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

Rarotonga, Cook Islands, May 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 monument 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 Rarotonga, Cook Islands from 24th to 31st May 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 Rarotonga, which runs approximately 1.9 km. Previous levelling surveys have been conducted along this route using the Total Station differential levelling technique in 2007, 2008, 2009, 2011, 2012, 2014, 2016 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 Andrick Lal from the Geodetic Survey at SPC and Namanoku Benson from the National Hydrography & Geoscience Division of Ministry of Infrastructure. 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 at Avatiu. The levelling run goes from tide gauge at the Rarotonga wharf along the road up to the GNSS pillar at airport compound.

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2.2 Survey Support

The survey team very much appreciated the assistance from the Senior Manager, National Hydrography & Geoscience of Ministry of Infrastructure who made available their surveyor Mr. Namanoku Benson to assist with survey duties during the survey.

Gratitude also goes to the Mr. Vaipo Mataora, Ministry of Infrastructure and Mr. Arona Ngari, Cook Islands Met services for their continued 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
CKISBM	Reference benchmark in the base of the GNSS CORS pillar
COO10	SEAFRAME project plaque benchmark
COO56	SEAFRAME sensor reference benchmark
BM27	Deep driven benchmark
BM28	Deep driven benchmark
BM33	Deep driven benchmark
BM25	Deep driven benchmark
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,108, 107, 106,104, 103, 77 and BM18.

3.1.1 PSLGMP Vertical Reference Frame Wiring Diagram

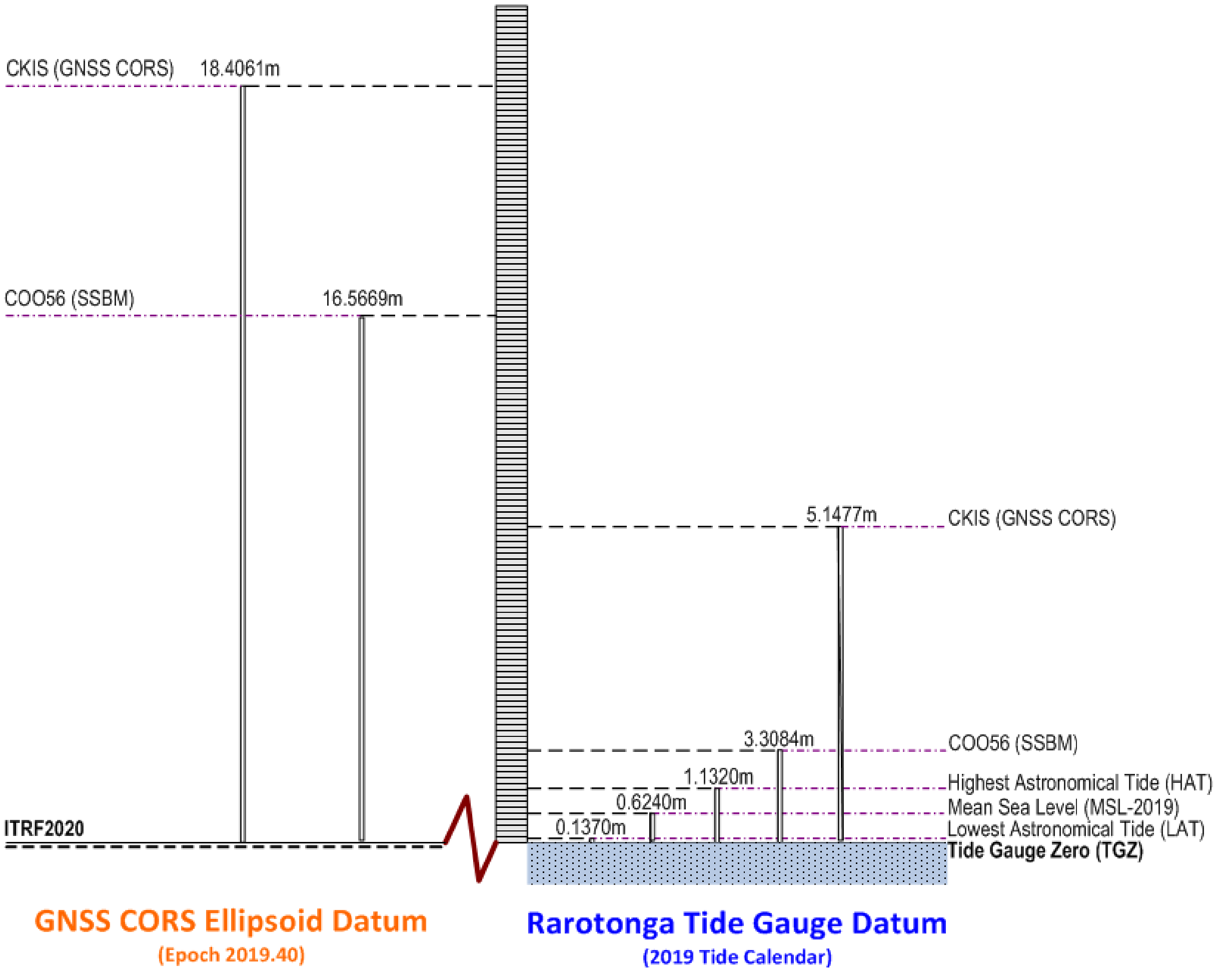

Figure 3.1 Wiring diagram depicting the offsets between surveyed marks. The left-hand side shows the height of the GNSS CORS pillar (CKIS) and SEAFRAME sensor reference benchmark (COO56), with respect to the International Terrestrial Reference Frame 2020 at epoch 2019.40. The right-hand side shows the height of CKIS, COO56, 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)*]

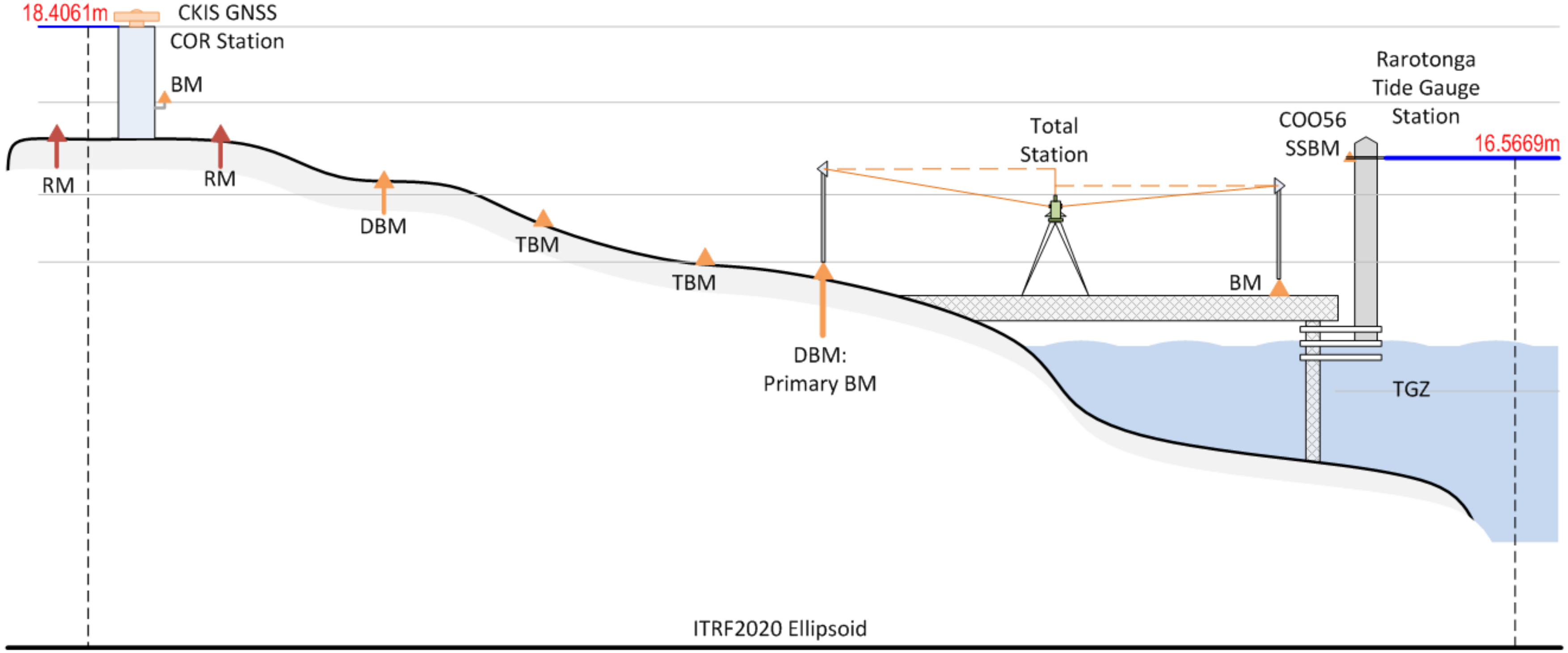

Figure 3.2 Simplified representation of the Total Station differential levelling survey carried out between the GNSS CORS and the SEAFRAME Tide Gauge.

Figure 3.3 Tide Gauge Station at the Rarotonga Wharf. The red circle denotes the location of the SEAFRAME sensor reference benchmark (COO56).

Figure 3.4 GNSS CORS pillar. The red circle denotes the location of the GNSS CORS benchmark (CKISBM).

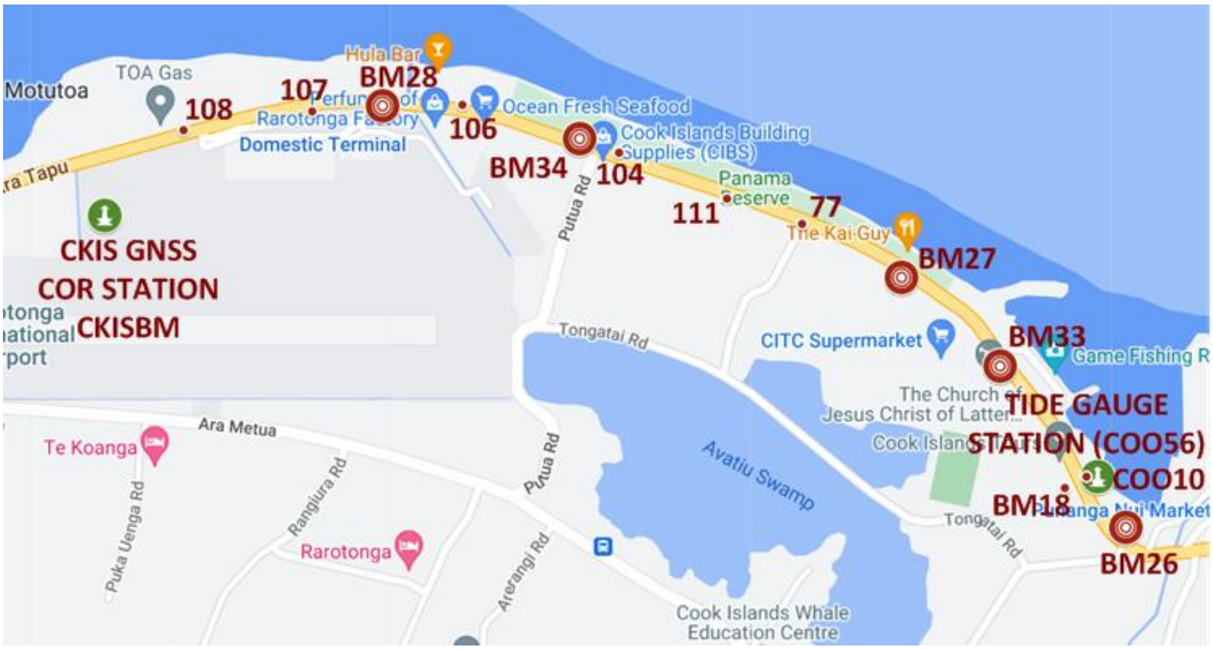

Figure 3.5 Levelling benchmark array. Source: Adopted from Google Maps.

3.1.2 GNSS CORS and Reference Marks

The GNSS CORS site is located within the airport compound. The site consists of a GNSS building to house the technical equipment and a 1.9 m high antenna pillar. The pillar is approximately 40 metres from the GNSS building, access is via arrangement with the airport security, 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.

