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

Nuku’alofa, Tonga, April 2019

GEOSCIENCE AUSTRALIA
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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 the 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 Nukualofa, Tonga from 7th to 19th July 2019. It also provides an updated height of the tide gauge derived from GNSS time series analysis and precise levelling observations.

GNSS Monitoring Survey

A high precision geodetic terrestrial survey is undertaken to monitor the stability of the GNSS CORS monument. This survey is used to complement GNSS analysis by determining whether movement detected by GNSS analysis is caused by localised movement of the pillar, or movement of the land across a larger area. Local movement is monitored by examining and comparing the results of repeat surveys to the monument and permanent reference marks approximately 20 m from the GNSS monument.

Levelling Survey

The Total Station differential levelling technique is used to observe differences in height along the deep driven benchmark array in Nuku'alofa, which runs approximately 4.0 km from the tide gauge to the GNSS CORS. Previous levelling surveys have been conducted along this route using this technique in 2006, 2007, 2009, 2010, 2012, 2013, 2014, 2016, and 2018 This report contains an analysis of the 2019 Total Station differential levelling and GNSS monitoring results as well as a combined comparison of the previous levelling surveys.

Personnel

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

Tide Gauge Stations in Nuku'alofa

A new tide gauge station was established at the Vuna Wharf in Tonga with the support of the COSPPac2, Bureau of Meteorology, Geoscience Australia, Pacific Community, and the Kingdom of Tonga. This tide gauge station is to replace the tide gauge at Queen Salote wharf. The old tide gauge continues to deteriorate in structure, and this warrants the need to establish a new one and to serve its purpose for the project. The new location is around three kilometres away from the old site. The old tide gauge will be decommissioned in due cause by the Bureau of Meteorology and the project partners, SPC.

2.1 Site Description and Contacts

The levelling benchmark array, GNSS CORS, and SEAFRAME are located approximately 1.2 km east of the Nuku'alofa town centre; from the Tide Gauge at the main ferry terminal, along Bypass Road, to Apifo'ou College where the GNSS CORS is located. The new survey array is of additional 2.8 km from Queen Salote Wharf to Vuna Wharf, where the new Tide Gauge Station is installed.

Access to the site is generally unrestricted during daylight hours, being mindful of school activities and the usual working restrictions on weekends.

Before accessing the tide gauge and conducting works in the wharf area, a courtesy call should be made to the port's authority to advise on working times and intent.

Local Project Contact:	Viliami Folau – Principal Surveyor, Lands and Survey Department Office
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Phone:	+61 8 8366 2621

2.2 Survey Support

The survey team very much appreciated the assistance from the Lands & Survey Division, who made available a staff member for assistance with survey duties across the week and access to office space when required. Ms. Siotasia Malolo and two survey assistants; Mr. Penaia Loamanu and Mr. Netane Ahofono assisted the team during the survey.

Thanks to Mr. Viliami Folau for arranging customs clearance of the survey equipment from the customs authority and sorting it out on time before the team's arrival into Tonga

3 Measurement Network

3.1 Terrestrial Network

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

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

Name	Description
TON15	Brass plaque set in concrete
TON16	SEAFRAME sensor benchmark
TON1	Deep driven benchmark
TON2	Deep driven benchmark
TON60	Deep driven benchmark
TON61	Deep driven benchmark
TON62	Deep driven benchmark
TON63	Deep driven benchmark
TON65	Deep driven benchmark
TON66	Stainless steel benchmark set in concrete base at Vuna Wharf
TONGBM	Reference benchmark for the GNSS CORS pillar
TONG	Pin on GNSS COR Station base plate equipment mounted on concrete pillar
TOGT	Pin on GNSS COR Station base plate at Vuna wharf Tide Gauge Station
AQUA	SEAFRAME sensor benchmark for Vuna wharf Tide gauge station
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.

All other temporary holding marks used in the previous survey were located as per their locality diagrams.

Note: Whilst setting up or using the deep driven benchmark, TON60, which is, in front of the ANZ building, one must be aware that it is impossible to setup a telescopic tripod over the mark; only the bipod can be levelled over the mark; the fence wall is very close to the benchmark

3.1.1 PSLGMP Vertical Reference Frame Wiring Diagram

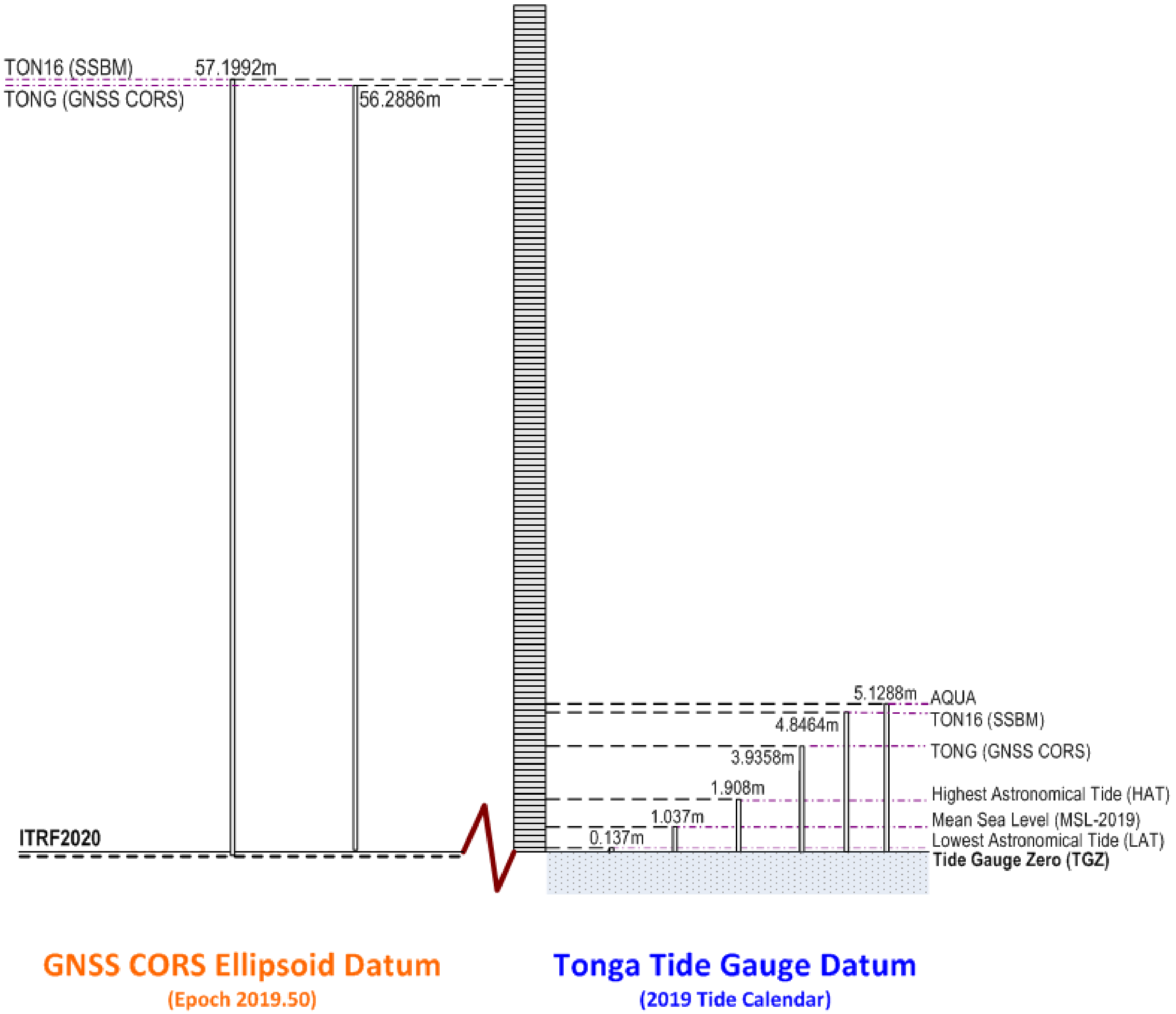


Figure 3.1 Wiring diagram depicting the offsets between surveyed marks. The left-hand side shows the height of the GNSS CORS pillar (TONG), SEAFRAME sensor reference benchmark (TON16), with respect to the International Terrestrial Reference Frame 2020 at epoch 2019.51. The right-hand side shows the height of TONG, TON16, AQUA and tidal datums with respect to tide gauge zero. For more information on tidal datums, please refer to [Pacific Sea Level and Geodetic Monitoring Project File information and Instructions (bom.gov.au)]

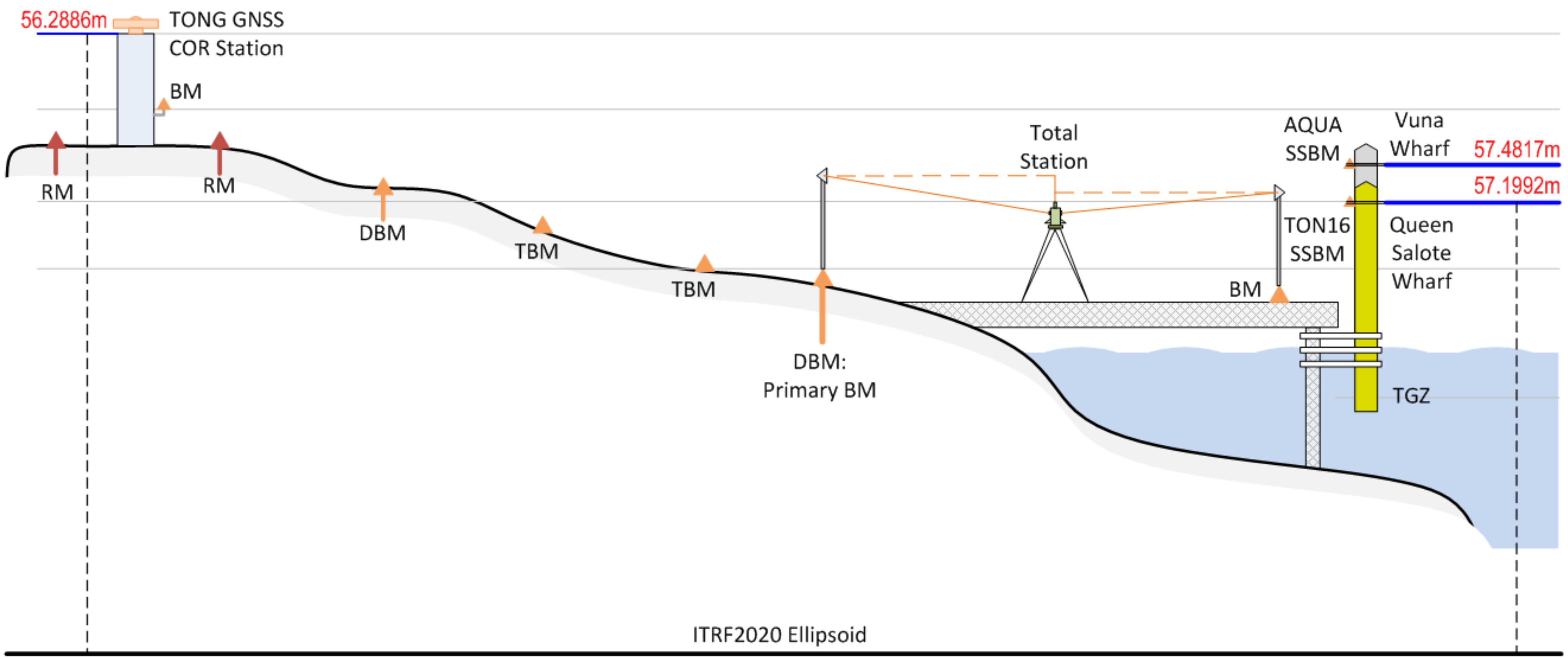


Figure 3.2 Simplified representation of the Total Station differential levelling survey carried out between the GNSS CORS and the SEAFRAME Tide Gauge

Figure 3.3 Tide Gauge Station. The red circle denotes the location of the SEAFRAME sensor reference benchmark (TON16) at the Queen Salote Wharf.

Figure 3.4 Tide gauge facility at Vuna wharf with the tide gauge reference point. (AQUA) Image from 2020.

