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

Manus Island, Papua New Guinea, March 2019

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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 Manus Island, Papua New Guinea from 25th to 31st March 2019. It also provides an updated ellipsoidal 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 differential 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 Manus, which runs approximately 1.5 km. Previous levelling surveys have been conducted along this route using the Total Station differential levelling technique in 2006, 2007, 2009, 2010, 2014, 2015, and 2017. 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 Marika Kalouniviti and Veenil Rattan, 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, GNSS CORS, and SEAFRAME are located within the Compound of Lombrum Naval Base. The levelling run goes from tide gauge at the Navy Jetty along the road up to the GNSS pillar opposite the church.

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2.2 Survey Support

The survey team very much appreciated the assistance from the Lombrum Naval base and the Manus Island Weather Service Office, especially to Mr Hymson for his ongoing support with the project.

3 Measurement Network

3.1 Terrestrial Network

The Total Station differential levelling survey was carried out between the SEAFRAME tide gauge sensors, the GNSS CORS along 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
PNGMBM	Reference benchmark in the base of the GNSS CORS pillar
PNG14	SEAFRAME sensor reference benchmark
PNG1	Deep driven Benchmark at the road junction to tide gauge
PNG2	Deep Driven Benchmark at Navy parade ground
PNG3	Deep driven Benchmark in front of the church
PNG31	Deep driven Benchmark near the navy hall
RM1	GNSS CORS reference mark 1
RM2	GNSS CORS reference mark 2
RM3	GNSS CORS reference mark 3

Upon inspection, all the deep benchmarks were located, found in good order, and undisturbed. Included in the survey were the temporary holding marks, PNG102, PNG104, PNG105, PNG106 and PNG107.

3.1.1 PSLGMP Vertical Reference Frame Wiring Diagram

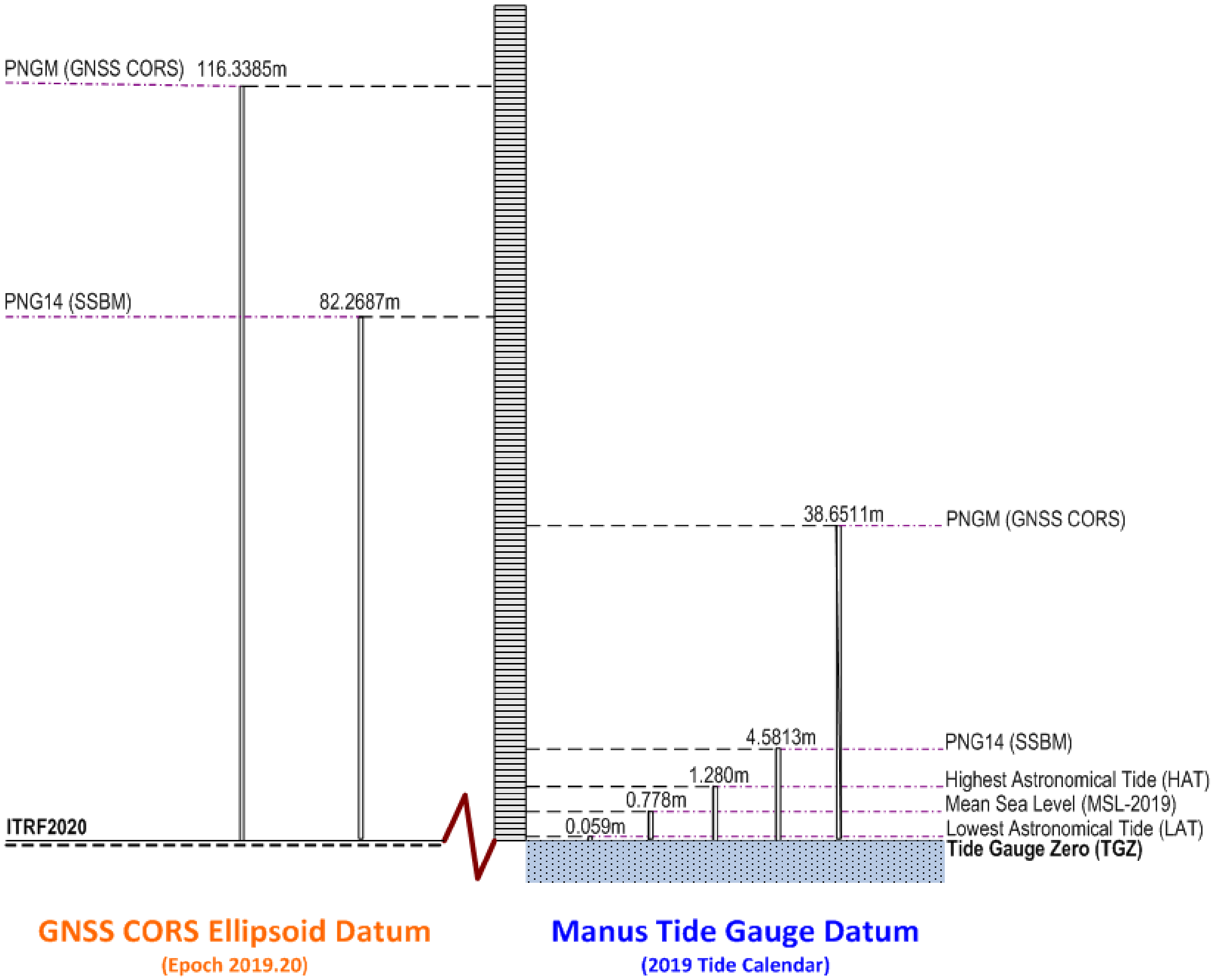

Figure 3.1 Wiring diagram depicting the offsets between surveyed marks. The left-hand side shows the height of the GNSS CORS pillar (PNGM) and SEAFRAME sensor reference benchmark (PGNM14), with respect to the International Terrestrial Reference Frame 2020 at epoch 2019.20. The right-hand side shows the height of PNGM, PNGM14, 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)]

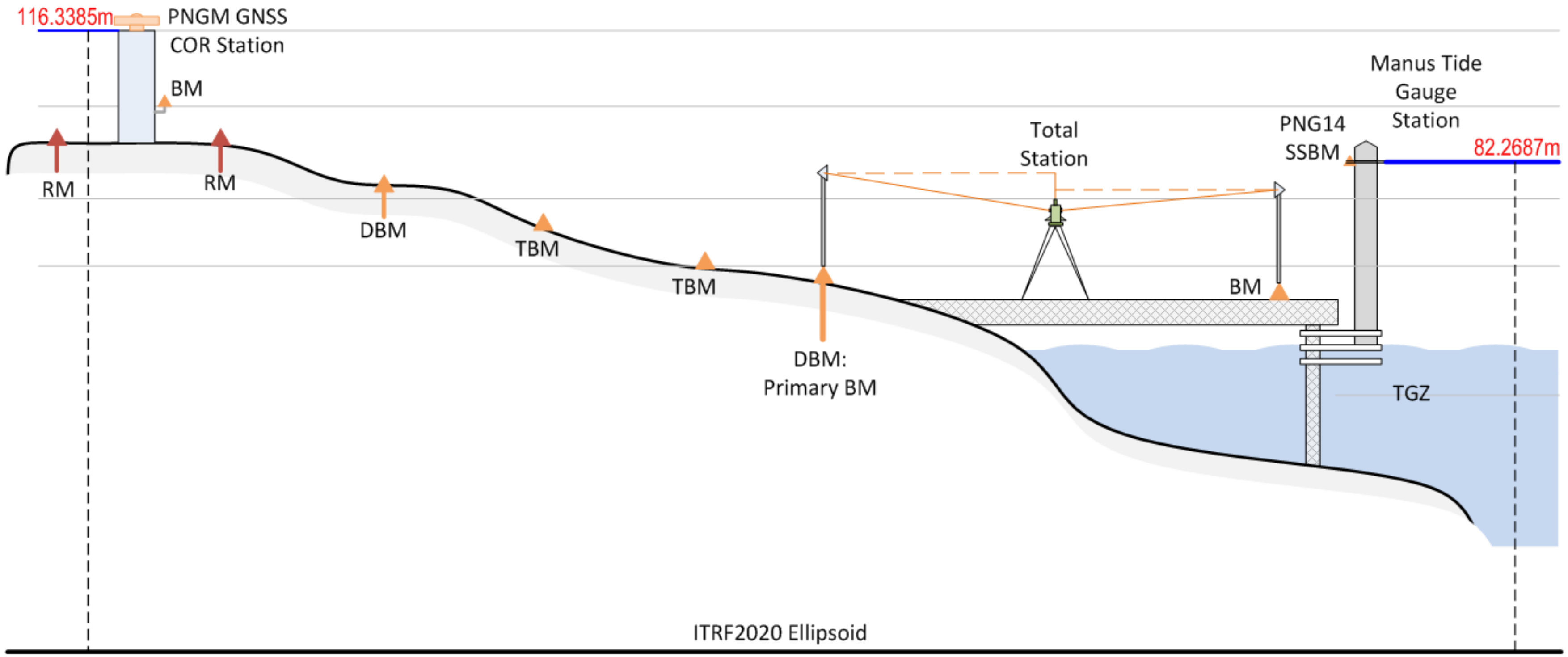

Figure 3.2 Simplified representation of the Total Station differential levelling survey carried out between the GNSS CORS and the SEAFRAME Tide Gauge.

Figure 3.3 Tide Gauge Station at the Lombrum Naval Base Jetty

Figure 3.4 GNSS COR Station in Manus Island. The red circle denotes the location of the GNSS CORS benchmark (PNGMBM).

3.1.2 Levelling Benchmark Network

Figure 3.5 Levelling benchmark array. Source: Adopted from Google Maps.

3.1.3 GNSS CORS and Reference Marks

The GNSS CORS site is located within the Navy compound. The site consists of a GNSS building to house the technical equipment and a 1.9 m high antenna pillar. The pillar is 40 metres from the GNSS building, access is via arrangement with the PNG Lombrum Naval Base but should otherwise be open once they have been informed of the survey intentions.

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.

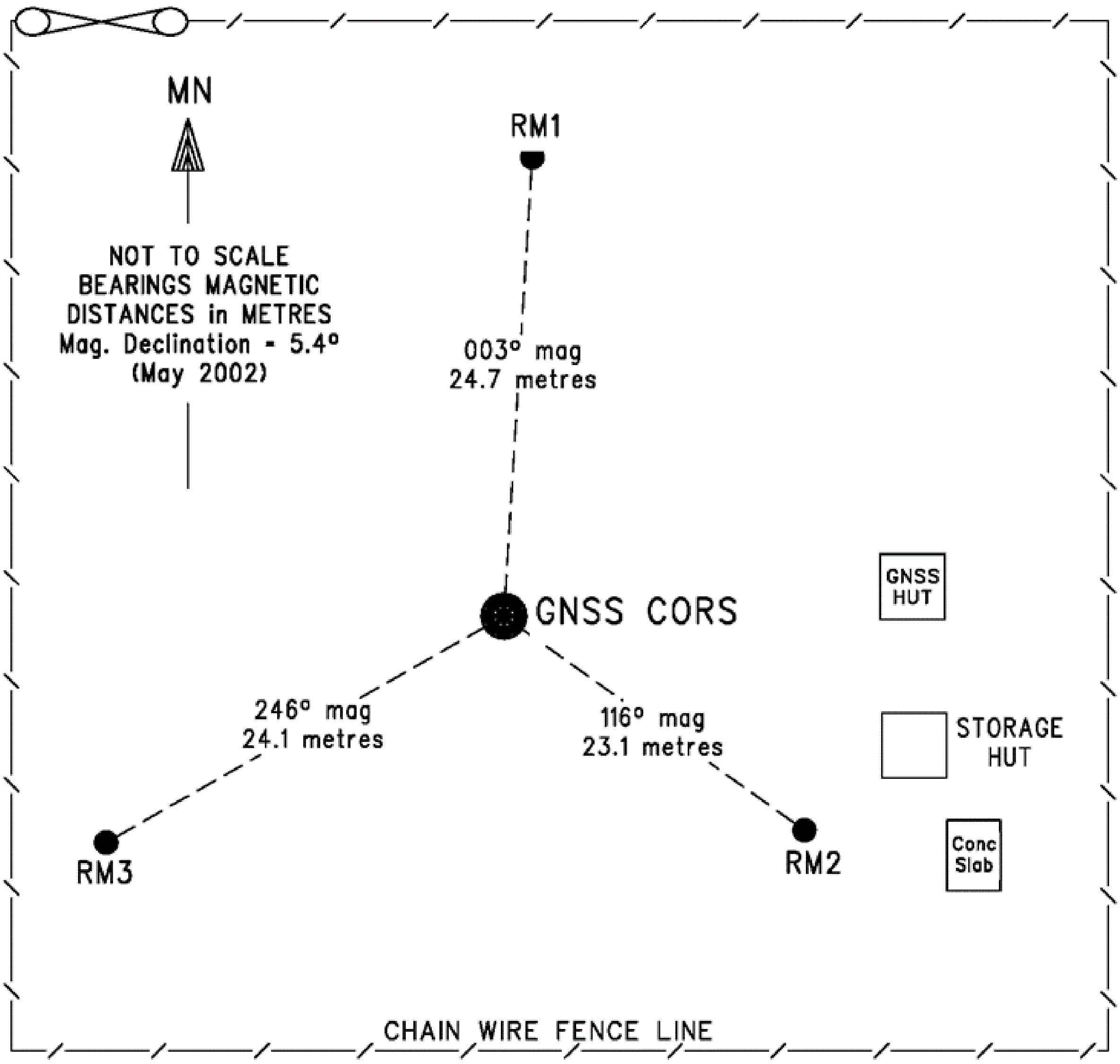

Figure 3.6 GNSS CORS site monitoring survey reference marks.

