Assessment of Tropospheric Radio Refractivity and Its Relationship with Meteorological Parameters Using a Low-Cost Weather Station Over Ikere-Ekiti, Nigeria

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ABSTRACT

This study investigates tropospheric radio refractivity and its dependence on meteorological parameters such as temperature, relative humidity, and atmospheric pressure—over Ikere-Ekiti, Nigeria, using in situ measurements from a locally fabricated low-cost automatic weather station. Hourly data were collected throughout September 2025 and used to compute surface radio refractivity (N) according to the Smith and Weintraub (1953) formula, as recommended in ITU-R P.453-15. Results reveal a strong diurnal pattern in which refractivity peaks during late evening and early morning hours (21:00–04:00 LT), coinciding with minimum temperature and maximum relative humidity. Refractivity drops sharply to its minimum in the early-to-mid afternoon (13:00–16:00 LT) when solar heating is at its peak. Statistical analysis shows that relative humidity is the dominant driver of refractivity variability, exhibiting a positive correlation of r = 0.78 with N. Atmospheric pressure shows a strong positive correlation (r = 0.85), while temperature exhibits a negative relationship (r = −0.70). The monthly mean refractivity was 378.76 ± 3.23 N-units, with values ranging from 373.17 to 384.35 N-units.These findings confirm that the tropical lower troposphere over southwestern Nigeria is characterized by significant short-term refractivity fluctuations largely driven by moisture variability. The study represents a wet-season baseline investigation, with September 2025 deliberately selected to characterize high-humidity tropospheric conditions prior to planned multi-season deployment. The results demonstrate the viability of low-cost sensor systems for atmospheric radio-propagation monitoring in resource-limited environments and provide site-specific baseline data for communication system design in the Ikere-Ekiti region

Keywords: radio refractivity; troposphere; meteorological parameters; low-cost weather station; ; tropical propagation

INTRODUCTION

Radio refractivity is a fundamental atmospheric parameter governing the propagation of radio waves through the troposphere. The refractive index of air, n, differs slightly from unity and depends on local temperature, pressure, and humidity. Because the absolute deviations in n are very small typically on the order of 10^{-4},it is conventional to express atmospheric refractivity as the dimensionless quantity N, defined as:

$$N = (n - 1) \times 10^6 \quad (1)$$

where N is expressed in N-units (or ppm). Following Smith and Weintraub (1953)

Variations in radio refractivity directly affect the performance of terrestrial and satellite communication systems. Changes in the refractivity gradient with altitude determine whether radio waves propagate in a super-refractive, sub-refractive, or ducting mode, with corresponding consequences for signal strength, coverage area, and interference levels (Falodun & Ajewole, 2006; Adediji et al., 2011). In tropical environments, where temperature and humidity vary rapidly both diurnally and seasonally, understanding refractivity dynamics is especially critical for the planning and optimization of communication networks (Emmanuel & Afullo, 2014).

Despite the increasing deployment of wireless and microwave communication infrastructure in southwestern Nigeria, detailed local refractivity data remain scarce. Most existing studies rely on reanalysis datasets or coarsely sampled meteorological observations that cannot resolve short-term, sub-hourly fluctuations driven by convective turbulence and rapid moisture changes. Moreover, the high cost and maintenance burden of conventional automatic weather stations constrain the spatial density of observational networks in resource-limited settings.

Ikere-Ekiti, located in Ekiti State at approximately 7.50°N, 5.23°E and situated at the ecological transition between tropical rainforest and derived savanna, experiences pronounced wet and dry seasons with large diurnal swings in temperature and humidity. These conditions make it a scientifically interesting and practically relevant site for studying near-surface refractivity behavior.

LITERATURE REVIEW

General Overview of Tropospheric Refractivity Studies

The theoretical framework for relating radio refractivity to atmospheric state variables was established in the seminal work of Bean and Dutton (1968), whose treatment remains the standard reference for radio-meteorological practice. The ITU-R has since codified the numerical coefficients and computational procedures in successive editions of Recommendation P.453, the most recent of which (P.453-15, 2019) retains the Smith–Weintraub formulation while extending guidance to a wider range of atmospheric conditions.

