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Mathematical Modeling of a UHF Signal's Propagation Curve

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ABSTRACT: This work takes rigorous measurement of the Received Signal Strength (RSS), Elevation (ELV) and Line of Sight (LOS) from a base station (UHF television channel 23 transmitter on Lat. 7.304^{0}N and Long. 5.161^{0}E) in Akure, Ondo State, Nigeria using a Signal Level Meter and a Global Positioning System (GPS) receiver respectively. Data collected along the two routes (Ondo North and Ondo South) were analyzed using both Regression and Correlation Analyzes. Along route A (from base station towards Ondo North), the result showed a moderate positive non-significant relationship (0.4228) between the Line of Sight and Elevation, a negative significant relationship between the Line of Sight and the Signal Strength and a low positive insignificant relationship between Elevation and Signal Strength. For route B (from base station towards Ondo South), the analysis carried out showed that there is a very high significant negative correlation (-0.9599) between the Line of Sight and Elevation, a relatively high negative correlation of -0.8321 for the relationship between the Line of Sight and Signal Strength and a very high significant positive correlation between Elevation and Signal Strength along the route implying significant increase in the signal strength as the elevation increases along the route. The regression models obtained for both routes are significant. The derived mathematical models that can be used to calculate the Received Signal Strength (RSS), for route A and B, for given values of Elevation (ELV) and Line of Sight (LOS) are given respectively as RSS_A and RSS_B;

$$RSS_A = 20.8643 - 0.5158LOS + 0.1157ELV$$

$$RSS_B = 7.3929 - 0.0012LOS + 0.1379ELV$$

The overall general model that can be used to predict the Received Signal Strength (RSS) across the state is given as; $RSS_G = 14.1286 - 0.2585LOS + 0.1268ELV$ which is the mean of the two derived models along the routes. These findings would be useful for radio wave propagation and reception on the UHF channel in the study areas in particular and in other similar environment in Nigeria.

KEY WORDS: *Mathematical Modeling, Signal Strength, Elevation (ELV), Line of Sight (LOS)*

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I. INTRODUCTION

Propagation curve is an essential parameter in radio wave propagation theory and equipment design. It is the variation of the electric field strength of a radio signal with distance [1]. It helps to predict the Received Signal Strength (RSS) [2] from locations away from the transmitter. It depends on transmitter power, the nature of signal path (rural or urban) and the terrain of the locations involved (see [3] - [4]). It is used for radio propagation planning and equipment design (see [3]-[5]). Since 1963, the VHF/UHF propagation curves which have been in use for international planning are those published by the (ITU-R). The curves depict the decay of field strength with distance for a range of transmitting antenna heights, the latter being defined in terms of the altitude of the antenna above the mean height of the terrain within the range 3 to 15km of the transmitting mast [6]- [9].

Transmission of signal on the UHF broadcast band is by space wave which propagates on line of sight from the transmitter through the troposphere. Thus, the signal received at locations away from the transmitter could be the direct transmitted wave, the reflected wave or the diffracted wave [7]. This is due to the effect of terrestrial objects on the propagation path as given in [7] - [8]. Other factors that determine the quality of signal received from the transmitter on the UHF band include: transmitter output power or the effective isotropic power of the transmitter (EIRP), transmitting antenna height, and the nature of the signal path [9]. Others are transmitter-receiver distance and elevation of the receiver, the gain of the receiving antenna and the quality of the receiver (see [4]-[9]). There is also the attenuation effect on UHF signal caused by precipitation [7] and foliage [10].

This work was conceived to investigate the received signal strength with a view to generate the mathematical modeling for the propagation curve for a UHF broadcast channel in Ondo State, Nigeria. Findings from this work are very important for radio wave propagation, channel estimation and equipment design on the UHF band by radio scientists and engineers. Propagation curves can help at predicting the power received or lost at a given distance from the transmitter which is useful in path loss calculation and modeling. Among published works that had shown that path loss modeling plays a key role in coverage estimation are presented in [9], [11], and [12]). In addition, determination of coverage areas of broadcast stations has a significant influence on the socio-economic life of the populace in this part of the world [8] thus making it a good scientific feedback mechanism. Its findings would be useful for radio wave propagation and reception on the UHF channel in the study area in particular and other similar environment in general.

