# Pacific Sea Level and Geodetic Monitoring Project: Levelling & GNSS Monitoring Survey Report

## Yaren, Nauru, October 2019

GEOSCIENCE AUSTRALIA
RECORD 2023/21

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Geoscience Australia acknowledges the traditional custodians of the country where this work was undertaken. We also acknowledge the support provided by individuals and communities to access the country, especially in remote and rural Australia.



**ISSN 2201-702X (PDF)**
**ISBN 978-1-922625-57-1 (PDF)**
**eCat 148872**

**Bibliographic reference:** Lal, A., Rattan, V., Kalouniviti, M., Brown, N. J., Thomas, B. R., 2023 *Pacific Sea Level and Geodetic Monitoring Project: Levelling & GNSS Monitoring Survey Report: Yaren, Nauru, October 2019.* Record 2023/21. Geoscience Australia, Canberra. https://dx.doi.org/10.26186/148872

# Contents

# 1 Motivation

The Australian Bureau of Meteorology (Bureau), Geoscience Australia (GA) and the Pacific Community (SPC) work together on the Australian Aid funded Pacific Sea Level and Geodetic Monitoring Project (PSLGMP). The project is focused on determining the long-term variation in sea level through observation and analysis of changes in the height of the land using Global Navigation Satellite System (GNSS) data and changes in the sea level using tide gauges managed and operated by the Bureau. It is the role of GA and SPC to provide information about ‘absolute’ movement of the tide gauge (managed by Bureau) using GNSS to continuously monitor land motion and using levelling (SPC) to measure the height difference between the tide gauge and GNSS pillar every 18 months.

Land movement caused by earthquakes, subsidence and surface uplift have an important effect on sea level observations at tide gauges. For example, a tide gauge connected to a pier which is subsiding at a rate of 5 mm per year would be observed as a rate of 5 mm per year of sea level rise at the tide gauge. Because of this, it is important to measure, and account for, the movement of land when measuring ‘absolute’ sea level variation - the change in the sea level relative to the centre of the Earth. Relative sea level variation on the other hand is measured relative to local buildings and landmass around the coastline.

Geoscience Australia’s work enables more accurate 'absolute' sea level estimates by providing observations of land motion which can be accounted for by Bureau when analysing the tide gauge data.

# 2 Introduction

This report provides the results of the GNSS monitoring survey & high precision level survey completed between the Sea Level Fine Resolution Acoustic Measuring Equipment (SEAFRAME) tide gauge and the GNSS Continuously Operation Reference Station (CORS) in Yaren, Nauru from 24th to 29th October 2019. It also provides an updated height of the tide gauge derived from GNSS time series analysis and precise levelling observations.

**GNSS Monitoring Survey**

A high precision geodetic terrestrial survey is undertaken to monitor the stability of the GNSS CORS monument. This survey is used to complement GNSS analysis by determining whether movement detected by GNSS analysis is caused by localised movement of the pillar, or movement of the land across a larger area. Local movement is monitored by examining and comparing the results of repeat surveys to the monument and permanent reference marks approximately 15 m from the GNSS monument.

**Levelling Survey**

The Total Station levelling technique is used to observe the difference in height between the Tide Gauge and GNSS monument. The levelling route includes a deep driven benchmark array in Nauru, which runs approximately 3.7 km. Previous levelling surveys have been conducted along this route using the Total Station differential levelling technique in 2005, 2007, 2009, 2010, 2012, 2013, 2015, 2016 and 2018. This report contains an analysis of the 2019 Total Station differential levelling and GNSS monitoring results as well as a combined comparison of the previous levelling surveys.

**Personnel**

Personnel involved in the GNSS monitoring and levelling surveys were Andrick Lal and Zulfikar Begg, from the Geodetic Survey at SPC. The GNSS time series analysis and derivation of the tide gauge ellipsoidal height was undertaken by the GNSS analysis team at Geoscience Australia

## 2.1 Site Description and Contacts

The levelling benchmark array between the GNSS CORS, and SEAFRAME is approximately 3.2kms long, running from the GNSS CORS pillar (NAUR) at the southern end of the runway, along its length, then along the main road, and through the phosphate offices, to the tide gauge at the harbour on the west side of the island.

| | | | |
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| | |
|---|---|
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## 2.2 Survey Support

The survey team very much appreciated the assistance from the Republic of Nauru Lands Department, who received the survey equipment freight, and were able to make a staff member available to assist us during the survey work.

The PSLGM Survey team would also like to acknowledge the continued support of the Republic of Nauru Lands Department and appreciate the continued working relationship that has been in place since 2003.

# 3 Measurement Network

## 3.1 Terrestrial Network

The Total Station differential levelling survey was carried out between the GNSS CORS and the SEAFRAME Tide Gauge using the existing deep driven benchmark array. This consists of Primary deep driven benchmarks, and temporary holding marks (Table 3.1).

*Table 3.1 The primary survey control network. Locality diagrams of these marks are provided in Appendix A.*

| Name | Description |
|---|---|
| **NAU1** | Deep driven benchmark |
| **NAU2** | Deep driven benchmark |
| **NAU33** | Deep driven benchmark |
| **NAU36** | Deep driven benchmark |
| **NAU37** | Deep driven benchmark |
| **NAU38** | Deep driven benchmark |
| **NAU16** | Deep driven benchmark |
| **NAU15** | SEAFRAME sensor benchmark |
| **NAU14a** | SEAFRAME Project benchmark |
| **NAURBM** | Reference benchmark for the GNSS CORS pillar |
| **RM1** | GNSS CORS reference mark 1 |
| **RM2** | GNSS CORS reference mark 2 |
| **RM3** | GNSS CORS reference mark 3 |

Upon inspection, all the deep driven benchmarks were located, found in good order, and undisturbed. Included in the survey were the temporary holding marks; 53, 104, 103, 110, 101, 47, 109, 44, 43, 107, 106, 100, and 28 (Fig 3.6). The benchmark, NAU14, was not found, and therefore replaced with a new benchmark, NAU14A (masonry nail in concrete).

### 3.1.1 PSLGMP Vertical Reference Frame Wiring Diagram

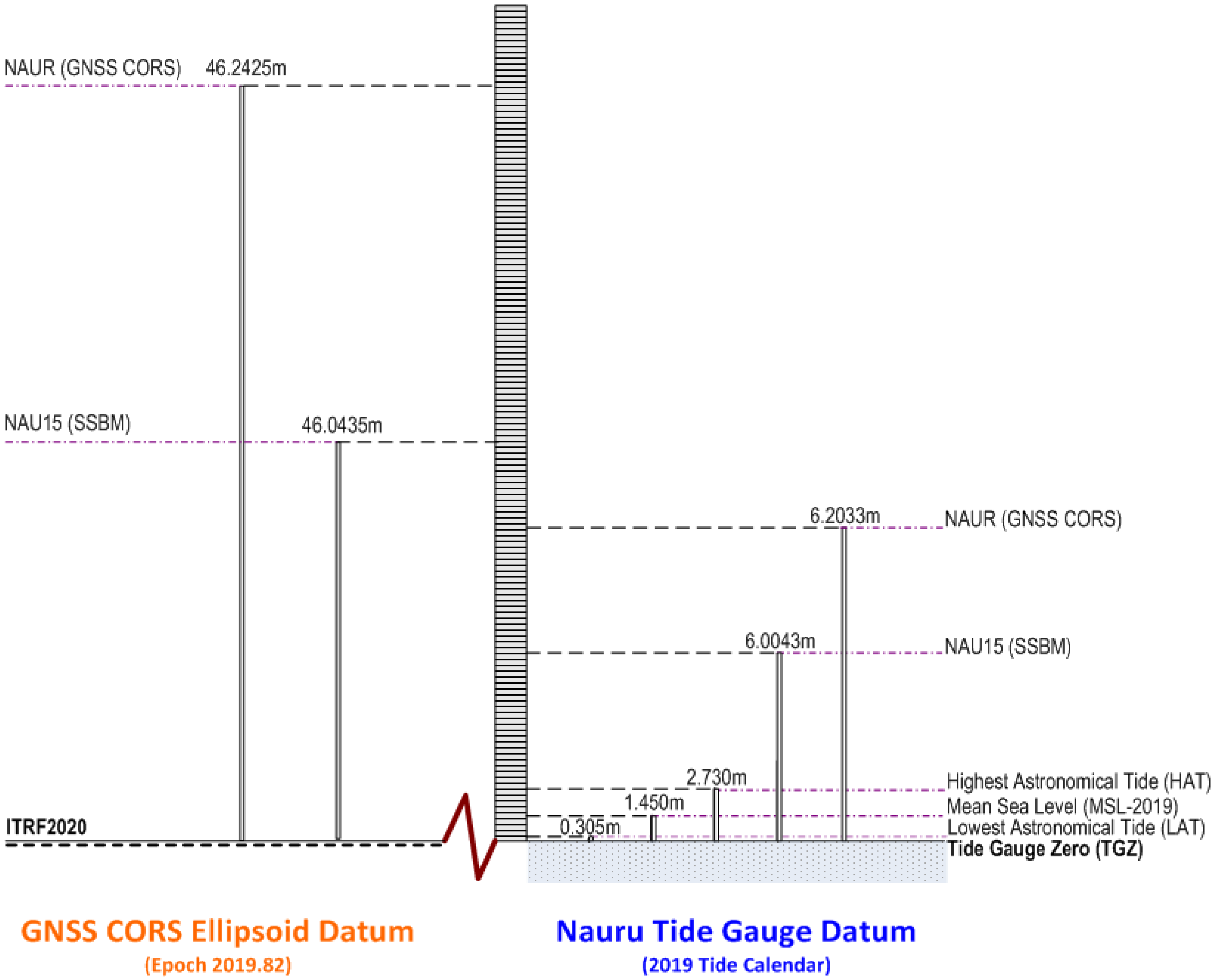


*Figure 3.1 Wiring diagram depicting the offsets between surveyed marks. The left-hand side shows the height of the GNSS CORS pillar (NAUR), SEAFRAME sensor reference benchmark (NAU15), with respect to the International Terrestrial Reference Frame 2020 at epoch 2019.82. The right-hand side shows the height of NAUR, NAU15, and tidal datums with respect to tide gauge zero. For more information on tidal datums, please refer to [Pacific Sea Level and Geodetic Monitoring Project File information and Instructions (bom.gov.au)]*

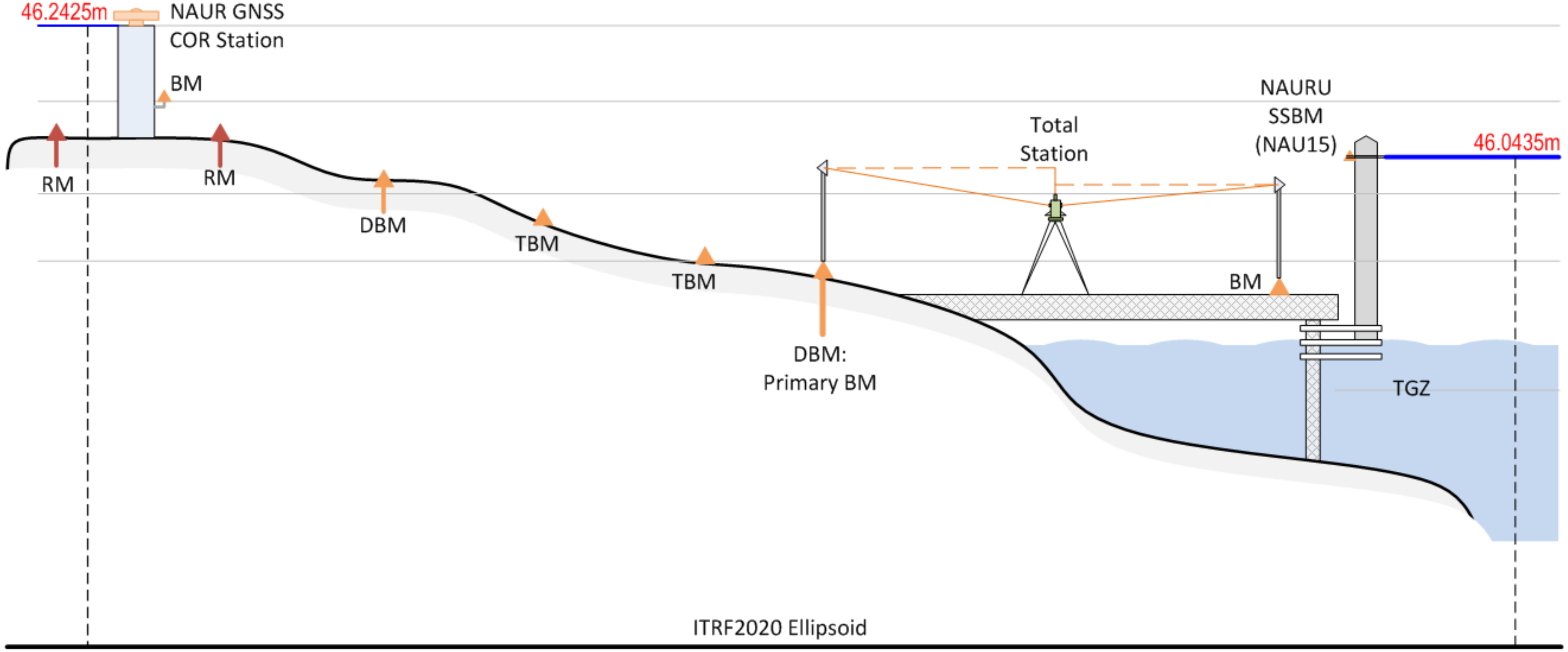


*Figure 3.2 Simplified representation of the Total Station differential levelling survey carried out between the GNSS CORS and the SEAFRAME Tide Gauge.*

*Figure 3.3 Tide Gauge Station. The red circle denotes the location of the SEAFRAME sensor benchmark (NAU15) at the port harbour.*

*Figure 3.4 GNSS COR Station (NAUR) at the Yaren District in Nauru.*

### 3.1.2 Levelling Benchmark Network


*Figure 3.6 Levelling benchmark array. Source: Adopted from Google Maps.*

### 3.1.3 GNSS CORS and Reference Marks

The GNSS CORS site is located within a compound adjacent to the southern end of the airport runway, at the intersection of the island circuit road and the airport bypass road. The site consists of a building to house the technical equipment and a 1.5 m GNSS CORS antenna pillar. The pillar is 25 metres from the GNSS CORS hut. Access can be arranged with the survey office who holds the key for the gate. Entry is unrestricted after initial visit to the Lands & Survey department.

Three primary deep driven Reference Marks (RM) benchmarks were placed at the time of installation at a distance of 20 m to 30 m from the GNSS monument at approximately 120 degree radial spacing from true north (Fig 3.6). The RM's consist of capped 20 mm stainless steel rods driven to refusal and are protected by 150mm PVC pipe within circular poly carbonate boxes.

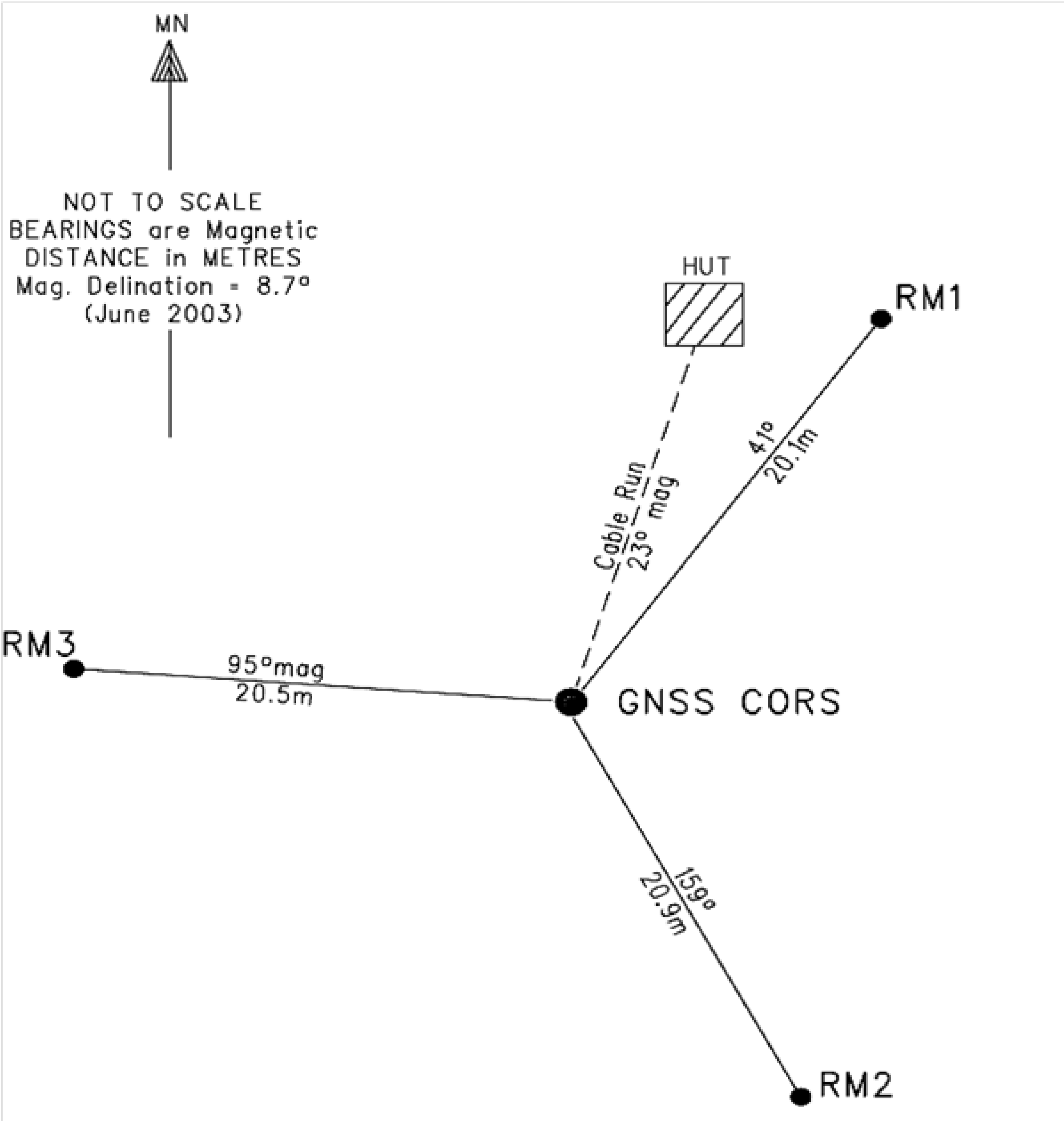


*Figure 3.7 GNSS CORS site monitoring survey reference marks.*

## 3.2 Datum

### 3.2.1 Survey Datum

The adopted reference point for the levelling survey is the levelling benchmark connected to the side of the GNSS CORS pillar (NAURBM) fixed at 0.0000m.

### 3.2.2 Historical Survey Datum

The datum for the previous surveys was the Nauru Island Datum (NID). And the adopted reference point from the levelling survey was NAU1 fixed at RL of 7.2930m. This value was determined by the National Tidal Centre Australia (NTCA) in 1993 by adopting the height from the old survey benchmark, UH1 with RL of 4.130m (NID) and in 1994 by adopting the height from the old survey benchmark, U2B with RL of 3.8894m NID.

# 4 Monitoring Survey

## 4.1 Background

A local monitoring survey is undertaken routinely to monitor for any local horizontal or vertical movement of the GNSS pillar, relative to the RMs. The RMs are all located within 30 m of the GNSS pillar. We acknowledge that this monitoring does not account for any movement over the wider area – i.e., movements that might be consistent across all RM's.

### 4.1.1 Methodology

The Total Station is used to observe and record all horizontal and vertical angles and slope distances in the network by setup and observation from each RM.

Two monitoring techniques can be used to determine movement of the GNSS monument.

The conventional 'Direct Method', involves removing the GNSS antenna and setting up the Total Station on the pillar to directly observe to a prism setup on a tripod over each RM. The Total Station is then moved to each RM in turn and observations are made directly to the pillar and other RMs from each setup. This method can also provide a direct observation to the height of the antenna mount, but obviously requires an interruption to the GNSS data when the antenna is removed, which is not ideal.

The 'Indirect Method' was developed to leave the antenna undisturbed. The symmetrical properties of the antenna are used to indirectly measure the centre of the antenna by triangulation from each RM. To measure the horizontal position of the Antenna Reference Point (ARP), angular direction observations are made to symmetrically coupled points on the external profile of the antenna (Figure 4.1) from each RM. The angular observations from all setups can be averaged and intersected to give a position of the central axis of the antenna by way of triangulation from the three RMs.

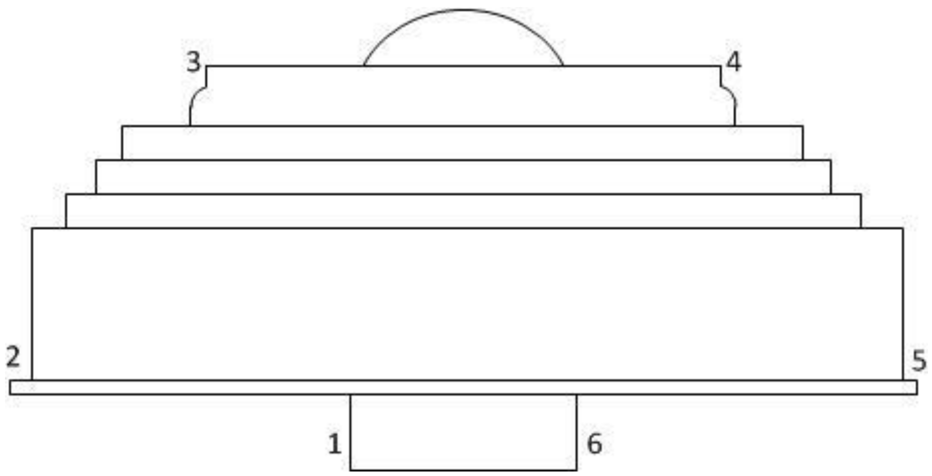


*Figure 4.1 Symmetrical points on the antenna profile (LEIAR25.R3) observed from each RM.*

The Indirect Method does not allow for a measurement of the vertical position of the monument. Instead, the result of the RM levelling survey (from each RM to the GNSS BM) is used, and then the known offset from the BM to the antenna mounting plate is applied.