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 (PNGMBM).

3.2.2 Historical Survey Datum

In the past, the adopted reference point for the levelling survey was PNG1 fixed at 2.2987675 metres. This value was determined by the National Tidal Centre Australia (NTCA) by adopting the Tide Staff Zero (TSZ) datum from the 1994 survey.

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

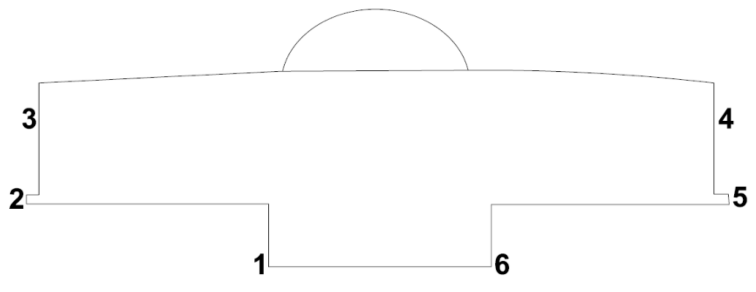

Figure 4.1 Symmetrical points on the antenna profile (TRM59800.00) observed from each RM.

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 in-direct method of observation be used.

4.2 Horizontal Observations

The indirect methodology was used during the 2019 local monitoring survey

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 PNGMBM at the PNGM GNSS CORS Site

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
PNGMBM				0.0000		0.0000
RM1	**RM1**	0.0000	-1.8025	-1.8025	0.0250	0.0250
RM2	**RM2**	1.4266	0.0000	-0.3759	0.0401	0.0652
RM3	**RM3**	0.2873	0.0000	-0.0886	0.0430	0.1080
RM2	**RM2**	0.0000	-0.2873	-0.3759	0.0430	
RM1	**RM1**	0.0000	-1.4266	-1.8025	0.0401	
	PNGMBM	1.8023	0.0000	-0.0002	0.0250	
	Sum:	3.5162	-3.5164			
	Misclose:		-0.0002	-0.0002	0.216	(Total Dist.)
			ALLOWABLE (m):	**0.0007**	**2 x Sqrt (km) test:**	**PASS**

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
PNGMBM				0.0000		0.000
RM2	**RM2**	0.0000	-0.3756	-0.3756	0.023	0.023
PNGMBM	**PNGMBM**	0.3756	0.0000	0.0000	0.023	
	Sum:	0.3756	-0.3756			
	Misclose:		0.0000	0.0000	0.046	(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)
PNGMBM				0.0000		0.000
RM3	**RM3**	0.0000	-0.0885	-0.0885	0.024	0.024
	PNGMBM	0.0884	0.0000	0.0000	0.024	
	Sum:	0.0884	-0.0885			
	Misclose:		0.0000	0.0000	0.048	(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 (PNGM) was tightly constrained to its ITRF2014 coordinates and aligned to PNGM-RM1 with an azimuth of 8° 24’ 00.43”, which had been determined in the 2002 survey by GNSS observation to RM1. The angular observations were given a precision of 1.0” and the slope distances a precision of 1.0 mm. The estimated coordinates and associated variance-covariance matrix were outputted in a SINEX file format and have been provided to Geoscience Australia.

The ITRF2014@2010.0 latitude and longitude coordinates adopted at PNGM 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@2019.2 ellipsoidal height were adopted at PNGM. CCC means all 3 dimensions (in XYZ) were constrained in the adjustment FFF means they were all free.

Station	Constraint	Latitude	Longitude	Ellipsoidal height (m)
PNGM	**CCC**	-2° 02’ 35.62577”	147° 21’ 57.6302”	116.3385
RM1	**FFF**	-2° 02’ 34.83057”	147° 21’ 57.7470”	113.5745
RM2	**FFF**	-2° 02’ 36.02782”	147° 21’ 58.2629”	115.0018
RM3	**FFF**	-2° 02’ 35.89156”	147° 21’ 56.8955”	115.2887

Table 4.3.3 Earth Centred Cartesian coordinates and associated standard deviations (metres) for the GNSS & RM stations. ITRF2014@2010.0 Latitude, Longitude coordinates (as per https://gnss.ga.gov.au/network), and ITRF2020@2019.2 ellipsoidal height were adopted at PNGM.

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

Description	X	Y	Z	SD(e)	SD(n)	SD(up)
PNGM	-5367942.9653	3437431.5540	-225885.8351	0	0	0
RM1	-5367943.3175	3437427.4965	-225861.3266	0.0001	0.0004	0.0003
RM2	-5367952.0122	3437414.1326	-225898.1290	0.0004	0.0004	0.0003
RM3	-5367929.5914	3437449.9536	-225893.9563	0.0004	0.0004	0.0003

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

FROM	To	ΔE	ΔN	ΔU
PNGM	**RM1**	3.6069	24.4255	-2.7641
PNGM	**RM2**	19.5499	-12.3494	-1.3368
PNGM	**RM3**	-22.7070	-8.1639	-1.0499

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 ΔE, ΔN and ΔU. 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
2002	**PNGM**	**RM1**	3.6069	24.4257	-2.7622
2003	**PNGM**	**RM1**	3.6069	24.4258	-2.7625
2006	**PNGM**	**RM1**	3.6069	24.4258	-2.7647
2007	**PNGM**	**RM1**	3.6070	24.4261	-2.7638
2009	**PNGM**	**RM1**	3.6070	24.4264	-2.7638
2010	**PNGM**	**RM1**	3.607	24.4263	-2.7637
2014	**PNGM**	**RM1**	3.6069	24.4254	-2.764
2019	**PNGM**	**RM1**	3.6069	24.4255	-2.7641
Ref RL	**(as at 2014)**		**3.6069**	**24.4259**	**-2.7635**

YEAR	FROM	To	ΔE	ΔN	ΔU
2002	**PNGM**	**RM2**	19.5514	-12.3486	-1.3352
2003	**PNGM**	**RM2**	19.5498	-12.3496	-1.3355
2006	**PNGM**	**RM2**	19.5495	-12.3497	-1.3376
2007	**PNGM**	**RM2**	19.5502	-12.3502	-1.3367

2009	**PNGM**	**RM2**	19.5499	-12.3492	-1.3367
2010	**PNGM**	**RM2**	19.549	-12.351	-1.3366
2014	**PNGM**	**RM2**	19.5498	-12.3495	-1.337
2019	**PNGM**	**RM2**	19.5499	-12.3494	-1.3368
Ref RL	**(as at 2014)**		**19.5499**	**-12.3497**	**-1.3365**

YEAR	FROM	To	ΔE	ΔN	ΔU
2002	**PNGM**	**RM3**	-22.7066	-8.1649	-1.0484
2003	**PNGM**	**RM3**	-22.7068	-8.1633	-1.0482
2006	**PNGM**	**RM3**	-22.707	-8.1634	-1.0507
2007	**PNGM**	**RM3**	-22.7076	-8.1632	-1.0500
2009	**PNGM**	**RM3**	-22.7072	-8.1632	-1.0499
2010	**PNGM**	**RM3**	-22.7085	-8.1633	-1.0505
2014	**PNGM**	**RM3**	-22.7069	-8.1634	-1.0500
2019	**PNGM**	**RM3**	-22.7070	-8.1639	-1.0499
Ref RL	**(as at 2014)**		**-22.7072**	**-8.1635**	**-1.0497**

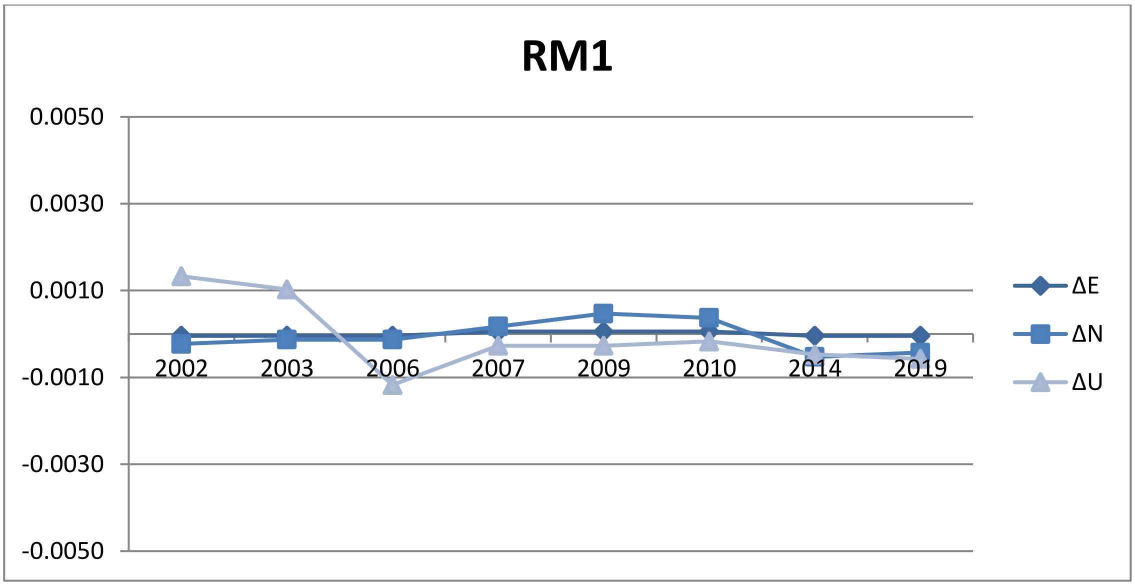

Figure 4.4.1 Time series of RM1 movement relative to GNSS pillar (0 = REF pre 2014 mean).

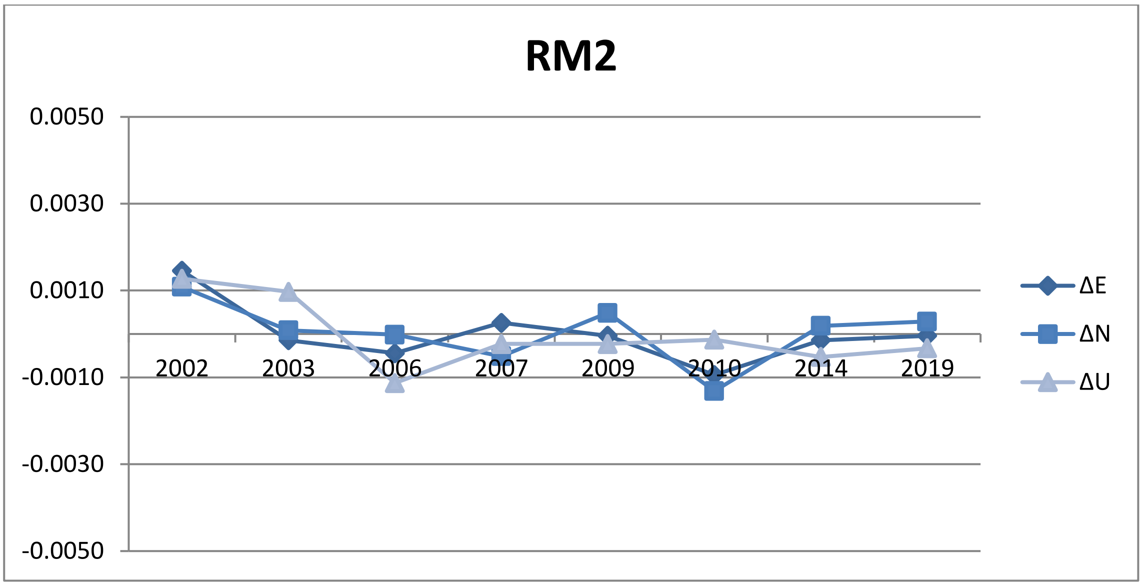

Figure 4.4.2 Time series of RM2 movement relative to GNSS pillar (0 = REF pre 2014 mean).

