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Assessment of Terrain Shadowing and Knife Edge Diffraction Effects on VHF Radio Propagation in Saki, Oyo State, Nigeria

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ABSTRACT

Very High Frequency (VHF) radio waves operate within 30–300 MHz frequency range and are widely used for terrestrial communication, particularly Frequency Modulation (FM) broadcasting. They propagate through direct and near Line of Sight (LOS) paths, making them sensitive to terrain between the transmitter and receiver. Obstructions create terrain shadowing along the propagation path, while diffraction allows part of the radio signal to bend around such obstacles and reach locations behind them. This study examined the effects of terrain shadowing and knife edge diffraction on VHF radio propagation using measured Received signal strength measured at 70 locations along seven selected routes using a tinySA Ultra spectrum analyser, while SRTM elevation data were processed in QGIS to examine terrain obstruction, LOS conditions, Fresnel zone clearance and knife edge diffraction. Out of the 70 propagation locations analysed, 51 (72.86%) experienced terrain obstruction, while 19 (27.14%) maintained clear LOS. The calculated knife edge diffraction loss averaged 8.99 dB across all paths and 12.33 dB for obstructed paths, with a maximum value of 22.12 dB. The mean RSS was -73.72 dBm, while the Egli and Free Space Path Loss (FSPL) models predicted -78.30 dBm and -21.22 dBm, respectively. Egli recorded Mean Absolute Error (MAE) of 17.97 dB and Root Mean Square Error (RMSE) of 22.83 dB, compared with 52.50 dB and 55.51 dB for FSPL. Their Coefficients of Determination (R^2) were -0.815 and -9.733, respectively. The findings show that terrain plays an important role in VHF signal behaviour in the study area.

INTRODUCTION

Very High Frequency (VHF) radio propagation is influenced by the physical features of the environment through which radio waves travel. Hills, ridges, valleys and vegetation can obstruct the direct signal path, causing changes in received signal strength (RSS). When terrain blocks the line of sight (LOS), diffraction allows some radio energy to reach locations beyond the obstruction, although additional loss may occur. Kolawole and Faruk (2015) and Faruk et al. (2018) examined terrain and clutter effects on radio propagation and showed the importance of environmental conditions in path loss prediction. However, their studies did not provide a combined assessment of Fresnel zone clearance, terrain shadowing and knife edge diffraction for the FM broadcast paths considered in the present study. Zang and Wang (2017) examined diffraction over uneven terrain. Akaninyene et al. (2019) developed an Epstein–Peterson approach for estimating multiple knife edge diffraction loss. These studies provided analytical methods for assessing obstructed paths but did not directly relate diffraction calculations to measured RSS from Asabari FM. Fresnel zone clearance is also important because a path may have geometric LOS while nearby terrain still intrudes into the region needed for effective propagation. Popoola et al. (2018) combined RSS measurements with local terrain profile data for radio network planning at GSM frequencies. Although the approach demonstrated the value of geographical information, its frequency bands differed from FM broadcasting. Faruk et al. (2021) examined VHF/UHF propagation measurements and model predictions, providing further evidence that conventional models require assessment under local conditions. Ajani et al. (2022) measured Sobi FM signals at 101.9 MHz along the Ilorin-Jebba road and found differences between measured attenuation and free space predictions, which they associated partly with hills, valleys and vegetation. However, the study did not

quantify the contribution of individual terrain obstructions through knife edge diffraction calculations.

Yusuf and Gbalaja (2022) investigated signal strength from five FM stations in Lokoja and Okene, identifying distance and environmental obstructions as possible causes of poor reception. Their assessment did not include detailed Fresnel clearance or diffraction loss calculations. Akinbolati et al. (2025) examined UHF path loss in Kano and incorporated elevation and LOS distance into a modified Hata model, although their investigation concerned television rather than VHF-FM transmission. Ugbeh et al. (2024) evaluated propagation models in a maritime environment, where distance and environmental conditions influenced prediction accuracy. Neither study directly assessed the combined terrain mechanisms.

