International Journal of Electronics Communication and Computer Engineering
Volume 6, Issue 2, ISSN (Online): 2249–071X, ISSN (Print): 2278–4209

Long-Term Average of Effective Earth Radius Factor Over West Africa Using Satellite Meteorological Dataset

Ajileye, O. O
email:ajileyeseun@rocketmail.com

Abstract: **For microwave link design, a parameter such as the Equivalent Earth Radius factor, (k-factor) must be set carefully to optimize its linkage and performance. It is therefore important to evaluate clearances from path obstructions over a wide range of k-factor in order to determine whether adequate path clearances are maintained under various degrees of refraction. Raw point datasets for 22 years (1983 – 2005) including air temperature, relative humidity and atmospheric pressure at 2 m and 10 m, averaged daily were extracted from National Aeronautic Space Administration meteorological databank through Notepad basic text editor using text import wizard to delimit the general data format into numeric values and number. Monthly and annual averages of equivalent earth radius factor (k-factor) were estimated for different climatic zones over West African continental areas. Results from satellite dataset were compared with results from in-situ measurements and the reliability of satellite dataset in the estimation of k-factor that are close to actual values was validated. Climatic zone 2 had average k-factor of 1.45 and 1.51 in satellite and ground stations respectively. Zone 3 had 1.37 and 1.42 in satellite and ground dataset while zone 4 had 1.31 and 1.34 in satellite and ground dataset.**

Keywords: **Climatic Zones, Equivalent Earth Radius Factor, Satellite Meteorological Dataset, West Africa.**

I. INTRODUCTION

For proper planning of terrestrial and earth-space radio links, it is necessary to have appropriate procedures for assessing refractivity effects on radio signals. Over predictions of the refractivity variations can result in a costly overdesign of a system, on the other hand, under prediction results in the design of an unreliable system. Radio waves may bend while propagating through different atmospheric layers due to variations of refractivity (Tamosiunas *et al.*, 2006). For microwave link design, a parameter such as the Equivalent Earth Radius factor, (k-factor) must be set carefully to optimize its linkage and performance. The k-factor, which is directly related to the vertical gradient of surface refractivity, is the radius of a hypothetical spherical earth for which propagation paths follow straight lines, the heights and ground distances being the same as for the actual earth in an atmosphere with a constant vertical gradient of refractivity (Zilinskas and Tamosiunas, 2008).

The k-factor describes the bending of the wave front relative to the true earth radius. The refractive index can change drastically with time and thus cause the microwave beam between path endpoints to "bend" to a greater or lesser extent. In fact, it may "bend" in an upward or a downward direction, depending on the value of k-factor at the time. It is therefore important to evaluate clearances from path obstructions over a wide range of k-factor in order to determine whether adequate path clearances are maintained under various degrees of refraction (Afullo and Odedina 2008).

Often, three values of k-factor are used in the calculations. Two of the three values describe the limits or boundaries of refraction that might occur (although with anomalous conditions, values exist outside these limits), while the third describes what is considered "normal" or expected. The value of k-factor at infinity depicts "super-standard" atmosphere and is one extreme where the wave front follows the true curvature of the earth(ITU-R, 2001).

The other extreme value of k-factor typically used is two-third and is termed "sub-standard" atmosphere. It is also a condition commonly referred to as "earth bulge." The median value of k-factor which is equal to 1.33 is used to evaluate the path under "normal" atmospheric conditions. The various Equivalent Earth Radii represented by the different values of k-factor correspond to the refractive conditions where k = ∞, k = 4/3 and k = 2/3(Afullo and Odedina 2004). Elevations of terrain features between path endpoints using the flat baseline as a reference can be deduced from these values. Elevation of all terrain features are added to that of the bowed baseline reference. The profile makes it possible to see if there is sufficient path clearance over the terrain for each value of k-factor (Palmer and Baker, 2004).