Both techniques used will allow comparison to previous years, to monitor any movement of the pillar over time. The reduced observations are put into a least squares adjustment program, DynAdjust (Fraser et al., 2018), to determine the final coordinates by holding the point at the centre of the GNSS pillar plate fixed and calculating the relative movement of each RM in ΔE, ΔN & ΔU, and an estimate of the error.

To avoid introducing any discontinuities into the GNSS time-series it is preferred, where possible, that the Indirect Method of observation be used.

## 4.2 Horizontal Observations

The heights of the RMs are observed using the Total Station levelling (EDM height traversing) technique, with a Leica Total Station and two fixed height rods with precision reflectors (see Appendix C).

A horizontal control survey was conducted following the ICSM SP1 Guideline for Conventional Traverse Surveys (ICSM, 2021). Five sets of observations were completed at each standpoint; a set consists of a round of face left observations, followed by a round of face right observations to each of the visible survey marks. For each observation a horizontal direction, zenith angle and slope distance was recorded. At each instrument set-up atmospheric conditions (temperature, pressure and relative humidity) were recorded. Atmospheric conditions were applied during the post-processing stage and not directly into the Total Station. Instrument and target heights were measured using an offset tape.

## 4.3 Data Analysis and Results

### 4.3.1 Levelling Survey

Reduction of the digital data was computed using the Geoscience Australia levelling program “leveling1.exe” and LevellingFIELD_3.pl. This program computes the height difference between the two reflectors by taking the mean average of the measured height differences and also providing standard deviations and a misclose for the levelling loop. Refer to Section 5 for a detailed description of the levelling process.

*Table 4.3.1 Reduced Level (RL) Shown is the height relative to NAURBM.*

| From | To | Rise (m) | Fall (m) | RL (m) | Dist (km) | Acc Dist (km) |
|---|---|---|---|---|---|---|
| **NAURBM** | | | | 0.0000 | | 0.000 |
| **RM1** | **RM1** | 0.0000 | -0.7124 | -0.7124 | 0.020 | 0.020 |
| **RM2** | **RM2** | 0.0000 | -0.1625 | -0.8749 | 0.0355 | 0.0557 |
| **RM3** | **RM3** | 0.0978 | 0.0000 | -0.7771 | 0.036 | 0.092 |
| **RM2** | **RM2** | 0.0000 | -0.0980 | -0.8750 | 0.036 | 0.000 |
| **RM1** | **RM1** | 0.1625 | 0.0000 | -0.7125 | 0.0353 | 0 |
| | **NAURBM** | 0.7125 | 0.0000 | -0.0001 | 0.020 | 0.000 |
| | Sum: | 0.9727 | -0.9728 | | | |
| | Misclose: | | -0.0001 | -0.0001 | 0.183 | (Total Dist) |
| | | | **ALLOWABLE (m):** | **0.0006** | **2 x Sqrt (km) test:** | **PASS** |

| From | To | Rise (m) | Fall (m) | RL (m) | Dist (km) | Acc Dist (km) |
|---|---|---|---|---|---|---|
| **NAURBM** | | | | 0.0000 | | 0.000 |
| **RM2** | **RM2** | 0.0000 | -0.8749 | -0.8749 | 0.021 | 0.021 |
| **NAURBM** | **NAURBM** | 0.8750 | 0.0000 | 0.0001 | 0.021 | 0.000 |
| | Sum: | 0.8750 | -0.8749 | | | |
| | Misclose: | | 0.0001 | 0.0001 | 0.041 | (Total Dist) |
| | | | **ALLOWABLE (m):** | **0.0003** | **2 x Sqrt (km) test:** | **PASS** |

| From | To | Rise (m) | Fall (m) | RL (m) | Dist (km) | Acc Dist (km) |
|---|---|---|---|---|---|---|
| **NAURBM** | | | | 0.0000 | | 0.000 |
| **RM3** | **RM3** | 0.0000 | -0.7771 | -0.7771 | 0.023 | 0.023 |
| | **NAURBM** | 0.7770 | 0.0000 | -0.0001 | 0.023 | 0.000 |
| | Sum: | 0.7770 | -0.7771 | | | |
| | Misclose: | | -0.0001 | -0.0001 | 0.045 | (Total Dist) |
| | | | **ALLOWABLE (m):** | **0.0003** | **2 x Sqrt (km) test:** | **PASS** |

### 4.3.2 Geodetic Adjustment

All observations were combined into a geodetic adjustment using DynAdjust (Fraser et al., 2018). In the adjustment, the point on the GNSS pillar plate (NAUR) was tightly constrained to its ITRF2014 coordinates and aligned to NAUR-RM1 with an azimuth of 49° 42' 00.33", which had been determined in the 2003 survey by GNSS observation to RM1. The angular observations were given an uncertainty of 1.0" and the slope distances an uncertainty of 1.0 mm. The estimated coordinates and associated variance-covariance matrix were output in a SINEX file format and have been provided to Geoscience Australia.

The ITRF2014@2010.0 latitude and longitude coordinates adopted at NAUR as GNSS constraint are taken from the Geoscience Australia GNSS portal[1]. The ellipsoidal height is the ITRF2020 height from the week of the survey. For more information on how this ellipsoidal height was computed, see Brown et al. (2020).

*Table 4.3.2 Latitude, Longitude and Ellipsoidal Height (metres) for the GNSS & RM stations ITRF2014@2010.0 Latitude, Longitude coordinates, and ITRF2020@2019.82 ellipsoidal height were adopted at NAUR. CCC means all 3 dimensions (in XYZ) are constrained and FFF means they were all free,*

| Station | Constrain | Latitude | Longitude | Ellipsoidal height (m) |
|---|---|---|---|---|
| **NAUR** | **CCC** | -0° 33' 06.22602'' | 166° 55' 31.97186'' | 46.2425 |
| **RM1** | **FFF** | -0° 33' 05.80272'' | 166° 55' 32.46768'' | 44.5818 |
| **RM2** | **FFF** | -0° 33' 06.89241'' | 166° 55' 32.11098'' | 44.4185 |
| **RM3** | **FFF** | -0° 33' 06.02644'' | 166° 55' 31.33880'' | 44.5176 |

*Table 4.3.3 Earth Centred Cartesian coordinates and associated standard deviations (metres) for the GNSS & RM stations. ITRF2014@2010.00 Latitude, Longitude coordinates as per https://gnss.ga.gov.au/network ITRF2020@2019.82 ellipsoidal height were adopted at NAUR*

| Description | X | Y | Z | SD(e) | SD(n) | SD(up) |
|---|---|---|---|---|---|---|
| **NAUR** | -6212555.0485 | 1442787.0098 | -61006.8008 | 0.0000 | 0.0000 | 0.0000 |
| **RM1** | -6212557.0210 | 1442771.7287 | -60993.5887 | 0.0005 | 0.0004 | 0.0006 |
| **RM2** | -6212554.0529 | 1442781.3624 | -61027.0557 | 0.0009 | 0.0006 | 0.0006 |
| **RM3** | -6212549.9977 | 1442805.7001 | -61000.4593 | 0.0006 | 0.0009 | 0.0006 |

*Table 4.3.4 Difference in XYZ coordinates between the GNSS pillar and RMs (metres)*

| FROM | To | ΔE | ΔN | ΔU |
|---|---|---|---|---|
| **NAUR** | **RM1** | 15.3312 | -20.4705 | -1.6608 |
| **NAUR** | **RM2** | 4.3017 | -20.4684 | -1.8240 |
| **NAUR** | **RM3** | -19.5746 | 6.1301 | -1.7250 |

[1] GNSS Network Portal (ga.gov.au)

## 4.4 Assessment of Results

Table 4.4.1 and Figures 4.4.1 – 4.4.3 show the movement of the reference marks with respect to the GNSS pillar in ∆E, ∆N and ∆U. No obvious errors or movement are apparent in the time series.

*Table 4.4.1 Topocentric vectors showing delta east, delta north and delta up between the GNSS pillar and each Reference Mark (metres).*

| YEAR | FROM | To | ΔE | ΔN | ΔU |
|---|---|---|---|---|---|
| **2003** | **NAUR** | **RM1** | 15.3306 | 13.0013 | -1.6593 |
| **2004** | **NAUR** | **RM1** | 15.3310 | 13.0016 | -1.6592 |
| **2005** | **NAUR** | **RM1** | 15.3306 | 13.0012 | -1.6607 |
| **2007** | **NAUR** | **RM1** | 15.3308 | 13.0015 | -1.6609 |
| **2009** | **NAUR** | **RM1** | 15.3304 | 13.0011 | -1.6609 |
| **2010** | **NAUR** | **RM1** | 15.3309 | 13.0015 | -1.661 |
| **(2010 ID)** | **NAUR** | **RM1** | 15.3308 | 13.0015 | -1.661 |
| **2015** | **NAUR** | **RM1** | 15.3302 | 13.0009 | -1.6606 |
| **2016** | **NAUR** | **RM1** | 15.3298 | 13.0005 | -1.6608 |
| **2018** | **NAUR** | **RM1** | 15.3312 | 13.0017 | -1.6609 |
| **2019** | **NAUR** | **RM1** | 15.3305 | 13.0012 | -1.6601 |
| **Ref RL** | **(as at 2016)** | | **15.3306** | **13.0012** | **-1.6605** |

| YEAR | FROM | To | ΔE | ΔN | ΔU |
|---|---|---|---|---|---|
| **2003** | **NAUR** | **RM2** | 4.3036 | -20.4697 | -1.8218 |
| **2004** | **NAUR** | **RM2** | 4.3033 | -20.4697 | -1.8217 |
| **2005** | **NAUR** | **RM2** | 4.303 | -20.4708 | -1.8233 |
| **2007** | **NAUR** | **RM2** | 4.3039 | -20.4705 | -1.8234 |
| **2009** | **NAUR** | **RM2** | 4.3036 | -20.4699 | -1.8235 |
| **2010** | **NAUR** | **RM2** | 4.3031 | -20.4695 | -1.8235 |
| **(2010 ID)** | **NAUR** | **RM2** | 4.3031 | -20.4696 | -1.8235 |
| **2015** | **NAUR** | **RM2** | 4.3026 | -20.4687 | -1.8233 |
| **2016** | **NAUR** | **RM2** | 4.3017 | -20.4678 | -1.8234 |
| **2018** | **NAUR** | **RM2** | 4.3017 | -20.4684 | -1.8242 |
| **2019** | **NAUR** | **RM2** | 4.302 | -20.4689 | -1.8236 |
| **Ref RL** | **(as at 2016)** | | **4.3031** | **-20.4696** | **-1.8230** |

| YEAR | FROM | To | ΔE | ΔN | ΔU |
|---|---|---|---|---|---|
| **2003** | **NAUR** | **RM3** | -19.5738 | 6.1246 | -1.7238 |
| **2004** | **NAUR** | **RM3** | -19.5743 | 6.1257 | -1.7236 |
| **2005** | **NAUR** | **RM3** | -19.5744 | 6.1254 | -1.7253 |
| **2007** | **NAUR** | **RM3** | -19.5743 | 6.1247 | -1.7254 |
| **2009** | **NAUR** | **RM3** | -19.5745 | 6.1269 | -1.7255 |
| **2010** | **NAUR** | **RM3** | -19.5746 | 6.1258 | -1.7256 |
| **(2010 ID)** | **NAUR** | **RM3** | -19.5747 | 6.1257 | -1.7255 |
| **2015** | **NAUR** | **RM3** | -19.5741 | 6.126 | -1.7255 |
| **2016** | **NAUR** | **RM3** | -19.5753 | 6.1264 | -1.7254 |
| **2018** | **NAUR** | **RM3** | -19.5746 | 6.1301 | -1.7253 |
| **2019** | **NAUR** | **RM3** | -19.5754 | 6.1274 | -1.7262 |
| **Ref RL** | **(as at 2016)** | | **-19.5744** | **6.1257** | **-1.7251** |

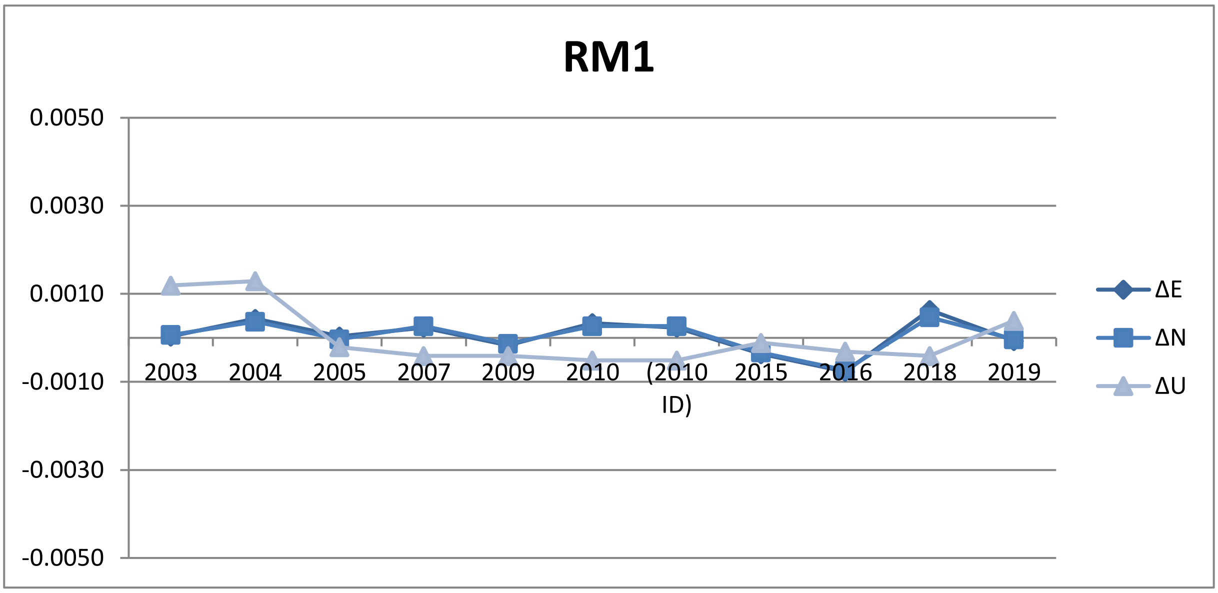


*Figure 4.4.1 Time series of RM1 movement relative to GNSS pillar (0 = REF pre 2016 mean).*

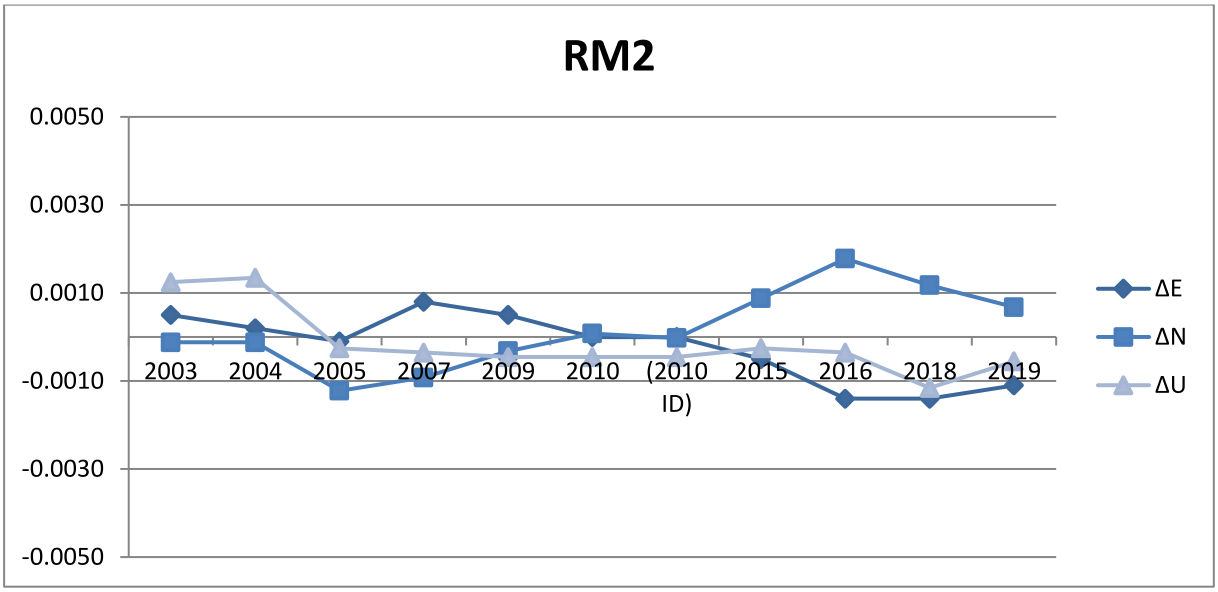


*Figure 4.4.2 Time series of RM2 movement relative to GNSS pillar (0 = REF pre 2016 mean).*

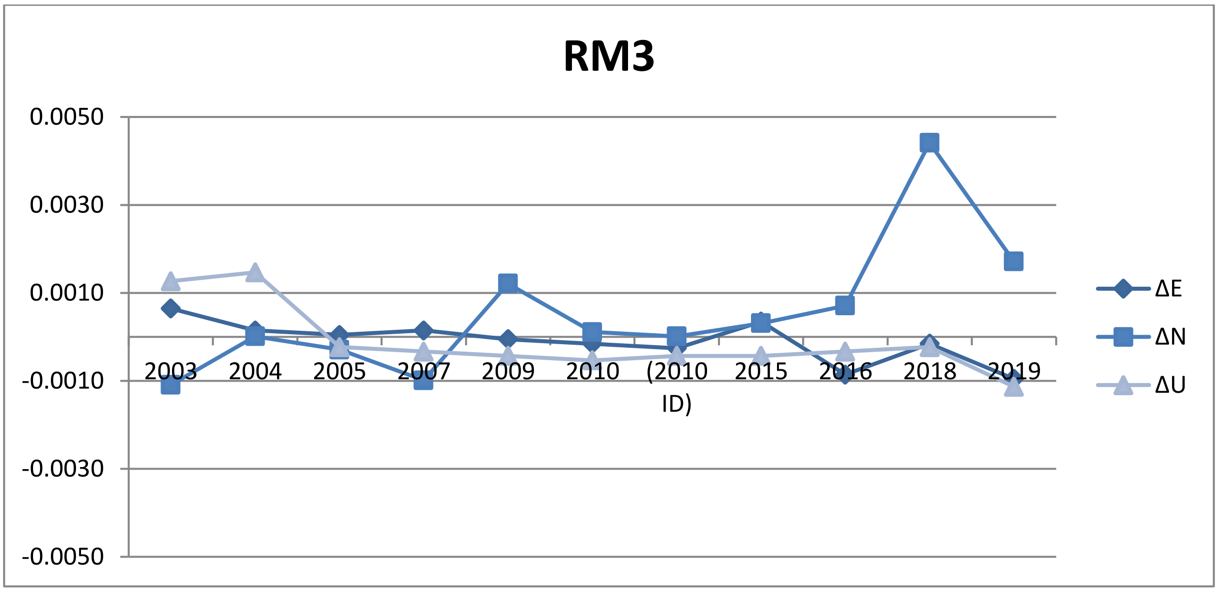


*Figure 4.4.3 Time series of RM3 movement relative to GNSS pillar (0 = REF pre 2016 mean).*

# 5 Tide Gauge Level Connection

## 5.1 Background

The Total Station differential levelling technique was performed in accordance with the SP1 levelling guidelines (ICSM, 2021). After reduction an internal precision of 1mm√K or better was achieved within each survey bay, where K is distance in kilometres.

## 5.2 Survey Methodology

The Total Station differential levelling technique was used for the Nauru tide gauge levelling survey. This technique uses a 'leap-frog' method which involves setting up a Total Station midway between two target/reflectors (on a reflector rod with bi-pod). The targets remain at a particular change point for the backsight and foresight observations and all levelling runs start and finish with the same reflector and reflector rod to eliminate any reflector rod 'zero error'.

This technique can also be performed using a single set-up / single rod configuration which was the case when levelling between benchmarks which are close together e.g., between the GNSS CORS RMs.

The levelling run was divided into bays between each holding benchmark. Observations were completed in both directions within the bay to close each loop along the way. This method provides a closure between bench marks and allows a hold point in the survey in case of severe weather, physical interference, or time restrictions while completing the survey across the week.

In support of the slope distance observations, the ambient temperature, pressure and humidity are recorded (Kestral 4000 pocket weather tracker) and input into the instrument to apply the first velocity correction to the observed distances (Rüeger & Brunner, 1982). Five rounds of observations are taken to the backsight and foresight targets from each instrument setup. The instrument measures slope distances (±1mm) and vertical angle (1") to derive height differences.

Table 5.2.2 contains the values of the constants or calibrated heights used throughout the analysis.

*Table 5.2.2 Calibrations and constants.*

| Name | Value (m) | Description |
|---|---|---|
| **NAUR (Ellipsoidal ht)** | 46.2425 | Observed RL at the ARP of NAUR (Ellipsoidal) @ 2019.82 |
| **NAUR - NAURBM** | -0.9484 | Offset constant between GNSS Monument (Pillar plate) & GNSSBM |
| **Primary Pole & 1/2m Pole** | 1.00048 | Height difference between poles used (Calibrated September 2019) |

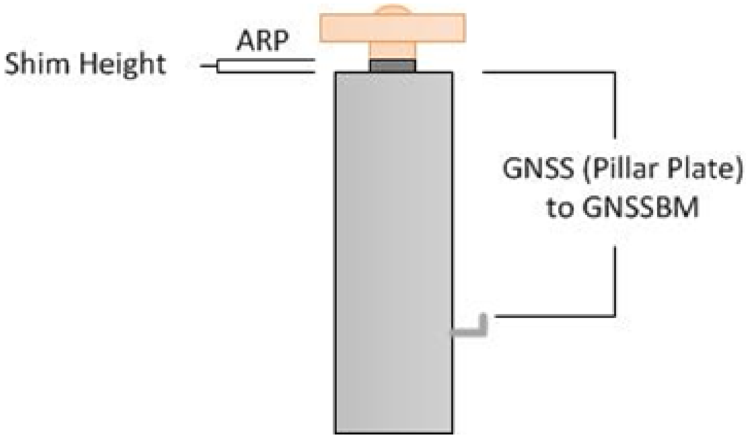


*Figure 5.2.1 GNSS Pillar Offsets*

## 5.3 Data Analysis and Results

Reduction of the digital data was computed using the Geoscience Australia levelling program “leveling1.exe” and LevellingFIELD_3.pl. This program computes the height difference between the two reflectors by taking the mean average of the measured height differences and providing standard deviations and a misclose for the input levelling loop.

