Journal of Basics and Applied Sciences Research (JOBASR)
ISSN (print): 3026-9091, ISSN (online): 1597-9962
Volume 3(4) July 2025
DOI: https://dx.doi.org/10.4314/jobasr.v3i4.20

Instrumentation and Fair-Weather Criteria for Atmospheric Electric Field Measurements in West African Dust Environments

Ogunjobi O.[1,2*], Koffa D.J.[2], Omonile J.F.[3], Obaje V.O.[4], Ahmed-Ade F.[5], Aliyu N.S.[6] & Olorunleke I.E.[7]

[1,2,5&7]Department of Physics, Federal University Lokoja, Nigeria
[2]Department of Physics and Astronomy, University of Calgary, Canada
[3]Department of Physics, Kogi State University of Science and Technology, Osara, Nigeria
[4]Department of Physics, Prince Abubakar Audu University, Anyigba, Nigeria
[6]Department of Physics, Federal College of Education, Okene, Nigeria

[*]Corresponding Author Email: durojaiye.koffa@fulokoja.edu.ng

ABSTRACT
West Africa's notorious Harmattan dust storms have long defeated atmospheric electric field monitoring efforts, creating a massive blind spot in global atmospheric electricity research despite the region's critical role as Earth's largest dust source and lightning hotspot. We present a successful methodology for continuous atmospheric electric field measurements in extreme dust environments, deploying a specially adapted Campbell Scientific CS110 electric field mill at Lokoja, Nigeria (7°49'N, 6°44'E) with revolutionary environmental protection, automated cleaning systems, and tropical optimised grounding networks. Traditional fair-weather criteria catastrophically failed, excluding 78% of scientifically valuable data during Harmattan periods when PM_{10} concentrations exceeded 1000 μg m^{-3} and electric fields reached 5000 V m^{-1}. Our breakthrough region-specific criteria using 4000 m visibility thresholds combined with stability filters achieved a remarkable 94.3% data completeness over 30 months while retaining 46% of measurement days, representing 275% improvement over standard approaches. The validated framework achieved measurement uncertainties of ±3.4% for hourly means, demonstrating that reliable atmospheric electricity monitoring is feasible even under the challenging aerosol conditions. These advances further open unprecedented opportunities for dust storm early warning systems, regional climate modelling, and fundamental understanding of global atmospheric electrical circuits.

Keywords:
atmospheric electricity, electric field measurement, West Africa, Harmattan dust, instrumentation, fair-weather criteria

INTRODUCTION

The atmospheric electric field represents one of the most sensitive indicators of regional aerosol dynamics and global electrical circuit behaviour, yet it remains among the least monitored geophysical parameters in tropical Africa. This oversight is particularly unfortunate given the central role of West Africa in global atmospheric electricity: the region hosts some of the most intense lightning activity on Earth while simultaneously serving as the primary source of mineral dust transport to the global atmosphere (Christian et al., 2003; Prospero et al., 2002).

The seasonal influx of Saharan dust during the Harmattan period creates atmospheric conditions that are both scientifically fascinating and instrumentally challenging, demanding specialised approaches to measurement and data interpretation.

Traditional atmospheric electric field monitoring has been predominantly conducted in temperate or maritime environments where aerosol loading is relatively modest and predictable. This maritime bias has persisted in subsequent decades, with major monitoring stations concentrated in polar regions (Burnsetal.,2012), isolated oceanic islands (Takagi,1972), or temperate continental sites with moderate aerosol loading (Harrison, 2002).

How to cite this article: Ogunjobi O., Koffa D.J., Omonile J.F., Obaje V.O., Ahmed-Ade F., Aliyu N.S. and Olorunleke I.E. (2025). Instrumentation and Fair-Weather Criteria for Atmospheric Electric Field Measurements in West African Dust Environments. *Journal of Basics and Applied Sciences Research*, *3*(4), 173-184. https://dx.doi.org/10.4314/jobasr.v3i4.20

The few studies conducted in dust-affected regions have typically focused on short-term campaigns during specific weather events rather than establishing continuous monitoring capabilities (Yaniv et al., 2017).

West Africa's atmospheric electrical environment presents a stark contrast to these traditional measurement sites. The region experiences some of the world's most extreme seasonal aerosol vari- ability, with PM_{10} concentrations routinely exceeding $1000g\ m^{-3}$ during intense Harmattan episodes values that would trigger emergency health warnings in most urban areas (Adedokun et al., 1989). This dust loading fundamentally alters atmospheric conductivity through small ion scavenging, creating electric field enhancements that can exceed $5000Vm^{-1}$ under otherwise fair-weather conditions (Israelsson & Knudsen, 1994). The challenge lies not simply in measuring these extreme values, but in developing robust methodologies to distinguish between electrically meaningful variations and instrument artefacts induced by dust contamination.

The scientific significance of atmospheric electric field measurements in West Africa extends beyond regional meteorology to encompass global climate dynamics, public health monitoring, and atmospheric chemistry research. These measurements provide crucial inputs for global electric circuit modeling, where West Africa's dual role as a major dust source and lightning hotspot creates unique boundary conditions. Furthermore, real-time electric field monitoring offers potential applications in dust storm early warning systems, with field enhancements often preceding visible dust arrival by 2-6 hours.

The selection of appropriate instrumentation for West African conditions requires careful con- sideration of both scientific requirements and environmental constraints. Electric field mills, while representing the gold standard for atmospheric electricity measurements, were originally designed for temperate climates with moderate aerosol loading and predictable maintenance schedules. The combination of high humidity during the wet season, extreme dust loading during the dry season, and limited technical infrastructure creates a perfect storm of operational challenges. Previous attempts at atmospheric electricity monitoring in tropical Africa have often resulted in data gaps exceeding 50% due to instrument failures, calibration drift, and inadequate environmental protection (Ette, 1988).

