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Dependence of Surface Refractivity Gradient Variation on Precipitation in the Tropical West Africa

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Abstract: *The boundary layer experiences strong and dynamic changes in atmospheric properties due to surface mechanisms. As such, radio waves are susceptible to modulations near the surface. This study therefore focuses on the influence of precipitation distribution on seasonal and annual refractivity gradient patterns within 10 meters height from the surface in the troposphere over West African continental areas.The West African continental areas were partitioned into four climatic zones based on rainfall distribution pattern. Meteorological data from thirty-six geo-referenced stations containing raw point datasets for 22 years including air temperature, relative humidity and atmospheric pressure at 2 m and 10 m, averaged daily with attributes of geographic features (longitude and latitude) were used to compute dry and wet terms of surface refractivity and its gradients. Seasonal and annual variations with respect to precipitation distribution were analyzed. Surface Refractivity Gradient (SRG) variations in all the climatic zones were influenced by topographical features and the prevailing atmospheric conditions which is dependent on the seasonal north – south movement of the Inter – tropical discontinuity. Climatic zone 1 had prevalence of super-refractivity characteristic except in July and August and climatic zone 2 was super-refractive throughout the year. In climatic zone 3, dry months had sub-refractivity while wet months had sub-refractivity characteristics. Climatic zone 4 was entirely sub-refractive. Climatic zone 1 had annual SRG range of 18 N-Units/km; zone 2 hadannual range of 19 N-Units/km; zone 3 had annual range 49 N-Units/km and zone 4 had annual range of 57 N-Units/km within the period of 1983 – 2005.*
Keywords: *Surface refractivity, precipitation, inter-tropical discontinuity, climatic zones*

I. Introduction

The variation of radio refractive index, *n*, in thelower part of the atmosphere is a very important parameterin planning of communication links. It is defined as aratio of radio wave propagation velocity in free spaceto its velocity in a specified medium [15]. Radio wavepropagation is determined by changes in the refractiveindex of air in the troposphere [2]. Changes in the value ofthe troposphericradio refractive index can bend the path ofthe propagating radio wave.At standard atmosphere conditions near the earthsurface, radio refractive index is equal toapproximately 1.0003 [6].

As the conditions of propagationin the atmosphere vary from the standard value, anomalous radio wave propagation is observed. Suchanomalies are incident with some meteorologicalconditions such as inversion of temperature, high evaporation andhumidity, passing of the cold air over the warm surface [13].The atmospheric radio refractive index depends on airtemperature, humidity, atmospheric pressure and watervapour pressure. Furthermore, air temperature, pressureand humidity depend on the height above theground surface where the measurement was observed. Even small changes in any of thesevariables can make a significant influence on radio wavepropagation, because radio signals can be refracted overwhole signal path [11]. In a well–mixed atmosphere,pressure, temperature and humidity decrease exponentiallyas a function of height [5].Refractivity gradient statistics for the lowest 100 m from the surface of the earth are used toestimate the probability of occurrence of ducting and multipath conditions [10].

Although, radio propagation takes place virtually at various heights in the atmosphere, reception mostly occurs within a height of 10 meters in the boundary layer. The boundary layer experiences strong and dynamic changes in atmospheric properties due to surface mechanisms. As such, radio waves are susceptible to modulations near the surface. This study therefore focuses on the influence of precipitation distribution on seasonal and annual refractivity gradient patterns within 10 meters height from the surface in the troposphere over West African continental areas.

II. Estimation of Surface Refractivity Gradient

The ITU Radio communication bureau, considered the necessity of using a single formula for calculation of the index of refraction of the atmosphere. The need for reference data on Surface Refractivity Gradients (SRG) all over the world was also investigated. The necessity to have a mathematical method to express the statistical distribution of refractivity gradients led to a recommendation that the atmospheric refractive index, n, be computed by means of the formula given by [8]:

$$n = 1 + N \times 10^{-6} \qquad 1.0$$

where N is the surface refractivity expressed by

$$N = N_{dry} + N_{wet} = \frac{77.6}{T}\left(P + 4810\,\frac{e}{T}\right)(N - \text{Units}) \qquad 2.0$$

The dry term, N_{dry} of surface refractivity is given by

$$N_{dry} = 77.6\,\frac{P}{T} \qquad 3.0$$

The wet term, N_{wet} of surface refractivity is given by

$$N_{wet} = 3.732 \times 10^{5}\,\frac{e}{T^{2}} \qquad 4.0$$

P is atmospheric pressure (hPa), e is water vapour pressure (hPa), and T is absolute air temperature (K). The expression in eq. 2.0 may be used for all radio frequencies; for frequencies up to 100 GHz, the error is less than 0.5%. For representative profiles of temperature, pressure and water vapour pressure, the dry term generally contributes about 70 % to the total value of the refractivity while the wet term contributes substantially to its variation [12]. The dry term is proportional to the density and change in distribution of gas molecules in the atmosphere. The value of wet term of refractivity is due to the polar nature of water molecules [1].

