Enhancing Geodetic Reference Systems in Kiribati: Installation and Impact of a Secondary CORS Site

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Keywords: Geodetic Infrastructure, Continuously Operating Reference Stations (CORS), Sustainable Development Goals (SDGs), Australia Online Positioning Service (AUSPOS), Small Island Development States (SIDS).

SUMMARY

The geographic isolation of the Republic of Kiribati has contributed to long-standing geodetic inequalities that hinder accurate spatial data management, modern surveying practices, and the integrity of land administration systems. In late 2025, a team of surveying academics and students from the University of Southern Queensland (UniSQ) travelled to Tarawa to support the Land Management Division (LMD) through targeted technical assistance and capacity building. A central focus of the collaboration was the investigation and correction of a persistent 9m horizontal error in the national datum, significantly improving the reliability of infrastructure mapping, coastal monitoring, and planning activities. Simultaneously, field-based survey training sessions were delivered to strengthen local technical skills and institutional capacity, aligning with the United Nations Sustainable Development Goals (SDGs) relating to quality education, reduced inequalities, and strong institutions.

Complementing this work, an independent honours research project evaluated the contribution of a donated Continuously Operating Reference Station (CORS). The research demonstrated how the introduction of a second CORS enhances redundancy, improves network geometry, and delivers more stable and accurate GNSS positioning solutions to support surveying, mapping, and infrastructure development across Tarawa. The heavy reliance on Kiribati's single existing CORS during the collaboration highlighted the vulnerability of the current system and reinforced the need for a more resilient multi-station network, consistent with the objectives of FIG Commission 5 and the needs of small island developing states.

The installation of the CORS required close collaboration with LMD staff, local businesses, and international partners, supporting sustainable local industry engagement and effective partnerships. Beyond national benefits, the enhanced GNSS infrastructure contributes to regional and global reference frames, strengthening geodetic coverage in an under-observed region. Collectively, these initiatives demonstrate how modern geospatial technology,

partnerships, and capacity building can reduce geodetic inequality and support sustainable development in Kiribati and the wider Pacific region.

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1 INTRODUCTION

Reliable geodetic infrastructure is fundamental to accurate positioning, mapping, construction, navigation, and disaster risk management. Continuously Operating Reference Stations (CORS) form the backbone of modern GNSS-based positioning systems; however, the establishment and maintenance of Tier-1 CORS installations require substantial financial investment, specialised equipment, and sustained technical support. In many Pacific Island nations, these requirements present significant barriers to the expansion and long-term sustainability of national geodetic networks. Geographic isolation, limited access to equipment and expertise, and constrained budgets further exacerbate these challenges, resulting in sparse reference station coverage and reduced positioning capability.

This study investigates the feasibility of a low-cost CORS solution constructed using region-specific and locally sourced materials, with the aim of assessing its potential contribution to geodetic infrastructure development in resource-constrained environments. Using daily GNSS solutions processed through Geoscience Australia's AUSPOS service, this research assesses the relative stability of the new GNSS CORS and examines whether low-cost CORS installations can provide sufficiently stable positioning performance to support practical geospatial applications across the Pacific.

2 CONTEXT

2.1 Existing guidelines for CORS

The use of Global Navigation Satellite System (GNSS) Continuously Operating Reference Stations (CORS) provides positioning services and are governed by national, state and territory governments as well as private companies. Internationally, GNSS CORS have been established to serve different purposes such as monitoring earth movement, maintaining geodetic reference frames, and providing access to positioning data and services. To distinguish GNSS CORS use according to their purpose, CORS can be classified into either 'Tier 1', 'Tier 2' or 'Tier 3' as proposed by Rizos (2007) tiered hierarchy. 'Tier 1' CORS follows strict installation and design guidelines established by the International GNSS Service (IGS) to support ultra-high positioning data to develop geoscientific networks (IGS or equivalent) and the International Terrestrial Reference Frame (ITRF) globally or regionally (IGS, 2023). 'Tier 2' CORS are high accuracy sites that define federal geodetic networks, and support national geodesy like reference frames, systems and datums. ‘Tier 3’ GNSS CORS promote geospatial data for state or private GNSS networks and represent lower stability requirements for the purpose of densification. The tiered system of GNSS CORS requires varying site requirements for installation and design of monuments to provide fit-for-purpose data. Together with the IGS ‘Tier 1’ criteria, the Intergovernmental Committee of Surveying and Mapping (ICSM) has adopted this tiered hierarchy to provide a uniform national-scale guideline for the design, installation and operation of CORS in Australia which is compatible with IGS CORS network. Despite the tier system, the location and design decisions of each CORS is governed by the general principles that must be upheld (ICSM, 2020):

- Antenna Reference Point (ARP) and monument stability;
- signal quality, sky visibility and data completeness;
- a continuous and reliable power supply; and
- a reliable communications system with minimum latency.

Since high-accuracy data depends on the short- and long-term stability of the CORS monuments and antenna mounting, the site requirements for the tier hierarchy are reflected in Table 1:

Table 1: Summary of recommendations for CORS location and design (ICSM 2020)

Recommendation:	ICSM Guidelines		
	Tier 1 (IGS equivalent)	Tier 2	Tier 3
Foundation:			
Bedrock or mass concrete base	■	■	□
Competent rock through layers of soil or fractured rock	■	■	□
Mounted on buildings or similar structures	X	X	■
Monumentation:			
Reinforced concrete pillar	■	■	□
Stainless steel or galvanised mild steel mounts attached to building or concrete plinth	X	X	■
Interference:			
Minimum sky obstruction	■	■	■
Minimise multipath sources	■	■	■
Long-term site tenure	■	■	■
CORS network inter-station distance:			
500-1500 kilometres	■	X	X
80-500 kilometres	X	■	X
20-80 kilometres	X	X	■

Legend
■ Strongly Recommended
□ Recommended
X Not Recommended

It is to be noted that there are no overarching international standards for various purpose-specific CORS. These site guidelines are all critically subject to perpetual and secure land tenure, availability of materials and cost margins. Thus, the requirements for the CORS hierarchy may be achievable in first-world countries, however in resource-poor nations such as Kiribati, these recommendations may be rendered unsuitable. As reflected in both the IGS and ICSM guidelines (IGS, 2023; ICSM, 2020), every CORS is subject to site-specific issues where existing guidelines may need to be reconsidered to align the site planning and CORS design with the resource limits in developing countries.

2.2 Isolation and geodetic gaps in Kiribati

Kiribati heavily relies on foreign aid due to its remote island economy, vulnerability to climate change, poor infrastructure and absence of financial resources to support long-term survival (International Monetary Fund, 2025). Due to limited local production, Kiribati's economy predominately depends on its fishing industry including fishing licences, seaweed and copra, and limited exports, necessitating foreign investment and creating a structural trade deficit. Therefore, its small economic base requires imported manufactured goods and resources from foreign support to facilitate national infrastructure projects and longevity. The isolation of the Republic of Kiribati inherits geodetic inequalities that limit the nation's abilities to maintain accurate spatial data, adopt modern surveying practices and ensure the integrity of the land administration and cadastre systems. During the three-month collaboration between UniSQ representatives and LMD staff, Kiribati's only CORS station (KIRI) was found to be relied upon heavily for national surveying and mapping that aid sustainable urbanisation and coastal analysis endeavours. This CORS site is located at the western port centre of Betio, South Tarawa, and is the sole contributor to the regional GNSS framework of Kiribati, providing data corrections across 3.4 million square kilometres (International Monetary Fund, 2025).