The Reduced Level (RL) shown in Table 5.3.1 below is the height relative to NAURBM (GNSS BM)

*Table 5.3.1 Reduced level data – NAUR (GNSS CORS) to NAU14A (Tide Gauge Benchmark)*

| From | To | Rise(m) | Fall (m) | RL (m) | Dist (km) | Acc Dist (km) |
|---|---|---|---|---|---|---|
| **NAUR** | | | | 0.9484 | | |
| **NAURBM** | **NAURBM** | 0.0000 | -0.9484 | 0.0000 | 0.000 | 0.000 |
| **53** | **53** | 0.2250 | 0.0000 | 0.2250 | 0.088 | 0.088 |
| **104** | **104** | 0.0000 | -0.2889 | -0.0639 | 0.192 | 0.280 |
| **103** | **103** | 0.4290 | 0.0000 | 0.3651 | 0.199 | 0.479 |
| **110** | **110** | 0.6543 | 0.0000 | 1.0194 | 0.202 | 0.681 |
| **101** | **101** | 0.0369 | 0.0000 | 1.0563 | 0.197 | 0.878 |
| **47** | **47** | 0.0000 | -0.4721 | 0.5842 | 0.200 | 1.078 |
| **109** | **109** | 0.0000 | -0.1319 | 0.4523 | 0.198 | 1.276 |
| **44** | **44** | 0.7781 | 0.0000 | 1.2304 | 0.200 | 1.476 |
| **43** | **43** | 0.0000 | -0.5694 | 0.6610 | 0.204 | 1.680 |
| **108** | **108** | 0.9443 | 0.0000 | 1.6053 | 0.177 | 1.856 |
| **NAU33** | **NAU33** | 0.5450 | 0.0000 | 2.1503 | 0.179 | 2.035 |
| **107** | **107** | 0.3701 | 0.0000 | 2.5204 | 0.131 | 2.166 |
| **NAU38** | **NAU38** | 0.0000 | -0.2074 | 2.3130 | 0.200 | 2.365 |
| **NAU37** | **NAU37** | 0.1266 | 0.0000 | 2.4396 | 0.056 | 2.422 |
| **106** | **106** | 0.3469 | 0.0000 | 2.7865 | 0.118 | 2.540 |
| **100** | **100** | 0.1638 | 0.0000 | 2.9503 | 0.200 | 2.740 |
| **NAU2** | **NAU2** | 0.0000 | -0.4249 | 2.5254 | 0.167 | 2.907 |
| **28** | **28** | 0.0145 | 0.0000 | 2.5399 | 0.166 | 3.073 |
| **NAU36** | **NAU36** | 0.0000 | -0.5810 | 1.9589 | 0.199 | 3.272 |
| **NAU1** | **NAU1** | 0.0737 | 0.0000 | 2.0326 | 0.185 | 3.457 |
| **NAU14A** | **NAU14A** | 0.0000 | -3.3695 | -1.3369 | 0.100 | 3.557 |
| **NAU1** | **NAU1** | 3.3696 | 0.0000 | 2.0327 | 0.101 | |
| **NAU36** | **NAU36** | 0.0000 | -0.0740 | 1.9587 | 0.185 | |
| **28** | **28** | 0.5808 | 0.0000 | 2.5394 | 0.199 | |
| **NAU2** | **NAU2** | 0.0000 | -0.0147 | 2.5247 | 0.167 | |
| **100** | **100** | 0.4250 | 0.0000 | 2.9497 | 0.167 | |
| **106** | **106** | 0.0000 | -0.1642 | 2.7855 | 0.200 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **NAU37** | **NAU37** | 0.0000 | -0.3471 | 2.4384 | 0.118 | |
| **NAU38** | **NAU38** | 0.0000 | -0.1268 | 2.3116 | 0.056 | |
| **107** | **107** | 0.2073 | 0.0000 | 2.5189 | 0.200 | |
| **NAU33** | **NAU33** | 0.0000 | -0.3701 | 2.1488 | 0.131 | |
| **108** | **108** | 0.0000 | -0.5453 | 1.6035 | 0.178 | |
| **43** | **43** | 0.0000 | -0.9445 | 0.6590 | 0.177 | |
| **44** | **44** | 0.5695 | 0.0000 | 1.2286 | 0.204 | |
| **109** | **109** | 0.0000 | -0.7784 | 0.4502 | 0.200 | |
| **47** | **47** | 0.1318 | 0.0000 | 0.5820 | 0.196 | |
| **101** | **101** | 0.4721 | 0.0000 | 1.0541 | 0.200 | |
| **110** | **110** | 0.0000 | -0.0372 | 1.0169 | 0.197 | |
| **103** | **103** | 0.0000 | -0.6546 | 0.3624 | 0.202 | |
| **104** | **104** | 0.0000 | -0.4288 | -0.0664 | 0.199 | |
| **53** | **53** | 0.2887 | 0.0000 | 0.2223 | 0.192 | |
| **NAURBM** | **NAURBM** | 0.0000 | -0.2251 | -0.0027 | 0.086 | |
| **NAUR** | **NAUR** | 0.9484 | 0.0000 | 0.9457 | 0.000 | |
| | Sum: | 11.7013 | -11.7040 | | | |
| | Misclose: | | -0.0027 | -0.0027 | 7.112 | (Total Dist) |
| | | | **ALLOWABLE (m):** | **0.0038** | **2 x Sqrt (km) test:** | **PASS** |

*Table 5.3.2 Reduced level data – NAU14A (Tide Gauge Benchmark) to NAU15 (SEAFRAME sensor benchmark)*

| From | To | Rise(m) | Fall(m) | RL(m) | Dist (Km) | Acc Dist (km) |
|---|---|---|---|---|---|---|
| **NAU14A** | | | | -1.3369 | 0.000 | 3.557 |
| **NAU15** | **NAU15** | 2.0864 | 0.0000 | 0.7494 | 0.010 | 3.567 |
| **NAU14A** | **NAU14A** | 0.0000 | -2.0863 | -1.3369 | 0.010 | |
| | Sum: | 2.0864 | -2.0863 | | | |
| | Misclose: | | 0.0000 | 0.0000 | 0.021 | (Total Dist) |
| | | | **ALLOWABLE (m):** | **0.0002** | **2 x Sqrt (km) test:** | **PASS** |

*Table 5.3.3 Reduced level data – NAU33 to NAU16*

| From | To | Rise(m) | Fall(m) | RL(m) | Dist (Km) | Acc Dist (km) |
|---|---|---|---|---|---|---|
| **NAU33** | | | | 2.1496 | | 2.035 |
| **NAU16** | **NAU16** | 0.0000 | -0.7157 | 1.4338 | 0.131 | 2.166 |
| | **NAU33** | 0.7157 | 0.0000 | 2.1496 | 0.131 | 0.000 |
| | **Sum:** | 0.7157 | -0.7157 | | | |
| | **Misclose:** | | 0.0000 | 0.0000 | 0.262 | (Total Dist) |
| | | | **ALLOWABLE (m):** | **0.0007** | **2 x Sqrt (km) test:** | **PASS** |

*Table 5.3.4 Measured height differences (in metres) between all BMs ($\Delta RL_{2019}$).*

| | NAURBM | NAU16 | NAU38 | NAU37 | NAU2 | NAU36 | NAU1 | NAU15 | RM1 | RM2 | RM3 | NAUR | NAU14A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **NAURBM** | - | 1.4338 | 2.3123 | 2.4390 | 2.5250 | 1.9588 | 2.0326 | 0.7494 | -0.7125 | -0.8749 | -0.7771 | 0.9484 | -1.3369 |
| **NAU16** | -1.4338 | - | 0.8785 | 1.0052 | 1.0912 | 0.5250 | 0.5988 | -0.6844 | -2.1463 | -2.3088 | -2.2109 | -0.4854 | -2.7708 |
| **NAU38** | -2.3123 | -0.8785 | - | 0.1267 | 0.2127 | -0.3535 | -0.2797 | -1.5629 | -3.0248 | -3.1873 | -3.0894 | -1.3639 | -3.6492 |
| **NAU37** | -2.4390 | -1.0052 | -0.1267 | - | 0.0860 | -0.4802 | -0.4064 | -1.6896 | -3.1515 | -3.3140 | -3.2161 | -1.4906 | -3.7759 |
| **NAU2** | -2.5250 | -1.0912 | -0.2127 | -0.0860 | - | -0.5663 | -0.4924 | -1.7756 | -3.2375 | -3.4000 | -3.3021 | -1.5766 | -3.8620 |
| **NAU36** | -1.9588 | -0.5250 | 0.3535 | 0.4802 | 0.5663 | - | 0.0738 | -1.2094 | -2.6712 | -2.8337 | -2.7359 | -1.0104 | -3.2957 |
| **NAU1** | -2.0326 | -0.5988 | 0.2797 | 0.4064 | 0.4924 | -0.0738 | - | -1.2832 | -2.7451 | -2.9076 | -2.8097 | -1.0842 | -3.3696 |
| **NAU15** | -0.7494 | 0.6844 | 1.5629 | 1.6896 | 1.7756 | 1.2094 | 1.2832 | - | -1.4619 | -1.6244 | -1.5265 | 0.1990 | -2.0864 |
| **RM1** | 0.7125 | 2.1463 | 3.0248 | 3.1515 | 3.2375 | 2.6712 | 2.7451 | 1.4619 | - | -0.1625 | -0.0646 | 1.6609 | -0.6245 |
| **RM2** | 0.8749 | 2.3088 | 3.1873 | 3.3140 | 3.4000 | 2.8337 | 2.9076 | 1.6244 | 0.1625 | - | 0.0979 | 1.8233 | -0.4620 |
| **RM3** | 0.7771 | 2.2109 | 3.0894 | 3.2161 | 3.3021 | 2.7359 | 2.8097 | 1.5265 | 0.0646 | -0.0979 | - | 1.7255 | -0.5599 |
| **NAUR** | -0.9484 | 0.4854 | 1.3639 | 1.4906 | 1.5766 | 1.0104 | 1.0842 | -0.1990 | -1.6609 | -1.8233 | -1.7255 | - | -2.2853 |
| **NAU14A** | 1.3369 | 2.7708 | 3.6492 | 3.7759 | 3.8620 | 3.2957 | 3.3696 | 2.0864 | 0.6245 | 0.4620 | 0.5599 | 2.2853 | - |

*Table 5.3.5 Time-series of Reduced Levels (with respect to NAURBM)*

| Year | NAURBM | NAU16 | NAU38 | NAU37 | NAU2 | NAU36 | NAU1 | NAU14 | NAU15 | RM1 | RM2 | RM3 | NAUR | NAU14A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1993.5** | | | | | 2.5267 | | 2.0360 | -1.4111 | 0.7474 | | | | | |
| **1994.2** | | 1.4345 | | | 2.5279 | | 2.0360 | -1.4108 | 0.7471 | | | | | |
| **1995.2** | | 1.4353 | | | 2.5279 | | 2.0360 | -1.4111 | 0.7468 | | | | | |
| **1996.7** | | 1.4353 | | | 2.5266 | | 2.0360 | -1.4101 | 0.7478 | | | | | |
| **1997.9** | | 1.4350 | | | 2.5279 | | 2.0360 | -1.4108 | 0.7457 | | | | | |
| **1999.5** | | 1.4346 | | | 2.5265 | | 2.0360 | -1.4108 | 0.7462 | | | | | |
| **2000.6** | | 1.4350 | | | 2.5271 | | 2.0360 | -1.4105 | 0.7480 | | | | | |
| **2002.4** | | 1.4350 | 2.3141 | 2.4407 | 2.5268 | 1.9621 | 2.0360 | -1.4106 | 0.7476 | | | | | |
| **2003.9** | 0.0000 | 1.4345 | 2.3144 | 2.4409 | 2.5272 | 1.9621 | 2.0360 | -1.4098 | 0.7476 | -0.7124 | -0.8750 | -0.7769 | | |
| **2005.8** | 0.0000 | 1.4364 | 2.3152 | 2.4417 | 2.5276 | 1.9623 | 2.0360 | -1.4092 | 0.7494 | | | | | |
| **2005.8** | 0.0000 | 1.4326 | 2.3116 | 2.4381 | 2.5238 | 1.9579 | 2.0317 | -1.4137 | 0.7457 | -0.7124 | -0.8750 | -0.7770 | 0.9484 | |
| **2007.5** | 0.0000 | 1.4319 | 2.3106 | 2.4374 | 2.5233 | 1.9567 | 2.0305 | -1.4146 | 0.7445 | -0.7126 | -0.8750 | -0.7771 | 0.9483 | |
| **2009.1** | 0.0000 | 1.4331 | 2.3121 | 2.4388 | 2.5243 | 1.9582 | 2.0326 | -1.4125 | 0.7469 | -0.7123 | -0.8750 | -0.7770 | 0.9485 | |
| **2010.5** | 0.0000 | 1.4313 | 2.3097 | 2.4366 | 2.5212 | 1.9548 | 2.0283 | -1.4175 | 0.7414 | -0.7124 | -0.8750 | -0.7770 | 0.9486 | |
| **2012.2** | 0.0000 | 1.4355 | 2.3142 | 2.4408 | 2.5266 | 1.9610 | 2.0350 | -1.4099 | 0.7472 | -0.7124 | -0.8749 | -0.7770 | | |
| **2013.7** | 0.0000 | 1.4346 | 2.3133 | 2.4402 | 2.5258 | 1.9596 | 2.0337 | -1.4116 | 0.7439 | -0.7117 | -0.8751 | -0.7769 | 0.9484 | |
| **2015.3** | 0.000 | 1.4352 | 2.3142 | 2.4409 | 2.5262 | 1.9600 | 2.0339 | -1.4114 | 0.7483 | -0.7122 | -0.8749 | -0.7771 | 0.9484 | |
| **2016.6** | 0.000 | 1.4338 | 2.3127 | 2.4394 | 2.5261 | 1.9603 | 2.0341 | -1.4111 | 0.7470 | -0.7124 | -0.8750 | -0.7770 | 0.9484 | |
| **2018.3** | 0.000 | 1.4349 | 2.3143 | 2.4411 | 2.5274 | 1.9617 | 2.0354 | -1.4090 | 0.7530 | -0.7125 | -0.8752 | -0.7774 | 0.9484 | |
| **2019.8** | 0.000 | 1.4338 | 2.3123 | 2.4390 | 2.5250 | 1.9588 | 2.0326 | #N/A | 0.7494 | -0.7125 | -0.8749 | -0.7771 | 0.9484 | -1.3369 |

## 5.4 Comparison with previous surveys

All historic data has been readjusted relative to the benchmark attached to the base of the GNSS pillar (NAURBM) (Table 5.3.5). To investigate whether BMs have moved over time, the RLs from the 2019 survey (RL2019) have been compared to a reference height (RH) defined as the average of all previously calculated RLs. In cases where a site has undergone known movement (e.g., BM removed and reinstalled), the RH is the latest measured RL.

### 5.4.1 Difference in Reference Height values

*Table 5.4.1.1 $\Delta RL_{REF}$ - $\Delta RL_{2019}$ values (in metres). Shows the difference in height between two marks from the current survey compared to the reference height difference.*

| REF - 2019 | NAURBM | NAU16 | NAU38 | NAU37 | NAU2 | NAU36 | NAU1 | NAU15 | RM1 | RM2 | RM3 | NAUR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **NAURBM** | - | 0.0010 | 0.0015 | 0.0015 | 0.0017 | 0.0017 | 0.0032 | -0.0023 | 0.0001 | -0.0001 | 0.0001 | 0.0000 |
| **NAU16** | -0.0010 | - | 0.0005 | 0.0005 | 0.0006 | 0.0007 | 0.0022 | -0.0034 | -0.0010 | -0.0011 | -0.0009 | -0.0010 |
| **NAU38** | -0.0015 | -0.0005 | - | 0.0000 | 0.0001 | 0.0002 | 0.0017 | -0.0039 | -0.0015 | -0.0016 | -0.0014 | -0.0015 |
| **NAU37** | -0.0015 | -0.0005 | 0.0000 | - | 0.0002 | 0.0002 | 0.0018 | -0.0038 | -0.0014 | -0.0015 | -0.0014 | -0.0015 |
| **NAU2** | -0.0017 | -0.0006 | -0.0001 | -0.0002 | - | 0.0001 | 0.0016 | -0.0040 | -0.0016 | -0.0017 | -0.0016 | -0.0017 |
| **NAU36** | -0.0017 | -0.0007 | -0.0002 | -0.0002 | -0.0001 | - | 0.0015 | -0.0040 | -0.0016 | -0.0018 | -0.0016 | -0.0017 |
| **NAU1** | -0.0032 | -0.0022 | -0.0017 | -0.0018 | -0.0016 | -0.0015 | - | **-0.0056** | -0.0032 | -0.0033 | -0.0032 | -0.0033 |
| **NAU15** | 0.0023 | 0.0034 | 0.0039 | 0.0038 | 0.0040 | 0.0040 | **0.0056** | - | 0.0024 | 0.0023 | 0.0024 | 0.0023 |
| **RM1** | -0.0001 | 0.0010 | 0.0015 | 0.0014 | 0.0016 | 0.0016 | 0.0032 | -0.0024 | - | -0.0001 | 0.0000 | -0.0001 |
| **RM2** | 0.0001 | 0.0011 | 0.0016 | 0.0015 | 0.0017 | 0.0018 | 0.0033 | -0.0023 | 0.0001 | - | 0.0001 | 0.0001 |
| **RM3** | -0.0001 | 0.0009 | 0.0014 | 0.0014 | 0.0016 | 0.0016 | 0.0032 | -0.0024 | 0.0000 | -0.0001 | - | -0.0001 |
| **NAUR** | 0.0000 | 0.0010 | 0.0015 | 0.0015 | 0.0017 | 0.0017 | 0.0033 | -0.0023 | 0.0001 | -0.0001 | 0.0001 | - |

Table 5.4.1.1 values are calculated by subtracting the difference in height between $RL_{2019}$ values (Table 5.3.5) from the difference in height between $RL_{REF}$ values.

Comparing the change in relative heights between all benchmarks can help identify movement of a particular BM, inconsistency in survey, or even deformation between the GNSS pillar and levelling run BMs.

