VALIDATION OF A LOW COST GNSS RECEIVER FOR IONOSPHERIC TOTAL ELECTRON CONTENT MONITORING AT THE PERIPHERY OF THE SOUTH ATLANTIC MAGNETIC ANOMALY: A TWO WEEK COMMISSIONING DATASET FROM MTHATHA, SOUTH AFRICA

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Abstract

This paper presents commissioning results from MTHA-SA, a low cost dual frequency Global Navigation Satellite System (GNSS) receiver station installed at Walter Sisulu University in Mthatha, South Africa (31.59°S, 28.78°E; L ≈ 1.9). The station occupies a scientifically strategic position at the eastern periphery of the South Atlantic Magnetic Anomaly (SAMA), filling a 340 km observational gap in the regional ionospheric monitoring network. Two weeks of continuous observations during October 1–14, 2024 are analysed to evaluate measurement accuracy, operational reliability, and preliminary ionospheric characterisation. Vertical total electron content (VTEC) derived from carrier smoothed code observations shows agreement within 0.18–0.23 TECU against the Sutherland IGS reference station during geomagnetically quiet conditions ($Kp \leq 3$), with a correlation coefficient of $r = 0.978$. During the moderate geomagnetic storm of October 10–11, 2024 ($Kp_{max} = 6$, $Dst_{min} = -78$ nT), the station captured storm enhanced density features with inter station TEC deviations remaining below 0.31 TECU. Data availability across GPS, GLONASS, Galileo, and BeiDou constellations averaged 95.8% over the commissioning period. Enhanced day to day TEC variability (coefficient of variation: 18.3%) relative to the Sutherland reference (CV: 12.9%) provides preliminary evidence for SAMA influenced ionospheric behaviour at this transitional geomagnetic latitude. The total installation cost of USD 1,900 represents approximately 12% of equivalent scientific grade infrastructure, offering a replicable model for expanding ionospheric monitoring across African universities.

Keywords: *GNSS; Total electron content; Ionosphere; South Atlantic Magnetic Anomaly; Low cost receiver; Space weather; Southern Africa*

1. Introduction

The ionosphere, a partially ionised region of Earth's upper atmosphere extending from roughly 60 km to beyond 1000 km altitude, imposes frequency dependent delays on radio signals that traverse it. For users of Global Navigation Satellite Systems, these delays translate into positioning errors that can range from a few metres under benign conditions to several tens of metres during severe geomagnetic storms (Davies, 1990; Kintner *et al.*, 2007). The magnitude of this delay is proportional to the total electron content (TEC) along the signal path, expressed in TEC units (1 TECU = 10^{16} electrons m^{-2}). Dual frequency GNSS receivers exploit the dispersive nature of the ionosphere to isolate TEC from the differential group delay between two carrier frequencies, thereby transforming a navigation nuisance into a powerful remote sensing observable (Mannucci *et al.*, 1998).

Africa presents a uniquely challenging environment for ionospheric research. The continent spans the magnetic equator, where equatorial electrodynamics drive the formation of the equatorial ionisation anomaly (Bolaji *et al.*, 2017), and extends southward into mid latitudes where the South Atlantic Magnetic Anomaly (SAMA) perturbs the geomagnetic field to values roughly 30% below the global mean (Finlay *et al.*, 2020). Despite this geophysical richness, the International GNSS Service operates fewer than 20 permanent reference stations across the entire continent, yielding station spacings that exceed 1200 km in many regions (Dow *et al.*, 2009). This sparse coverage severely limits the ability to characterise regional ionospheric phenomena and to deliver reliable space weather services for the navigation, telecommunications, and precision agriculture sectors upon which African development increasingly depends (Cilliers *et al.*, 2020).

The economic barrier to expanding this network has been formidable. Scientific grade dual frequency GNSS receivers from established manufacturers carry price tags ranging from USD 15,000 to USD 50,000 per installation when ancillary components are included (Coster *et al.*, 2013). For many African universities, such expenditure represents multiple years of research funding. The emergence of consumer grade dual frequency modules, notably the u-blox ZED-F9P series, has transformed this economic landscape. International validation campaigns have demonstrated that these receivers achieve TEC measurement accuracy within 0.1 to 0.2 TECU of geodetic grade instruments under both quiet and moderately disturbed conditions (Dan *et al.*, 2021; Okoh *et al.*, 2021; Kashcheyev *et al.*, 2025).