Recent FM investigations also show the need for location specific analysis. Adoga et al. (2025) compared measured FM signal strength in Benin City with Hata, Egli, Free Space and Durkin predictions. Akonjom et al. (2025) modified the Stanford University Interim model for 105.5 MHz transmission in Calabar but still reported a prediction error of 11.65 dB. These studies focused mainly on model performance rather than identifying individual terrain obstructions and their diffraction losses. Isabona and Imoize (2021) also investigated terrain based model adaptation, while Soo et al. (2025) examined radio propagation over uneven terrain. Their work supports terrain aware prediction but does not replace a site specific investigation of the 88.3 MHz signal in Saki. Amalu et al. (2023) examined atmospheric refractivity, an additional propagation influence, rather than terrain induced diffraction.

There is the limited integration of measured VHF-FM signal strength, actual terrain profiles, LOS obstruction, 60% first Fresnel zone clearance and quantitative knife edge diffraction loss within the Saki propagation environment. This study addresses the gap using 70 measurements along seven routes from Asabari FM (88.3 MHz), SRTM digital elevation data and QGIS terrain analysis. It identifies shadowed paths and critical obstructions, estimates diffraction losses, and compares measured RSS with Egli and Free Space Path Loss predictions to assess how terrain conditions relate to signal behaviour and model accuracy.

MATERIALS AND METHODS

Study Design and Field Measurement

This study used an analytical and experimental methodology to evaluate the effects of knife edge diffraction and terrain shadowing on VHF radio propagation. The 88.3 MHz signal from Asabari FM, Saki, Oyo State, Nigeria was used for the field measurement. A total of 70 measurement locations were selected along seven routes within the study area. The measurement points were not equally distributed among the routes because of differences in route length, terrain characteristics, road accessibility, physical obstructions and the suitability of available locations for field measurements. Greater attention was given to locations where changes in terrain elevation could influence line of sight conditions, signal attenuation and diffraction. This approach allowed the study to capture variations in received signal strength across different terrain conditions rather than maintaining an equal number of measurement points along every route.

A TinySA Ultra ZS 407 spectrum analyzer was used to measure the RSS at each observation point. An Apex GPS land meter was used to determine the ground elevation and geographic coordinates. The telescopic receiving antenna was connected to the spectrum analyzer and kept at a height 1.5 m above ground level (AGL).

Terrain Data and GIS Processing

Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) data with a spatial resolution of 30 m were processed using Quantum Geographic Information System (QGIS) software to examine terrain variations along the propagation paths. Field coordinates recorded in WGS 84 were transformed into WGS 84/Universal Transverse Mercator (UTM) Zone 31N (EPSG:32631) to enable distance calculations in metres. The DEM was reprojected to the same coordinate reference system, and propagation paths were constructed by connecting the transmitter to individual receiver locations. Elevation values extracted along these paths produced terrain profiles showing ground variations and obstructions. The transmitting antenna elevation was 515 m above mean sea level (AMSL), while the receiving antenna elevation was obtained by adding 1.5 m to the local ground elevation.

The profiles were used to assess line of sight (LOS), 60% first Fresnel zone clearance, critical obstructions and knife edge diffraction losses. Buildings, vegetation, surface clutter and weather conditions were not explicitly studied; therefore, the analysis focused on terrain related propagation effects.

Line of Sight and Fresnel Zone Analysis

Each receiver's LOS was compared to its corresponding terrain profile. To determine whether the propagation path was clear or blocked, the terrain elevation along the path was compared with the straight line connecting the transmitter and the receiver antenna.

The radius of the first Fresnel zone at a selected point along the propagation path was given as:

$$r_1 = \sqrt{\frac{\lambda d_1 d_2}{d_1 + d_2}} \qquad 1$$

r_1 = radius of the first Fresnel zone in metres (m).