Figure 1: Location of Betio in Tarawa atoll (Google Maps, 2021)

'KIRI' CORS is a 'Tier 1' site that operates under Australia's Bureau of Meteorology and Geoscience Australia (GA) as part of the Pacific Sea Level and Geodetic Monitoring Project (PSLGM) that operates under the Australian government-funded Climate and Oceans Support Program in the Pacific (COSPPac) (Lal, 2024). Due to Kiribati's limited resources and narrow economy, 'KIRI' CORS was financially supported by Australia Aid, the Australian Government, the New Zealand Government and the Pacific Community (SPC) who funded its construction from expensive materials and imported resources to initialise Kiribati's GNSS geodetic framework. Following standardised tiered CORS protocol, the 'KIRI' monument is a 400mm diameter concrete pillar built 1.5 metres above ground surface with a 250mm diameter stainless steel plate and has an antenna mount centred into the top of monument (Figure 2).

Figure 2: KIRI CORS choke-ring antenna (top left), monument pillar (top right) and protective pillars around CORS (bottom)

As part of the PSLGM, the KIRI CORS pillar monument is one component of an extensive Tier 1 CORS system which consists of a weather station, GNSS hut to facilitate the receiver and communications and back-up power, and solar panels.

Figure 3: Fenced weather station (top left), solar panels for GNSS hut (top right), GNSS hut (bottom left); and KIRI CORS monument and antenna (bottom right)

To aid high-quality correctional data calculations, the weather station (Figure 3) collects atmospheric conditions that affect the speed and path of GNSS signals for precise atmospheric modelling to refine raw GNSS data consistently over time. The equipment hut (Figure 3) provides a protected enclosure against weathering and damage from external harsh environments or human intervention like vandalism. It also serves as a centralised hub for managing power distribution, communications link with internet and satellite systems, and for simplified maintenance and troubleshooting. The solar panels (Figure 3) are paramount for an essential uninterrupted power supply required for Tier 1 stations in remote areas where power outages are common. The integration of two solar panels creates a hybrid power system which maximises redundancy and reliability to support the continuous operation of the CORS station. This setup is rigorous, and its deployment presents challenges due to its complexity and cost that make its repeatability unrealistic for small island development states (SIDS).

Although 'KIRI' has been thoroughly installed and configured as part of the robust IGS CORS network, the limited accuracy and single-point vulnerability of the singular CORS present the need for densification of CORS geodetic infrastructure. Since the establishment and operation of a tiered CORS is crucially dependent on availability of resources and funding, the implementation of a low-cost CORS solution can help improve the region's GNSS network geometry by enhancing redundancy and providing more stable, high-quality, real-time GNSS data. The low-cost CORS solution will complement the existing 'KIRI' CORS in the under-serviced region and create a resilient multi-station system that bridges the gap between the need for densified GNSS infrastructure and the affordability of modern positioning solutions.

3 CORS FABRICTION AND INSTALLATION

3.1 Site selection

In SIDS, power outages, land tenure security and extreme environmental conditions are critical considerations that affect site selection for a new CORS. The location of the secondary CORS site in South Tarawa reflects these regional challenges, which undermine the rigorous and regimented site planning criteria set by IGS and ICSM. Although 'KIRI' CORS is a 'Tier 1' site, its construction received funding and crucial resources that support its high-quality, high-accuracy data. However, for the purpose of densifying the geodetic infrastructure in Kiribati, the installation of the new CORS was welcomed at the LMD building in Bairiki. This site was ideal due to its existing power and communication system that services commercial land management efforts and was therefore deemed contextually reliable, despite the power outages that are common throughout Tarawa. The building offered an elevated mounting point for the antenna, where its south-east facing A-frame fascia was ideal for installation (Figure 4).

Figure 4: A-frame fascia of the Bairiki LMD building (street view and close-up)

The A-frame fascia supports the stability of a mounting bracket for the GNSS CORS as it anchors directly into the building's structure to reduce movement and facilitates easy adjustment to orient the antenna precisely to True North. Due to the tropical landscape of the island, GNSS multipath is often created by tall palm trees and thick vegetation. This site allowed the antenna to be installed higher than the surrounding tree and building line, to ensure a clear sky view with minimal obstruction for satellite signals (Table 1). Paired with the elevated location, the site also provides a visibility advantage for security reasons, as it can be easily seen from the street and is protected from vandalism, thus enhancing security. However, Bairiki is only approximately 10km away from 'KIRI' CORS at Betio, which is unideal for long baselines and impacts positioning accuracy. However, since the site selection is limited by permissions, power supply and cost, the purpose of CORS densification outweighs expected inter-station distance recommendations (Table 1).

3.2 Design of bracket

The design of the CORS mounting structure was undertaken as a collaborative and capacity-building exercise involving UniSQ students and staff from the Kiribati Lands Management Division (LMD). To develop practical field skills, a survey assistant from LMD measured the existing fascia under the supervision of a UniSQ student using a Trimble total station, ensuring to include all frame dimensions. Slope distances and angles were then extracted directly from the instruments in-built functions, allowing the fascia to be modelled in the Computer Aided Design (CAD) software AutoCAD (Figure 5). This process provided an immersive, hands-on training opportunity while also ensuring that the proposed structure would be compatible with the existing building geometry.

Using the collected measurements, the UniSQ student produced a detailed CAD drawing of the proposed A-frame bracket. Note, this design was refined collaboratively with the LMD assistant to ensure it could be practically fabricated using locally sourced materials and welding capabilities. Consideration was given to structural rigidity, alignment and the need to securely house the GNSS receiver mounting pole while maintaining vertical and rotational stability, and ensuring the antenna remains level to ensure precise point positioning and prevent distortion from movement and cross polarisation which is crucial for sub-centimetre level accuracy. Once finalised, the 2D design was then turned into a 3D model using Autodesk Fusion360 software where a visual representation of the final product could be reviewed by LMD staff ensuring that the design was appropriate and achievable given the mounting location, and material availability on the island (Figure 5). Once approved, the 2D dimensions were printed and provided to a local welder in Bikenibeu. This approach supported local industry whilst also ensuring the technical requirements for the CORS station were met. This reflects the project's alignment with SDG 11 (Sustainable cities & communities) and SDG 17 (Partnership for the Goals) by outsourcing the fabrication to local businesses, building partnerships with the community and creating a stronger presence for surveyors in the region.

The welder worked directly from these plans to fabricate the A-frame bracket. This design to fabrication workflow ensured that the final structure met the dimensional requirements identified during the survey while remaining achievable within the local resource and time constraints. Note that the frame was constructed with scrap materials (left over from other projects), supporting ongoing recycling efforts in the country (cost of welded bracket: $200).