II. THEORETICAL BACKGROUND FOR ESTIMATING EQUIVALENT EARTH RADIUS FACTOR

The International Telecommunication Union(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 ITU-R, (2001):

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

N is the surface refractivity expressed by

$$N = N_{dry} + N_{wet} = \frac{77.6}{T}\left(P + 4810\,\frac{e}{T}\right) \tag{2}$$

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The statistics of the vertical gradient of surface refractivity in 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 (Otolia and Marian, 2004). The gradient of surface refractivity, SRG, can be calculated using

$$\Delta N = N_1 - N_2 \quad (3)$$

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

The k-factor can be calculated from Snell's law in spherical geometry. This value is multiplied by the actual earth's radius, a, in order to plot the propagation paths as straight lines, it follows that (Serdega and Ivanovs, 2007):

$$k = [1 + a\Delta N \times 10^{-6}]^{-1} \quad (4)$$

a is the radius of the earth (≈ 6380 km) and ΔN is Surface Refractivity Gradient.

III. PREVIOUS RESULTS OF K-FACTOR OVER NIGERIA

Seasonal variation of the monthly mean of surface refractivity gradient and k-factor) from in-situ measurements of meteorological variables (temperature, relative humidity and atmospheric pressure) for stations in different climatic zones across Nigeria had been determined by Willoughby *et al.*, (2002). The results covered the dry and wet seasons occurring in different climatic zones over Nigeria. The results are shown in Table I. The rainy season is from March to October while the dry season is from November to February. Results from satellite-based meteorological dataset would be compared with these results with a view to determine possible variations.

Table I: Annual Average of k-factor Estimated from Ground Station Data

Average	Oshodi	Zaria	Sokoto
Annual	1.51	1.42	1.34
Dry months	1.54	1.31	1.26
Wet months	1.48	1.49	1.39

IV. DATA SOURCE AND PROCEDURES OF ANALYSIS

In this work, the West Africa continental areas, within Latitude 3° and 20°N, have been partitioned into four climatic zones (as shown 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. 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). The 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 (Duchame *et al*, 2000).

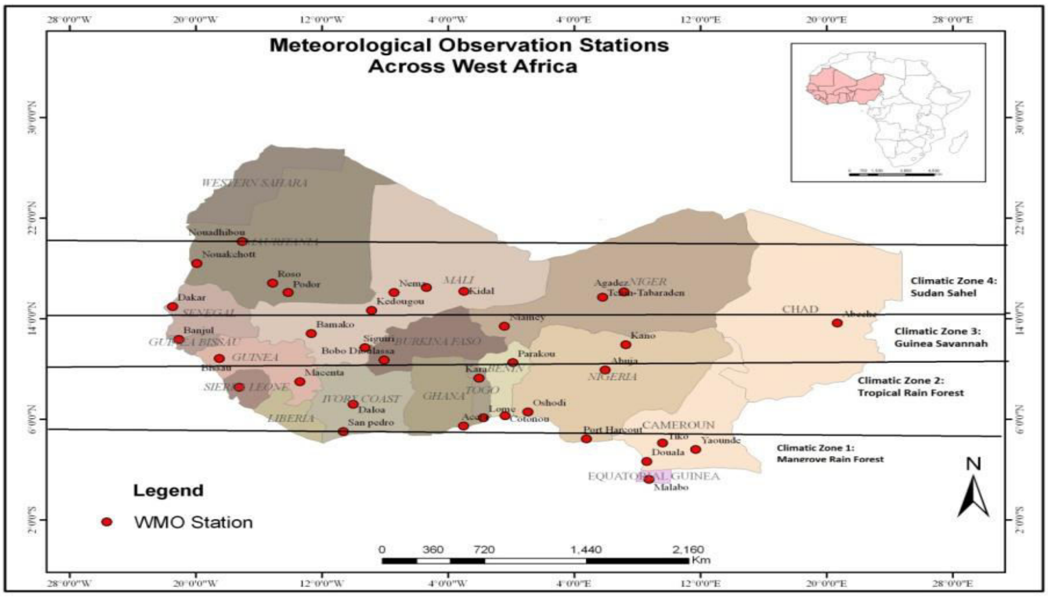

Figure 1: Map of West Africa showing the Study Location

Raw point datasets for 22 years (1983 – 2005) 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.

