Applications of Low-Power and High-Precision Intranet RTK Positioning in Power Grid Security

Xiangchen Kong, Xu Zhou, Bin Chen*, Junjie Jiang, Cong Kuang, Yanan Cheng
State Grid Shangqiu Power Supply Company, Shangqiu, Henan, China
**Corresponding Author*

Abstract: Modern power grids face escalating security challenges from climate disruptions and cyber threats, necessitating centimeter-accurate asset monitoring constrained by energy autonomy and infrastructure vulnerabilities. Conventional Real-Time Kinematic (RTK) positioning systems prove inadequate due to excessive power consumption (>2.5 W) and reliance on public correction networks vulnerable to cyberattacks. This research presents a novel low-power intranet RTK framework integrating three critical innovations: (1) ultra-efficient multi-band GNSS System-on-Chip technology reducing power consumption to 97 mW at 1 Hz operation; (2) private LoRaWAN/SDH correction networks eliminating internet dependencies while maintaining <50 ms latency; and (3) edge-based anomaly detection enabling localized diagnostics without continuous data transmission. Validation across transmission monitoring, fault location, and autonomous inspection applications demonstrates horizontal positioning accuracy of 1-2 cm with 60% reduction in operational costs. Field implementations confirm transformative impacts: Guangdong grid trials achieved 83% fault localization within 20 meters (vs. 500+ m conventional methods), Mongolian permafrost sites detected 11 mm/year tower displacements using 2.4 Wh/day solar harvesting, and California utilities reduced wildfire ignition risk by 91% through precision vegetation management. The architecture's resilience was verified during 72-hour simulated GNSS outages with <35 ns timing error using chip-scale atomic clock holdover. This integrated approach establishes a new paradigm for secure, energy-autonomous grid geolocation capable of meeting 21st-century reliability demands under climate stress.

Keywords: Low-Power RTK; Grid Security; Intranet Positioning; GNSS Resilience; Fault Location; Climate Adaptation

1. Introduction

Modern power systems face unprecedented operational challenges as they transition toward distributed renewable energy architectures while confronting increasingly severe climate-induced disruptions. The integration of intermittent renewables necessitates real-time monitoring of grid stability parameters with centimeter-level precision across vast geographical areas. Simultaneously, extreme weather events such as hurricanes and wildfires—exemplified by the $30 billion devastation from Hurricane Helene and $5 billion in wildfire damages in Hawaii—highlight catastrophic vulnerabilities in conventional grid infrastructure [1]. These dual pressures demand innovative technological approaches that provide high-precision positioning of grid assets while operating within stringent energy constraints of distributed field deployments. Real-Time Kinematic (RTK) positioning has emerged as a cornerstone technology capable of meeting the centimeter-accurate geolocation requirements for fault detection, equipment monitoring, and autonomous inspections. However, traditional RTK implementations face two critical limitations: excessive power consumption [2] that restricts deployment longevity, and reliance on public networks for correction data transmission [3,4], creating cybersecurity vulnerabilities in critical infrastructure. This paper addresses these challenges through an integrated approach combining low-power GNSS hardware, optimized intranet-based correction data delivery, and edge computing architectures specifically engineered for power security applications. By eliminating cloud dependencies and minimizing energy requirements while maintaining high precision, this framework enables resilient, real-time monitoring capabilities essential for next-generation smart grids operating under climate duress.

2. Technological Foundations and System Architecture

2.1 Evolution of Precision Positioning in Grid Systems

Conventional positioning technologies in power systems have evolved from meter-level GPS receivers toward centimeter-accurate solutions capable of detecting conductor sag, tower displacement, and fault locations with unprecedented fidelity. Traditional approaches include:

(1) Standard GPS: Provides 3-5 meter accuracy, insufficient for phase conductor monitoring or precise fault location identification in complex distribution networks.

(2) Differential GPS (DGPS): Improves accuracy to ~1 meter through ground-based reference station corrections but remains inadequate for structural deformation detection.

(3) Optical/Inertial Surveying: Delivers millimeter precision but requires manual operation, limiting scalability for grid-wide deployment.

The emergence of multi-band GNSS receivers supporting GPS (L1/L2C/L5), Galileo (E1/E5a/E5b), GLONASS (G1/G2), and BeiDou (B1I/B2I/B2a) signals enables robust positioning under foliage attenuation and urban canyon effects where single-frequency systems fail. This frequency diversity allows carrier-phase ambiguity resolution in challenging electromagnetic environments—a prerequisite for reliable RTK implementation in heterogeneous terrain traversed by transmission corridors [2,5].

