac{300}{T_0}$$

T_0 is the temperature at the surface in Kelvin [2].

The total gaseous attenuation in the atmosphere, A, over a path length r_0 (km) is given by:

$$A = \int_0^{\beta_0} \{\beta_0(r) + \beta_w(r)\} dr, d\beta \qquad (2)$$

where β_0 and β_w are the attenuation coefficients (in decibels per kilometer) for oxygen and water vapour, respectively [3].

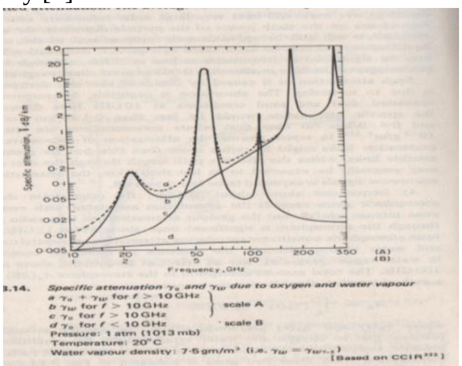

Fig 1: Specific Attenuation due to atmospheric gases for a standard atmosphere in UHF, SHF and EHF bands [3].

As shown in Fig-1, dry air has an oxygen absorption line at 60 GHz. The first absorption band at 22.2 GHz is due to water vapour, followed by absorption at 60 GHz due to dry air and at 118GHz and 123GHz again due to water vapour. The Atmospheric windows' between these absorption bands are available for practical earth-space communications. It is evident from Fig-1 that below 22.3 GHz, the specific attenuation increases with frequency tremendously and it can be more than 10 times higher at 15 GHz than at 2 GHz. Also, the gaseous absorption is less than 1 dB for most paths below 100 GHz as indicated in Fig.1. Taking into account the relative contribution, it is obvious that there will be more attenuation in presence of water vapour than in dry air because of the presence of more molecules in water vapour. Water vapour is a polar molecule with an electric dipole resulting in two absorption lines in the microwave region at 22.2 GHz and 183.3 GHz, where as Oxygen molecule has a permanent magnetic moment that produces multiple absorption lines that spread out between 50 and 70 GHz. The variation of vapour density variation over Nigeria is presented in Fig. 2. It shows that water vapour density increases from north to south. This presented different level of attenuation across the country. The vapour density variation around the north central area especially around the confluence of River Niger and Benue appear to be more dense. This is probably due to the influence River Niger and Benue.

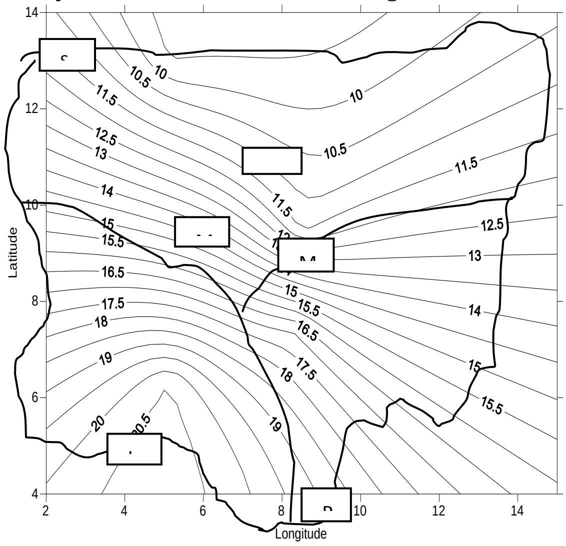

Fig. 2: Vapour Density Variation over Nigeria

In conclusion, Atmospheric oxygen and particularly atmospheric water vapour cause a minor level of attenuation to satellite signals. The effects generally increase with frequency and are greatest near lines in the absorption spectra for each molecule. The line of most interest normally is the water absorption line at 22.3 GHz because the SHF band, 3 to 30 GHz, is often used. Besides frequency the amount of absorption depend on the humidity (water vapour concentration), the elevation angle, pressure and temperature. The drastic change in weather condition over Nigeria from north to south makes the study of atmospheric gases attenuation over Nigeria very significant.

III. ATTENUATION DUE TO PRECIPITATIONS AND CLOUDS

The strength of satellite signal may be degraded or reduced under rain conditions; in particular radio waves above 10 GHz are subject to attenuation by molecular absorption and rain [4]. Presence of rain drops can severely degrade the reliability and performance of communication links. Attenuation due to rain effect is a function of various parameters including elevation angle, carrier frequency, height of earth station, latitude of earth station and rain fall rate. The primary parameters, however, are drop-size distribution and the number of drops that are present in the volume shared by the wave with the rain. It is important to note that, attenuation is determined not by how much rain has fallen but the rate at which it is falling, however, where this cannot be determine, the rain rate is calculated from total rain fall [5].