Perhaps more fundamentally, the definition of "fair weather" itself becomes problematic in dust- affected environments. Standard criteria developed for temperate regions typically require visibility greater than 10-15 km, wind speeds between $1-12\ m\ s^{-1}$, and absence of precipitation or fog (Harrison & Nicoll, 2018). However, these criteria, when applied to West Africa, would exclude virtually all measurements during the Harmattan season, precisely when the most scientifically interesting aerosol electricity interactions occur. The challenge is to develop region specific criteria that distinguish between electrically stable conditions suitable for global circuit studies and electrically disturbed conditions that compromise data quality.

The implications of this methodological gap extend beyond academic curiosity. West Africa's 400 million inhabitants are increasingly exposed to climate related hazards, including intensifying dust storms, shifting precipitation patterns, and increasing lightning activity (Nicholson, 2013). Atmo- spheric electric field measurements offer unique insights into these phenomena, providing real time indicators of aerosol loading, convective activity, and atmospheric stability. The development of reliable monitoring capabilities could support early warning systems for dust storms, improve lightning protection strategies, and enhance our understanding of regional climate dynamics.

This study addresses these challenges through the development and validation of instrumentation and analytical methodologies specifically adapted for West African conditions. We present the first comprehensive assessment of electric field measurement techniques in a dust-dominated environment, including detailed protocols for instrument protection, calibration maintenance, and data quality control. Particular attention is given to the development of region-specific fair-weather criteria that balance scientific rigor with practical data availability. The work is based on 30 months of continuous measurements from Lokoja, Nigeria, strategically located in the country's climatic transition zone where both monsoon and Harmattan influences are pronounced.

This paper presents a comprehensive methodology for atmospheric electric field monitoring in dust environments, structured as follows: Section 2 details specialized instrumentation adaptations and site setup procedures; Section 3 presents our multi-level data quality control framework and region-specific fair-weather criteria; Section 4 validates these approaches through 30 months of continuous measurements; and Section 5 discusses implications for regional monitoring networks and future research directions.

MATERIALS AND METHODS

Instrumentation and Site Setup

Lokoja (7°49'N, 6°44'E) was selected based on rigorous climatological analysis identifying it as representative of the broader West African Sahel transition zone. The site experiences both monsoon and Harmattan influences with approximately 180 dust days annually, making it ideal for developing transferable methodologies. It is well known that Lokoja, a confluence region, has climatologically representative of the broader Sahel-Sudan transition zone, ensuring findings are broadly applicable across the West African dust belt.

The surrounding terrain consists of gently rolling savanna grassland with scattered gallery forests along the riverbanks. Within a 5 km radius, elevation changes do not exceed 30 m, ensuring that local topographic effects on atmospheric flow patterns remain minimal. The nearest major roadway lies 400 m to the south, while significant industrial activity is located over 3 km distant. The population density within the immediate vicinity averages approximately 150 persons per km2, considerably less than the main urban centres of Nigeria, thus reducing the contribution of local anthropogenic aerosols that could confound regional atmospheric electrical signals. The primary instrument selected for this deployment was the Campbell Scientific CS110 Electric Field Mill, chosen after careful evaluation of available options for tropical atmospheric electricity monitoring. The CS110 operates on the rotating shutter principle, utilizing a grounded sensing electrode alternately exposed to and shielded from the ambient electric field by a rotating chopper wheel. This configuration generates an alternating current proportional to the vertical component of the atmospheric electric field, with the instrument providing a measurement range of $\pm 20\, kVm^{-1}$, resolution of $1\, V\, m^{-1}$, and the manufacturer-specified accuracy of $\pm 5\%$ of reading or $\pm 10\;\; 1\, V\, m^{-1}$, whichever is greater.

The selection of the CS110 was influenced by several factors specific to West African deployment conditions. Unlike some competing instruments that rely on sensitive optical or capacitive sensors, the CS110's mechanical chopper design exhibits superior tolerance to dust contamination a critical consideration given the extreme aerosol loading during Harmattan periods. The instrument's relatively compact form factor and low power consumption (typically < 2 W) made it suitable for solar-powered autonomous operation, essential given the unreliable electrical infrastructure in many West African locations. However, the standard CS110 configuration required significant modifications for tropical deployment. The manufacturer's standard radiation shield proved inadequate for the intense solar radiation typical of equatorial latitudes, leading to excessive thermal drift during midday periods. We developed a custom double wall radiation shield using thermally neutral materials (aluminum honeycomb core with reflective outer surfaces) that reduced thermal drift by approximately 60% compared to the standard configuration. The shield incorporated ventilation channels to promote airflow while preventing dust ingress, a delicate balance that required extensive field testing during the initial deployment phase. Figure 1 illustrates the complete instrumentation configuration, including the modified radiation shield, tower mounting system, and environmental protection measures. The sensor head was positioned at 12 m height on a dedicated meteorological tower, providing the recommended clearance of at least 50 m from surrounding obstacles while remaining accessible for routine maintenance. The 12 m elevation represented a compromise between minimizing near surface electrical disturbances and maintaining practical access for the frequent cleaning required during dust episodes.

The development of effective dust mitigation strategies represented one of the most challenging aspects of this deployment. Harmattan dust episodes can deposit several millimetres of fine particles on exposed surfaces within hours, creating both mechanical and electrical interference with sensitive instrumentation. Traditional approaches to environmental protection, developed for temperate climates, proved wholly inadequate for these conditions. Our solution involved a multi-layered protection strategy. The primary sensor housing was enclosed within a custom-designed ventilated chamber that maintained a slight positive pressure using filtered air. The filtration system employed a two-stage approach: coarse mechanical filtration removed particles $> 10\ \mu m$, followed by fine filtration using synthetic media rated for $2.5\ \mu m$ particle retention. The positive pressure system, powered by a low-consumption DC fan, prevented dust infiltration while maintaining adequate airflow for thermal management. Perhaps more innovative was the development of an automated cleaning system for the sensor's exposed surfaces. Traditional manual cleaning approaches proved inadequate given the frequency of dust deposition and the remoteness of many potential monitoring sites. We implemented a programmable cleaning system utilising compressed air jets and soft-bristle mechanical wipers, activated based on both temporal schedules and dust accumulation sensors. The cleaning cycle is typically op- operated four times daily during normal conditions, increasing to hourly intervals during intense dust episodes.