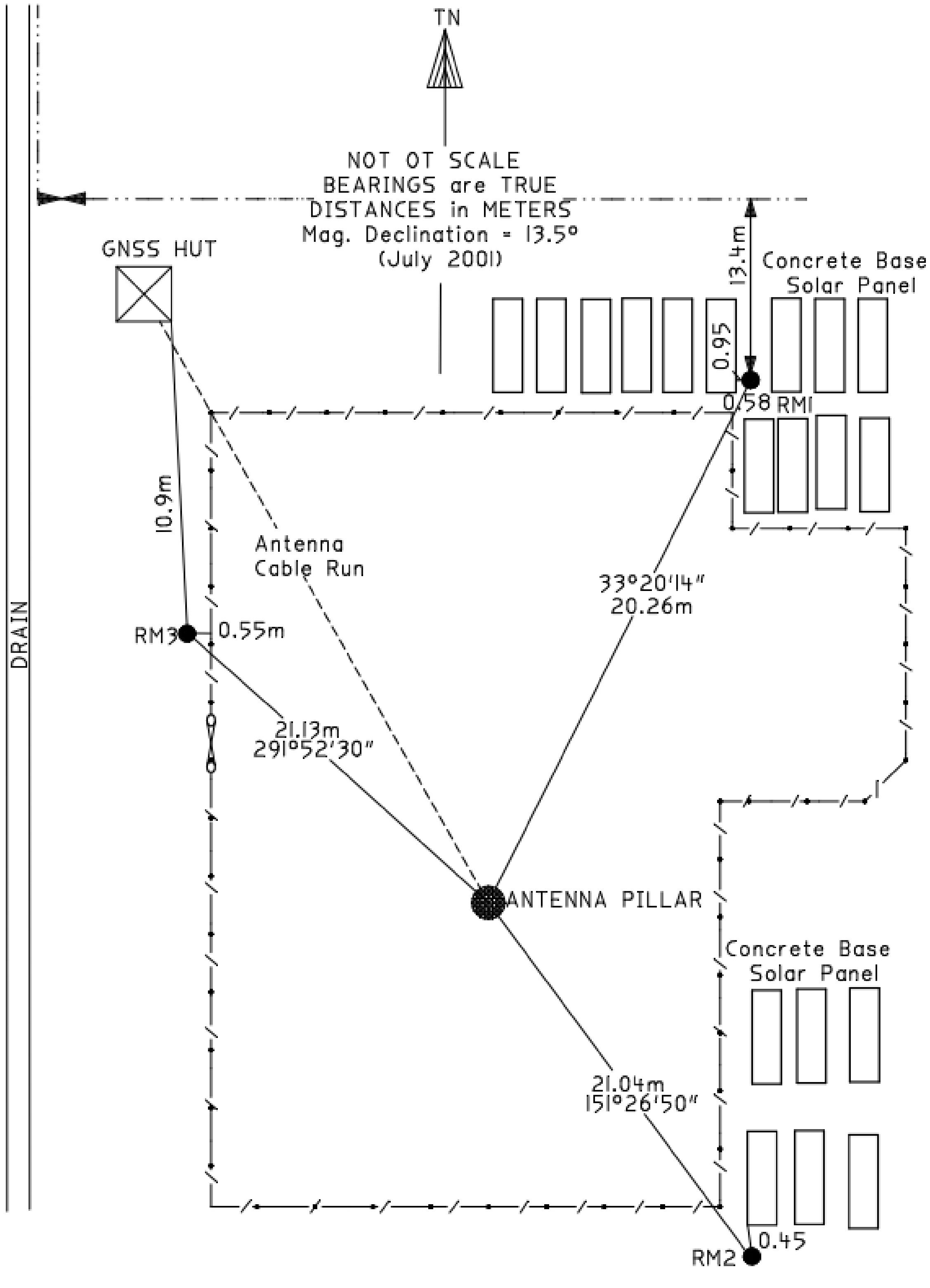

Figure 3.6 GNSS CORS site monitoring survey reference marks.

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 (CKISBM).

3.2.2 Historical Survey Datum

In the past, the adopted reference point for the levelling survey was BM27 fixed at a RL of 4.7407740m. This value was determined by the National Tidal Centre Australia (NTCA) in 1998.

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

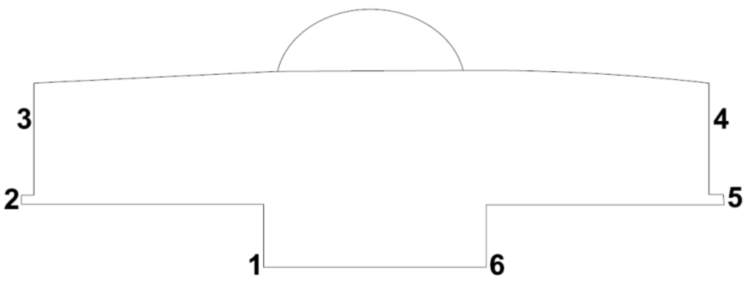

Figure 4.1 Symmetrical points on the antenna profile (TRM59800.00) observed from each RM.

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 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 The Reduced Level (RL) shown is the height relative to CKISBM.

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
CKISBM				0.0000	0.0000	0.0000
RM1	**RM1**	0.0000	-0.6196	-0.6196	0.0200	0.0200
RM2	**RM2**	0.0000	-0.1899	-0.8095	0.0384	0.0586
RM3	**RM3**	0.3629	0.0000	-0.4466	0.0400	0.0980
RM2	**RM2**	0.0000	-0.3631	-0.8097		
RM1	**RM1**	0.18999	0.0000	-0.6197		
	CKISBM	0.6196	0.0000	0.0000		
	Sum:	1.1725	-1.1726			
	Misclose:		0.0000	0.0000	0.198	(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)
CKISBM				0.0000		0.000
RM2	**RM2**	0.0000	-0.8096	-0.8096	0.021	0.021
	CKISBM	0.8096	0.0000	0.0000	0.021	
	Sum:	0.8096	-0.8096			
	Misclose:		0.0000	0.0000	0.042	(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)
CKISBM				0.0000		0.000
RM3	**RM3**	0.0000	-0.4468	-0.4468	0.021	0.021
	CKISBM	0.4467	0.0000	0.0000	0.021	
	Sum:	0.4467	-0.4468			
	Misclose:		0.0000	0.0000	0.043	(Total Dist.)
			ALLOWABLE (m):	**0.0003**	**2 x Sqrt (km) test:**	**PASS**

4.3.2 Geodetic Adjustment

NOTE: Below results are from the 2017 survey.

All observations were combined into a geodetic adjustment using DynAdjust (Fraser et al., 2018). In the adjustment, the point on the GNSS pillar plate (CKIS) was tightly constrained to its ITRF2014 coordinates and aligned to CKIS-RM1 with an azimuth of 33° 20' 13.7069", which had been determined in the 2001 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. Due to logistics in the field (fixed solar panel obstructed the sight line between observation points), there was no survey undertaken in 2019. Below results are from the 2017 survey.

The ITRF2014@2010.0 latitude and longitude coordinates adopted at CKIS as GNSS constraint are taken from the Geoscience Australia GNSS portal1. The ellipsoidal height is the ITRF2014 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 and ellipsoidal coordinates were adopted at CKIS. 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)
CKIS	**CCC**	-21° 12' 03.69210"	-159° 48' 02.20769"	18.4011
RM1	**FFF**	-21° 12' 03.14164"	-159° 48' 01.82157"	16.5197
RM2	**FFF**	-21° 12' 04.29311"	-159° 48' 01.85888"	16.3298
RM3	**FFF**	-21° 12' 03.43612"	-159° 48' 02.88761"	16.6927

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

Description	X	Y	Z	SD(e)	SD(n)	SD(up)
CKIS	-5583182.3262	-2054143.271	-2292166.5418	0	0	0
RM1	-5583182.5806	-2054155.231	-2292150.0776	0.0002	0.0003	0.0001
RM2	-5583170.7665	-2054149.738	-2292183.0261	0.0004	0.0003	0.0001
RM3	-5583190.2745	-2054125.300	-2292158.5841	0.0003	0.0004	0.0001

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

From	To	ΔE	ΔN	ΔU
CKIS	**RM1**	11.1364	16.9297	-1.8815
CKIS	**RM2**	10.0604	-18.4844	-2.0714

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

CKIS	**RM3**	-19.6101	7.8727	-1.7084

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
2001	**CKIS**	**RM1**	11.1365	16.9298	-1.8803
2003	**CKIS**	**RM1**	11.1369	16.9304	-1.8801
2007	**CKIS**	**RM1**	11.137	16.9306	-1.8817
2008	**CKIS**	**RM1**	11.1367	16.9301	-1.8817
2009	**CKIS**	**RM1**	11.1370	16.9305	-1.8817
2011	**CKIS**	**RM1**	11.1369	16.9304	-1.8816
2012	**CKIS**	**RM1**	11.1363	16.9295	-1.8812
2014	**CKIS**	**RM1**	11.1364	16.9297	-1.8815
2017	**CKIS**	**RM1**	11.1364	16.9297	-1.8815
Ref RL	**(as at 2012)**		**11.1368**	**16.9302**	**-1.8812**

Year	From	To	ΔE	ΔN	ΔU
2001	**CKIS**	**RM2**	10.0578	-18.4833	-2.07
2003	**CKIS**	**RM2**	10.059	-18.4849	-2.07
2007	**CKIS**	**RM2**	10.06	-18.485	-2.0714
2008	**CKIS**	**RM2**	10.0595	-18.4849	-2.0714
2009	**CKIS**	**RM2**	10.0593	-18.485	-2.0714
2011	**CKIS**	**RM2**	10.0585	-18.4856	-2.0713
2012	**CKIS**	**RM2**	10.0587	-18.4842	-2.071
2014	**CKIS**	**RM2**	10.0593	-18.4848	-2.0713
2017	**CKIS**	**RM2**	10.0603	-18.4844	-2.0713
Ref RL	**(as at 2012)**		**10.0590**	**-18.4847**	**-2.0709**

Year	From	To	ΔE	ΔN	ΔU
2001	**CKIS**	**RM3**	-19.6097	7.8732	-1.7071
2003	**CKIS**	**RM3**	-19.6099	7.8725	-1.7067
2007	**CKIS**	**RM3**	-19.6104	7.873	-1.7085
2008	**CKIS**	**RM3**	-19.6095	7.8734	-1.7086
2009	**CKIS**	**RM3**	-19.6101	7.8729	-1.7086
2011	**CKIS**	**RM3**	-19.611	7.874	-1.7085
2012	**CKIS**	**RM3**	-19.6102	7.8729	-1.7081
2014	**CKIS**	**RM3**	-19.61	7.8727	-1.7084
2017	**CKIS**	**RM3**	-19.6101	7.8727	-1.7084
Ref RL	**(as at 2012)**		**-19.6101**	**7.8731**	**-1.7080**

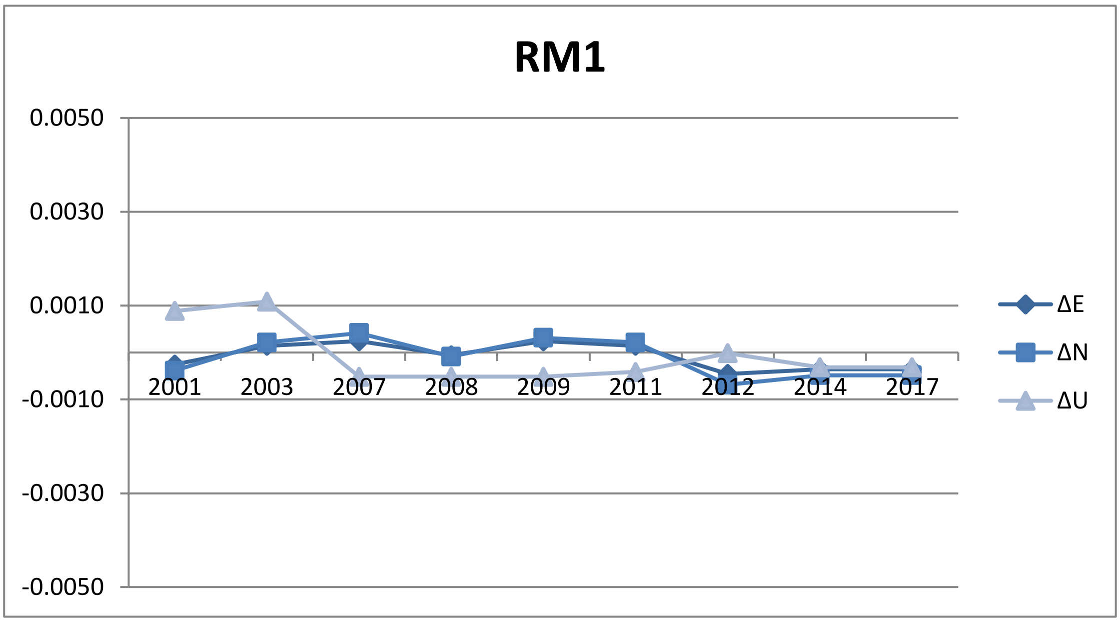

Figure 4.4.1 Time series of RM1 movement relative to GNSS pillar (0 = REF pre 2012 mean).

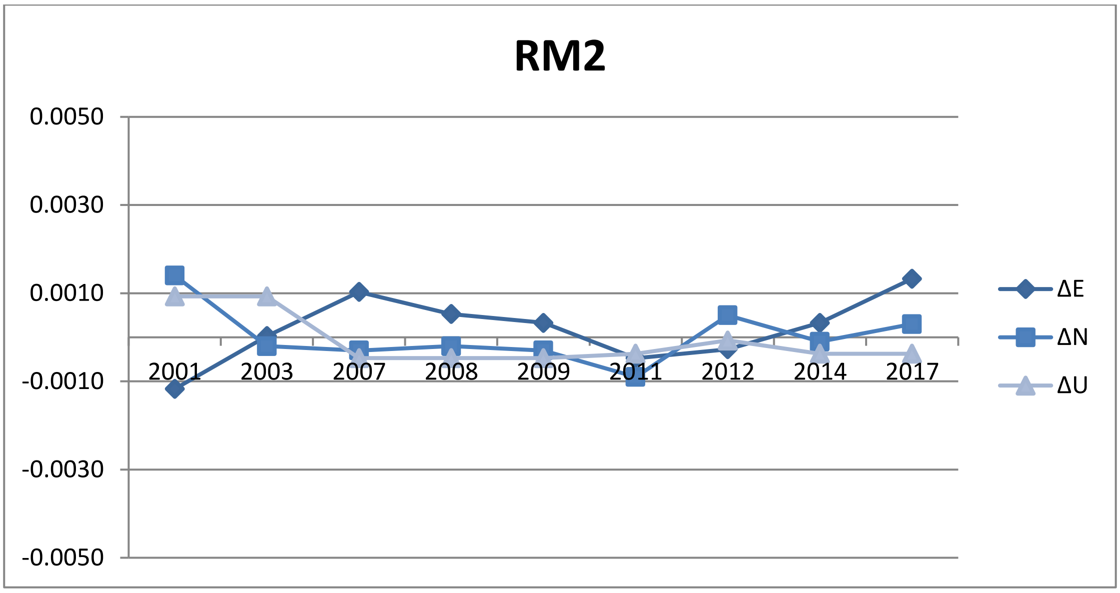

Figure 4.4.2 Time series of RM2 movement relative to GNSS pillar (0 = REF pre 2012 mean).