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The propagation loss due to rain is given by:

$$L = 10\log\frac{P_r(0)}{P_r(r)} \qquad (3)$$

where P_0 is the signal power before the rain region, P_r is the signal power after the rain region, and r is the path length through the rain region.

The propagation loss due to rain attenuation is usually expressed by specific attenuation γ, in decibels per kilometre, so propagation loss is:

$$L = \gamma l_r \qquad (4)$$

where γ is specific attenuation in dB/km and l_r is rain path length in km [6].

Based on ITU-R specific attenuation model [7] . it is found that γ depends only on rainfall rate, measured in millimetres per hour.

From this model, the usual form of expressing γ is:

$$\gamma = aR^b \qquad (5)$$

where a and b are frequency dependent coefficients and γ is specific attenuation in dB/km.

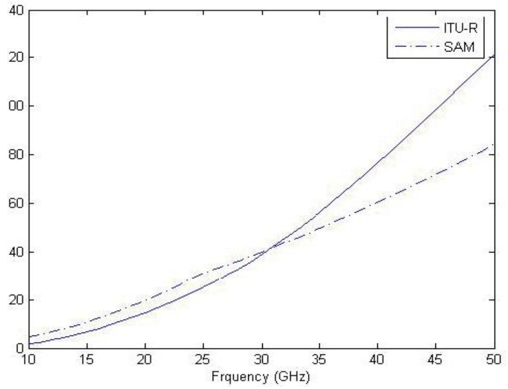

Fig 3: Rain Attenuation As Determined By ITU-R Model And Simple Attenuation Model (SAM) At Frequencies Above 10 GHz [7].

Rain attenuation is a key limiting factor in using high frequency bands in satellite and terrestrial microwave systems [1]. Rain drops both absorb and scatter radio-wave energy. Very intense rain rate may cause link outage. If the rain drop size approaches half the wavelength of the signal in diameter, the signal will be attenuated. Higher frequencies exhibit more attenuation than lower frequencies due to smaller wavelength as shown in Fig. 3. Rain intensity and drop size varies across Nigeria from north to south. While the extreme north is prone to high intensity rainfall accompanied by storm over a short period of time, the south often experience rain shower over a long period of time. The variation in rain pattern and amount of rain fall (Fig. 4) is as a result of dramatic change in climatic condition from arid or semi arid region in the north to tropical coastal region in the south. This variation makes the rain attenuation study over Nigeria very important. Clouds are also important sources of attenuation at higher frequencies. Due to diverse nature of clouds, attenuation of different intensities may occur. Each type of cloud has different water droplet concentration. Clouds having ice crystals cause less attenuation. Non precipitating clouds are also not very significant as the liquid content is too low to cause much absorption of energy, and the droplets are too small to scatter the energy and also they are spherical so they can not cause cross polarisation. In warmer climates, such as Nigeria, the clouds are thicker and so cloud attenuation may be higher. Rain degrades the performance of a satellite communication system by increasing the noise temperature of the earth station antenna as shown in Fig. 5 [8]. While raining, the earth station receives thermal radiation from rain drops which cause an increase in the overall noise temperature.