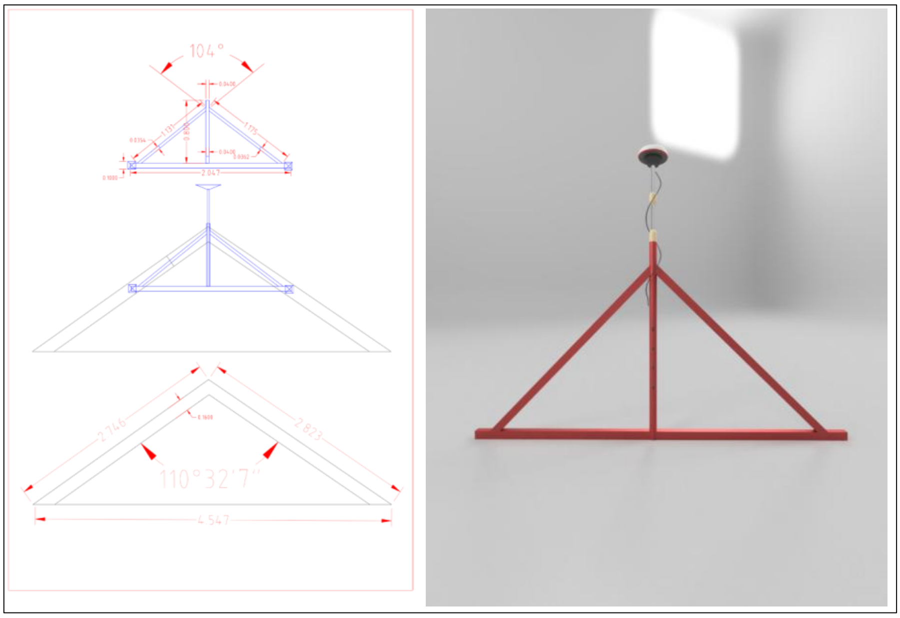

Figure 5: CORS bracket 2D CAD design (left) and CORS bracket 3D render model (right)

3.3 Construction of bracket

Whilst the A-frame bracket was being fabricated, preparation of the internal mounting components commenced. An old, damaged Trimble survey pole with a ⅝-inch threaded screw for mounting standard survey gear, was dismantled and repurposed, with the inner aluminium pipe being retained for mounting the GNSS antenna. Sections of the carbon fibre outer pole were cut into four 15cm long spacers and wrapped with three layers of duct tape to ensure a tight fit between the inner pole and the external steel frame as can be seen in Figure 6 (top left) below. To allow for bolted fixations, the existing holes in the inner pole, originally spaced at 0.5m with an 8mm diameter, were drilled out to 11mm to accommodate M10 bolts. This modification ensures that the inner pipe can be fixed both vertically and rotationally within the bracket and ensures stability as material wear ensures. After two days of fabrication, the mild steel A-frame bracket was completed and collected from the welders' workshop as can be seen in Figure 6 (top right) below.

Upon return to the LMD office, UniSQ students procured materials required for waterproofing and assembly, including galvanised fasteners, epoxy putty and resin, roofing silicone and an exterior waterproof paint. While the electronic components were being fitted and the inner pole finalised, the steel A-Frame was coated with seven layers of all-purpose waterproof paint. Adequate drying time was allowed between each coat to maximise protection against corrosion and promote the longevity of the structure. See Figure 6 (bottom left) for a snapshot into this process during the penultimate coating.

Once all components were ready, the bolt hole positions from the inner pipe were transferred onto the steel frame and drilled to the same 11mm diameter, allowing for accurate alignment during assembly. Assembly began by inserting the inner pole (with carbon fibre spacers installed) into the steel frame. Epoxy putty was applied to the base of the inner pipe so that when driven into position, the putty would spread and bond the bottom of the pole to the frame, creating both a secure connection and a waterproof seal. Note that this process caused minor alignment issues with the bolt holes, which were resolved by applying downward pressure to the inner pole until the bolts could be inserted.

Four stainless steel M10 x 50mm bolts were then passed through the frame and inner pole and permanently secured with locking nuts. Epoxy resin was then applied to both the bolt heads and the nut, locking them in place and sealing each drill hole against moisture ingress. Once the epoxy resin cured, the top spacer was removed, allowing for roofing silicone to be poured into the bracket pipe. This served two purposes:

- Providing additional reinforcement to prevent relative movements between the pipes;
- Displacing air and moisture that could otherwise contribute to internal corrosion.

The top spacer was then driven back into the pipe until it sat approximately 10mm below the top of the frame. To complete the waterproofing, epoxy putty was packed into the remaining gap at the top of the frame and shaped to form a protective cap, ensuring that water running down the pole would be shed away from the frame opening. All remaining holes in both the frame and inner pole were sealed using epoxy putty, and a final coat of exterior waterproofing paint was applied to cover any scratches or exposed steel surfaces, further increasing the durability required to withstand the harsh coastal climate. See Figure 6 (bottom right) below for the final CORS bracket before installation and receiver attachment, and Appendix A for a summary table of the materials used.

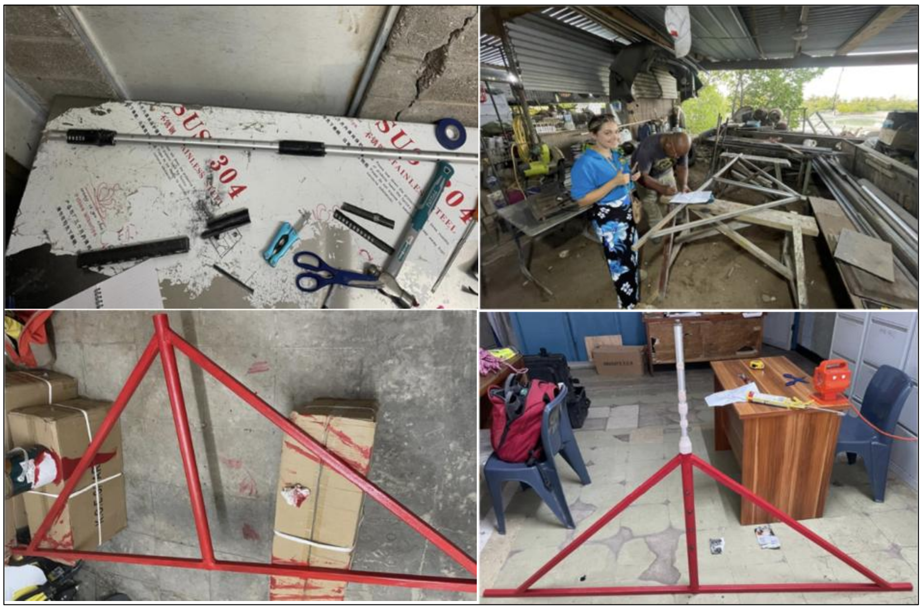

Figure 6: CORS bracket construction process–pole (top left), welded bracket (top right), waterproofed bracket (bottom left), pole attached to bracket (bottom right)

3.4 CORS Installation process

The installation process commenced with verification of compatibility between the completed A-frame bracket and the external GNSS components, specifically the SparkFun RTK mosaic-X5 reference station and the Trimble Zephyr Model 2 antenna (TRM57971), kindly donated by Ryan Keenan on behalf of Positioning Insights (VIC), see Figure 7 (top left) below for the SparkFun equipment supplied. Although the Sparkfun SPK6618H antenna originally supplied with the receiver would have been sufficient for CORS operation, the Trimble Zephyr 2 was selected due to its high stability and repeatable phase centre characteristics. This stability is critical for maintaining consistent weekly and monthly coordinate solutions and for enabling meaningful velocity estimation (tectonic plate movement). Furthermore, the Zephyr 2 antenna has been absolutely calibrated by Geoscience Australia (GA), with an associated calibration file available, making it a preferred option for a permanent reference station.