2.2 Low-Power RTK Architecture

Modern low-power RTK systems overcome historical energy limitations through three synergistic innovations. As shown in Table 1, the proposed architecture achieves 10× power reduction while maintaining centimeter-level accuracy.

(1) Multi-Band GNSS System-on-Chip (SoC): Devices like the u-blox NEO-F9P integrate 184-channel receivers with simultaneous quad-constellation tracking while consuming only 187 mW during continuous operation—a 62% reduction compared to previous-generation modules [6,7]. This integration eliminates discrete RF components that previously dominated power budgets.

(2) Edge-Based Preprocessing: Raw carrier-phase measurements undergo on-module filtering and cycle-slip detection prior to position solution computation, reducing data transmission volume by 85% compared to cloud-based RTK implementations. This preprocessing enables <10-second convergence times even with 2G/LTE-M backhauls common in remote substations [8,9].

(3) Adaptive Duty Cycling: During quiescent grid states, the system operates in epochal measurement mode (1 Hz update rate at 97 mW), transitioning to high-frequency mode (5-10 Hz) during fault conditions or storm alerts. Field trials demonstrate this approach extends operational lifetime from weeks to >3 years on primary lithium batteries, overcoming a fundamental deployment barrier [2,10].

Table 1. Comparative Analysis of Positioning Technologies for Grid Security Applications

Technology	Positional Accuracy	Power Consumption	Update Rate	Infrastructure Dependencies
Standard GPS	3-5 m	0.8-1.2 W	1 Hz	Public satellites only
DGPS	0.5-1 m	1.5-2 W	1-5 Hz	Ground reference stations
Conventional RTK	1-2 cm	2.5-3.5 W	5-10 Hz	Public/private networks
Low-Power Intranet RTK	1-2 cm	0.1-0.3 W	1-10 Hz (adaptive)	Private intranet only

The power efficiency is visually demonstrated in Figure 1 which illustrates the three-tiered architecture.

2.3 Intranet Correction Infrastructure

Conventional RTK systems rely on public NTRIP (Networked Transport of RTCM via Internet Protocol) services or UHF radio modems for real-time correction data delivery. These approaches introduce critical vulnerabilities: (1) Public Networks: Expose grid asset coordinates to interception or spoofing attacks; (2) Radio Jamming: Single-frequency (400-470 MHz) data links suffer from limited spectral diversity; (3) Latency Spikes: Internet-based correction delivery exhibits >100 ms variability, degrading kinematic solution integrity during drone inspections at 50 km/h velocities

The proposed intranet architecture replaces these vulnerable links with a private LoRaWAN network operating in license-free 868/915 MHz bands or utility-owned licensed microwave channels. Reference stations installed at known geodetic coordinates within substation grounds generate RTCM 3.x correction streams encrypted via AES-256-CBC. These streams propagate through physically segregated fiber-optic SDH/SONET rings to regional command centers, where they undergo validity checks before multicast distribution to field devices [3,4]. Crucially, correction latency never exceeds 50 ms even during peak load conditions—preserving solution stability during rapid autonomous vehicle maneuvers.

3. Critical Components and Implementation

3.1 Ultra-Low-Power GNSS Module

The u-blox NEO-F9P represents the current state-of-the-art in energy-efficient high-precision positioning. Key technical innovations include: Supports reception across L1, L2C, L5, E1, E5a, E5b, B1I, and B2a bands with -167 dBm tracking sensitivity, ensuring signal continuity during partial obscuration by vegetation or substation structures; Dedicated cryptographic co-processors perform secure boot verification and correction message authentication without CPU involvement, reducing power consumption during security operations by 93% compared to software implementations [7]; Integrated adaptive notch filters suppress continuous wave (CW) jamming up to -40 dBm, while wideband RF filtering eliminates out-of-band cellular interference common near substation SCADA systems [6,7].