II. THEORETICAL BACKGROUND

2.1 Electromagnetic Waves

Electromagnetic waves are transverse waves. The electric and magnetic fields are perpendicular to the direction of propagation. They carry both the electric and magnetic energy of the wave. The electric and the magnetic fields are in phase. They are mutually perpendicular and their amplitudes are related by:

$$\bar{B}_0 = \frac{k}{\omega} E_0 = \frac{1}{c} E_0 \tag{1}$$

where k is the propagation constant, ω is the angular frequency of the wave, c is the speed of light in space and E_o is the magnitude of the electric field intensity.

In general for a sinusoidal wave, the variation of the electric field Intensity in space and time is represented as;

$$\bar{E}(r,t) = \frac{1}{c} \bar{E}_0 e^{i(k.r-\omega t)}.\hat{n} \tag{2}$$

and the magnetic field strength

$$\bar{B}(r,t) = \frac{1}{c} \bar{E}_0 e^{i(k.r-\omega t).(\hat{k}\times\hat{n})} \tag{3}$$

where $\hat{k}$ is the propagation vector, $\hat{n}$ is a unit vector in the direction of propagation of the wave called the polarization vector and r is the space coordinate.

The ratio of the electric field intensity to the magnetic field intensity is defined as

$$\frac{|E|}{|H|} = \frac{E_x}{H_y} = \sqrt{\frac{\mu_0}{\varepsilon_0}} = Z_0 \tag{4}$$

Where, Z_o is the wave impedance or characteristic impedance of the wave in free space $Z_0 = 377\Omega$

2.2 Power Density (The Inverse Square Law)

Power density is defined as the radiated power per unit area [3]. It is inversely proportional to the square of the distance from the source and directly proportional to the transmitted power [3]- [4]. That is, if the distance from a transmitter is doubled, the power density of the radiated wave at the new location is reduced to one-quarter of its previous value. [9] This is the inverse square law, which universally applies to all forms of radiation in free space.

Therefore,

$$P_d \alpha \frac{P_t}{r^2} \tag{5}$$

$$P_d = \frac{P_t}{4\pi r^2} \tag{6}$$

where, P_d is the power density at a distance r (m), from the transmitter, $P_{t(w)}$ is the transmitted power.

At distance r from the transmitter, the electric field strength is represented as;

$$|E| = \frac{\sqrt{30P_t}}{r} \tag{7}$$

|E | is in Volt/meter, r, is in meters and P_t is the power transmitted in watts. When the gain of the transmitting antenna is considered, then |E| becomes:

$$|E| = \frac{\sqrt{30P_tG_t}}{r} \tag{8}$$

G_t is the gain of the transmitting antenna measured in dB From (8), it is clear that the electric field strength value of a radio signal away from the transmitter is inversely proportional to the transmitter-receiver distance. This gives a good premise for mathematical modeling of the field strength and the line of sight (distance, r) which would be based on data collection of the necessary parameters needed for the modeling in the study areas.

2.3 Study Areas and the Experimental Station

Ondo State is one of the thirty six states in Nigeria located in the south west geo-political zone of the Country, with Akure as the State Capital. The State has eighteen local government areas and lies between latitude $7^0$10'north and longitude 5^0,05' east with a landmass of 15,300km^2. It has a population of 3,460,877 [13] and a population density of 220/km^2. The State is the largest producer of cocoa, and the fifth producer of crude oil in Nigeria. It has three major divisions- Ondo North, Ondo Central and Ondo South. The experimental station is the UHF channel 23 television station owned by the Ondo State government of Nigeria. It is the station with the highest transmitter power in the State on the UHF band (see [8]-[9]). Table 1, presents the characteristics of the experimental station.

Table 1. Characteristic of the experimental station

S/No.	Parameter	Height of receiving antenna (m)
1	Base station's location	Lat. 7.304^0 N, Long. 5.161^0 E
2	Base station transmitted power (W)	16,000
3	Base station frequency (MHz)	487.25
4	Transmitter in use	Harris 40kW UHF Sigma Diamond Drive
5	Height of transmitting mast (m)	333.0
6	Height of transmitting antenna (m)	18.30
7	Transmitting antenna gain (dB)	31.70
8	Height of receiving antenna (m)	1.80

III. MATERIALS AND METHOD

3.1 Instrumentation

A Digital Field Strength Meter, Dagatron TM10 was used for the field strength measurement, whereas a Global Positioning System Receiver (GPS Map 76 personal navigator) was used for the measurement of elevation, geographic coordinates and the line of sight of the various data locations from the base station. A field vehicle was used for the field campaign with the receiving antenna attached. Other accessories used were an I-Connector, Coaxial Cable, a Dual Dipole Receiving Antenna and the Administrative map of Ondo State for route guide.