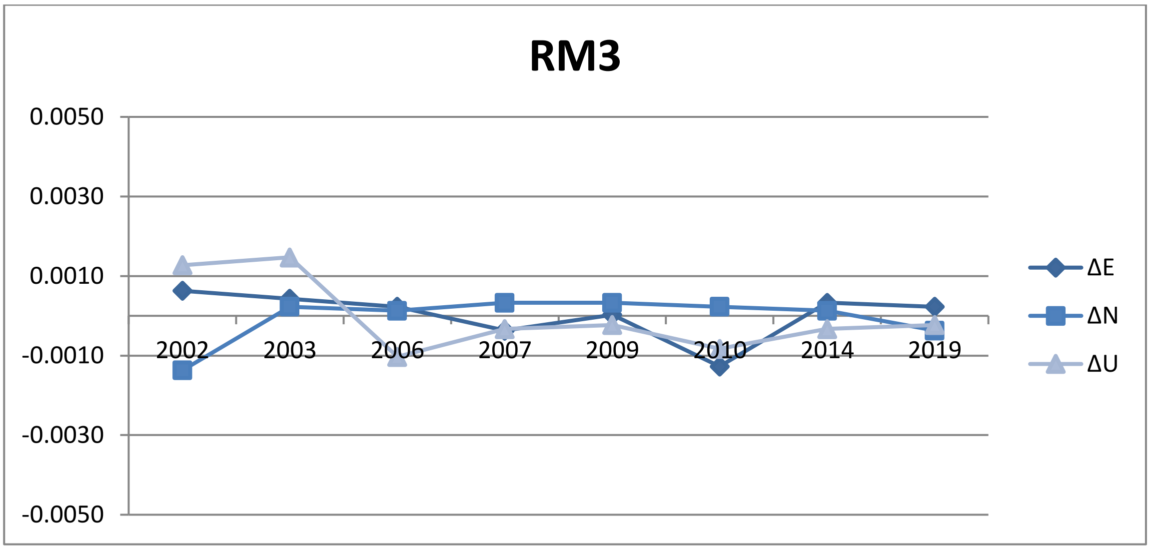

Figure 4.4.3 Time series of RM3 movement relative to GNSS pillar (0 = REF pre 2014 mean).

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 Manus Island 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
PNGM (Ellipsoidal ht)	116.3385	Observed RL at the ARP of PNGM (Ellipsoidal) @2019.20
PNGM - PNGMBM	-0.9612	Offset constant between BM at GNSS pillar plate
Primary Pole & 1/2m Pole	1.00064	Height difference between poles used (Calibrated March 2019)
Primary Pole & TG Pole	1.42979	Height difference between poles used (Calibrated March 2019)

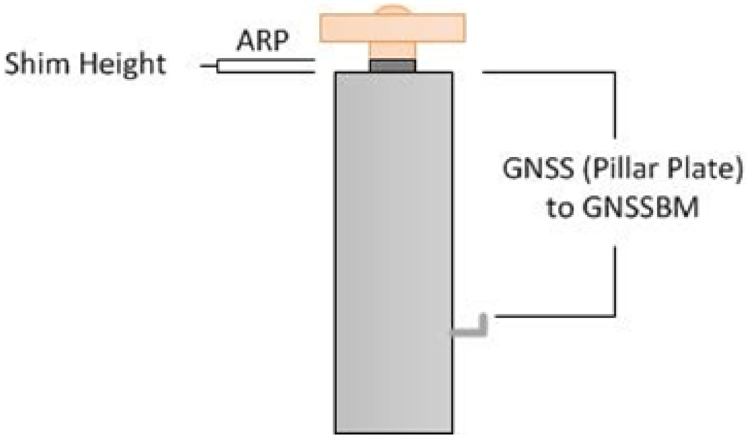

Figure 5.2.1 GNSS Pillar Offsets

5.3 Data Analysis and Results

Reduction of the digital data was computed using the Geoscience Australia levelling program “levelingFIELD_3.pl” and “leveling1.exe”. 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 input levelling loop.

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

Table 5.3.1 Reduced level data – PNGM (GNSS CORS) to PNG1 (Primary Benchmark)

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
PNGM				0.9612		
PNGMBM	**PNGMBM**	0.0000	-0.9612	0.0000	0.000	0.000
PNG31	**PNG31**	0.0000	-4.5808	-4.5808	0.072	0.072
PNG3	**PNG3**	1.0391	0.0000	-3.5417	0.175	0.247
102	**102**	0.0000	-8.0286	-11.5703	0.181	0.428
105	**105**	0.0000	-18.0965	-29.6667	0.214	0.643
106	**106**	0.0000	-3.1683	-32.8350	0.104	0.746
PNG1	**PNG1**	0.0000	-2.5546	-35.3896	0.167	0.914
106	**106**	2.5543	0.0000	-32.8353	0.165	
105	**105**	3.1681	0.0000	-29.6672	0.104	
102	**102**	18.0968	0.0000	-11.5704	0.215	
PNG3	**PNG3**	8.0289	0.0000	-3.5415	0.182	
PNG31	**PNG31**	0.0000	-1.0394	-4.5809	0.175	
PNGMBM	**PNGMBM**	4.5808	0.0000	-0.0001	0.074	
PNGM	**PNGM**	0.9612	0.0000	0.9611	0.000	
	Sum:	38.4291	-38.4292			
	Misclose:		-0.0001	-0.0001	1.827	(Total Dist.)
			ALLOWABLE (m):	**0.0019**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.2 Reduced level data – PNG1 (Primary BM) to PNG14 (Tide Gauge Sensor Benchmark)

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
PNG1				-35.3896	0.000	0.914
PNG107	**PNG107**	0.9241	0.0000	-34.4655	0.152	1.065
PNG14	**PNG14**	1.3569	0.0000	-33.1086	0.003	1.069
PNG107	**PNG107**	0.0000	-1.3569	-34.4655	0.003	
PNG1	**PNG1**	0.0000	-0.9241	-35.3896	0.152	
	Sum:	2.2810	-2.2810			
	Misclose:		0.0000	0.0000	0.310	(Total Dist.)
			ALLOWABLE (m):	**0.0008**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.3 Reduced level data – PNG1 (Primary Benchmark) to PNG2

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
PNG1				-35.3896		0.914
104	**104**	0.5162	0.0000	-34.8734	0.191	1.105
PNG2	**PNG2**	0.0000	-0.3190	-35.1924	0.0749	1.18
104	**104**	0.3189	0.0000	-34.8735	0.0749	
	PNG1	0.0000	-0.5166	-35.3901	0.1932	
	Sum:	0.8350	-0.8355			
	Misclose:		-0.0005	0.0005	0.266	(Total Dist.)
			ALLOWABLE (m):	**0.0007**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.4 Measured height differences (in metres) between all BMs (ΔRL$_{2019}$)

	PNGMBM	PNG31	PNG3	PNG1	PNG107	PNG14	PNG2	RM1	RM2	RM3	PNGM
PNGMBM	-	-4.5808	-3.5416	-35.3896	-34.4655	-33.1086	-35.1924	-1.8025	-0.3759	-0.0886	0.9612
PNG31	4.5808	-	1.0392	-30.8088	-29.8846	-28.5278	-30.6116	2.7783	4.2049	4.4922	5.5420
PNG3	3.5416	-1.0392	-	-31.8480	-30.9238	-29.5670	-31.6508	1.7391	3.1657	3.4530	4.5028
PNG1	35.3896	30.8088	31.8480	-	0.9241	2.2810	0.1972	33.5871	35.0137	35.3010	36.3508
PNG107	34.4655	29.8846	30.9238	-0.9241	-	1.3569	-0.7269	32.6630	34.0896	34.3768	35.4267
PNG14	33.1086	28.5278	29.5670	-2.2810	-1.3569	-	-2.0838	31.3061	32.7327	33.0200	34.0698
PNG2	35.1924	30.6116	31.6508	-0.1972	0.7269	2.0838	-	33.3899	34.8165	35.1038	36.1536
RM1	1.8025	-2.7783	-1.7391	-33.5871	-32.6630	-31.3061	-33.3899	-	1.4266	1.7139	2.7637
RM2	0.3759	-4.2049	-3.1657	-35.0137	-34.0896	-32.7327	-34.8165	-1.4266	-	0.2873	1.3371
RM3	0.0886	-4.4922	-3.4530	-35.3010	-34.3768	-33.0200	-35.1038	-1.7139	-0.2873	-	1.0498
PNGM	-0.9612	-5.5420	-4.5028	-36.3508	-35.4267	-34.0698	-36.1536	-2.7637	-1.3371	-1.0498	-

Table 5.3.5 Time-series of Reduced Levels (with respect to PNGMBM).

YEAR	PNGMBM	PNG31	PNG3	PNG1	PNG107	PNG14	PNG2	RM1	RM2	RM3	PNGM
2002.4	0.000	-4.5813	-3.5406	-35.3874		-33.1067	-35.1853				0.0000
2003.7	0.000	-4.5805	-3.5430	-35.3899		-33.1102	-35.1926				0.0000
2006.1	0.000	-4.5808	-3.5410	-35.3888		-33.1072					0.0000
2006.1	0.000	-4.5812	-3.5416	-35.3907		-33.1098					0.0000
2007.7	0.000	-4.5805	-3.5409	-35.3896		-33.1092	-35.1924	-1.8026	-0.3755	-0.0888	0.0000
2009.5	0.000	-4.5807	-3.5404	-35.3880		-33.1067	-35.1908	-1.8026	-0.3755	-0.0886	0.0000
2010.9	0.000	-4.5819	-3.5392	-35.3864		-33.1050	-35.1888	-1.8027	-0.3755	-0.0893	0.0000
2012.6	0.000	-4.5793	-3.5419	-35.3906		-33.1103	-35.1937	-1.8069	-0.3797	-0.0936	0.0000
2014.3	0.000	-4.5812	-3.5414	-35.3894		-33.1087	-35.1913	-1.8027	-0.3758	-0.0888	0.9612
2015.9	0.000	-4.5815	-3.5393	-35.3859		-33.1055	-35.1880	-1.8024	-0.3753	-0.0889	0.9612
2017.3	0.000	-4.5796	-3.5425	-35.3916	-34.4672	-33.1117	-35.1940	-1.8022	-0.3757	-0.0884	0.9612
2019.2	0.000	-4.5808	-3.5416	-35.3896	-34.4655	-33.1086	-35.1924	-1.8025	-0.3759	-0.0886	0.9612

5.4 Comparison with previous surveys

All historic data has been readjusted relative to the benchmark attached to the base of the GNSS pillar (PNGMBM) (Table 5.3.5). To investigate whether BMs have moved over time, the RLs from the 2019 survey (RL_{2019}) 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 ΔRL_{REF} - ΔRL_{2019} values (in metres). Shows the difference in height between two marks from the current survey compared to the reference height difference.