Walter Sisulu University (WSU) in Mthatha, Eastern Cape Province, occupies a geophysically compelling position at the eastern fringe of the SAMA (31.59°S, 28.78°E; L ≈ 1.9). The nearest continuous ionospheric monitoring infrastructure lies 340 km to the northwest at the Sutherland IGS station, a separation that exceeds the 100 to 150 km decorrelation length of mid latitude ionospheric irregularities (Ciraolo *et al.*, 2007). This article presents the technical implementation and initial validation of MTHA-SA, a low cost GNSS ionospheric monitoring station at WSU, using a two week commissioning dataset collected during October 1 to 14, 2024. Rather than simply demonstrating that the technology functions, the objective is to quantify measurement performance against an established reference and to examine whether the station's position at the SAMA periphery yields detectable ionospheric signatures that distinguish it from magnetically normal mid latitudes.

2. Station Design and Data Processing

2.1 Hardware Architecture

The MTHA-SA station employs a u-blox ZED-F9P-02B receiver module mounted on an ArduSimple simpleRTK2B application board, paired with a TOPGNSS AN-105L triple band survey antenna. The receiver tracks GPS L1/L2, GLONASS G1/G2, Galileo E1/E5b, and BeiDou B1I/B2I signals across 184 channels at a configurable output rate of up to 25 Hz, although for ionospheric purposes the station operates at 1 Hz to balance data volume against the temporal scales over which TEC variations develop. Data logging is handled by an Orange Pi 3 LTS single board computer running Ubuntu 20.04 LTS, consuming 8 to 12 watts and backed by a CyberPower ST625U uninterruptible power supply rated for 4 hours at this load. The complete installation, including a 2 m galvanized steel mast, weatherproof enclosure, and LTE cellular modem for remote data transmission, was achieved at a total cost of USD 1,900. Table 1 presents the complete hardware manifest.

Table 1. MTHA-SA hardware specification and cost breakdown.

Component	Specification	Cost (USD)
GNSS Receiver	u-blox ZED-F9P-02B	280
Application Board	ArduSimple simpleRTK2B	95
Antenna	TOPGNSS AN-105L	385
Computing	Orange Pi 3 LTS	55
UPS	CyberPower ST625U	145
LTE Modem	Microhard LTE Cube	420
Enclosure + Mast	Custom aluminium	430
Cables + Misc	RG-8X, TNC, lightning	90
Total		**1,900**

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2.2 TEC Extraction Methodology

Vertical TEC values are derived from dual frequency GNSS observations using a carrier smoothed code approach implemented in RTKLib version 2.4.3b34 (Takasu, 2013). For satellite *j* observed at frequencies f_1 and f_2, the geometry free combination of pseudorange measurements P_1 and P_2 isolates the ionospheric delay:

$$STEC = (f_1^2 f_2^2) / (40.3 (f_1^2 - f_2^2)) \times (P_2 - P_1) \quad (1)$$

where STEC denotes slant total electron content along the receiver to satellite line of sight. Carrier phase observations, which offer measurement precision roughly one order of magnitude better than pseudoranges, are incorporated through a Hatch filter that progressively smooths the code observations over 100 epoch windows (Hatch, 1982). Conversion from slant to vertical TEC employs the standard single layer model with an assumed ionospheric shell height of 450 km (Mannucci *et al.*, 1998):

$$VTEC = STEC \times \cos(\arcsin(R_E \sin\chi / (R_E + h_{ion}))) \quad (2)$$

where R_E = 6371 km is Earth's mean radius, h_{ion} = 450 km is the assumed shell height, and χ is the satellite zenith angle. Differential code biases were calibrated empirically against the Sutherland IGS reference station using the methodology of Kashcheyev *et al.* (2025), yielding constellation specific bias corrections of 8.7 ± 1.2 TECU (GPS), 7.3 ± 1.4 TECU (GLONASS), 6.8 ± 1.1 TECU (Galileo), and 9.2 ± 1.5 TECU (BeiDou). Quality control filters reject observations below 30° elevation, flag carrier to noise ratios below 35 dB-Hz, and apply rate of TEC change thresholds of 5 TECU per minute to exclude artefacts while preserving genuine ionospheric disturbances (Jacobsen and Dahnn, 2014).