λ = wavelength of the radio signal in metres (m).

d_1 = distance from transmitter to the obstruction or point of interest.
d_2 = distance from the obstruction or point of interest to the receiver.
(International Telecommunication Union [ITU], 2025)
The propagation paths were evaluated using a 60 percent first Fresnel zone clearance. Even in case where there was no complete geometrical LOS obstruction, terrain that penetrated the necessary clearance region was thought to have the potential to impact propagation.

Terrain Shadowing and Knife Edge Diffraction
Terrain shadowing and knife edge diffraction were analysed using terrain profiles generated from the 30 m resolution SRTM DEM. Shadowing was identified where terrain elevations exceeded the direct line of sight (LOS) between the transmitter and receiver, indicating potential shadowed regions.
The critical obstruction along each affected path was identified using the Fresnel-Kirchhoff diffraction parameter (ν)**,** which describes the obstruction height relative to the LOS in relation to the wavelength and distances from the transmitter and receiver. According to the International Telecommunication Union (ITU, 2025), the parameter is expressed as:

$$\upsilon = h\sqrt{\frac{2(d_1+d_2)}{\lambda d_1 d_2}} \qquad 2$$

h = height of the obstruction above the line of sight path in meters (m).
λ = wavelength in meters (m).
d_1 = distance from transmitter to the obstruction.
d_2 = distance from obstruction to receiver.
The obstruction with the greatest positive ν value was selected for the single knife edge diffraction model to estimate additional propagation loss. The calculated losses were examined alongside measured received signal strength (RSS) and terrain characteristics.
Some paths contained multiple significant obstructions, but the single knife edge approximation considered only the dominant obstruction. Multiple knife edge methods, including Deygout and Bullington, were not implemented. Therefore, the calculated losses represent estimates associated with the dominant obstruction rather than the combined diffraction effects of multiple obstacles or total measured signal attenuation.

Propagation Model Prediction
Measured received signal strength (RSS) was compared with predictions from the Free Space Path Loss (FSPL) and Egli models. FSPL represents ideal propagation without terrain or environmental losses, while Egli estimates terrestrial propagation loss using frequency, distance and antenna heights. However, neither model explicitly calculates diffraction loss from individual terrain obstructions.
Propagation losses were calculated using the respective model equations, and predicted RSS was obtained by subtracting each loss from the effective radiated power expressed in dBm. Model predictions were compared with field measurements to assess their performance.
Knife edge diffraction losses were calculated independently from the dominant terrain obstructions and were not added to either model prediction. This preserved the original model formulations and avoided potential double counting of terrain related losses in the empirical Egli model.
According to ITU (2024), the FSPL is expressed as:

$$FSPL\ (dB) = 32.44 + 20\ \log_{10}(f) + 20\ \log_{10}(d) \qquad 3$$

FSPL = free space path loss (dB).
f = operating frequency (MHz).
d = distance between the transmitter and receiver in kilometers (km).
32.44 = constant used when frequency is expressed in MHz and distance in km.
The Egli median path loss was calculated with (Egli, 1957):

$$L_{Egli} = 117 + 40\log_{10}(d) - 20\log_{10}(h_t) - 20\log_{10}(h_r) - 20\log_{10}(f) \qquad 4$$

L_{Egli} = Egli median path loss (dB).
d = distance between transmitter and receiver (km).
h_t = transmitter antenna height (m).
h_t = receiver antenna height (m).
f = frequency MHz).

Statistical Evaluation
Root Mean Square Error (RMSE), Mean Absolute Error (MAE) and Coefficient of Determination (R^2) were used to assess prediction accuracy. The metrics were computed as follows:
The MAE was calculated using:

$$\text{MAE} = \frac{1}{\text{N}}\sum_{\text{i=1}}^{\text{N}}\left(\text{PL}_{\text{measured,i}} - \text{PL}_{\text{predicted,i}}\right) \qquad 5$$

MAE = Mean Absolute Error
N = total number of observations
The RMSE is expressed as:

$$\sqrt{\frac{1}{\text{N}}\sum_{\text{i=1}}^{\text{N}}\left(\text{PL}_{\text{measured,i}} - \text{PL}_{\text{predicted,i}}\right)^2} \qquad 6$$