Figure 3.5: GNSS COR Station (TONG)

Figure 3.6 GNSS COR Station (TOGT) at Vuna Wharf with the Radar Tide Gauge

3.1.2 Levelling Benchmark Network

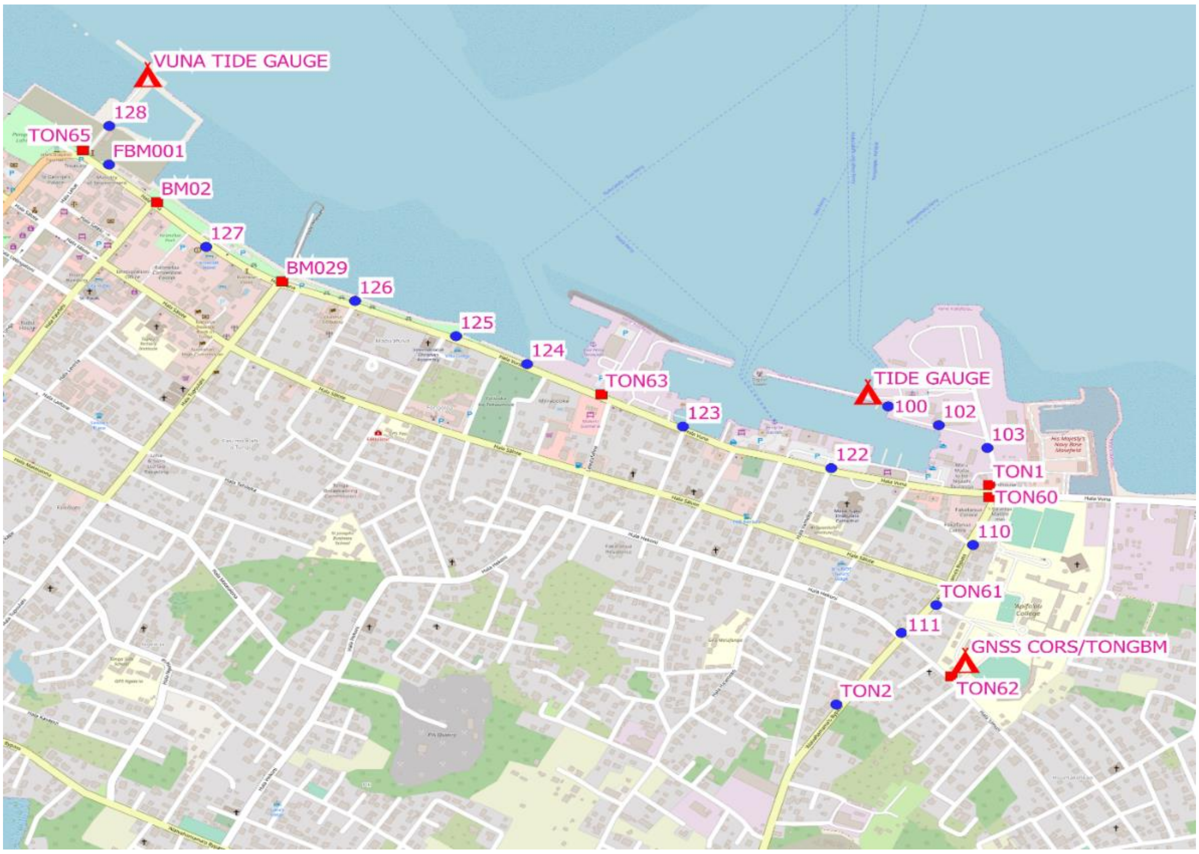


Figure 3.7 Levelling benchmarks in Nukualofa. Source: OSM.org

3.1.3 GNSS CORS and Reference Marks

The GNSS CORS site is located within the Apifou College grounds in Nuku'alofa, Tonga. Access information and the key can be obtained from the Lands and Survey Department if required. The pillar is approximately 40 metres from the building.

Three primary deep driven benchmarks were placed at the time of installation at a distance of 20m to 30m from the GNSS monument at approximately 120-degree radial spacing from true north (Fig 3.8). The RM's consist of capped 20mm stainless steel rods driven to refusal and are protected by 150mm PVC pipe within circular polycarbonate boxes.

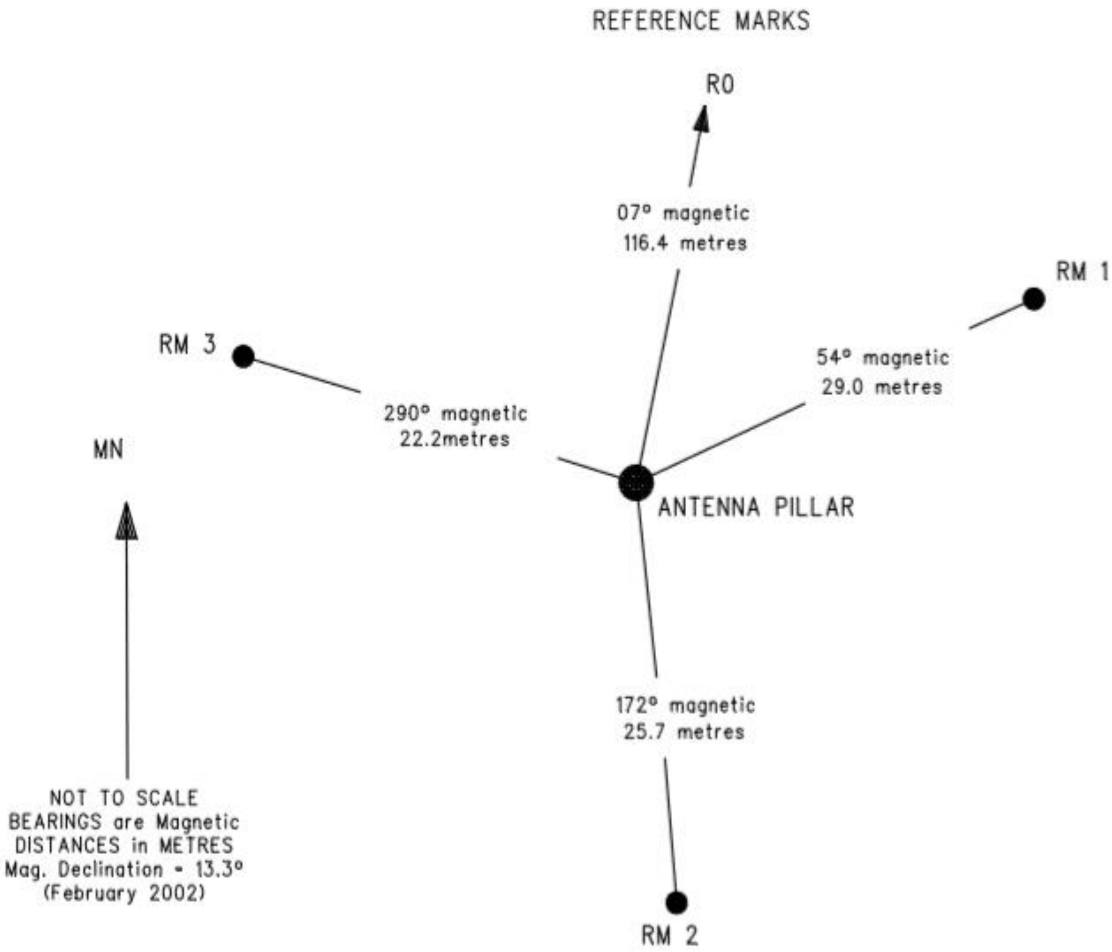


Figure 3.8 GNSS CORS site monitoring survey reference marks

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 TONGBM fixed at 0.0000m.

3.2.2 Historical Survey Datum

The datum for the 2013 and previous surveys is Mean Sea Level (1990) and the adopted reference point for the levelling survey was TON1 fixed at RL of 1.118552m. This value was determined by the National Tidal Centre Australia (NTCA) in October 1993 by adopting the height from the old survey benchmark, BM41 with RL of 1.619m (MSL)

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 the 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.

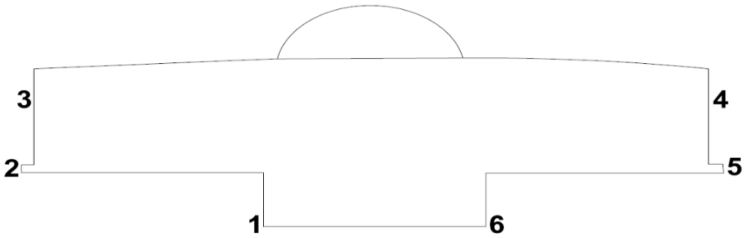


Figure 4.1 Symmetrical points on the antenna profile (TRM59800.00) observed from each RM.

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_.pl. This program computes the height difference between the two reflectors by taking the mean average of the measured height differences and providing standard deviations and a misclose for the input levelling loop. 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 TONGBM.

From	To	Rise(m)	Fall(m)	RL(m)	Dist (km)	Acc Dist (km)
TONGBM				0.0000		0.0000
RM1	**RM1**	0.0000	-1.2390	-1.2390	0.0290	0.0290
RM2	**RM2**	0.0640	0.0000	-1.1750	0.0469	0.0759
RM3	**RM3**	0.0926	0.0000	-1.0824	0.0410	0.1170
RM2	**RM2**	0.0000	-0.0927	-1.1751	0.0410	
RM1	**RM1**	0.0000	-0.0641	-1.2392	0.0469	
	TONGBM	1.2390	0.0000	-0.0003	0.0290	
	Sum:	1.3955	-1.3958			
	Misclose:		-0.0003	-0.0003	0.2340	(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)
TONGBM				0.0000		0.0000
RM2	**RM2**	0.0000	-1.1750	-1.1750	0.0260	0.0260
	TONGBM	1.1749	0.0000	-0.0001	0.0260	
	Sum:	1.1749	-1.1750			
	Misclose:		-0.0001	-0.0001	0.0520	(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)
TONGBM				0.0000		0.0000
RM3	**RM3**	0.0000	-1.0823	-1.0823	0.0230	0.0230
	TONGBM	1.0823	0.0000	0.0000	0.0230	
	Sum:	1.0823	-1.0823			
	Misclose:		0.0000	0.0000	0.0450	(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 (TONG) was tightly constrained to its ITRF2014 coordinates and aligned to TONG-RM1 with an azimuth of 68° 00' 9.79", 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 TONG 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).

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

Table 4.3.2 Latitude, Longitude, and Ellipsoidal Height (metres) for the GNSS & RM stations. ITRF2014@2010.0 Latitude, Longitude coordinates, and ITRF2020@2019.51 ellipsoidal height were adopted at TONG. CCC means all 3 dimensions (in XYZ) are constrained and FFF means they were all free,

Station	Const	Latitude	Longitude	Ellipsoidal height (m)
TONG	**CCC**	-21° 08’ 40.96780”	-175° 10’ 45.18235”	56.2886
RM1	**FFF**	-21° 08’ 40.61425”	-175° 10’ 44.24945”	54.0832
RM2	**FFF**	-21° 08’ 41.79906”	-175° 10’ 45.26991”	54.1474
RM3	**FFF**	-21° 08’ 40.57301”	-175° 10’ 45.82600”	54.2400

Table 4.3.3 Earth Centred Cartesian coordinates and associated standard deviations (metres) for the GNSS & RM stations. ITRF2014@2010.00 Latitude, Longitude coordinates as per https://gnss.ga.gov.au/network ITRF2020@2019.51 ellipsoidal height were adopted at TONG

Description	X	Y	Z	SD(e)	SD(n)	SD(up)
RM1	-5930303.2224	-500174.7981	-2286355.2815	0.0003	0.0001	0.0001
RM2	-5930292.6583	-500144.3593	-2286389.2909	0.0002	0.0003	0.0001
RM3	-5930307.6469	-500129.5215	-2286354.1551	0.0002	0.0002	0.0001
TONG	-5930303.6256	-500147.8195	-2286366.2186	0.0000	0.0000	0.0000

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

FROM	To	ΔE	ΔN	ΔU
TONG	**RM1**	26.9170	10.8737	-2.0486
TONG	**RM2**	-2.5263	-25.5659	-2.1412
TONG	**RM3**	-18.5712	12.1421	-2.0486

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	**TONG**	**RM1**	26.9161	10.8703	-2.2038
2003	**TONG**	**RM1**	26.9159	10.8701	-2.2035
2005	**TONG**	**RM1**	26.9161	10.8705	-2.2052
2007	**TONG**	**RM1**	26.9159	10.8701	-2.2035
2010	**TONG**	**RM1**	26.9154	10.873	-2.2054
2014	**TONG**	**RM1**	26.9150	10.8729	-2.2054
2016	**TONG**	**RM1**	26.9137	10.8724	-2.2054

2018	**TONG**	**RM1**	26.9158	10.8732	-2.2046
2019	**TONG**	**RM1**	26.9170	10.8738	-2.2054
Ref RL	**(as at 2014)**		**26.9157**	**10.8712**	**-2.2045**

Year	From	To	ΔE	ΔN	ΔU
2002	**TONG**	**RM2**	-2.5247	-25.5697	-2.1396
2003	**TONG**	**RM2**	-2.5258	-25.5696	-2.1394
2005	**TONG**	**RM2**	-2.5243	-25.5699	-2.1412
2007	**TONG**	**RM2**	-2.5258	-25.5696	-2.1394
2010	**TONG**	**RM2**	-2.5244	-25.5702	-2.1411
2014	**TONG**	**RM2**	-2.5238	-25.5701	-2.1411
2016	**TONG**	**RM2**	-2.5234	-25.5696	-2.1411
2018	**TONG**	**RM2**	-2.5268	-25.5663	-2.141
2019	**TONG**	**RM2**	-2.5263	-25.5659	-2.1412
Ref RL	**(as at 2014)**		**-2.5248**	**-25.5699**	**-2.1403**

Year	From	To	ΔE	ΔN	ΔU
2002	**TONG**	**RM3**	-18.5731	12.1370	-2.0469
2003	**TONG**	**RM3**	-18.5728	12.1370	-2.0467
2005	**TONG**	**RM3**	-18.5729	12.1371	-2.0484
2007	**TONG**	**RM3**	-18.5728	12.1371	-2.0467
2010	**TONG**	**RM3**	-18.5735	12.1359	-2.0485
2014	**TONG**	**RM3**	-18.5738	12.1352	-2.0484
2016	**TONG**	**RM3**	-18.5739	12.1350	-2.0485
2018	**TONG**	**RM3**	-18.5718	12.1417	-2.049
2019	**TONG**	**RM3**	-18.5712	12.1421	-2.0486
Ref RL	**(as at 2014)**		**-18.5732**	**12.1366**	**-2.0476**