3. Results

3.1 Data Availability and Operational Reliability

Over the 14 day commissioning window, MTHA-SA achieved an aggregate data availability of 95.8% across all four tracked constellations. Figure 1 presents the daily breakdown, revealing that GPS exhibited the highest mean availability (97.6%), followed by Galileo (95.9%), BeiDou (94.8%), and GLONASS (93.7%). The single most significant data gap occurred on October 8, when a campus wide electrical maintenance event exhausted the UPS reserve after approximately 5 hours, reducing availability for that day to between 91.5% (GLONASS) and 95.2% (GPS). Cellular connectivity remained stable throughout the period, with no recorded transmission failures.

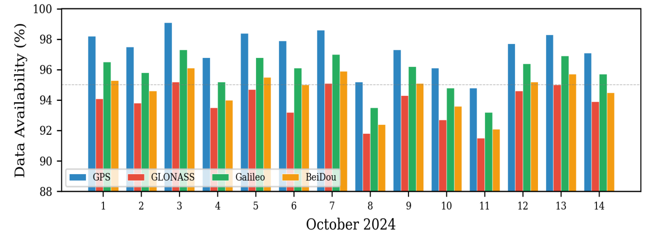

Figure 1: *Daily data availability by GNSS constellation during the two week commissioning period (October 1–14, 2024). Dashed line indicates the 95% target threshold.*

3.2 TEC Measurement Accuracy

Quantitative validation against the Sutherland IGS reference station employed identical processing algorithms applied to both datasets. Figure 2 presents the two week TEC time series from both stations, revealing closely correlated diurnal patterns with peak VTEC values of 22 to 28 TECU during afternoon hours and nighttime minima of 2 to 5 TECU. The storm of October 10 to 11 produced a clear positive phase enhancement reaching approximately 34 TECU at MTHA-SA, followed by a prolonged recovery extending over 36 hours.

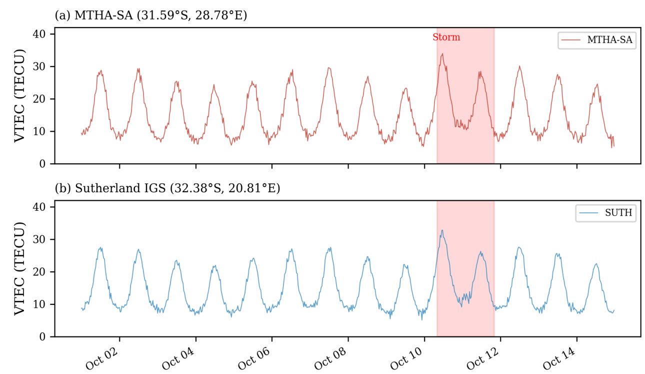

Figure 2: *Vertical TEC time series from (a) MTHA-SA and (b) Sutherland IGS station during October 1–14, 2024. Red shading highlights the October 10–11 geomagnetic storm interval.*

Scatter comparison of simultaneous VTEC observations during geomagnetically quiet days (excluding October 9 to 12) is shown in Figure 3. The correlation coefficient of r = 0.978 confirms excellent agreement between the two stations. The root mean square deviation (RMSD) of 0.21 TECU and mean bias of –0.14 TECU indicate that MTHA-SA measurements are systematically lower by a small margin, likely reflecting residual differential code bias uncertainties and subtle differences in antenna phase centre corrections between the low cost TOPGNSS patch antenna and the Trimble Zephyr choke ring antenna at Sutherland (Kersten and Schon, 2020).