The relationship between water vapour pressure *e* and relative humidity (RH) is given by

$$e = \frac{RHe_{s}}{100}\,(\text{hPa}) \qquad 5.0$$

with

$$e_{s} = a\exp\left(\frac{b\,t}{t + c}\right)\ (\text{hPa}) \qquad 6.0$$

where RH is relative humidity (%), t is air temperature (^{o}C), e_s is saturation vapour pressure (hPa) at the temperature t (^{o}C) and the coefficient a, b, c are as follows:

a = 6.1121
b = 17.502
c = 240.97

The values of constants a, b, and c are valid for temperatures from -20 ^{o}C to +50 ^{o}C with an accuracy of ±0.20%.Vapour pressure e can be obtained from the water vapour density ρ using

$$e = \frac{\rho\,T}{216.7}\,(\text{hPa}) \qquad 7.0$$

where ρ is given in g/cm^{3}.

The statistics of the vertical gradient of surfacerefractivityin the lowest layer of the atmosphere are important parameters for the estimation of path clearance and propagation associated effects such as ducting on trans-horizon paths, surface reflection, multipath fading and distortion on terrestrial line-of-sight links [9].The gradient of surface refractivity, SRG, can be calculated using

$$SRG = N_1 - N_2 \qquad 8.0$$

where N_1 is surface refractivity at height h_1(2 m) and N_2 is surface refractivity at height h_2 (10 m), $h_1 < h_2$.

III. Data Source and Procedures of Analysis

In this work, the West African continental areas have been partitioned into four climatic zones based on rainfall distribution pattern (as shown in figure 1). Meteorological data from thirty-six geo-referenced stations corresponding to World Meteorological ground stations across West Africa and comprising six stations in climatic zone 1; ten stations in zone 2; ten stations in zone 3; and ten stations in zone 4 were used in this study (as shown in figure 2). The stations were evenly distributed across the four climatic zones. A geo-referenced location map of the area under study was prepared showing station points across West African region.

The Surface Meteorology and Solar Energy (SSE) dataset used for this study are satellite and model-based products (http://eosweb.larc.nasa.gov/sse). These long-term estimates of meteorological quantities and surface solar fluxes, which were specifically formulated by the National Aeronautical Space Administration (NASA) to aid the design and planning of communication systems, had been compared to ground site data on a global basis, and they were found to be sufficiently consistent to provide reliable solar and meteorological resource data over regions where surface measurements are sparse or nonexistent [4].

Raw point datasets for 22 years including air temperature, relative humidity and atmospheric pressure at 2 m and 10 m, averaged daily with attributes of geographic features (longitude and latitude), were extracted from NASA meteorological databank through Notepad basic text editor using text import wizard to delimit the general data format into numeric values and number. The data were assembled together in an attribute table created on the Microsoft Excel spread sheet. The data contained three variables including atmospheric pressure at 2 m and 10 m, temperature at 2 m and 10 m, and relative humidity at 2 m and 10 m. Data covering thirty-six meteorological stations in four climatic zones across West Africa within Latitude 3^o and 20^oN were used for the study.

Some tools were employed in the analysis of the meteorological data. The tools were Microsoft Excel 2007, ArcGIS 9.3 and Origin 6.1. Microsoft Excel was used to rearrange the meteorological data from text scripts to tabular format. The computation of dry and wet terms of surface refractivity at 2 m and 10 m was carried out using equations 3.0 and 4.0 respectively; Surface refractivity was calculated using equation 2.0. Estimation of gradients of surface refractivity was carried out with the aid of Microsoft Excel using equation 8.0. The results were averaged for dry and wet seasons, monthly and annually. Mean values and standard deviations of the parameters calculated were also estimated in each climatic zone for a period of 22 years (1983 – 2005). Origin was used to plot the graphs and to carry out statistical analysis of the plots to be able to deduce the spatial and temporal variations of the parameters calculated.