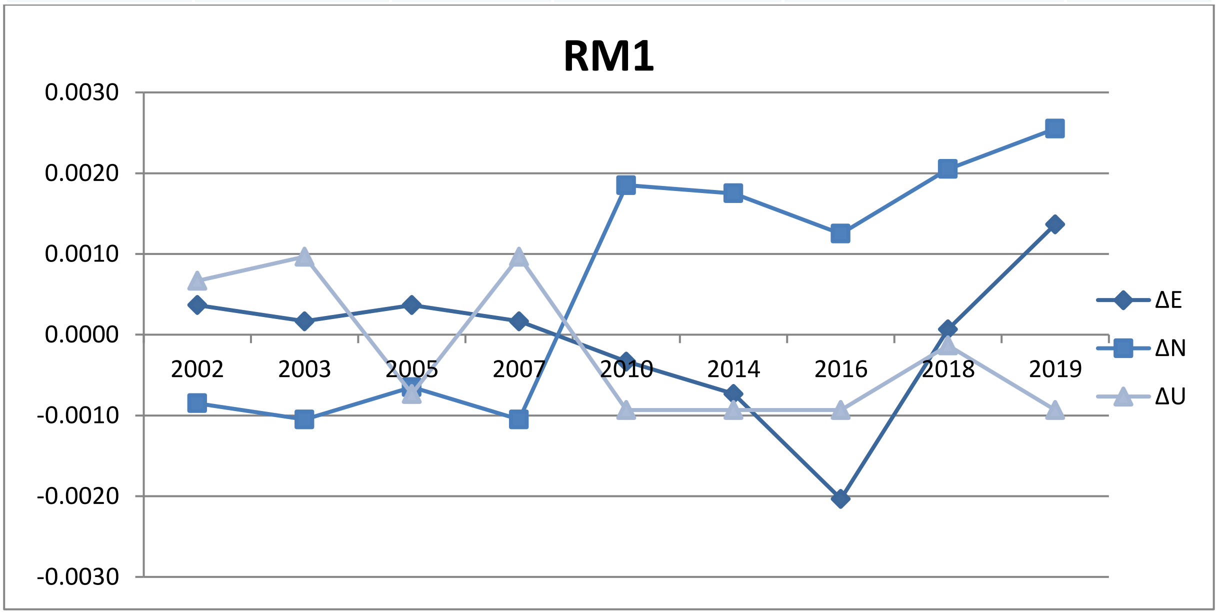


Figure 4.4.1 Time series of RM1 movement relative to GNSS (0 = REF pre 2014 mean)

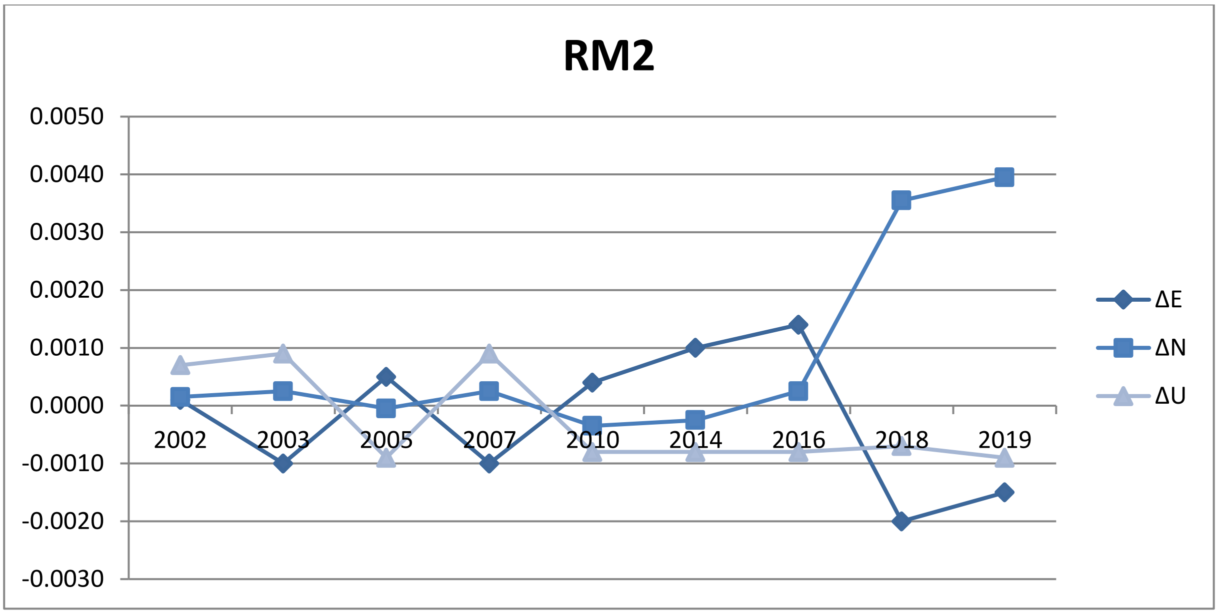


Figure 4.4.2 Time series of RM2 movement relative to GNSS (0 = REF pre 2014 mean)

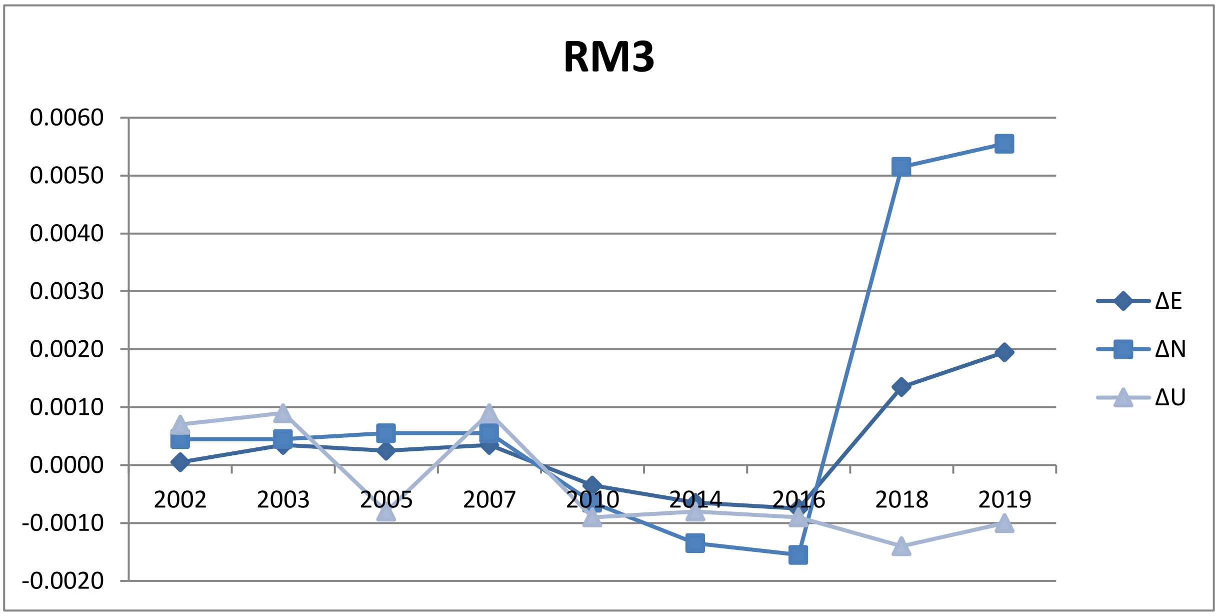


Figure 4.4.3 Time series of RM3 movement relative to GNSS (0 = REF pre 2014 mean)

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 Nuku'alofa tide gauge levelling survey. This technique uses a 'leapfrog' method which involves setting up a Total Station midway between two target/reflectors (on a reflector rod with bipod). 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 benchmark 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
TONG (Ellipsoidal ht)	56.2886	Observed RL at the ARP of TONG (Ellipsoidal) @ 2019.51
TONG - TONGBM	-0.9662	Offset constant between GNSS Monument (Pillar plate) & GNSSBM
Primary Pole & 1/2m Pole	1.00081	Height difference between poles used (Calibrated July 2019)
Primary Pole & TG Pole	1.42996	Height difference between poles used (Calibrated July 2019)

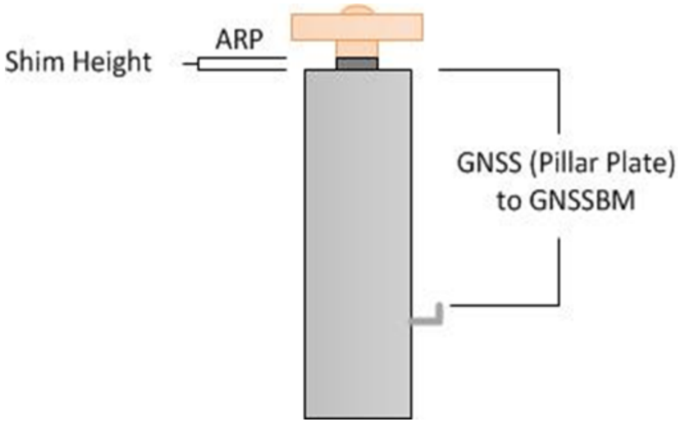


Figure 5.2.1 GNSS Pillar Offsets

5.3 Data Analysis and Results

Reduction of the digital data was computed using the Geoscience Australia levelling program "levelingFIELD_3.pl" and Levelling1.exe. This program computes the height difference between the two reflectors by taking the mean average of the measured height differences and providing standard deviations and a misclose for the input levelling loop.

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

Table 5.3.1 Reduced Level data – TONG (GNSS CORS) to TON15 (Tide Gauge Benchmark)

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
TONG				0.9662		
TONGBM	**TONGBM**	0.0000	-0.9662	0.0000	0.000	0.000
TON62	**TON62**	0.0000	-0.8621	-0.8621	0.062	0.062
111	**111**	0.2747	0.0000	-0.5873	0.174	0.235
TON61	**TON61**	0.0000	-0.3034	-0.8907	0.111	0.347
110	**110**	0.5923	0.0000	-0.2984	0.182	0.528
TON60	**TON60**	0.0000	-0.2428	-0.5412	0.154	0.683
TON1	**TON1**	0.0000	-0.3222	-0.8634	0.055	0.737
103	**103**	0.0458	0.0000	-0.8176	0.139	0.877
102	**102**	0.7873	0.0000	-0.0303	0.110	0.986
100	**100**	0.0000	-0.4981	-0.5285	0.140	1.126
TON15	**TON15**	0.8164	0.0000	0.2880	0.054	1.180
100	**100**	0.0000	-0.8166	-0.5286	0.054	
102	**102**	0.4983	0.0000	-0.0303	0.141	
103	**103**	0.0000	-0.7873	-0.8175	0.104	
TON1	**TON1**	0.0000	-0.0455	-0.8631	0.140	
TON60	**TON60**	0.3222	0.0000	-0.5409	0.055	
110	**110**	0.2430	0.0000	-0.2979	0.155	
TON61	**TON61**	0.0000	-0.5921	-0.8900	0.183	
111	**111**	0.3033	0.0000	-0.5867	0.111	
TON62	**TON62**	0.0000	-0.2745	-0.8612	0.174	
TONGBM	**TONGBM**	0.8620	0.0000	0.0008	0.062	
	TONG	0.9662	0.0000	0.9670	0.000	
	Sum:	5.7115	-5.7107			
	Misclose:		0.0008	0.0008	2.357	(Total Dist.)
			ALLOWABLE (m):	**0.0022**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.2 Reduced level data – 111 to TON2

From	To	Rise (m)	Fall (m)	RL (m)	Dist (Km)	Acc Dist (km)
111				-0.5870		0.235
129	**129**	0.0000	-0.0856	-0.6726	0.148	0.384
TON2	**TON2**	0.0000	-0.5106	-1.1832	0.100	0.484
129	**129**	0.5103	0.0000	-0.6729	0.100	
	111	0.0856	0.0000	-0.5873	0.148	
	Sum:	0.5959	-0.5962			
	Misclose:		-0.0002	-0.0002	0.248	(Total Dist.)
			ALLOWABLE (m):	**0.0007**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.3 Reduced level data – TON15 (Tide Gauge Benchmark) to TON16 (Tide Gauge Sensor Benchmark)

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
TON15				0.2880		1.180
TON16	**TON16**	1.5888	0.0000	1.8768	0.011	1.191
	TON15	0.0000	-1.5889	0.2879	0.011	0.000
	Sum:	1.5888	-1.5889			
	Misclose:		0.0000	0.0000	0.023	(Total Dist.)
			ALLOWABLE (m):	**0.0002**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.4 Reduced level from TON1 to TOGT (Tide Gauge GNSS Reference benchmark point)

From	To	Rise(m)	Fall(m)	RL(m)	Dist (km)	Acc Dist (km)
TON1				-0.8632	0.000	0.737
120	**120**	0.7549	0.0000	-0.1083	0.210	0.947
121	**121**	0.4168	0.0000	0.3084	0.190	1.136
122	**122**	0.0000	-0.4269	-0.1185	0.209	1.345
123	**123**	0.0000	-0.3195	-0.4380	0.193	1.538
TON63	**TON63**	0.0000	-0.0950	-0.5330	0.124	1.662
124	**124**	0.0154	0.0000	-0.5176	0.190	1.852
125	**125**	0.5467	0.0000	0.0291	0.202	2.054
126	**126**	0.0189	0.0000	0.0480	0.195	2.249
BM039	**BM039**	0.0000	-0.1206	-0.0727	0.195	2.444
127	**127**	0.1287	0.0000	0.0561	0.204	2.648
TT4P	**TT4P**	0.0000	-0.5340	-0.4779	0.152	2.800
FBM001A	**FBM001A**	0.0000	-0.0060	-0.4839	0.141	2.941
TON65	**TON65**	0.2118	0.0000	-0.2721	0.087	3.028
128	**128**	0.0119	0.0000	-0.2602	0.096	3.124
TON66	**TON66**	0.1772	0.0000	-0.0830	0.154	3.278
TOGT	**TOGT**	2.4257	0.0000	2.3427	0.022	3.300
TON66	**TON66**	0.0000	-2.4258	-0.0831	0.022	
128	**128**	0.0000	-0.1770	-0.2601	0.154	
TON65	**TON65**	0.0000	-0.0120	-0.2720	0.096	
FBM001A	**FBM001A**	0.0000	-0.2118	-0.4838	0.087	
TT4P	**TT4P**	0.0058	0.0000	-0.4780	0.141	
127	**127**	0.5338	0.0000	0.0558	0.152	
BM039	**BM039**	0.0000	-0.1288	-0.0730	0.204	
126	**126**	0.1205	0.0000	0.0475	0.195	
125	**125**	0.0000	-0.0189	0.0286	0.195	
124	**124**	0.0000	-0.5466	-0.5179	0.202	
TON63	**TON63**	0.0000	-0.0157	-0.5336	0.190	