RMSE = Root Mean Square Error
N = total number of observations
The following equation expresses the coefficient of determination (R^2):

$$R^2 = \frac{\sum_{\text{i=1}}^{\text{N}}\left(\text{Y}_\text{i} - \hat{\text{Y}}_\text{i}\right)^2}{\sum_{\text{i=1}}^{\text{N}}\left(\text{Y}_\text{i} - \overline{\text{Y}}\right)^2} \qquad 7$$

R^2 = coefficient of determination
$\hat{Y}_i$ = model predicted path loss at point i
Y_i = measured path loss at point i
$\overline{Y}$ = mean of the measure path loss value
N = total number of measured points
While R^2 assesses how well the anticipated values replicate the variability in the measured data, lower MAE and RMSE values show smaller prediction errors.

Data Analysis

The analytical procedure comprises field RSS measurement, coordinate and elevation acquisition, SRTM terrain extraction, terrain profile generation, LOS assessment, 60% Fresnel zone evaluation, identification of critical obstructions, terrain shadowing assessment, knife edge diffraction calculation, Egli and FSPL prediction, and statistical model evaluation. This combined procedure allowed the measured signal behaviour to be investigated alongside the physical terrain characteristics and the performance of the selected propagation models.

RESULTS AND DISCUSSION

The terrain analysis covered 70 measurement locations distributed across seven routes from Asabari FM (88.3 MHz), Saki, Oyo State. The number of measurement points varied among the routes because of differences in route length, accessibility and terrain conditions. Five representative terrain profiles were selected to illustrate the different propagation conditions observed as presented in Figures 1-5.

Terrain Obstruction, Fresnel Clearance and Diffraction

The results showed that 51 propagation paths (72.86%) experienced direct LOS obstruction, while 19 (27.14%) remained geometrically clear. 55 paths (78.57%) did not satisfy the 60% first Fresnel zone clearance requirement. These findings indicate that terrain obstruction was common across the measurement locations and that geometric visibility alone was insufficient to describe the propagation conditions.

The calculated knife edge diffraction loss averaged 8.99 dB across all measurement points and 12.33 dB for obstructed paths, with a maximum of 22.12 dB. The variation reflects differences in obstruction height and position along the propagation paths. However, these losses represent estimates associated with the dominant terrain obstructions rather than the total attenuation experienced by the measured signals.

Route 1 Point 5, located approximately 6.34 km from the transmitter, recorded an RSS of -87.9 dBm. Although the path maintained clear LOS and had zero calculated diffraction loss, its Fresnel margin of -5.54 m indicated partial intrusion into the required clearance region. This demonstrates that a geometrically clear path may still experience Fresnel zone obstruction.