REF - 2019	PNGMBM	PNG31	PNG3	PNG1	PNG107	PNG14	PNG2	RM1	RM2	RM3	PNGM
PNGMBM	-	-0.0001	0.0005	0.0003	-0.0018	0.0000	0.0009	-0.0001	0.0003	-0.0002	0.0000
PNG31	0.0001	-	0.0006	0.0005	-0.0016	0.0001	0.0011	0.0001	0.0005	-0.0001	0.0001
PNG3	-0.0005	-0.0006	-	-0.0001	-0.0023	-0.0005	0.0004	-0.0006	-0.0001	-0.0007	-0.0005
PNG1	-0.0003	-0.0005	0.0001	-	-0.0021	-0.0004	0.0006	-0.0004	0.0000	-0.0005	-0.0003
PNG107	0.0018	0.0016	0.0023	0.0021	-	0.0018	0.0027	0.0017	0.0021	0.0016	0.0018
PNG14	0.0000	-0.0001	0.0005	0.0004	-0.0018	-	0.0010	-0.0001	0.0004	-0.0002	0.0000
PNG2	-0.0009	-0.0011	-0.0004	-0.0006	-0.0027	-0.0010	-	-0.0010	-0.0006	-0.0011	-0.0009
RM1	0.0001	-0.0001	0.0006	0.0004	-0.0017	0.0001	0.0010	-	0.0004	-0.0001	0.0001
RM2	-0.0003	-0.0005	0.0001	0.0000	-0.0021	-0.0004	0.0006	-0.0004	-	-0.0005	-0.0003
RM3	0.0002	0.0001	0.0007	0.0005	-0.0016	0.0002	0.0011	0.0001	0.0005	-	0.0002
PNGM	0.0000	-0.0001	0.0005	0.0003	-0.0018	0.0000	0.0009	-0.0001	0.0003	-0.0002	-

Table 5.4.1.1 values are calculated by subtracting the difference in height between RL_{2019} values (Table 5.3.4) 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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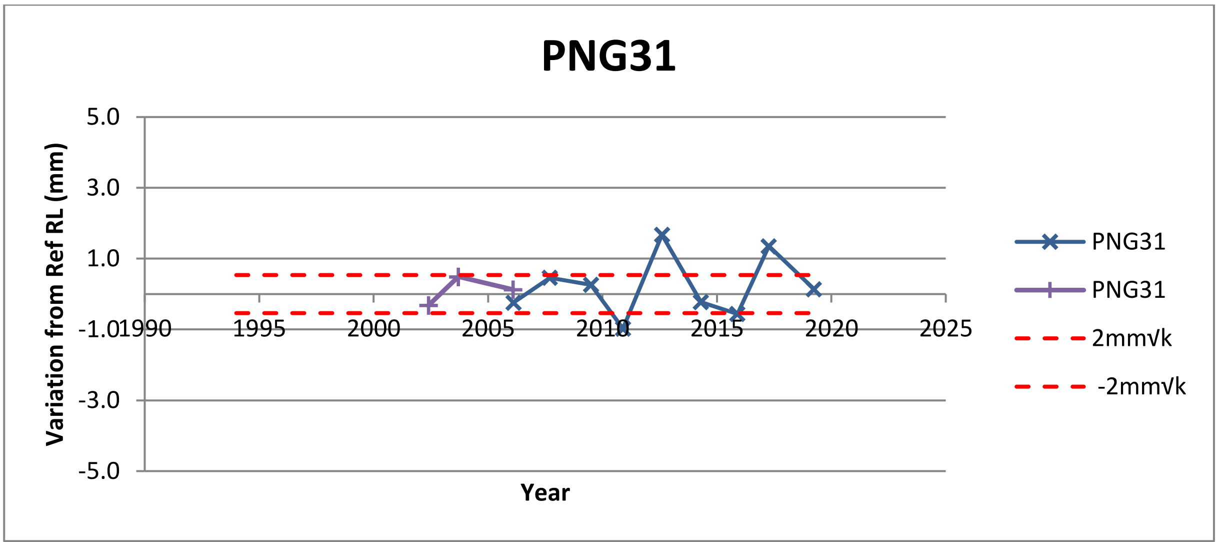
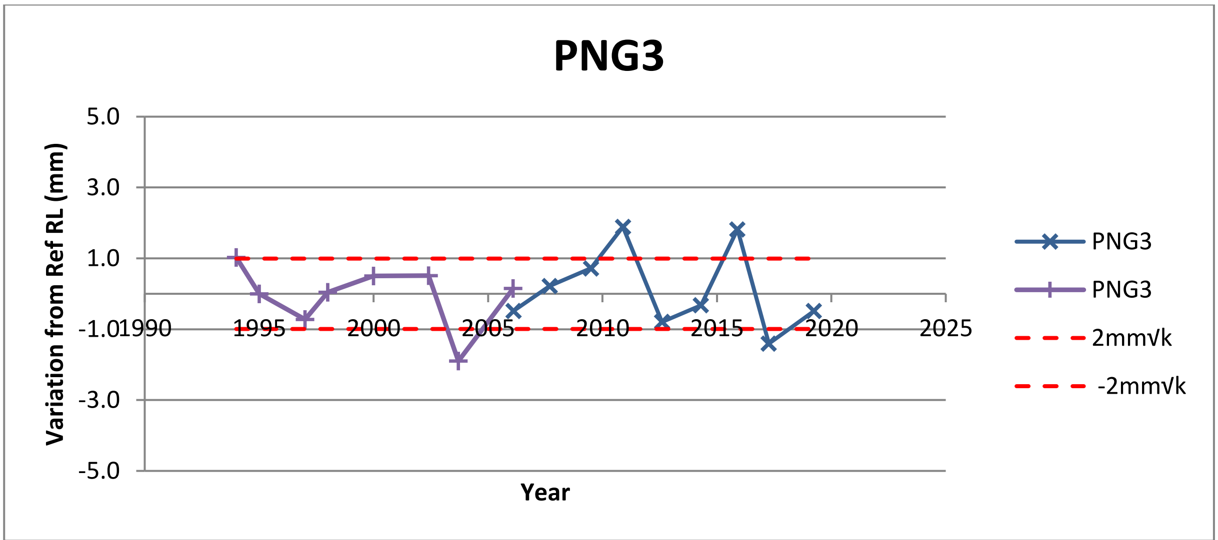
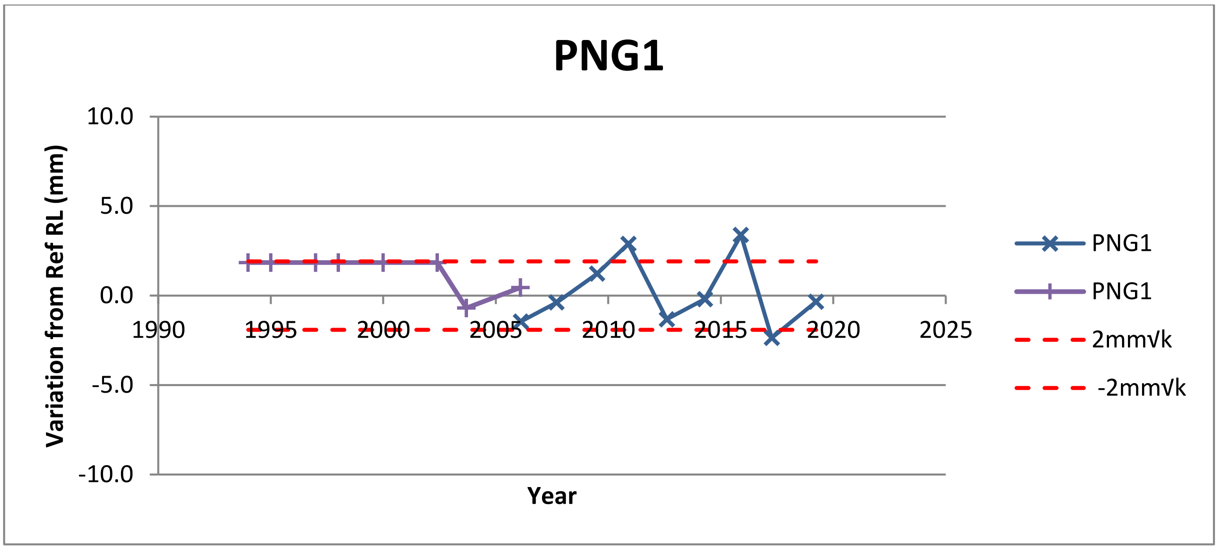
5.4.2 Time Series Charts for each BM

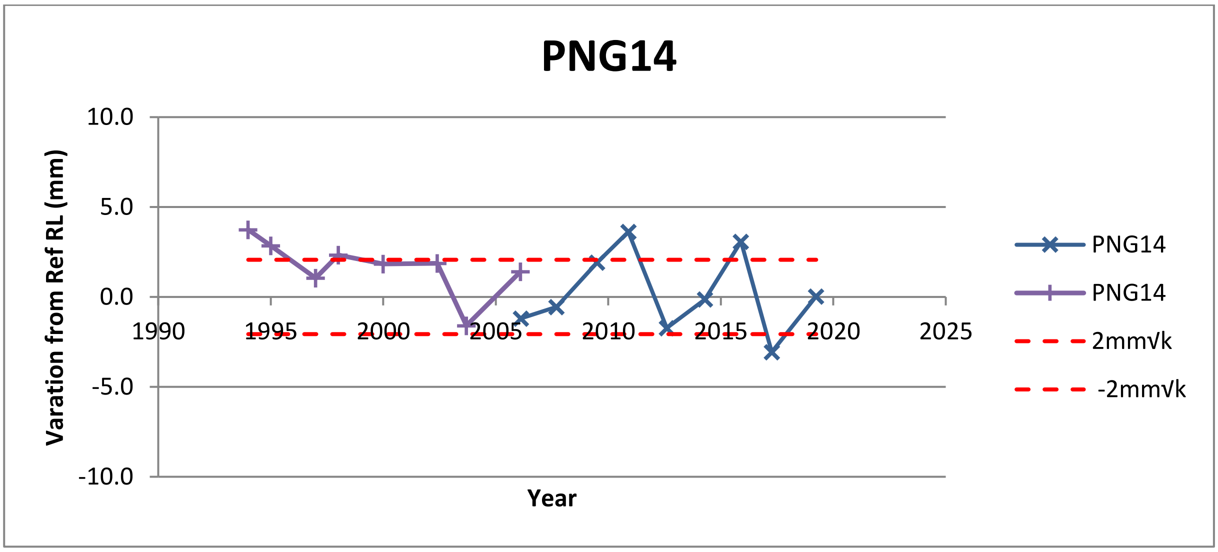
The change in RL over time can be used to detect trends of movement or survey errors. In the series of figures below, the red dashed lines represent the allowable error in height based on the levelling technique used and distance of the benchmark from the GNSS pillar ($2mm\sqrt{K}$). The purple line (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.



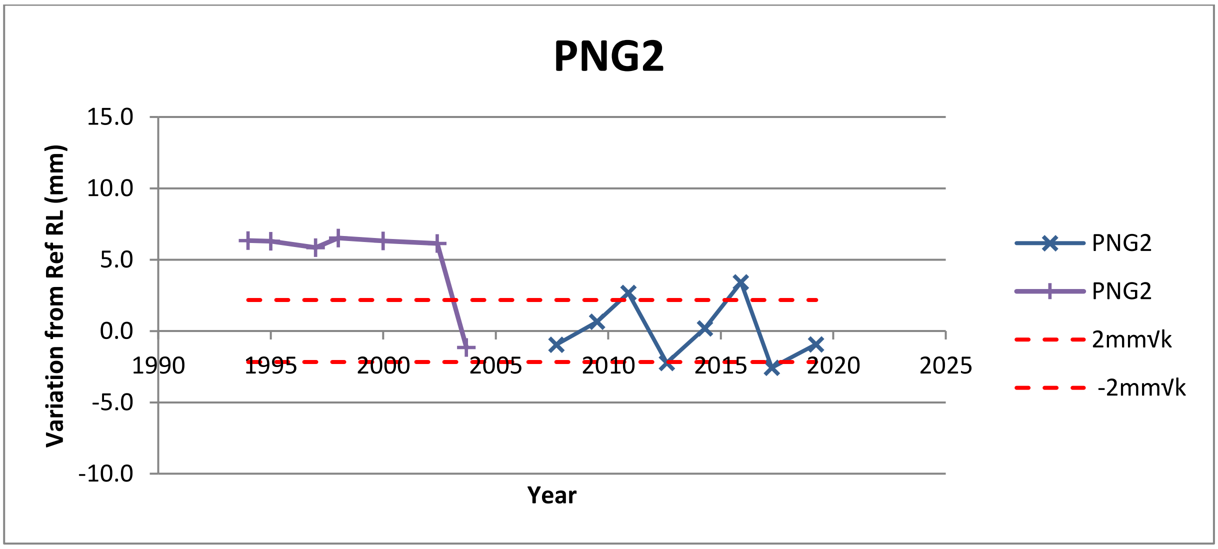




PNG1
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
2025
Variation from Ref RL (mm)
Year
PNG1
PNG1
2mm√k
-2mm√k



PNG14
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
2025
Varation from Ref RL (mm)
Year
PNG14
PNG14
2mm√k
-2mm√k



PNG2
15.0
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
2025
Variation from Ref RL (mm)
Year
PNG2
PNG2
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:

The survey from the primary GNSS BM (PNGMBM) to the TG Plaque (PNG107) shows no statistically significant change in height. This means the wharf structure is still solid, and any movement measured on the tide gauge is not due to deformation at the jetty.

