IoT-Enabled Nanosatellite Constellation for Environmental Sensing and Flood Risk Monitoring Along the River Niger: A Case Study of Lokoja, Kogi State

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Abstract: The confluence of the River Niger and River Benue at Lokoja, Kogi State, is a critical hydrological node in West Africa, historically prone to catastrophic flooding. Traditional flood monitoring systems in Nigeria rely on sparse terrestrial gauges and infrequent Earth Observation (EO) satellite passes, leading to high-latency data and delayed early warning signals. This paper proposes a technically robust, low-cost architectural framework integrating a 3U CubeSat/nanosatellite constellation with a terrestrial Internet of Things (IoT) sensor network to achieve real-time environmental sensing and flood risk monitoring. Operating in a 550 km Sun-Synchronous Orbit (SSO), the proposed 6-satellite constellation interfaces directly with ground-based LoRaWAN-enabled water level, soil moisture, and meteorological sensors via Direct-to-Satellite IoT (DtS-IoT) links operating in the UHF/Sband. The study details the complete system architecture which encompasses the space segment, payload, IoT, communications, and ground segments. Rigorous engineering analyses, including orbital mechanics, coverage geometry, link budgets, and power budgets are also detailed. Results indicate that the constellation achieves a temporal resolution (revisit time) of under 4 hours, compared to the 2–3 days typical of legacy systems like NigeriaSat-2. With an expected IoT uplink margin of +8.4 dB and a sustainable solar power budget allowing continuous sensor polling, this architecture presents a scalable, indigenous solution aligned with the National Space Research and Development Agency (NASRDA) mandate for disaster mitigation and national security.

Keywords: *Nanosatellite Constellation, Direct-to-Satellite IoT, Flood Monitoring, River Niger, NASRDA, Link Budget, Remote Sensing, Lokoja.*

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I. INTRODUCTION

Nigeria's geographical position within the Niger Basin makes it highly susceptible to seasonal flooding. The most devastating impacts are routinely observed at Lokoja, Kogi State where the confluence of the River Niger and the River Benue occur. Historical events, notably the 2012, 2017, and 2022 floods, displaced millions, decimated agricultural output in the Fadama plains, and caused billions of Naira in infrastructural damage [1]. Selected communities in Kogi showed very high flood vulnerability due to factors such as poor building structures and limited evacuation measures [2]. In Ibaji LGA, flood-prone communities are affected by annual Niger River floods and associated socioeconomic losses, with elevation, slope, drainage density, land cover and soil type further increasing their vulnerability to floods [3]. The National Space Research and Development Agency (NASRDA) has historically leveraged medium-to-high resolution optical satellites (e.g., NigeriaSat-1, NigeriaSat-2, and NigeriaSat-X) for disaster monitoring [4]. While these assets provide invaluable high-resolution geographic mapping (2.5 m to 32 m GSD), their single-platform orbital mechanics restrict revisit times, creating critical temporal gaps during rapidly evolving hydrological disasters [5].

In recent years, the convergence of nanosatellite technology (CubeSats) and the Internet of Things (IoT) has revolutionized remote environmental sensing. By utilizing

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Low Earth Orbit (LEO) constellations in tandem with autonomous, distributed ground sensors, continuous telemetry can be achieved. [6] This paper proposes an integrated IoT-Nanosatellite architecture specifically tailored to the hydrological dynamics of Lokoja. By deploying a 6-node 3U CubeSat constellation communicating via LoRaWAN/DtS-IoT protocols, the system bypasses vulnerable terrestrial telecommunications infrastructure, delivering low-latency early warning data directly to the NASRDA ground station in Abuja.

This paper outlines the technical parameters, system architecture, and engineering validation required to actualize this system, offering a blueprint for Nigeria's next generation of indigenous space infrastructure.