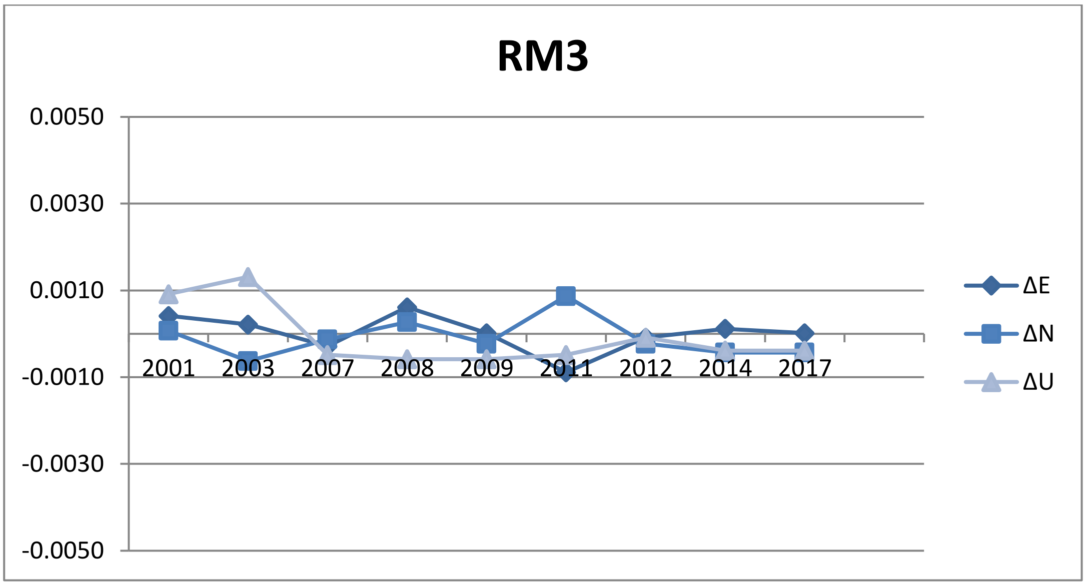

Figure 4.4.3 Time series of RM3 movement relative to GNSS pillar (0 = REF pre 2012 mean).

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 Rarotonga 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
CKIS (Ellipsoidal ht)	18.4061	Observed RL at the ARP of CKIS (Ellipsoidal) @ 2019.40
CKIS - CKISBM	-1.2618	Offset constant between BM at GNSS pillar plate
Primary Pole & 1/2m Pole	1.00092	Height difference between poles used (Calibrated May 2019)

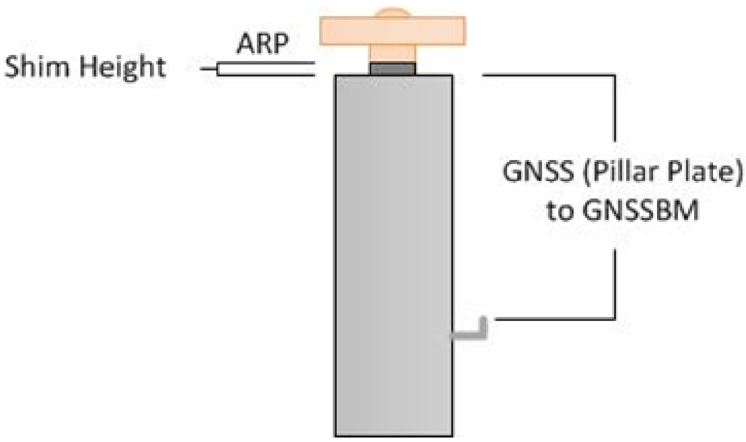

Figure 5.2.1 GNSS Pillar Offsets

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 CKISBM (GNSS BM)

Table 5.3.1 Reduced level data – CKIS (GNSS CORS) to BM18

From	To	Rise	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
CKIS				1.2618		
CKISBM	**CKISBM**	0.0000	-1.2618	0.000	0.000	0.000
108	**108**	0.6498	0.0000	0.6498	0.220	0.220
107	**107**	0.0000	-0.3334	0.3164	0.203	0.422
BM28	**BM28**	0.0000	-0.3743	-0.0579	0.135	0.557
106	**106**	0.3705	0.0000	0.3127	0.126	0.683
BM34	**BM34**	1.0865	0.0000	1.3991	0.189	0.872
104	**104**	0.2115	0.0000	1.6106	0.067	0.940
111	**111**	0.3310	0.0000	1.9416	0.190	1.129
77	**77**	0.0000	-0.3301	1.6114	0.131	1.260
BM27	**BM27**	0.0000	-0.1258	1.4857	0.187	1.447
BM33	**BM33**	0.0000	-1.2806	0.2051	0.210	1.657
BM18	**BM18**	0.1309	0.0000	0.3360	0.222	1.879
BM33	**BM33**	0.0000	-0.1313	0.2047	0.222	
BM27	**BM27**	1.2803	0.0000	1.4850	0.210	

77	**77**	0.1254	0.0000	1.6104	0.187	
111	**111**	0.3303	0.0000	1.9407	0.131	
104	**104**	0.0000	-0.3309	1.6098	0.190	
BM34	**BM34**	0.0000	-0.2114	1.3984	0.067	
106	**106**	0.0000	-1.0864	0.3120	0.189	
BM28	**BM28**	0.0000	-0.3706	-0.0586	0.126	
107	**107**	0.3744	0.0000	0.3158	0.135	
108	**108**	0.3332	0.0000	0.6489	0.203	
CKISBM	**CKISBM**	0.0000	-0.6494	-0.0004	0.219	
CKIS	**CKIS**	1.2618	0.0000	1.2614	0.000	
	Sum:	6.4855	-6.4860			
	Misclose:		-0.0004	-0.0004	3.759	(Total Dist.)
			ALLOWABLE (m):	**0.0027**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.2 Reduced level data – BM18–COO10 (Tide Gauge Benchmark)

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
BM18				0.3360	0.000	1.879
COO10	**COO10**	0.0000	-2.0477	-1.7117	0.051	1.931
BM18	**BM18**	2.0475	0.0000	0.3358	0.051	
	Sum:	2.0475	-2.0477			
	Misclose:		-0.0002	-0.0002	0.102	(Total Dist.)
			ALLOWABLE (m):	**0.0005**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.3 Reduced level data – COO10 (Tide Gauge Benchmark) to COO56 (Tide Gauge Sensor Benchmark)

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
COO10				-1.71174	0.0000	1.9306
COO56	**COO56**	1.13429	0.0000	-0.57745	0.0150	1.9456
	COO10	0.00000	-1.13423	-1.71168	0.0152	
	Sum:	1.1343	-1.1342			
	Misclose:		0.0001	0.0001	0.015	(Total Dist.)
			ALLOWABLE (m):	**0.0002**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.4 Reduced level data – BM18 to BM26

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
BM18				0.3360		1.879
COO10	**COO10**	0.00000	-2.0477	-1.7117	0.0512	1.9306
BM26	**BM26**	0.59501	0.0000	-1.11673	0.104	2.0346
COO10	**COO10**	0.00000	-0.59496	-1.71169	0.104	
	BM18	2.04754	0.0000	0.33585	0.051	
	Sum:	2.6426	-2.6427			
	Misclose:		-0.0002	-0.0001	0.155	(Total Dist.)
			ALLOWABLE (m):	**0.0006**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.5 Measured height differences (in metres) between all BMs (ΔRL_{2019})

	CKISBM	BM28	BM34	BM27	BM33	BM18	COO10	COO56	BM26	RM1	RM2	RM3	CKIS
CKISBM	-	-0.0582	1.3988	1.4853	0.2049	0.3360	-1.7117	-0.5775	-1.1167	-0.6196	-0.8096	-0.4466	1.2618
BM28	0.0582	-	1.4570	1.5436	0.2631	0.3942	-1.6535	-0.5192	-1.0585	-0.5614	-0.7513	-0.3883	1.3200
BM34	-1.3988	-1.4570	-	0.0866	-1.1939	-1.0628	-3.1105	-1.9762	-2.5155	-2.0184	-2.2083	-1.8453	-0.1370
BM27	-1.4853	-1.5436	-0.0866	-	-1.2805	-1.1493	-3.1971	-2.0628	-2.6021	-2.1050	-2.2949	-1.9319	-0.2235
BM33	-0.2049	-0.2631	1.1939	1.2805	-	0.1311	-1.9166	-0.7823	-1.3216	-0.8245	-1.0144	-0.6514	1.0569
BM18	-0.3360	-0.3942	1.0628	1.1493	-0.1311	-	-2.0477	-0.9135	-1.4527	-0.9556	-1.1456	-0.7826	0.9258
COO10	1.7117	1.6535	3.1105	3.1971	1.9166	2.0477	-	1.1343	0.5950	1.0921	0.9022	1.2652	2.9735
COO56	0.5775	0.5192	1.9762	2.0628	0.7823	0.9135	-1.1343	-	-0.5393	-0.0422	-0.2321	0.1309	1.8393
BM26	1.1167	1.0585	2.5155	2.6021	1.3216	1.4527	-0.5950	0.5393	-	0.4971	0.3072	0.6702	2.3785
RM1	0.6196	0.5614	2.0184	2.1050	0.8245	0.9556	-1.0921	0.0422	-0.4971	-	-0.1899	0.1731	1.8814
RM2	0.8096	0.7513	2.2083	2.2949	1.0144	1.1456	-0.9022	0.2321	-0.3072	0.1899	-	0.3630	2.0714
RM3	0.4466	0.3883	1.8453	1.9319	0.6514	0.7826	-1.2652	-0.1309	-0.6702	-0.1731	-0.3630	-	1.7084
CKIS	-1.2618	-1.3200	0.1370	0.2235	-1.0569	-0.9258	-2.9735	-1.8393	-2.3785	-1.8814	-2.0714	-1.7084	-

Table 5.3.6 Time-series of Reduced Levels (with respect to CKISBM).

YEAR	CKISBM	BM28	BM34	BM27	BM33	BM18	COO10	COO56	BM26	RM1	RM2	RM3	CKIS
1993.1	0.000	-0.0574					-1.7073						
1994.9	0.000	-0.0587					-1.7076						
1996.5	0.000	-0.0580					-1.7079						
1998.5	0.000	-0.0582					-1.7071	-0.5717					
1999.9	0.000	-0.0586					-1.7076	-0.5716					
2001.5	0.000	-0.0584	1.3982		0.2046		-1.7042	-0.5656					
2002.9	0.000	-0.0576	1.3995		0.2055		-1.7075	-0.5693					
2004.6	0.000	-0.0576	1.4008		0.2068		-1.7075	-0.5692					
2004.6	0.000	-0.0590	1.3984		0.2047		-1.7081	-0.5698					
2007.0	0.000	-0.0585	1.3982		0.2042		-1.7088	-0.5730					
2008.5	0.000	-0.0577	1.3990	1.4872	0.2071	0.3430	-1.7061	-0.5715	-1.1080				
2009.9	0.000	-0.0564	1.4013	1.4886	0.2082	0.3444	-1.7049	-0.5702	-1.1066				
2011.4	0.000	-0.0567	1.4007	1.4879	0.2074	0.3415	-1.7064	-0.5711	-1.1097				
2012.9	0.000	-0.0580	1.3999	1.4872	0.2066	0.3402	-1.7081	-0.5747					
2014.5	0.000	-0.0571	1.4000	1.4872	0.2066	0.3396	-1.7086	-0.5755	-1.1122	-0.6195	-0.8092	-0.4466	
2016.2	0.000	-0.0563	1.4011	1.4882	0.2080	0.3408	-1.7072	-0.5747	-1.1112	-0.6193	-0.8093	-0.4462	1.2618
2017.6	0.000	-0.0569	1.4008	1.4881	0.2078	0.3388	-1.7091	-0.5758	-1.1134	-0.6196	-0.8095	-0.4466	1.2618
2019.4	0.000	-0.0582	1.3988	1.4853	0.2049	0.3360	-1.7117	-0.5775	-1.1167	-0.6196	-0.8096	-0.4466	1.2618

5.4 Comparison with previous surveys

All historic data has been readjusted relative to the benchmark attached to the base of the GNSS pillar (CKISBM) (Table 5.3.6). 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	CKISBM	BM28	BM34	BM27	BM33	BM18	COO10	COO56	BM26	RM1	RM2	RM3	CKIS
CKISBM	-	0.0004	0.0014	0.0028	0.0022	0.0046	0.0042	**0.0059**	**0.0058**	0.0002	0.0003	0.0000	0.0000
BM28	-0.0004	-	0.0010	0.0024	0.0018	0.0042	0.0037	0.0055	0.0054	-0.0003	-0.0001	-0.0004	-0.0004
BM34	-0.0014	-0.0010	-	0.0014	0.0009	0.0032	0.0028	0.0045	0.0044	-0.0012	-0.0011	-0.0014	-0.0014
BM27	-0.0028	-0.0024	-0.0014	-	-0.0005	0.0019	0.0014	0.0032	0.0031	-0.0026	-0.0025	-0.0028	-0.0028
BM33	-0.0022	-0.0018	-0.0009	0.0005	-	0.0024	0.0019	0.0037	0.0036	-0.0021	-0.0019	-0.0023	-0.0022
BM18	-0.0046	-0.0042	-0.0032	-0.0019	-0.0024	-	-0.0005	0.0013	0.0012	-0.0045	-0.0043	-0.0047	-0.0046
COO10	-0.0042	-0.0037	-0.0028	-0.0014	-0.0019	0.0005	-	0.0018	0.0017	-0.0040	-0.0038	-0.0042	-0.0042
COO56	**-0.0059**	-0.0055	-0.0045	-0.0032	-0.0037	-0.0013	-0.0018	-	-0.0001	**-0.0058**	-0.0056	**-0.0059**	**-0.0059**
BM26	**-0.0058**	-0.0054	-0.0044	-0.0031	-0.0036	-0.0012	-0.0017	0.0001	-	-0.0057	-0.0055	**-0.0058**	**-0.0058**
RM1	-0.0002	0.0003	0.0012	0.0026	0.0021	0.0045	0.0040	**0.0058**	0.0057	-	0.0002	-0.0002	-0.0002
RM2	-0.0003	0.0001	0.0011	0.0025	0.0019	0.0043	0.0038	0.0056	0.0055	-0.0002	-	-0.0003	-0.0003
RM3	0.0000	0.0004	0.0014	0.0028	0.0023	0.0047	0.0042	**0.0059**	**0.0058**	0.0002	0.0003	-	0.0000
CKIS	0.0000	0.0004	0.0014	0.0028	0.0022	0.0046	0.0042	**0.0059**	**0.0058**	0.0002	0.0003	0.0000	-