Equation 2.0 was employed to calculate surface refractivity; the gradients of surface refractivity were estimated using equation 3.0 while k-factor was estimated using equation 4.0. The annual averages of k-factor were obtained from monthly averages while the overall average for a period of 22 years (1983 – 2005) was obtained for each station in each climatic zone. The overall averages for each year and month within the period 1983 – 2005 were also deduced from the estimated values. The results were plotted to deduce the monthly and annual variation patterns of k-factor.

V. MONTHLY VARIATION OF K-FACTOR FOR DIFFERENT CLIMATIC ZONES ACROSS WEST AFRICA

Monthly averages of k-factor for different climatic zones across West Africa are shown in Table II. Also, figure 2 shows the monthly variation of k-factor for different climatic zones across West Africa. In December, January and February, k-factor decreased as latitude increases from climatic zones 1 to 4; in March, April and November, k-factor decreased from climatic zones 1 to 4 except in zone 2. In May and October, k-factor increased as latitude increases except in climatic zone 4; from June to September, k-factor increased from climatic zone 1 to 4 as latitude increases from 0^o to 20^o N.

When k-factor increases (k > 1.33), the effective flattening of the equivalent earth's curvature increases, this was observed during wet months in climatic zones 3 and 4. This characteristic was dominant in climatic zone 2. One of the conditions which may cause this type of abnormal refraction is the passage of warm air over a cool body of water. Water evaporation causes an increase in moisture content and a decrease in temperature near surface, thus producing a temperature inversion. But, it is not only the temperature inversion itself which causes the abnormal bending of the microwave beam.

Table II: Monthly Averaged k - factor for different Climatic Zones across West Africa (1983 – 2005)

Month	**Equivalent Earth Radius factor (k - factor)**			
	Zone 1	**Zone 2**	**Zone 3**	**Zone 4**
Jan	1.42	1.35	1.11	1.05
Feb	1.47	1.44	1.15	1.05
Mar	1.53	1.54	1.25	1.09
Apr	1.56	1.60	1.47	1.17
May	1.53	1.59	1.64	1.38
Jun	1.42	1.48	1.57	1.60
Jul	1.34	1.38	1.48	1.67
Aug	1.32	1.37	1.47	1.69
Sep	1.35	1.40	1.50	1.60
Oct	1.39	1.44	1.45	1.29
Nov	1.42	1.44	1.28	1.12
Dec	1.42	1.39	1.15	1.06
Annual Av	1.43	1.45	1.37	1.31

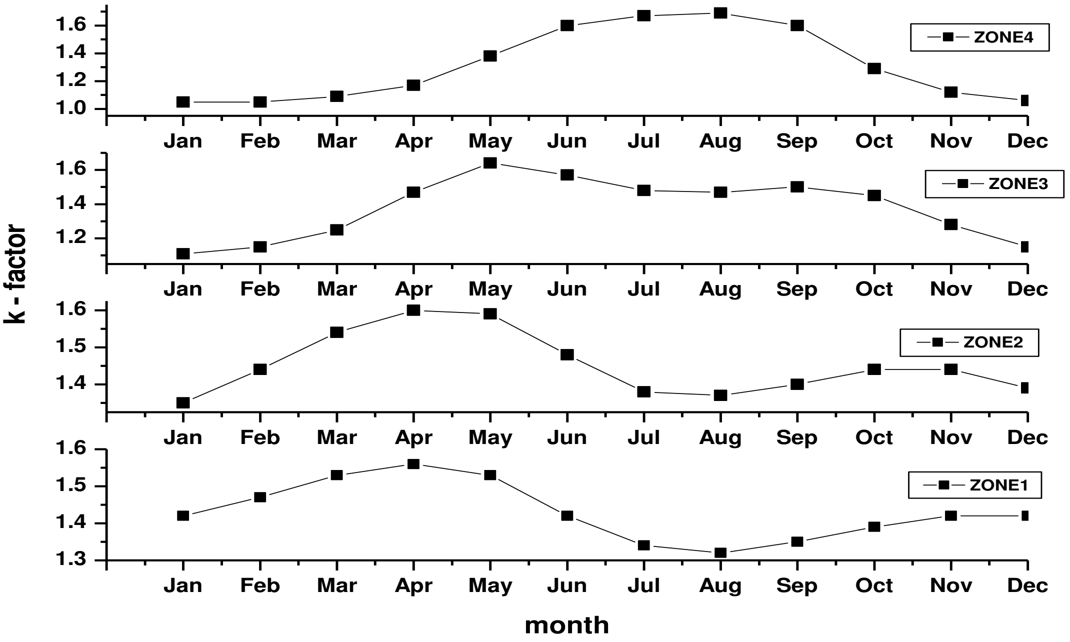

Figure 2: Monthly Variation of Equivalent Earth Radius factor (k-factor) for different Climatic Zones across West Africa