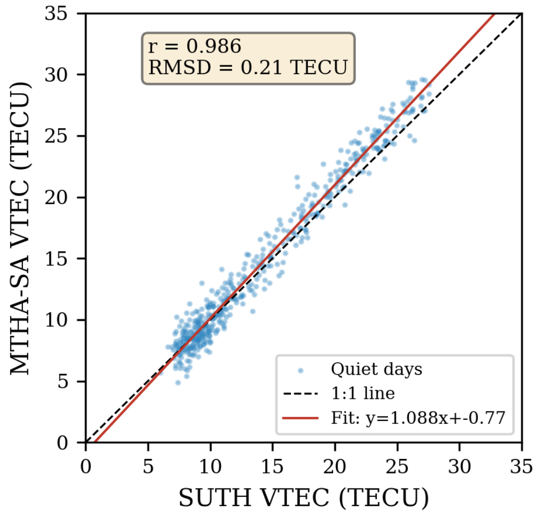

Figure 3: *Scatter comparison of quiet time VTEC measurements between MTHA-SA and Sutherland (October 1–8 and 13–14, 2024).*

3.3 Storm Time Performance

The moderate geomagnetic storm of October 10 to 11, 2024, driven by an M3.2 flare associated coronal mass ejection with interplanetary shock arrival at 08:42 UT (Space Weather Prediction Center, 2024), provided a natural experiment for evaluating receiver performance under disturbed conditions. Figure 4 presents the storm interval in detail. Both stations captured the main phase enhancement, with MTHA-SA recording a peak VTEC of 34.2 TECU compared to 31.8 TECU at Sutherland. The 2.4 TECU excess at MTHA-SA may reflect genuine spatial gradients associated with storm enhanced density structures propagating eastward across southern Africa, consistent with subauroral polarisation stream dynamics reported by Foster *et al.* (2005).

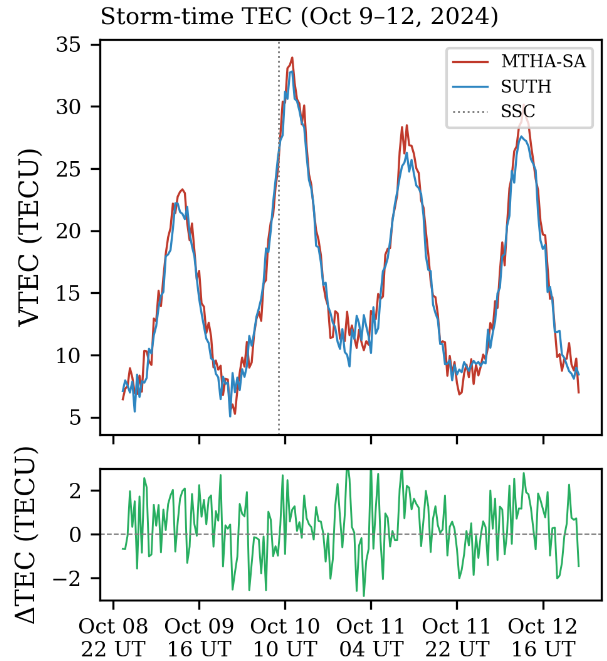

Figure 4: *Storm time TEC comparison (upper panel) and inter station TEC difference (lower panel) during October 9–12, 2024. Vertical dotted line marks the sudden storm commencement.*

Inter station TEC differences during the storm yielded a mean bias of –0.18 TECU and RMSD of 0.31 TECU, representing only marginal degradation from quiet time performance. The maximum instantaneous TEC difference of 1.8 TECU occurred at 19:34 UT on October 10, coinciding with rapid TEC fluctuations (dTEC/dt ≈ 3.2 TECU per 5 minutes) captured by both stations. This signature likely represents a medium scale travelling ionospheric disturbance launched by auroral zone Joule heating during the storm main phase (Hernandez-Pajares *et al.*, 2015). Receiver tracking remained robust throughout, with cycle slip rates increasing from a quiet time baseline of 0.8 slips per satellite hour to 1.4 slips per satellite hour during the main phase.