Following confirmation of external component compatibility, a suitable internal location of the SparkFun RTK mosaic–X5 receiver was identified. Consideration was given to minimising the risk of accidental interference or tampering by LMD staff or clients, as well as addressing the environmental challenges specific to Tarawa, including high humidity and a significant rodent population. To mitigate these risks, the receiver was placed in a well-ventilated and secure area within the LMD director's office. Rodent-proof conduit was used to protect the antenna cable, preventing chew-throughs that could result in a loss of satellite connectivity or system failure.

Prior to the installation of the bracket, a reliable method for ensuring the antenna's levelness was established. After some trialling of several approaches, a tribrach was temporarily mounted to the top of the bracket (using the screw on the survey pole), with all levelling screws fully retracted so that the base and top plates were parallel. This configuration allowed the installer to centre the tribrach bubble during mounting, thereby ensuring that the bracket and hence antenna would be installed level. To facilitate safe access to the fascia, an LMD assistant (the one who measured the fascia) coordinated the procurement of a cherry picker. After an extended search, Kiribati Green Energy Solutions (KGES) generously hired out the equipment to the survey department for the day.

Once on site, an LMD surveyor and KGES operator elevated the bracket (with the tribrach attached) to the roof and secured it to the fascia using the previously sourced fasteners. Throughout the mounting process, care was taken to maintain the tribrach bubble in a level position while all fasteners were tightened. See Figure 7 (bottom left and right) below showing the cherry picker install. After the bracket was securely installed, a UniSQ student accessed the roof via the cherry picker to remove the tribrach, mount the Zephyr antenna, and route the antenna cable into the roof cavity, to which an LMD staff member was waiting inside to pull the cable through into the receiver location. During antenna installation, the antenna's north reference mark was carefully aligned to true north, and the cable was secured to the frame using cable ties to minimise movement and strain. Once all hardware connections were completed, the receiver was connected to power and internet, where it was confirmed that the unit was successfully receiving satellite signals and was logging to an in-built SD card. This marked the completion of the CORS station installation.

Figure 7: CORS bracket installation & SparkFun equipment — SparkFun kit (top left), antenna install (bottom left) and CORS bracket installation (right)

4 METHODS OF ANALYSIS

4.1 Visibility analysis

The quality of GNSS data is dependent on the physical monument, receiver measurement specifications and the visibility between the antenna and satellites. However stable and advanced the GNSS CORS may be, positional correction data can be easily disrupted by surrounding physical obstructions that cause multi-path error. Using Septentrio's RxTools, the SBF (Septentrio Binary Format) Analyzer was utilised to produce a sky plot map of each daily SBF file.

The Septentrio RxLauncher application will bring up a panel of tools where the SBF Analyzer function will appear as the 'pie-chart on paper' icon in the middle. Once selected, the application will open and from the file explorer icon, navigate to the appropriate SBF file, tick the 'Sky Plot' option under 'Plots to Analyze', then finally hit 'Analyze'.

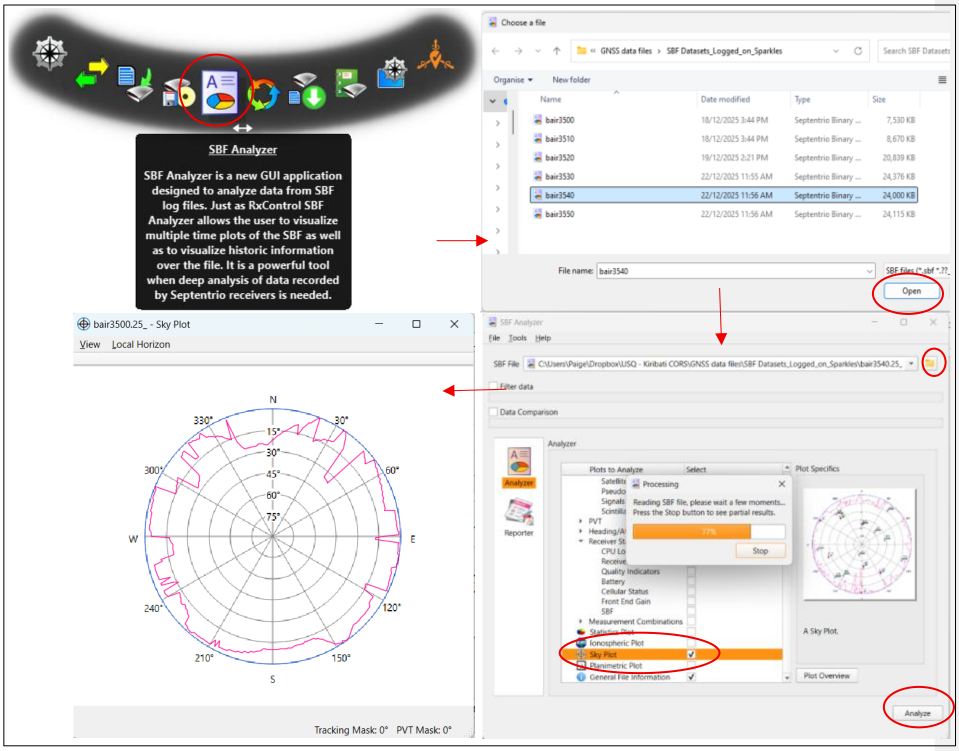

Figure 8: Sky Plot generation using Septentrio SBF Analyser tool

Since the CORS was installed on the apex of the two-storey LMD in a commercial area and near tall trees, it is expected that there would be some minor obstructions from nearby trees and buildings, and thus the sky plot diagrams from a six-day GNSS data sample were investigated (Appendix B). The satellite tracking elevation mask was set to 0° and all the daily sample sky plots showed a consistent and good visibility of the GNSS CORS. Upon investigation of potential local obstructions, the hindrance spikes in the sky plots align with the surrounding trees and two-storey buildings to the SW, NW and NE, however, most sit around 15° elevation mark. The highest obstruction was shown to the NE which can be traced back to the tall, overhanging tree that is located north of the LMD building (Figure 9).

Figure 9: Map of potential surrounding obstructions aligning with CORS Sky Plot

The visibility map for the GNSS CORS confirms there is a mostly clear line of sight for satellite tracking and reduced interference from nearby obstructions. Therefore, the quality of the positioning data is minimally affected by multipath errors and can be regarded as reliable and accurate for use.

4.2 Stability Analysis

The new GNSS installed in Bairiki is temporarily named ‘BAIR’ to distinguish its Receiver Independent Exchange Format (RINEX) files for processing from KIRI and will be referenced henceforth in the analysis of this report. For BAIR, the daily observation SBF files are set to collect 23hours, 59mins and 30seconds of GNSS data, which begin at 0:00:00 and log data at 30 second intervals. This allows for comprehensive capture of the Earth’s rotation for improved averaging out of systematic errors (orbital and atmospheric), reliable precise positioning and creates a robust file size for geodetic processing services like GA’s Online GNSS Positioning Service (AUSPOS) (Geoscience Australia, 2024).

From Australia, Septentrio RxTools is used to monitor the data logging status of the overseas receiver to detect any issues such as power outages that may affect the workflow of the CORS. The daily SBF files for BAIR were downloaded over the Ethernet network which connects the computer in Australia with the receiver in Bairiki. To convert the SBF files into RINEX files to begin processing, the 'SBF Converter' function on Septentrio RxTools was used and advantageously allowed all SBF files to be uploaded at once and converted them seamlessly to RINEX (Figure 10).

Kommenterede [PC1]: Take out?

Kommenterede [ry2R1]: synergy??