123	**123**	0.0952	0.0000	-0.4384	0.124	
122	**122**	0.3192	0.0000	-0.1192	0.193	
121	**121**	0.4267	0.0000	0.3076	0.209	
120	**120**	0.0000	-0.4169	-0.1093	0.190	
	TON1	0.0000	-0.7552	-0.8645	0.206	
	Sum:	6.2092	-6.2105			
	Misclose:		-0.0013	-0.0013	3.063	(Total Dist.)
			ALLOWABLE (m):	**0.0025**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.5 Reduced level from TON66 to RTGP (Radar Tide Gauge Point)

From	To	Rise(m)	Fall(m)	RL(m)	Dist (km)	Acc Dist (km)
TON66				-0.0830		3.278
RTGP	**RTGP**	2.1664	0.0000	2.0834	0.023	3.301
	TON66	0.0000	-2.1665	-0.0831	0.023	
	Sum:	2.1664	-2.1665			
	Misclose:		-0.0001	-0.0001	0.046	(Total Dist.)
			ALLOWABLE (m):	**0.0003**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.6 Reduced level from TON66 to AQUA (Tide Gauge Sensor Benchmark)

From	To	Rise(m)	Fall(m)	RL(m)	Dist (km)	Acc Dist (km)
TON66				-0.0830		3.278
AQUA	**AQUA**	2.2423	0.0000	2.1593	0.027	3.305
	TON66	0.0000	-2.2422	-0.0829	0.027	
	Sum:	2.2423	-2.2422			
	Misclose:		0.0001	0.0001	0.054	(Total Dist.)
			ALLOWABLE (m):	**0.0003**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.7 Measured height differences (in metres) between all BMs (ΔRL_{2019})

	TONGBM	TON62	TON61	TON60	TON1	TON2	TON15	TON16	TON63	TON65	TON66	TOGT	TONG	RTGP	AQUA
TONGBM	-	-0.8617	-0.8904	-0.5411	-0.8632	-1.1832	0.2880	1.8768	-0.5333	-0.2721	-0.0830	2.3427	0.9662	2.0834	2.1593
TON62	0.8617	-	-0.0287	0.3206	-0.0016	-0.3216	1.1496	2.7385	0.3284	0.5896	0.7786	3.2044	1.8279	2.9450	3.0209
TON61	0.8904	0.0287	-	0.3493	0.0272	-0.2928	1.1784	2.7672	0.3571	0.6183	0.8074	3.2331	1.8566	2.9738	3.0497
TON60	0.5411	-0.3206	-0.3493	-	-0.3222	-0.6422	0.8290	2.4179	0.0078	0.2690	0.4580	2.8838	1.5073	2.6245	2.7003
TON1	0.8632	0.0016	-0.0272	0.3222	-	-0.3200	1.1512	2.7401	0.3300	0.5912	0.7802	3.2060	1.8294	2.9466	3.0225
TON2	1.1832	0.3216	0.2928	0.6422	0.3200	-	1.4712	3.0600	0.6499	0.9111	1.1002	3.5259	2.1494	3.2666	3.3425
TON15	-0.2880	-1.1496	-1.1784	-0.8290	-1.1512	-1.4712	-	1.5889	-0.8213	-0.5600	-0.3710	2.0548	0.6782	1.7954	1.8713
TON16	-1.8768	-2.7385	-2.7672	-2.4179	-2.7401	-3.0600	-1.5889	-	-2.4101	-2.1489	-1.9599	0.4659	-0.9106	0.2066	0.2824
TON63	0.5333	-0.3284	-0.3571	-0.0078	-0.3300	-0.6499	0.8213	2.4101	-	0.2612	0.4503	2.8760	1.4995	2.6167	2.6926
TON65	0.2721	-0.5896	-0.6183	-0.2690	-0.5912	-0.9111	0.5600	2.1489	-0.2612	-	0.1890	2.6148	1.2383	2.3555	2.4313
TON66	0.0830	-0.7786	-0.8074	-0.4580	-0.7802	-1.1002	0.3710	1.9599	-0.4503	-0.1890	-	2.4258	1.0492	2.1664	2.2423
TOGT	-2.3427	-3.2044	-3.2331	-2.8838	-3.2060	-3.5259	-2.0548	-0.4659	-2.8760	-2.6148	-2.4258	-	-1.3765	-0.2593	-0.1835
TONG	-0.9662	-1.8279	-1.8566	-1.5073	-1.8294	-2.1494	-0.6782	0.9106	-1.4995	-1.2383	-1.0492	1.3765	-	1.1172	1.1931
RTGP	-2.0834	-2.9450	-2.9738	-2.6245	-2.9466	-3.2666	-1.7954	-0.2066	-2.6167	-2.3555	-2.1664	0.2593	-1.1172	-	0.0759
AQUA	-2.1593	-3.0209	-3.0497	-2.7003	-3.0225	-3.3425	-1.8713	-0.2824	-2.6926	-2.4313	-2.2423	0.1835	-1.1931	-0.0759	-

Table 5.3.8 Time-series of Reduced Levels (with respect to TONGBM)

Year	TONGBM	TON62	TON61	TON2	TON60	TON1	TON3	TON15	TON16	TON63	TON65	TON66	TOGT	TONG	RTGP	AQUA	RM1	RM2	RM3
2002.1	0.000	-0.8628	-0.8912	-1.1845		-0.8640	5.6401	0.2877											
2003.5	0.000	-0.8624	-0.8905	-1.1840		-0.8632	5.6411	0.2882											
2005.5	0.000	-0.8625	-0.8908	-1.1840		-0.8635	5.6407	0.2878											
2005.5	0.000	-0.8625	-0.8907	-1.1844		-0.8642	5.6404	0.2864											
2007.2	0.000	-0.8624	-0.8912	-1.1847	-0.5405	-0.8646	5.6408	0.2891											
2008.8	0.000	-0.8623	-0.8912	-1.1845	-0.5409	-0.8644	5.6407	0.2884											
2010.3	0.000	-0.8622	-0.8909	-1.1837	-0.5412	-0.8644	5.6420	0.2888											
2011.4	0.000	-0.8621	-0.8909	-1.1830	-0.5421	-0.8653	5.6435	0.2867											
2013.3	0.000	-0.8620	-0.8905	-1.1834	-0.5407	-0.8634	5.6420	0.2892											
2014.5	0.000					-0.8644		0.2876											
2014.5	0.000					-0.8644		0.2876						0.9662			-1.2390	-1.1748	-1.0823
2014.7	0.000	-0.8631	-0.8926	-1.1847	-0.5445	-0.8671	5.6411	0.2850	1.8862					0.9662			-1.2390	-1.1748	-1.0823
2016.5	0.000	-0.8620	-0.8904	-1.1827	-0.5417	-0.8639	#N/A	0.2878	1.8807					0.9662			-1.2390	-1.1749	-1.0823
2018.3	0.000	-0.8620	-0.8906	-1.1830	-0.5420	-0.8642	#N/A	0.2875	1.8778	-0.5326	-0.2724	-0.0825	2.3429	0.9662	2.0836	2.1589	-1.2390	-1.1747	-1.0822
2019.5	0.000	-0.8617	-0.8904	-1.1832	-0.5411	-0.8632	-1.1832	0.2880	1.8768	-0.5333	-0.2721	-0.0830	2.3427	0.9662	2.0834	2.1593	-1.2391	-1.1750	-1.0824

5.4 Comparison with previous surveys

All historic data has been readjusted relative to the benchmark attached to the base of the GNSS pillar (TONGBM) (Table 5.3.8). 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.

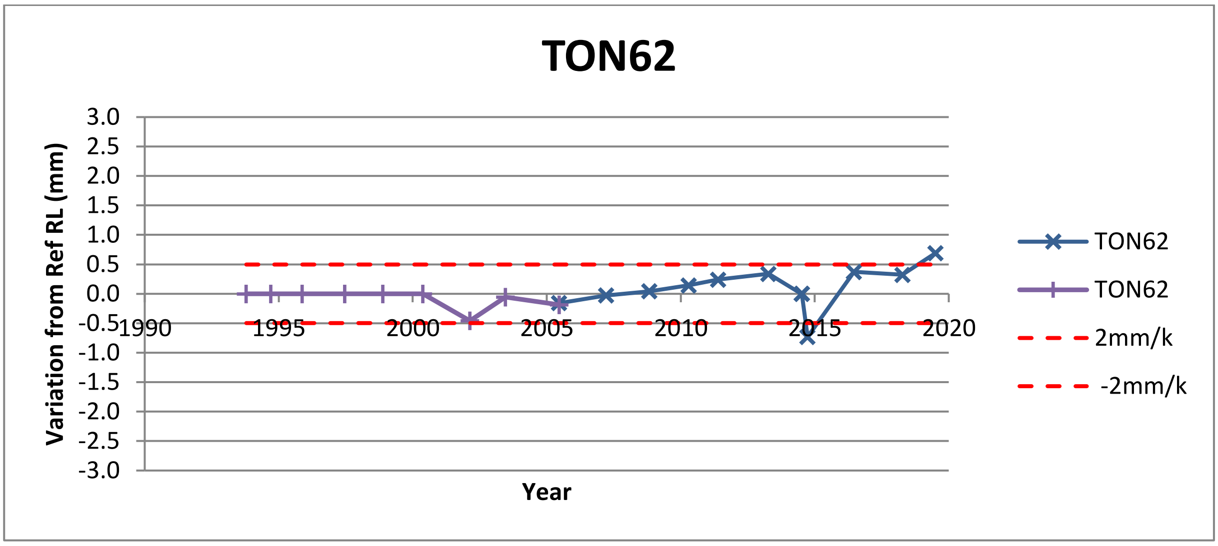
REF - 2019	TONGBM	TON62	TON61	TON60	TON1	TON2	TON15	TON16	TON63	TON65	TON66	TOGT	TONG	RTGP	AQUA
TONGBM	-	-0.0007	-0.0004	-0.0005	-0.0011	-0.0010	-0.0002	0.0024	0.0007	-0.0003	0.0005	0.0001	0.0000	0.0003	-0.0004
TON62	0.0007	-	0.0003	0.0002	-0.0004	-0.0003	0.0005	0.0031	0.0014	0.0004	0.0012	0.0008	0.0007	0.0009	0.0003
TON61	0.0004	-0.0003	-	-0.0001	-0.0007	-0.0006	0.0002	0.0028	0.0011	0.0001	0.0009	0.0005	0.0004	0.0007	0.0000
TON60	0.0005	-0.0002	0.0001	-	-0.0005	-0.0005	0.0003	0.0029	0.0013	0.0002	0.0011	0.0007	0.0005	0.0008	0.0002
TON1	0.0011	0.0004	0.0007	0.0005	-	0.0001	0.0008	0.0035	0.0018	0.0008	0.0016	0.0012	0.0011	0.0013	0.0007
TON2	0.0010	0.0003	0.0006	0.0005	-0.0001	-	0.0008	0.0034	0.0017	0.0007	0.0015	0.0011	0.0010	0.0012	0.0006
TON15	0.0002	-0.0005	-0.0002	-0.0003	-0.0008	-0.0008	-	0.0026	0.0010	-0.0001	0.0008	0.0004	0.0002	0.0005	-0.0001
TON16	-0.0024	-0.0031	-0.0028	-0.0029	-0.0035	-0.0034	-0.0026	-	-0.0017	-0.0027	-0.0019	-0.0022	-0.0024	-0.0021	-0.0028
TON63	-0.0007	-0.0014	-0.0011	-0.0013	-0.0018	-0.0017	-0.0010	0.0017	-	-0.0010	-0.0002	-0.0006	-0.0007	-0.0005	-0.0011
TON65	0.0003	-0.0004	-0.0001	-0.0002	-0.0008	-0.0007	0.0001	0.0027	0.0010	-	0.0008	0.0004	0.0003	0.0005	-0.0001
TON66	-0.0005	-0.0012	-0.0009	-0.0011	-0.0016	-0.0015	-0.0008	0.0019	0.0002	-0.0008	-	-0.0004	-0.0005	-0.0003	-0.0009
TOGT	-0.0001	-0.0008	-0.0005	-0.0007	-0.0012	-0.0011	-0.0004	0.0022	0.0006	-0.0004	0.0004	-	-0.0001	0.0001	-0.0005
TONG	0.0000	-0.0007	-0.0004	-0.0005	-0.0011	-0.0010	-0.0002	0.0024	0.0007	-0.0003	0.0005	0.0001	-	0.0003	-0.0004
RTGP	-0.0003	-0.0009	-0.0007	-0.0008	-0.0013	-0.0012	-0.0005	0.0021	0.0005	-0.0005	0.0003	-0.0001	-0.0003	-	-0.0006
AQUA	0.0004	-0.0003	0.0000	-0.0002	-0.0007	-0.0006	0.0001	0.0028	0.0011	0.0001	0.0009	0.0005	0.0004	0.0006	-

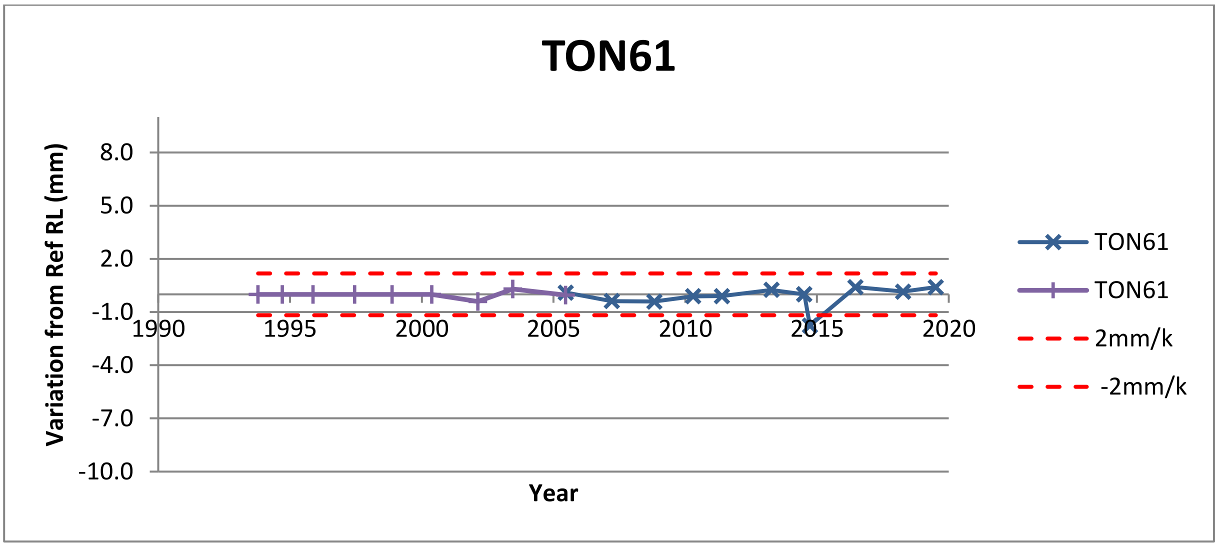
Table 5.4.1.1 values are calculated by subtracting the difference in height between RL$_{2019}$ values (Table 5.3.5) from the difference in height between RL$_{REF}$ values.