3.2 Data collection and logging

Measurement of electric field strength of the Ondo State Radiovision Corporation (OSRC) Channel 23, Ultra High Frequency (UHF) Television Station was carried out radially from the base Station along different routes in the State using a digital field strength meter. However, for the purpose of this work, the two major routes from the base station in Akure towards the northern and southern parts would be concentrated on for the modeling work. Detail of the routes categorization is as presented in Table 2. The station's transmitting antenna located at Orita-Obele, Akure, was marked and used as the reference point using the GPS receiver for all the routes. The line of sight from the base station was monitored during the drive. The GPS equally measures the location's longitude, latitude, and the elevation.

In summary, the electric field strength values, geographic coordinates, elevation above sea level as well as the line of sight of the various data locations were recorded and collated for necessary analysis. Transmission Parameters were kept constant by the transmitting station throughout the period of measurement.

Table 2: Route definition for the field work

Route	Direction/ Definition
A	Transmission base in Akure towards Isua-Akoko (0-85km LOS)
B	Transmission base in Akure towards Okitipupa/Igbokoda (0-120km LOS)

IV. REGRESSION AND CORRELATION ANALYSIS

4.1 Regression

Regression deals with obtaining mathematical model that describes relationship between two or more variables. It is used to predict or estimate the value of one or more variables from given values of other variables related to it [14]. It is however necessary to visualize the data before determining appropriate regression model to be used. Various data transformations are available to choose from depending on the relationship existing between variables of interest. Regression Model could be simple linear, multiple, legit, probit, multivariate, etc. as in [15]. While simple linear regression is used for one dependent variable and one independent variable, multiple regressions involve establishing relationship between a dependent variable and several independent variables. Hence, multiple regressions is a logical extension of the simple linear regression which utilizes two or more independent variables to estimate values of the dependent variable.

Given ***n*** independent observations $X_1, X_2, \ldots, X_n$ and ***n*** dependent observations $Y_1, Y_2, \ldots, Y_n$.
in simple regression, the required model is of this form:

$$y = \beta_0 + \beta_1 x + \varepsilon \tag{9}$$

The variable ε represents the random error associated with the prediction of ***Y*** for a known or assumed value of X which is unpredictable. It is assumed that $E(\varepsilon) = 0$ Hence;

$$E(y) = \beta_0 + \beta_1 x + E(\varepsilon) = \beta_0 + \beta_1 \text{ i.e } \hat{Y} = b_0 + b_1 X \tag{10}$$

where b_0 is the intercept and b_1 is the slope or the regression coefficient,

$$b_1 = \frac{n\sum XY - \sum X \sum Y}{n\sum X^2 - \left(\sum X\right)^2} = \frac{\text{cov}\,arianceXY}{\text{var}\,ianceX} \tag{11}$$

$$b_0 = \frac{\sum Y - b_1 \sum X}{n} = \bar{Y} - b_1 \bar{X} \tag{12}$$

For multiple regression analysis, given ***k*** independent variables with ***n*** observations $X_{11}, X_{12}, \ldots, X_{1n}, \ldots, X_{kn}$ in ***n***x***k*** vector and ***n*** dependent observation $Y_1, Y_2, \ldots, Y_n$ in $n \times 1$ column vector, the multiple regression model is given by [16] as:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_m X_m + \mu \tag{13}$$

For ease of explanation, multiple regressions are preferably represented in matrix form:

$$\begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ . \\ . \\ . \\ Y_N \end{bmatrix} = \begin{bmatrix} 1 & X_{11}X_{12} & \ldots & X_{1n} \\ 1 & X_{21}X_{22} & \ldots & X_{2n} \\ . & . & \ldots & . \\ . & . & \ldots & . \\ . & . & \ldots & . \\ 1 & X_{k1}X_{k2} & \ldots & X_{kn} \end{bmatrix} \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \\ . \\ . \\ . \\ \beta_k \end{bmatrix} + \begin{bmatrix} \mu_1 \\ \mu_2 \\ \mu_3 \\ . \\ . \\ . \\ \mu_n \end{bmatrix} \tag{14}$$

i.e.