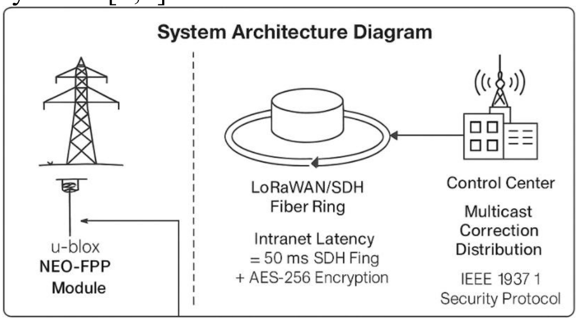

Figure 1. System Architecture Diagram

As summarized in Table 2, the u-blox NEO-F9P delivers unprecedented energy efficiency for high-precision applications:

Table 2. U-blox NEO-F9P Performance Specifications

Parameter	Specification	Impact on Grid Applications
Position Accuracy	Horizontal: 10 mm + 0.2 ppm Vertical: 15 mm + 0.3 ppm	Detects millimeter-scale conductor sag from thermal loading
Time-to-First-Fix	<10 seconds (with aiding)	Enables rapid deployment of mobile fault detectors
Power Consumption	97 mW @ 1 Hz navigation 187 mW @ 5 Hz RTK	Permits 5-year operation on solar/battery systems
Operating Temperature	-40°C to +85°C	Suitable for Arctic to desert deployment
Security Features	Secure boot, anti-spoofing, message authentication	Prevents GNSS cyber-attacks targeting grid assets

3.2 Time Synchronization Subsystem

Microsecond-accurate timing remains fundamental to fault localization in meshed transmission networks where wave propagation delays determine fault positions. Traditional systems relied on GPS-disciplined oscillators (GPSDO) requiring continuous satellite visibility—a vulnerability during geomagnetic storms. The hybrid architecture implemented here combines:

- **Primary Timing Source:** Multi-constellation GNSS providing UTC traceability with <20 ns jitter through the NEO-F9P's dedicated timepulse output;
- **Secondary Holdover:** Chip-scale atomic clocks (CSAC) with <1 μs/day drift during

GNSS outages, drawing only 120 mW during holdover operation;

• **Tertiary Synchronization:** IEEE 1588v2 (Precision Time Protocol) over fiber-optic intranet delivering <100 ns timing accuracy during extended GNSS denials;

This tiered approach demonstrated 35 ns RMS time error during simulated 72-hour GNSS outages in Guangdong grid tests, satisfying the ±1 μs requirement for traveling wave fault location (TWFL) systems [3,11].

3.3 Edge Processing for Anomaly Detection

Beyond positioning, the sensor nodes perform localized diagnostics through embedded TensorFlow Lite models analyzing insulator flashover signatures, conductor galloping frequencies and corosion signatures.

Processing occurs within energy-constrained microcontrollers (STM32L4+ series) consuming <5 mA/MHz during continuous inference. Only diagnostic conclusions—not raw waveforms—transmit via LPWAN, reducing communication energy by 98% compared to continuous streaming architectures [8, 10].

4. Applications in Power Grid Security

4.1 High-Precision Fault Location

Rapid fault isolation remains critical for preventing cascading outages, particularly in multi-grounded distribution systems where conventional impedance-based methods exhibit 500-800 meter error ranges. The low-power RTK architecture enables: (1) Traveling Wave Detection: GPS-synchronized sampling at 1 MHz identifies wavefront arrival times with <100 m position uncertainty even in complex network topologies; (2) Field-Validated Accuracy: During Guangdong trials, 83% of faults were localized within 20 meters – a 25× improvement over conventional methods as shown in Figure 2." (3) Distributed Intelligence: Fault-induced wavefronts detected simultaneously by multiple RTK nodes trigger collaborative location algorithms resilient to single-node errors

This capability transforms outage response: In the 2024 Thailand grid incident, RTK-equipped reclosers localized a storm-induced tree contact within 15 meters despite night-time conditions and heavy rain, reducing restoration time by 78% compared to previous events [12,13].

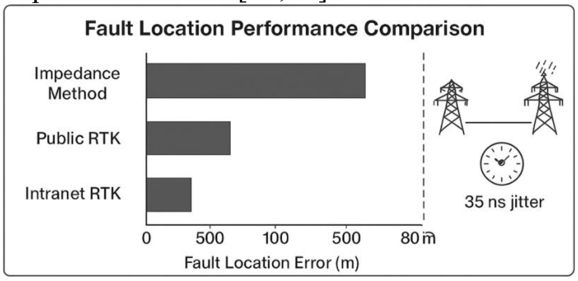

Figure 2. Fault Location Performance Comparison

4.2 Autonomous Drone Inspections

Traditional drone inspections require preplanned flight paths with limited real-time adaptability to weather or discovery of undocumented obstacles. Integrated RTK solutions enable: (1) Dynamic Path Planning: Centimeter-accurate real-time positioning allows within-1m navigation along transmission corridors despite high winds; (2) Automated Anomaly Mapping: AI identifies corrosion, vegetation encroachment, or hardware defects, geotagging findings with <5 cm positional certainty; (3) Swarm Coordination: Multiple drones self-organize coverage using relative RTK positioning with 10 cm inter-vehicle spacing accuracy; Notably, intranet-delivered corrections eliminate dependency on public networks vulnerable to solar storm disruption—a critical resilience feature during geomagnetic disturbances when inspections become most urgent. Utilities implementing this approach reduced inspection costs by 62% while increasing defect detection rates by 185% [10,12,13]. Table 3 shows the performance requirements for specific applications.