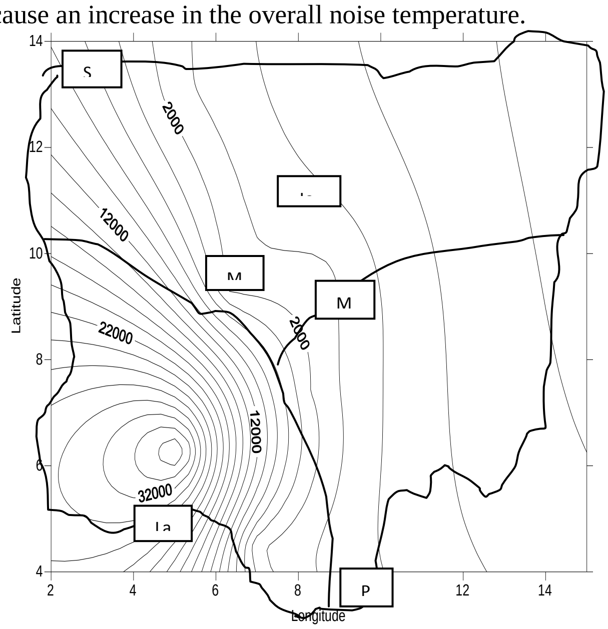

Fig. 4: Rainfall Variation over Nigeria

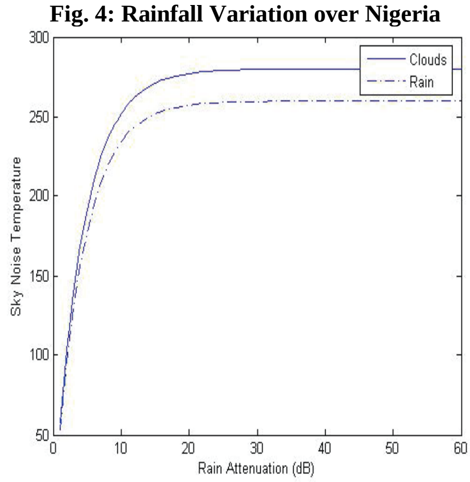

Fig 5: Sky Noise Temperature As Seen By the Antenna [8].

The antenna collect noise from ground, atmosphere (whether cloud or rain), and extraterrestrial sources. Antenna noise temperature varies with elevation angle, antenna size, frequency and weather conditions.

IV. BEAM SPREADING LOSS

Due to the regular decrease of the radio refractive index of the atmosphere with height, downward ray bending is produced, which increases by reducing the

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ISO 9001:2008 Certified
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elevation angle of the ray. The effect is significant at elevations below about 3° [9].

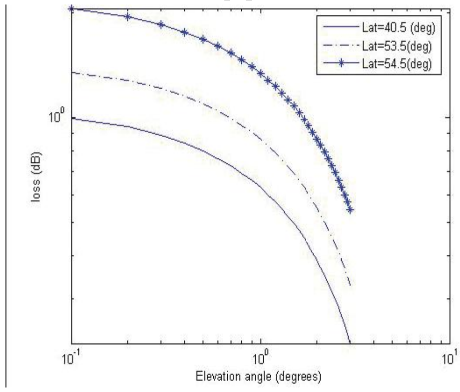

Fig 6: Loss With Respect To Elevation Angle as a Function of Latitude [9].

Rays at the top and bottom of the antenna main beam travel with slight different elevation angles and an additional divergence of the beam is produced in the vertical plane due to the resulting differential ray bending. There is no increase in the divergence of the beam in horizontal plane. In satellite communications, beam-spreading loss results from the spreading of the earth-satellite signals as they pass through the earth's atmosphere. Beam spreading loss is maximum at lowest elevation angle and decrements by increasing the elevation angle as shown in Fig. 6. At 3°, the loss becomes constant. It is also clear from the figure above that the loss is comparatively smaller if the antenna is closer to the equatorial region than the one which is far from equator. The radio refractivity over Nigeria also have a significant variation in the horizontal direction in Nigeria as well as the vertical direction (Fig. 7). This variation due to in atmospheric vagaries from one climatic region to the other.

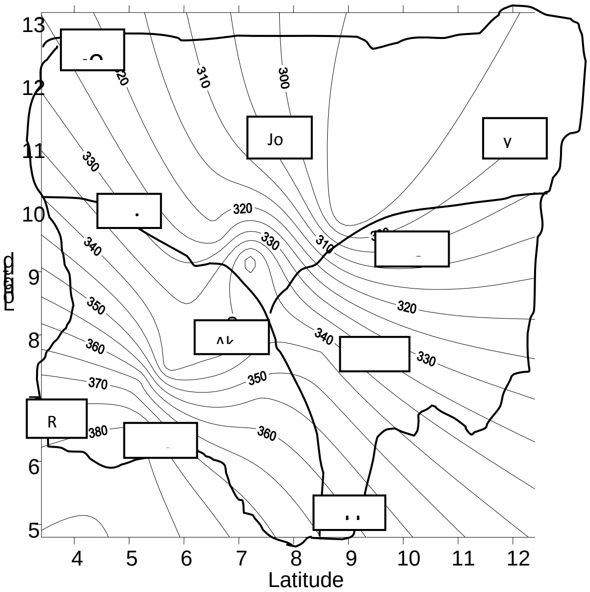

Fig. 7: Surface Refractivity Variation over Nigeria [10].