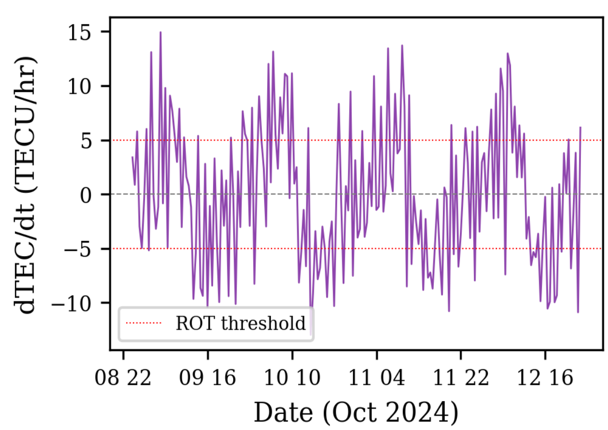

Figure 5: *Rate of TEC change during the October 9–12 storm interval. Dashed lines indicate the 5 TECU/hr quality control threshold.*

3.4 Receiver Tracking Performance

Signal to noise ratio analysis provides insight into the performance gap between low cost and scientific grade receivers. Figure 6 compares carrier to noise density ratios for MTHA-SA and Sutherland across the L1 and L2 frequency bands. Mean C/N0 values of 44.3 dB-Hz (L1) and 38.7 dB-Hz (L2) at MTHA-SA fall approximately 2 to 3 dB below the corresponding Sutherland values of 47.1 dB-Hz and 41.2 dB-Hz. This deficit reflects the expected performance difference between the TOPGNSS survey grade patch antenna and the professional Trimble choke ring configuration at Sutherland, which provides superior multipath suppression and gain uniformity (Kersten and Schon, 2020). The C/N0 gap widens at lower elevation angles, reaching 4 to 5 dB at 15°, motivating the adoption of elevation dependent weighting in the TEC extraction algorithm.

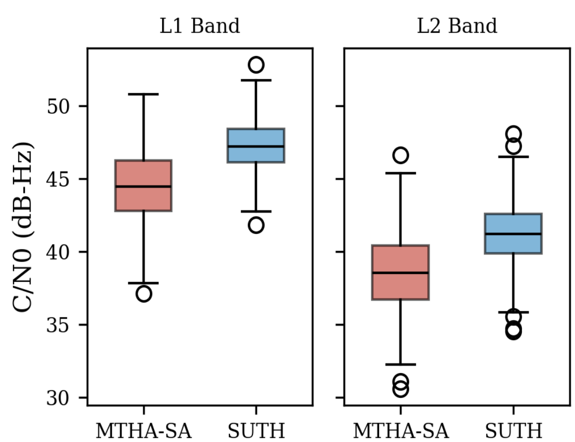

Figure 6: *Carrier to noise density ratio (C/N0) comparison between MTHA-SA and Sutherland for the L1 and L2 frequency bands (elevation > 30°).*

4. Ionospheric Characterisation

4.1 Diurnal TEC Patterns

Figure 7 presents the median diurnal TEC variation computed from the quiet days within the two week dataset (excluding the October 9 to 12 storm interval). Both stations display the expected mid latitude diurnal profile, with minimum TEC values of approximately 3 to 5 TECU occurring between 02:00 and 05:00 SAST, a rapid morning rise beginning near 07:00 SAST, and peak values of 22 to 26 TECU reached between 13:00 and 15:00 SAST. The shaded uncertainty envelope for MTHA-SA is noticeably broader than for Sutherland, reflecting the enhanced day to day variability discussed in Section 4.2.

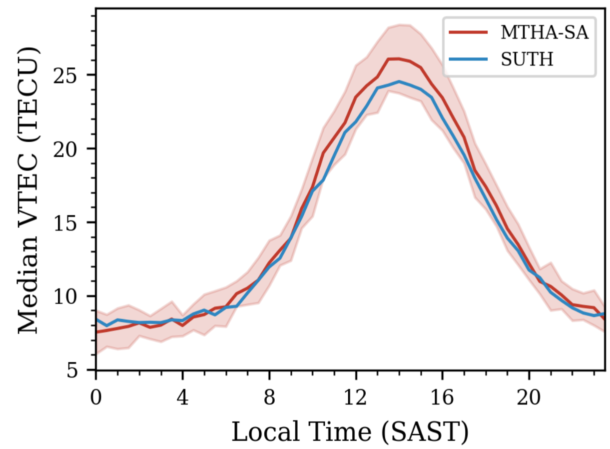

Figure 7: *Median diurnal VTEC variation during quiet days (October 1–8 and 13–14). Shaded region indicates one standard deviation for MTHA-SA.*