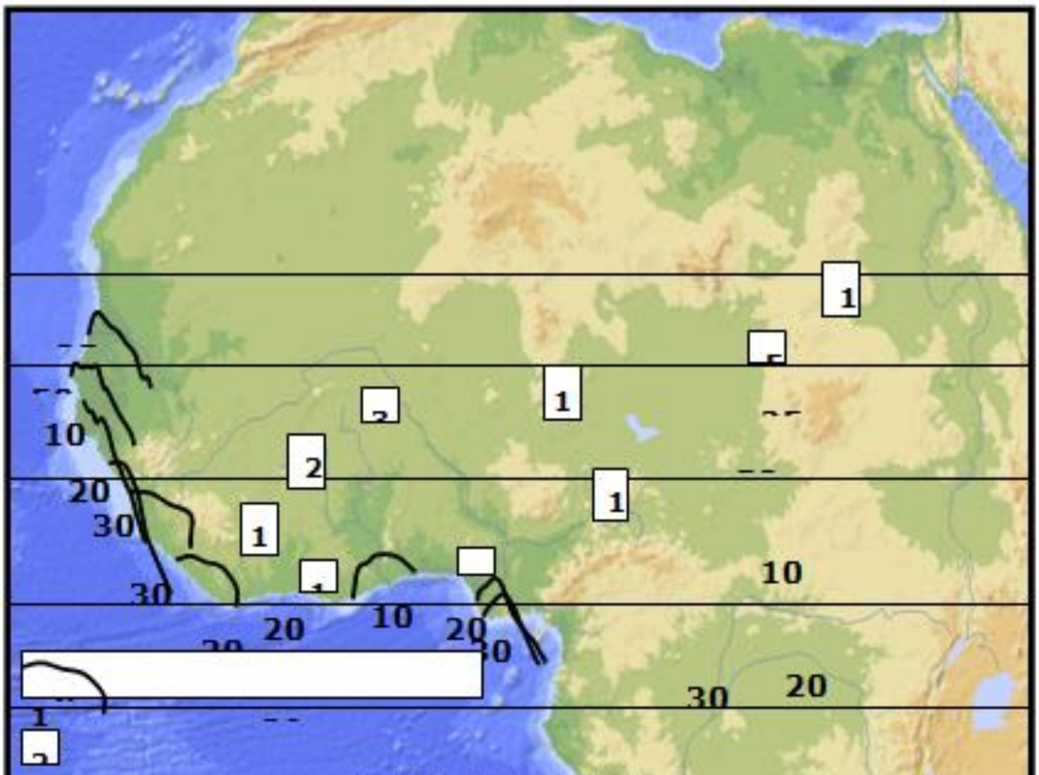

Figure 1: Rainfall Distribution in Climatic Zonesacross West Africa [7]