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The large increase in water vapour content and, hence, in the dielectric constant near the surface further increases this effect. This condition was observed in climatic zones 1 and 2 throughout the period except in August. This characteristic was also observed from April – October in climatic zone 3 and May – September in climatic zone 4. The k-factor, in sub-refractive condition, (when $k < 1.33$) causes dielectric constant to increase with height. This condition causes an upward curvature of the microwave beam often called inverse beam bending. This unusual refractive condition is also called earth bulging.

This condition occurs less frequently than superrefraction in the coastal areas. If substandard refraction causes path blockage for a total of only 1.4 minutes a day, the microwave reliability considering outages due to this alone will be reduced to 99.9 percent if suitable clearance is not provided. This may exist when a low fog is formed by nocturnal cooling of the ground, since the contribution to the increase of the atmospheric dielectric constant due to water in the form of droplets is much less than that due to water in the form of vapour.

The dielectric constant will then be lower near the ground than at higher elevations, causing an upward bending of the rays. At low values of k, the rays will be bent in such a way that the earth appears to obstruct the direct path, giving rise to diffraction fading. When $k > 1$, the ray beam is bent toward the earth, which essentially allows the shortening of radio-link towers. If $k < 1$, the earth bulge is effectively increased and the path of a propagating signal in the zone is shortened. This characteristic was observed in August in climatic zone 1; January – March and November – December in climatic zone 3; January – April and October – December in climatic zone 4.

VI. ANNUAL VARIATION OF K-FACTOR FOR DIFFERENT CLIMATIC ZONES ACROSS WEST AFRICA

The annual averages of the k-factor across climatic zones in West Africa were observed to have higher values in ground data as presented in Table 2 than the results from the satellite dataset presented in figure 3. The percentage difference was 5.59% in zone 1, 3.64% in zone 3, and 6.10% in zone 4. In both cases, the annual averages of k-factor decreased with increasing latitude. The reliability of satellite dataset in the estimation of k-factor that are close to actual values was validated. Climatic zone 2 had average k-factor of 1.45 and 1.51 in satellite and ground stations respectively. Zone 3 had 1.37 and 1.42 in satellite and ground dataset while zone 4 had 1.31 and 1.34 in satellite and ground dataset.

The annual averages of k-factor across West Africa for different climatic zones are shown in figure 3. The least annual average is 1.38 in 1986 and the highest value is 1.48 in 1998 for zone 1. The least annual average is 1.40 in 1986 and the maximum of 1.50 occurred in 1987 and 1999 respectively in zone 2. Climatic zone 3 had the least annual average of 1.32 in 1986 and 1994 and the maximum of 1.40 in 2005. Climatic zone 4 had the least annual average of 1.25 in 1992, 1994, and 2004 and the maximum of 1.31 in 1987. The k-factor decreased in annual average from climatic zone 1 to climatic zone 4. The annual averages decreased as the latitude increases. The k-factor depends upon the refractivity gradient and subject to short and extreme variations with wind, clouds, and moisture. These variations are estimated from limited statistical information and are important because they cause fading.

The variations of k-factor are usually smaller in high altitudes and dry areas but greater in low latitudes and humid areas. The effect of the changes in k-factor leads to wide fluctuation in path clearance from excessive as k-factor approaches infinity to possibly grazing or less as k-factor drops to 0.5. For the proper planning of terrestrial and earth-space radio links, it is necessary to have appropriate procedures for assessing the refractivity effects on radio signals. The k-factor actually varies between 1 and 2 with lower values existing in cold, dry climates and high altitudes. The higher values of k-factor are common in warm, wet coastal areas where the humidity is high.