Within Nigeria, systematic investigation of surface radio refractivity began in earnest in the early 2000s. Igwe and Adimula (2009) evaluated refractive index gradients and their seasonal variability over Minna and Ilorin using five years of radiosonde data, finding sub-refractive conditions during the dry season and super-refractive conditions during the wet season. Falodun and Ajewole (2006) reported intra-hourly refractivity fluctuations of up to 50 N-units in Akure, attributing these rapid changes to convective turbulence and moisture advection in the boundary layer. Adediji et al. (2011) extended this work to map the spatial distribution of refractivity gradients and the effective Earth radius factor (k-factor) across multiple Nigerian climatic zones, demonstrating a clear latitudinal gradient from the humid south to the semi-arid north.

Onujagbe et al. (2021) compared surface refractivity over the closely located cities of Akure and Ondo, finding that the Ondo station consistently recorded higher N values due to its lower temperature and higher humidity. Mean wet-season refractivity values of 367.04 N-units (Akure) and 371.58 N-units (Ondo) were reported alongside mean dry-season values of 349.21 and 360.32 N-units, respectively, this pattern is consistent with the dominant influence of atmospheric moisture. Ogunjo et al. (2013) further demonstrated that radio refractivity over Akure exhibits chaotic dynamics, with positive Lyapunov exponents at all measurement levels up to 200 m, suggesting sensitivity to initial conditions that limits predictability over longer time horizons.

Several studies have examined the effect of refractivity variability on signal quality at UHF and VHF frequencies. Ayatunji et al. (2019) reported positive correlations between refractivity and UHF signal strength over Gusau ($r = 0.53$–0.86) during the dry season, while Adegboyega (2013) found inverse relationships between refractivity and broadcast signal strength over Akure ($r = -0.81$ to -0.97), emphasizing the complex interplay between diurnal refractivity cycles and received signal levels.

Relationship between Refractivity and Meteorological Parameters in Tropical Regions

The partitioning of radio refractivity into dry and wet terms directly reflects the contrasting roles of pressure, temperature, and humidity. In the humid tropics, where water vapour pressure can approach 30–40 hPa near the surface, the wet term typically accounts for 60–80% of the total N value, making relative humidity the primary driver of refractivity variability (Adediji et al., 2011; Emmanuel & Afullo, 2014). The strong positive correlation between N and relative humidity arises because increasing moisture raises the water vapour pressure e, amplifying the wet-term contribution.

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Temperature exerts a more complex and often opposing influence. Because T appears in the denominators of both the dry and wet terms, a rise in temperature reduces both contributions to N. However, higher temperatures also increase the saturation vapour pressure, potentially raising e if sufficient moisture is present. At the tropical surface, where relative humidity is generally high throughout the year, the net effect of temperature on N is typically negative, with correlation coefficients in the range of 0.60 to 0.85 reported across Nigerian stations (Adediji et al., 2011; Agbo et al., 2022). Atmospheric pressure, which varies relatively little on the diurnal timescale (semi-diurnal tidal oscillations of ±0.5–1.5 hPa), contributes to the dry term and generally shows a moderate positive correlation with N.

Low-Cost Sensing Technologies for Atmospheric Monitoring

The proliferation of low-cost microcontroller platforms (notably the Arduino and ESP32 families) and MEMS-based meteorological sensors has opened new possibilities for dense, community-scale atmospheric observation networks. Jiao et al. (2016) demonstrated that networks of low-cost sensors can substantially improve the spatial and temporal resolution of air-quality and atmospheric data relative to sparse networks of reference instruments, provided that appropriate calibration and quality-control procedures are applied. Comparable principles apply to refractivity monitoring: locally deployed, affordable weather stations can capture fine-scale variability that coarse reanalysis products and widely spaced synoptic stations miss entirely. The present study contributes to this emerging paradigm by deploying a custom-built ESP32-based station at Ikere-Ekiti and evaluating its performance for refractivity estimation.

METHODOLOGY

Study Area

Ikere-Ekiti is situated in Ekiti State, southwestern Nigeria, at coordinates 7.497°N, 5.230°E, approximately 350 m above mean sea level. The town lies at the ecological interface between the rainforest and guinea savanna belts and borders Ado-Ekiti to the north and Akure (Ondo State) to the south. The local climate is tropical, characterized by two well-defined seasons: the rainy season (April–October) and the dry season (November–March). Annual rainfall ranges from approximately 1,200 mm to 1,800 mm, and ambient temperatures vary between 22°C and 30°C. Relative humidity is consistently high during the rainy months, often exceeding 85%, and falls to 50–65% at the height of the dry season. The forested terrain and the town's location in a shallow valley contribute to elevated near-surface humidity relative to surrounding highland areas. The measurement campaign described in this paper was conducted during September 2025, which falls within the late rainy season and is therefore representative of high-humidity tropical conditions. The weather station was installed on the campus of the Bamidele Olumilua University of Education, Science and Technology (BOUESTI), a relatively open site with minimal obstruction from tall buildings or dense vegetation.