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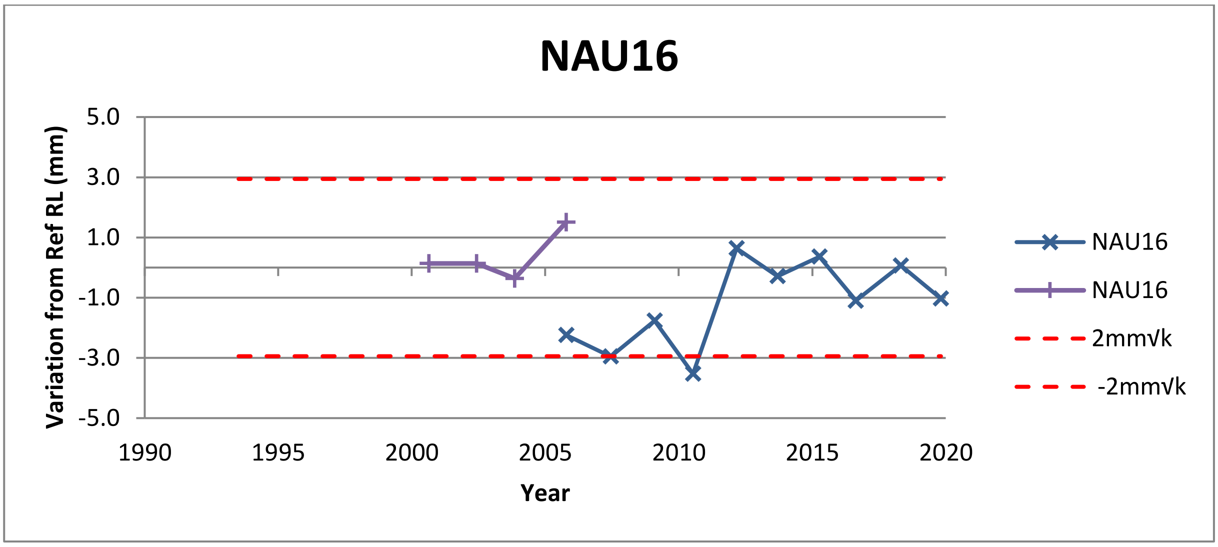
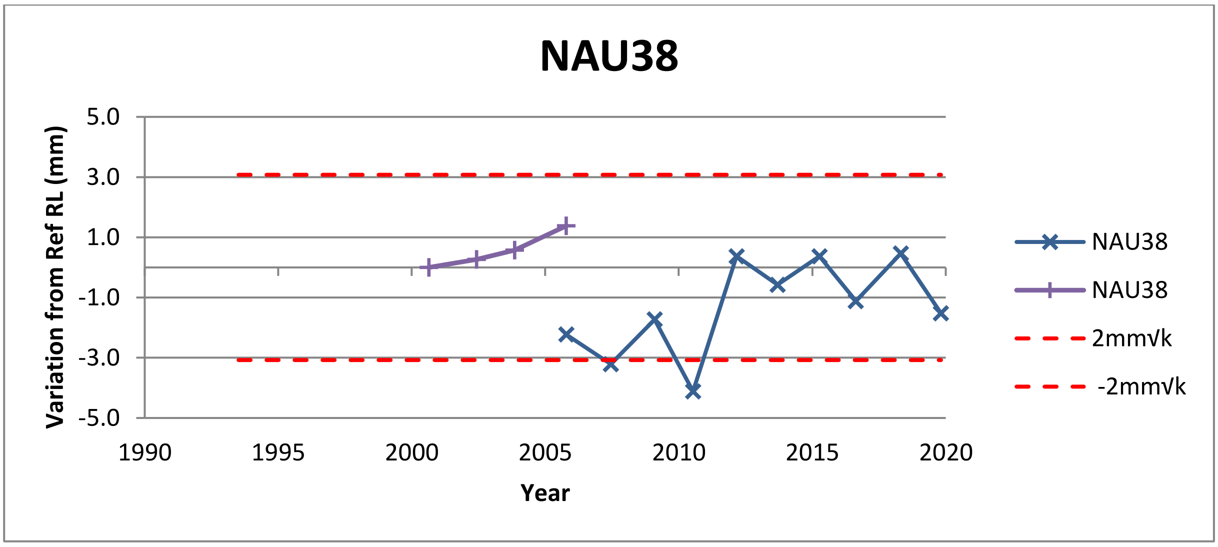
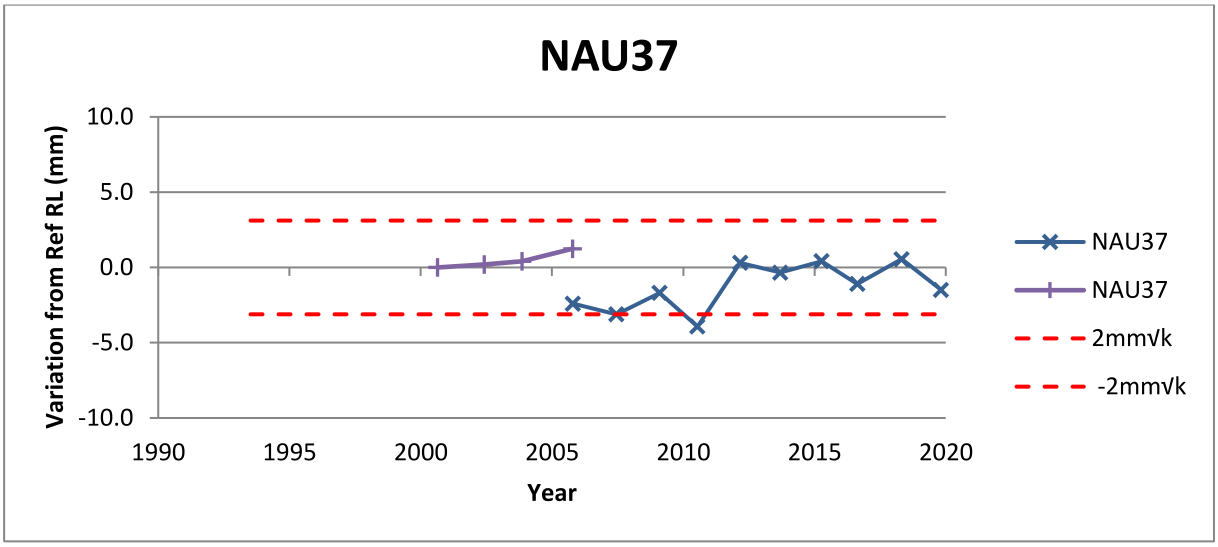
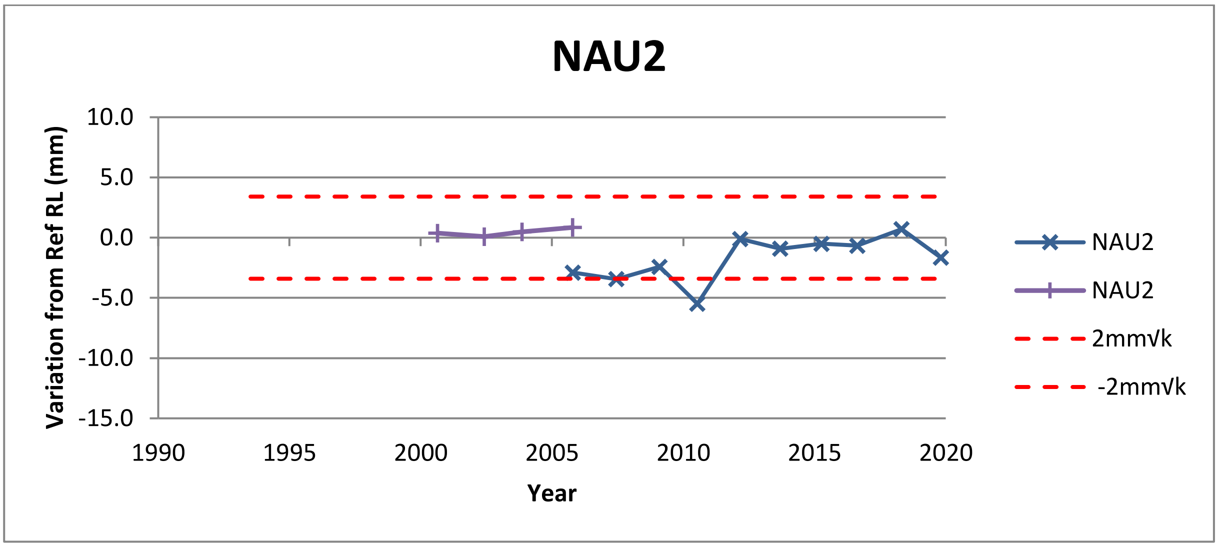
### 5.4.2 Time series charts for each BM

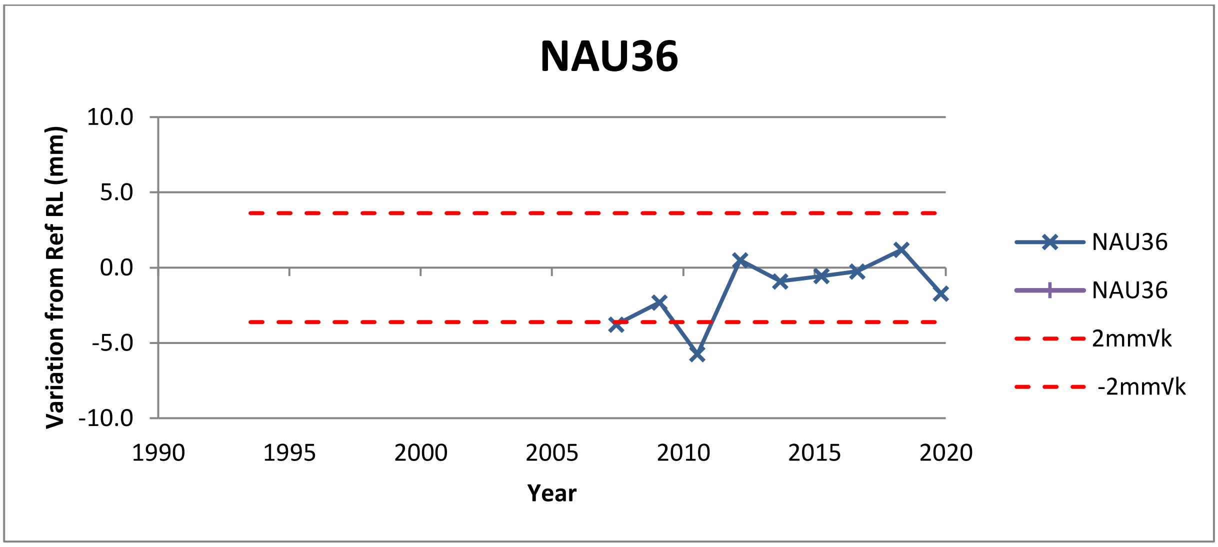
The change in RL over time can be used to detect trends of movement or survey errors. In the series of figures below, the red dashed lines represent the allowable error in height based on the levelling technique used and distance of the benchmark from the GNSS pillar ($2mm\sqrt{K}$). The purple line (with crosses) shows the results achieved using precise differential levelling [with a levelling instrument and survey staff] and the blue line with crosses show the levelling results based on the Total Station differential levelling technique.

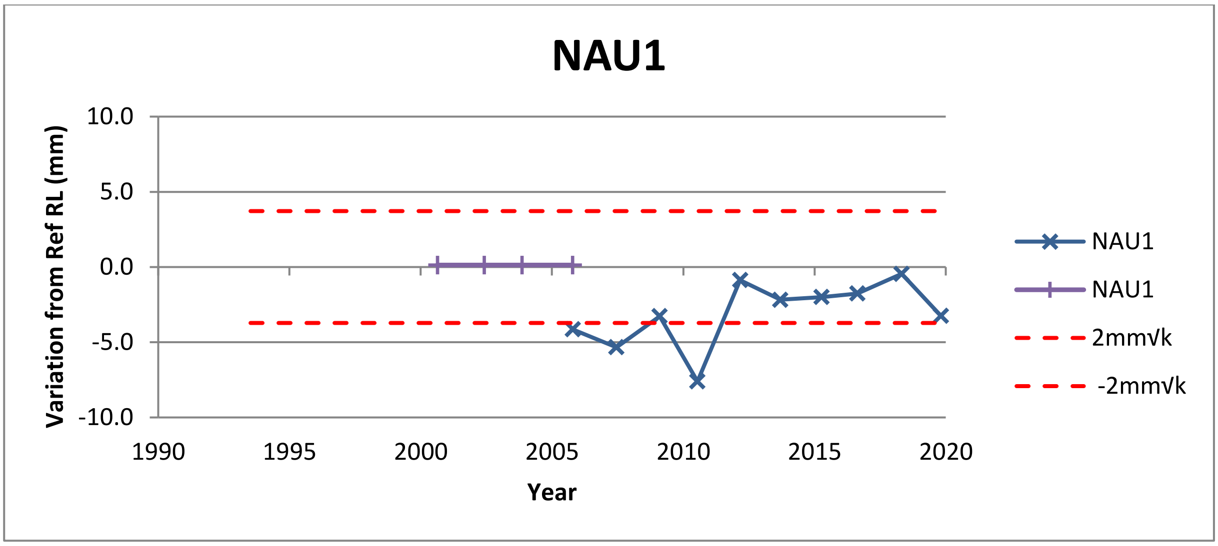


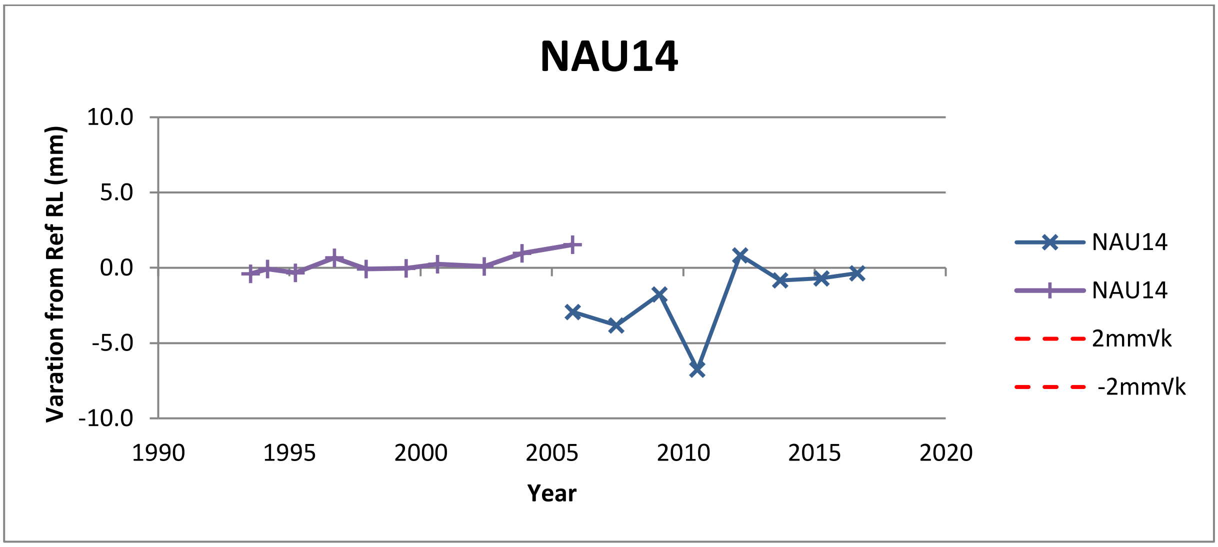



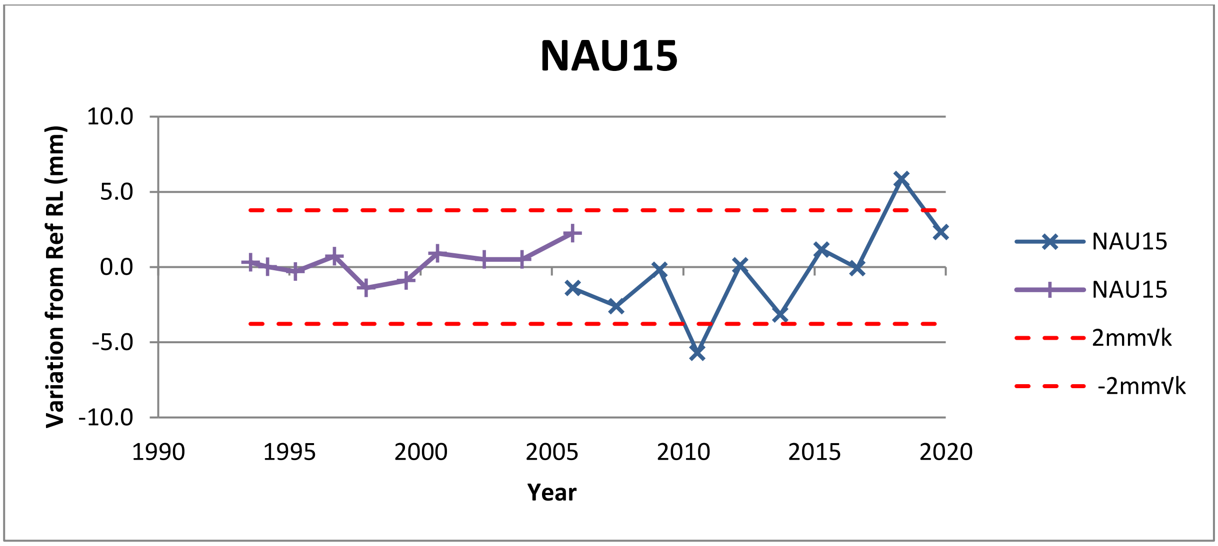

NAU37
Variation from Ref RL (mm)
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Year
NAU37
NAU37
2mm√k
-2mm√k


NAU2
Variation from Ref RL (mm)
10.0
5.0
0.0
-5.0
-10.0
-15.0
1990
1995
2000
2005
2010
2015
2020
Year
NAU2
NAU2
2mm√k
-2mm√k


NAU36
Variation from Ref RL (mm)
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Year
NAU36
NAU36
2mm√k
-2mm√k


NAU1
Variation from Ref RL (mm)
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Year
NAU1
NAU1
2mm√k
-2mm√k


NAU14
Variation from Ref RL (mm)
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Year
NAU14
NAU14
2mm√k
-2mm√k


NAU15
Variation from Ref RL (mm)
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Year
NAU15
NAU15
2mm√k
-2mm√k

# 6 Assessment of Results

After a full analysis of the monitoring and levelling survey results, the following conclusions can be drawn. There is one difference above 0.003 m:

- NAU15, which is likely due to:
    - localised movement where the tide gauge structure has been deteriorating over the years. There are developments of a new tide gauge facility underway to replace the current tide gauge station.

The survey from the primary BM (NAU1) to the Tide Gauge Station show that the tide gauge is stable, and no deformation has occurred since the previous survey.

The survey from the GNSS CORS pillar, NAURBM to the primary BM (NAU1) shows that the height difference between these two marks has remained consistent to previous years, and any variation is still within the expected tolerance of the survey.

*Table 6.1 Comparison of results with Reference ^H (m).*

| PT ID | Reference ^H (m) | 2019.82 Value (m) | Difference |
|---|---|---|---|
| **NAURBM - Primary BM (NAU1)** | 2.0359 | 2.0326 | -0.0033 |
| **NAU1 - TG Plaque BM (NAU14a)** | -3.3728 | -3.3696 | -0.0033 |
| **NAU1 - TG ref pin (NAU15)** | -1.2887 | -1.2832 | -0.0055 |
| | | | |
| **NAURBM - NAU1** | 2.0359 | 2.0326 | -0.0033 |
| **NAU1 - NAU14a** | -3.3728 | -3.3696 | -0.0033 |
| **NAU14a - NAU15** | 2.0841 | 2.0864 | 0.0022 |
| | | | |
| **NAUR - TG Plaque** | -2.2853 | -2.2853 | 0.0000 |
| **NAUR - TG BM** | -0.2012 | -0.1990 | -0.0022 |
| **NAUR - TGZ** | -6.2055 | -6.2033 | -0.0022 |

*Table 6.2 List of height differences from NAURBM to primary benchmarks, and conversion to TGZ & ITRF2020.*

| PT ID | Reference RL (m) | 2019.82 Value (m) | Difference | TGZ | ITRF2020 |
|---|---|---|---|---|---|
| **NAURBM** | 0.0000 | 0.0000 | 0.0000 | 5.2549 | 45.2941 |
| **NAU16** | 1.4350 | 1.4338 | -0.0011 | 6.6887 | 46.7279 |
| **NAU38** | 2.3139 | 2.3123 | -0.0016 | 7.5672 | 47.6064 |
| **NAU37** | 2.4406 | 2.4390 | -0.0016 | 7.6939 | 47.7331 |
| **NAU2** | 2.5270 | 2.5250 | -0.0019 | 7.7799 | 47.8191 |
| **NAU36** | 1.9600 | 1.9588 | -0.0012 | 7.2137 | 47.2529 |
| **NAU1** | 2.0359 | 2.0326 | -0.0033 | 7.2875 | 47.3267 |
| **NAU15** | 0.7472 | 0.7494 | 0.0022 | 6.0043 | 46.0435 |
| **RM1** | -0.7124 | -0.7125 | -0.0001 | 4.5424 | 44.5817 |
| **RM2** | -0.8750 | -0.8749 | 0.0000 | 4.3799 | 44.4192 |
| **RM3** | -0.7770 | -0.7771 | -0.0001 | 4.4778 | 44.5170 |
| **NAUR** | 0.9484 | 0.9484 | 0.0000 | 6.2033 | 46.2425 |
| **NAU14A** | -1.3369 | -1.3369 | 0.0000 | 3.9180 | 43.9572 |
| **TGZ** | -5.2571 | -5.2549 | 0.0022 | 0.0000 | 40.0392 |

# 7 Absolute height of the tide gauge

When combined, the GNSS and levelling data provide information about the absolute movement of the tide gauge. This information can be used by Bureau to translate relative sea level into absolute sea level.

## 7.1 GNSS time series analysis

The ellipsoidal height of the GNSS pillar is computed using Geoscience Australia's weekly cumulative GNSS solution and modelled using Chebyshev polynomials[2] (Figure 7.1). Uncertainty regions (95% confidence) were determined using the residuals with respect to the polynomial model. Large outliers (>50cm) were removed manually as they have a significant impact on the estimated uncertainties. The ellipsoidal heights are with respect to the International Terrestrial Reference Frame 2020 (ITRF2020).

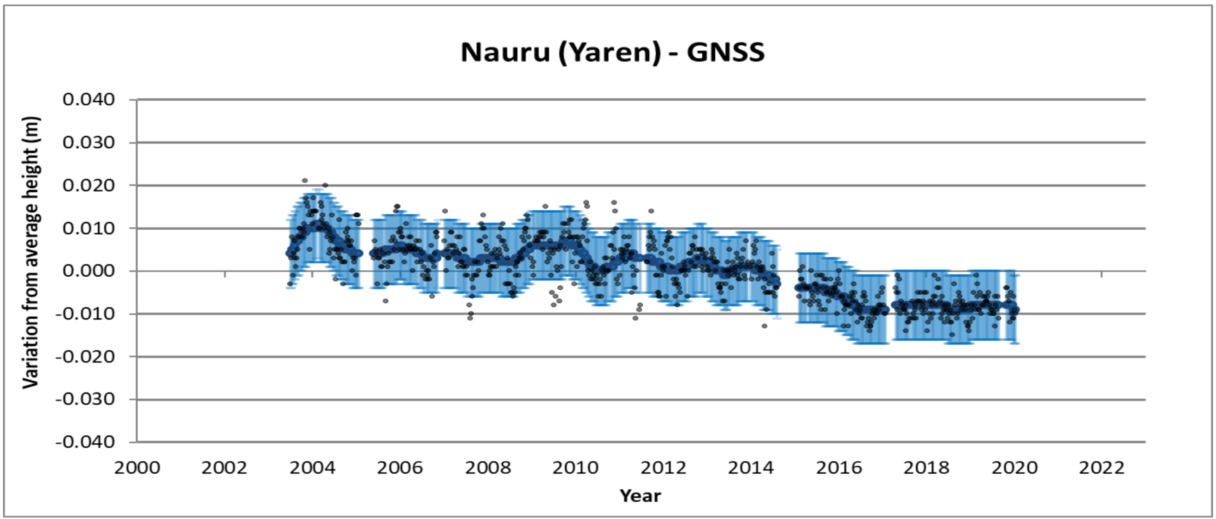



*Figure 7.1 Time series of GNSS analysis (dark blue line) with 95%CI uncertainty (light blue lines).*

[2] The order of the polynomial was determined iteratively by evaluating the significance of the improvement in model misfit Chi-Squared by an F test. The number of terms used in the preferred models ranged from 2 (i.e. linear) to 10 across the analysed time series and depends on the complexity of the observed signal.