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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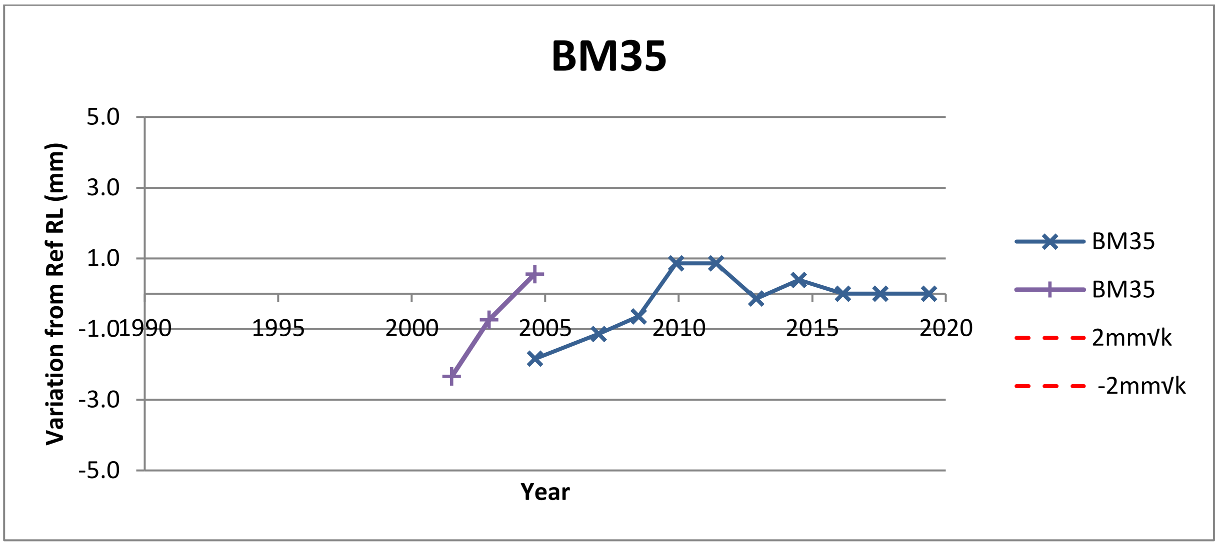
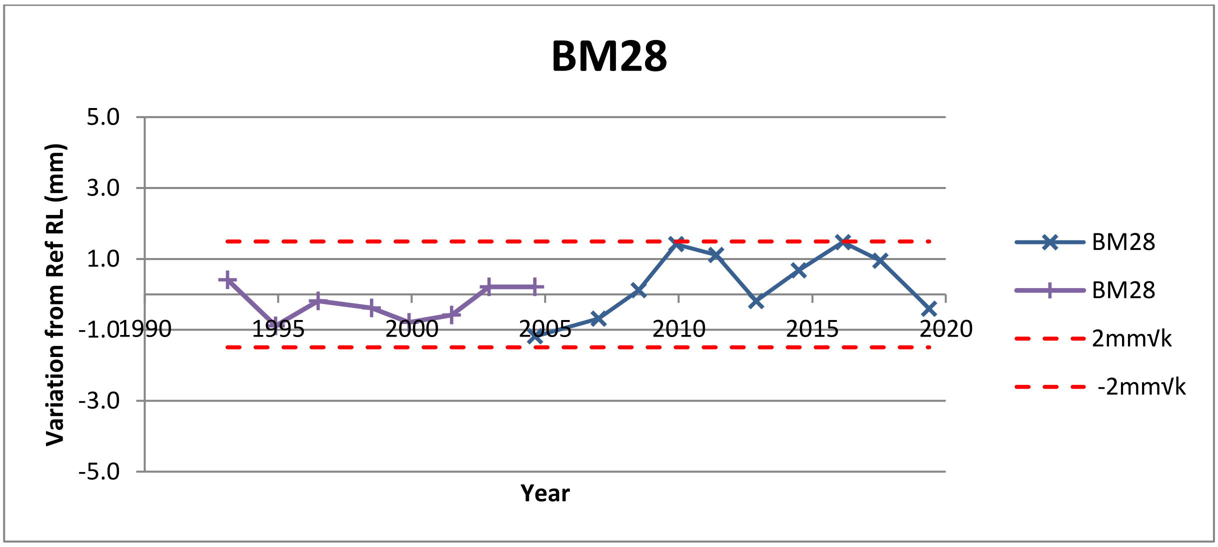
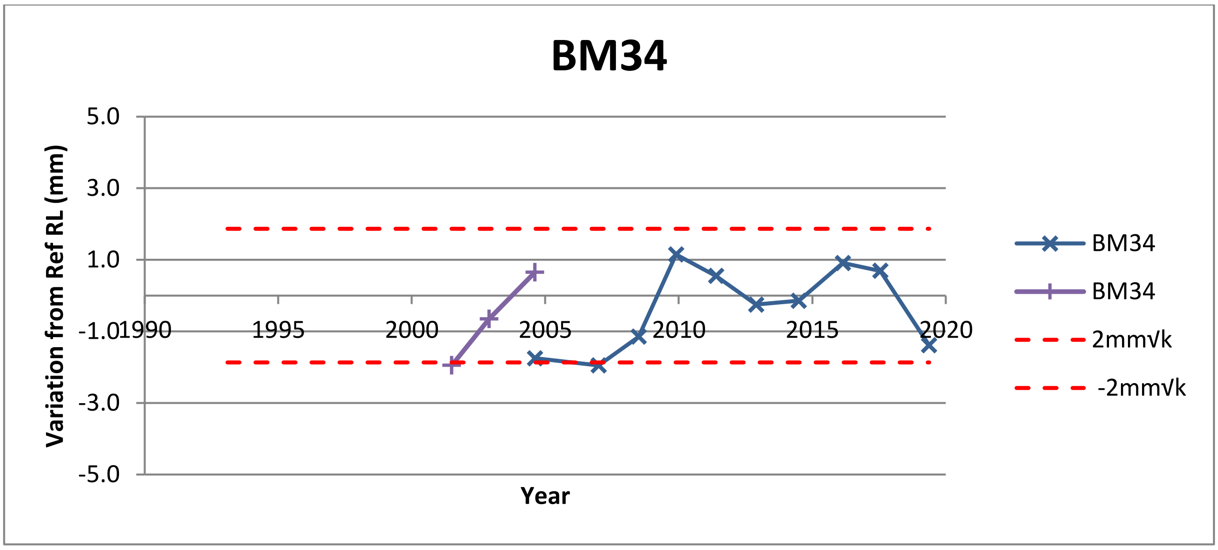
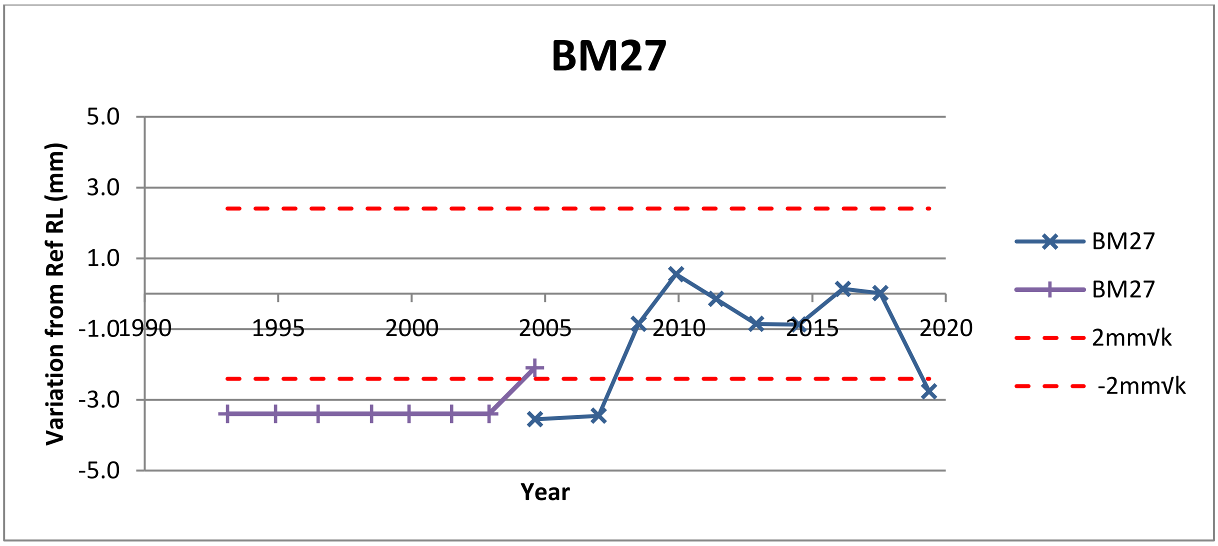
5.4.2 Time series charts for each BM

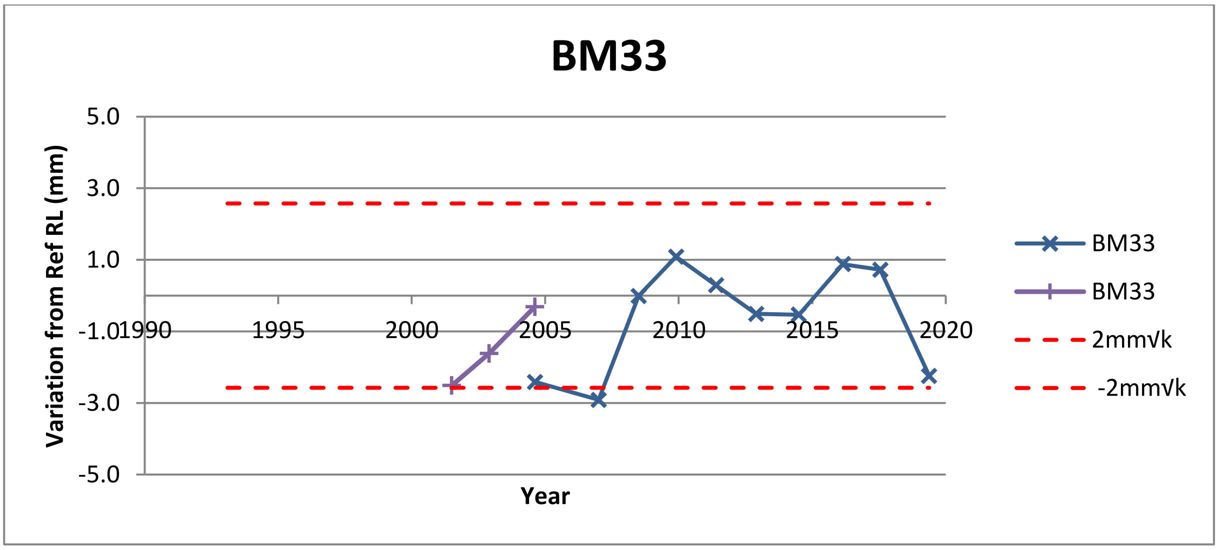
The change in RL over time can be used to detect trends of movement or survey errors. In the series of figures below, the red dashed lines represent the allowable error in height based on the levelling technique used and distance of the benchmark from the GNSS pillar ($2mm\sqrt{K}$). The purple line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

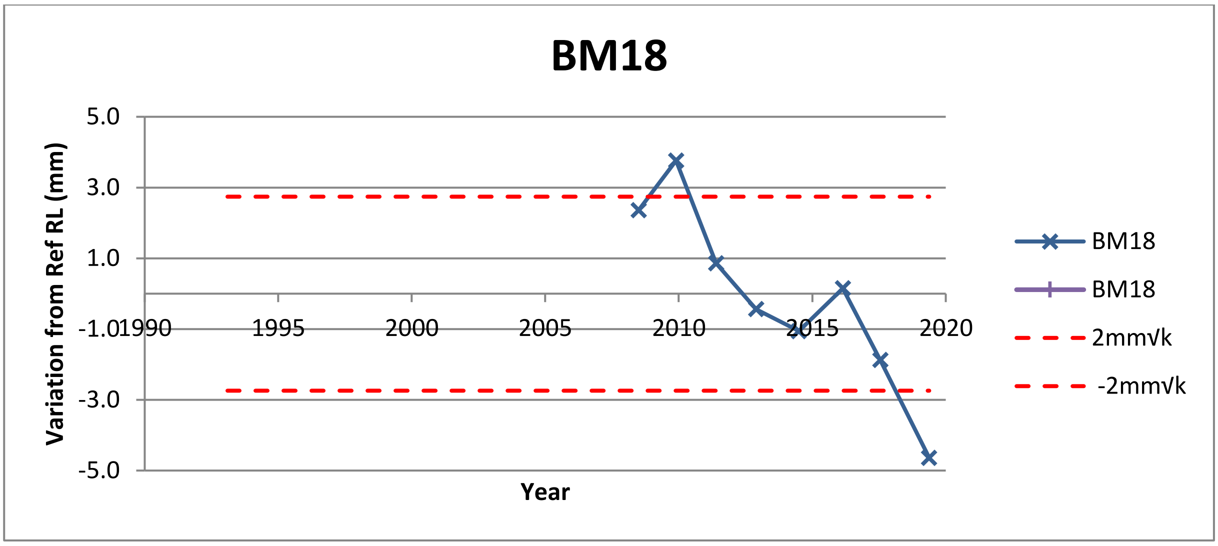




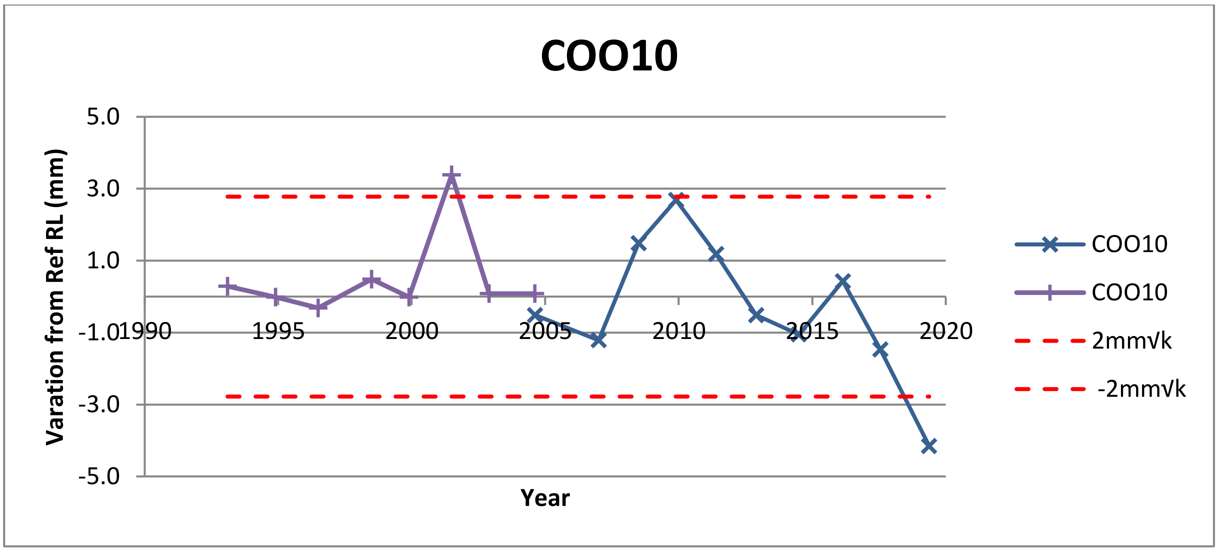

BM34
5.0
3.0
1.0
-1.0
-3.0
-5.0
Variation from Ref RL (mm)
1990
1995
2000
2005
2010
2015
2020
Year
BM34
BM34
2mm√k
-2mm√k