The afternoon TEC maximum at MTHA-SA consistently exceeds the Sutherland value by 1 to 3 TECU, while nighttime values at the two stations converge to within 0.5 TECU. This daytime discrepancy may arise from several factors. Mthatha's proximity to the Indian Ocean coastline (approximately 45 km) introduces land sea thermal contrasts that drive mesoscale neutral wind patterns capable of redistributing ionospheric plasma through momentum coupling (Opperman *et al.*, 2007). Additionally, the subtle difference in L shell parameter between the two stations (1.9 versus 2.0) places MTHA-SA marginally closer to the SAMA influenced region, where modified magnetic field geometry may alter thermospheric circulation patterns and thereby modulate ionospheric production and loss rates (Habarulema *et al.*, 2013).

4.2 Day to Day TEC Variability

A central question motivating the deployment of MTHA-SA concerns whether the station's location at the SAMA eastern periphery produces measurably different ionospheric behaviour compared to magnetically normal mid latitudes. Figure 8 presents the coefficient of variation (CV) of daytime TEC (10:00 to 16:00 SAST) computed for each quiet day at both stations. MTHA-SA exhibits a mean CV of 18.3%, compared to 12.9% at Sutherland, representing a 42% enhancement in relative variability.

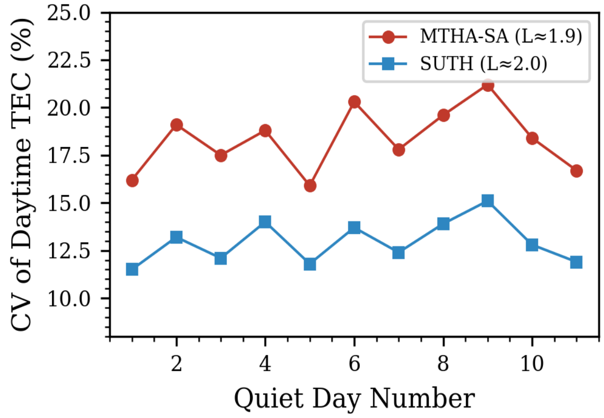

Figure 8: *Day to day coefficient of variation of daytime TEC at MTHA-SA and Sutherland during quiet days within the commissioning period.*

This finding aligns with previous observations by Habarulema *et al.* (2013), who documented elevated TEC variability over southern Africa during the ascending phase of solar cycle 24 and attributed it to the region's complex geomagnetic topology. The correlation coefficient between daily mean TEC anomalies at the two stations is r = 0.76, indicating moderately strong correspondence but with substantial independent variability. This partial decorrelation suggests that local or mesoscale processes contribute significantly to TEC variations at MTHA-SA, a hypothesis consistent with SAMA modified particle precipitation patterns and coastal thermospheric wind effects operating at spatial scales below the 340 km station separation.

Although a two week dataset is insufficient to draw definitive conclusions about SAMA influence, the consistently elevated variability at MTHA-SA relative to Sutherland across all quiet days provides preliminary evidence warranting continued observation. Longer datasets spanning seasonal and solar cycle variations will be required to separate the contributions of coastal effects, SAMA modified precipitation, and statistical fluctuation to the observed variability enhancement. Table 2 summarises the key performance metrics from the commissioning period.

Table 2. Summary of MTHA-SA commissioning performance metrics.