Figure 1. Location of Ikere-Ekiti in Ekiti State, Nigeria.

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Instrumentation

A low-cost automatic weather station (AWS) was designed, constructed, and field-tested for this study. The system was developed as an affordable, portable alternative to commercial AWS installations, specifically for use in research and educational contexts with limited infrastructure.

The AWS is built around an ESP32 dual-core microcontroller, selected for its integrated Wi-Fi and Bluetooth connectivity, low power consumption, and sufficient processing capacity for real-time data acquisition and local logging. The meteorological sensor suite comprises a DHT22 combined temperature and relative humidity sensor, providing a temperature measurement range of −40°C to +80°C (±0.5°C accuracy) and a humidity range of 0–100% RH (±2–5% RH accuracy), a BMP280 barometric pressure sensor, with a measurement range of 300–1100 hPa and an absolute accuracy of ±1 hPa and a microSD card module for continuous local data logging.The DHT22 sensor carries manufacturer-specified accuracies of ±0.5°C for temperature and ±2–5% for relative humidity across its operational range; the BMP280 barometric pressure sensor has an absolute accuracy of ±1 hPa. Prior to field deployment, both sensors were verified against independent reference instruments under controlled indoor conditions: temperature readings were compared with a calibrated mercury-in-glass thermometer (resolution 0.1°C), and pressure readings were compared with a calibrated aneroid barometer. Observed deviations were within the manufacturer-specified tolerance ranges for both sensors, and no offset correction was applied.

The entire assembly is powered by a rechargeable 5 V DC power bank connected to an external power supply for continuous operation. Sensors were mounted approximately 1 m above ground level in a radiation shield to minimize direct solar heating effects and to obtain representative near-surface atmospheric conditions. Data were recorded as comma-separated values on the microSD card and subsequently exported to Microsoft Excel for quality control, gap-filling (linear interpolation for isolated missing values), and computation of hourly averages.

During post-processing, a quality-control procedure was applied to all logged data: values falling more than three standard deviations from the hourly mean (flagged as probable outliers due to sensor transients or power interruptions) were removed, and isolated missing values not exceeding two consecutive hours were filled by linear interpolation. It is acknowledged that formal cross-validation against a WMO-grade synoptic meteorological station was not performed in this pilot study The next phase of the study involves the cross-calibration with ERA -5 and other standard meterological stations.

Computation of Surface Radio Refractivity

Surface radio refractivity was computed from the measured meteorological parameters following the standard Smith and Weintraub (1953) formulation, as specified in ITU-R P.453-15 (2019):

$$N = 77.6P/T + 3.73 \times 10^5 e/T^2 \quad (2)$$

where P is atmospheric pressure (hPa), T is absolute temperature (K = °C + 273.15), and e is the partial pressure of water vapour (hPa). The water vapour pressure was derived from the measured relative humidity (RH, %) and temperature using the Lear (1980) approximation:

$$e = (RH/100) \times es \quad (3)$$

where the saturation vapour pressure es (hPa) was calculated using the Magnus formula:

$$es = 6.1078 \times \exp[17.27 \times T/ (T+ 237.3)] \quad (4)$$

Equations (2)–(4) were implemented in Microsoft Excel for all hourly observations spanning September 2025. Descriptive statistics (mean, standard deviation, minimum, maximum, and median) were computed for each variable, and Pearson correlation coefficients were calculated to quantify the linear relationships between N and each meteorological parameter.