The survey from the primary GNSS BM (PNGMBM) to the TG Ref Pin (PNG14) show that the tide gauge is stable, and no deformation has occurred since the previous survey.

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

PT ID	Reference ^H (m)	2019.24 Value (m)	Difference
PNGMBM - Primary BM (PNG1)	-35.3892	-35.3896	0.0003
PNG1 - TG Plaque BM (PNG107)	0.9220	0.9241	0.0021
PNG1 - TG ref pin (PNG14)	2.2806	2.2810	0.0004
PNGMBM - PNG1	-35.3892	-35.3896	0.0003
PNG1 - PNG107	0.9220	0.9241	0.0021
PNG107 - PNG14	1.3586	1.3569	-0.0018
PNGM - TG Plaque	-35.4284	-35.4267	-0.0018
PNGM - TG BM	-34.0698	-34.0698	0.0000

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

PT ID	Reference RL (m)	2019.24 Value (m)	Difference	TGZ	ITRF2020
PNGMBM	0.000	0.000	0.0000	37.6899	115.3773
PNG31	-4.5810	-4.5808	0.0001	33.1091	110.7963
PNG3	-3.5411	-3.5416	-0.0005	34.1483	111.8362
PNG1	-35.3892	-35.3896	-0.0003	2.3003	79.9881
PNG107	-34.4672	-34.4655	0.0018	3.2244	80.9101
PNG14	-33.1086	-33.1086	0.0000	4.5813	82.2687
PNG2	-35.1914	-35.1924	-0.0009	2.4975	80.1859

RM1	-1.8026	-1.8025	0.0001	35.8874	113.5747
RM2	-0.3755	-0.3759	-0.0003	37.3140	115.0018
RM3	-0.0888	-0.0886	0.0002	37.6013	115.2885
PNGM	0.9612	0.9612	0.0000	38.6511	116.3385
TGZ	-37.6899	-37.6899	0.0000	0.0000	77.6874

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).

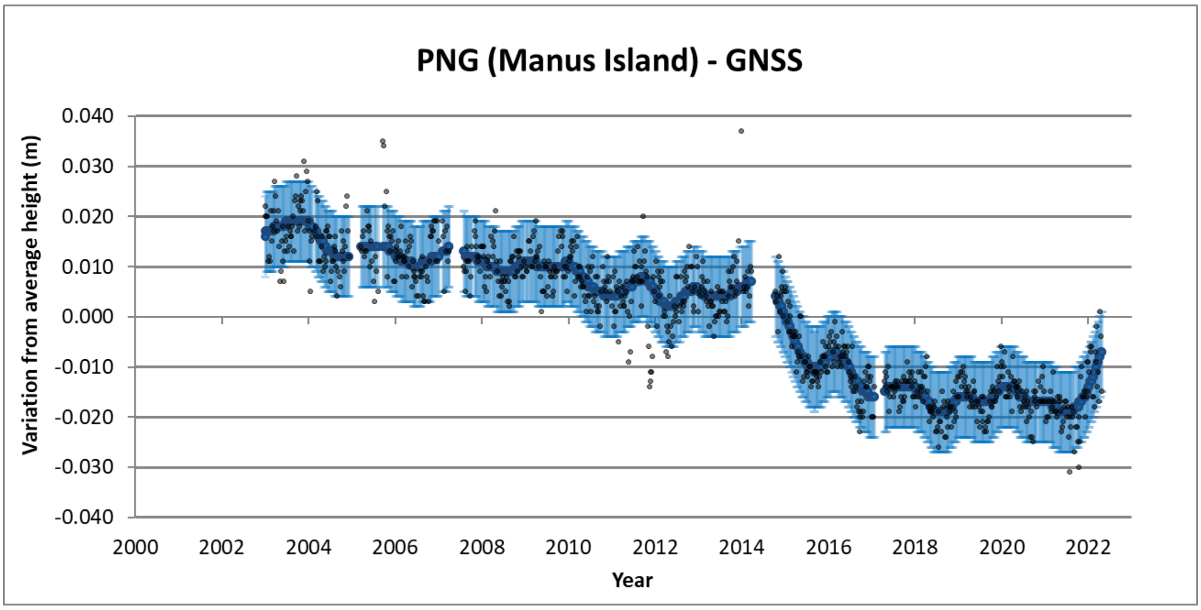


Figure 7.1 Time series of GNSS analysis (dark blue line) with 95%CI uncertainty (light blue lines).

[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.

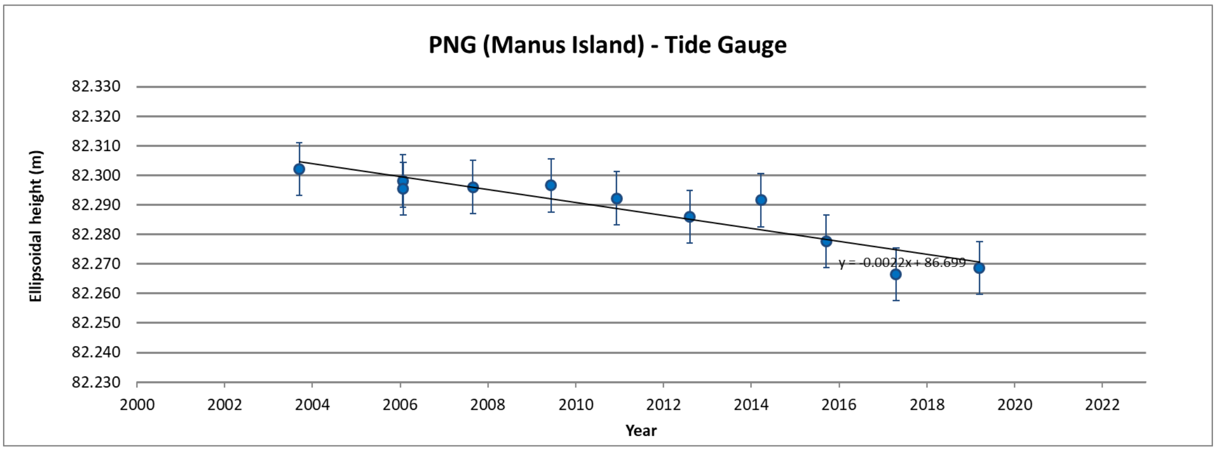


Figure 7.2 The height of the SEAFRAME sensor reference benchmark (with respect to ITRF2020).

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)
2003.70	82.3021	0.009
2006.06	82.2981	0.009
2006.07	82.2955	0.009
2007.66	82.2961	0.009
2009.44	82.2966	0.009
2010.93	82.2923	0.009
2012.60	82.2860	0.009
2014.22	82.2916	0.009
2015.71	82.2777	0.009
2017.30	82.2666	0.009
2019.20	82.2687	0.009

[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 Reference

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

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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

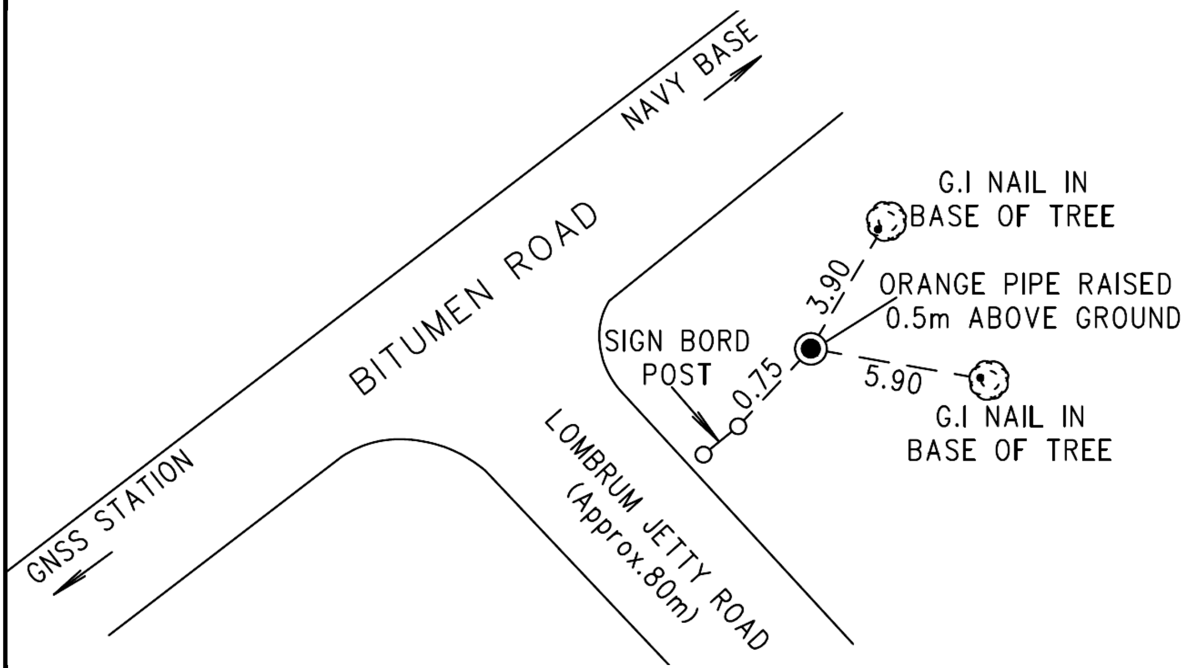
<u>SURVEY BENCH MARK RECORD</u>

Bench Mark Number: PNG1

Original Bench Mark Established by: National Tidal Centre Australia, Oceanographic Services, Bureau of Meteorology, 25 college Rd, Kent Town, SA.	*Date: 26/09/1994*
Existing Bench Mark Established by:	*Date:*
Notes / References: Deep Survey Benchmark This survey mark is not in a good locality for GNSS occupation.	
Country: Papua New Guinea *Island: Manus Island*	*City: Lombrum*

<u>MARKING AND LOCALITY SKETCH</u>

Bench Mark: 4.0m of 19mm diameter stainless steel capped rod driven until refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite, for 0.4m. Top of mark 0.2m below ground level. Locality sketch Mark approximately 150m from the tide gauge station. Not to scale distances in meters & Magnetic bearing



NOT TO SCALE | Distances in Metres | Magnetic Bearings

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

PACIFIC SEA LEVEL MONITORING PROJECT

Australian Government
Geoscience Australia

SPC
Secretariat of the Pacific Community

SURVEY BENCH MARK RECORD

Bench Mark Number: PNG2

Original Bench Mark Established by: National Tidal Centre Australia, Oceanographic Services, Bureau of Meteorology, 25 college Rd, Kent Town, SA.