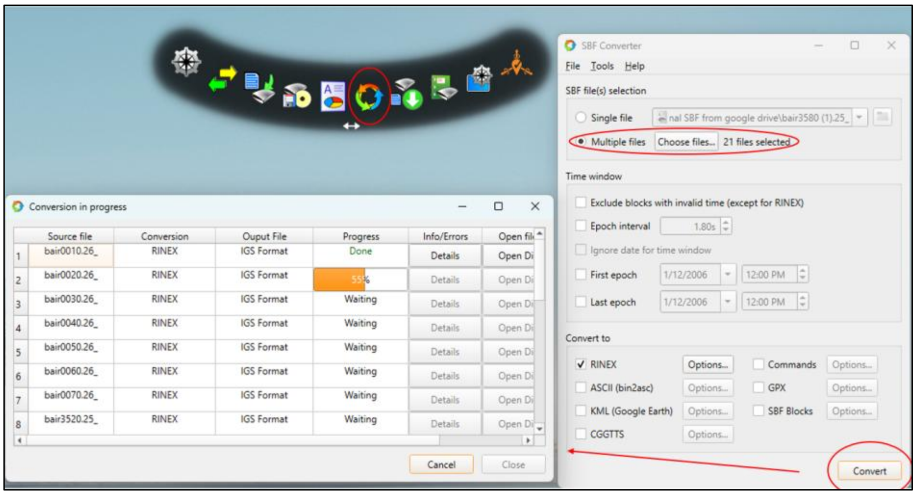

Figure 10: Septentrio RxTools SBF converter for multiple SBF format files

For clarity and improved organisation, the naming convention is: "BAIRXXX0.YYO", where XXX is the numerical day of year (e.g. 344), YY (e.g. 25) indicates the last two numbers of the year, and the suffix 'O' denotes the observation. The AUSPOS website created by GA was used whereby each BAIR RINEX file was uploaded and the antenna type was set to 'TRM57971.00 NONE' to match the Trimble antenna used. Since there was no time overlap between the files, each RINEX was uploaded individually and therefore, an AUSPOS report was generated and sent separately to the nominated email address (Figure 11).

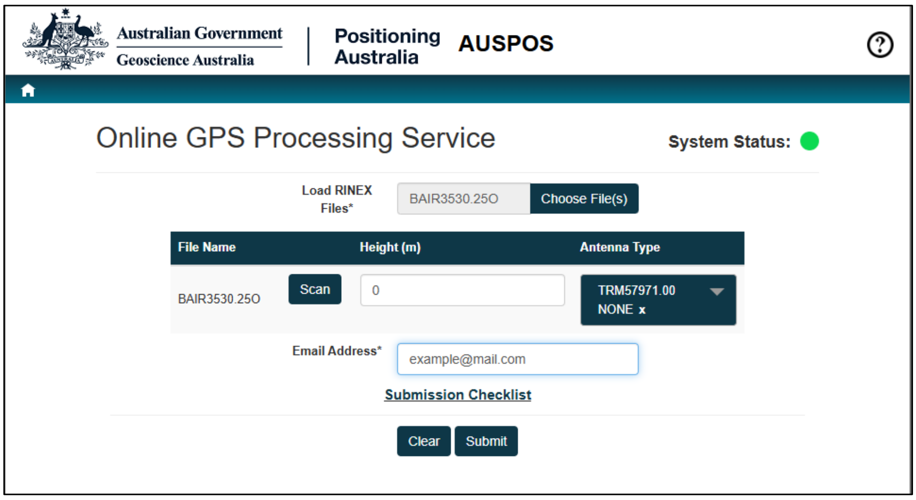

Figure 11: Processing BAIR RINEX files on AUSPOS website (Geoscience Australia, 2024b)

The corresponding dates of RINEX files for KIRI were downloaded from GA's GNSS Data Repository (v1.3.0) (Geoscience Australia, 2024a) which is the portal for Australia's national collection of historical GNSS CORS RINEX files from the Australian Regional GNSS Network (ARGN), the South Pacific Regional GNSS Network (SPRGN) and the AuScope Network. The checkbox options were selected (Fig) to search the appropriate KIRI observation RINEX files which have been compressed as Hatanaka (.crx.gz) and after download will require unzipping before use.

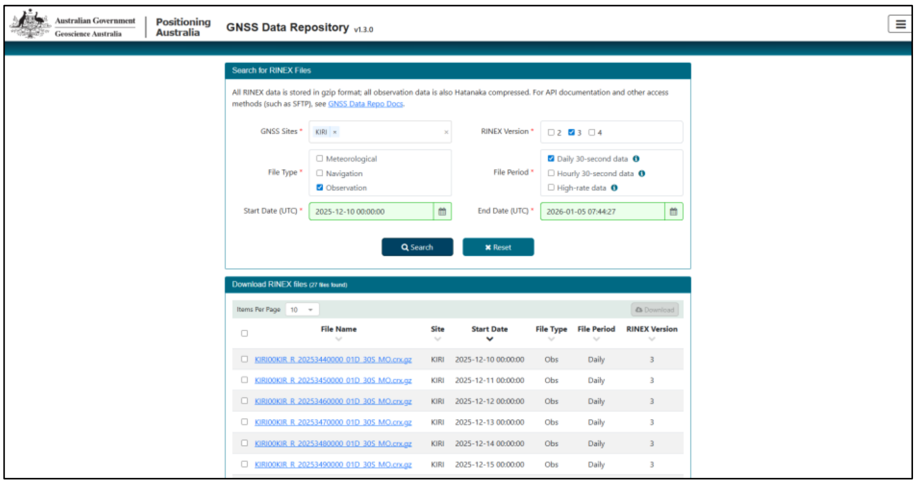

Figure 12: GNSS Data Repository portal for historical KIRI RINEX files (Geoscience Australia, 2024a)

The AUSPOS reports computed the daily GNSS position of BAIR and KIRI CORS during the observation period 29 December 2025 to 7 January 2026 as varying coordinates like: Cartesian (X, Y, Z) in ITRF2020, geodetic (latitude, longitude, ellipsoidal height) referenced to the GRS80 ellipsoid in ITRF2020, and projected UTM grid coordinates. For the purpose of assessing station stability, Cartesian coordinates in ITRF2020 and geodetic (latitude and longitude) were adopted as the primary analysis dataset, as they provide a linear, distortion-free representation of station motion and are standard for geodetic time-series investigations.

5 RESULTS

The stability of the BAIR GNSS CORS site was evaluated relative to the Tier 1 KIRI station using daily AUSPOS solutions due to the limitations of the AUSPOS software not supporting the exclusion of the KIRI CORS site to process the BAIR position.