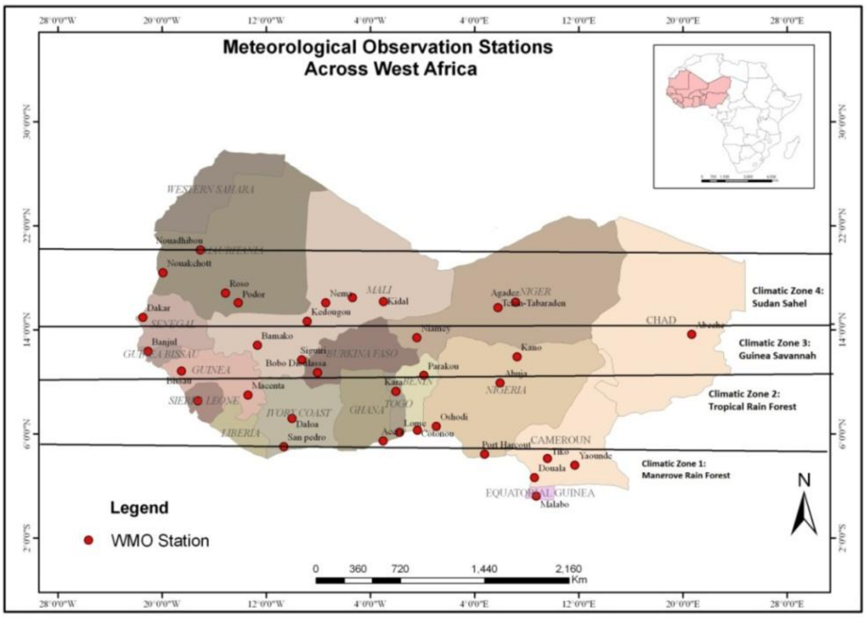

Figure 2: The Selected WMO Meteorological Stations in West Africa

IV. Results and Discussion

4.1 Monthly Variation of Surface Refractivity Gradient and Precipitation for Different Climatic Zones across West Africa

Table I showed the monthly averages of Surface Refractivity Gradient (SRG) from 1983 – 2005 estimated from satellite dataset. The results are compared with the values published from ground stations by Willoughby *et al.*, [14]. In zone 2, annual average of SRG was 52.6 N-Units/km and 49.4 N-Units/km from ground and satellite stations respectively. Other zones are 45.4 N-Units/km and 39.0 N-Units/km in zone 3; 39.0 N-Units/km and 31.5 N-Units/km in zone 4. The ground station results were of higher values than satellite results in dry months while satellite results were higher in wet months than results from ground stations.

The percentage difference between previous ground measured and calculated values from satellite dataset was 9.83% in zone 1, 16.4% in zone 3, and 23.80% in zone 4. Surface Refractivity Gradient results from ground station were not available for zone 2. The discrepancies in the measurement of meteorological parameters from ground and satellite stations, most especially relative humidity, were very conspicuous in the results. In the two results, zones 1 and 2 had a prevalence of super-refractivity characteristics while zones 3 and 4 had a prevalence of sub-refractivity characteristics.

Table I: Monthly Average and Standard Deviation of Surface Refractivity Gradient for different Climatic Zones across West Africa (1983 – 2005)

Month	Surface Refractivity Gradient (SRG)			
	Zone 1	**Zone 2**	**Zone 3**	**Zone 4**
Jan	46.7±8.2	41.1±13.1	16.5±7.7	7.1.±3.3
Feb	50.7±7.6	48.4±13.0	20.9±9.2	8.4±3.1
Mar	54.8±8.6	55.6±15.3	31.2±10.8	13.9±5.6
Apr	56.5±7.6	59.8±8.1	50.8±17.8	23.0±11.8
May	54.8±7.6	58.7±8.0	61.0±17.0	43.1±19.6
Jun	46.7±5.9	51.8±6.6	57.6±7.9	59.6±18.3
Jul	40.2±4.4	43.3±6.0	51.5±6.6	63.5±16.1
Aug	38.7±3.6	38.3±5.6	50.8±6.2	64.3±14.2
Sep	41.7±4.8	45.3±5.4	52.4±5.1	59.9±13.2
Oct	44.2±5.4	48.1±6.0	49.2±11.1	35.3±9.7
Nov	46.0±6.8	48.6±8.5	34.4±15.0	17.4±6.2
Dec	46.0±8.3	44.8±9.6	20.4±7.3	9.2±3.4
Annual Av	**47.8**	**49.4**	**39.0**	**31.5**

In figures 3 – 6, the monthly averages of Surface Refractivity Gradient (SRG) and precipitation for different climatic zones across West Africa were plotted. Generally, the plots showed a strong correlation between precipitation values and monthly averages of SRG across the climatic zones. High values of SRG were observed when there was increase in moisture due to precipitation, and it reaches the peak as the maximum value of precipitation was recorded in the zone. The rainfall pattern remains the major determining factor of SRG distribution across West Africa for different climatic zones.

In climatic zone 1 (as shown in figure 3), January - July and September - December had prevalence of super-refractivity characteristics while August was the only month that had sub-refractivity characteristics in climatic zone 1. The highest SRG of 56 N-Units/km (7.3 mm/day of rainfall) was observed in April while the least value of 38 N-Units/km (1.5 mm/day of rainfall) was noticed in August. Climatic zone 1 had annual SRG range of 18 N-Units/km. The precipitation data showed that the zone had two rainfall regimes with aslight break in July/August. This was responsible for sub-refractivity characteristics in August when Inter – Tropical Discontinuity (ITD) zone was in the farthest position from the coast.