Date: 26/09/1994

Existing Bench Mark Established by:

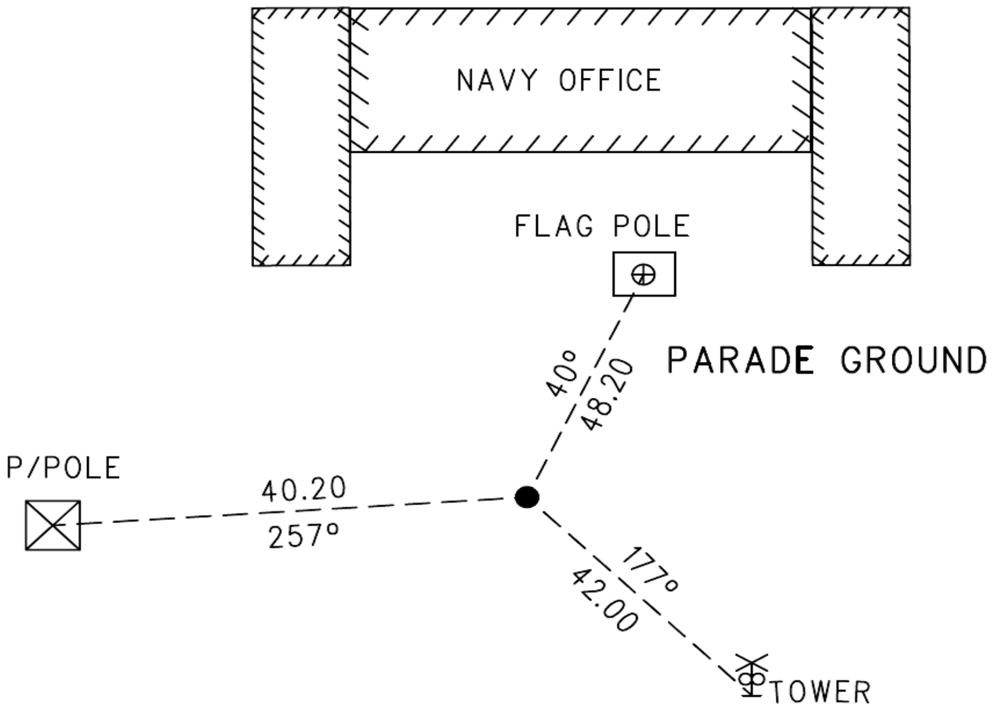
Date:

Notes / References: Deep Survey Benchmark
This survey mark is in a good locality for GNSS occupation

Country: Papua New Guinea
Island: Manus Island
City: Lombrum

MARKING AND LOCALITY SKETCH

Bench Mark: 2.0m of 19mm diameter stainless steel capped rod driven until refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite, for 0.4m, top of mark 0.1m below ground level. Locality sketch Mark approximately 500m from the tide gauge station. Not to scale distances in meters & Magnetic bearing



NOT TO SCALE   Distances in Metres   Magnetic Bearings

Approved by: Geoscience Australia / SPC

Date: April 2008

PACIFIC SEA LEVEL MONITORING PROJECT

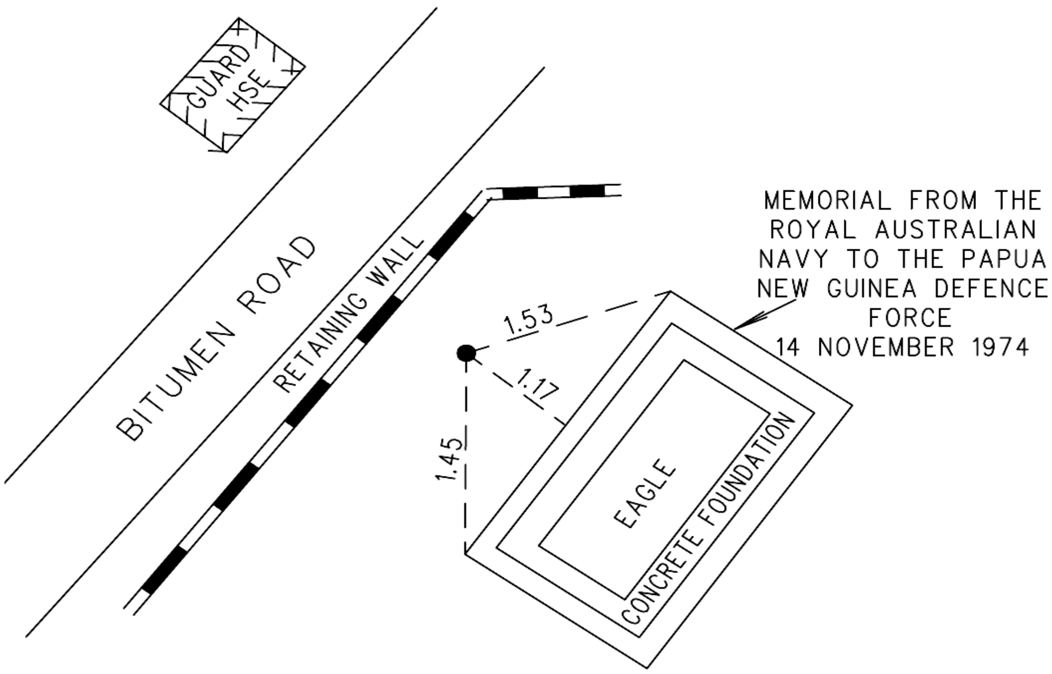
SURVEY BENCH MARK RECORD

Bench Mark Number: PNG3

Original Bench Mark Established by: National Tidal Centre Australia, Oceanographic Services, Bureau of Meteorology, 25 college Rd, Kent Town, SA.	*Date: 27/09/1994*
Existing Bench Mark Established by:	*Date:*
Notes / References: Deep Survey Benchmark This survey mark is in a good locality for GNSS occupation	
Country: Papua New Guinea *Island: Manus Island*	*City: Lombrum*

MARKING AND LOCALITY SKETCH

Bench Mark: 9.1m of 19mm diameter stainless steel capped rod driven until 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 425m from the tide gauge station. Not to scale distances in meters & Magnetic bearing



NOT TO SCALE | Distances in Metres | Magnetic Bearings

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

PACIFIC SEA LEVEL MONITORING PROJECT

SURVEY BENCH MARK RECORD

Bench Mark Number: PNG31

Original Bench Mark Established by: National Tidal Centre Australia, Oceanographic Services, Bureau of Meteorology, 25 college Rd, Kent Town, SA. — *Date: 11/12/2002*

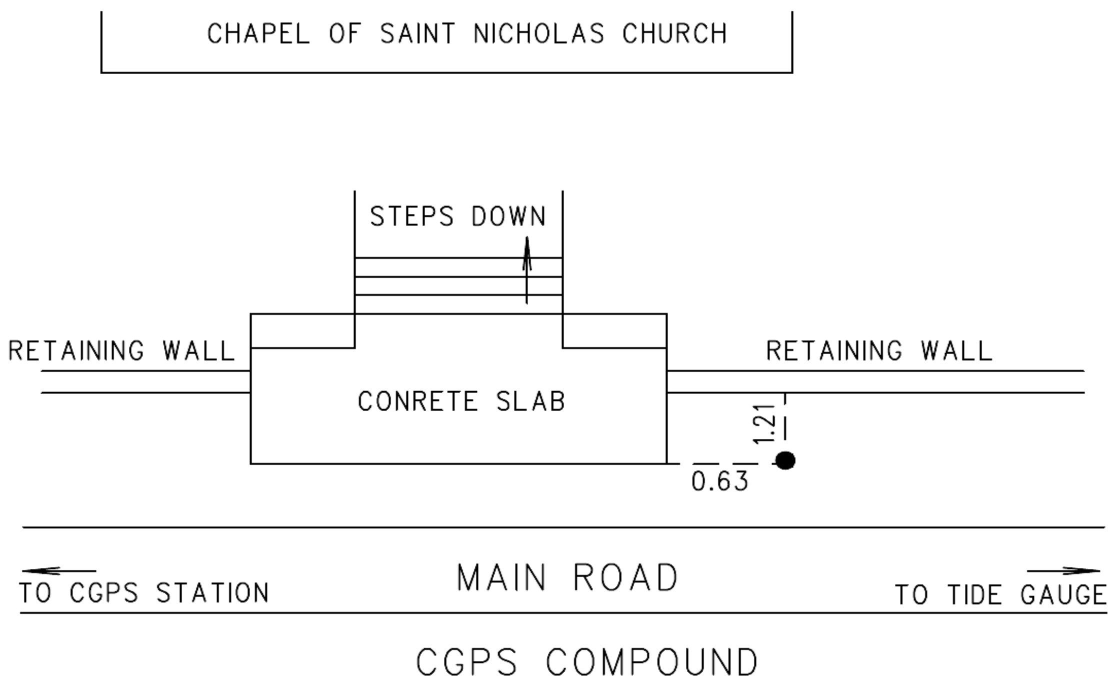
Existing Bench Mark Established by: — *Date:*

Notes / References: Deep Survey Benchmark
This survey mark is in a good locality for GNSS occupation

Country: Federated States of Micronesia
Island: Pohnpei
City: Kolonia

MARKING AND LOCALITY SKETCH

Bench Mark: 19mm diameter stainless steel capped rod driven until refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite, for 0.4m, top of mark 0.2m below ground level. Locality sketch Mark approximately 1000m from the tide gauge station. Not to scale distances in meters & Magnetic bearing

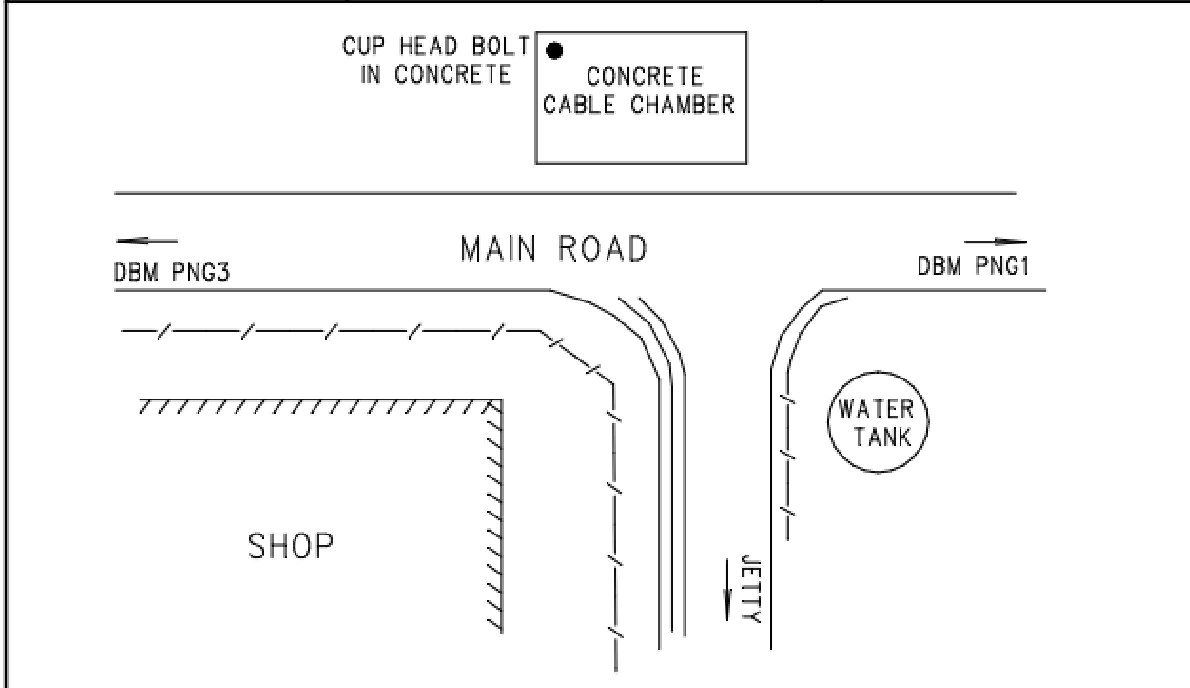


NOT TO SCALE — Distances in Metres — Magnetic Bearings

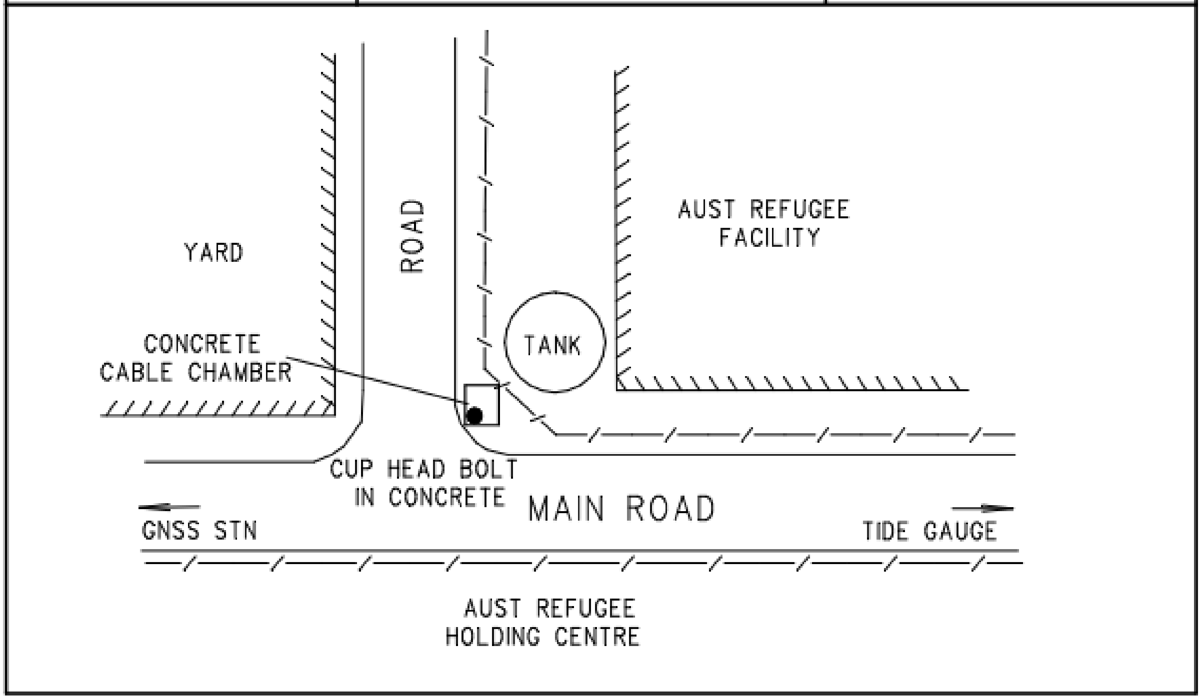
Approved by: Geoscience Australia / SPC — *Date: September 2006*