As KIRI was used as a reference station in AUSPOS, the most informative signal is the relative difference (Δ) between the two stations using the Cartesian coordinates of BAIR relating to KIRI as shown in Equations 1-3:

$$\Delta X = X_{BAIR} - X_{KIRI} \qquad \text{(Equation 1)}$$

$$\Delta Y = Y_{BAIR} - Y_{KIRI} \qquad \text{(Equation 2)}$$

$$\Delta Z = Z_{BAIR} - Z_{KIRI} \qquad \text{(Equation 3)}$$

This removes common-mode errors from orbits, clocks and the troposphere and directly tests the daily BAIR monument stability ensuring there is no evidence of systematic drift or abrupt coordinate offsets. AUSPOS gives Earth-Centred Earth-Fixed (ECEF) Cartesian coordinates in ITRF2020 where the relative differences represent a 3D displacement in global space. To interpret monument behaviour, the vector must be rotated into a local topocentric frame at KIRI where 'North' (N) and 'East' (E) are horizontal and are towards geodetic north and geodetic east respectively, and 'Up' (U) is perpendicular to the ellipsoid. The reference position for KIRI was found by averaging the geodetic latitude (ϕ) and geodetic longitude (λ) from AUSPOS. The following transformation equations (4-6) are used to change ECEF to local NEU components:

$$\Delta N = -sin\phi cos\lambda \Delta X - sin\phi sin\lambda \Delta Y + cos\phi \Delta Z \quad \textit{(Equation 4)}$$

$$\Delta E = -sin\lambda \Delta X + cos\lambda \Delta Y \quad \textit{(Equation 5)}$$

$$\Delta U = cos\phi cos\lambda \Delta X + cos\phi sin\lambda \Delta Y + sin\phi \Delta Z \quad \textit{(Equation 6)}$$

This is beneficial to increase the immediate visibility of each day's vertical instability in 'Up' and any concerning horizontal monument behaviour in 'North/East' which all originate from Cartesian ITRF2020 coordinates.

The stability is analysed by detrending ($\Delta N', \Delta E', \Delta U'$) the local NEU components by removing the mean ($\bar{N}, \bar{E}, \bar{U}$) from each:

$$\Delta N' = \Delta N - \bar{N} \quad \textit{(Equation 7)}$$

$$\Delta E' = \Delta E - \bar{E} \quad \textit{(Equation 8)}$$

$$\Delta U' = \Delta U - \bar{U} \quad \textit{(Equation 9)}$$

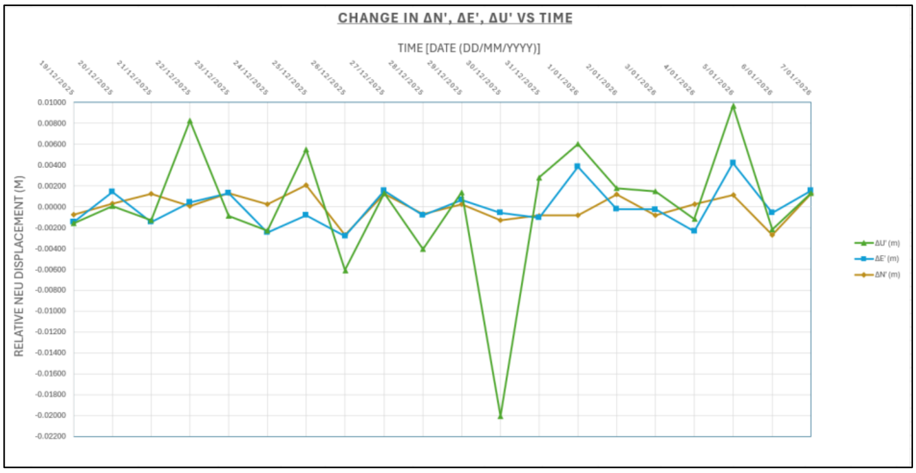

Figure 13: Time series of detrended relative north, east, and up displacements of BAIR with respect to the Tier 1 KIRI station.

The results in Figure 13 indicate that the BAIR stability relative to KIRI is performing as expected as: the values are centred close to zero, there is mostly millimetre-level scatter, and the 'Up' component is nosier than 'North'/'East'. The expected GNSS behaviours of horizontal stability is ±1-3mm while vertical stability is forecasted between ±5-20mm. Examination of the horizontal components (ΔN′ and ΔE′) show minimal variability, generally remaining within ±2–3mm, with no observable long-term trend or step change. On the 1/1/2026 and 5/1/2026 there are two slight ΔE′ displacement spikes above the expected range at around +4mm, however both are impermanent. Vertical motion (ΔU′) displays greater short-term variability, with 70% of daily observations within ±5mm, consistent with expected GNSS height precision. There is one major vertical displacement spike in 'Up' which exhibit a short-lived excursion of up to approximately ±18mm**.** This behaviour is consistent with the reduced precision of GNSS-derived vertical estimates and is commonly attributed to residual atmospheric effects and satellite geometry rather than true monument movement. Therefore, the results do not raise instability concerns and there is no systematic drift detected.

In addition to analysing individual NEU components, the total relative displacement magnitude was computed to provide a single, direction-independent indicator of short-term station stability. The relative displacement Equation 10 is used:

$$D = \sqrt{(\Delta N')^2 + (\Delta E')^2 + (\Delta U')^2} \qquad \textit{(Equation 10)}$$

This gives a single stability metric per day and highlights transient events of low-cost stations when ranking stability performance.

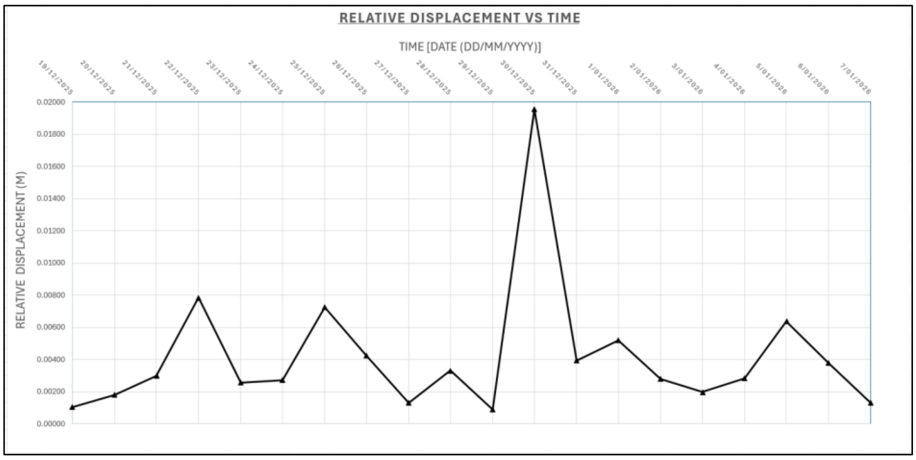

Figure 14: Relative displacement vs time results

Relative displacement between BAIR and the Tier 1 KIRI reference station was computed from detrended local north, east, and up (N’, E’, U’) components to indicate short-term station stability. Across the 20 analysed daily solutions, relative displacement magnitudes remain low, with a mean value of approximately 4mm and a maximum of approximately 18mm. Importantly, elevated displacement values are observed on only at a single epoch (30/12/2025), indicating that the large excursions are infrequent and not representative of the overall behaviour of the site. The limited frequency, short duration, and vertical dominance of these excursions, combined with the absence of any persistent trend or step change, indicate that BAIR maintains a stable spatial relationship with KIRI. Overall, the results demonstrate consistent and repeatable positioning performance, supporting the suitability of the low-cost BAIR installation for ongoing geodetic and land administration applications.

6 DISCUSSION

This research evaluated the performance of the BAIR continuously operating reference station (CORS), a low-cost GNSS installation constructed using region-specific and locally sourced materials to assess its suitability for enhancing geodetic infrastructure in the Pacific. Although donated, the SparkFun RTK mosaic-X5 kit (receiver, cables, antenna, MicroSD card) is valued at approximately $1,866 AUD as of January 2026 (SparkFun Electronics, 2026). Therefore, the new GNSS CORS totalled approximately AUD $2,500 (see section 3.2 and Appendix A). The results demonstrate that BAIR provides a stable and reliable positioning solution that is well aligned with the practical constraints faced by many Pacific Island nations, where financial limitations, geographic isolation, and restricted access to specialised geodetic resources present significant challenges to infrastructure development.