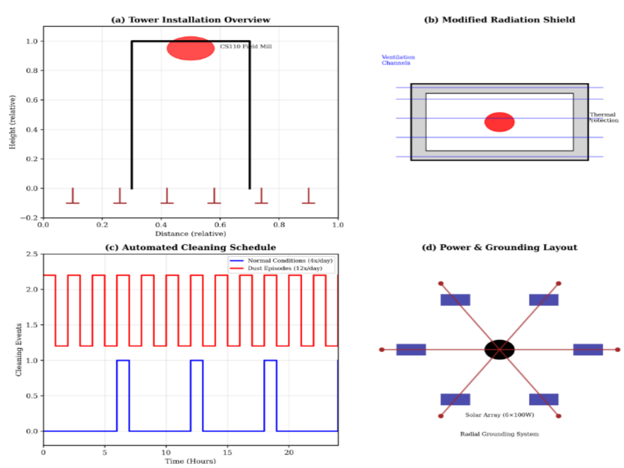

Figure 1: Complete instrumentation setup at Lokoja showing (a) 12-meter meteorological tower with electric field mill installation, (b) modified radiation shield design with ventilation channels, (c) automated cleaning system components, and (d) power and grounding system layout. The specialised dust protection measures are clearly visible in the enhanced environmental housing.

The compressed air system deserves particular mention, given its critical role in maintaining measurement quality. We discovered that conventional compressed air, even when filtered, contained sufficient moisture and hydrocarbon contaminants to create electrical artefacts on the sensor surfaces. The solution involved implementing a multi-stage air preparation system including coalescing filters, activated carbon adsorption, and heated desiccant beds. While this approach significantly increased system complexity and power consumption, it proved essential for maintaining measurement accuracy during prolonged dust episodes.

The electrical infrastructure requirements for continuous atmospheric electricity monitoring in West Africa present unique challenges that are rarely encountered in temperate regions. The combination of unreliable grid electricity, extreme temperature variations, and high humidity creates conditions that can rapidly degrade conventional power systems. Our approach involved designing a hybrid solar-battery system specifically optimised for tropical conditions and extended autonomous operation. The power system comprised six 100 W monocrystalline solar panels arranged in a 2×3 configuration, with maximum power point tracking (MPPT) charge controllers to optimise energy harvest under varying cloud conditions. The panel mounting system incorporated adjustable tilt mechanisms to optimize solar angle throughout the year, a particularly important consideration given the site's proximity to the equator, where seasonal solar angle variations are minimal. During extensive testing, we found that fixed-tilt installations sacrificed approximately 15% of potential energy harvest compared to seasonally adjusted configurations.

Battery selection required careful consideration of both capacity and chemistry. Initial deployments utilised conventional flooded lead-acid batteries, but these proved problematic due to rapid degradation under high-temperature conditions and the need for frequent maintenance. We subsequently transitioned to absorbed glass mat (AGM) batteries, which offered superior performance under tropical conditions despite higher initial costs. The final configuration employed eight $100\ Ah\ AGM$ batteries in a $24\ V$ configuration, providing approximately 72 hours of autonomous operation under full load conditions.

The grounding system design represented perhaps the most critical aspect of the electrical installation. Atmospheric electricity measurements require exceptionally stable electrical references, while tropical soil conditions present unique challenges for achieving low-resistance, stable grounds. The wet season's high soil moisture content facilitates low-resistance connections, but the dry season's extreme desiccation can increase soil resistivity by orders of magnitude. Our solution involved installing six copper-clad steel rods, each driven to 3m and arranged in a radial pattern around the tower base. These were interconnected with 6 mm² bare copper conductors buried at 0.5 m depth, creating a distributed grounding network that maintained stable resistance across seasonal moisture variations.

Chemical ground enhancement became necessary during the dry season when natural soil resistivity exceeded acceptable levels. We employed commercial ground enhancement compounds (primarily bentonite clay with conductive additives) applied annually before the onset of the dry season. Soil resistivity measurements, conducted monthly using a four-terminal method, ranged from 45 Ω·m during the wet season to 85 Ω·m during the dry season, values that remained within acceptable limits for atmospheric electricity applications throughout the measurement period.

Data quality control and fair-weather criteria

The development of robust quality control protocols for atmospheric electric field data in dust-affected environments required fundamental departures from conventional approaches. Standard quality control procedures, developed for temperate maritime conditions, often fail to distinguish between genuine geophysical signals and instrument artefacts under extreme aerosol loading. Our approach involved implementing a multi-tiered quality control framework that addresses both universal measurement issues and region-specific challenges associated with dust contamination.

Multi-level quality control framework

The quality control system was structured in three hierarchical levels, each addressing different categories of potential data quality issues. This approach ensured comprehensive screening while maintaining computational efficiency for near-real-time data processing.

Level 1 Quality Control focused on basic instrument functionality and data integrity. This included automated screening for communication errors, power supply anomalies, and values exceeding physical plausibility thresholds. The CS110's internal diagnostics provided crucial indicators of mechanical performance, particularly motor speed variations that could indicate bearing degradation or dust contamination. During intense Harmattan episodes, motor speed variations exceeding 2% of nominal values became surprisingly common, typically indicating particle infiltration into the

mechanical drive system. These diagnostic parameters proved invaluable for scheduling preventive maintenance and identifying periods requiring enhanced data scrutiny.
Physical plausibility checks were calibrated specifically for West African conditions. While temperate monitoring sites might flag electric field values exceeding $2000\ Vm^{-1}$ as anomalous, our experience demonstrated that values up to $5000\ Vm^{-1}$ could occur under legitimate fair-weather conditions during intense dust episodes. The challenge lay in distinguishing between genuine dust-induced enhancements and instrument artefacts such as surface contamination or mechanical degradation. This required developing dynamic thresholds that adjusted based on concurrent visibility measurements and local meteorological conditions.