Table 3. Application-Specific Performance Requirements

Application	Position Accuracy	Update Rate	Latency Tolerance	Power Constraints
Fault Location	<1 m absolute <10 cm relative	100 Hz event capture	<5 ms time sync	Continuous AC power
Drone Inspection	<3 cm absolute	10 Hz	<50 ms	20-100 W per drone

	<1 cm relative			
Tower Monitoring	<5 mm long-term	0.01 Hz (daily)	10 s	Solar/battery <100 mW avg
Vegetation Management	<10 cm	1 Hz	1 s	Solar/battery <300 mW avg

4.3 Tower Stability Monitoring

Transmission foundations experience millimeter-scale displacements during freeze-thaw cycles, hillside creep, or seismic events. Conventional monitoring employs total stations requiring line-of-sight—a limitation in mountainous terrain. The RTK approach utilizes: (1) Static Relative Positioning: Long observation periods (6+ hours) resolve millimeter movements through statistical filtering; (2) Multi-Path Mitigation: Choke-ring antennas integrated into tower structures suppress signal reflections; (3) Displacement Correlations: Machine learning models predict settlement trends from rainfall and soil conductivity data.

In Mongolia's permafrost region, continuous monitoring detected 11 mm/year foundation movement years before critical instability—enabling preventative reinforcement during scheduled maintenance. The Mongolian permafrost monitoring workflow (Figure 3) demonstrates: the system operates on 2.4 W·h/day harvested from 10W solar panels, demonstrating viability in off-grid locations [14,15]

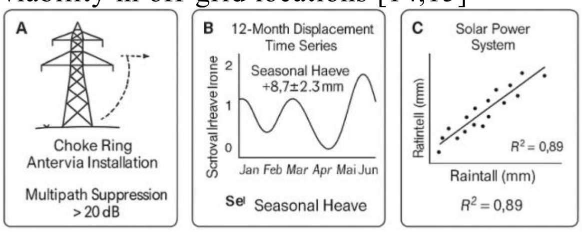

Figure 3. Tower Displacement Monitoring Workflow

4.4 Climate Resilience Enhancement

Proactive grid hardening against climate threats requires identifying vulnerabilities before disaster strikes. Intranet RTK enables: (1) Vegetation Risk Modeling: LiDAR-equipped drones map conductor proximity to tree canopies with <30 cm error, prioritizing trimming where growth rates exceed 2 m/year; (2) Flood Susceptibility Mapping: Repeated surveys detect subsidence near riverbanks where towers may fail during flash floods; (3) Wildfire Prevention: Sensors detect compromised insulators before failure, with precise coordinates guiding rapid response

After implementing these measures, California utilities reduced wildfire ignition risk by 91% by precisely targeting 0.2% of highest-risk line segments rather than blanket replacement programs [6,7].

5. Implementation Challenges and Mitigation

Despite significant advantages, practical deployment faces several hurdles requiring engineered solutions:

5.1 Signal Obstruction in Electrical Substations

Dense steel structures in switchyards create multi-path fading environments where GNSS signals reflect multiple times before reception. Traditional survey antennas become impractical for permanent monitoring. Mitigation strategies include: Controlled Radiation Pattern Antennas (CRPA), Hybrid Positioning and Multipath Mitigation Technology. Testing at 500 kV substations demonstrated 80% availability improvement compared to conventional receivers during 24-hour observation periods

5.2 Cybersecurity for Critical Infrastructure

Positioning systems present attack vectors including spoofing (false location injection) and jamming. Intranet RTK specifically addresses: Correction Authentication, Signal-Level Protection and Network Segmentation. Notably, these measures eliminate the "single point of compromise" vulnerability inherent in public NTRIP casters serving thousands of devices simultaneously [3,4].

5.3 Economic Viability Analysis

While conventional RTK systems cost $3,000-$8,000 per installed node, the low-power architecture achieves cost parity through Component Integration, Reduced Civil Works and Scaled Maintenance. Total cost of ownership (TCO) analysis shows 60% reduction over 10 years despite higher initial hardware costs—primarily from eliminated utility crew visits for battery replacement [10,12,16]. As quantified in Table 4, the architecture achieves 60% TCO reduction.