Time series analysis (Figure 14) of detrended North, East, and Up (N', E', U') displacement components indicates that BAIR maintains a consistent spatial relationship with the nearby Tier-1 KIRI reference station throughout the observation period. Horizontal displacement variability is generally constrained within ±2–3 mm, while vertical variations are typically within ±5 mm, apart from the short-lived excursion representing approximately 5% of the dataset. These transient spikes are dominated by the Up component and are likely attributable to short-term atmospheric effects or satellite geometry rather than monument instability or installation deficiencies. The absence of systematic drift or persistent offsets supports the conclusion that BAIR is geodetically stable despite its low-cost construction.

The significance of these findings is best understood through a cost–benefit lens. A Tier-1 CORS installation typically incorporates geodetic-grade receivers and antennas, reinforced monumentation, continuous power and communications infrastructure, environmental sensors, and dedicated technical support. When equipment procurement, installation, operation, and maintenance are considered, the total cost of establishing and on-going operation a Tier-1 CORS commonly approaches AUD$100,000. For many Pacific Island nations and developing countries, such expenditure is prohibitive, particularly given competing national priorities and the ongoing costs associated with system upkeep.

In contrast, BAIR demonstrates that a functional and stable CORS can be established at less than 1% of the cost of a Tier-1 station. The use of affordable hardware, locally available materials, and simplified construction methods substantially reduces both initial capital investment and long-term operational requirements. This approach is particularly well suited to regions where access to specialised equipment, replacement parts, and technical expertise is limited. By lowering financial and logistical barriers, low-cost CORS solutions enable broader deployment, increased network density, and improved redundancy within national geodetic frameworks.

While BAIR is not intended to replace Tier-1 CORS for the most demanding geodetic applications, its demonstrated stability indicates that it is well suited for a wide range of practical uses, including mapping, construction, navigation support, and cadastral control densification. Importantly, the ability to deploy multiple low-cost stations for the price of a single Tier-1 installation offers a compelling strategic advantage in data-sparse regions.

Crucially, the BAIR installation process aligned strongly with capacity-building objectives and the Sustainable Development Goals. The collaborative sourcing of materials and construction of the monument engaged local businesses and technicians, directly supporting SDG 11 (Sustainable Cities and Communities) and SDG 17 (Partnerships for the Goals). Concurrent training activities enhanced local surveying capability and institutional knowledge, contributing to SDG 4 (Quality Education) and SDG 10 (Reduced Inequalities). The presence of a second

CORS also mitigates the single-point vulnerability associated with reliance on KIRI alone, improving network geometry and resilience, which is essential for modern land administration and infrastructure governance (SDG 16).

In the context of Pacific geodetic infrastructure development, the BAIR CORS represents a pragmatic and scalable solution. The results of this study suggest that low-cost, regionally constructed CORS installations can play a critical role in expanding GNSS capability, improving spatial data resilience, and supporting sustainable development outcomes in resource-constrained environments.

7 CONCLUSION

This study demonstrates that the BAIR low-cost CORS provides a stable and consistent GNSS reference solution when evaluated relative to the Tier-1 KIRI station in South Tarawa. Analysis of relative NEU displacements indicates that BAIR maintains millimetre-level horizontal stability and stable vertical behaviour over the observation period, with no evidence of long-term drift or systematic instability. Although short-lived displacement excursions were observed on one day, this event was isolated and did not compromise the overall stability of the station. From a cost–benefit perspective, the findings are particularly significant. While Tier-1 CORS installations commonly require investments approaching AUD $100,000 (GNSS receiver, antenna, cabling, monument, materials and construction) to construct and operate, BAIR was deployed for approximately AUD $2,500, representing a substantial reduction in financial and logistical requirements. This cost differential highlights the feasibility of deploying multiple low-cost stations to improve network density and redundancy in regions where traditional geodetic infrastructure is impractical. Overall, the results indicate that low-cost, regionally constructed CORS installations such as BAIR can play a meaningful role in expanding GNSS capability in the Pacific. While not a replacement for Tier-1 infrastructure, such solutions offer a fit-for-purpose practical and scalable pathway toward improved geodetic resilience, supporting sustainable development and enhanced spatial data availability in resource-constrained environments.

ACKNOWLEDGEMENTS

This project was kindly supported through the donation of the SparkFun GNSS receiver and provision of on-going technical contributions from Dr. Ryan Keenan (Positioning Insights) used in the establishment of the BAIR CORS. The co-authors extend a special acknowledgement to the LMD team, particularly Romano Reo (Director of LMD), Tawewere Roota, Hywaki Kaogotao and Terenga Bakoroa for their collaboration, local knowledge and on-going commitment to strengthening Kiribati's geodetic capability.

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APPENDICES

Appendix A

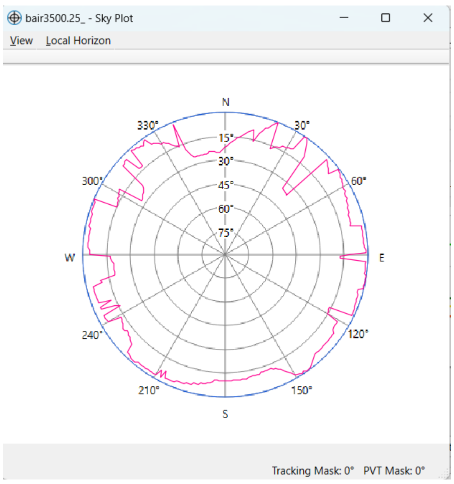
Table 2: Material and cost breakdown for CORS fabrication

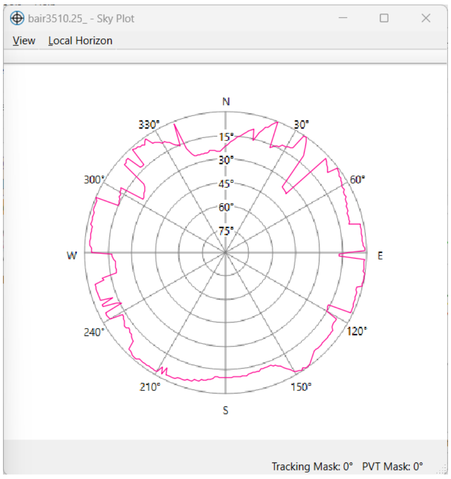
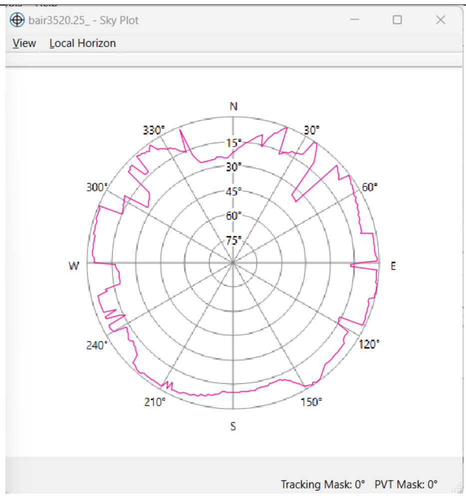
Material	Quantity	Total Cost (AUD)	Description
17cm galvanised fasteners	20	$32	14 x 17cm galvanised fasteners to mount the frame to the fascia apex. Given the screws were designed for wood, pilot holes were drilled through the steel frame slightly smaller than the screw diameter to maintain friction and hold tight. The longest available screws were used as the plan was to mount them through both the steel and fascia board with some screwing into the main trusses to ensure stability and structure strength. Overall, 4 fasteners were screwed into the trusses and the remaining 13 were screwed into the fascia board only. This proved sufficient for stability purposes.
10mm x 50mm bolts + nuts	4	$5	4 stainless steel bolts were placed down the vertical frame tube through the frame and the holes in the interior pipe. These added a second level of security to the stability and locked the interior pole inside the steel frame. Note that a second effect was that it also prevented rotation of the interior pipe relative to the exterior.
100g epoxy putty + hardener	4	$68	4 packets of epoxy putty were employed to seal all holes that allowed water to enter inside the frame and interior pipe, this use can be seen in Figure 6. A second purpose of the putty was to be placed on the bottom of the interior pipe such that when jammed into the frame the putty would harden fixing the bottom of the interior pole.
Tube of roofing silicone	1	$24	Roofing silicone was used to fill up the A-frame tube once all cross bolts were employed. The purpose of which was to displace any air/water within the tube limiting rust and served a second purpose of glueing the interior tube to the exterior.
Silicone tube gun	1	$20	For application of roofing silicone
Epoxy resin and hardener	2	$55	Like the epoxy putty, epoxy resin was used to seal up all exterior holes and lock the cross drilled bolts such that the interior pole would be fixed permanently, this can be seen in Figure 6 where the