BM27
5.0
3.0
1.0
-1.0
-3.0
-5.0
Variation from Ref RL (mm)
1990
1995
2000
2005
2010
2015
2020
Year
BM27
BM27
2mm√k
-2mm√k

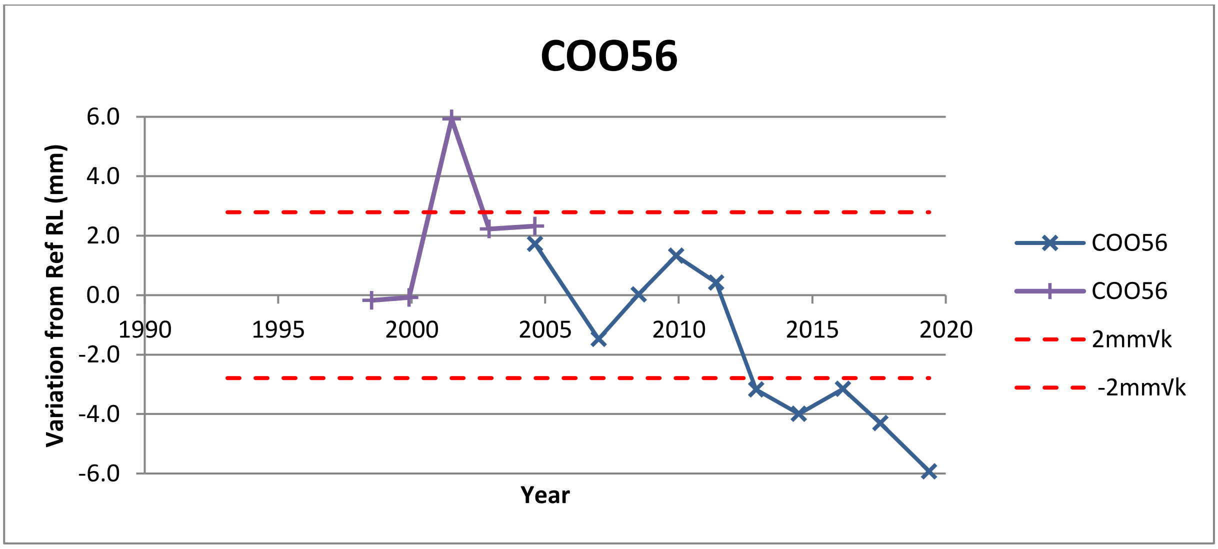

BM33
5.0
3.0
1.0
-1.0
-3.0
-5.0
Variation from Ref RL (mm)
1990
1995
2000
2005
2010
2015
2020
Year
BM33
BM33
2mm√k
-2mm√k



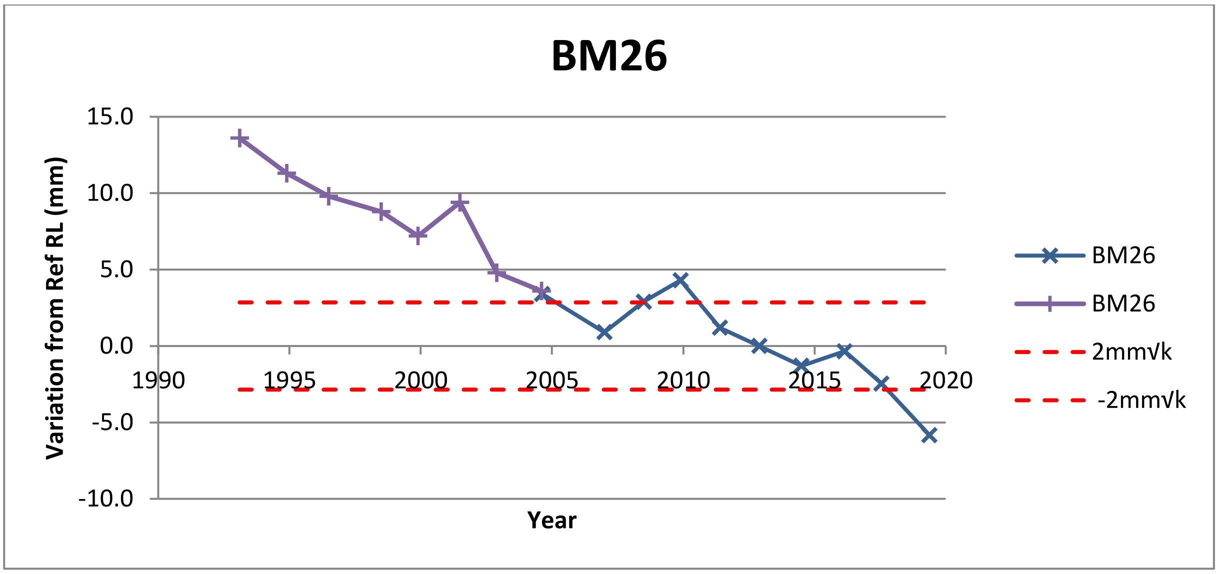
BM18
5.0
3.0
1.0
-1.0
-3.0
-5.0
1990
1995
2000
2005
2010
2015
2020
Variation from Ref RL (mm)
Year
BM18
BM18
2mm√k
-2mm√k



COO10
5.0
3.0
1.0
-1.0
-3.0
-5.0
1990
1995
2000
2005
2010
2015
2020
Variation from Ref RL (mm)
Year
COO10
COO10
2mm√k
-2mm√k



COO56
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
1990
1995
2000
2005
2010
2015
2020
Variation from Ref RL (mm)
Year
COO56
COO56
2mm√k
-2mm√k


BM26
15.0
10.0
5.0
0.0
-5.0
-10.0
Variation from Ref RL (mm)
1990
1995
2000
2005
2010
2015
2020
Year
BM26
BM26
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 are several differences greater than 0.003 m:

- BM18 and BM28, which is likely due to:
    - localised movement of BM18 – which is located close to the road side, where there is heavy movement of vehicles in the car park of the hardware shop and along the road.
    - the combined impact is a relative height difference of 0.0042 m.
- COO10 and CKISBM, which is likely due to:
    - localised movement of COO10 – which is located on the base of the Tide gauge Station, where there is heavy movement of vehicles in the wharf area
    - the combined impact is a relative height difference of 0.0046 m.
- COO56 and CKISBM, which is likely due to:
    - localised movement of COO56 – which is the Tide gauge Station, where there is heavy movement of vehicles in the wharf area, leading to movement of the wharf structure.
    - the combined impact is a relative height difference of 0.0059 m.
- BM26 and CKISBM, which is likely due to:
    - localised movement of BM26 – is in the same area where BM18, COO10 and COO56, where there is heavy movement of vehicles in the wharf area.
    - the combined impact is a relative height difference of 0.0058 m.

The survey from the primary GNSS BM (CKISBM) to the TG Plaque (COO10) shows 4.2mm change. Even though the wharf structure appears solid, we are still detecting movement near the tide gauge and the wharf area.

The survey from the primary GNSS BM (CKISBM) to the TG Ref Pin (COO56) indicates the tide gauge may be subsiding.

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

PT ID	Reference ^H (m)	2019.38 Value (m)	Difference
CKISBM - Primary BM (BM18)	0.3406	0.3360	-0.0046
BM18 - TG Plaque BM (COO10)	-2.0482	-2.0477	-0.0005
BM18 - TG ref pin (COO56)	-0.9122	-0.9135	0.0013
CKISBM - BM27	1.4881	1.4853	-0.0028

BM27 - COO10	-3.1957	-3.1971	0.0014
COO10 - COO56	1.1361	1.1343	-0.0018
CKIS - TG Plaque	-2.9694	-2.9735	0.0042
CKIS - TG BM	-1.8333	-1.8393	0.0059
CKIS - TGZ	-5.1417	-5.1477	0.0059

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

PT ID	Reference RL (m)	2019.38 Value (m)	Difference	ITRF2020	TGZ
CKISBM	0.000	0.000	0.0000	17.1443	3.8859
BM28	-0.0578	-0.0582	-0.0004	17.0861	3.8276
BM34	1.4002	1.3988	-0.0014	18.5431	5.2846
BM27	1.4881	1.4853	-0.0028	18.6296	5.3712
BM33	0.2071	0.2049	-0.0022	17.3492	4.0907
BM18	0.3406	0.3360	-0.0046	17.4803	4.2219
COO10	-1.7076	-1.7117	-0.0042	15.4326	2.1741
COO56	-0.5715	-0.5775	-0.0059	16.5669	3.3084
BM26	-1.1109	-1.1167	-0.0058	16.0276	2.7691
RM1	-0.6195	-0.6196	-0.0002	16.5247	3.2662
RM2	-0.8093	-0.8096	-0.0003	16.3347	3.0763
RM3	-0.4466	-0.4466	0.0000	16.6977	3.4393
CKIS	1.2618	1.2618	0.0000	18.4061	5.1477
TGZ	-3.8799	-3.8859	-0.0059	13.2585	0.0000

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 BoM 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).

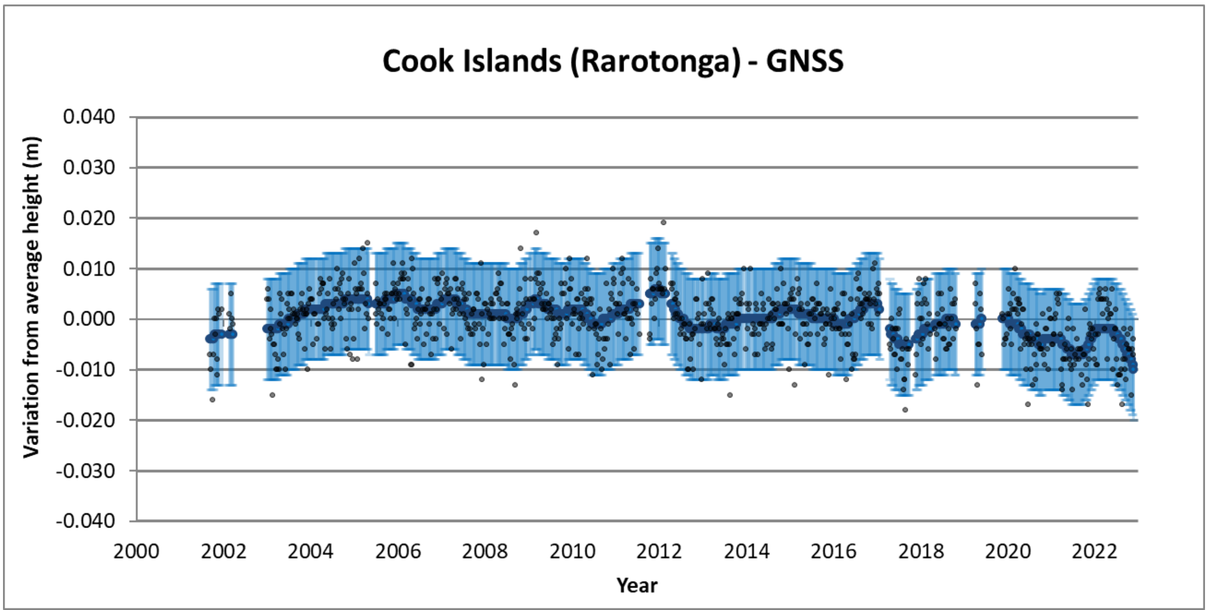


Figure 7.1 Time series of GNSS analysis (dark blue line) with 95%CI uncertainty (light blue lines).

[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.

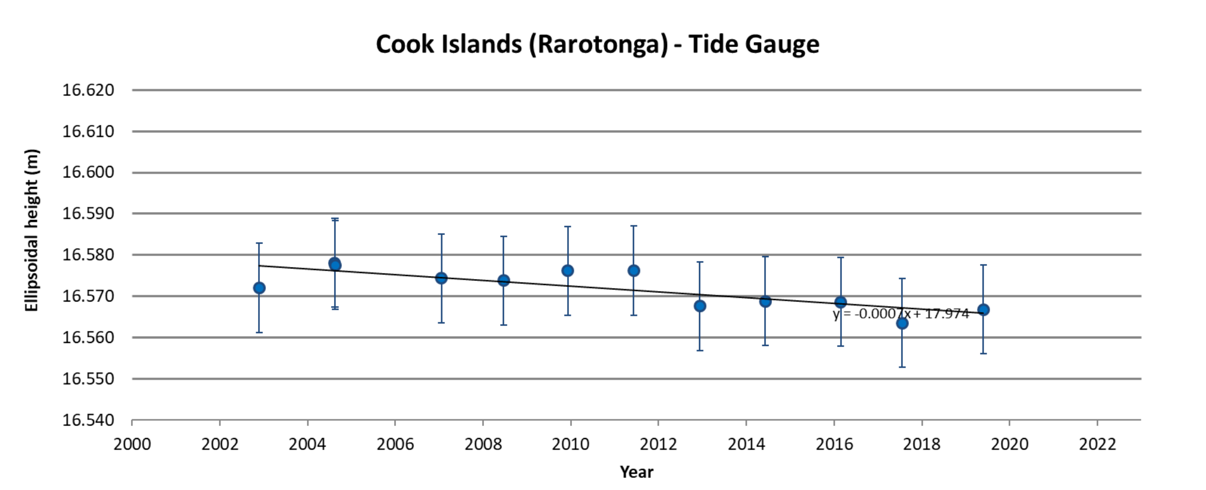


Figure 7.2 The height of the SEAFRAME sensor reference benchmark (with respect to ITRF2020).