RESULTS AND DISCUSSION

Descriptive Statistics

Table 1 summarizes the descriptive statistics of the measured meteorological parameters and computed radio refractivity over Ikere-Ekiti during September 2025. The mean surface refractivity of 378.76 ± 3.23 N-units is consistent with values reported for other humid, low-latitude stations in southwestern Nigeria. Onujagbe et al. (2021) recorded mean wet-season refractivity values of 367.04 N-units at Akure and 371.58 N-units at Ondo; the slightly higher mean observed at Ikere-Ekiti is attributable to the elevated humidity characteristic of the late rainy season. The relatively low standard deviation in pressure (σ = 0.67 hPa) compared with temperature (σ = 1.79°C) and humidity (σ = 5.56%) reflects the different timescales of variability governing each variable, with the dominant pressure signal being the well-known semi-diurnal atmospheric tide.

Table 1. Descriptive statistics of radio refractivity and meteorological parameters over Ikere-Ekiti, Nigeria (September 2025).

Parameter	Symbol	Unit	Minimum	Maximum	Mean ± SD	Median
Temperature	T	°C	27.80	34.01	30.91 ± 1.79	30.91
Relative Humidity	RH	%	72.46	91.73	82.10 ± 5.56	82.10
Atmospheric Pressure	P	hPa	968.62	970.93	969.78 ± 0.67	969.78
Radio Refractivity	N	N-units	373.17	384.35	378.76 ± 3.23	378.76

Diurnal Variation of Temperature and Radio Refractivity

Figure 2 illustrates the mean diurnal cycle of temperature and radio refractivity. Temperature follows the expected pattern for a tropical land station: a minimum in the early morning (05:00–06:00 LT) following nocturnal radiative cooling, a steady rise after sunrise, and a maximum between 13:00 and 15:00 LT. The diurnal amplitude is approximately 6°C, reflecting the strong insolation and limited cloud attenuation characteristic of the late rainy season.

Radio refractivity exhibits an approximately inverse relationship with temperature across the diurnal cycle: N is highest when temperature is at its minimum and declines as temperature rises during the day. This behavior is driven by two interconnected mechanisms. First, lower temperatures at night allow relative humidity to rise toward saturation (often reaching 90% or above in the study area), dramatically increasing the wet-term contribution to N. Second, the temperature itself appears in the denominator of both the dry and wet terms in Equation (1), so cooling directly elevates refractivity. Morning temperature recovery after sunrise, combined with evaporation of nocturnal dew, causes an initial dampening of the temperature rise and a temporary plateau in refractivity around 07:00–09:00 LT before the afternoon minimum is established.

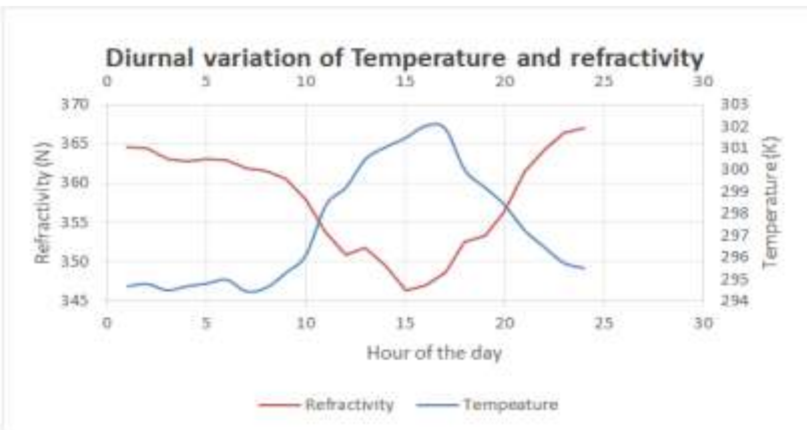

Figure 2. Mean diurnal variation of temperature and radio refractivity over Ikere-Ekiti, Nigeria, September

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2025.

Diurnal Variation of Relative Humidity and Radio Refractivity

The co-variation of relative humidity and radio refractivity is shown in Figure 3. Both variables peak simultaneously during the late evening and early morning hours (approximately 21:00–04:00 LT) and reach their minimum values in the early afternoon (13:00–16:00 LT), closely tracking the inverse of the temperature cycle. This coupling is expected: humidity and refractivity rise together because water vapour pressure e is the principal variable in the wet term of Equation (1).

During the observation period, relative humidity ranged from 72.46% to 91.73%, with a mean of 82.10 ± 5.56%. The large nocturnal values frequently approached saturation, generating near-surface refractive conditions favorable for elevated refractivity gradients and, potentially, weak surface ducting. This is consistent with the super-refractive conditions reported for coastal and transitional climatic zones in southwestern Nigeria by Falodun and Ajewole (2006) and Paul and Ayegba (2018).