II. LITERATURE REVIEW

The application of space technology for flood monitoring has transitioned from purely optical and Synthetic Aperture Radar (SAR) Earth observation to hybridized systems incorporating in-situ IoT data [7]. Global Navigation Satellite Systems (GNSS) provides accurate positioning for many applications including environmental monitoring [8].

Traditionally, NASRDA's approach relied on the Disaster Monitoring Constellation (DMC).

As detailed in early SSTL-NASRDA joint architectures, NigeriaSat-1 and NigeriaSat-2 provided push-broom optical imagery [9]. However, optical sensors are severely limited by cloud cover a ubiquitous condition during Nigeria's rainy season (June–October) and cannot measure subsurface soil saturation or real-time river discharge rates [10].

Recent literature highlights the efficacy of Direct-to-Satellite IoT (DtS-IoT) using Low-Power Wide-Area Networks (LPWAN). LoRa (Long Range) modulation, utilizing Chirp Spread Spectrum (CSS) techniques, has been successfully demonstrated in LEO-to-ground links by organizations like ESA and commercial entities like Lacuna Space [11]. There are similar studies that have integrated IoT sensors and AI-based image segmentation to develop long-term flood risk evaluation frameworks [12]. Despite these advancements, there is a distinct research gap regarding the deployment of localized, high-density LoRa-satellite topologies optimized for equatorial and near-equatorial hydrological basins in West Africa, where dense foliage and extreme atmospheric attenuation present unique RF propagation challenges [13]. One solution is to deploy low-cost sensor stations with LoRa transmitters to relay data via small satellites [14].

➢ *Research Gaps Addressed:*

- Temporal Latency: Replacing days-long revisit times with sub-4-hour revisit intervals.
- Infrastructure Dependency: Decoupling flood warning systems from terrestrial cellular networks (GSM/LTE), which frequently fail during severe floods.
- Data Fusion: Integrating continuous in-situ telemetry (water levels) with periodic spatial imagery rather than relying solely on post-disaster spatial imaging.

III. STUDY AREA: LOKOJA, KOGI STATE

The study area focuses on the confluence of the River Niger and River Benue at Lokoja, Kogi State, Nigeria. The Coordinates are approximately 07°45′12″ N, 06°45′24″ E. With elevation of approximately 35m above sea level [15].

The Niger flows southeastward while the Benue enters from the east, contributing an annual mean runoff of over 13,000 MCM. The confluence creates a massive volumetric bottleneck. The terrain is characterized by broad alluvial floodplains (FADAMAS) that rapidly inundate when the discharge rate exceeds 3,500 m^3/s [16].

The deployment of terrestrial IoT nodes will span a 50 km radius upstream of both rivers and 30 km downstream, creating a predictive hydrological gradient [17].

➢ *Proposed System Architecture*

The architecture is divided into five interconnected segments: Space, Payload, IoT/Ground Sensors, Communications, and Cloud/Control.

➢ System Architecture:

IoT-Enabled Nanosatellite Constellation for Flood Monitoring.