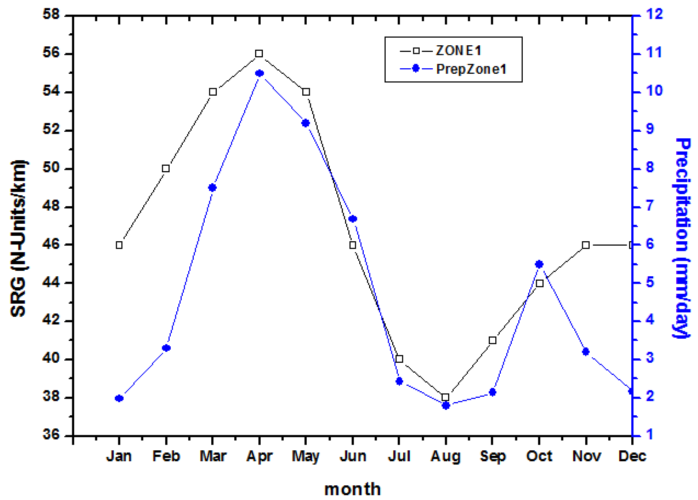

Figure 3: Monthly Variation of Surface Refractivity Gradient (SRG) and Precipitation for Climatic Zone 1 in West Africa (1983 – 2005)

In climatic zone 2 (as shown in figure 4), there was slight change in monthly variation of SRG when compared with climatic zone 1. SRG had the maximum value of 59 N-Units/km in April as at when the coverage of maritime airmass reaches between 6^oN – 9^oN. The minimum of 43 N-Units/km was observed in August as at when ITD reaches the northernmost location of between 18^oN – 24^oN. The minimum value of SRG was slightly sustained till the commencement of the migration of tropical airmass towards the south in December. The zone has unique characteristic of high elevations thereby giving rise to significant spatial variation of moisture distribution within the zone. The annual range in SRG was 19 N-Units/km. Climatic zone 2 was generally super-refractive from January to December. This was in agreement with values already obtained in Akure showing that super-refractivity was prevalent [3]. In zones 1 and 2, a slight depression in average SRG during the wet months was observed in August. This coincides with a brief reduction of rainfall. During this period, water vapour pressure is at the lowest value; consequently, the value of SRG falls.

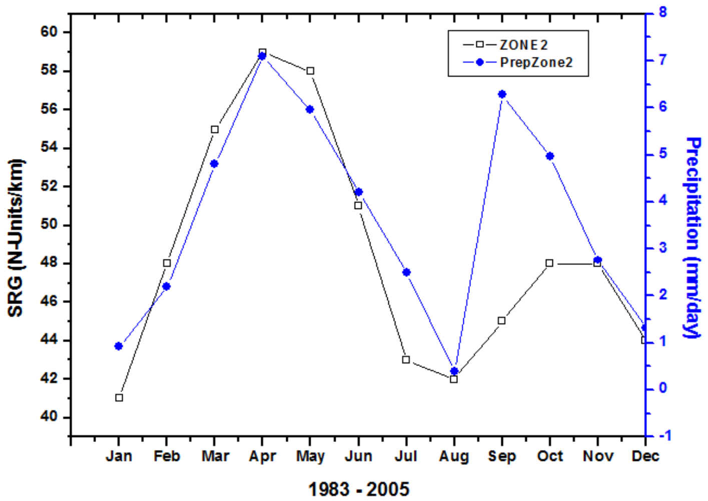

Figure 4: Monthly Variation of Surface Refractivity Gradient (SRG) and Precipitation for Climatic Zone 2 in West Africa (1983 – 2005)

In climatic zone 3 (as shown in figure 5), high amount of precipitation was recorded within July and September. Sub-refractivity characteristic was observed between January - March and from November - December. Super-refractivity was noticed from April - October. SRG has maximum value of 63 N-Units/km in May (8 mm/day) while the minimum SRG value of 15 N-Units/km was recorded in January (0.1 mm/day). The annual range of SRG was 49 N-Units/km. The climatic zone had a significant wide seasonal variation each year due to short duration of precipitation in the zone.

In climatic zone 4 (as shown in figure 6), sub-refractivity characteristic was observed from January - April and from October - December while super-refractivity occurred between May - September. A quick increase in the value of SRG (22 N-Units/km) was observed between April and May while a sharp decrease (25 N-Units/km) was noticed between September and October. The quick increase was due to ITD migrating closer to latitude 15°N while sharp decrease was observed as ITD retreats southwards in September.