$$Y = X\beta + \mu \tag{15}$$

where,

$$E(\mu)=E\begin{bmatrix}\mu_1\\ \mu_2\\ .\\ .\\ .\\ \mu_n\end{bmatrix}=\begin{bmatrix}0\\ 0\\ .\\ .\\ .\\ 0\end{bmatrix} \quad (16)$$

$$\beta=(X'X)^{-1}.X'Y \quad (17)$$

In this research, (13) is used for the regression of RSS on ELV and LOS to be in this form:

$$RSS=\beta_0+\beta_1 LOS+\beta_2 ELV \quad (18)$$

4.1 Correlation

Correlation studies the degree of relationship between two or more variables. It is linear when all the points (X, Y) on scatter diagram seem to cluster near a straight line or non-linear if otherwise. It is positive correlation when the increase in the value of one variable tends to be associated with increase in the value of the other and vice versa. If increase in the value of one variable tends to be associated with decrease in the value of the other and vice versa, it is a negative correlation. Two variables are un-correlated when they tend to change with no correlation to each other. Several types of correlation coefficients exist for different forms of data. Karl Pearson's Product Moment Correlation Coefficient [17] used for continuous data is given by:

$$r=\frac{n\sum xy-\sum x\sum y}{\sqrt{\left[n\sum x^2-\left(\sum x\right)^2\right]\left[n\sum y^2\left(\sum y\right)2\right]}}=\frac{\operatorname{cov} XY}{\sqrt{\operatorname{var} X.\operatorname{var} Y}} \quad (19)$$

Bivariate correlation analysis of all possible pairs of variables (RSS-ELV, RSS-LOS, and ELV-LOS) using (19) is obtained in order to observe the degree and direction of relationships between the pairs.

V. RESULTS AND DISCUSSIONS

5.1 Results

Tables 3 and 4 present the data obtained for routes A and B respectively.

Table 3: Data obtained for Route A

S/No.	Location	Lat.(°N)	Long.(°E)	Line of sight (LOS) from Base Station (km)	Elevation ASL(m)	Signal Strength dBμV
1	Akure (At Base Station)	7.304	5.161	0.00	387.1	82.50
2	Sasa Akure	7.276	5.248	10.08	340.1	40.95
3	Ogbese I	7.273	5.340	20.00	341.9	41.70
4	Ogbese II	7.259	5.374	24.02	316.0	39.80
5	Uso	7.273	5.431	30.02	327.8	40.50
6	Owo I	7.237	5.517	40.00	321.7	39.10
7	Owo II	7.211	5.558	45.00	312.0	33.1
8	Owo III	7.198	5.585	48.32	353.2	46.00
9	Owo IV	7.222	5.606	50.00	289.8	23.85
10	Oba Akoko	7.357	5.703	60.10	293.6	30.95

11	AkungbaAkoko	7.480	5.737	66.58	363.3	32.65
12	Oka Akoko I	7.445	5.761	68.05	357.3	41.15
13	Oka Akoko II	7.448	5.797	72.00	569.9	60.10
14	Oka Akoko III	7.456	5.814	74.00	551.3	33.60
15	EpinmiAkoko	7.454	5.860	78.97	422.4	18.80
16	Isua Akoko	7.454	5.911	84.43	369.8	15.65

Table 4: Data obtained for Route B

S/No.	Location	Lat.(°N)	Long.(°E)	Line of sight (LOS) from Base Station (km)	Elevation ASL(m)	Signal Strength dBμV
1	Akure (Base Station)	7.304	5.161	0.00	387.1	82.50
2	Aponmu	7.233	5.106	10.00	312.3	49.90
3	Owena Eleshin	7.192	5.012	20.61	267.2	45.15
4	Bolorunduro –Ondo I	7.170	4.964	26.38	298.5	44.90
5	Oboto	7.164	4.929	30.00	264.3	40.05
6	Ondo I	7.112	4.855	40.01	270.5	53.70
7	Ondo II	7.099	4.842	42.01	258.5	40.95
8	Ondo III	7.110	4.824	43.50	247.5	20.00
9	Ondo IV	7.064	4.843	44.06	263.5	40.40
10	Bagbe	6.982	4.849	49.75	242.3	38.70
11	Asewele	6.860	4.856	59.78	160.4	16.20
12	Omifon	6.833	4.860	62.00	156.9	30.65
13	Odigbo	6.781	4.873	66.26	122.0	22.85
14	Ore I	6.753	4.874	69.03	92.6	15.40
15	Ore II	6.742	4.876	70.00	80.9	15.35
16	Ode Aye	6.670	4.820	80.00	37.3	15.31
17	Okitipupa I	6.607	4.749	89.91	21.5	15.30
18	Okitipupa II	6.545	4.747	95.99	48.0	27.90
19	Okitipupa III	6.505	4.759	99.41	50.9	16.50
20	Gbodigo	6.486	4.786	100.00	43.6	15.00

4.2 Mathematical modeling

From the analysis carried out on data for both routes, the tables and the figures below show the summary of the result. Fig. 1, presents the line graph of line of sight, elevation of locations in km and signal strength in dBμV along route A while Fig. 2, shows that of route B.