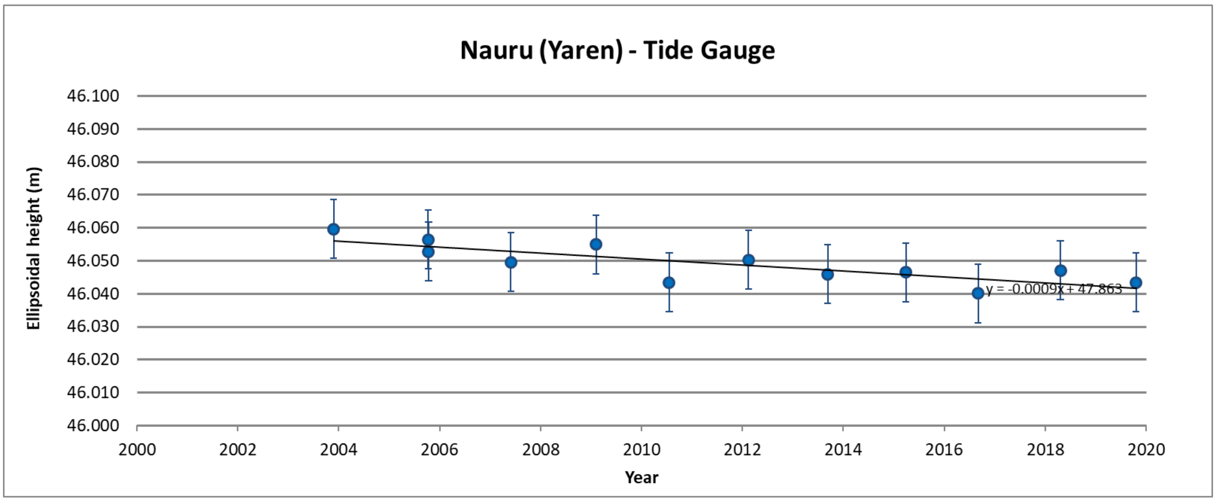



*Figure 7.2 The height of the SEAFRAME sensor reference benchmark (with respect to ITRF2020).*

The height of the SEAFRAME sensor reference benchmark is the sum of the ellipsoidal height of the GNSS pillar plate and the levelled height difference between the GNSS pillar plate and SEAFRAME sensor reference benchmark (Figure 7.2; Table 7.1)[3]. The height uncertainty is the combined uncertainty from the GNSS analysis and the levelling.

*Table 7.1 Height of the SEAFRAME sensor reference benchmark (and 95%CI uncertainty) derived from GNSS time series analysis and levelling. Height is with respect to the International Terrestrial Reference Frame 2020.*

| Date | Height (m) | Uncertainty (95%CI) (m) |
|---|---|---|
| **2003.90** | 46.0597 | 0.0089 |
| **2005.77** | 46.0565 | 0.0089 |
| **2005.78** | 46.0528 | 0.0089 |
| **2007.41** | 46.0496 | 0.0089 |
| **2009.10** | 46.0550 | 0.0089 |
| **2010.55** | 46.0435 | 0.0089 |
| **2012.12** | 46.0503 | 0.0089 |
| **2013.69** | 46.0460 | 0.0089 |
| **2015.24** | 46.0465 | 0.0089 |
| **2016.67** | 46.0401 | 0.0089 |
| **2018.32** | 46.0471 | 0.0089 |
| **2019.82** | 46.0435 | 0.0089 |

[3] It is recognised that the height of the SEAFRAME sensor reference benchmark is the sum of the geometric GNSS ellipsoidal height and the physical orthometric levelling height. No geoid corrections were applied to the levelling data because of the short distance of the levelling run and the lack of high resolution gravity data in this region.

# 8 References


Brown, N. J., Lal, A., Thomas, B., McClusky, S., Dawson, J., Hu, G., and Jia, M. 2020. Vertical motion of Pacific Island tide gauges: combined analysis from GNSS and levelling. Record 2020/03. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/Record.2020.003

Fraser, R., Leahy, F., Collier, P., 2018. *DynAdjust User's Guide Version 3.0*. Dynamic Network Adjustment Software.

Intergovernmental Committee on Surveying and Mapping (ICSM) 2021, Guideline for Conventional Traverse Surveys – SP1 V2.2.

Rüeger, J.M. & Brunner, F.K. 1982, '*EDM Height Traversing versus Geodetic Levelling'*, The Canadian Surveyor, vol. 36, no. 1, pp. 69-87.

Rueger, J. M., Brunner, F. K., 1981. *Practical Results from EDM-Height Traversing*. The Australian Surveyor. June 1981, Vol. 30, No 6.

# Appendix A Locality Diagrams


*Source: Adopted from Google Map*

## A 1 Deep Benchmarks

**PACIFIC SEA LEVEL MONITORING PROJECT**

Australian Aid | Australian Government — Geoscience Australia | SPC Secretariat of the Pacific Community

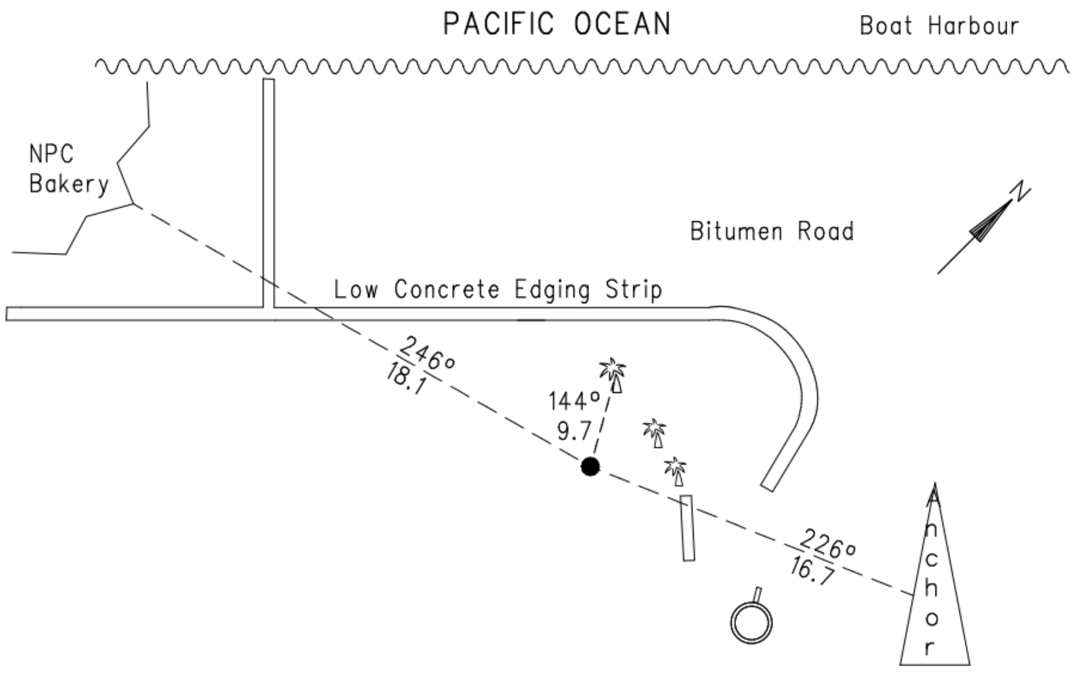
**<u>SURVEY BENCH MARK RECORD</u>**

**Bench Mark Number: NAU1**

| | |
|---|---|
| *Original Bench Mark Established by:* National Tide Centre Australia, Oceanographic Services, Bureau of Meteorology, 25 college Rd, Kent Town, SA. | *Date: 11/02/1992* |
| *Existing Bench Mark Established by:* | *Date:* |
| *Notes / References:* Deep Survey Benchmark<br>This survey mark is in a good locality for GNSS occupation. | |
| *Country:* Nauru<br>*Island: Nauru* | *City:Nauru* |

**<u>MARKING AND LOCALITY SKETCH</u>**

**Bench Mark**: 4.3m of 19mm diameter stainless steel capped rod driven to refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite, for 1.5m. Top of mark 0.2m below ground level. Locality sketch Mark approximately 100m from the tide gauge station.




NOT TO SCALE | Distances in Metres | Magnetic Bearings

Approved by: Geoscience Australia / SPC | *Date: 2/9/2014*

**PACIFIC SEA LEVEL MONITORING PROJECT**

Australian Aid

Australian Government
Geoscience Australia

SPC
Secretariat of the Pacific Community

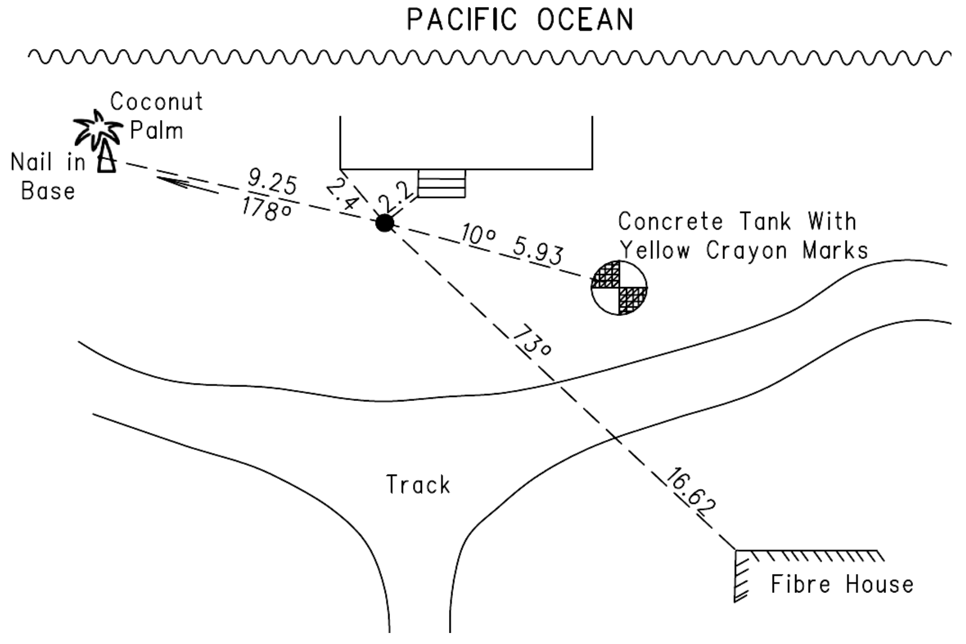
**SURVEY BENCH MARK RECORD**

**Bench Mark Number: NAU2**

| | |
|---|---|
| *Original Bench Mark Established by:*<br>National Tidal Centre Australia, Oceanographic Services,<br>Bureau of Meteorology, 25 College Rd, Kent Town SA. | *Date: 11/02/1992* |
| *Existing Bench Mark Established by:* | *Date:* |
| *Notes / References:* Deep Survey Benchmark<br>This survey mark is in a good locality for GPS occupation. | |
| *Country:* Nauru<br>*Island: Nauru* | *City: Nauru* |

**MARKING AND LOCALITY SKETCH**

**Bench Mark**: 4.8m of 19mm diameter stainless steel capped rod driven to refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite, for 1.8m. Top of mark 0.1m below ground level. Locality sketch Mark approximately 600m from the tide gauge station.




NOT TO SCALE Distances in Metres Magnetic Bearings

Approved by: Geoscience Australia / SPC *Date: November 2006*

**PACIFIC SEA LEVEL MONITORING PROJECT**

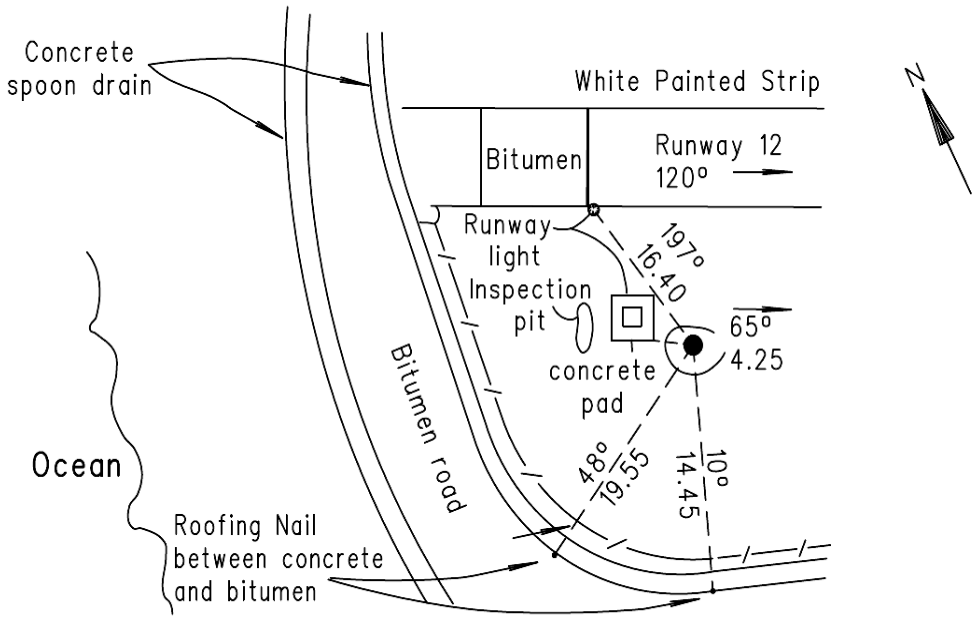
**SURVEY BENCH MARK RECORD**

**Bench Mark Number: NAU16**

| | |
|---|---|
| *Original Bench Mark Established by:*<br>National Tidal Centre Australia, Oceanographic Services,<br>Bureau of Meteorology, 25 College Rd, Kent Town SA. | *Date: 25/08/1993* |
| *Existing Bench Mark Established by:* | *Date:* |
| *Notes / References:* Deep driven Benchmark<br>This survey mark is not in a good locality for GPS occupation | |
| *Country:* Nauru<br>*Island: Nauru* | *City: Nauru* |

**MARKING AND LOCALITY SKETCH**

**Bench Mark**: 4.3m of 19mm diameter stainless steel capped rod driven to refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite, for 0.5m. Top of mark 0.1m below ground level. Locality sketch Mark approximately 1500m from the tide gauge station.




NOT TO SCALE — Distances in Metres — Magnetic Bearings

Approved by: Geoscience Australia / SPC — *Date: November 2006*

**PACIFIC SEA LEVEL MONITORING PROJECT**

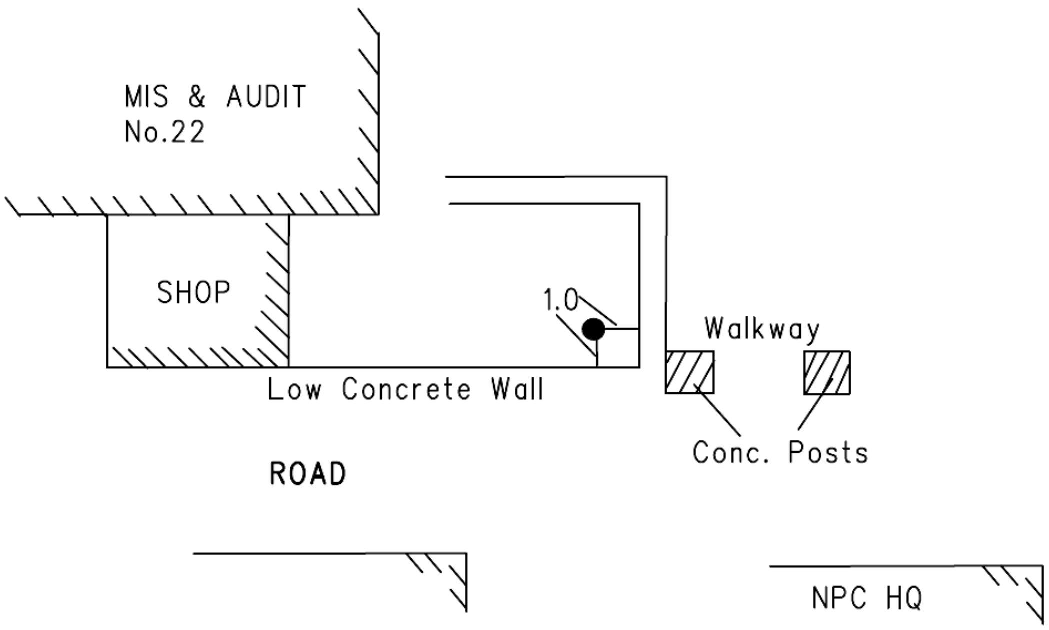
**SURVEY BENCH MARK RECORD**

**Bench Mark Number: NAU36**

| | |
|---|---|
| *Original Bench Mark Established by:*<br>National Tidal Centre Australia, Oceanographic Services,<br>Bureau of Meteorology, 25 College Rd, Kent Town SA. | *Date: 03/06/2002* |
| *Existing Bench Mark Established by:* | *Date:* |
| *Notes / References:* Deep Survey Benchmark<br>This survey mark is not in a good locality for GPS occupation. | |
| *Country:* Nauru<br>*Island: Nauru* | *City: Nauru* |

**MARKING AND LOCALITY SKETCH**

**Bench Mark**: 4.2m of 19mm diameter stainless steel capped rod driven to refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite, for 0.5m. Top of mark 0.1m below ground level. Locality sketch Mark approximately 600m from the tide gauge station.




NOT TO SCALE Distances in Metres Magnetic Bearings

Approved by: Geoscience Australia / SPC *Date: November 2006*

PACIFIC SEA LEVEL MONITORING PROJECT

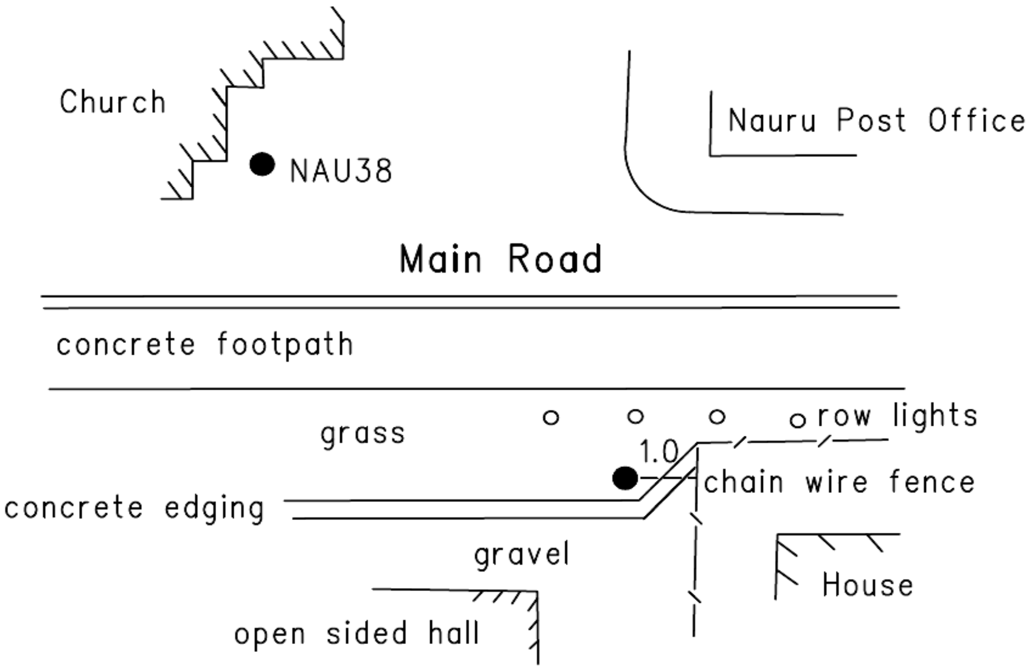
SURVEY BENCH MARK RECORD

**Bench Mark Number: NAU37**

| | |
|---|---|
| *Original Bench Mark Established by:*<br>National Tidal Centre Australia, Oceanographic Services,<br>Bureau of Meteorology, 25 College Rd, Kent Town SA. | *Date: 03/06/2002* |
| *Existing Bench Mark Established by:* | *Date:* |
| *Notes / References:* Deep Survey Benchmark<br>This survey mark is not in a good locality for GPS occupation. | |
| *Country:* Nauru<br>*Island: Nauru* | *City:Nauru* |

MARKING AND LOCALITY SKETCH

**Bench Mark**: 3.3m of 19mm diameter stainless steel capped rod driven to refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite, for 0.5m. Top of mark 0.1m below ground level. Locality sketch Mark approximately 1200m from the tide gauge station.




NOT TO SCALE | Distances in Metres | Magnetic Bearings

Approved by: Geoscience Australia / SPC | *Date: November 2006*

**PACIFIC SEA LEVEL MONITORING PROJECT**

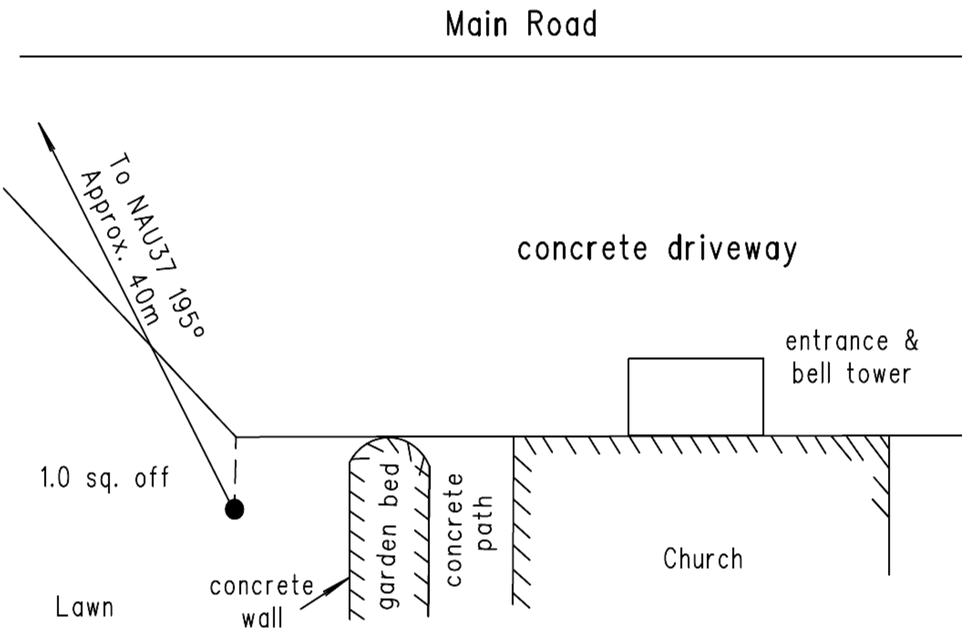
**SURVEY BENCH MARK RECORD**

**Bench Mark Number: NAU38**

| | |
|---|---|
| *Original Bench Mark Established by:*<br>National Tidal Centre Australia, Oceanographic Services,<br>Bureau of Meteorology, 25 College Rd, Kent Town SA. | *Date: 03/06/2002* |
| *Existing Bench Mark Established by:* | *Date:* |
| *Notes / References:* Deep Survey Benchmark<br>This survey mark is not in a good locality for GPS occupation. | |
| *Country:* Nauru<br>*Island: Nauru* | *City: Nauru* |

**MARKING AND LOCALITY SKETCH**

**Bench Mark**: 3.3m of 19mm diameter stainless steel capped rod driven to refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite, for 0.5m. Top of mark 0.1m below ground level. Locality sketch Mark approximately 1200m from the tide gauge station.