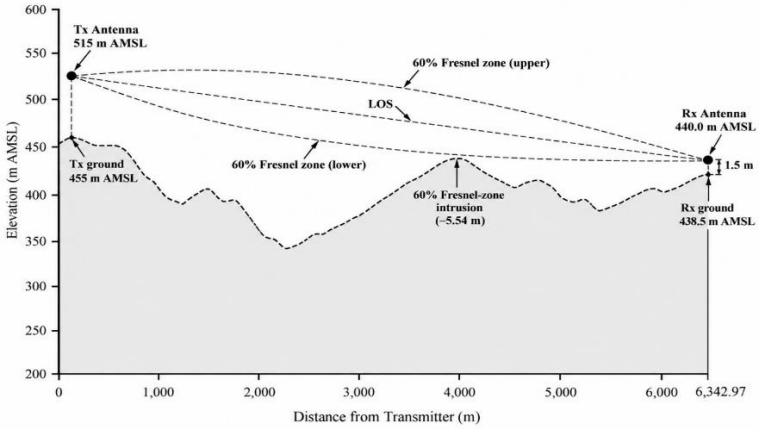


Figure 1: Terrain Profile Analysis for Route 1 Point 5

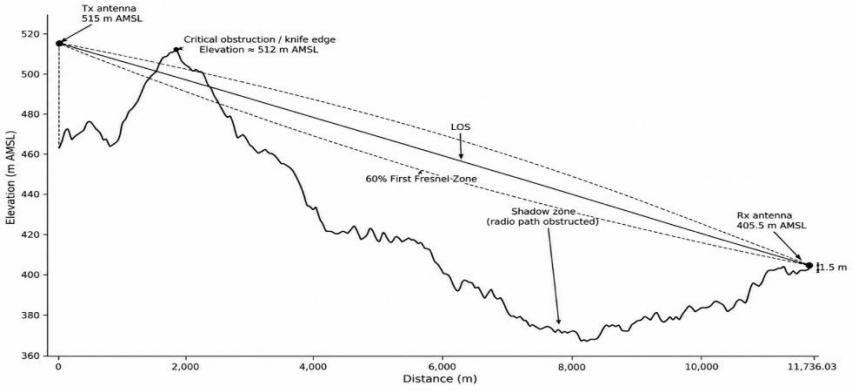


Figure 2: Terrain Profile Analysis for Route 2 Point 8

Route 2 Point 8 recorded an RSS of -72.2 dBm, with a Fresnel margin of -51.28 m and diffraction loss of 7.28 dB. Despite the obstruction, its measured signal was stronger than that of Route 1 Point 5. This difference suggests that RSS depends on several propagation factors beyond the calculated diffraction loss.

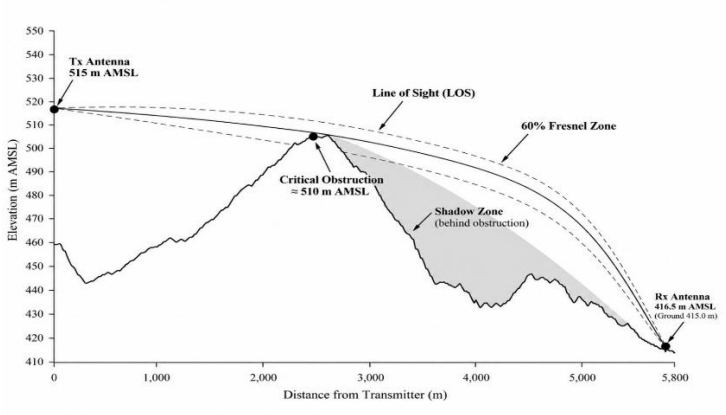


Figure 3: Terrain Profile Analysis for Route 5 Point 5

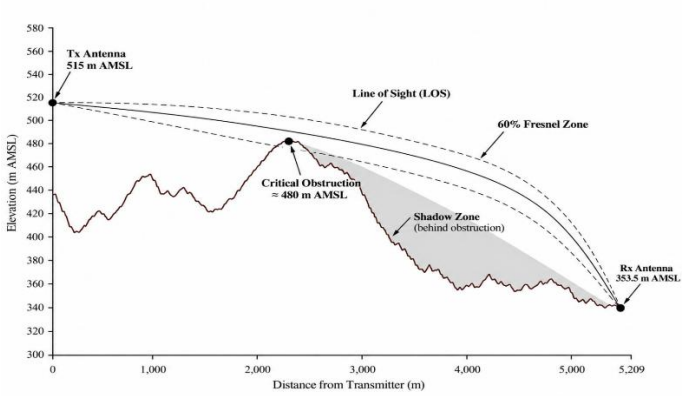


Figure 4.: Terrain Profile Analysis for Route 6 Point 7

More pronounced terrain effects were observed at Route 5 Point 5 and Route 6 Point 7. Their Fresnel margins were -93.16 m and -83.45 m, respectively, while the corresponding diffraction losses were 14.15 dB and 14.02 dB. However, their measured RSS values differed considerably at -71.5 dBm and -90.1 dBm. The difference, despite similar diffraction estimates, indicates that distance, antenna characteristics, local clutter, reflections and measurement conditions may also influence reception.