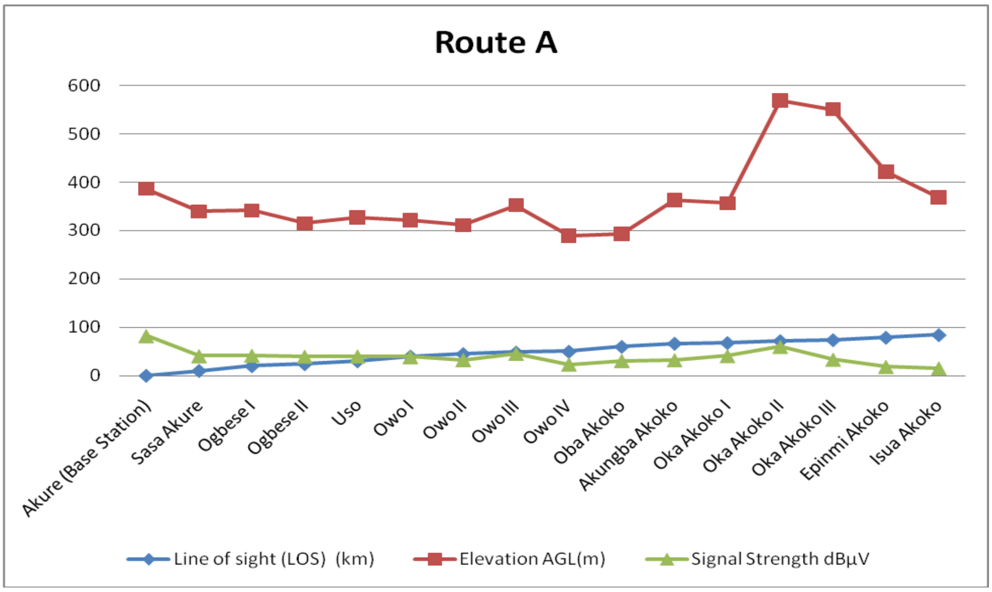

Fig. 1: Chart showing Elevation, Line of Sight, and Signal Strength for Route A

Table 5: Correlation Matrix for Route A

	LOS (km)	*Elevation (m)*	*Signal Strength (dbµV))*
LOS (km)	1		
Elevation (m)	0.4228 (0.103)	1	
Signal Strength	-0.5856 (0.017)	0.2444 (0.362)	1

Table 5 shows that there is a moderate positive non-significant relationship (0.4228) between the Line of Sight and Elevation along route A. A negative significant relationship exists between the Line of Sight and the Signal Strength. This implies that increase in Line of Sight reduces the Signal Strength along the route.
Table 5 also shows a low positive insignificant relationship between Elevation and Signal Strength indicating that there is a relatively low increase in the signal strength as the elevation increases along the route.

Table 6: Regression Table for Route A

	Coefficients	*P-value*	R^2	ANOVA (overall regression significance)
Intercept	20.8643	0.1109	0.6376	0.0014
LOS (km)	-0.5158	0.0005		
Elevation (m)	0.1157	0.0063		

The table of Regression of Signal Strength (RSS) on the Line of Sight (LOS) and Elevation (ELV) gives a coefficient of determination (R^2) 0.6376. This implies that 63.76 variations in the Signal Strength is jointly explained by the variation in the Line of Sight and the Elevation. Overall regression test (Analysis of Variance) shows a statistically significant regression model since the P-value (0.0014) is less than the specified level of significance (α = 0.05), hence, the acceptability of the model for predictive purpose. The model obtained is given by:

$$RSS = 20.8643 - 0.5158LOS + 0.1157ELV \quad (20)$$

The table reveals that all the regression coefficients are significant, supporting result obtained in the overall regression usefulness.