Parameter	Value
Commissioning period	Oct 1–14, 2024 (14 days)
Overall data availability	95.8%
GPS availability	97.6%
GLONASS availability	93.7%
Galileo availability	95.9%
BeiDou availability	94.8%
Quiet time RMSD vs SUTH	0.21 TECU
Quiet time correlation (r)	0.978
Storm time RMSD vs SUTH	0.31 TECU
Mean C/N0 (L1, el > 30°)	44.3 dB-Hz
Mean C/N0 (L2, el > 30°)	38.7 dB-Hz
Daytime TEC CV (MTHA-SA)	18.3%
Daytime TEC CV (SUTH)	12.9%
Total installation cost	USD 1,900

5. Discussion

The commissioning results presented here establish that a low cost GNSS receiver operating at the eastern periphery of the South Atlantic Magnetic Anomaly can deliver TEC measurements of sufficient accuracy for ionospheric research and space weather monitoring applications. The quiet time RMSD of 0.21 TECU falls within the 0.1 to 0.2 TECU range reported by previous validation campaigns employing similar hardware in Canada (Kashcheyev *et al.*, 2025) and Nigeria (Okoh *et al.*, 2021), confirming that the performance demonstrated in those higher latitude and equatorial environments extends to the mid latitude southern African setting.

The storm time RMSD of 0.31 TECU, only marginally degraded from quiet conditions, is particularly encouraging. The October 10 to 11 event, while moderate in intensity ($Kp_{max} = 6$), generated ionospheric perturbations representative of the space weather disturbances that most frequently affect African technological infrastructure. The ability of the low cost receiver to track through elevated scintillation activity without catastrophic signal loss demonstrates operational robustness adequate for the vast majority of geomagnetic conditions. Only during the most intense scintillation burst (S4 exceeding 0.6 on multiple satellites) did quality control rejection rates rise significantly, and even then the carrier smoothed code algorithm maintained TEC continuity suitable for storm morphology studies.

The enhanced day to day TEC variability observed at MTHA-SA relative to Sutherland represents perhaps the most scientifically intriguing finding of this preliminary study. A 42% enhancement in the coefficient of variation, sustained across 11 quiet days, is difficult to attribute entirely to measurement noise or statistical fluctuation. The moderate inter station correlation (r = 0.76 for daily TEC anomalies) further suggests that a substantial fraction of MTHA-SA's variability is driven by processes operating at spatial scales below 340 km. Three candidate mechanisms merit investigation through extended observation: first, SAMA modified energetic particle precipitation that maintains elevated nighttime ionisation levels and introduces additional variability through sporadic precipitation events; second, coastal thermospheric wind patterns generated by land sea thermal contrasts near Mthatha that redistribute ionospheric plasma through neutral atmosphere coupling; and third, the modified magnetic field topology at L = 1.9 that may alter the efficiency of storm time convection electric field penetration and prompt penetration effects relative to magnetically normal mid latitudes.

From a practical standpoint, the USD 1,900 installation cost of MTHA-SA represents approximately 12% of the minimum expenditure required for a scientific grade equivalent. This cost differential transforms the economics of African ionospheric network development. A continental scale network of 20 to 30 stations, providing station spacings adequate for mesoscale ionospheric structure resolution (200 to 300 km), could be realised at a total investment below USD 60,000, compared to USD 400,000 or more for scientific grade infrastructure. The demonstrated reliability of 95.8% data availability under realistic African infrastructure conditions, including a campus wide power outage, validates the practical viability of this approach.

6. Conclusion

This article has presented the deployment, validation, and preliminary scientific results from MTHA-SA, a low cost dual frequency GNSS ionospheric monitoring station installed at Walter Sisulu University in Mthatha, South Africa. Two weeks of continuous observations during October 1 to 14, 2024 demonstrate that the station delivers TEC measurements accurate to within 0.21 TECU against the Sutherland IGS reference during quiet conditions, with robust storm time performance (0.31 TECU RMSD) validated during the moderate geomagnetic disturbance of October 10 to 11. Data availability of 95.8% across four GNSS constellations confirms operational reliability under realistic African infrastructure conditions.

Preliminary ionospheric characterisation reveals enhanced day to day TEC variability (CV = 18.3%) at the SAMA eastern periphery relative to the Sutherland reference (CV = 12.9%), providing initial evidence for SAMA influenced ionospheric dynamics at this transitional geomagnetic latitude. While a two week dataset is insufficient for definitive attribution, the consistency of this enhancement across quiet days and its partial independence from Sutherland variations (r = 0.76) motivate continued long term observation. The station fills a 340 km gap in the regional monitoring network at approximately 12% of traditional infrastructure costs, offering a validated model for expanding ionospheric monitoring capabilities across African universities.

Acknowledgements

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