The variation of propagation condition over Nigeria as represented by k-factor variation is shown in Fig. 8 and the statistic of propagation condition is shown in Fig. 9 to Fig. 14 [11]. From Fig. The k-factor increase coastward which imply change from sub-refractive to super-refractive condition. The change in propagation condition is more explicitly shown in Fig.9 to Fig. 14 where it is obvious that while the extreme northern part of the country experience a predominantly sub-refractive condition, the extreme south and the middle belt region of the country experience a predominant super- refractive and in extreme case ducting. The results presented here showed the significance of in-depth study of radio meteorology over Nigeria for effective planning of communication system both on line of sight (LOS) and earth-satellite signal path.

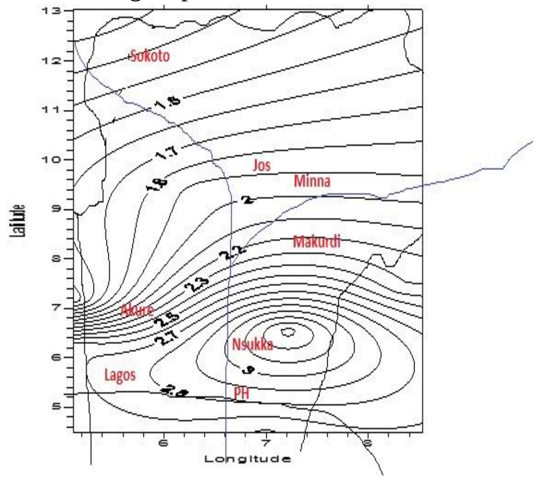

Fig. 8: Distribution of K-Factor over Nigeria [12]

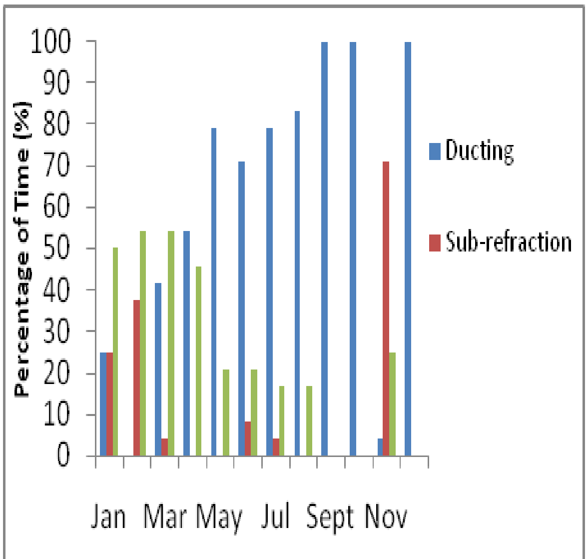

Fig. 9: Statistical Distribution of Propagation Effects at Minna

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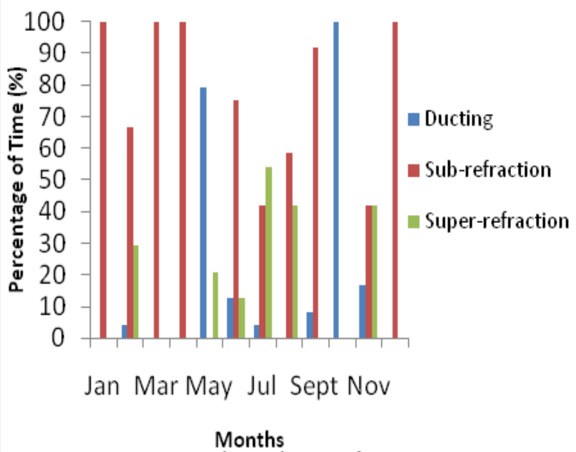