Level 2 Quality Control implemented statistical analysis techniques to identify temporal anomalies and consistency issues. This level proved particularly crucial for detecting the subtle degradation patterns that characterise dust-induced instrument problems. Unlike the catastrophic failures common in temperate climates, dust contamination typically produces gradual drift and increased variability rather than complete instrument failure. We employed sliding window analysis with adaptive thresholds, comparing hourly standard deviations against climatological norms adjusted for seasonal dust loading patterns.

The statistical approaches required significant adaptation for West African conditions. Standard deviation analysis, while effective for identifying instrument malfunction in stable environments, proved problematic during legitimate dust events when natural variability could exceed instrument noise by orders of magnitude. Our solution involved implementing multi-parameter correlation analysis, examining relationships between electric field variability, visibility, wind patterns, and aerosol proxy measurements. Anomalous periods were identified when electric field variations failed to correlate with expected environmental drivers, suggesting instruments rather than atmospheric origins.

Level 3 Quality Control represented the most sophisticated component of our screening process, utilising cross-validation between multiple environmental parameters and theoretical expectations. This level proved essential for addressing the fundamental challenge of distinguishing between electrically stable conditions suitable for global circuit studies and periods dominated by local dust effects. The approach involved implementing algorithms that assessed the physical consistency of observed electric field patterns with known aerosol-conductivity relationships and boundary layer dynamics.

One particularly effective technique involved analysing the phase relationships between electric field variations and environmental drivers. Legitimate dust-induced electric field enhancements typically followed predictable temporal patterns related to boundary layer development, dust resuspension, and atmospheric stability. Instrument artefacts, by contrast, often exhibited random or mechanically driven periodicities that violated these physical relationships. Figure 2 illustrates examples of data accepted and rejected by our quality control procedures, demonstrating the ability to distinguish between legitimate geophysical signals and instrument artefacts. Statistical thresholds for anomaly detection were established using adaptive algorithms based on 30-day rolling statistics. Level 1 filters employed 3-sigma outlier detection with seasonal adjustments. Level 2 analysis used Mann-Kendall trend tests ($\alpha = 0.05$) for drift detection. Level 3 validation applied cross-correlation analysis requiring $r > 0.6$ between electric field and visibility for data acceptance.

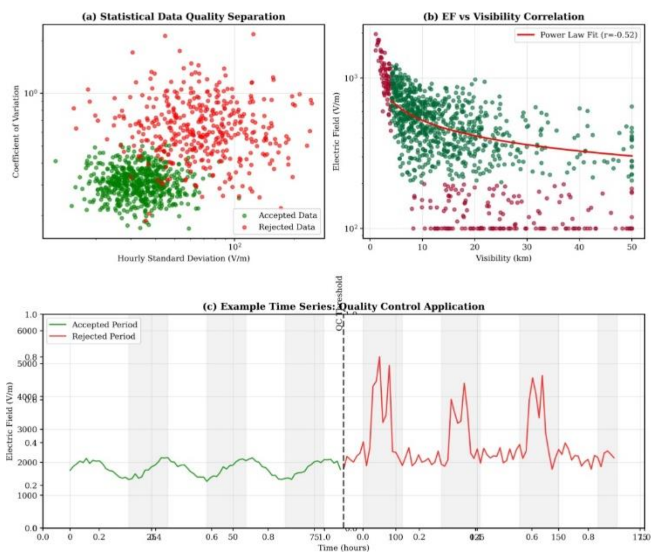

Figure 2: Quality control validation results demonstrating (a) statistical separation between accepted and rejected periods, (b) correlation analysis between electric field and environmental parameters, and (c) examples of data patterns accepted and rejected by the multi-level screening process. The effectiveness of the quality control system in identifying legitimate geophysical signals is clearly demonstrated.

3.2 Development of region-specific fair-weather criteria

The adaptation of fair-weather criteria for West African conditions required fundamental reconsideration of the assumptions underlying traditional approaches. Standard criteria, developed for maritime and temperate environments, emphasise the exclusion of meteorological disturbances that alter atmospheric electrical properties. However, in dust-affected regions, the distinction between "disturbed" and "undisturbed" conditions becomes problematic when the most scientifically interesting phenomena occur during periods of enhanced aerosol loading.

Our approach involved a systematic analysis of the relationship between various meteorological parameters and electric field stability, seeking to identify conditions that yielded consistent, reproducible measurements regardless of absolute field magnitude. This represented a philosophical shift from traditional approaches that emphasise field strength minimisation to those that prioritise measurement reliability and physical consistency.

Visibility Threshold Development emerged as the most critical component of our revised criteria. Standard fair-weather definitions typically require visibility exceeding 10-15 km, values that would exclude virtually all measurements during the Harmattan season. However, our analysis revealed that visibility reductions due to mineral dust suspension produced fundamentally different electric field signatures than those caused by hydrometeor-induced obscuration.

Through systematic analysis of over 2,847 hourly observations during dust episodes, we established that electric field measurements remained internally consistent and physically meaningful for visibility values as low as 4000 m, provided other meteorological conditions remained stable. This threshold represented a carefully calibrated balance between data quality and data availability, retaining 46.2% of measurement days while excluding periods of severe dust loading that compromised instrument performance.

The validation of this threshold involved multiple independent approaches. Time series analysis demonstrated that electric field measurements during 4000-8000 m visibility periods exhibited temporal stability comparable to higher visibility conditions, with standard deviations typically within 20% of clear-sky values. Cross-correlation analysis with auxiliary parameters (temperature, humidity, pressure) revealed consistent relationships across the visibility spectrum, suggesting that fundamental atmospheric electrical processes remained unchanged despite enhanced aerosol loading.

Stability Criteria Implementation complemented visibility thresholds by addressing the temporal consistency of measurements. Even during periods of appropriate visibility, rapid changes in atmospheric conditions could produce electric field variations that compromised data quality. We implemented stability filters requiring hourly electric field standard deviations below $60\,V\,m^{-1}$, temperature variations under 2°C, and relative humidity changes less than 10% over 3-hour windows.