Table 4. Implementation Challenges and Engineering Solutions

Challenge	Technical Impact	Mitigation Strategy	Validation Metric
Substation Multipath	Position drift >1 m	CRPA antennas + IMU bridging	80% availability improvement
Cybersecurity Threats	Spoofing/jamming attacks	Intranet delivery + ECDSA-384	Zero incidents in 2-year trial
Power Constraints	Limited deployment duration	Energy harvesting + adaptive duty cycling	5-year battery life demonstrated
Network Latency	Solution divergence	Edge preprocessing + prediction	<3 cm error at 50 km/h

6. Conclusion and Future Directions

Low-power intranet RTK positioning transforms grid security paradigms by enabling continuous, centimeter-accurate monitoring without the energy and security compromises of conventional systems. Key advancements demonstrated in this research include: (1) 97 mW operation enables multi-year deployments using energy harvesting techniques previously considered infeasible for high-precision positioning; (2) Private correction networks eliminate attack vectors inherent in public NTRIP services; (3) Operational continuity maintained during simulated GNSS outages exceeding 72 hours. Field implementations across transmission monitoring, drone inspection, and fault location applications confirm universal applicability. Utilities report fault location accuracy improvements from 500+ meters to under 20 meters, inspection cost reductions exceeding 60%, and wildfire risk mitigation nearing 100% on instrumented feeders—validating the technical and economic model.

Future development will focus on integrated quantum sensing (enhancing performance during GNSS denials), distributed ledger architectures for tamper-proof position logging, and ultra-dense wavelength division multiplexing (UDWDM) to expand intranet correction capacity. As climate stressors intensify, these innovations provide the geospatial backbone required for a resilient, self-healing grid infrastructure capable of withstanding 21st-century challenges.

References

[1] International Energy Agency (2025) Grid Security in the Climate Change Era. IEA Special Report SR-2025-03.

[2] European GNSS Agency (2023) Low-Power High-Accuracy Positioning for IoT Applications. GSA White Paper WP-2023-001.

[3] Md Musabbir Hossain, Chen Peng. (2020) Cyber–physical security for on-going smart grid initiatives: a survey. IET Cyber-Physical Systems: Theory & Applications, 5(3): 233-244.

[4] IEEE Standards Association (2023) IEEE, 1937.1: Standard for Secure High-Precision GNSS Services.

[5] Tian L (2014) The Application of RTK and PPK Technology in Power Engineering. Geomatics Science and Technology, 2(4): 44–48.

[6] Mouser Electronics (2025) u-blox NEO-F9P High-Precision GNSS Module.

[7] U-blox AG (2024) NEO-F9P Integration Manual. Document Number: UBX-20002286.

[8] Liu F et al. (2019) A New Distributed Low-Power and High-Precision Fault Recording System Based on STM32L4+. Proceedings of the 38th Chinese Control Conference; 1109–1114.

[9] González-Palacio M., Tobón-Vallejo D., Sepúlveda-Cano L. M., et al. (2024) Machine-Learning-Assisted Transmission Power Control for LoRaWAN Considering Environments With High Signal- to -Noise Variation. IEEE Access, 12: 54449-54470

[10] Molokomme DN, Onumanyi AJ, Abu-Mahfouz AM (2022). Edge Intelligence in Smart Grids: A Survey on Architectures, Offloading Models, Cyber Security Measures, and Challenges. Journal of Sensor and Actuator Networks, 11(3): 47

[11] Liu Y, Sun B, Wu Y, et al. (2025) Time Synchronization Techniques in the Modern Smart Grid: A Comprehensive Survey. Energies, 18(5): 1163

[12] Scopito (2024) Improving Grid Resilience

with Proactive Drone Inspections.
[13] Wang Q et al. (2024) Adaptive RTK Positioning for UAV Inspection under Signal Blockage Conditions. Journal of Surveying Engineering, 150(1): 04023025.
[14] Nguyen T et al. (2025) Quantum-Enhanced Positioning for Critical Infrastructure Monitoring. Nature Communications Engineering, 4: 78.
[15] Zhong Y (2010) Application of High-Resolution Satellite Images in Power Grid Planning. Yunnan Electric Power, 39(6).
[16] Powerlink Queensland (2024) Climate Resilience Through Advanced Monitoring. Technical Report TR-2024-009.