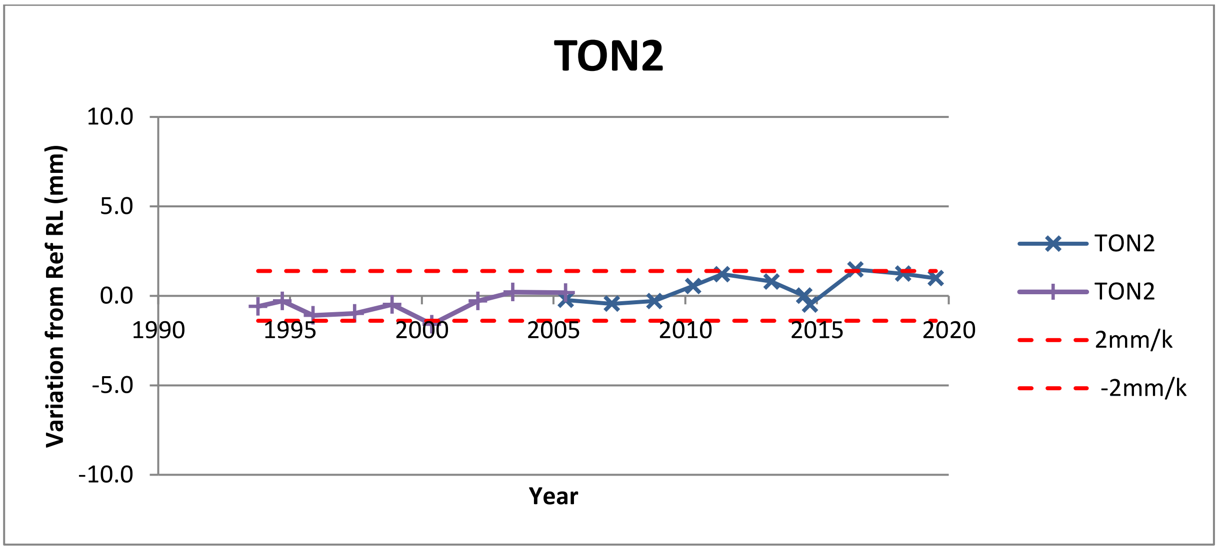
Comparing the change in relative heights between all benchmarks, will help identify the movement of a particular BM, inconsistency in the survey, or even deformation to the GNSS pillar and leveling run BM’s.

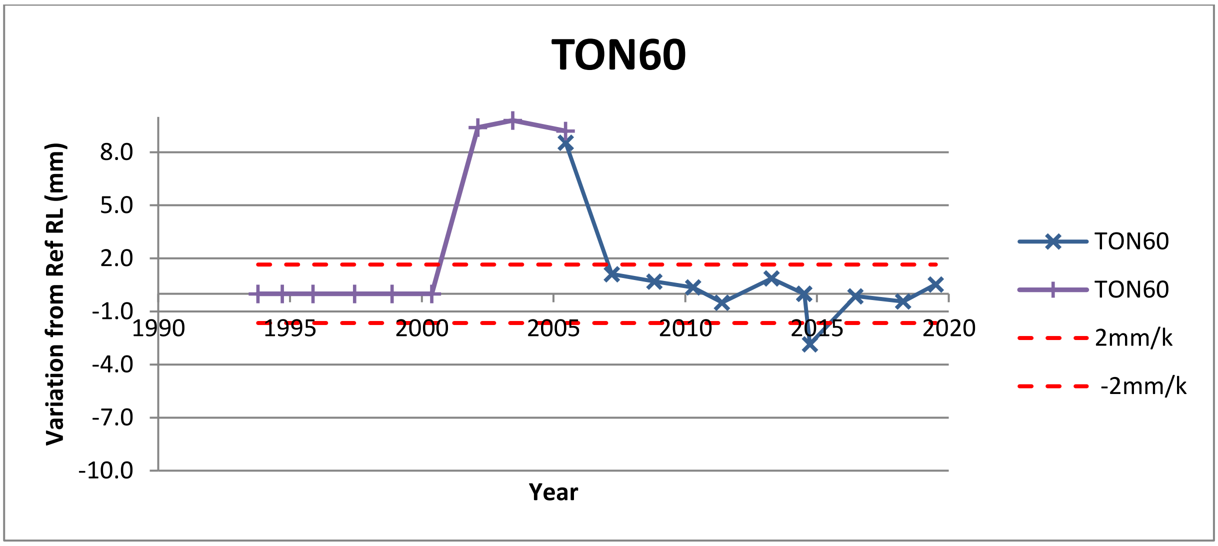
5.4.2 Time Series Charts for each BM

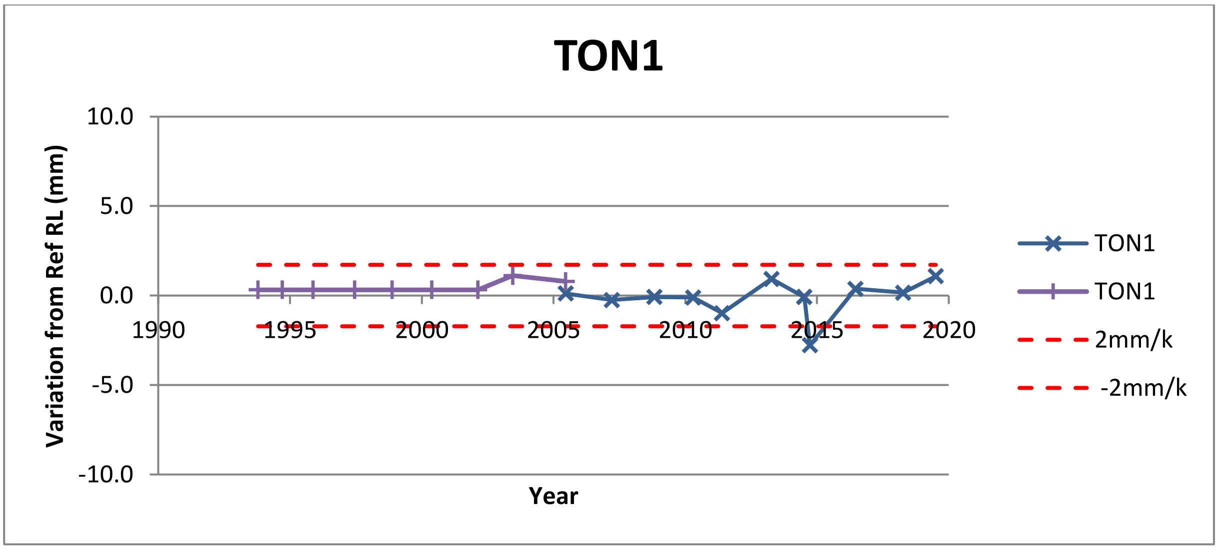
The change in RL over time can be used to detect trends of movement or survey errors. In the series of figures below, the red dashed lines represent the allowable error in height based on the levelling technique used and distance of the benchmark from the GNSS pillar (2mm√k). The purple line (with crosses)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

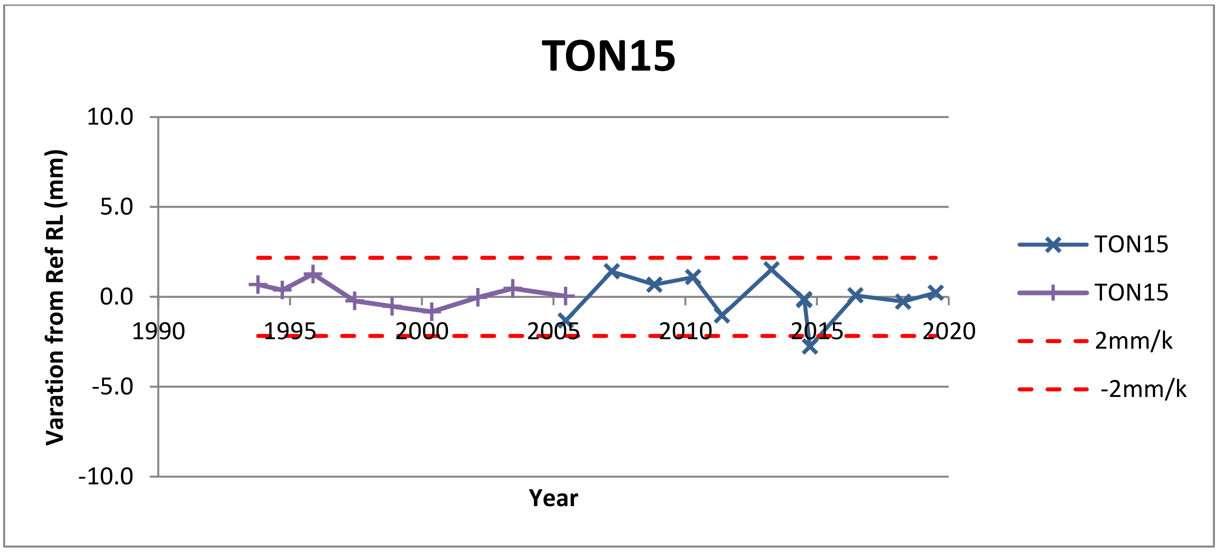


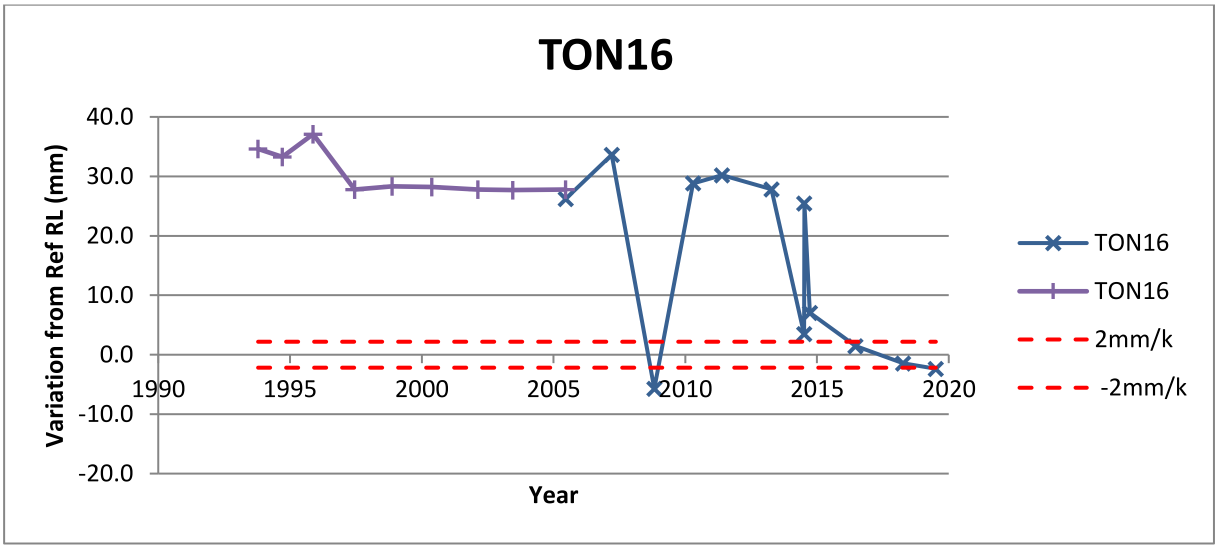


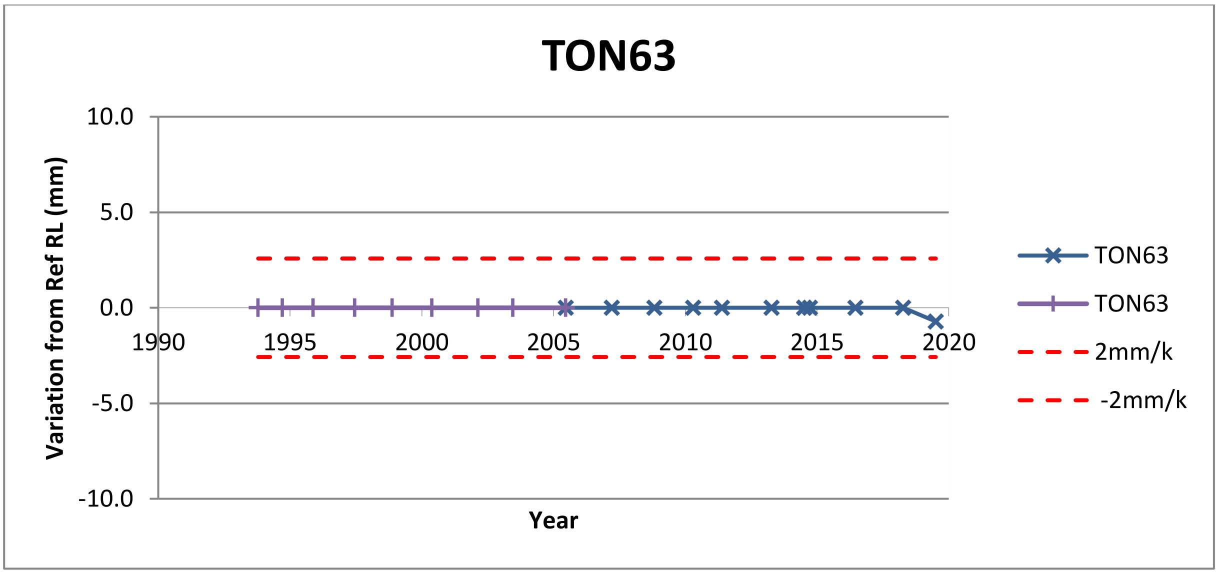

TON2
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Variation from Ref RL (mm)
Year
TON2
TON2
2mm/k
-2mm/k