A 2 Temporary Holdings Marks

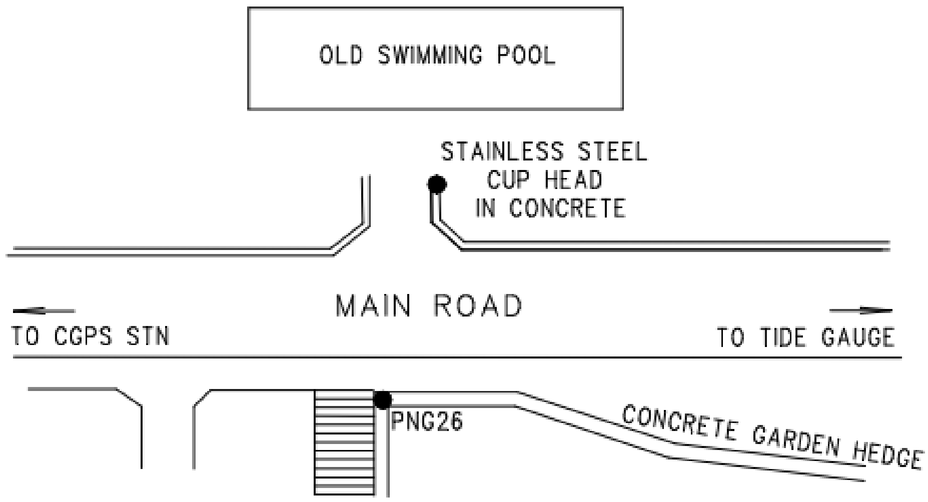
COUNTRY: Papua New Guinea	ISLAND: Manus Is CITY: Lombrum	L. D. P. POINT NO. 105
PROJECT: SPSLCMP	SURVEYOR: S M Turner	DATE:09-04-17



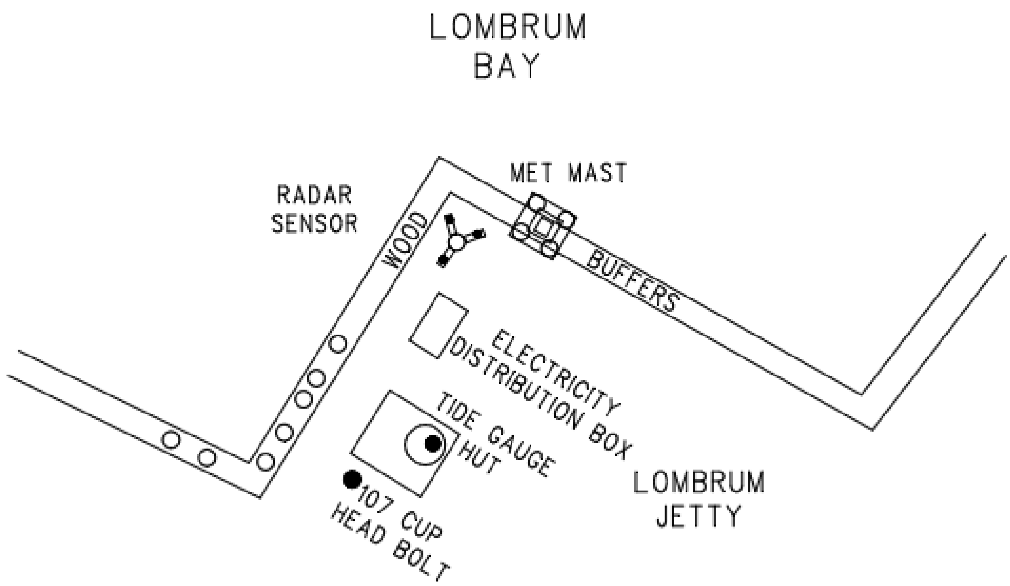
COUNTRY: Papua New Guinea	ISLAND: Manus Is CITY: Lombrum	L. D. P. POINT NO. 106
PROJECT: SPSLCMP	SURVEYOR: M Deo & A Lal	DATE: 09-04-17



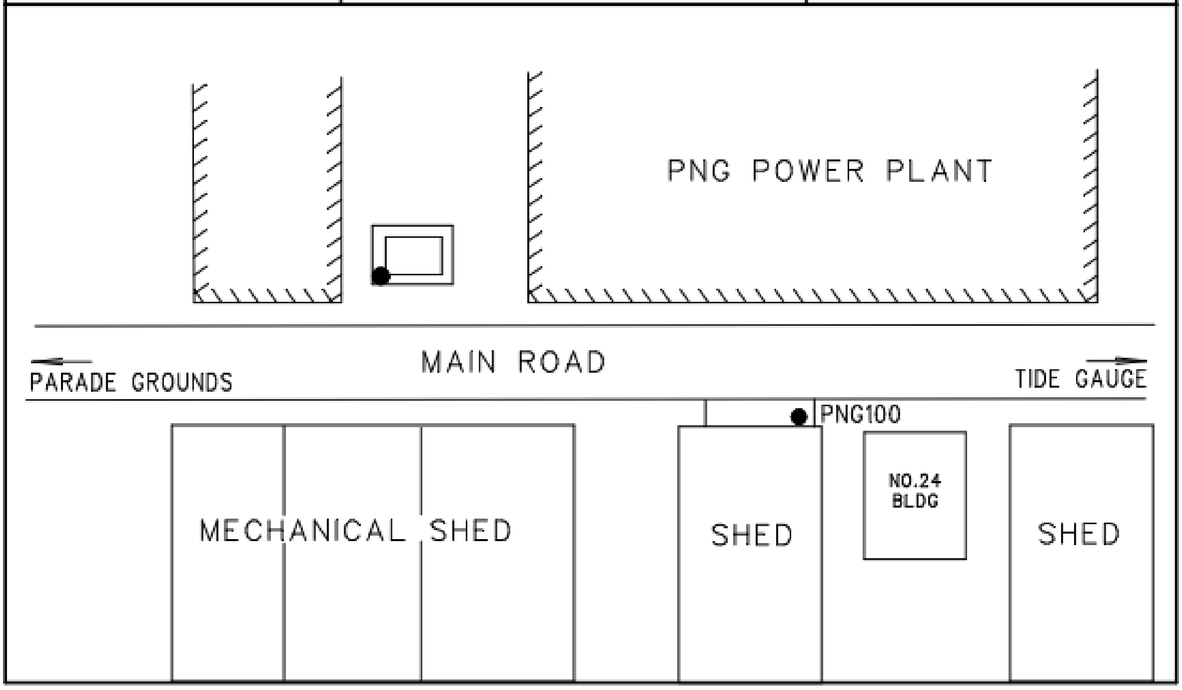
COUNTRY: Papua New Guinea	ISLAND: Manus Is CITY: Lombrum	L. D. P. 892 POINT NO. 102
PROJECT: SPSLCMP	SURVEYOR: AL, MK & VR	DATE: 09-05-02



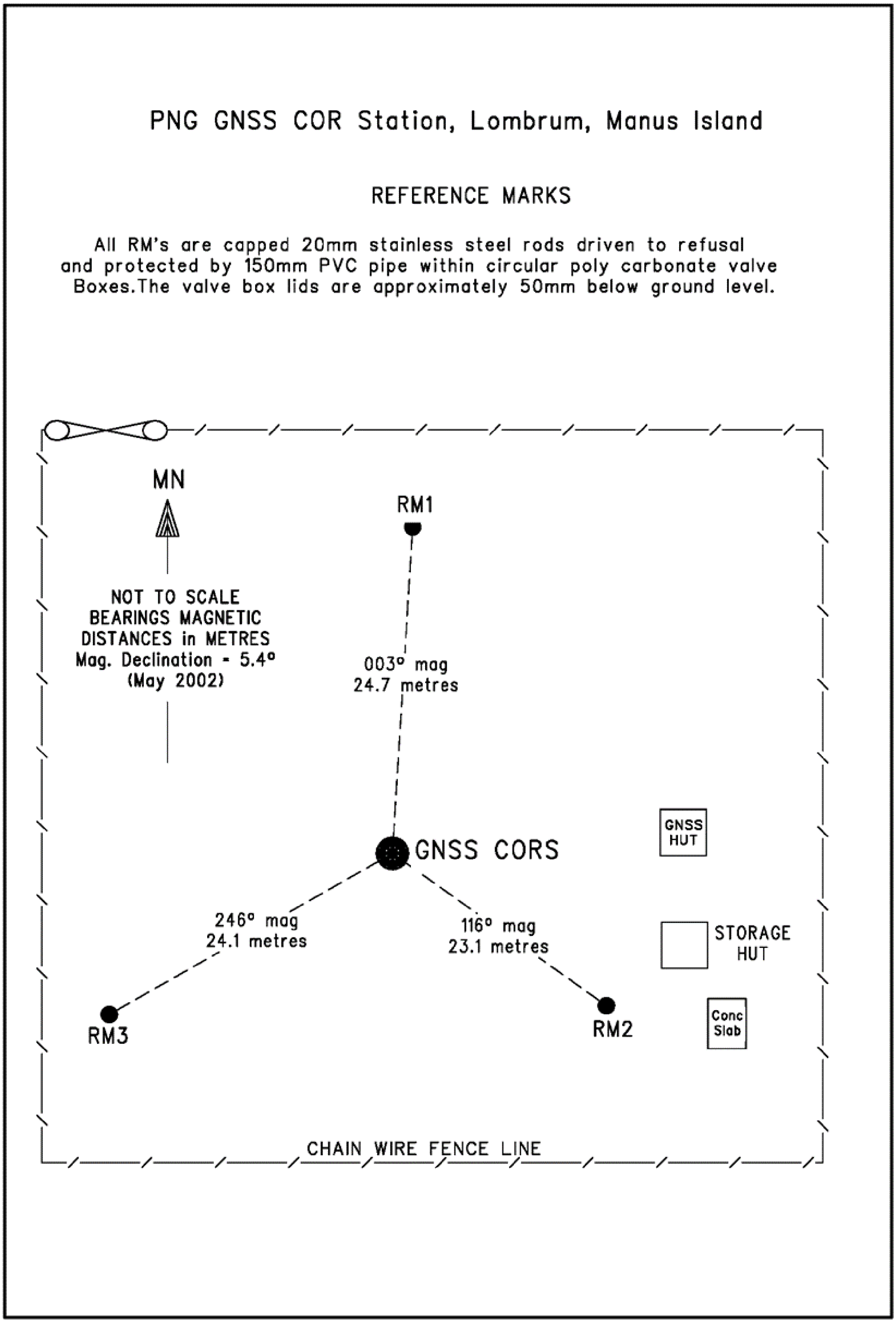
COUNTRY: Papua New Guinea	ISLAND: Manus Is CITY: Lombrum	L. D. P. 805 POINT NO. PNG14&107
PROJECT: SPSLCMP	SURVEYOR: AL, MK & VR	DATE: 10-09-12