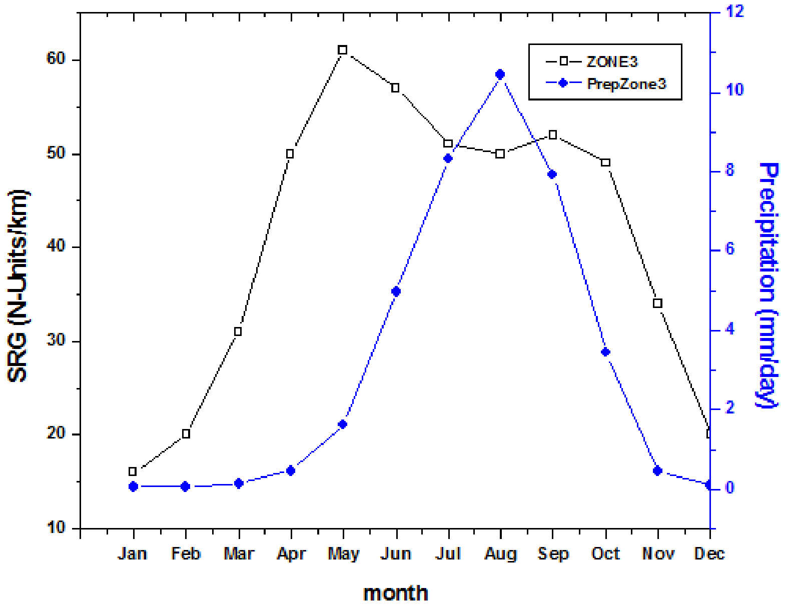

Figure 5: Monthly Variation of Surface Refractivity Gradient (SRG) and Precipitation for Climatic Zone 3 in West Africa (1983 – 2005)

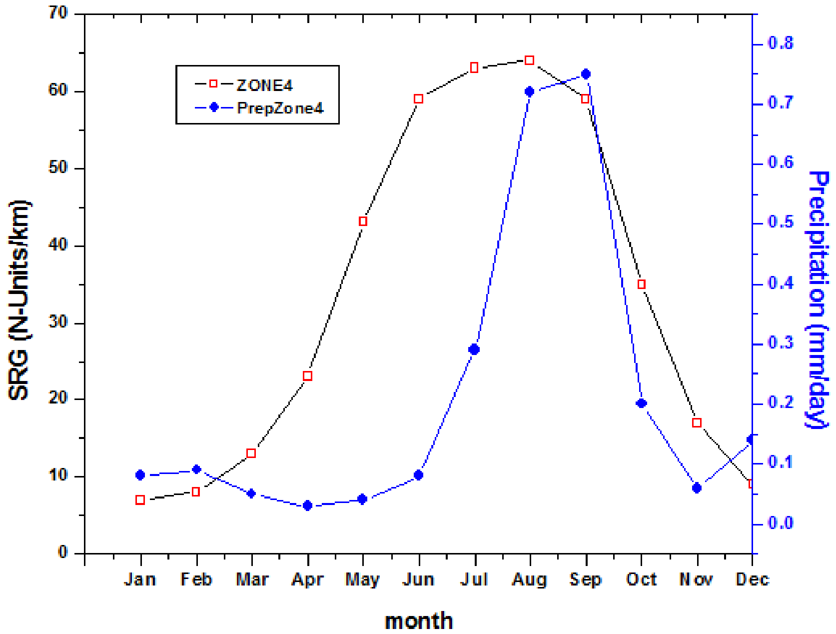

Figure 6: Monthly Variation of Surface Refractivity Gradient (SRG) and Precipitation for Climatic Zone 4 in West Africa (1983 – 2005)

Climatic zone 4 had the least precipitation of less than 1 mm/day and the widest seasonal range of SRG in West Africawhile the climatic zone 1 had the least seasonal range. In zone 4, the maximum monthly average of 64 N-Units/km was observed in August when ITD is within 18^{o}N – 24^{o}N. The least SRG value of 7 N-Units/km was observed in January (0.1 mm/day) while the annual range of SRG within the zone was 57 N-Units/km.

The monthly variation of SRG over the years in climatic zones 1 and 2 followed similar trend with the characteristic of dryness caused by August break and the dryness almost equal to peak of dry season (in January). Late rainfall was observed in climatic zones 3 and 4 and the duration was shorter than climatic zones 1 and 2. There was no characteristic of August break.

4.2 Annual Variation of Surface Refractivity Gradient and Precipitation for Different Climatic Zones across West Africa

Figures 7 – 10 showed the annual averages of SRG for different climatic zones across West Africa. Climatic zone 1 was entirely super-refractive throughout the period. 43 N-Unit/km was the least annual average of SRG observed in 1986 while the highest of 51 N-Units/km was observed in 1998. In figures 7 and 8, climatic zones 1 and 2 had the highest annual averages of SRG over West Africa due to very small vertical temperature and moisture difference throughout the years.