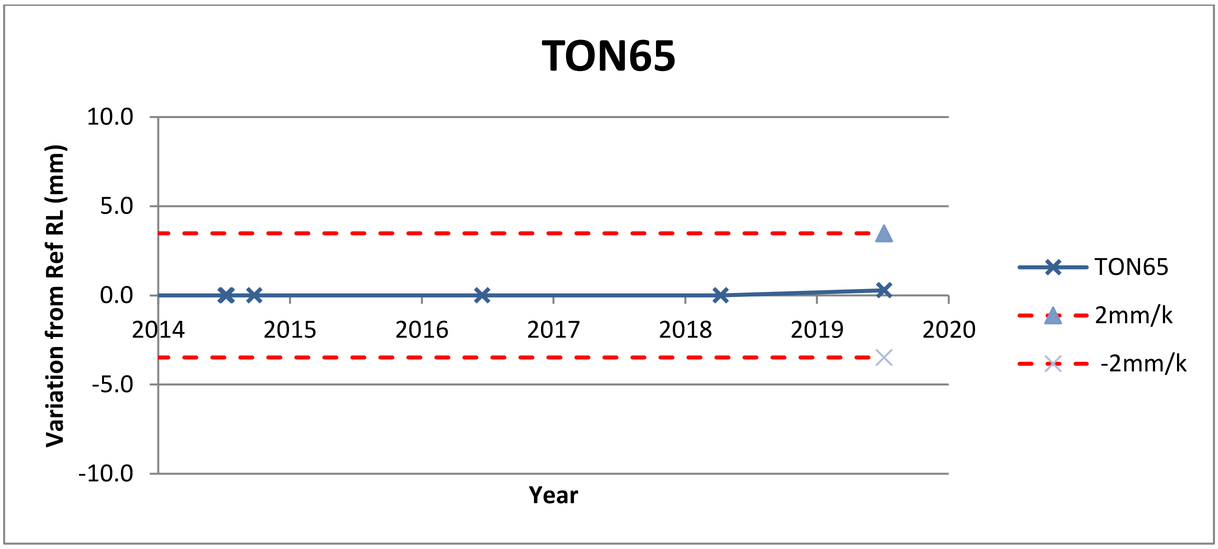

TON60
8.0
5.0
2.0
-1.0
-4.0
-7.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Variation from Ref RL (mm)
Year
TON60
TON60
2mm/k
-2mm/k

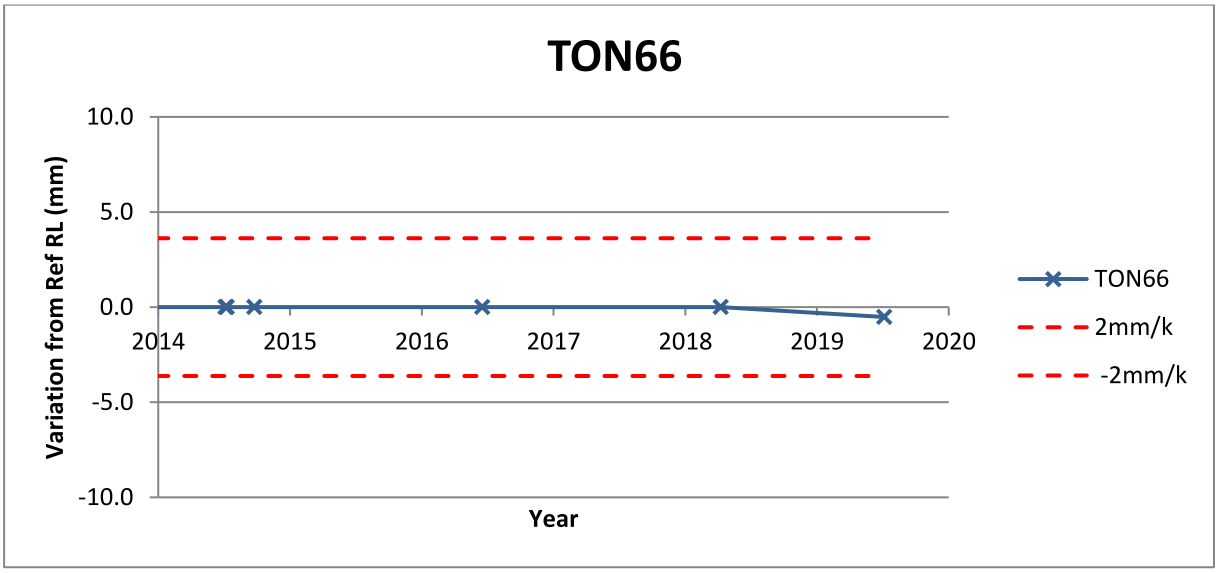

TON1
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Variation from Ref RL (mm)
Year
TON1
TON1
2mm/k
-2mm/k


TON15
10.0
5.0
0.0
-5.0
-10.0
Varation from Ref RL (mm)
1990
1995
2000
2005
2010
2015
2020
Year
TON15
TON15
2mm/k
-2mm/k


TON16
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
Variation from Ref RL (mm)
1990
1995
2000
2005
2010
2015
2020
Year
TON16
TON16
2mm/k
-2mm/k


TON63
10.0
5.0
0.0
-5.0
-10.0
Variation from Ref RL (mm)
1990
1995
2000
2005
2010
2015
2020
Year
TON63
TON63
2mm/k
-2mm/k


TON65
10.0
5.0
0.0
-5.0
-10.0
2014
2015
2016
2017
2018
2019
2020
Variation from Ref RL (mm)
Year
TON65
2mm/k
-2mm/k


TON66
10.0
5.0
0.0
-5.0
-10.0
2014
2015
2016
2017
2018
2019
2020
Variation from Ref RL (mm)
Year
TON66
2mm/k
-2mm/k

6 Assessment of Results

After a full analysis of the monitoring and levelling survey results, the following conclusions can be drawn. There is one difference above 0.003 m at TON 16 due to being struck by vessels and its damaged status.

The survey from the primary GNSSBM (TONGBM) to the TG Plaque (TON15) shows no statistically significant change in height. The wharf structure appears to be solid and not moving, and any movement of the tide gauge is not due to deformation at the wharf.

Figure 6.1 Tonga Tide Gauge Station at Queen Salote Wharf, in July 2019

Table 6.1 Comparison of results with Reference ^H

PT ID	Reference ^H (m)	2019.51 Value (m)	Difference
TONGBM - TON1	-0.8643	-0.8632	0.0011
TON1 - TG Plaque BM (TON15)	1.1520	1.1512	-0.0008
TON1 - TG ref pin (TON16)	2.7435	2.7401	-0.0035
TON15 - TON16	1.5915	1.5889	-0.0026

TONGBM - TON1	-0.8643	-0.8632	0.0011
TON1 - TON15	1.1520	1.1512	-0.0008
TON15 - TON16	1.5915	1.5889	-0.0026
TONG - TG Plaque	-0.6785	-0.6782	0.0002
TONG - TG BM	0.9130	0.9106	-0.0024
TONG - TGZ (original)	-3.9334	-3.9358	-0.0024
TONG - TOGT	1.3767	1.3765	-0.0001

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

PT ID	Reference RL (m)	2019.51 Value (m)	Difference	TGZ	ITRF2020
TONGBM	0.000	0.000	0.0000	2.9696	55.3224
TON62	-0.8623	-0.8617	0.0007	2.1079	54.4608
TON61	-0.8908	-0.8904	0.0004	2.0792	54.4320
TON60	-0.5416	-0.5411	0.0005	2.4285	54.7813
TON1	-0.8643	-0.8632	0.0011	2.1063	54.4592
TON2	-1.1842	-1.1832	0.0010	1.7864	54.1392
TON15	0.2877	0.2880	0.0002	3.2575	55.6104
TON16	1.8792	1.8768	-0.0024	4.8464	57.1992
TON63	-0.5326	-0.5333	-0.0007	2.4363	54.7891
TON65	-0.2724	-0.2721	0.0003	2.6975	55.0503
TON66	-0.0825	-0.0830	-0.0005	2.8865	55.2394
TOGT	2.3429	2.3427	-0.0001	5.3123	57.6651
TONG	0.9662	0.9662	0.0000	3.9358	56.2886
RTGP	2.0836	2.0834	-0.0003	5.0530	57.4058
AQUA	2.1589	2.1593	0.0004	5.1288	57.4817
TGZ (original)	-2.9672	-2.9696	-0.0024		52.3528

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).

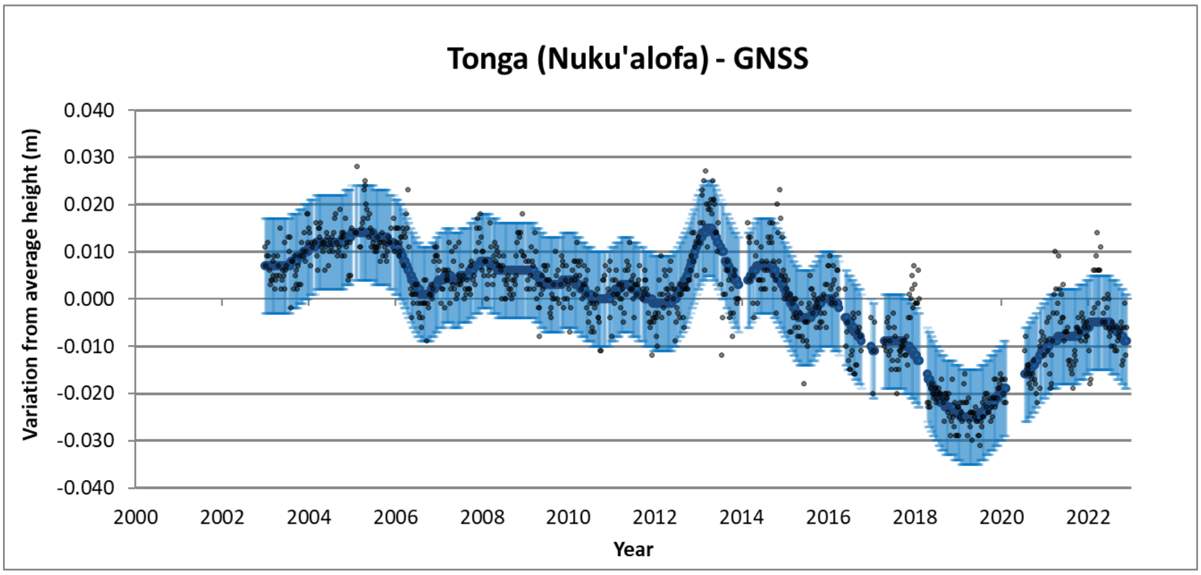


Figure 7.1 Time series of GNSS analysis (dark blue line) with 95%CI uncertainty (light blue lines).

[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.

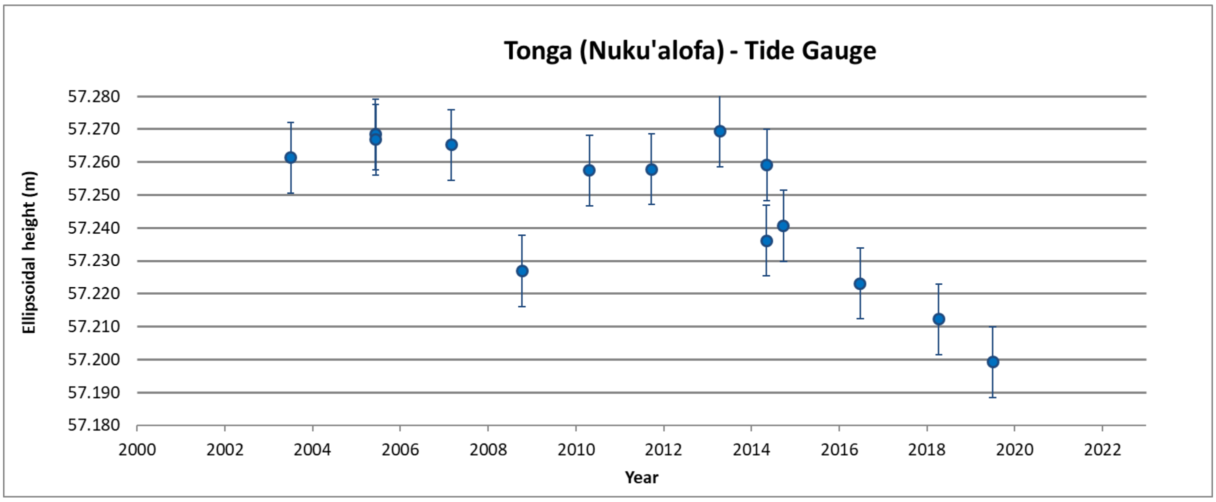


Figure 7.2 The height of the SEAFRAME sensor reference benchmark (with respect to ITRF2020).