COUNTRY: Papua New Guinea	ISLAND: Manus Is CITY: Lombrum	L. D. P. 805 POINT NO. 104
PROJECT: SPSLCMP	SURVEYOR: M.Deo & A Lal	DATE: 09-06-09



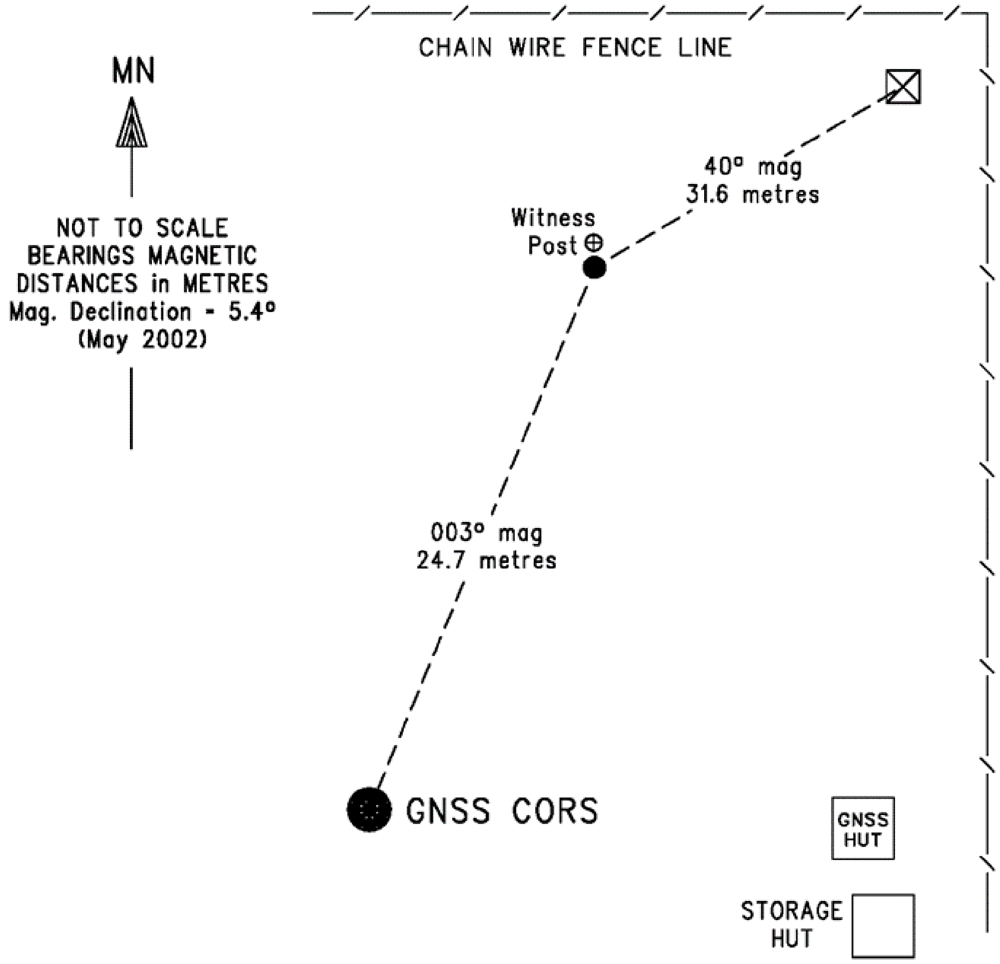
A 3 GNSS Site Reference Marks



PNG GNSS COR Station, Lombrum, Manus Island. - RM 1

REFERENCE MARKS

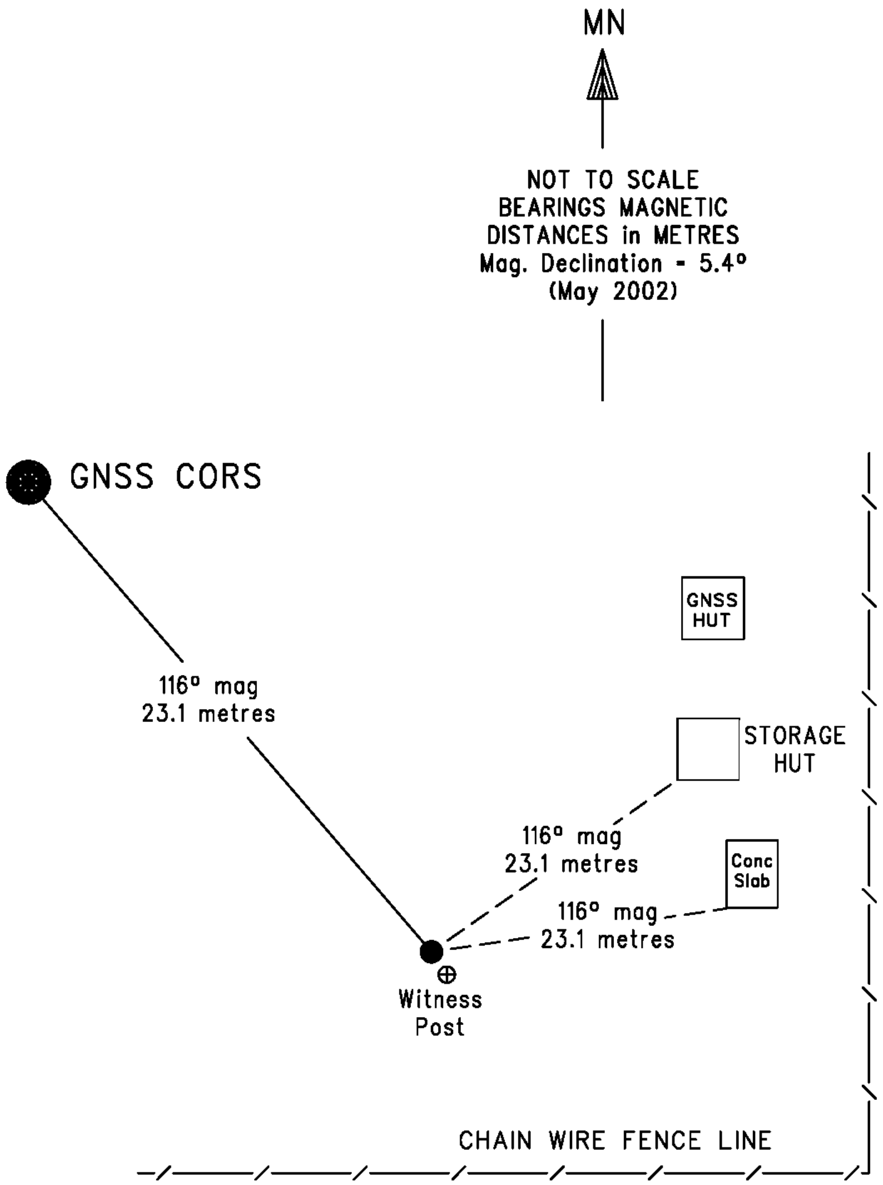
All RM's are capped 20 mm stainless steel rods driven to refusal and protected by 150mm PVC pipe within circular poly carbonate valve Boxes. The valve box lids are approximately 50mm below ground level.



PNG GNSS COR Station, Lombrum, Manus Island. - RM 2

REFERENCE MARKS

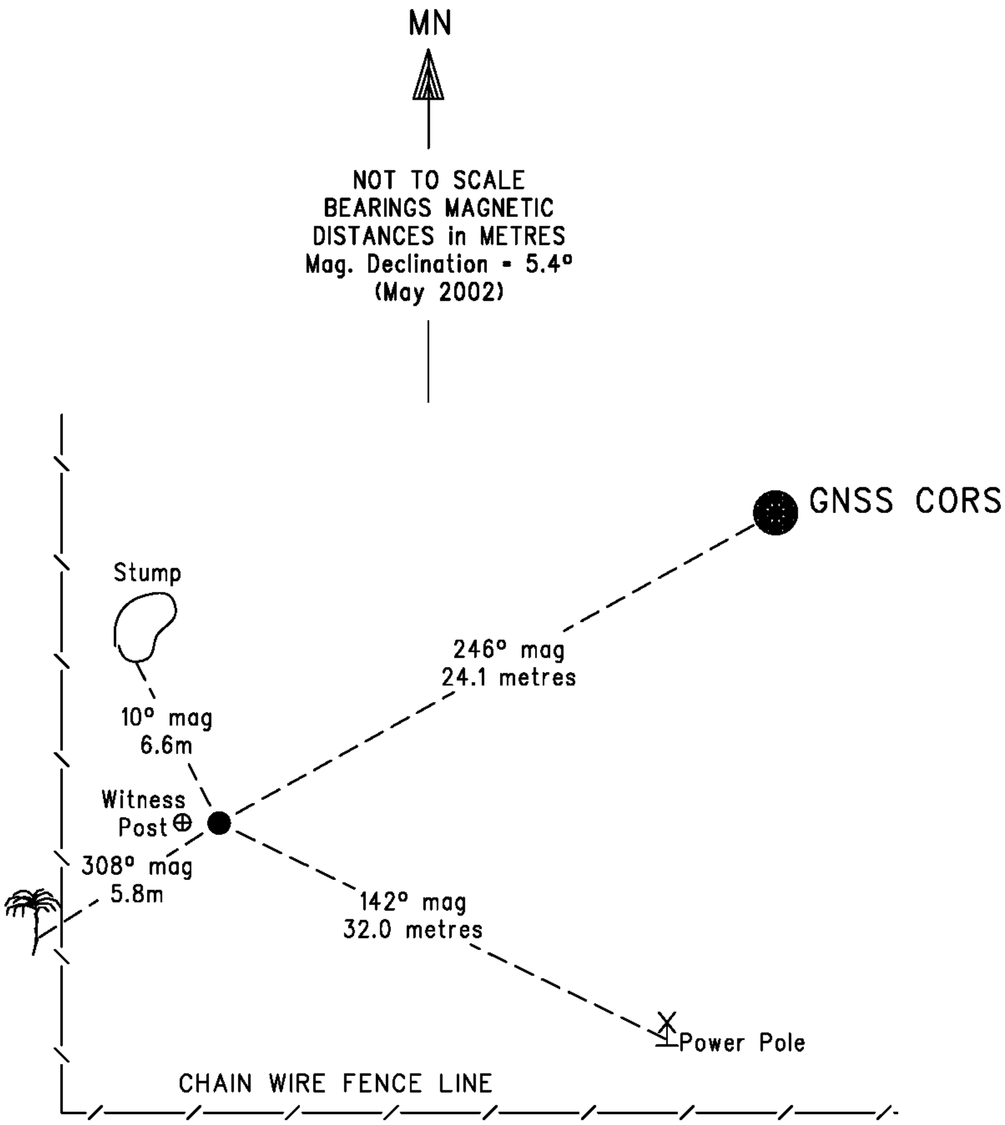
All RM's are capped 20 mm stainless steel rods driven to refusal and protected by 150mm PVC pipe within circular poly carbonate valve Boxes. The valve box lids are approximately 50mm below ground level.



PNG GNSS COR Station, Lombrum, Manus Island. - RM 3

REFERENCE MARKS

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 Manus Island, make contact with the project focal point at the Survey Office and the Weather Office in country at least one month in advance.

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

The Weather office in Manus islands has been very helpful in receiving and storing the equipment until the survey team arrives

DHL Express is commonly used for the delivery of the survey equipment into and out of PNG.

It is now recommended that the survey team to hand carry the two pieces (Total Station with Target Kit) on board the flight and that excess luggage is prepaid from Suva to PNG(Manus) to save freight costs.

The GNSS COR Station and the GNSS Pillar was also cleaned.

The following list of survey equipment is now in the country for future field surveys: -

Quantity	Item & description	Locations
1	**Tool Box**	Tide Gauge Station Hut.
2	*Prism Pole Clamps*	*Tools used by C&M Teams (Bureau & 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 0.44×10^{-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 tribraches.
- 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 bipod 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 1.00117m.

Tripods

Description

Leica GST20 heavy-duty timber tripods with adjustable legs were 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

Description

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

- Trimble NETR9 GNSS receiver (S/N 5041K71030) (firmware: 5.37)
- Trimble Choke Ring antenna (TRM59800.00) - S/N 5038353981