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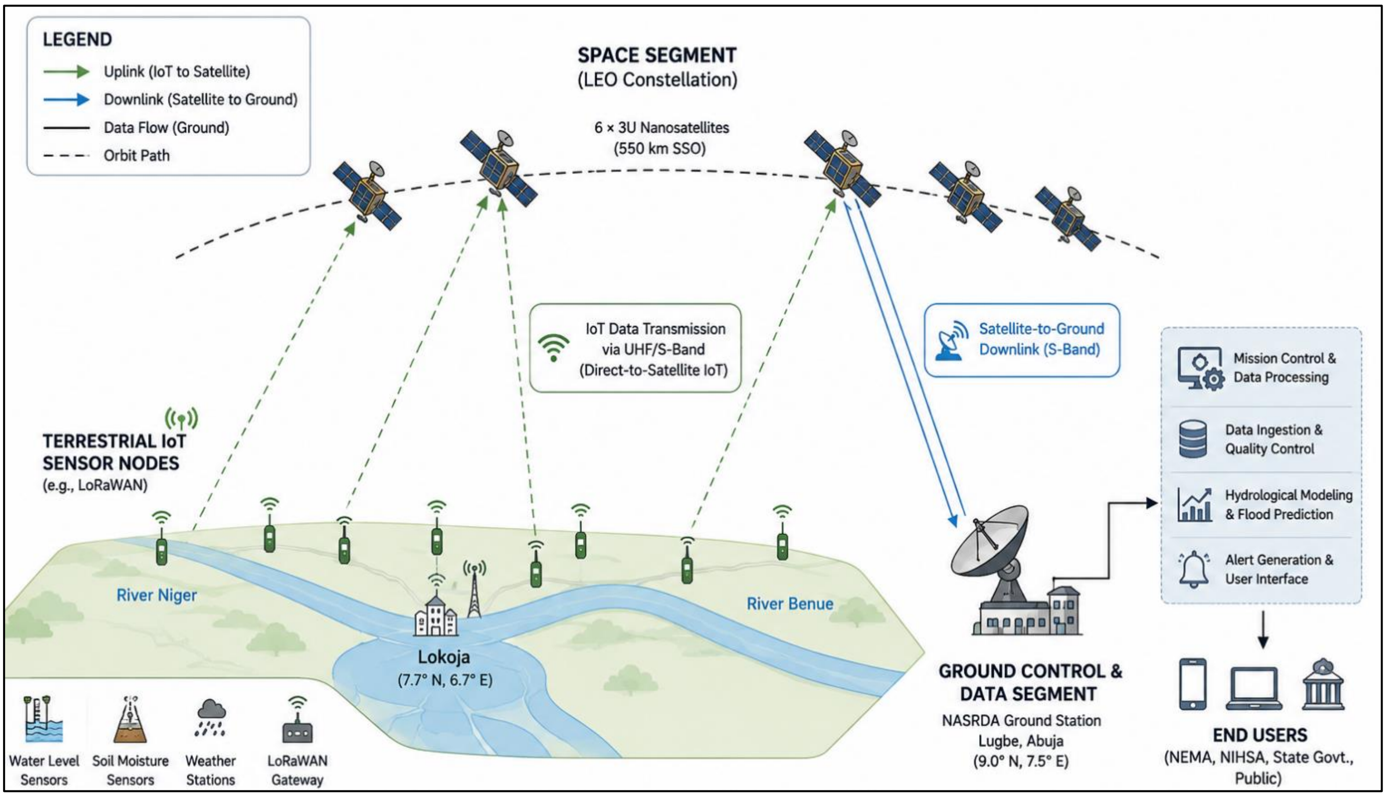

Fig 1 Sensor Node Architecture

- *Space Segment (Constellation Design)*

To achieve the required temporal resolution, a Walker-Delta constellation is proposed [18].

- ✓ Satellite Bus: 3U CubeSat form factor (10 × 10 × 34 cm), mass < 5 kg.
- ✓ Constellation Size: 6 satellites.
- ✓ Orbit: Sun-Synchronous Orbit (SSO) at 550 km altitude, Inclination $i \approx 97.6^\circ$. This ensures consistent illumination for power generation and predictable pass times.

- *Payload Segment*

Each nanosatellite carries a dual payload:

- ✓ SDR-based IoT Gateway: A Software Defined Radio (SDR) configured to demodulate LoRa signals (UHF 433 MHz/868 MHz) directly from ground sensors.
- ✓ Low-Resolution Optical Camera: For visual verification of gross flood extents (RGB, 30 m GSD), serving as a secondary backup to numerical data.