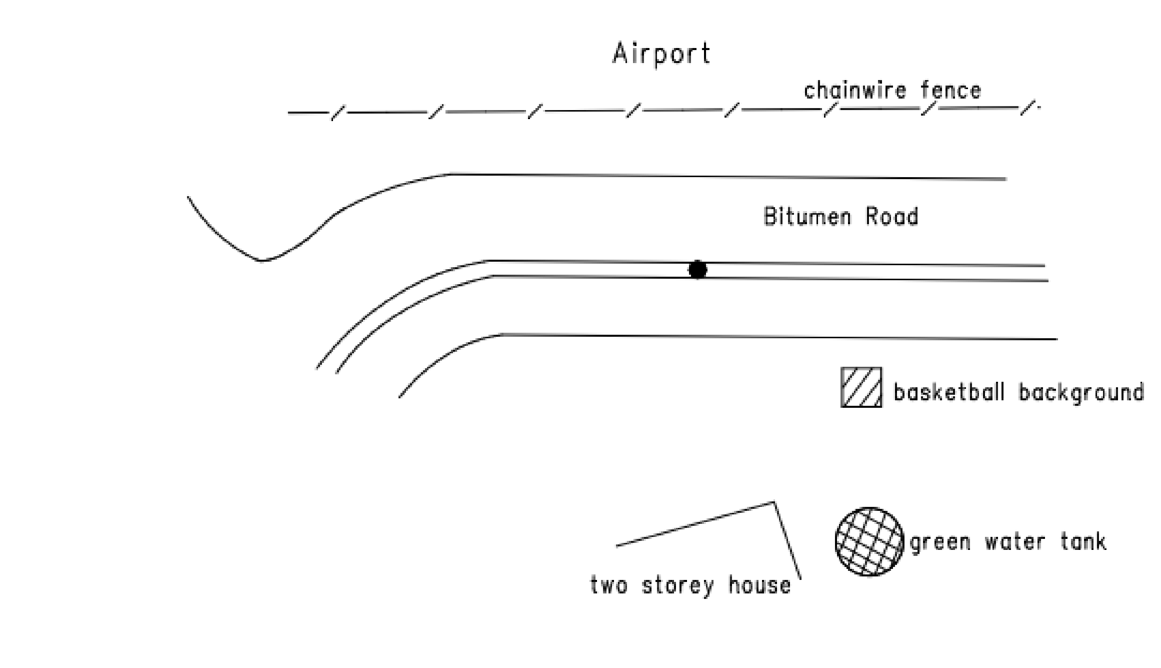



NOT TO SCALE | Distances in Metres | Magnetic Bearings

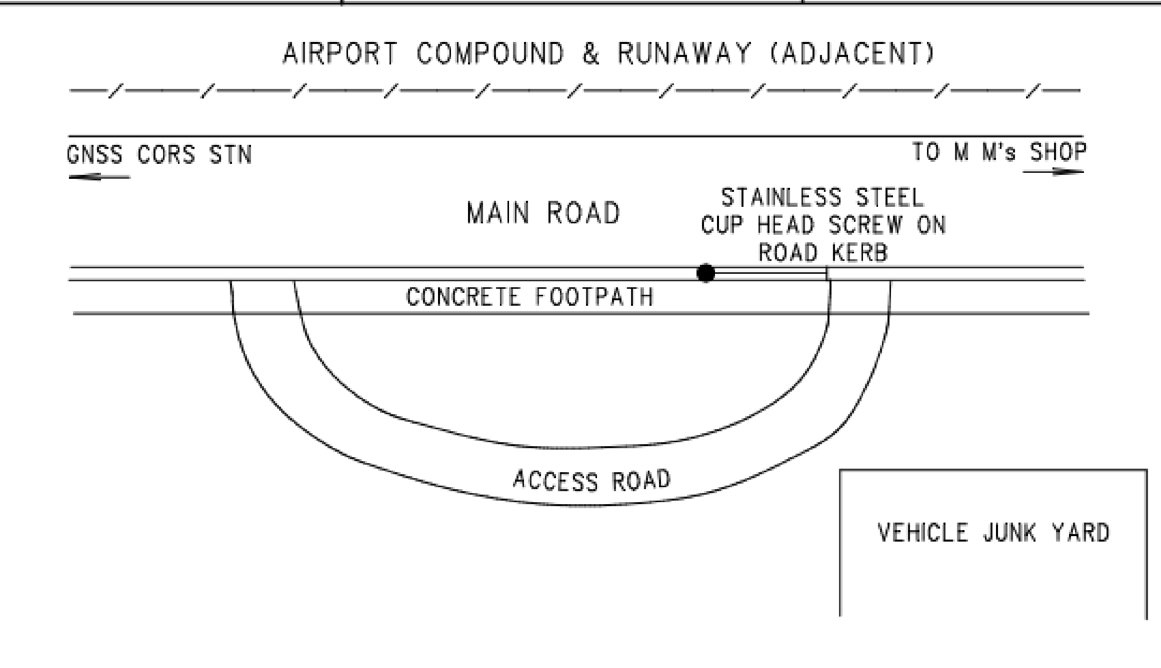
Approved by: Geoscience Australia / SPC | *Date: November 2006*

## A 2 Temporary Holdings Marks

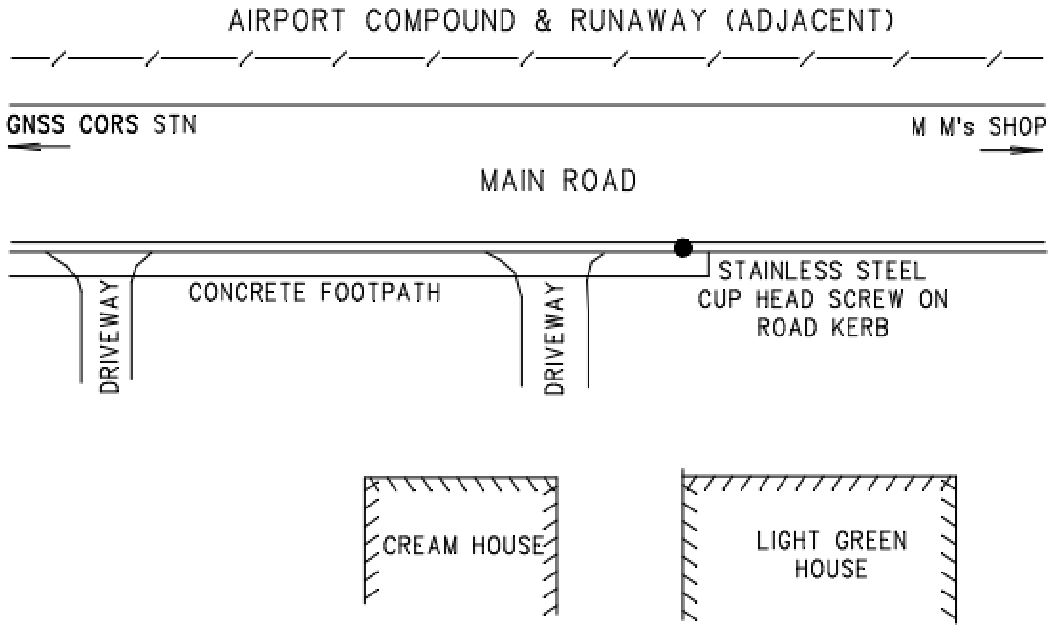
| | | |
|---|---|---|
| COUNTRY:<br>Nauru | ISLAND: Nauru<br>DISTRICT: Aiwo/Boe | L. D. P.<br>POINT NO. 53 |
| PROJECT: PSLGM | SURVEYOR: S. Turner | DATE: 07-09-03 |



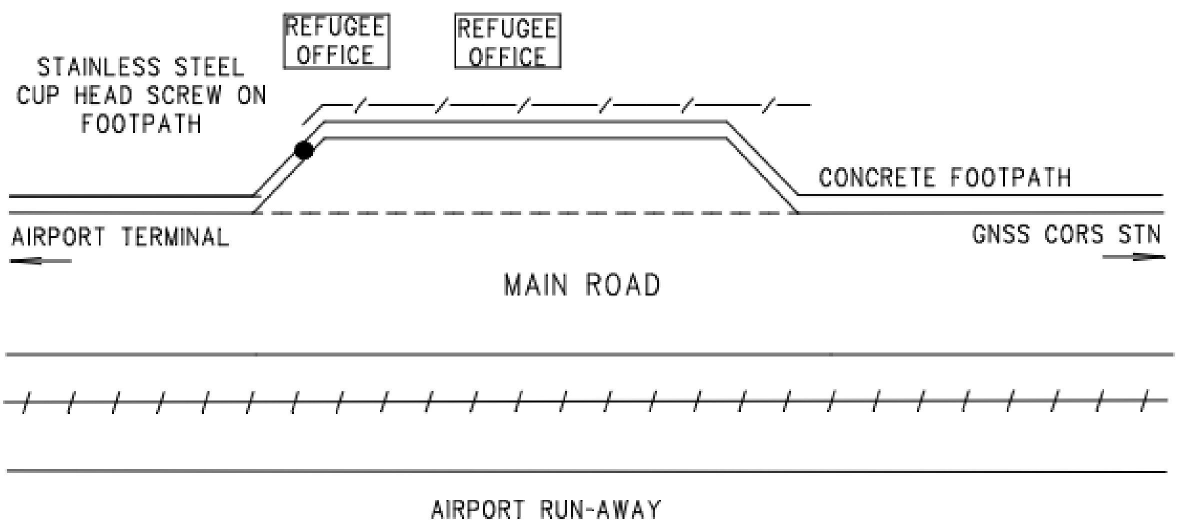

| | | |
|---|---|---|
| COUNTRY:<br>Nauru | ISLAND: Nauru<br>DISTRICT: Aiwo/Boe | L. D. P.<br>POINT NO. 104 |
| PROJECT: PSLGM | SURVEYOR: S. Yates & A Lal | DATE: 04-06-07 |



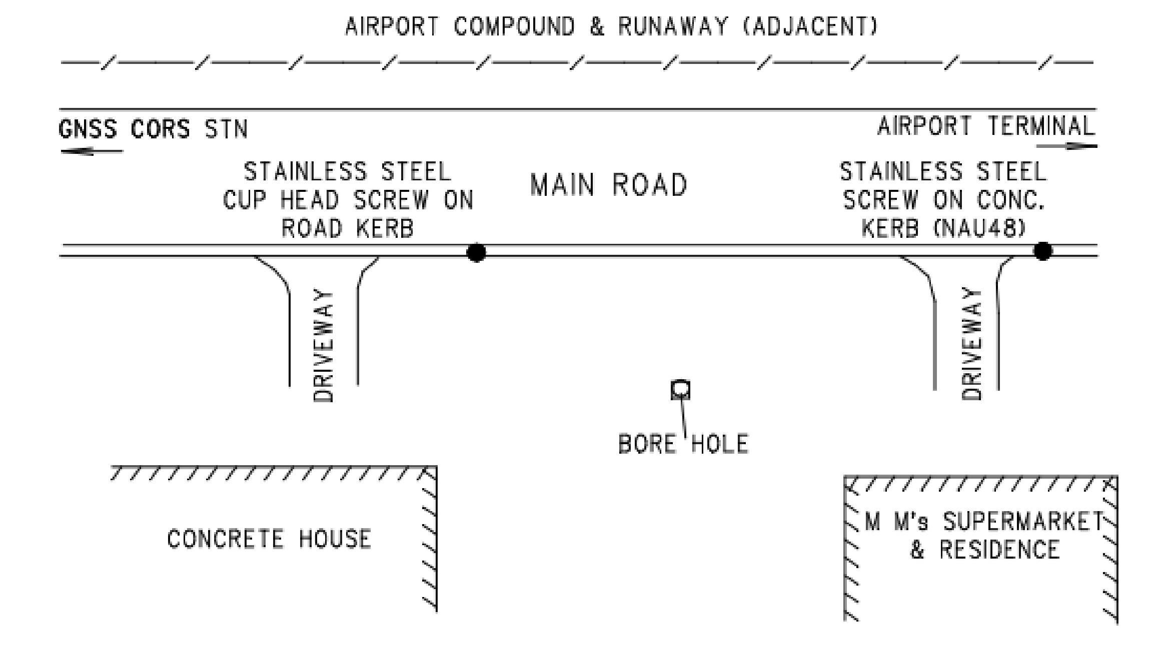
| | | |
|---|---|---|
| COUNTRY: Nauru | ISLAND: Nauru<br>DISTRICT: Aiwo/Boe | L. D. P.<br>POINT NO. 103 |
| PROJECT: PSLGM | SURVEYOR: S. Yates & A Lal | DATE: 04-06-07 |



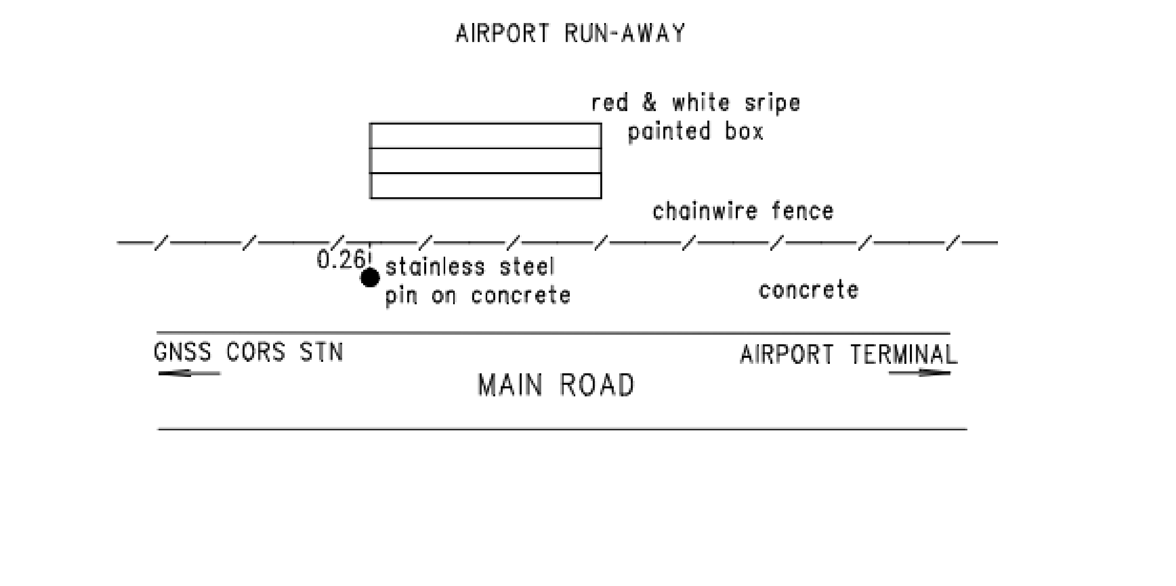

| | | |
|---|---|---|
| COUNTRY: Nauru | ISLAND: Nauru<br>DISTRICT: Aiwo/Boe | L. D. P.<br>POINT NO. 110 |
| PROJECT: PSLGM | SURVEYOR: AL, MK & VR | DATE: 24-08-16 |



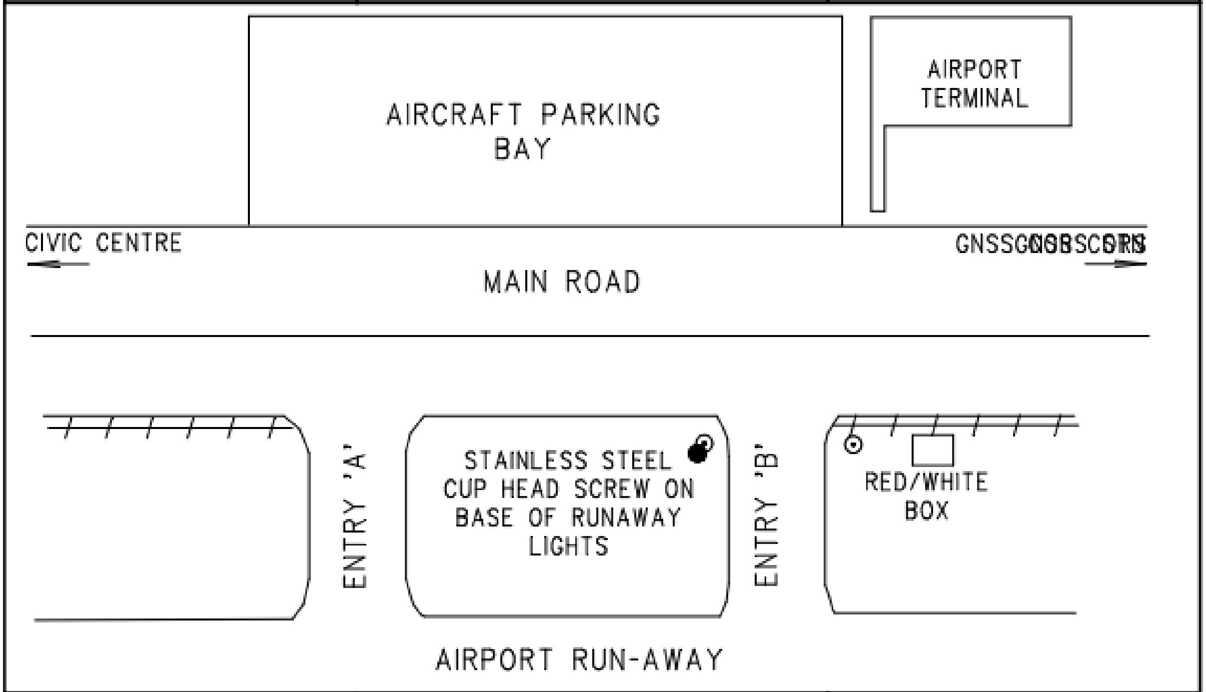
| | | |
|---|---|---|
| COUNTRY: Nauru | ISLAND: Nauru<br>DISTRICT: Aiwo/Boe | L. D. P.<br>POINT NO. 101 |
| PROJECT: PSLGM | SURVEYOR: S. Yates & A Lal | DATE: 04-06-07 |



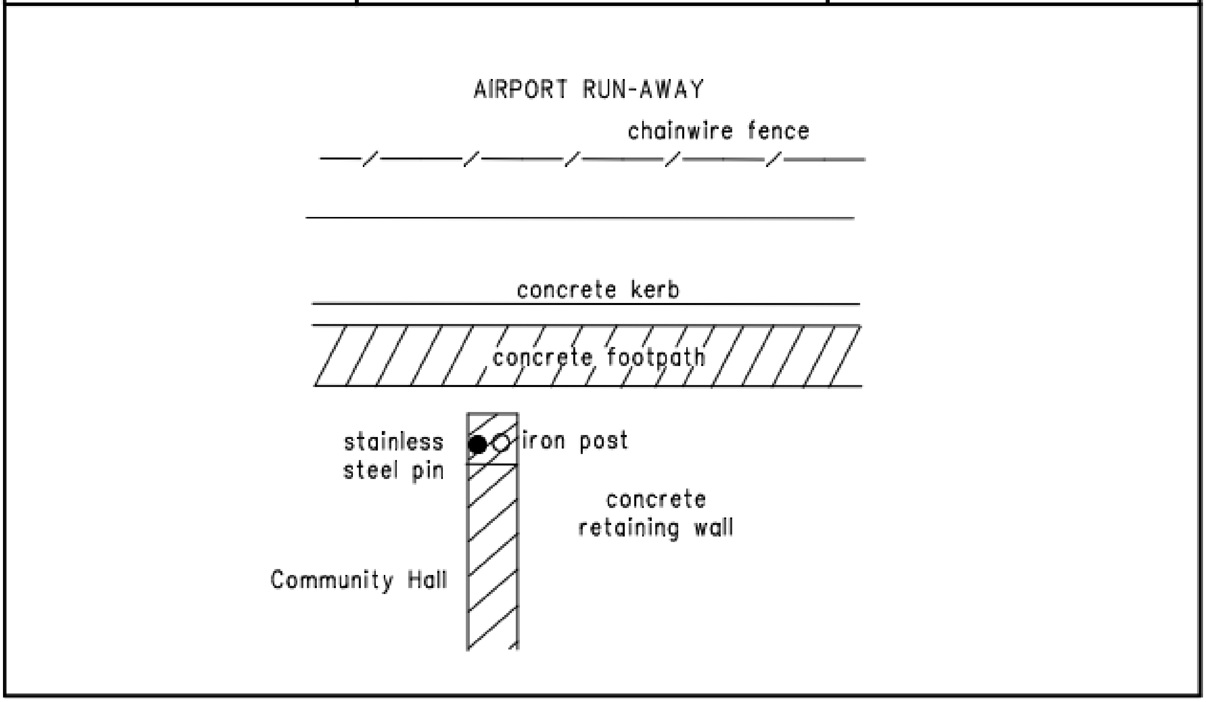

| | | |
|---|---|---|
| COUNTRY: Nauru | ISLAND: Nauru<br>DISTRICT: Aiwo/Boe | L. D. P.<br>POINT NO. 47 |
| PROJECT: PSLGM | SURVEYOR: S. Turner | DATE: 10-09-12 |