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)
2002.90	16.5720	0.011
2004.62	16.5781	0.011
2004.63	16.5775	0.011
2007.05	16.5743	0.011
2008.47	16.5738	0.011
2009.93	16.5761	0.011
2011.43	16.5762	0.011
2012.94	16.5676	0.011
2014.43	16.5688	0.011
2016.15	16.5686	0.011
2017.55	16.5635	0.011
2019.40	16.5668	0.011

[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

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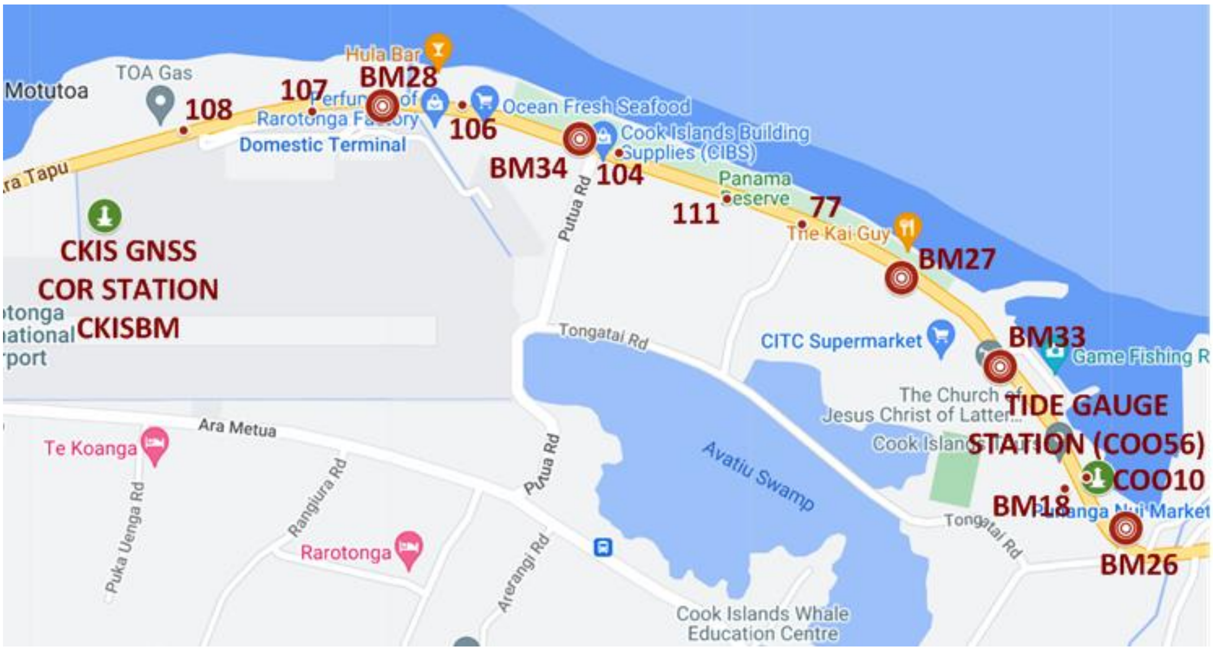
Rueger, J. M., Brunner, F. K., 1981. *Practical Results from EDM-Height Traversing*. The Australian Surveyor. June 1981, Vol. 30, No 6.

Appendix A Locality Diagrams



Source: Adopted from Google Map

A 1 Deep Benchmarks

PACIFIC SEA LEVEL MONITORING PROJECT

SURVEY BENCH MARK RECORD

Bench Mark Number: BM28

Original Bench Mark Established by: National Tidal Centre Australia, Oceanographic Services, Bureau of Meteorology, 25 college Rd, Kent Town, SA. — *Date: 3/12/1991*

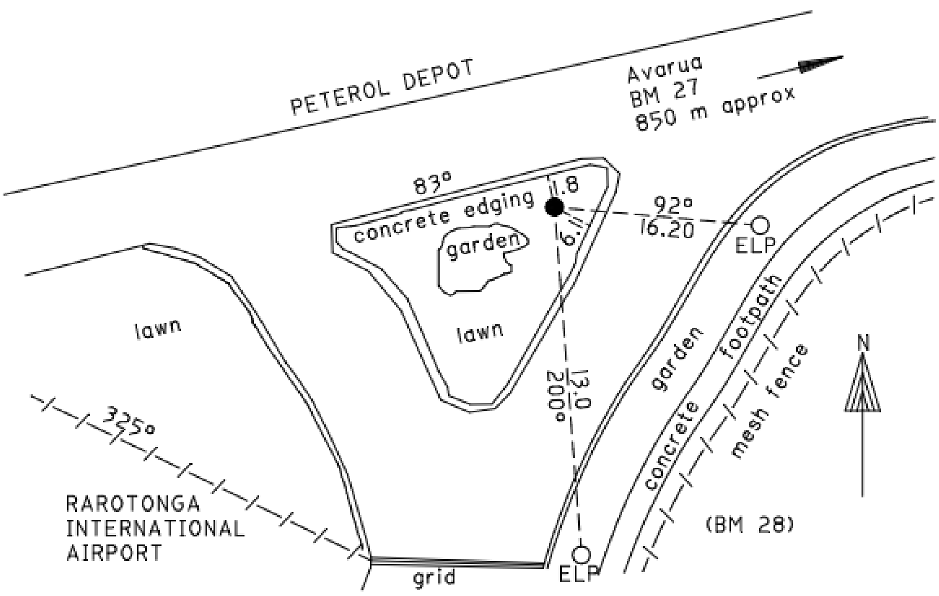
Existing Bench Mark Established by: — *Date:*

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

Country: Cook Islands
Island: Rarotonga — *City: Avatiu*

MARKING AND LOCALITY SKETCH

Bench Mark: 2.6m 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 0.2m below ground level. Locality sketch Mark approximately 1400m 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: Nov 2008*

PACIFIC SEA LEVEL MONITORING PROJECT

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Geoscience Australia

SPC Secretariat of the Pacific Community

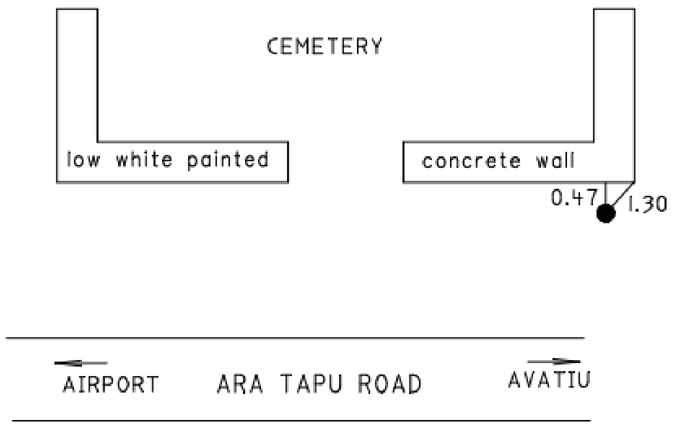
SURVEY BENCH MARK RECORD

Bench Mark Number: BM34

Original Bench Mark Established by: National Tidal Centre Australia, Oceanographic Services, Bureau of Meteorology, 25 college Rd, Kent Town, SA.	*Date: 18/11/2002*
Existing Bench Mark Established by:	*Date:*
Notes / References: Deep Survey Benchmark This survey mark is not in a good locality for GNSS occupation	
Country: Cook Islands *Island: Rarotonga*	*City: Avatiu*

MARKING AND LOCALITY SKETCH

Bench Mark: 1.5m 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 0.2m below ground level. Locality sketch Mark approximately 1200m 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: Nov 2008*

PACIFIC SEA LEVEL MONITORING PROJECT

Australian Government
Geoscience Australia

Australian Aid

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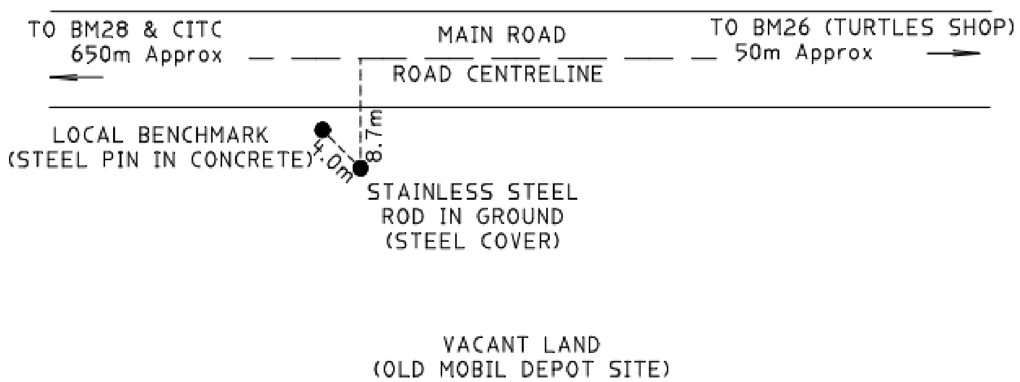
SURVEY BENCH MARK RECORD

Bench Mark Number: BM27

Original Bench Mark Established by: National Tidal Centre Australia, Oceanographic Services, Bureau of Meteorology, 25 college Rd, Kent Town, SA.	*Date: 03/12/1991*
Existing Bench Mark Established by:	*Date:*
Notes / References: Deep Survey Benchmark This survey mark is in a good locality for GNSS occupation	
Country: Cook Islands *Island: Rarotonga*	*City: Avatiu*

MARKING AND LOCALITY SKETCH

Bench Mark: 5.0m 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 550m 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: Nov 2008*

PACIFIC SEA LEVEL MONITORING PROJECT

Australian Government
Geoscience Australia

SPC Secretariat of the Pacific Community

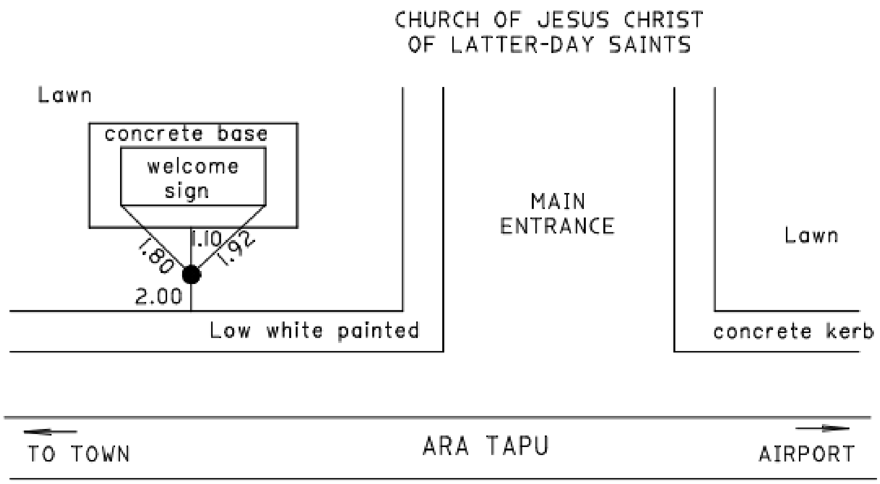
SURVEY BENCH MARK RECORD

Bench Mark Number: BM33

Original Bench Mark Established by: National Tidal Centre Australia, Oceanographic Services, Bureau of Meteorology, 25 college Rd, Kent Town, SA.	*Date: 18/11/2002*
Existing Bench Mark Established by:	*Date:*
Notes / References: Deep Survey Benchmark This survey mark is in a good locality for GNSS occupation	
Country: Cook Islands *Island: Rarotonga*	*City: Avatiu*

MARKING AND LOCALITY SKETCH

Bench Mark: 1.5m 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 0.2m below ground level. Locality sketch Mark approximately 480m 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: Nov 2008*

PACIFIC SEA LEVEL MONITORING PROJECT

Australian Government
Geoscience Australia

SPC Secretariat of the Pacific Community

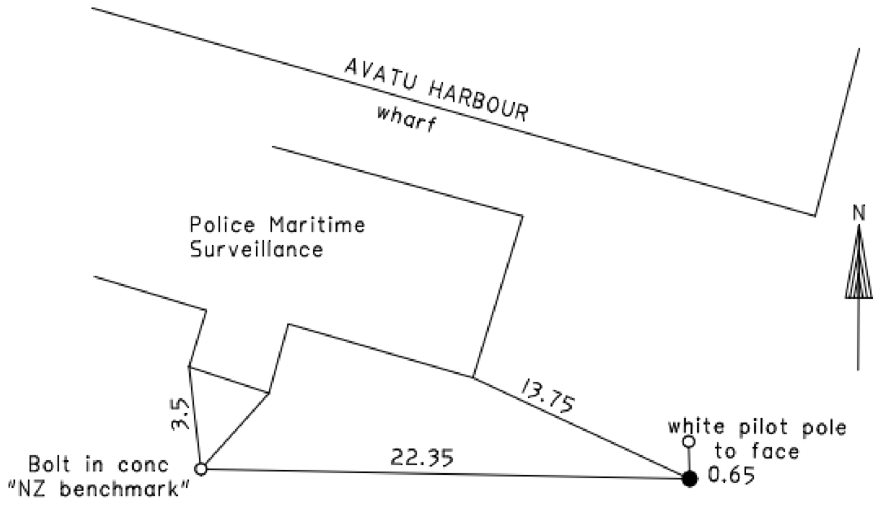
SURVEY BENCH MARK RECORD

Bench Mark Number: BM26

Original Bench Mark Established by: National Tidal Centre Australia, Oceanographic Services, Bureau of Meteorology, 25 college Rd, Kent Town, SA.	*Date: 03/12/1991*
Existing Bench Mark Established by:	*Date:*
Notes / References: Deep Survey Benchmark This survey mark is in a good locality for GNSS occupation	
Country: Cook Islands *Island: Rarotonga*	*City: Avatiu*