Table 1 Payload and CubeSat Subsystem Specifications

Subsystem	Specification	Component Example (Reference)
Form Factor	3U Nanosatellite	Standard ISISpace / GomSpace 3U
Mass / Volume	4.2 kg/3 Liters	-
IoT Payload	SDR LoRa Gateway, UHF	GomSpace NanoMind / SDR
Optical Payload	30m GSD RGB Camera	Gecko Imager
ADCS	3-axis stabilization, reaction wheels	CubeADCS
EPS	Deployable solar panel 30W peak	Clyde Space 3U EPS, 30Wh Li-Po
Telemetry (TT&C)	S-band (Downlink), UHF(Uplink)	Syrlinks EWC31 S-Band Transceiver

- *Terrestrial IoT Segment*

The ground segment consists of hardened, solar-powered sensor nodes deployed on bridge pilings, riverbanks, and anchored buoys.

Table 2 IoT Sensor Node Specifications

Sensor Type	Parameter Measured	Operating Range	Accuracy
Ultrasonic Transducer	River water level	0.5 m – 20 m	±10 mm
Capacitive Soil Sensor	Soil moisture / Saturation	0% – 100% VWC	±3%
Tipping Bucket	Precipitation rate	0 – 500 mm/hr	±2%
Microcontroller	Processing & Packaging	STM32 / ESP32	N/A
Transceiver	RF Transmission	LoRa SX1262 (868 MHz)	+22 dBm

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- *Communication Segment*

✓ IoT to Satellite (Uplink): Utilizing LoRa CSS modulation to mitigate Doppler shift typical of LEO passes. Frequencies will utilize the ISM band (868 MHz) or licensed UHF bands to avoid interference.

✓ Satellite to Ground Station (Downlink): S-band (2.2 GHz) for telemetry and aggregated IoT data dump to the primary NASRDA Ground Station in Lugbe, Abuja.

- *Cloud and Analytics Segment*

Data received at the ground station is pushed to a cloud-based hydrological model. Using Artificial Neural Networks (ANN) and historical topological data (Digital Elevation Models), the system predicts inundation vectors 24–48 hours before waters reach critical population centers in Lokoja.

IV. SYSTEM OPERATION AND WORKFLOW

The operational protocol relies on an asynchronous "Store-and-Forward" mechanism.

- Wake-up & Poll: Ground sensors sample water levels every 15 minutes. Data is compressed into a 50-byte packet.
- Overpass Synchronization: The node remains in deep sleep to conserve battery until the CubeSat is above the 15° elevation angle horizon. Ephemeris data preloaded on the sensor nodes dictates the wake-up schedule.
- Uplink: The sensor transmits the LoRa packet utilizing a Spreading Factor (SF) of 10 or 11 to balance range and time-on-air.
- Data Storage: The CubeSat's SDR demodulates the packet, tags it with a timestamp and node ID, and stores it in the On-Board Computer (OBC) flash memory.
- Downlink: Upon line-of-sight with the Abuja ground station (9°4′ N,7°29′ E), the CubeSat transmits the aggregated packets via a high-speed S-band link.

- System Architecture: IoT-Enabled Nanosatellite Constellation for Flood Monitoring