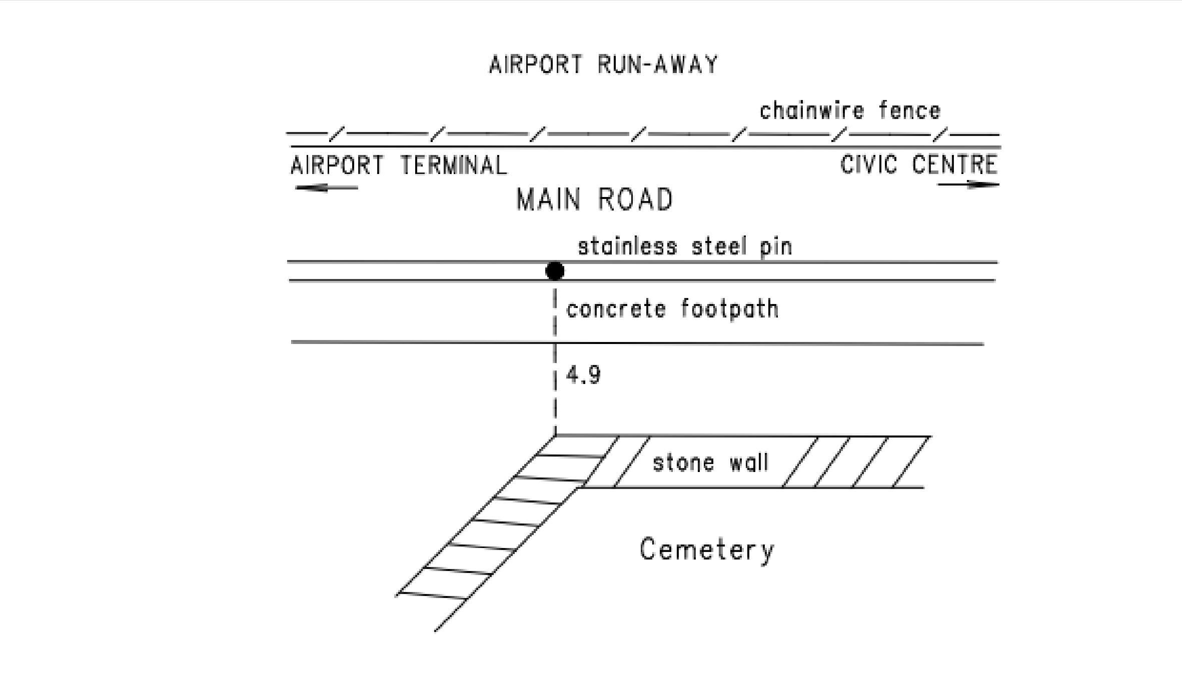
| | | |
|---|---|---|
| COUNTRY: Nauru | ISLAND: Nauru<br>DISTRICT: Aiwo/Boe | L. D. P.<br>POINT NO. 109 |
| PROJECT: PSLGM | SURVEYOR: S. Yates & A Lal | DATE: 05-02-09 |



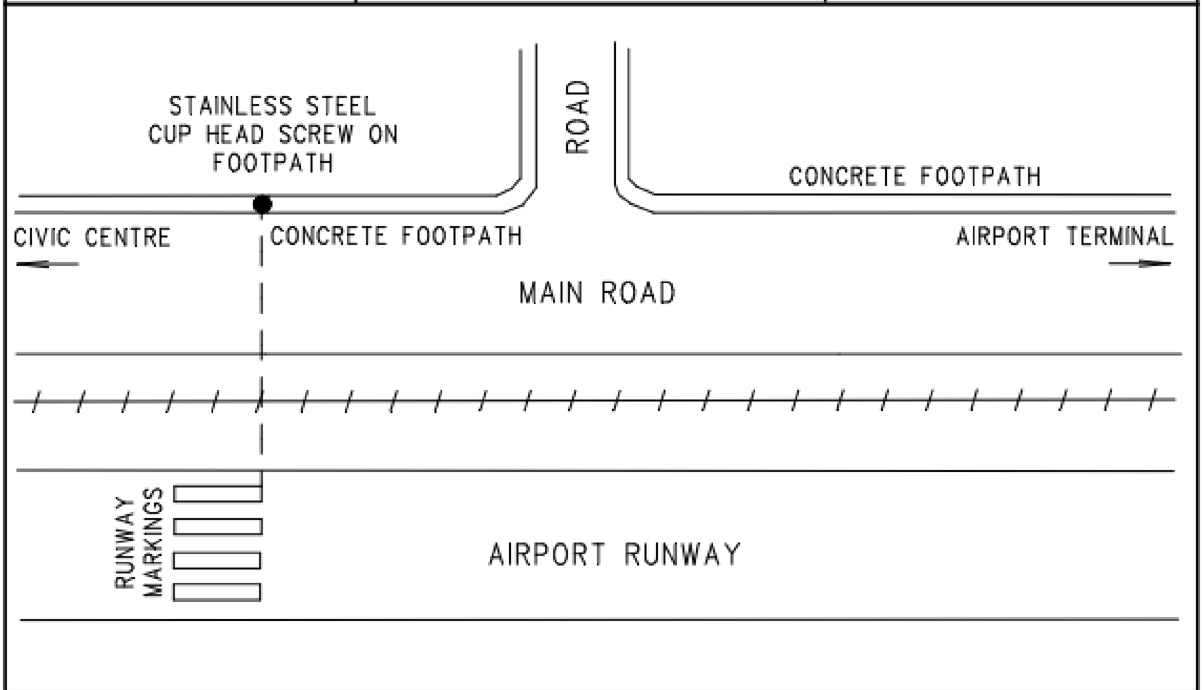

| | | |
|---|---|---|
| COUNTRY: Nauru | ISLAND: Nauru<br>DISTRICT: Aiwo/Boe | L. D. P.<br>POINT NO. 44 |
| PROJECT: PSLGM | SURVEYOR: S. Turner | DATE: 07-09-03 |



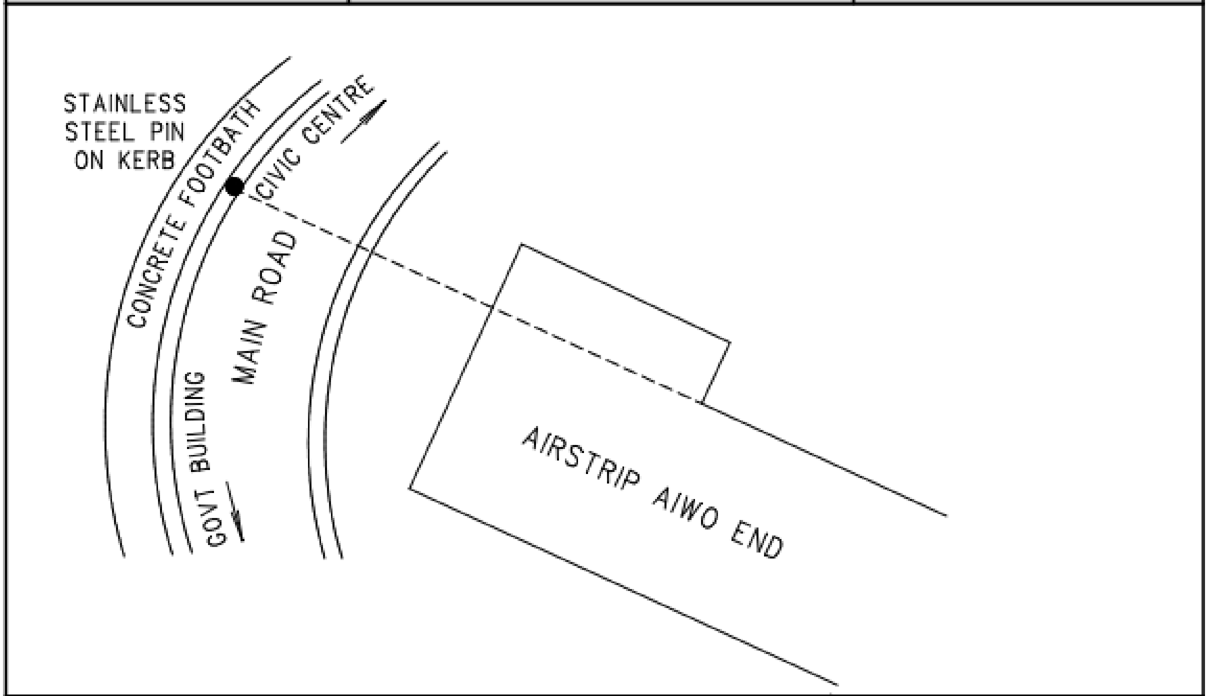
| | | |
|---|---|---|
| COUNTRY: Nauru | ISLAND: Nauru<br>DISTRICT: Aiwo/Boe | L. D. P.<br>POINT NO. 43 |
| PROJECT: PSLGM | SURVEYOR: STurner | DATE: 03-06-02 |



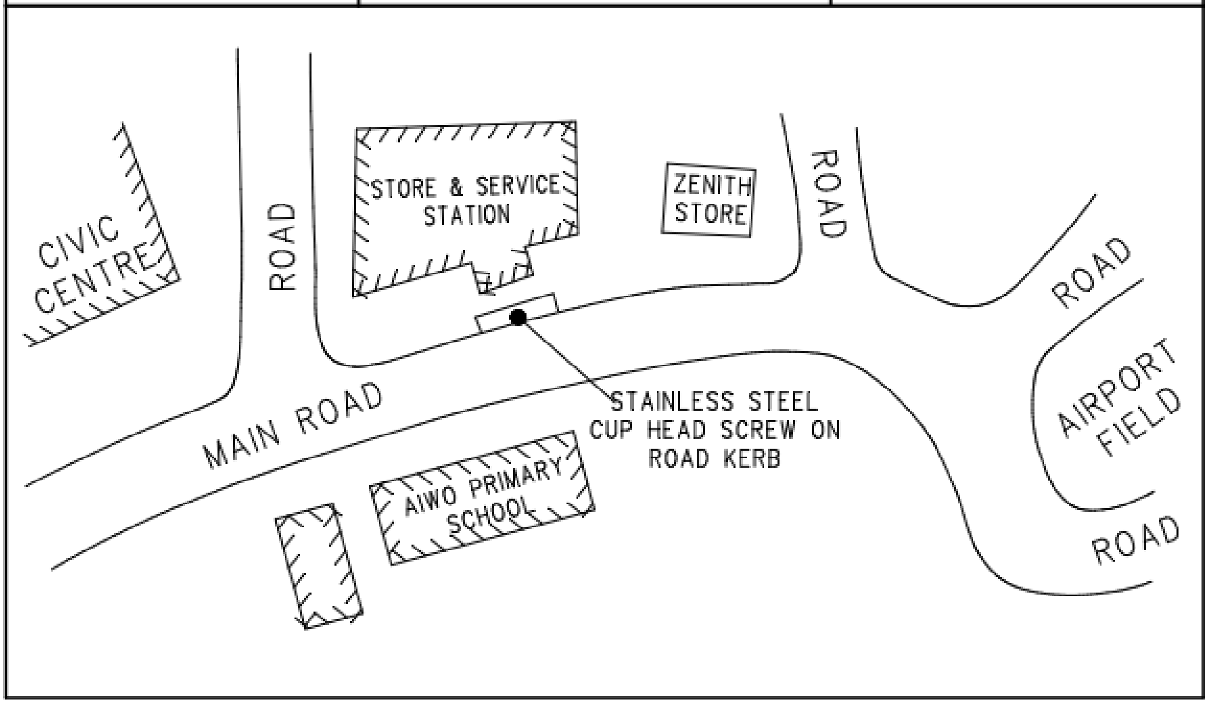

| | | |
|---|---|---|
| COUNTRY: Nauru | ISLAND: Nauru<br>DISTRICT: Aiwo/Boe | L. D. P.<br>POINT NO. 108 |
| PROJECT: PSLGM | SURVEYOR: S. Yates & A Lal | DATE: 05-02-09 |



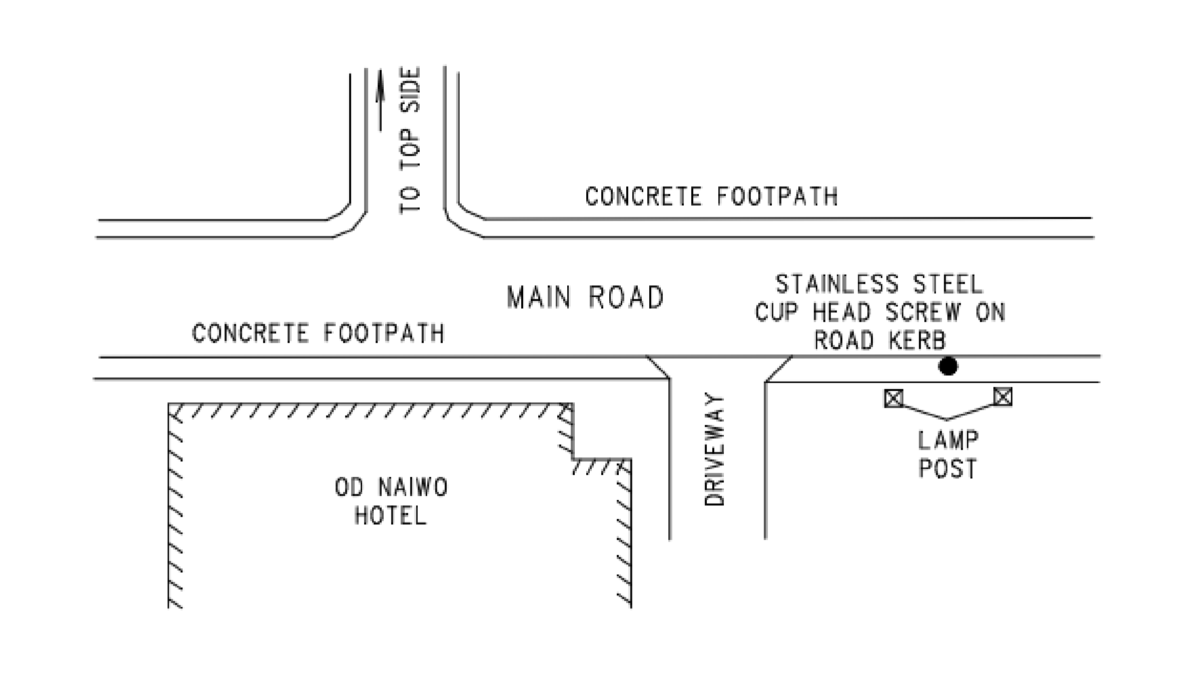
| COUNTRY: Nauru | ISLAND: Nauru<br>DISTRICT: Aiwo/Boe | L. D. P.<br>POINT NO. NAU33 |
|---|---|---|
| PROJECT: PSLGM | SURVEYOR: S. Turner | DATE: 31-05-02 |



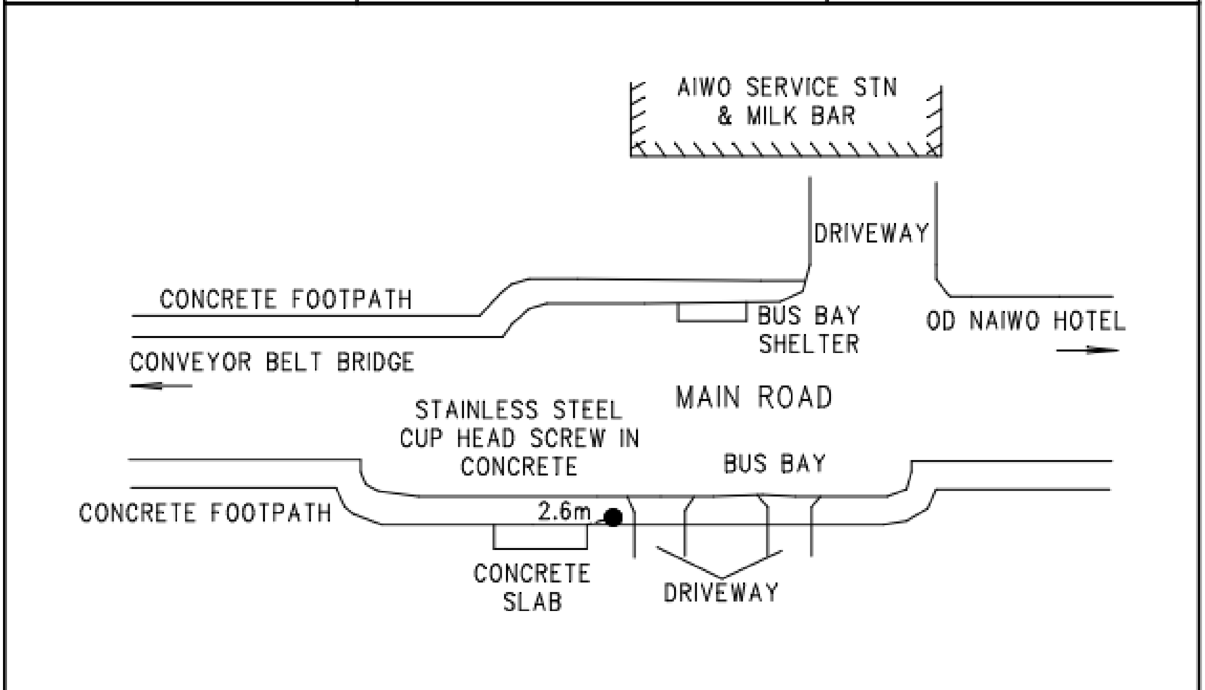

| COUNTRY: Nauru | ISLAND: Nauru<br>DISTRICT: Aiwo/Boe | L. D. P.<br>POINT NO. 107 |
|---|---|---|
| PROJECT: PSLGM | SURVEYOR: S. Yates & A Lal | DATE: 05-02-09 |



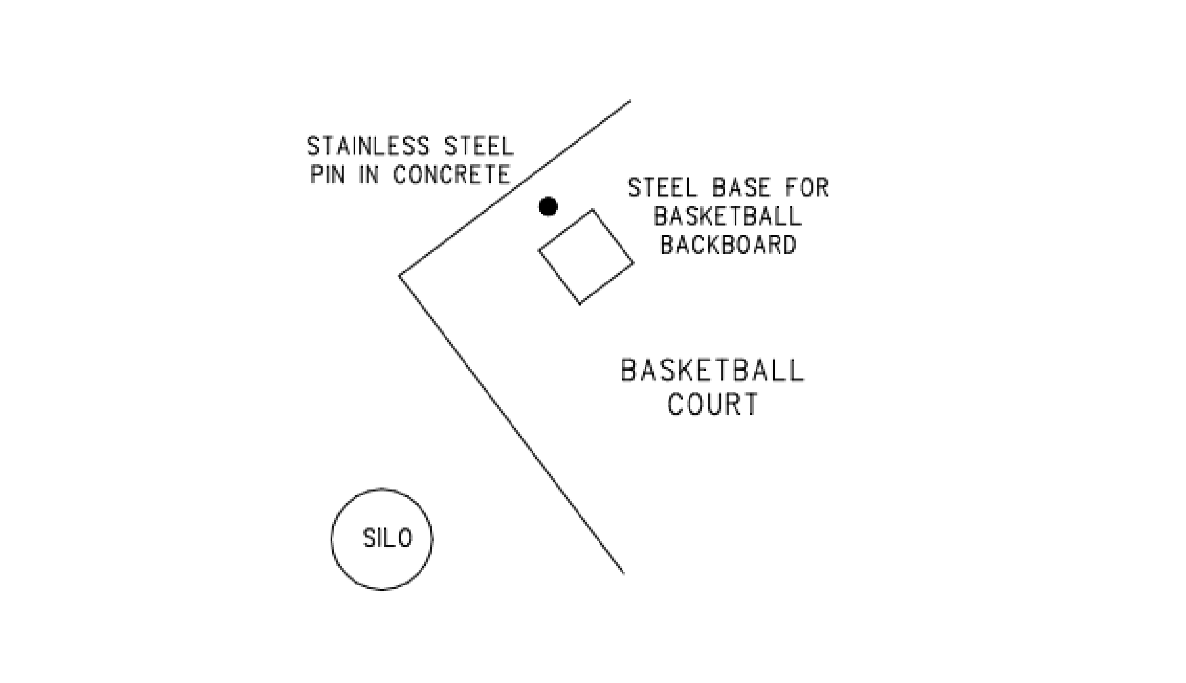
| COUNTRY: Nauru | ISLAND: Nauru<br>DISTRICT: Aiwo/Boe | L. D. P.<br>POINT NO. 106 |
|---|---|---|
| PROJECT: PSLGM | SURVEYOR: S. Yates & A Lal | DATE: 05-02-09 |