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 2014.

Date	Height (m)	Uncertainty (95%CI) (m)
2003.50	57.2613	0.011
2005.43	57.2684	0.011
2005.44	57.2668	0.011
2007.16	57.2652	0.011
2008.77	57.2269	0.011
2010.31	57.2574	0.011
2011.72	57.2578	0.011
2013.28	57.2694	0.011
2014.34	57.2361	0.011
2014.35	57.2591	0.011
2014.73	57.2406	0.011
2016.48	57.2231	0.011
2018.27	57.2122	0.011
2019.51	57.1992	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

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

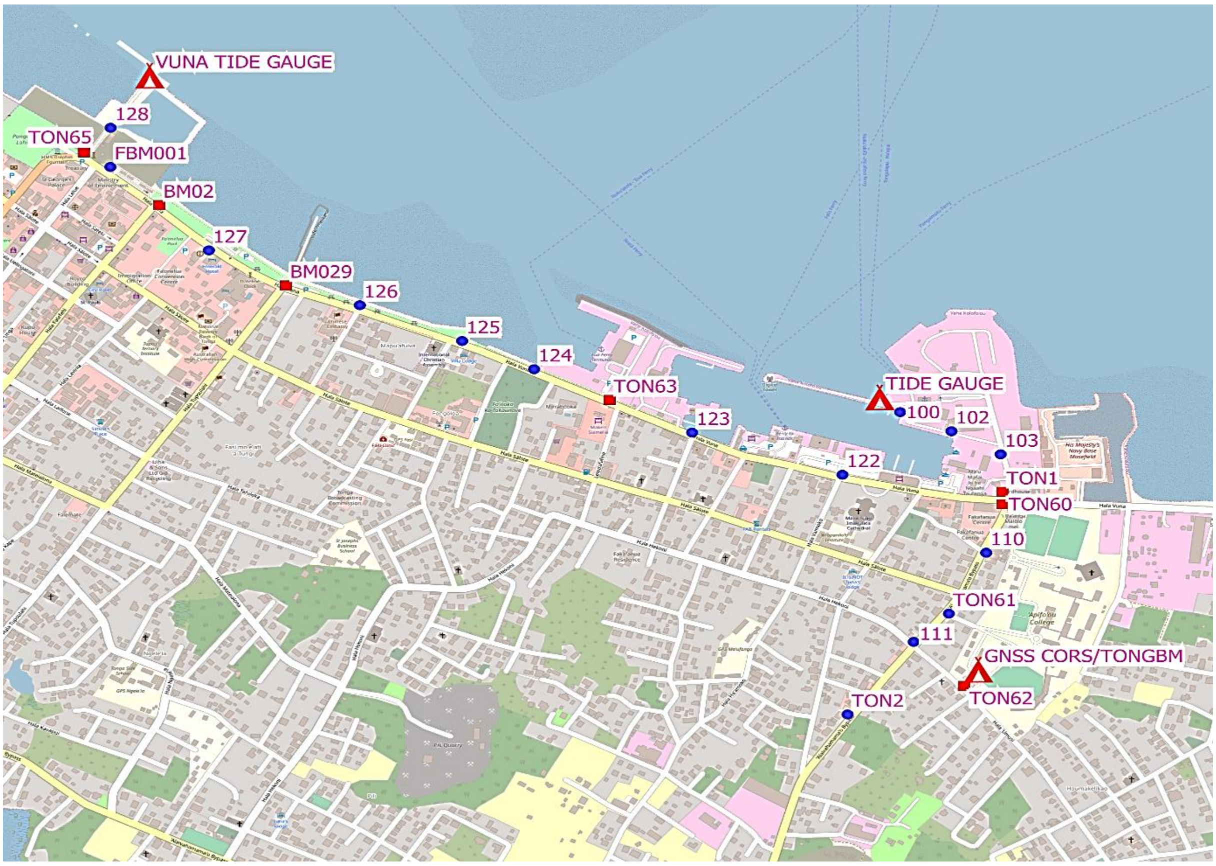
Fraser, R., Leahy, F., Collier, P., 2018. *DynAdjust User's Guide Version 3.0*. Dynamic Network Adjustment Software.

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

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

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

Appendix A Locality Diagrams



Mapping benchmarks on mapping applications to ease locating them for future monitoring surveys. Source: OSM.org

A 1. Deep Benchmarks

PACIFIC SEA LEVEL MONITORING PROJECT

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SURVEY BENCH MARK RECORD

Bench Mark Number: TON1

Original Bench Mark Established by: *Date: 10/10/08*

Geodesy Section, Geoscience Australia & Applied Geoscience and Technology Division, SPC

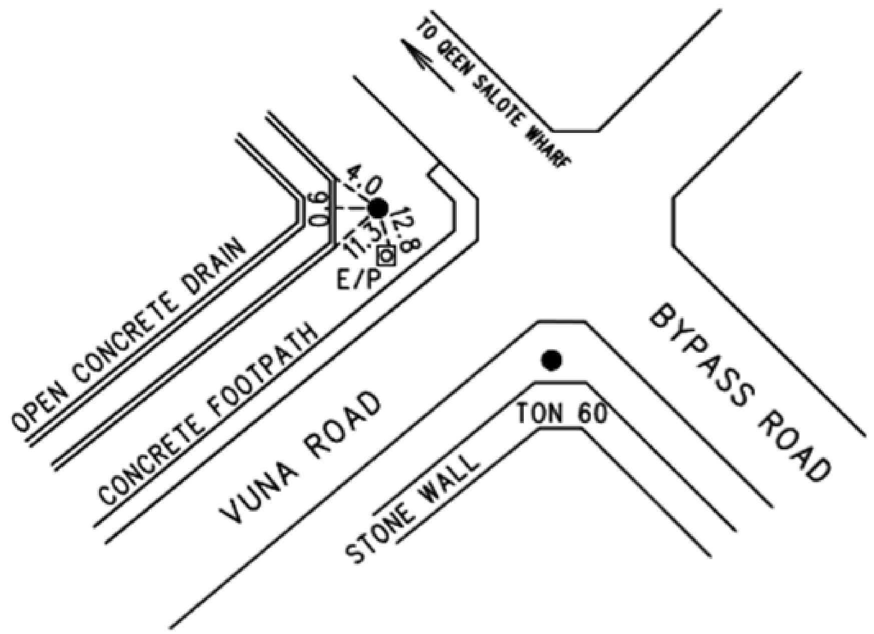
Existing Bench Mark Established by: *Date:*

Notes / References: Stainless Steel Deep Benchmark driven into refusal with casing and Is 20cm below earth surface.

Country: Tonga

Island: Tongatapu *City: Nuku'alofa*

MARKING AND LOCALITY SKETCH



NOT TO SCALE Distances in Metres Magnetic Bearings

Approved by: Geoscience Australia / SPC *Date: 10/10/2008*

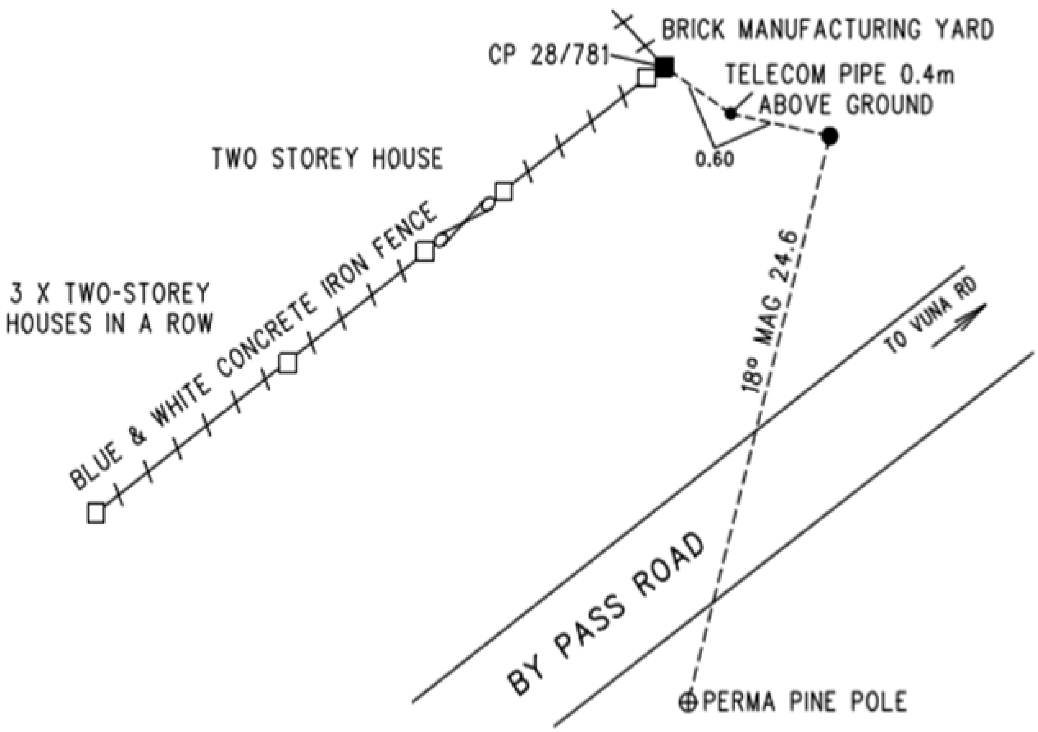
PACIFIC SEA LEVEL MONITORING PROJECT

SURVEY BENCH MARK RECORD

Bench Mark Number: TON2

Original Bench Mark Established by: Geodesy Section, Geoscience Australia & Applied Geoscience and Technology Division, SPC	*Date: 10/10/08*
Existing Bench Mark Established by:	*Date:*
Notes / References: Stainless Steel Deep Benchmark driven into refusal with casing and Is 20cm below earth surface.	
Country: Tonga *Island:* Tongatapu	*City:* *Nuku'alofa*

MARKING AND LOCALITY SKETCH



NOT TO SCALE — Distances in Metres — Magnetic Bearings

Approved by: Geoscience Australia / SPC — *Date: 10/10/2008*

PACIFIC SEA LEVEL MONITORING PROJECT

Australian Aid

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Geoscience Australia

SPC
Secretariat of the Pacific Community

SURVEY BENCH MARK RECORD

Bench Mark Number: TON60

Original Bench Mark Established by: *Date: 10/10/08*

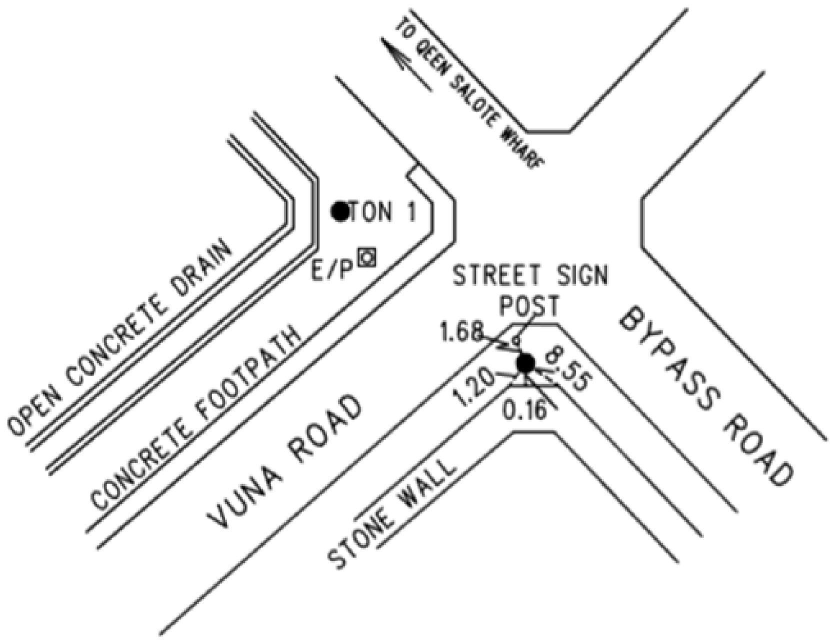
Geodesy Section, Geoscience Australia & Applied Geoscience and Technology Division, SPC

Existing Bench Mark Established by: *Date:*

Notes / References: Stainless Steel Deep Benchmark driven into refusal with casing and Is 20cm below earth surface.