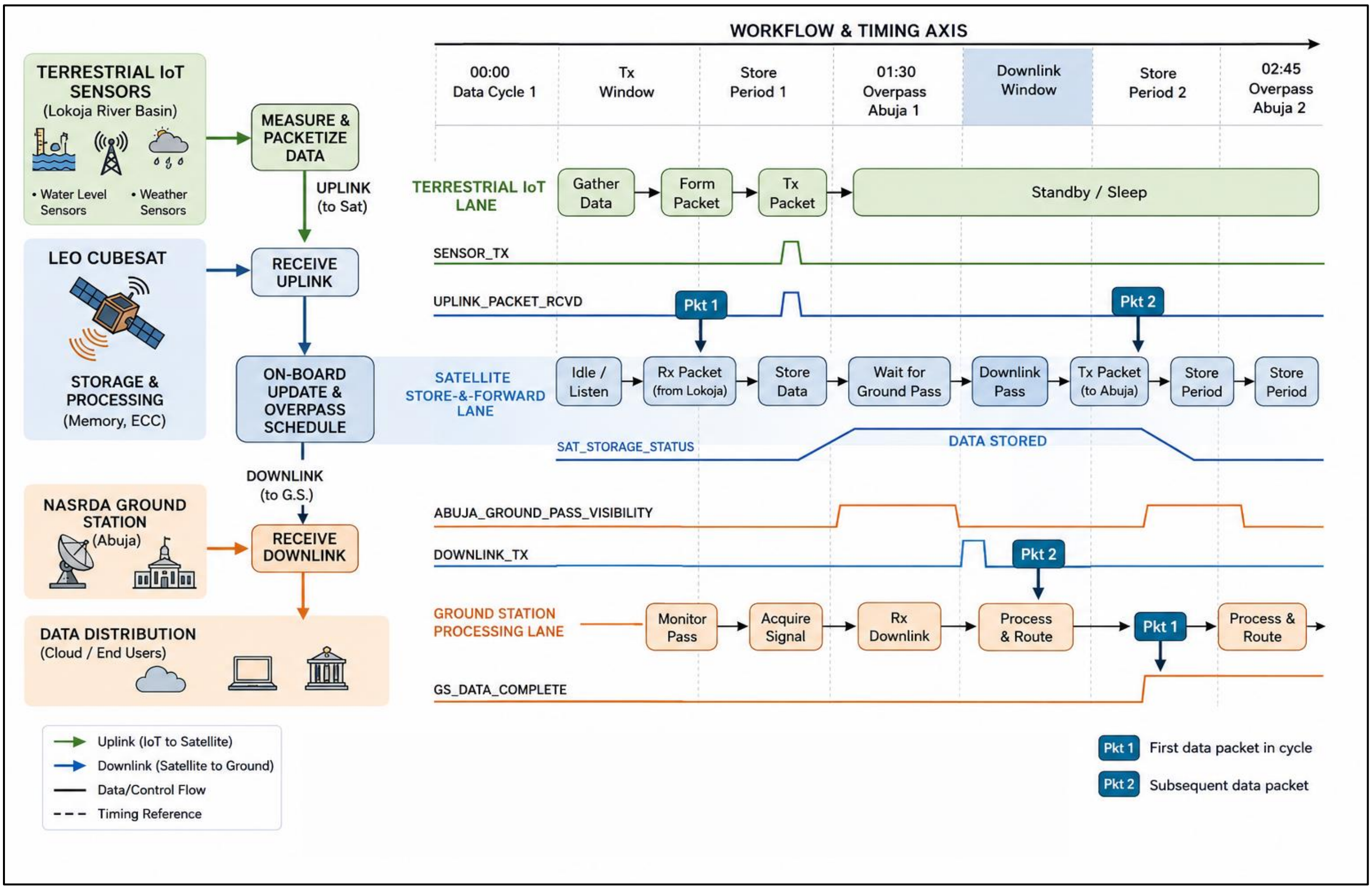

Fig 2 Communication Flow and Timing Diagram

- *Engineering Analysis*

- *Orbit Selection and Revisit Time*

For a satellite at altitude h = 550 km, the orbital period T is calculated using c:

$$T = 2\pi\sqrt{\frac{(R_E + h)^3}{\mu}}$$

Where:

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Earth's radius, R_E = 6371 km

Standard gravitational parameter, $\mu = 3.986 \times 10^5$ km^3/s^2

$$T = 2\pi\sqrt{\frac{(6921)^3}{398600}} = 5739\ seconds \approx 95.6\ minutes$$

The spacecraft completes approximately 15 orbits per day. To achieve continuous monitoring with minimal gaps, a constellation of N = 6 satellites in a single orbital plane or distributed in a Walker-Delta configuration $i/P/F$ = 97.6°/6/1 is utilized.