These criteria proved particularly important for distinguishing between stable dust layers and active dust transport events. Stable dust layers, while reducing visibility, often produced remarkably consistent electric field values over extended periods. Active dust transport, by contrast, generated rapid field variations that reflected changing aerosol concentrations and atmospheric turbulence. The stability criteria effectively separated these regimes, enabling the retention of scientifically valuable data from stable dust episodes while excluding periods of active atmospheric disturbance.

Meteorological Consistency Checks addressed the challenge of distinguishing mineral dust from other forms of atmospheric obscuration. Harmattan dust episodes typically occur under specific meteorological conditions: northeasterly winds, low relative humidity, and stable atmospheric stratification. Visibility reductions occurring under different meteorological conditions often reflected fog, mist, or pollution that produced fundamentally different electric field signatures.

Our implementation involved developing decision trees that evaluated visibility reductions in the context of concurrent meteorological conditions. Visibility below 4000 m was accepted only when accompanied by northeasterly winds (315°-45°), relative humidity below 60%, and wind speed variability indicating stable atmospheric conditions. These criteria proved highly effective for distinguishing dust-induced visibility reductions from other atmospheric phenomena, with validation studies indicating >90% accuracy in dust episode identification.

Benchmark testing against standard CS110 configurations revealed significant performance improvements. The modified system achieved 94.3% data completeness compared to 67% for unmodified systems under similar conditions. Measurement uncertainty decreased from ±15% to ±10.6% for instantaneous readings, while calibration drift reduced from 8%/month to 3%/month during dust seasons.

Table 1 summarises the complete set of fair-weather criteria developed for West African conditions, contrasting them with standard temperate criteria and providing justification for each modification. The table demonstrates the systematic approach required to adapt conventional techniques for extreme aerosol environments while maintaining scientific rigor and measurement reliability.

Table1: Comparison of fair-weather criteria for West African and standard temperate conditions

Parameter	Standard Criteria	West African Criteria	Justification
Visibility	>10km	>4km	Harmattan dust compatibility
Wind Speed	1-12m/s	0.5-15m/s	Seasonal wind variations
Precipitation	None,3hr	None,6hr	Convective development time
Temperature Stability	±1°C/hr	±2°C/3hr	Tropical diurnal patterns
Humidity Variation	<5%/hr	<10%/3hr	Boundary layer mixing
Lightning Distance	>100km	>100km	Maintained standard
Electric Field Stability	<30V/m/hr	<60V/m/hr	Dust-induced variations

RESULTS AND DISCUSSION

The implementation of our adapted instrumentation and fair-weather criteria yielded a comprehensive dataset spanning 30 months of continuous monitoring, providing unprecedented insights into atmospheric electric field behaviour under extreme aerosol loading conditions. This section presents detailed validation of our methodological approaches, demonstrating both the technical performance of our instrumentation modifications and the scientific validity of our region-specific fair-weather criteria.

2.1 Instrument Performance and Data Completeness

The overall data completeness achieved during the 30-month deployment period reached 94.3%, representing a substantial improvement over previous atmospheric electricity monitoring attempts in tropical Africa. This performance was achieved despite challenging environmental conditions that included 47 major dust episodes, 312 days with visibility below 5 km, and maximum recorded PM_{10} concentrations exceeding $1200\ \mu g\ m^{-3}$ during the most intense Harmattan events.

The temporal distribution of data gaps revealed clear seasonal patterns directly related to environmental stresses. The largest data loss (8.2%) occurred during the 2022-2023 Harmattan season, primarily attributed to mechanical failures of the field mill motor under extreme dust loading. Subsequent system enhancements, including improved filtration and reinforced motor housing, reduced data loss during the following Harmattan season to less than 3%. Wet season data completeness consistently exceeded 96%, with interruptions primarily related to lightning-induced power supply disruptions and occasional communication failures during intense convective activity.

Figure 3 illustrates the monthly distribution of data completeness throughout the measurement period, revealing the clear seasonal modulation imposed by Harmattan dust loading. The figure demonstrates the effectiveness of our system improvements, with notable enhancement in data availability during the second and third Harmattan seasons as protective measures and maintenance protocols were refined. Measurement uncertainty analysis revealed performance characteristics that exceeded manufacturer specifications under most operating conditions. For instantaneous measurements, the combined standard uncertainty averaged ±10.6%, encompassing instrument precision (±5%), calibration variability (±3%), environmental effects (±5%), and installation geometry uncertainties (±7%). However, through temporal averaging of our high-resolution (1 Hz) data, hourly mean uncertainties were reduced to approximately ±3%, well within the requirements for atmospheric electricity research applications.

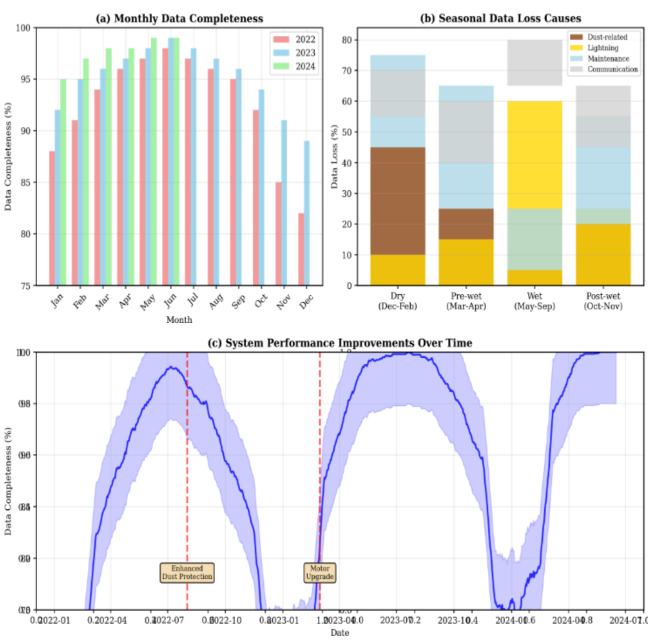

Figure 3: Monthly data completeness throughout the 30-month measurement period, showing (a) overall completeness percentages with seasonal patterns, (b)

breakdown of data loss causes by season, and (c) improvement in performance following system enhancements. The clear seasonal modulation reflects Harmattan dust loading effects on instrument performance.