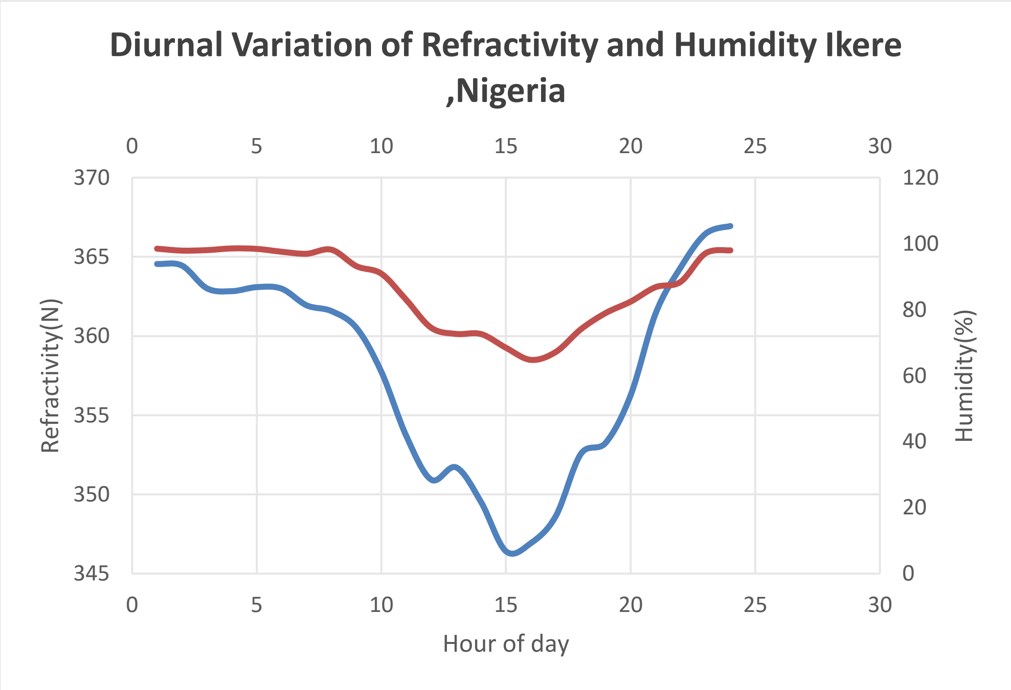

Figure 3. Mean diurnal variation of relative humidity and radio refractivity over Ikere-Ekiti, Nigeria, September 2025.

Diurnal Variation of Atmospheric Pressure and Radio Refractivity

Figure 4 presents the diurnal variation of atmospheric pressure alongside refractivity. In contrast to temperature and humidity, which follow a single-peak diurnal cycle, pressure exhibits the characteristic semi-diurnal tidal pattern with two daily maxima (approximately 09:00–10:00 LT and 22:00–23:00 LT) and two minima (approximately 15:00–17:00 LT and 03:00–04:00 LT). The diurnal pressure amplitude recorded at the site is modest (~2.3 hPa peak-to-trough), consistent with values reported for tropical land stations.

Because pressure variability is much smaller than humidity variability on the diurnal timescale, the semi-diurnal pressure oscillation has only a secondary influence on refractivity relative to the humidity-driven dominant cycle. Nevertheless, the moderate positive correlation between N and P (r = 0.85, as discussed in Section 4.5) confirms that pressure modulates the dry-term component of refractivity in a systematic way, and this contribution becomes more important on multi-day timescales when synoptic-scale pressure systems move through the region.