MARKING AND LOCALITY SKETCH

Bench Mark: 11.0m of 19mm diameter stainless steel capped rod driven until refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite, for 0.6m, top of mark 0.2m below ground level. Locality sketch Mark approximately 50m from the tide gauge station. Not to scale distances in meters & Magnetic bearing

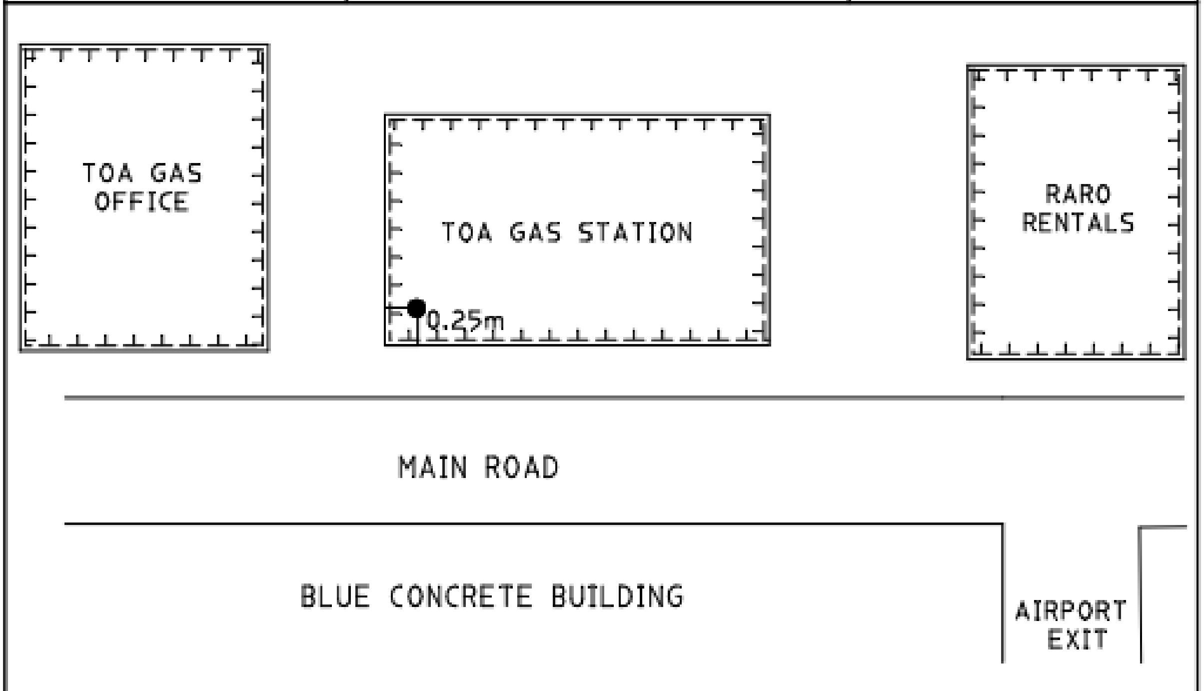


NOT TO SCALE Distances in Metres Magnetic Bearings

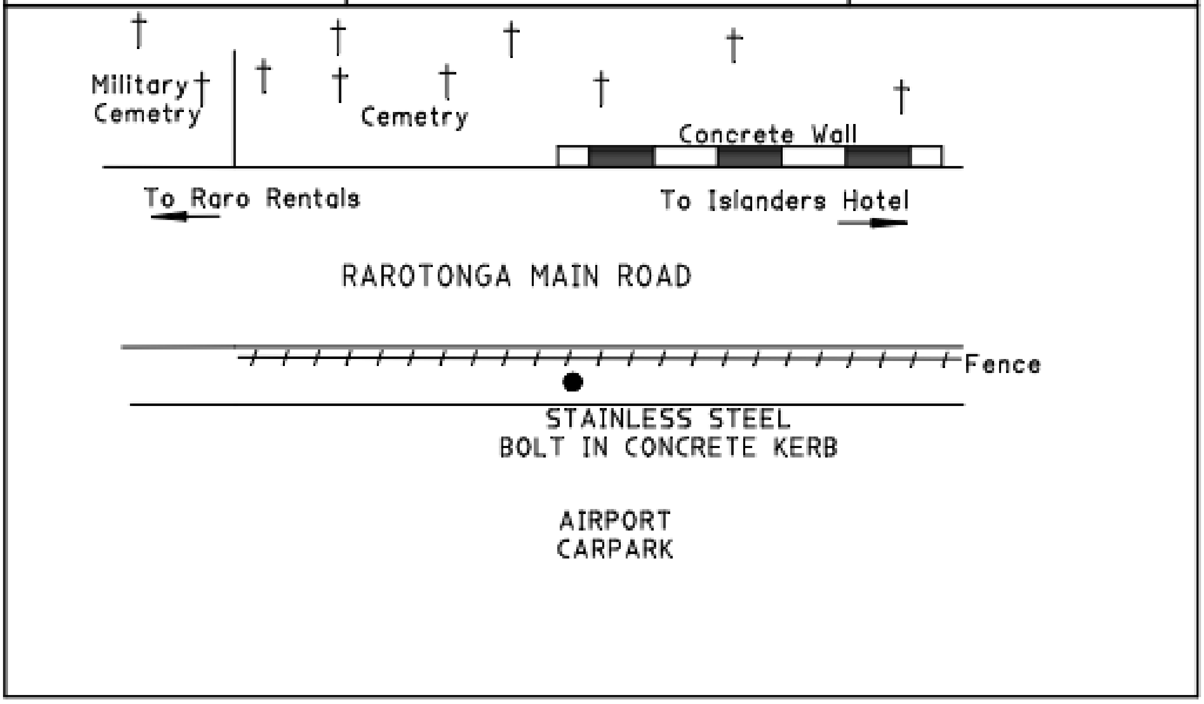
Approved by: Geoscience Australia / SPC *Date: Nov 2008*

A 2 Temporary Holdings Marks

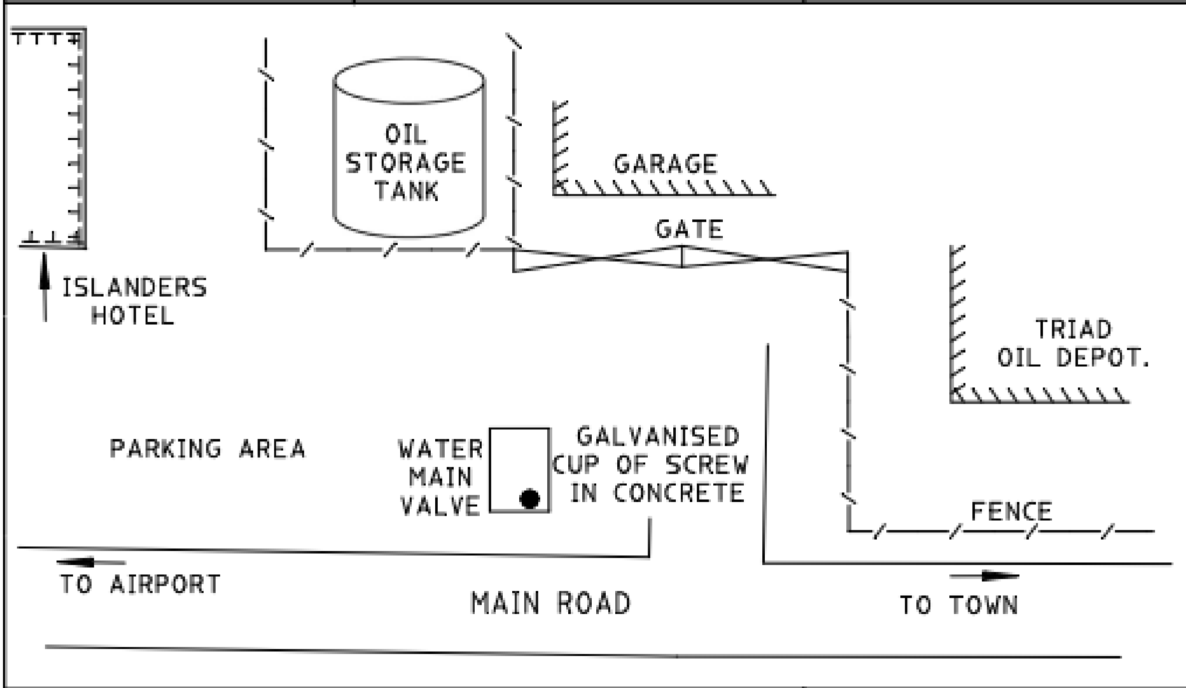
COUNTRY: Cook Islands	ISLAND: Rarotonga CITY: Avatiu	L. D. P. POINT NO. 108
PROJECT: PSLGMP	SURVEYOR: A Lal & M.Deo	DATE: 18-01-07



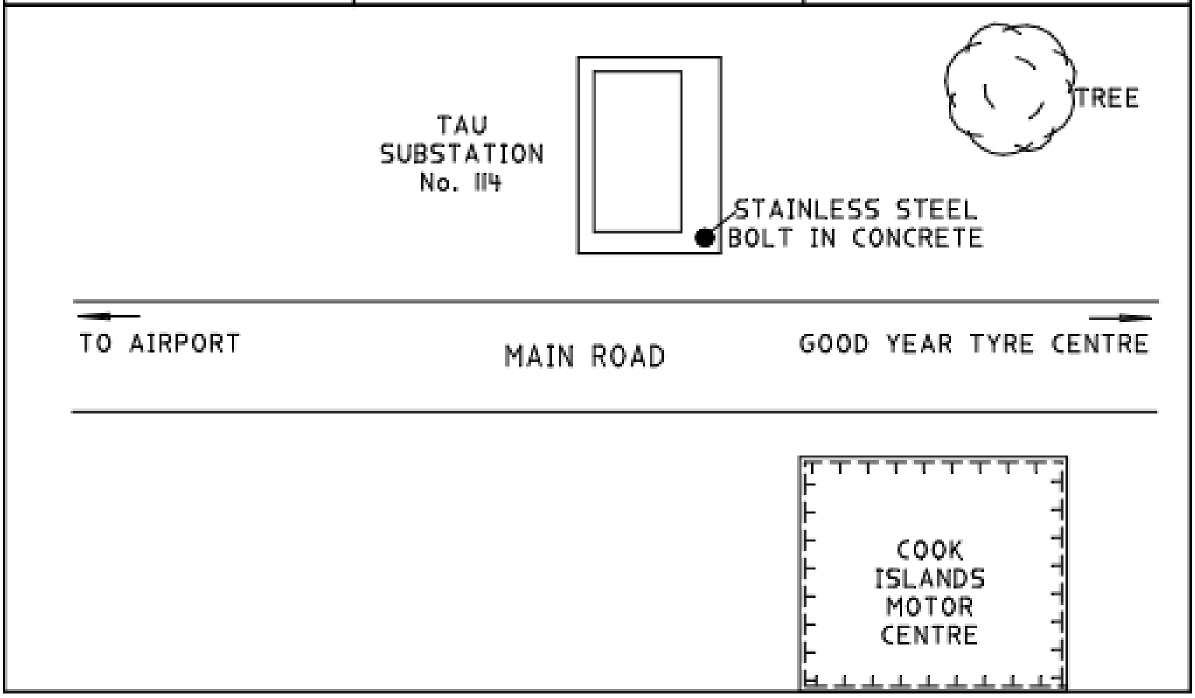
COUNTRY: Cook Islands	ISLAND: Rarotonga CITY: Avatiu	L. D. P. 774 POINT NO. 107
PROJECT: PSLGMP	SURVEYOR: S M Turner	DATE: 16-11-02



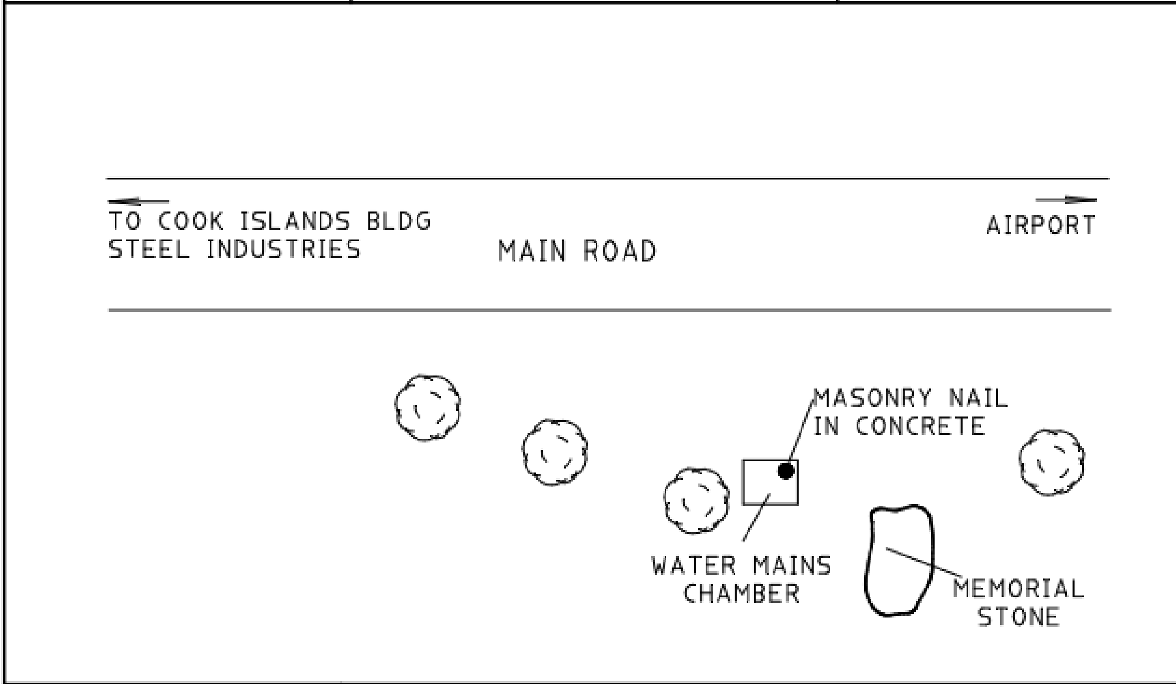
COUNTRY: Cook Islands	ISLAND: Rarotonga CITY: Avatiu	L. D. P. 773 POINT NO. 106
PROJECT: PSLGMP	SURVEYOR: A Lal	DATE: 06-06-14