The average revisit time $t_{re}visit$ for a mid-latitude/equatorial target like Lokoja (latitude ≈ 7.7∘) can be approximated based on the field of view (swath width). For a minimum elevation angle ϵ = 15∘, the Earth central angle λ is:

$$\lambda = 90° - \epsilon - sin^{-1}\left(\frac{R_E\, cos(\epsilon)}{R_E + h}\right)$$

$$\lambda = 90° - \epsilon - sin^{-1}\left(\frac{1}{R_E + h}\right)R_E\, cos(\epsilon) \approx 12.3°$$

The corresponding swath width W is:

$$W = 2 \times R_E \times \lambda\left(\frac{\pi}{180}\right) \approx 2735km$$

With 6 satellites, the maximum time gap between consecutive passes over the Nigerian airspace is reduced from ≈ 12 hours (single satellite) to under 3.5 hours, sufficient for real-time flood trajectory mapping.

- *Link Budget Analysis (IoT to LEO)*

A critical feasibility metric for DtS-IoT is the link budget, which ensures the LoRa signal can penetrate atmospheric moisture and free space to reach the SDR payload.

The received power P_{RX} is given by:

$$P_{Rx} = P_{Tx} + G_{Tx} - L_{FSPL} - L_{atm} - L_{poI} + G_{Rx}$$

Where:

- ✓ P_{Tx}= 22 dBm (maximum for LoRa SX1262)
- ✓ G_{Tx}= 3 dBi (ground omnidirectional antenna)
- ✓ G_{Rx}= 2 dBi (CubeSat UHF patch/dipole antenna)
- ✓ Frequency f = 868 MHz
- ✓ Maximum slant range at ϵ = 15∘, $d \approx$ 1620 km

- *Free Space Path Loss (FSPL):*

- ✓ = 32.44 + 20log$_{10}$(fMHz)+ 20log$_{10}$(dkm)
- ✓ = 32.44 + 20log$_{10}$(868) + 20log$_{10}$(1620)
- ✓ = 32.44 + 58.77 + 64.19 = 155.4 dB

Allowing L_{atm}= 1.5 dB (rain attenuation at UHF is minimal, but equatorial foliage adds margin) and L_{poI}= 3 dB (polarization mismatch).

- ✓ P_{Rx}= 22 + 3 − 155.4 − 1.5 − 3 + 2 = −132.9 dBm

- *Margin Calculation:*

The receiver sensitivity S_{Rx} of a LoRa SDR at Spreading Factor (SF) 11 and 125 kHz bandwidth is approximately −141.5 dBm.

$$Link\ Margin = P_{Rx} - s_{Rx} = 132.9 - (-141.5) = +8.6\,dB$$

A margin of +8.6 dB demonstrates that the UHF LoRa uplink from the Lokoja flood basin to the CubeSat is highly feasible, even under adverse weather conditions.

Table 3 Link Budget Summary for IoT-to-LEO Uplink (LoRa/UHF)

Parameter	Value	Unit
Frequency (f)	868	MHz
Transmit Power (P_{TX})	22.0	dBm
Ground Antenna Gain (G_{TX})	3.0	dBi
Slant Range (d)	1620	km
Free Space Path Loss ($L_{FSP}L$)	155.4	dB
Atmospheric/Polarization Loss	4.5	dB
Satellite Antenna Gain (G_{RX})	2.0	dBi
Received Power (P_{RX})	-132.9	dBm
LoRa Receiver Sensitivity (S_{RX})	-141.5	dBm
Link Margin	+8.6	dB

- *Power Budget Analysis*

The CubeSat relies on body-mounted and deployable solar arrays. In SSO, the eclipse time T_e is approximately 35 minutes, while the daylight time T_d is 60 minutes.