Climatic zone 2 was also super- refractive throughout the period but higher in values compared with climatic zone 1. 45 N-Units/km was the least annual average of SRG observed in 1986 and the highest of 52 N-Units/km were observed in 1987 and 1998.

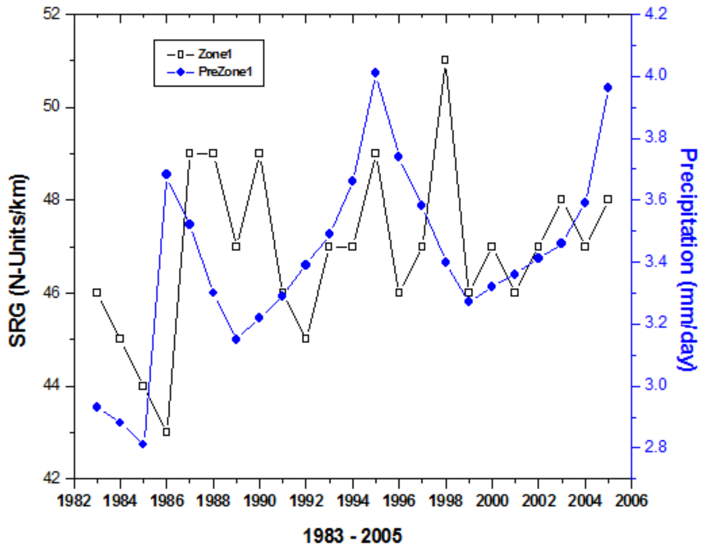

Figure 7: Annual Variation of Surface Refractivity Gradient (SRG) and Precipitation for Climatic Zone 1 in West Africa

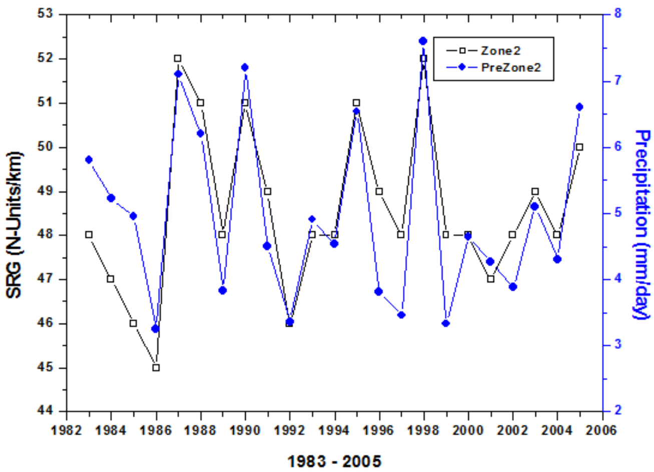

Figure 8: Annual Variation of Surface Refractivity Gradient (SRG) and Precipitation for Climatic Zone 2 in West Africa

In figure 9, climatic zone 3 had sub-refractivity characteristic in 1984, 1985, 1986, 1989, 1992, 1994, 1999, 2001, and 2002. The remaining years within 1983 – 2005 were super-refractive. Zone 3 was the only climatic belt in West Africa with both super-refractivity and sub-refractivity characteristics in annual averages. 38 N-Units/km was the least SRG observed in 1986 and 1994 while the highest of 45 N-Units/km was observed in 2005. In figure 10, climatic zone 4 was entirely sub-refractive throughout the period contrary to super-refractivity in climatic zone 1 and 2. 31 N-Units/km was the least annual average of SRG observed in 1992, 1993, and 2004 while the highest of 37 N-Units/km was observed in 1987. Climatic zone 4 had the least annual average of SRG over West Africa while climatic zone 3 was slightly higher than climatic zone 4.