Fig. 10: Statistical Distribution of Propagation effects at Sokoto

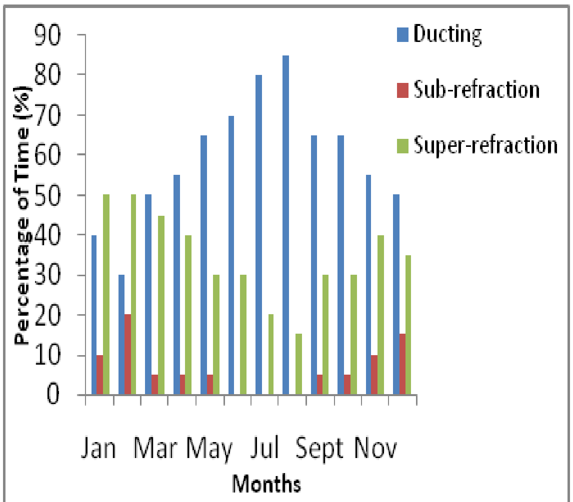

Fig. 11: Statistical Distribution of Propagation Effects Over Port-Harcourt

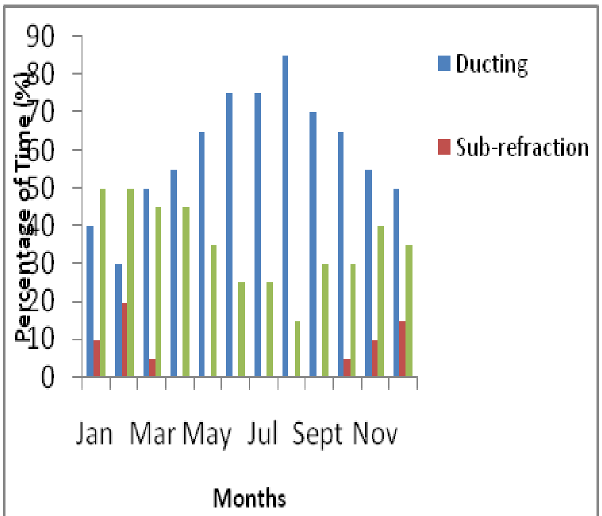

Fig. 12: Statistical Distribution of Propagation Effects over Lagos

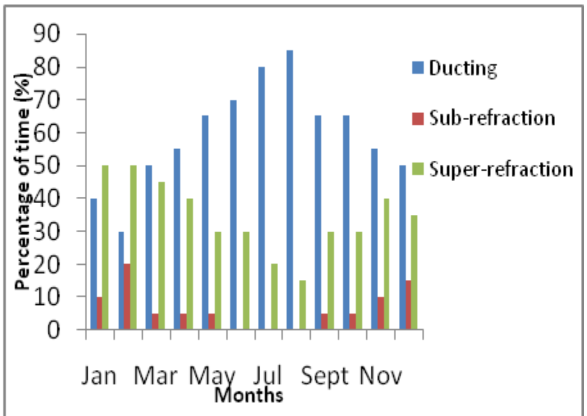

Fig. 13: Statistical Distribution of Propagation Effects Over Makurdi

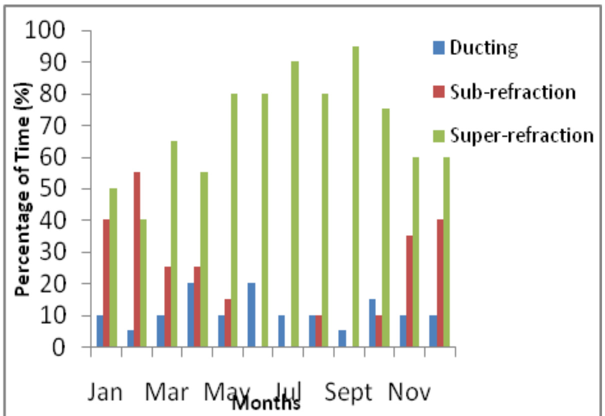

Fig. 14: Statistical Distribution of Propagation Effects over Jos

V. CROSS POLARISATION DISCRIMINATION

Large raindrops in the rain are not spherical but flatten and fall with their major axis almost horizontal. The horizontal component of the wave is thus more attenuated when it propagates through the rain. If we recombine the horizontal and vertical components at any point to reconstruct the wave, we will see that its polarization has rotated towards the component. Thus, a cross polarization component has come to existence [13]. Depolarization is induced by two factors: a) Rain and b) multipath propagation. Multipath induced depolarization is generally limited to terrestrial links. The major depolarization on satellite paths is caused by rain and ice. The wave while passing through the anisotropic medium exhibits attenuation and phase shift and thus its polarization state is altered, such that power is transferred from desired polarization state to the undesired orthogonal polarization state, resulting in interference. As earlier explained, rain pattern varies from one location to another in Nigeria. Results from previous researches showed that rain drop sizes also varies. It's important that the rain drop sizes over Nigeria be studied. The ITU-R prediction fail in most climatic regions of the world.

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VI. CONCLUSION

This paper describes how radio propagation is affected by tropospheric condition over Nigeria. Some results from previous and current research work was used to demonstrate different effects in some selected locations across the country. The need for more in-depth study is recommended both for signal on line of sight and slant path.

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