VII. CONCLUSION

The spatial and temporal variations of k-factor for different climatic zones across West Africa were calculated. In January, February and December, the k-factor decreased as latitude increases. Spatial variation of k-factor was found to be dependent on the prevalent weather condition in each month, a general trend of decrease in k-factor was observed in dry season and a general trend of increase was observed in wet season from coast to inland stations. It was observed that k-factor depends on the Surface Refractivity Gradient and is subject to short and extreme variations with wind, clouds, and temperature. Although these variations are estimated from limited statistical information, they are important because they cause fading.

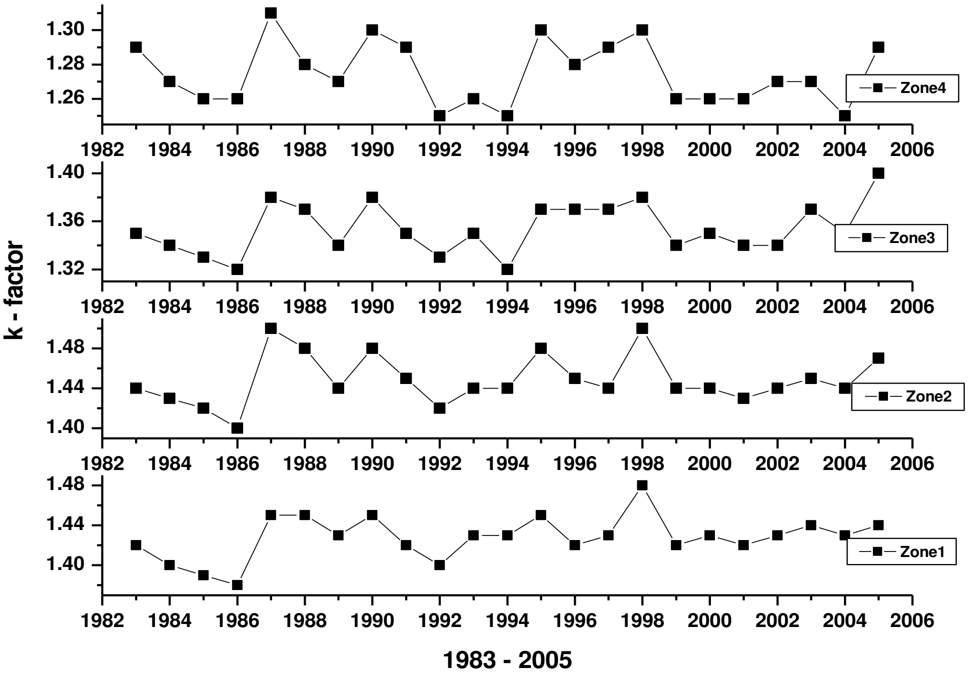

Figure 3: Annual Variation of Equivalent Earth Radius factor (k-factor) for different Climatic Zones across West Africa

ACKNOWLEDGEMENT

The author would like to thank the National Aeronautics and Space Administration for providing meteorological datasets used to conduct his study most especially for locations where there was no archived data. I also would like to thank my academic progenitors – Prof. O. O. Jegede and Dr. S. A. Adeniran – of Obafemi Awolowo University, Ile-Ife, for their painstaking mentoring and immense scientific contributions to the study. I am greatly indebted to them forever.

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AUTHOR’S PROFILE

Ajileye Oluwaseun Olasunmbo born in Ile – Ife, Southwest Nigeria on 23rd December, 1975. He had his first degree in Physics Education in 2001. He also had M.Sc. and Ph.D degrees in 2007 and 2014 respectively all from Obafemi Awolowo University, Ile – Ife. The area of his specialization is Atmospheric Science studies (troposphere).

He is presently a Principal Scientific Officer at Advanced Space Technology Applications Laboratory – one of the centers under National Space Research and Development Agency – in Obafemi Awolowo University. He is presently carrying out research in the areas of climate change and weather phenomena over West Africa using satellite captured data.

Dr. Ajileye is the editor – in – Chief of a scientific magazine published annually by Advanced Space Technology Applications Laboratory. It focuses on applications of Remote Sensing and Geographic Information System in natural resources inventory and climate studies. He has authored four publications in reputable journals.

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