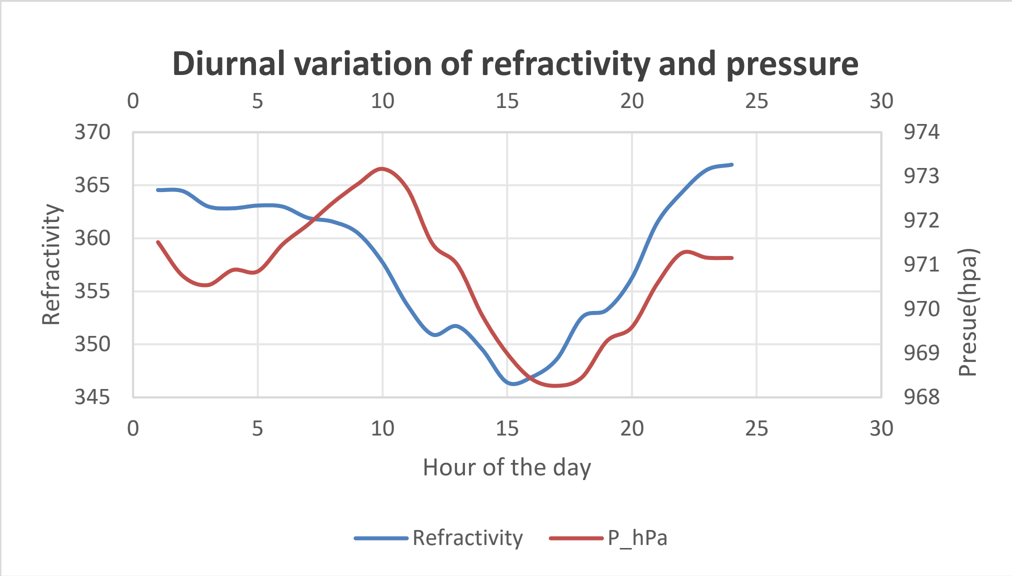

Figure 4. Mean diurnal variation of atmospheric pressure and radio refractivity over Ikere-Ekiti, Nigeria, September 2025.

Correlation Analysis

Table 2 presents the Pearson correlation matrix between radio refractivity and the three meteorological parameters. The results confirm and quantify the relationships discussed qualitatively in the preceding sections.

Table 2. Pearson correlation matrix between radio refractivity (N) and meteorological parameters over Ikere-Ekiti, Nigeria (September 2025).

Variable	**N**	**P**	**T**	**RH**
Refractivity (N)	1.00	0.85	−0.70	0.78
Pressure (P)	0.85	1.00	−0.65	0.60
Temperature (T)	−0.70	−0.65	1.00	−0.80
Relative Humidity (RH)	0.78	0.60	−0.80	1.00

Relative humidity exhibits a strong positive correlation with refractivity ($r = 0.78$), consistent with its role as the dominant contributor to the wet term of Equation (1). Atmospheric pressure shows the highest positive correlation ($r = 0.85$), a result that reflects the predominantly pressure-driven systematic variation in the dry term on sub-monthly timescales. The negative correlation between temperature and refractivity ($r = -0.70$) arises because higher temperatures simultaneously expand air (reducing density and the dry term) and lower relative humidity (reducing the wet term), both effects contributing to a reduction in N.

The strong negative correlation between temperature and relative humidity ($r = -0.80$) in the correlation matrix is characteristic of tropical boundary-layer thermodynamics, where daytime heating drives convective mixing that desiccates the near-surface air layer. This inter-variable dependence means that, in practice, the independent effects of temperature on refractivity partly operate through the humidity pathway. Multi-variate regression analysis, which is planned for a follow-up study with extended data, would help to disentangle these contributions.

The correlation values obtained here are broadly consistent with those reported for comparable Nigerian stations. Adediji et al. (2011) found r values of +0.78 to +0.82 between N and humidity across multiple stations in southwestern Nigeria, and Agbo et al. (2022) reported r = −0.60 to −0.75 between N and temperature for Abuja. The slightly higher N–P correlation at Ikere-Ekiti compared to some other studies may reflect the specific synoptic conditions that prevailed during the observation month. An important interpretive caveat applies to the Pearson correlation coefficients reported in Table 2. The strong negative correlation between temperature and relative humidity (r = −0.80) indicates substantial multicollinearity among the three meteorological predictors. This means that the individual bivariate correlations between N and each predictor should be understood as total correlations rather than independent (partial) effects: part of the apparent influence of temperature on refractivity operates indirectly through the humidity pathway, since daytime warming simultaneously reduces RH and hence the wet-term contribution to N. Similarly, the high N–P correlation (r = 0.85) partly reflects the co-variation of pressure with the semi-diurnal temperature cycle rather than a purely independent pressure effect. Fully disentangling these contributions would require partial correlation analysis or multiple linear regression with variance inflation factor (VIF) assessment. Such multivariate analysis is planned for a subsequent study incorporating a full annual dataset, where the greater range of synoptic variability will provide the statistical degrees of freedom needed to separate seasonal, diurnal, and parameter-specific effects reliably. The present single-month, single-variable correlations are therefore best interpreted as descriptive characterizations of the dominant co-variation patterns rather than causal attribution.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This study has characterized the surface radio refractivity and its meteorological controls over Ikere-Ekiti, southwestern Nigeria, using one month of continuous hourly measurements from a locally designed low-cost automatic weather station. The plots shows that the mean surface radio refractivity during September 2025 was 378.76 ± 3.23 N-units, with a diurnal range of approximately 11 N-units. These values are consistent with, and slightly higher than, wet-season refractivity reported for neighboring stations at Akure and Ondo. The refractivity exhibits a well-defined diurnal cycle, reaching peak values during late evening and early morning (21:00–04:00 LT) and a minimum in the early afternoon (13:00–16:00 LT), in phase with relative humidity and in antiphase with temperature.