Average power required during sunlight ($P_{re}q\_d$) and eclipse ($P_{re}q\_e$) dictates the Solar Array Power (P_SA):

$$P_{SA} = \frac{\left(\frac{P_{req\_e} \cdot T_e}{X_e} + \frac{P_{req-d} \cdot T_d}{X_d}\right)}{T_d}$$

Assuming standard EPS efficiencies for charge (X_e = 0.65) and direct power (X_d=0.85), with an average load of 7W (SDR listening + ADCS + OBC):

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$$P_{sA} = \frac{\left(\frac{7 \cdot 35}{0.65} + \frac{7 \cdot 60}{0.85}\right)}{60} = \frac{(376.9 + 494.1)}{60} \approx 14.5W$$

A 3U CubeSat with double-sided deployable arrays (approx. 0.06 m^2 effective area at 28% cell efficiency) generates ≈22W to 28W at End of Life (EOL). Thus, the power budget yields a comfortable margin, allowing continuous operation of the SDR receiver over the Nigerian landmass.

V. EXPECTED RESULTS

The integration of the 6-nanosatellite constellation with the ground-based Lokoja sensor network yields several transformational outcomes for Nigeria's disaster management framework.

➢ *Latency Reduction:*

Data transmission latency from the moment a critical water level threshold is breached at the Niger-Benue confluence to the time the warning is displayed at the NASRDA command center is reduced to a maximum of 3.5 hours, governed solely by the constellation's orbital phase.

➢ *Doppler Resilience:*

The use of CSS modulation successfully handles the Doppler shift (±20 kHz at UHF band) experienced during a LEO overpass, which typically lasts 8–10 minutes.

➢ *Cost Efficiency:*

Procuring, launching, and operating a 6-node 3U CubeSat constellation represents a fraction of the cost of a monolithic EO satellite.

➢ *Challenges and Mitigation Strategies*

While technically feasible, the architecture faces specific implementation hurdles within the West African context:

- *Vandalism of Ground Nodes:*

Remote sensors in the Lokoja/Benue regions are susceptible to theft.

✓ *Mitigation:*

Sensors will be camouflaged, physically embedded in bridge abutments, and lack standard commercial ports to deter theft.

- *High Collision Risk (Debris):*

The 550 km SSO is densely populated by mega constellations (e.g., Starlink).

✓ *Mitigation:*

Incorporation of a minimal cold-gas propulsion system or atmospheric drag sails for End-of-Life (EOL) deorbiting within the 25-year IADC guideline.

- *Radio Frequency Interference (RFI):*

Urban noise in the ISM band near Lokoja and Abuja could raise the noise floor, impacting the link margin.

✓ *Mitigation:*

Use of dynamic frequency hopping within the SDR payload and strict allocation of a licensed sub-band via the Nigerian Communications Commission (NCC).

VI. FUTURE WORK

Future iterations of this research will focus on expanding the IoT network upstream to the Jebba and Kainji Dams, which dictate the artificial flow rates of the River Niger before it reaches Lokoja. Furthermore, integrating Artificial Intelligence (Edge AI) directly on the CubeSat OBC could allow the satellite to discard null data (e.g., unchanged water levels) and downlink only anomalous spikes, drastically saving S-band bandwidth.

An active collaboration framework between NASRDA, the National Emergency Management Agency (NEMA), and the Nigeria Hydrological Services Agency (NIHSA) is required to translate the raw telemetry downlinked at the Abuja station into actionable evacuation policies.

VII. CONCLUSION

This paper has presented a comprehensive architectural framework for a 6-node 3U nanosatellite constellation coupled with a terrestrial IoT network designed to monitor flood risks at the River Niger and Benue confluence in Lokoja. Engineering analyses confirm that utilizing LoRa CSS modulation over a UHF uplink yields an 8.6 dB link margin, making Direct-to-Satellite IoT highly feasible despite equatorial atmospheric conditions. The proposed system effectively bridges the temporal data gap inherent in legacy Earth Observation satellites, offering a sub-4-hour revisit time at a fraction of the cost. By adopting this New Space paradigm, Nigeria can indigenous its disaster monitoring capabilities, pivoting from reactive disaster management to proactive, data-driven early warning systems.

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