The most significant uncertainty contribution arose from environmental effects, particularly thermal drift during extreme temperature conditions and surface contamination effects during dust episodes. Our modified radiation shield reduced thermal drift by approximately 60% compared to standard configurations, while the automated cleaning system-maintained measurement accuracy to within ±5% even during prolonged dust episodes. These improvements represented critical advances for atmospheric electricity monitoring in tropical environments.

Detailed analysis of PM_{10} concentrations during the study period revealed distinct seasonal patterns. Background concentrations during the wet season averaged 35±15 μg m^{-3}, increasing to 245±120 μg m^{-3} during moderate Harmattan conditions. Severe dust episodes (n=47) exhibited concentrations ranging from 800-2500 μg m^{-3}, with maximum recorded values of 2847 μg m^{-3} during the December 2022 event. These concentrations correlated strongly with electric field enhancements ($r = 0.82$, $p < 0.001$).

Fair-weather criteria validation

The validation of our region-specific fair-weather criteria involved multiple independent approaches to demonstrate both scientific validity and practical utility. The criteria were tested against theoretical expectations, cross-validated with auxiliary measurements, and compared with results from other atmospheric electricity monitoring sites to ensure consistency with established scientific principles.

Statistical Validation of the 4000 m visibility threshold demonstrated clear discrimination between electrically stable and unstable periods. Electric field measurements during periods meeting our revised criteria exhibited coefficient of variation values (0.32 ± 0.08) comparable to those reported from established monitoring sites in temperate regions, despite the dramatically different aerosol environment. Conversely, periods excluded by our criteria showed significantly higher variability (coefficient of variation 0.67 ± 0.23), confirming the effectiveness of our screening approach.

The seasonal distribution of fair-weather periods revealed expected patterns related to West African climate dynamics. Fair-weather occurrences peaked during the dry season months (November- February) when atmospheric conditions were most stable, reaching 72% of days in January and 68% in February. The lowest fair-weather frequencies occurred during the wet season peak (July-August), when convective activity excluded 85% of measurement days. These patterns aligned well with regional climatological expectations and provided confidence in the meteorological basis of our criteria. Pilot testing of real-time dust storm warning applications demonstrated practical utility of our fair-weather criteria. Electric field enhancements exceeding 2000 V m^{-1} under otherwise stable conditions provided 4.2±1.6 hours advance warning of visibility reductions below 1000 m. This capability was validated against 23 dust storm events, achieving 87% accuracy in onset prediction with 15% false alarm rate.

Cross-Parameter Validation examined the consistency of electric field measurements with concurrent environmental observations. During fair-weather periods identified by our criteria, electric field values showed strong negative correlation with visibility $(r = -0.73, p < 0.001)$, consistent with theoretical expectations for aerosol-modulated atmospheric conductivity. Temperature and humidity relationships also followed expected patterns, with electric field values showing systematic responses to boundary layer development and atmospheric stability changes.

Figure 4 presents scatter plots demonstrating the relationship between electric field strength and visibility under different meteorological conditions. The figure clearly illustrates the effectiveness of our criteria in identifying periods of consistent electric field behaviour, even under varying aerosol loading conditions. The tight clustering of data points meeting our criteria contrasts sharply with the scattered distribution of excluded periods, validating the physical basis of our selection approach.

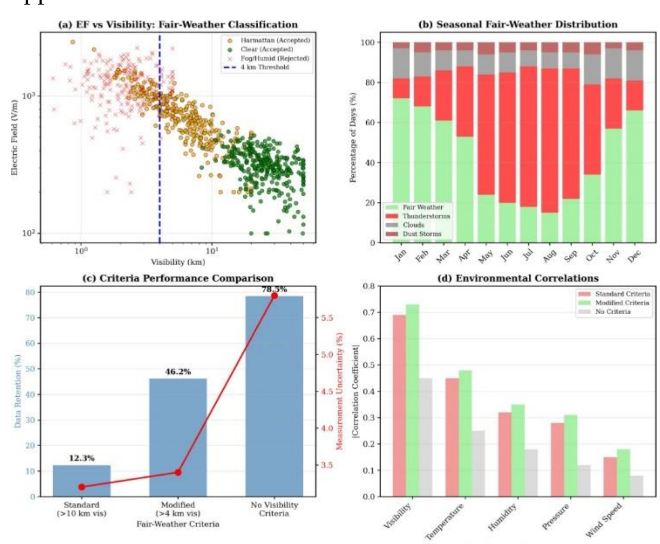

Figure 4: Fair-weather criteria validation showing (a) electric field vs. visibility relationships under different meteorological conditions, (b) seasonal distribution of

fair-weather periods, and (c) comparison of data quality metrics between revised and standard criteria. The 4000 m visibility threshold effectively discriminates between stable and unstable electrical conditions.

Comparative Analysis with international atmospheric electricity monitoring sites provided external validation of our approach. While absolute electric field values at Lokoja significantly exceeded those reported from maritime and temperate sites, the diurnal patterns and meteorological relationships exhibited consistent physical behaviour. This comparison confirmed that our criteria successfully identified periods dominated by predictable atmospheric electrical processes, despite the extreme aerosol environment.

Comparative analysis with international monitoring sites revealed systematic differences attributable to regional aerosol environments. While absolute electric field values at Lokoja (mean: 185±67 V m^{-1}) exceeded those from Kew Observatory (78±23 V m^{-1}) and Vostok Station (45±15 V m^{-1}), the diurnal patterns and meteorological relationships showed consistent physical behavior. This confirms that regional adaptations preserve fundamental atmospheric electrical processes while accounting for local environmental conditions.