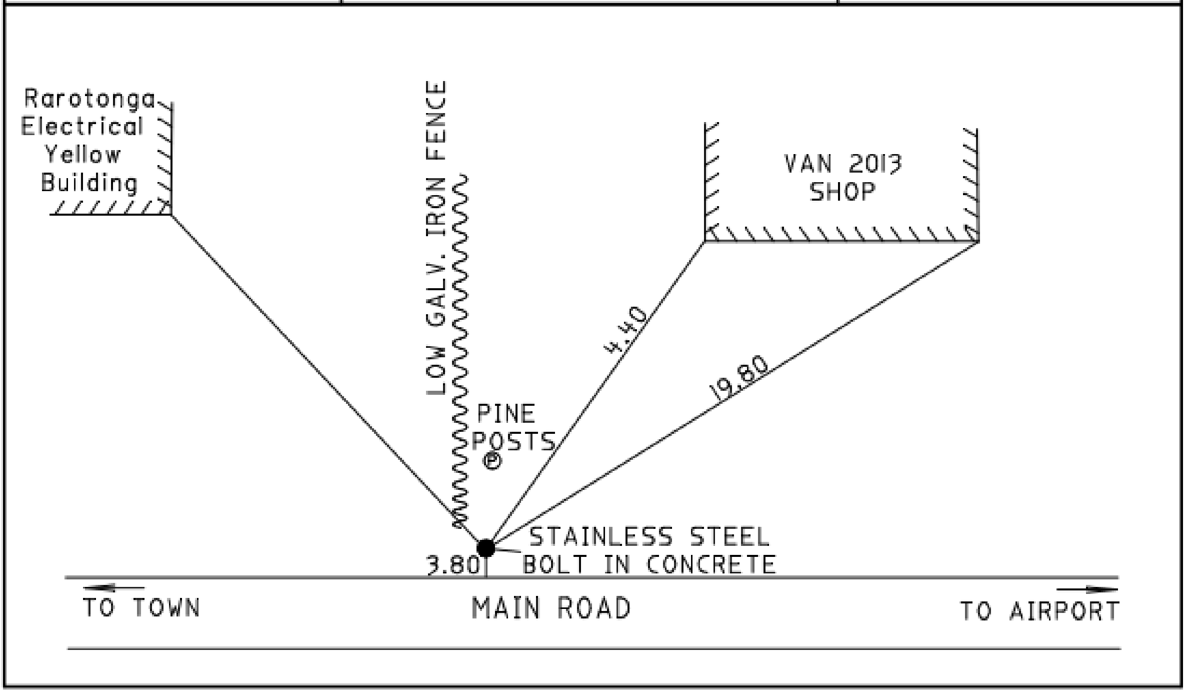
COUNTRY: Cook Islands	ISLAND: Rarotonga CITY: Avatiu	L. D. P. 776 POINT NO. 104
PROJECT: PSLGMP	SURVEYOR: A. Lal	DATE: 06-06-14



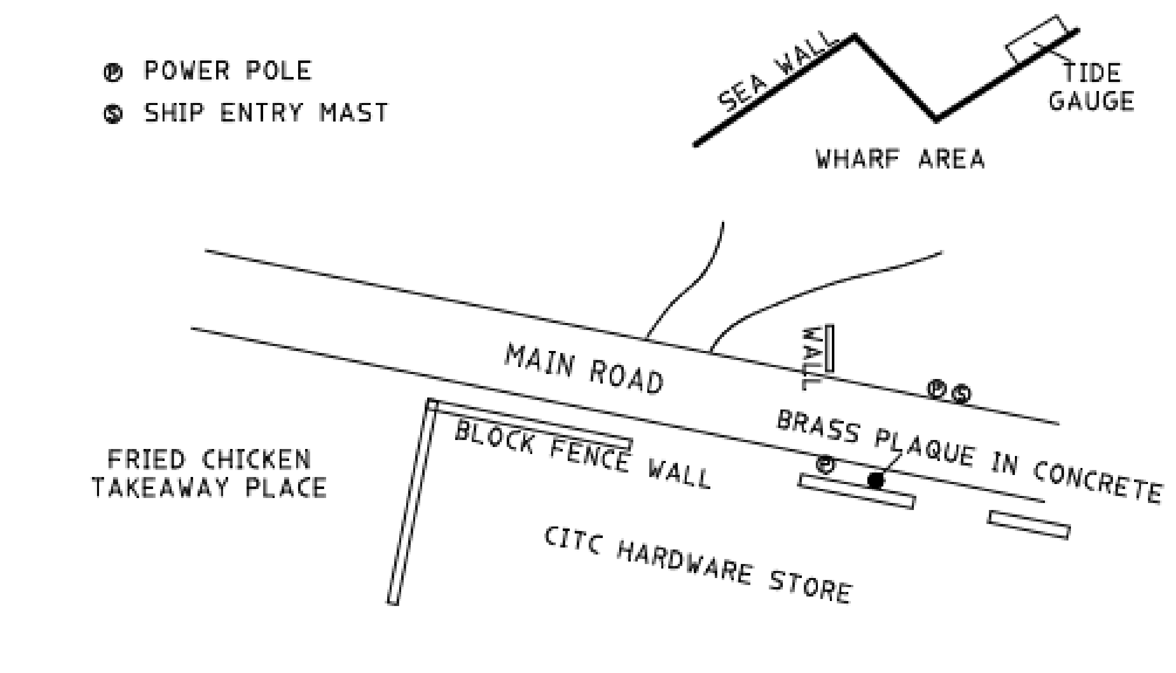
COUNTRY: Cook Islands	ISLAND: Rarotonga CITY: Avatiu	L. D. P. 769 POINT NO. III
PROJECT: PSLGMP	SURVEYOR: A Lal & M.Deo	DATE: 05-12-12



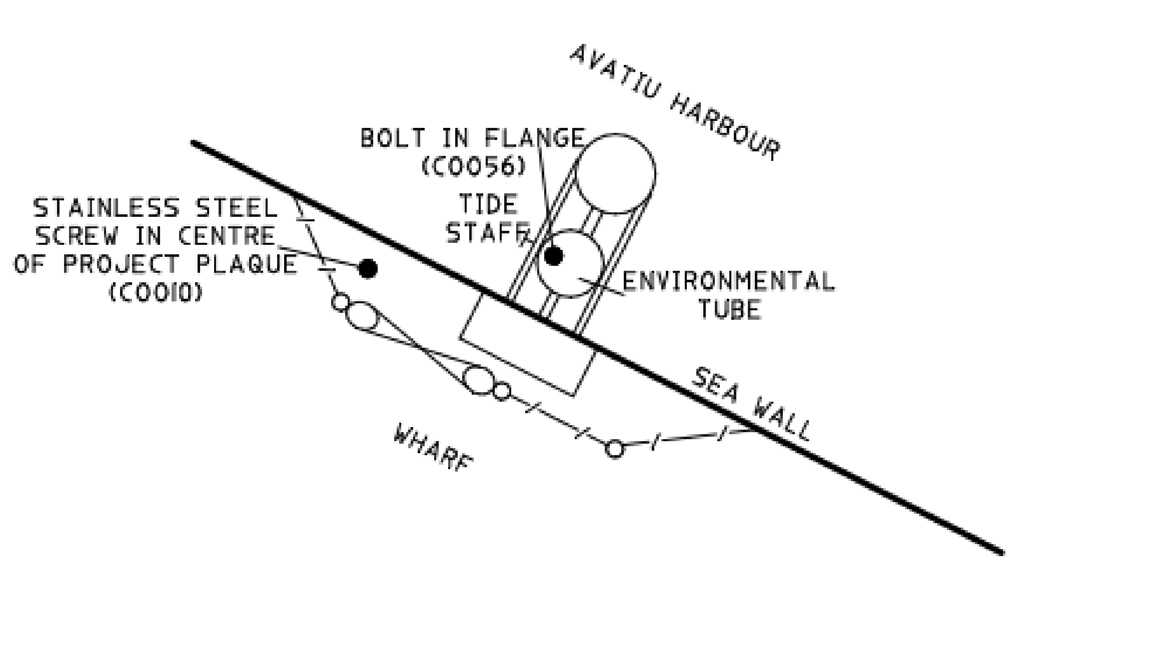
COUNTRY: Cook Islands	ISLAND: Rarotonga CITY: Avatiu	L. D. P. 772 POINT NO. 77
PROJECT: PSLGMP	SURVEYOR: S M Turner	DATE: 21-02-16



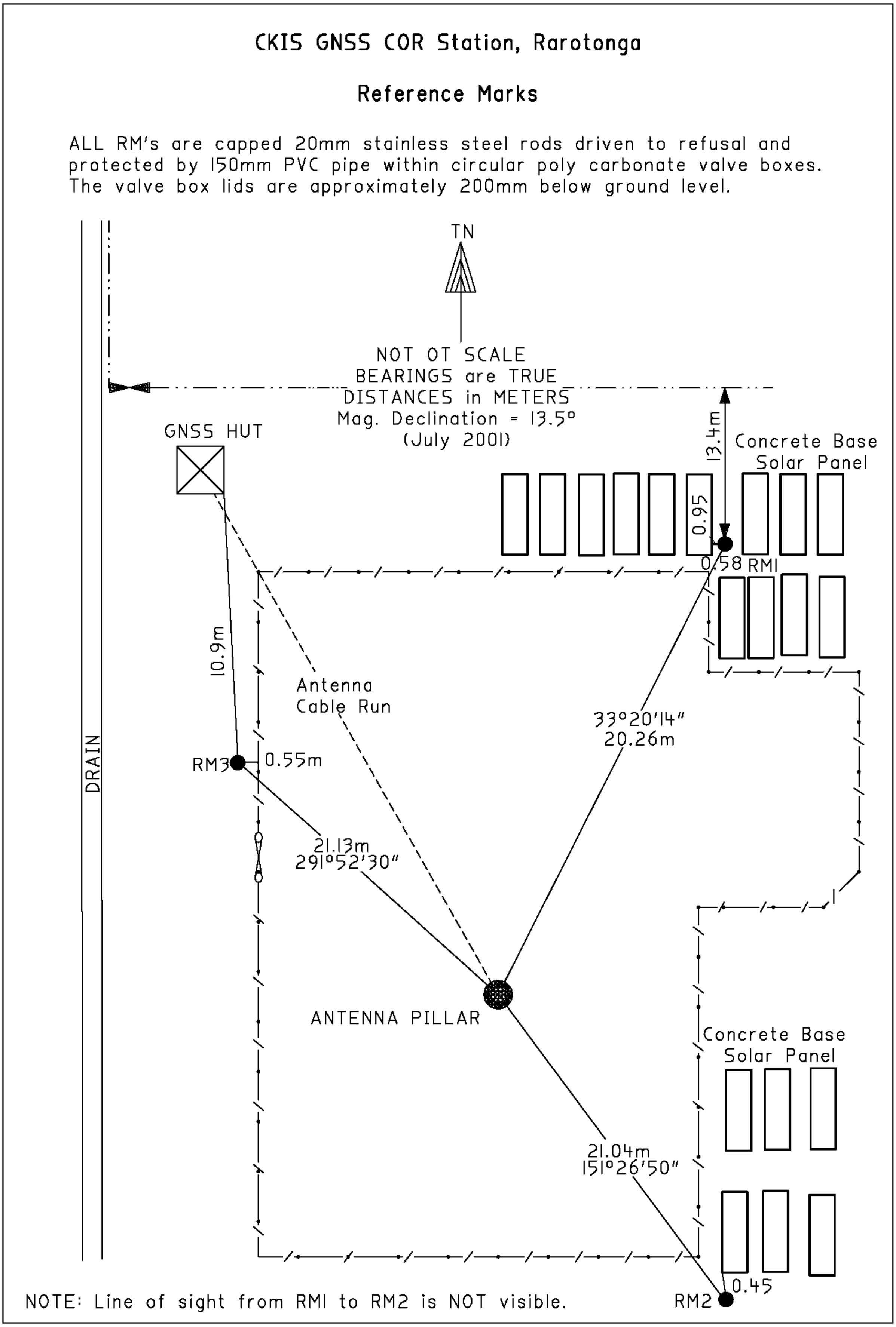
COUNTRY: Cook Islands	ISLAND: Rarotonga CITY: Avatiu	L. D. P. 770 POINT NO. BM 18
PROJECT: PSLGMP	SURVEYOR: A Lal & M.Deo	DATE: 18-01-07



COUNTRY: Cook Islands	ISLAND: Rarotonga CITY: Avatiu	L. D. P. 771 POINT NO. C00 10 & C0056
PROJECT: PSLGMP	SURVEYOR: S M Turner	DATE: 11-02-93



A 3 GNSS Site Reference Marks



Appendix B Planning Aspects and Notes

Upon arranging travel to Cook Islands, 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 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 Cook Islands.

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 Cooks Islands 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 $0.44x10^{-6}$ 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 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 1.00117m.

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

Description

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

- Trimble NETR9 GNSS receiver (S/N 5037K&0402) (firmware: 5.22)
- JAVRINGANT (JAVRINGANT_DM NONE) - S/N 02028