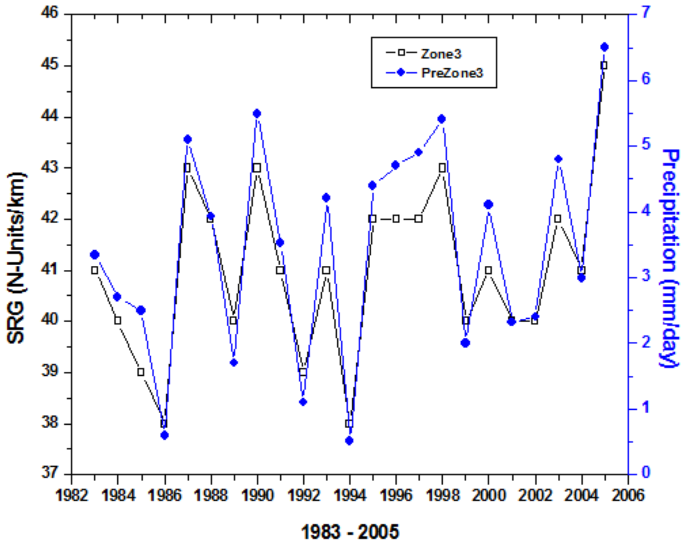

Figure 9: Annual Variation of Surface Refractivity Gradient (SRG) and Precipitation for Climatic Zone 3 in West Africa

SRG characteristic was tilted towards super-refractivity in the climatic zone 4 as shown in figure 10. The variations in SRG are as a result of moisture distribution and are very significant over West Africa because of the considerable change in climatic condition from the coastal region down south to the arid region in the extreme north. The annual averages across West Africa were observed to be highly susceptible to both super-refractivity and ducting at the coast. The sea breeze circulations responsible for the differential heating of land and sea causes warm air over land to become less dense and rise up giving way to cool moist air flowing in from the sea into land. This exchange of the thermally different air produces ground-based temperature inversion associated with large humidity lapse rate resulting in the formation of super-refractivity layers in zones 1 and 2 from Latitudes 3^0N - 10^0N.

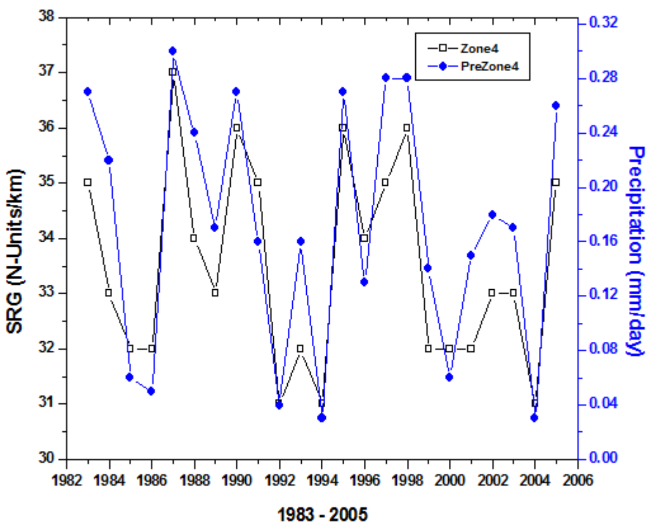

Figure 10: Annual Variation of Surface Refractivity Gradient (SRG) and Precipitation for Climatic Zone 4 in West Africa

The harmattan period over West Africa, which falls between November and February, favours both super-refractivity and trans-horizon propagation at VHF; this season represents the impact of dust particle from desert on tropospheric propagation. The probability of super-refractivity characteristic at higher latitudes 10^oN – 20^oN is rare compared with the prevalence of super-refractivity in latitudes 3^oN – 10^oN. The probability of super-refractivity characteristic occurrence is generally higher during rainy season than in dry season.

V. Conclusion

Monthly and Annual variations of SRG over West Africa for different climatic zone were estimated. The values were compared with precipitation values and the plots showed strong correlation of high values of SRG when precipitation is high and low values of SRG when precipitation is low. The intensity of rainfall across West Africa remains the strong determining factor of SRG spatial and temporal distributions for different climatic zones. Climatic zone 1 had prevalence of super-refractivity characteristic except in July and August and climatic zone 2 was super-refractive throughout the year. In climatic zone 3, dry months had sub-refractivity while wet months had sub-refractivity characteristics. Climatic zone 4 was entirely sub-refractive.

Climatic zones 3 and 4 had sub-refractivity while climatic zones 1 and 2 had super-refractivity characteristics in dry months. SRG variations in all the climatic zones were influenced by topographical features and the prevailing atmospheric conditions which is dependent on the seasonal north – south movement of the Inter – tropical discontinuity. The harmattan season across West Africa, which falls between November and February favours both sub-refractivity and trans-horizon propagation at VHF. The season represents the impact of dust particle from desert on tropospheric propagation. The spatial and temporal variations of Surface Refractivity Gradient for different climatic zones across West Africa offer empirical reference for tropospheric wave propagation, radar measurement and evaluation of amplitude scintillation for satellite communication in West Africa.

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