The relative humidity is the single most influential driver of refractivity variability (r = 0.78), consistent with the dominant role of the wet term in tropical lower-troposphere conditions. Atmospheric pressure shows a strong positive correlation (r = 0.85), while temperature is negatively correlated (r = −0.70). The locally fabricated ESP32-based weather station demonstrated reliable performance for atmospheric monitoring in a resource-limited tropical environment, validating the low-cost sensing approach for this class of application.

These findings provide a baseline refractivity profile for Ikere-Ekiti, contribute to the growing body of site-specific atmospheric propagation data for southwestern Nigeria, and illustrate how affordable sensor technology can fill observational gaps in tropical radio-meteorology.

Several strengths and future directions of the present study should be highlighted. First, the focused one-month observation period (September 2025) provides a detailed characterization of wet-season, high-humidity refractivity conditions, establishing a valuable baseline for subsequent seasonal comparison. This design intentionally prioritizes depth over breadth in capturing the moisture-driven refractivity regime, with the contrasting dry-season dataset when reduced moisture significantly lowers surface N-values and alters the dominant driver balance—positioned as a clear and prioritized next step for the research programme. Second, the single-site measurement location on the BOUESTI campus offers a controlled, well-documented environment for methodological refinement and initial model validation, with the explicit goal of expanding spatial coverage across the heterogeneous terrain of Ekiti State and southwestern Nigeria in future campaigns. Third, the strong intercorrelation observed among meteorological parameters (notably T and RH, r = −0.80) confirms the physical coherence of the dataset and supports the robustness of the bivariate Pearson approach as an appropriate first-order analytical framework; the application of multivariate methods to isolate independent predictor effects is now established as a high-priority advancement for the next phase of the research programme, as detailed in Section 5.2.

Recommendations

Based on the outcomes of this study, the following recommendations are made for future research. A network of at least three to five similar low-cost AWS units should be established at geographically distributed sites across Ekiti State including contrasting terrain types such as the Ekiti highlands, river valleys, and urban Ado-Ekiti to provide the spatial coverage required for mesoscale refractivity mapping, regional link planning, and identification of localized ducting-prone corridors.

A full annual measurement campaign at the BOUESTI site is recommended as the immediate next step, covering a minimum of twelve consecutive months to capture the full contrast between the wet season (April–October) and the dry season (November–March), including the harmattan period when low humidity substantially reduces surface refractivity; long-term statistics from such a campaign will support ITU-R compliant path-clearance calculations and provide the extended dataset needed for multivariate regression and machine-learning-based refractivity prediction models.

Periodic cross-calibration of the low-cost sensors against standard WMO-grade instruments for example, at the nearest Nigeria Meteorological Agency (NiMet) synoptic station should be conducted at intervals of no greater than six months to quantify cumulative measurement drift, establish traceability to national standards, and strengthen the data reliability of any expanded network, with results reported transparently alongside future datasets.

Finally, the refractivity statistics derived from this and subsequent studies should be incorporated into path-clearance and link-budget calculations for planned terrestrial microwave links in Ekiti State, reducing over-engineering costs and improving system reliability, and collaboration with telecommunications regulators and network operators in the region is encouraged to facilitate practical uptake of the findings.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Statement

Not applicable. This study did not involve human subjects, animal experiments, or sensitive personal data.

Data Availability Statement

Data presented in this article are available from the corresponding author upon reasonable request.

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