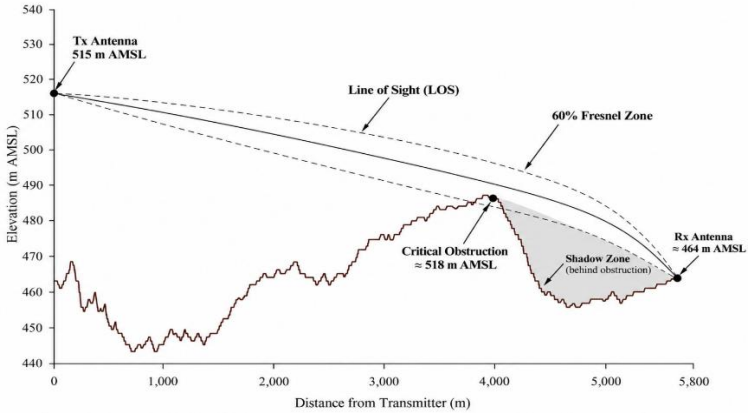


Figure 5: Terrain Profile Analysis for Route 7 Point 6

Route 7 Point 6, located approximately 11.34 km from the transmitter, recorded an RSS of -57.0 dBm. Its critical obstruction occurred 9,897.49 m from the transmitter at an elevation of 532.0 m AMSL. The LOS clearance and 60% Fresnel margin were -56.72 m and -95.93 m, respectively, with a calculated diffraction loss of 15.31 dB. These values indicate substantial terrain obstruction and shadowing. The relatively strong RSS shows that diffraction loss alone cannot explain the received signal level.

The representative profiles demonstrate that terrain elevation, obstruction geometry and Fresnel clearance influence propagation conditions. They also show why calculated diffraction losses should be interpreted alongside field measurements rather than treated as direct measurements of signal attenuation.

Propagation Model Comparison and Statistical Analysis

The mean measured RSS was -73.72 dBm, compared with -78.30 dBm predicted by Egli and -21.22 dBm predicted by Free Space Path Loss (FSPL). Egli produced a Mean Absolute Error (MAE) of 17.97 dB and Root Mean Square Error (RMSE) of 22.83 dB, while FSPL recorded 52.50 dB and 55.51 dB, respectively.

The coefficients of determination (R^2) were -0.815 for Egli and -9.733 for FSPL. These negative values indicate that neither model adequately reproduced the measured RSS variations. Although Egli gave lower prediction errors, its performance remained limited. FSPL assumes unobstructed propagation, while Egli does not explicitly represent individual terrain obstructions. The findings demonstrate the importance of combining measured RSS, terrain profiles, LOS assessment, Fresnel clearance and diffraction calculations when evaluating VHF propagation in Saki.

CONCLUSION

This study assessed terrain shadowing and knife edge diffraction effects on VHF propagation using received signal strength (RSS) measurements at 70 locations along seven routes from Asabari FM (88.3 MHz), Saki, Nigeria. Terrain profiles generated from 30 m-resolution SRTM data supported line-of-sight (LOS), 60% first Fresnel zone clearance, and diffraction analyses. Out of the 70 propagation paths, 51 (72.86%) experienced terrain obstruction, while 19 (27.14%) maintained clear geometric LOS. Some paths also experienced Fresnel zone intrusion, indicating that geometric LOS does not guarantee adequate 60% Fresnel clearance. The mean knife edge diffraction loss was 8.99 dB across all paths and 12.33 dB for obstructed paths, with a maximum of 22.12 dB.

The Egli model produced lower MAE (17.97 dB) and RMSE (22.83 dB) than FSPL (52.50 dB and 55.51 dB, respectively). However, the negative R^2 values (-0.815 and -9.733) indicated poor agreement with measured RSS variations. The findings show terrain's importance in FM propagation, although other environmental and measurement factors may also influence RSS. The study was limited to one station and a single knife edge approximation, which excluded combined diffraction from multiple obstructions. Further studies should incorporate multiple knife-edge methods, terrain-sensitive models and wider-field measurements, which will include more than one transmitting station.

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