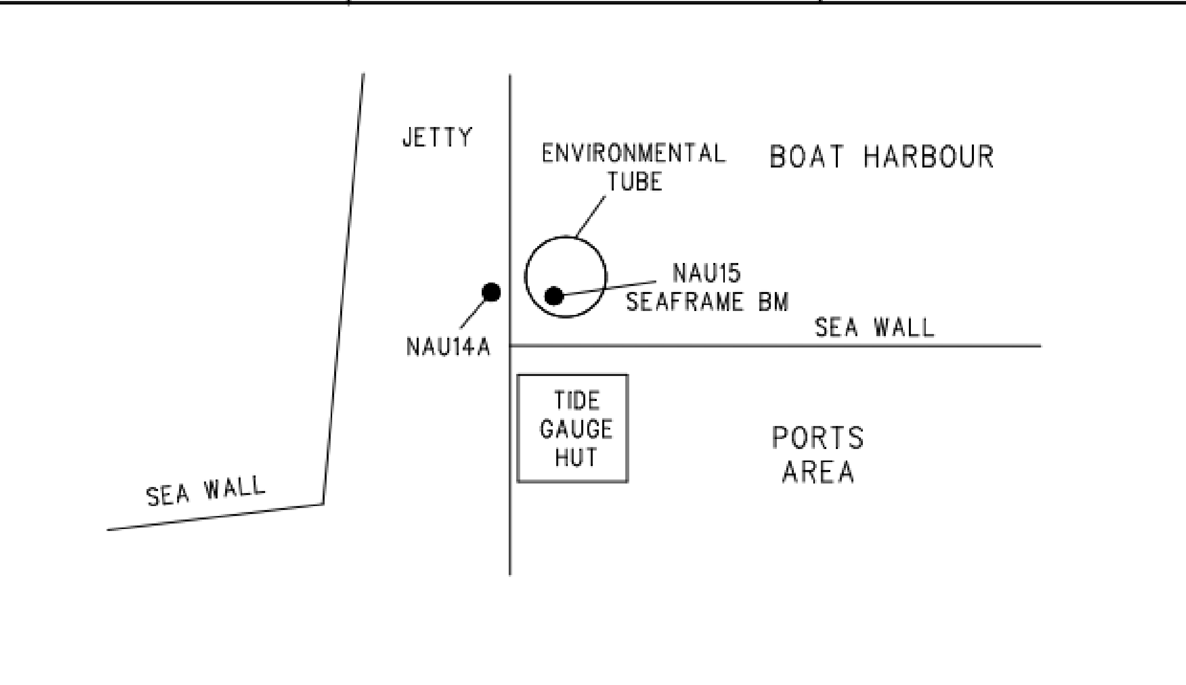

| COUNTRY: Nauru | ISLAND: Nauru<br>DISTRICT: Aiwo/Boe | L. D. P.<br>POINT NO. 100 |
|---|---|---|
| PROJECT: PSLGM | SURVEYOR: S. Yates & A Lal | DATE: 04-06-07 |



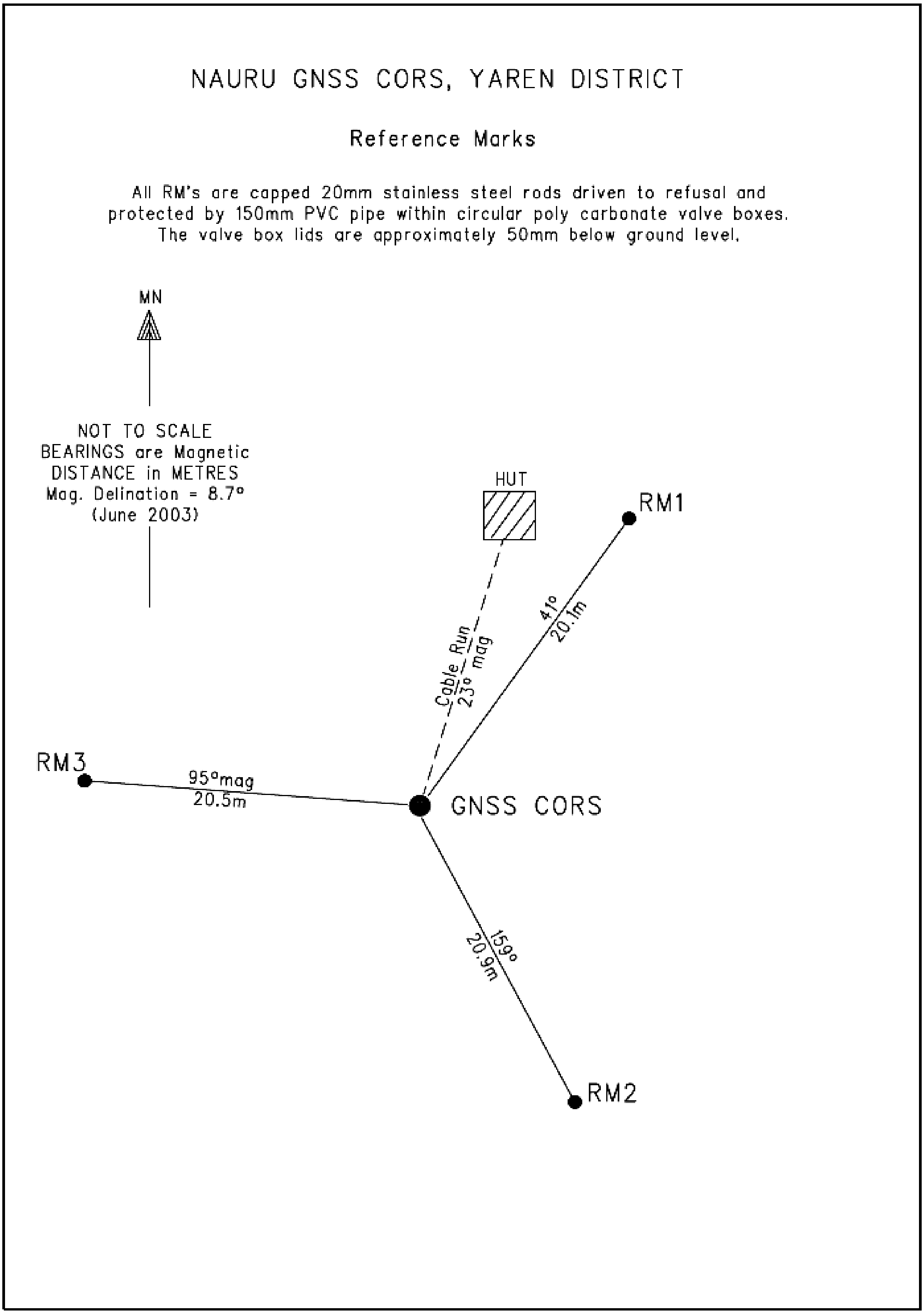
| | | |
|---|---|---|
| COUNTRY: Nauru | ISLAND: Nauru<br>DISTRICT: Aiwo/Boe | L. D. P.<br>POINT NO. 28 |
| PROJECT: PSLGM | SURVEYOR: S. Turner | DATE: 31-05-02 |




| | | |
|---|---|---|
| COUNTRY: Nauru | ISLAND: Nauru<br>DISTRICT: Aiwo/Boe | L. D. P.<br>POINT NO. NAU 14A & 15 |
| PROJECT: PSLGM | SURVEYOR: S. Yates & A Lal | DATE: 05-02-09 |



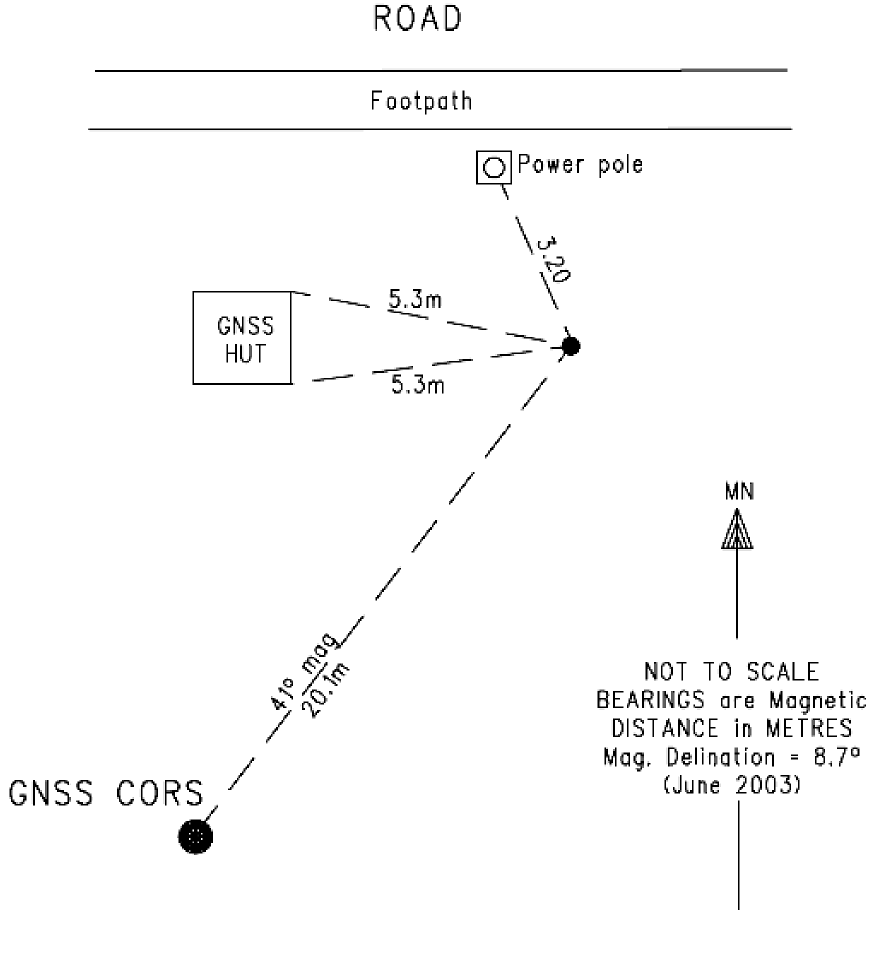
## A 3. GNSS Site Reference Marks



NAURU GNSS CORS, YAREN DISTRICT - RM1

Reference Mark

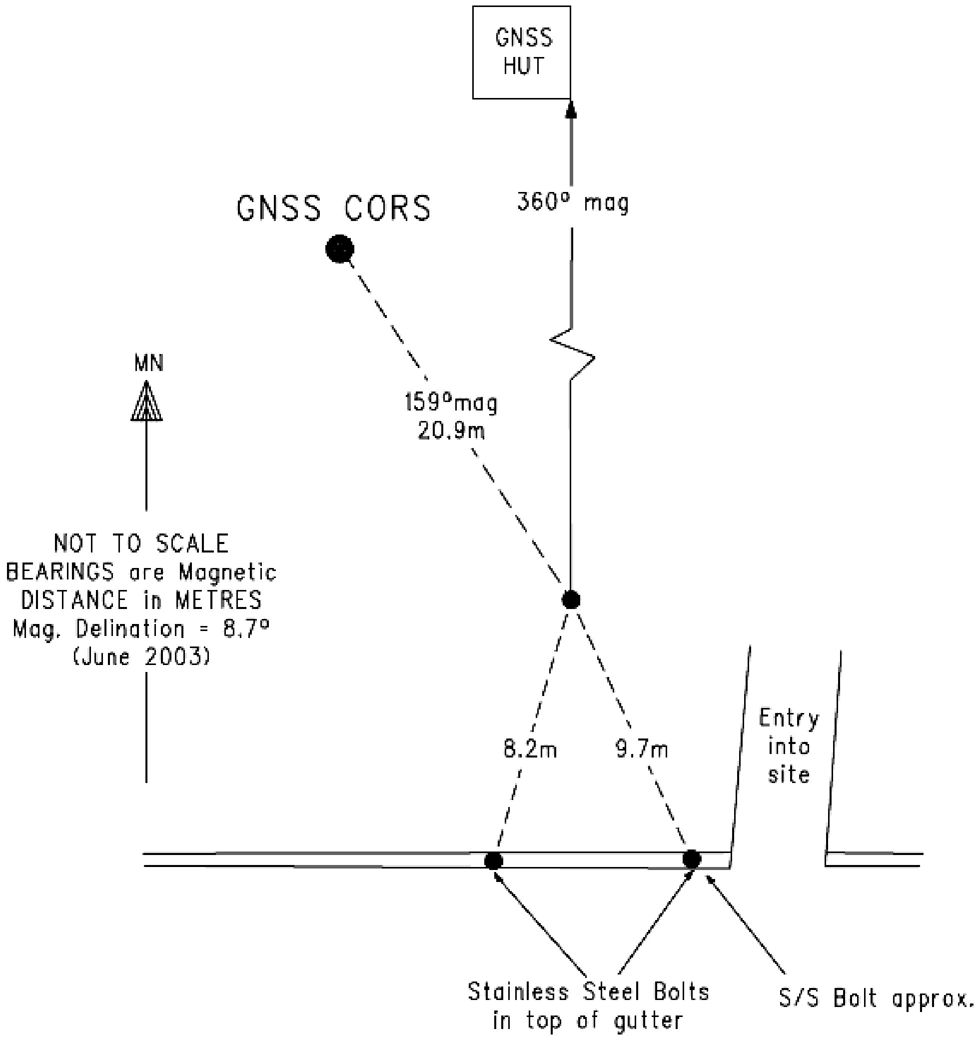
All RM's are capped 20mm stainless steel rods driven to refusal and protected by 150mm PVC pipe within circular poly carbonate valve boxes. The valve box lids are approximately 50mm below ground level.



## NAURU GNSS CORS, YAREN DISTRICT - RM2

### Reference Mark

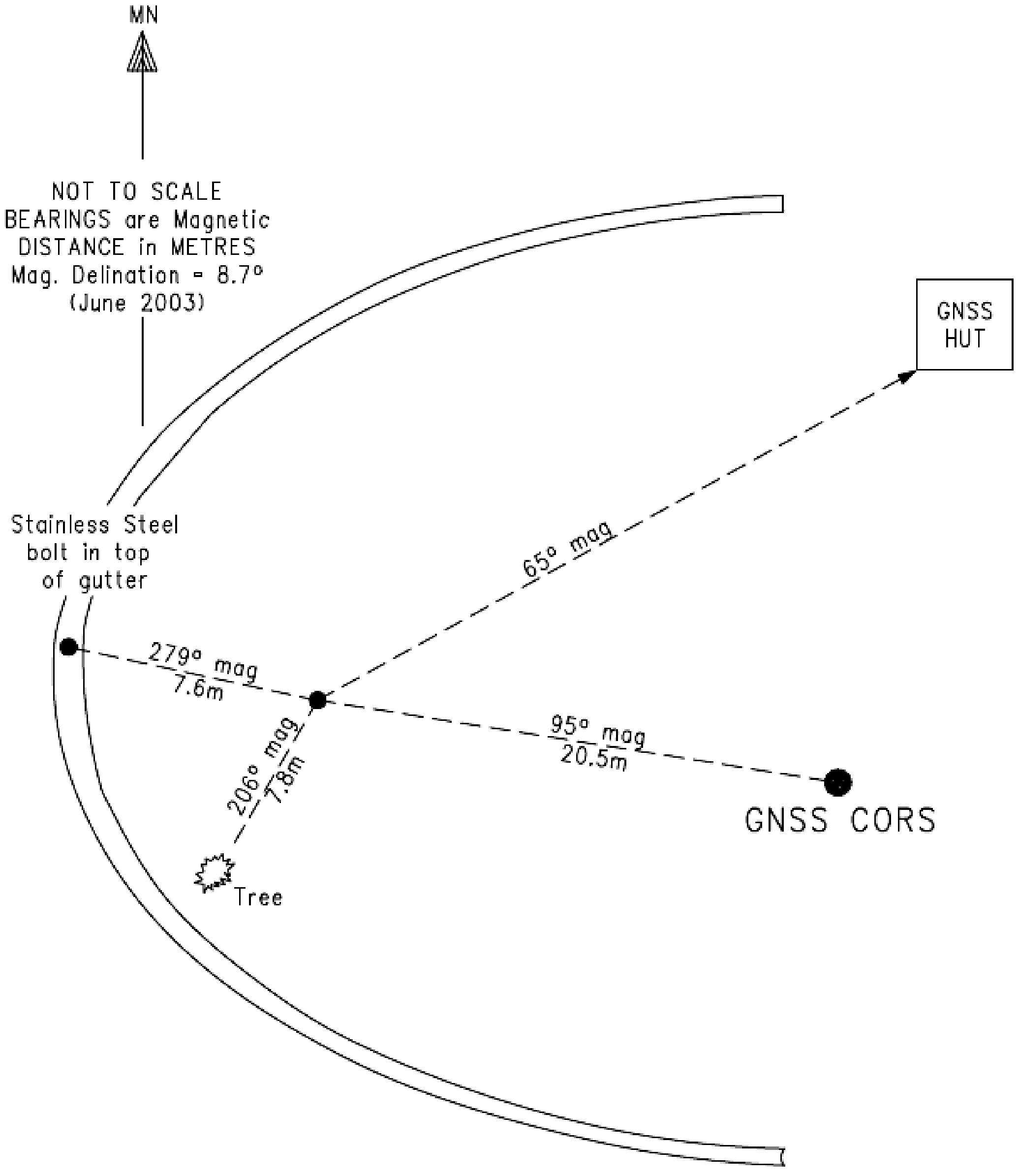
All RM's are capped 20mm stainless steel rods driven to refusal and protected by 150mm PVC pipe within circular poly carbonate valve boxes. The valve box lids are approximately 50mm below ground level.



# NAURU GNSS CORS, YAREN DISTRICT - RM3

## Reference Mark

All RM's are capped 20mm stainless steel rods driven to refusal and protected by 150mm PVC pipe within circular poly carbonate valve boxes. The valve box lids are approximately 50mm below ground level.



# Appendix B Planning Aspects and Notes

Upon arranging travel to Nauru, make contact with the project support officer in country well in advance. Passport details provided to project focal point to allow entry on arrival, and a visa issued once in country. Copy of visa should be on hand before arrival into Nauru.

Prior arrangements with the local counterpart made for the clearance of the survey equipment from the Customs Authority when shipped across.

DHL Express commonly used for freight inwards and outward for the Survey Equipment into Nauru.

- For freight payment inwards and outward, cash payment recommended to avoid excess charges.
- The survey equipment freighted to the Land Management Division as the project focal point in the country.

When levelling across the airport apron, contact airport security, and airport manager, and advise them of the intended work. NAU19 exists on the concrete footing of a taxiway light, and security advised before stopping at this point. An escort to arrange to access NAU16.

Plan carefully around the arrival of international aircraft. Roads and access shut down for a few hours while the airport is operating.

| Quantity | Item & description | Locations |
|---|---|---|
| **1** | **Tool Box** | Tide Gauge Station Hut. |
| *2* | *Prism Pole Clamps* | *Tools used by C&M Teams (BoM & SPC)* |
| *1* | *50m Measuring Tape* | |
| *1* | *Engineers Hammer* | |
| *1* | *Carpenters Hammer* | |
| *1* | *Set of Allen Keys* | |
| *1* | *Torx Drivers* | |
| *2* | *Multigrips pliers* | |
| *1* | *Set of Screw Drivers* | |
| **1** | **PVC Pipe (1.2m)** | GNSS COR Station Hut |
| *1* | *Aluminium GST6 tripod with Feet* | |
| **1** | **PVC Pipe (1.7m)** | GNSS COR Station Hut |
| *1* | *Ground Base Plate* | |
| *4* | *Telescopic-Bi-pods* | |
| *2* | *Stainless-steel levelling prism poles* | |
| *1* | *Half Stainless-steel levelling prism pole* | |
| **3** | **Black Bags - Leica GST20 Telescopic Tripods** | GNSS COR Station Hut |
| **1** | **Green Bag - Leica GST40 Rigid Tripod** | GNSS COR Station Hut |
| **1** | **Spade** | GNSS COR Station Hut |
| **1** | **Crow Bar** | GNSS COR Station Hut |

# Appendix C Equipment Specifications

## Tachymeters, EDM and Theodolites

A Leica TM30 (S/N 361441) Total Station was used to record all angles and distance measurements.

Specification

- EDM (infrared) distance standard deviation of a single measurement (DIN 18723, part 6): 0.6 mm ± 1 ppm.
- Angular standard deviation of a mean direction measured in both faces (DIN 18723, part 3): 0.3 mgon (≈ 1°).

Calibration

The Leica TM30 electronic distance measuring instrument (Serial No. 361441) was calibrated by the Australian National Measurement Institute (NMI) in July 2013. It was found to have an average error of $0.44 \times 10^{-6}$ mm, which has been added to the Total Station.

## Meteorological Sensor

Description

A NK Kestrel 4000 Pocket Weather Tracker (S/N 625479) was used to record meteorological observations (temperature, pressure and relative humidity).

Specification

- Temperature is accurate to 1.0°C between -29.0°C and 70.0°C.
- Pressure is accurate to 1.5 mb at 25°C between 750 mb and 1100 mb.
- Relative humidity is accurate to 3.0%.

## Forced Centring

Description

An FG0L30 (S/N 609030) zenith and nadir optical plummet was used to centre and level all instrument and target setups.

Specification

- Accuracy is 1:30 000 (1 mm at 30 m).

## Targets and Reflectors

Description

The standard target kit includes:

- 4 x Leica GDF21 tribrachs.
- 4 x Leica GZR3 prism carriers with optical plummet.
- 4 x Leica GPH1P precision prisms.

Calibration

The additive constant for the Leica GPH1P precision prism is -34.4 mm which was applied directly into the Leica TM30 Total Station. All prisms were calibrated on a tripod baseline at Geoscience Australia in July 2009. Approximate prism corrections of 0.0 mm were applied to observations during data processing.

## Precision Levelling

Levelling Instruments

Refer to section 2.1 for a description of the Leica TM30 Total Station

Levelling Rods

A fixed height stainless steel rod (SP Primary Pole) approximately 1.6 m in height with Leica style bayonet mount on top for mounting a precision prism was used with a Leica bi-pod for stability.

A fixed height short stainless-steel rod (SP 1/2m TG Pole) approximately 0.5 m in height with Leica style bayonet mount on top for mounting a precision prism was used.

A height offset between the pole (SP Primary Pole) and the short pole (SP 1/2m TG Pole) was determined by observing both on a low mark. Multi-set, dual face observations were used to eliminate collimation effects. The resulting height offset was 1.00054m.

## Tripods

Description

Leica GST20 heavy-duty timber tripods with adjustable legs was used on all marks, with the exception of the pillars, during the monitoring survey.

A Leica rigid timber tripod was used to mount the TM30 on for the purpose of this levelling survey.

Note: Three Leica adjustable leg tripods was left on site in the current GNSS hut for carrying out the associated RM horizontal survey.

## GNSS Equipment

At the time of the survey, the GNSS equipment in use at the GNSS CORS site was:

- Septentrio GNSS receiver SEPT POLARX4TR Firmware Version 2.9.6 (S/N 3007597)
- Leica Choke Ring antenna (LEIAR25.R3) - S/N 10150005