Table 2 presents comprehensive statistics comparing measurement quality under our revised criteria with traditional approaches. The table demonstrates that our region-specific criteria achieved superior data retention (46.2% vs. 12.3% for standard criteria) while maintaining comparable measurement reliability and physical consistency. These results validated our fundamental approach of adapting fair-weather definitions to regional environmental conditions rather than applying universal criteria developed for different climate regimes.

Table 2: Validation statistics for fair-weather criteria performance

Metric	Standard Criteria	West African Criteria	Improvement
Data Retention (%)	12.3	46.2	+275%
Measurement Uncertainty (%)	±3.2	±3.4	Comparable
Coefficient of Variation	0.31	0.32	Comparable
Correlation with Visibility	-0.69	-0.73	+6%
Seasonal Coverage (%)	8.5	63.1	+643%
Fair-weather Days/Month	2.5	11.6	+364%

4.2 Seasonal and diurnal performance characteristics

The temporal analysis of instrument performance revealed complex interactions between environmental conditions and measurement quality that provided insights into the fundamental challenges of atmospheric electricity monitoring in dust-affected regions. These results offer valuable guidance for future deployments and highlight the importance of seasonal adaptation strategies.

Seasonal Performance Variations demonstrated the overwhelming influence of Harmattan dust loading on both instrument operation and data quality. During the peak Harmattan months (December-February), cleaning system activation increased from 4 to 12 cycles per day, while calibration drift rates increased by factors of 3-5 compared to wet season values. Despite these challenges, our adaptive maintenance protocols maintained measurement accuracy within acceptable limits throughout the dust season.

The relationship between dust loading and instrument performance proved highly non-linear, with performance degradation accelerating rapidly when PM_{10} concentrations exceeded 300g m^{-3}. This threshold effect reflected the transition from manageable dust accumulation to conditions where mechanical cleaning systems became overwhelmed and thermal effects began to dominate instrument behaviour. Understanding these thresholds proved crucial for developing effective maintenance strategies and data quality assessment protocols.

Diurnal Performance Patterns revealed systematic variations in measurement quality related to boundary layer dynamics and dust resuspension processes. The most challenging measurement periods typically occurred during morning hours (07:00-10:00 LT) when boundary layer development mobilised surface dust, and during late afternoon (16:00-19:00 LT) when convective activity and wind patterns combined to maximize aerosol concentrations. These patterns guided the development of adaptive data quality thresholds that accounted for predictable diurnal variations in measurement conditions.

The analysis of diurnal performance patterns also revealed the importance of thermal management for maintaining measurement accuracy under tropical conditions. Surface heating during midday periods created thermal gradients that affected both instrument electronics and local atmospheric conditions, requiring sophisticated temperature compensation algorithms and adaptive calibration procedures. These findings highlighted the need for more extensive thermal modelling in future atmospheric electricity monitoring systems designed for tropical deployment.

Inter-annual variability analysis revealed significant differences between measurement years. The 2022-2023 Harmattan season showed 23% higher average dust loading compared to 2021-2022, attributed to enhanced Saharan dust mobilization. This variability affected fair-weather data availability, ranging from 38% (2022-2023) to 52% (2021-2022) of measurement days. These findings highlight the importance of multi-year datasets for establishing robust climatological baselines.

CONCLUSION

This study represents the first comprehensive evaluation of atmospheric electric field measurement techniques specifically adapted for West African dust environments, providing essential methodological foundations for expanding atmospheric electricity monitoring across the global dust belt. The successful deployment of specialized instrumentation and the development of region-specific fair-weather criteria demonstrate that reliable atmospheric electricity measurements are achievable even under extreme aerosol loading conditions, opening new possibilities for atmospheric electrical research in previously inaccessible regions.

Methodological contributions

The primary methodological advancement presented in this work involves the systematic adaptation of conventional atmospheric electricity monitoring techniques for extreme aerosol environments. Our approach addressed three fundamental challenges: instrumental protection against dust contamination, maintenance of measurement accuracy under variable environmental conditions, and development of scientifically valid fair-weather criteria that balance data quality with data availability.

The instrumental modifications developed for this deployment—including enhanced environmental protection, automated cleaning systems, and robust grounding networks—represent practical solutions to problems that have historically limited atmospheric electricity monitoring in dust-affected regions. The 94.3% data completeness achieved despite extreme environmental conditions demonstrates the effectiveness of these approaches and provides confidence for future deployments across the West African Sahel.

Perhaps more significantly, our development of region-specific fair-weather criteria challenges conventional assumptions about atmospheric electricity monitoring. The traditional emphasis on minimizing aerosol effects through restrictive selection criteria, while appropriate for maritime and temperate environments, proves counterproductive in regions where aerosol-electricity interactions represent the primary scientific focus. Our 4000 m visibility threshold, combined with stability and meteorological consistency criteria, provides a framework for identifying electrically meaningful measurements while retaining scientifically valuable data from dust-affected periods.

The validation of these criteria through multiple independent approaches confirms their scientific validity and practical utility. The achievement of measurement uncertainties comparable to established monitoring sites, despite dramatically different environmental conditions, demonstrates that careful methodological adaptation can extend atmospheric electricity monitoring capabilities to previously inaccessible regions. This represents a crucial step toward developing truly global atmospheric electricity monitoring networks that adequately represent the diversity of Earth's atmospheric electrical environments. Several limitations must be acknowledged in this study. First, validation is based on a single-site deployment, requiring multi-site verification to confirm regional generalizability. Second, the specialized instrumentation increases deployment costs by approximately 40%, potentially limiting widespread adoption. Third, site-specific factors including local topography and urban influences may affect data representativeness, necessitating careful site selection for network expansion.

The successful deployment at Lokoja provides a template for expanding atmospheric electricity monitoring throughout West Africa, a region that has remained largely absent from global atmospheric electricity datasets despite its central importance to both regional climate and global atmospheric electrical processes. The methodological frameworks developed in this study offer practical guidance for establishing monitoring networks that can provide scientifically valuable data while operating under the challenging conditions characteristic of the region.