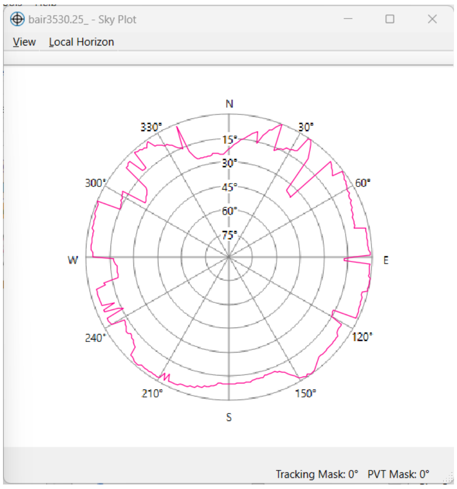
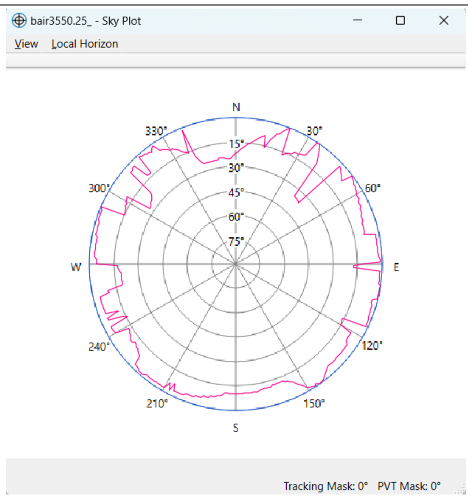
			dark grey dots down the central pipe are the bolt holes and nuts covered and seal in this resin
All-purpose exterior coating paint	1	$29	To help increase the longevity of the frame, multiple layers of all-material weatherproof paint was applied, note no metal primer was used as product availability in country was limited. The specific brand of paint used was unknown as like most of the other materials, they were exported from Chinese sources. As stated above the paint was applied in layers allowing time for each layer to dry.
Extra tools/machinery	1	$195	— L screwdriver bit set ($35) — Scissor Lift/Cherry Picker Hire ($160)

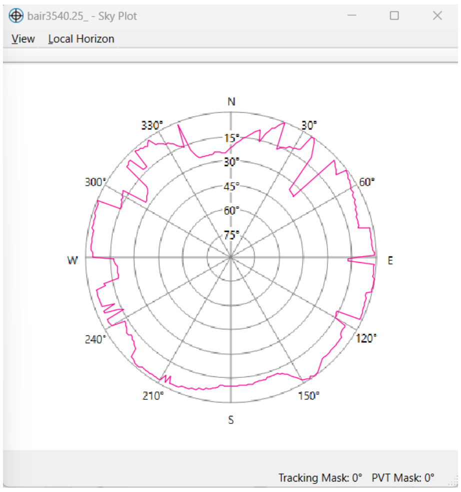
Appendix B

Table 3: Comparison of sky plot diagrams from six-day sample (Hexagon, 2025)

Date (DD/MM/YYYY)	Sky Plot Diagram (Septentrio – SBF Analyzer)
16/12/2025	

17/12/2025	
18/12/2025	

19/12/2025	
20/12/2025	

21/12/2025	

BIOGRAPHICAL NOTES

Paige Carriglio is an undergraduate at the University of Southern Queensland (UniSQ) undertaking a Bachelor of Surveying (Honours) degree in Australia. Paige has been working at SDG – a land surveying firm in Sydney – for five years and has been involved in a variety of projects. Paige Carriglio is trained in cadastral surveys, work as executed/identification surveys, laser scanning (using Lecia scanners such as BLK360, RTC360, P40), construction surveys, strata surveys, detail and level surveys, and monitoring surveys.

Paige Carriglio has participated in the New Colombo Plan Program whereby selected students from UniSQ collaboratively worked alongside the Land Management Division (LMD) team in South Tarawa, Kiribati for five weeks. Through this program she worked overseas as a surveyor, trainer and contributed to efforts that lead to capacity building and improving the national geospatial system of Kiribati.

Dr. Ryan Keenan is Principal Consultant at Positioning Insights in Melbourne, Australia, specialising in capacity building and knowledge transfer around geodesy, GNSS, CORS and location-based services, to governments and SMEs around the world. Dr. Keenan earlier worked at Leica Geosystems (part of Hexagon) at various roles within their GNSS CORS Team, including as Business Director of SmartNet Australia – a commercial CORS RTK Service provider in Australia.

To date, Dr. Keenan has designed, installed and supported GNSS CORS networks in more than 25 countries, and he is active across the global geodesy community, and currently holds a number of roles including:

- Chair, International Federation of Surveyors' (FIG) Commission 5 on Positioning and Measurement,
- Member, International Advisory Committee (IAC) to the United Nations Global Geodetic Centre of Excellence (UN-GGCE), Bonn, Germany,
- Member, United Nations Global Geographic Information Management (UN-GGIM) Private Sector Network (PSN).

Joshua Bested is currently an undergraduate at the University of Southern Queensland (UniSQ), undertaking a four-year Bachelor of Surveying (Honours) degree. Joshua graduated from college in 2022 and has been working part-time as a surveyor's assistant at John C Bested & Associates, located in central Adelaide, and has had the opportunity to work on a variety of projects, including the major South Road upgrade. Joshua has been trained in large-scale second-order GNSS surveys, Laser Scanning (utilising the Reigel VZ400i), cadastral surveys, set out surveys, photogrammetric surveys (utilising drones), engineering surveys and monitoring surveys (bridges & dam faces):

Alongside five other UniSQ students, Joshua Bested participated in the Australian Government's New Colombo Plan program, which entailed nine weeks of integration with Land Management Division (LMD) staff. During this time, Joshua performed cadastral, engineering, GNSS static and bathymetric surveys alongside LMD staff on the Tarawa atoll. This experience also included survey training programs, developing the LMD offices, and teaching sessions upon which new survey directions were supplied after staff undertook real-world training.

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