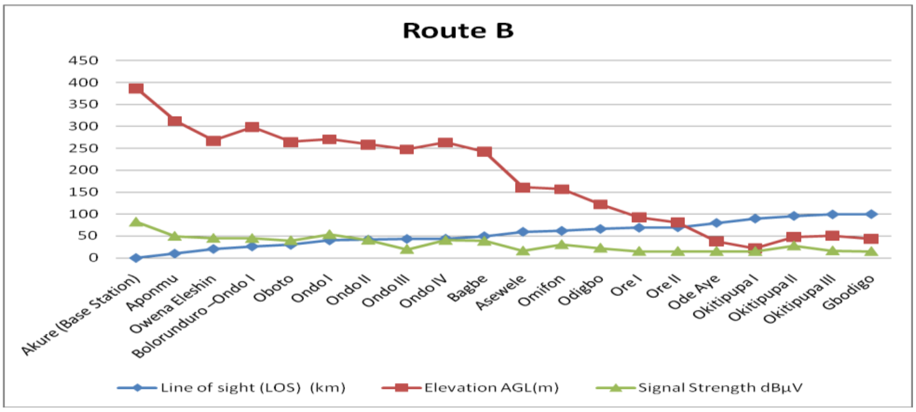

Fig. 2: Chart showing Elevation, Line of Sight, and Signal Strength for Route B

Table 7: Correlation Matrix for Route B

	LOS (km)	***Elevation (m)***	***Signal Strength (dbµV))***
LOS (km)	1		
Elevation (m)	-0.9599 (0.000)	1	
Signal Strength	-0.8321 (0.000)	0.8667 (0.000)	1

It is noted from the correlation matrix table for route B that there is a very high significant negative correlation (-0.9599) between the Line of Sight and Elevation along route B. This implies that as the elevation increases along the route, the strength of signal significantly reduces accordingly (elevation drops sharply in route B and the signal strength follows accordingly).
Also, a relatively high negative correlation of -0.8321 is observed for the relationship between the Line of Sight and Signal Strength. This also indicates that increase in the Line of Sight along route B is accompanied by decrease in the Signal Strength. There is however a very high significant positive correlation between Elevation and Signal Strength along the route implying significant increase in the signal strength as the elevation increases along the route.

Table 8: Regression Table for Route B

	Coefficients	*P-value*	R^2	ANOVA (overall regression significance)
Intercept	7.3929	0.7850	0.7512	0.0000
LOS (km)	-0.0012	0.9965		
Elevation (m)	0.1379	0.0612		

Regression table reveals that the overall regression model along route B is significant since the P-value for ANOVA is less than the α(0.05). Also, 75.12% variation in the Signal Strength is jointly explained by the variation in Line of Sight and Elevation along the route. This is observed from the coefficient of determination (R^2=0.7512).
The model obtained is given by:

$$RSS = 7.3929 - 0.0012LOS + 0.1379ELV \quad (21)$$

VI. CONCLUSION

This study presented the result of the electric field strength measurement and the modeling (through statistical analyses) of the Received Signal Strength (RSS) of UHF channel 23 Television Signal in Ondo State, Nigeria. However, the major findings are as follows; for route A, (Base station towards Ondo North) the result shows a moderate positive non-significant relationship (0.4228) between the Line of Sight and Elevation, and a negative significant relationship between the Line of Sight and the Signal Strength whereas a low positive significant relationship was established between Elevation and Signal Strength. For route B (from base station towards Ondo South), the analysis carried out showed that there is a very high significant negative correlation (-0.9599) between the Line of Sight and Elevation, a relatively high negative correlation of -0.8321 was established between the Line of Sight and Signal Strength and a very high significant positive correlation between Elevation and Signal Strength. This implies a significant increase in the signal strength as the elevation increases along the route B. The regression models obtained for both routes are significant. The derived mathematical models that can be used to calculate the Received Signal Strength (RSS), for route A and B, for given values of Elevation (ELV) and Line of Sight (LOS) are given respectively as RSS_A and RSS_B ;

$$RSS_A = 20.8643 - 0.5158LOS + 0.1157ELV$$

$$RSS_B = 7.3929 - 0.0012LOS + 0.1379ELV$$

The overall general model that can be used to predict the Received Signal Strength (RSS) across the state is given as; $RSS_G = 14.1286 - 0.2585LoS + 0.1268ELV$ which is the mean of the two derived models along the routes. These findings would be useful for radio wave propagation and reception on the UHF channel in the study areas in particular and in other similar environment in Nigeria.

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