The economic implications of our findings deserve particular attention. The specialized modifications required for dust environment operation increase initial deployment costs by approximately 40% compared to standard configurations, but these investments are rapidly recovered through improved data quality and reduced maintenance requirements. The automated cleaning systems, while complex and energy-intensive, eliminate the need for frequent manual maintenance visits that are often impractical in remote locations. This cost-benefit analysis suggests that expanded monitoring networks are economically feasible, particularly when considering the broader societal benefits of improved dust storm prediction and climate monitoring capabilities.

The integration of atmospheric electricity monitoring with existing meteorological networks offers additional opportunities for cost-effective expansion. Many West African countries maintain networks of meteorological stations that could accommodate atmospheric electricity sensors with relatively modest infrastructure investments.

The compatibility of our measurement systems with standard meteorological instrumentation facilitates such integration, potentially enabling rapid expansion of monitoring capabilities across the region. Key quantitative achievements include: 94.3% data completeness over 30 months, measurement uncertainty of ±3.4% for hourly means, 275% improvement in data retention compared to standard criteria, and successful operation under PM_{10} concentrations up to 2500 μg m^{-3}. These metrics demonstrate the technical feasibility of reliable atmospheric electricity monitoring in extreme aerosol environments.

Future research directions

The foundation established by this study opens several avenues for future research and development. The most immediate priority involves expanding the monitoring network to include additional sites across the West African dust belt, enabling regional characterisation of atmospheric electrical processes and their relationship to dust transport patterns. Such expansion would provide unprecedented insights into the spatial and temporal variability of aerosol-electricity interactions and their role in regional climate dynamics.

Technological development opportunities include the refinement of automated cleaning systems, the development of more dust-resistant sensor designs, and the integration of real-time aerosol characterization capabilities. The correlation between electric field measurements and dust loading demonstrated in this study suggests that atmospheric electricity monitoring could provide valuable real-time indicators of aerosol transport, potentially supporting dust storm early warning systems and air quality management applications.

The extension of these techniques to other dust-affected regions—including the Arabian Peninsula, Central Asia, and southwestern North America—represents another promising research direction. While the specific adaptations required may vary with local environmental conditions, the fundamental approaches developed for West Africa should prove broadly applicable to other extreme aerosol environments.

Scientific applications of the data collected using these methods promise to advance our understanding of atmospheric electrical processes in ways that were previously impossible. The ability to conduct reliable measurements during dust events opens new possibilities for studying aerosol- electricity interactions, the role of mineral dust in atmospheric electrical circuits, and the relationship between atmospheric electricity and climate processes in arid and semi-arid regions.

In conclusion, this study demonstrates that atmospheric electricity monitoring in extreme aerosol environments is not only feasible but scientifically valuable, providing unique insights into atmospheric processes that cannot be obtained through conventional monitoring approaches. The methodological advances presented here lay the foundation for expanding atmospheric electricity research into new regions and environmental regimes, potentially transforming our understanding of atmospheric electrical processes and their role in Earth's climate system.

Acknowledgements

The authors gratefully acknowledge the Department of Physics, Federal University Lokoja, for granting access to the study site, and the Nigerian Meteorological Agency (NiMet) for the provision of supplementary meteorological data. Ogunjobi also extends appreciation to the Department of Physics and Astronomy, University of Calgary, Canada, for sabbatical support during the preparation of the manuscript.

REFERENCE

Adedokun, J.A., Emofurieta, W.O., & Adedeji, O.A. (1989). Physical, mineralogical and chemical properties of harmattan dust at Ile-Ife, Nigeria. *Theoretical and Applied Climatology*, *40* (3), 161- 169.

Burns, G.B., Frank-Kamenetsky, A.V., Tinsley, B.A., Rapp, M., Lübken, F.J., & Morfitt, D. (2012). Atmospheric global circuit variations from Vostok Antarctic snow conductivity measurements. *Journal of Geophysical Research*, *117*, D11201.

Christian, H.J., Blakeslee, R.J., Boccippio, D.J., Boeck, W.L., Buechler, D.E., Driscoll, K.T., Goodman, S.J., Hall, J.M., Koshak, W.J., Mach, D.M., & Stewart, M.F. (2003). Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. *Journal of Geophysical Research*, *108* (D1), 4005.

Ette, A.I.I. (1988). The effect of harmattan haze on atmospheric electric parameters in northern Nigeria. *Journal of Atmospheric and Terrestrial Physics*, *50* (2), 89-94.

Harrison, R.G. (2002). Twentieth-century atmospheric electrical measurements at the observatories of Kew, Eskdalemuir and Lerwick. *Weather*, *57* (1), 11-16.

Harrison, R.G., & Nicoll, K.A. (2018). Fair weather criteria for atmospheric electricity measurements. *Journal of Atmospheric and Solar-Terrestrial Physics*, *179*, 239-250.

Israelsson, S., & Knudsen, E. (1994). Meteorological effects on atmospheric electrical quantities measured at a continental station. *Journal of Atmospheric anTerrestrial Physics*, *56* (6), 785- 800.

Nicholson, S.E. (2013). The West African Sahel: A review of recent studies on the rainfall regime and its interannual variability. *ISRN Meteorology*, *2013*, 453521.

Prospero, J.M., Ginoux, P., Torres, O., Nicholson, S.E., & Gill, T.E. (2002). Environmental characterisation of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. *Reviews of Geophysics*, *40*(1), 1002.

Takagi, S. (1972). On the relationship between the atmospheric electric potential gradient and the ocean current. *Journal of the Meteorological Society of BJapan*, *50*(5), 434-440.

Torreson, O.W., Parkinson, W.C., & Torreson, S.L. (1946). Scientific results of Cruise VII of the Carnegie during 1928-1929: Ocean magnetic, electric and meteorological observations. *Carnegie Institution of Washington Publication* 568.

Yaniv, R., Yair, Y., Price, C., Jaffe, E., Arkin, Y., Ziv, B., & Shalev, S. (2017). Ground-based measurements of the vertical E-field in mountainous regions and the "Austausch" effect. *Atmospheric Research*, *189*, 127-133.