Country: Tonga
Island: Tongatapu *City:* *Nuku'alofa*

MARKING AND LOCALITY SKETCH



NOT TO SCALE Distances in Metres Magnetic Bearings

Approved by: Geoscience Australia / SPC *Date: 10/10/2008*

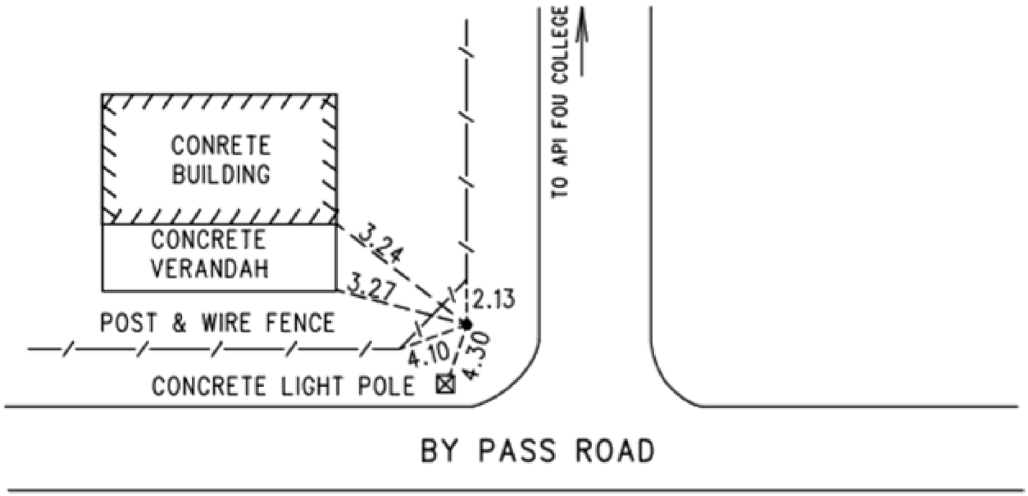
PACIFIC SEA LEVEL MONITORING PROJECT

SURVEY BENCH MARK RECORD

Bench Mark Number: TON61

Original Bench Mark Established by: Geodesy Section, Geoscience Australia & Applied Geoscience and Technology Division, SPC	*Date: 10/10/08*
Existing Bench Mark Established by:	*Date:*
Notes / References: Stainless Steel Deep Benchmark driven into refusal with casing and Is 20cm below earth surface.	
Country: Tonga *Island:* Tongatapu	*City:* *Nuku'alofa*

MARKING AND LOCALITY SKETCH



NOT TO SCALE Distances in Metres Magnetic Bearings

Approved by: Geoscience Australia / SPC *Date: 10/10/2008*

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SURVEY BENCH MARK RECORD

Bench Mark Number: TON62

Original Bench Mark Established by: *Date: 10/10/08*

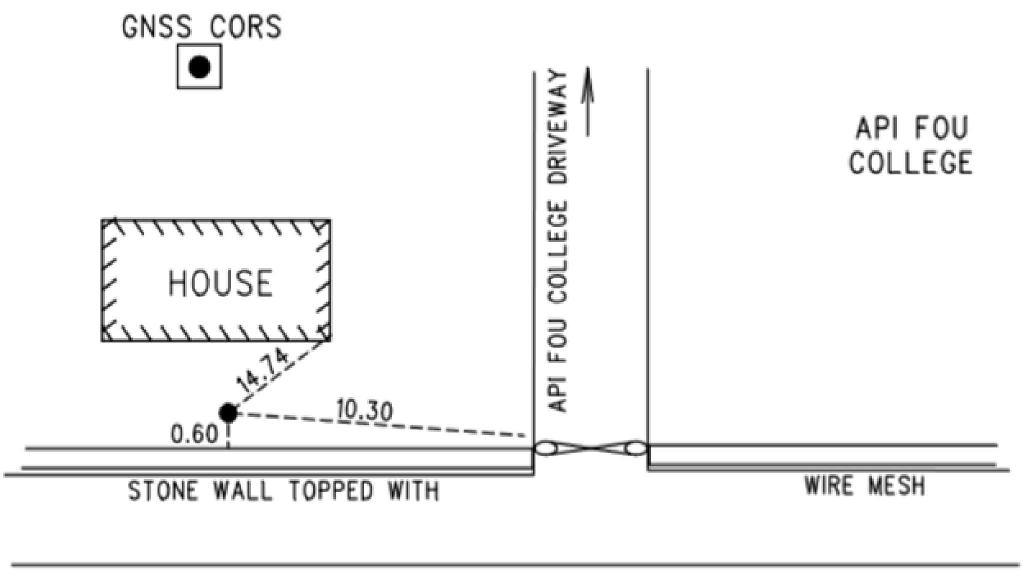
Geodesy Section, Geoscience Australia & Applied Geoscience and Technology Division, SPC

Existing Bench Mark Established by: *Date:*

Notes / References: Stainless Steel Deep Benchmark driven into refusal with casing and Is 20cm below earth surface.

Country: Tonga
Island: Tongatapu *City:* *Nuku'alofa*

MARKING AND LOCALITY SKETCH



NOT TO SCALE Distances in Metres Magnetic Bearings

Approved by: Geoscience Australia / SPC *Date: 10/10/2008*

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Geoscience Australia

SPC Secretariat of the Pacific Community

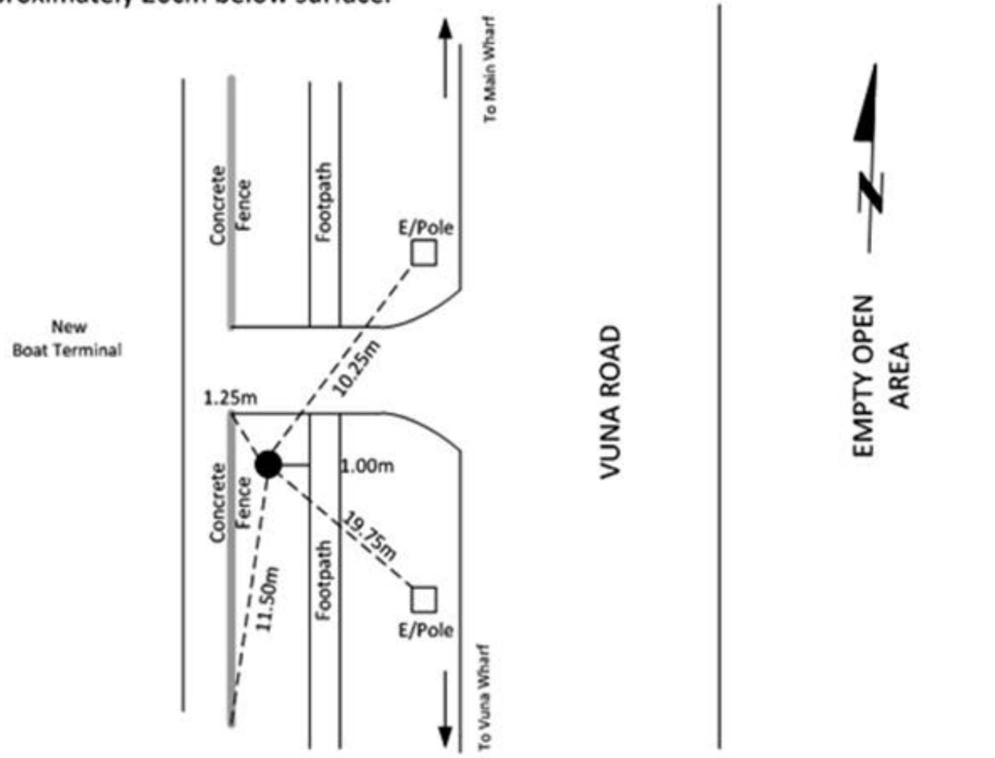
SURVEY BENCH MARK RECORD

Bench Mark Number: TON63

Original Bench Mark Established by: Geodesy Section, Geoscience Australia & Applied Geoscience and Technology Division, SPC	*Date: 17/04/2018*
Existing Bench Mark Established by:	*Date:*
Notes / References: Stainless Steel Deep Driven Benchmark .	
Country: Tonga *Island:* Tongatapu	*City:* *Nuku'alofa*

MARKING AND LOCALITY SKETCH

Bench Mark: Stainless steel Deep Driven Benchmark driven into refusal and approximately 20cm below surface.



NOT TO SCALE Distances in Metres Magnetic Bearings

Approved by: Geoscience Australia / SPC *Date: 30/6/2018*

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SURVEY BENCH MARK RECORD

Bench Mark Number: **TON65**

Original Bench Mark Established by: *Date: 5/06/2018*

Geodesy Section, Geoscience Australia & Applied Geoscience and Technology Division, SPC

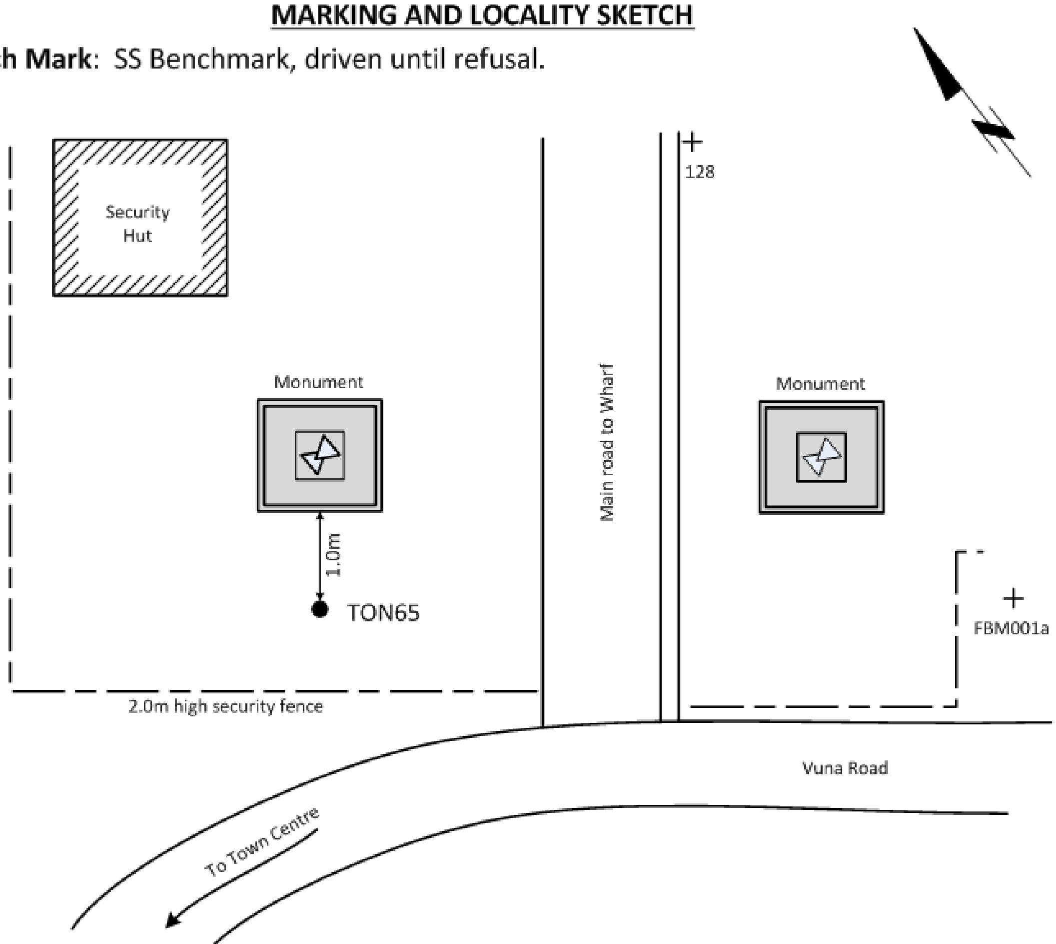
Existing Bench Mark Established by: *Date:*

Notes / References: Stainless Steel Deep Driven Benchmark – 8.0m length.

Country: Tonga
Island: Tongatapu *City:* *Nuku'alofa*

MARKING AND LOCALITY SKETCH

Bench Mark: SS Benchmark, driven until refusal.



NOT TO SCALE Distances in Metres Magnetic Bearings

Approved by: Geoscience Australia / SPC *Date: 30/6/2018*

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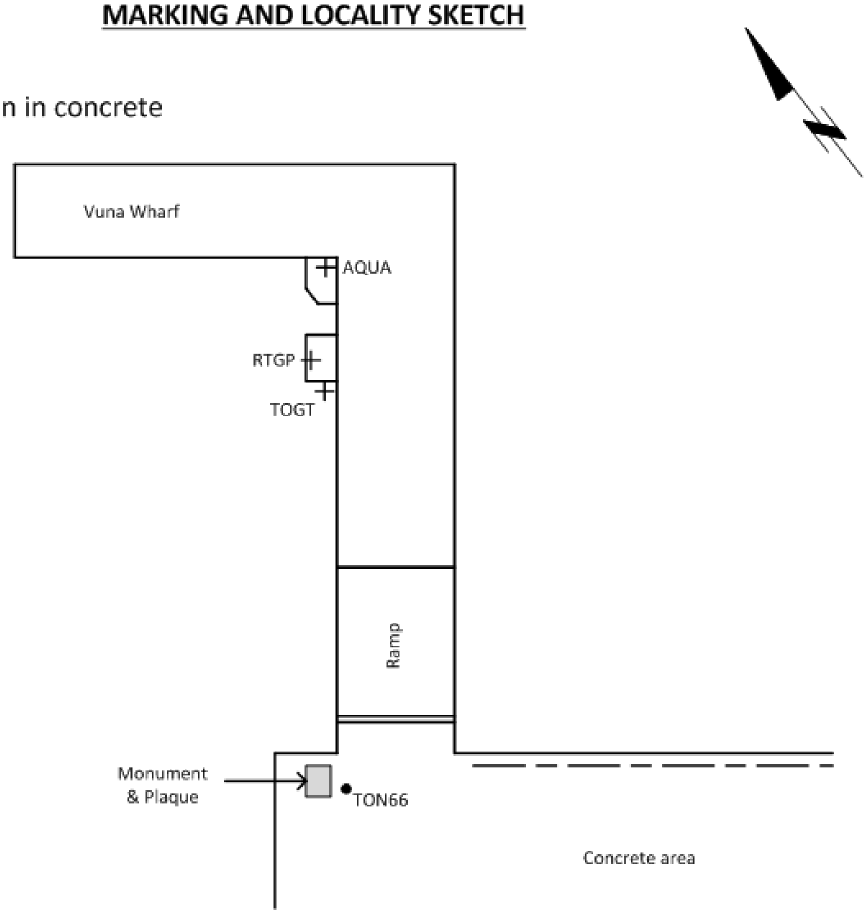
SURVEY BENCH MARK RECORD

Bench Mark Number: TON66

Original Bench Mark Established by: Geodesy Section, Geoscience Australia & Applied Geoscience and Technology Division, SPC	*Date: 5/06/2018*
Existing Bench Mark Established by:	*Date:*
Notes / References: Stainless Steel Pin in concrete foundation	
Country: Tonga *Island:* Tongatapu	*City:* *Nuku'alofa*

MARKING AND LOCALITY SKETCH

Bench Mark: SS pin in concrete



NOT TO SCALE Distances in Metres Magnetic Bearings

Approved by: Geoscience Australia / SPC *Date: 30/6/2018*

PACIFIC SEA LEVEL MONITORING PROJECT

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

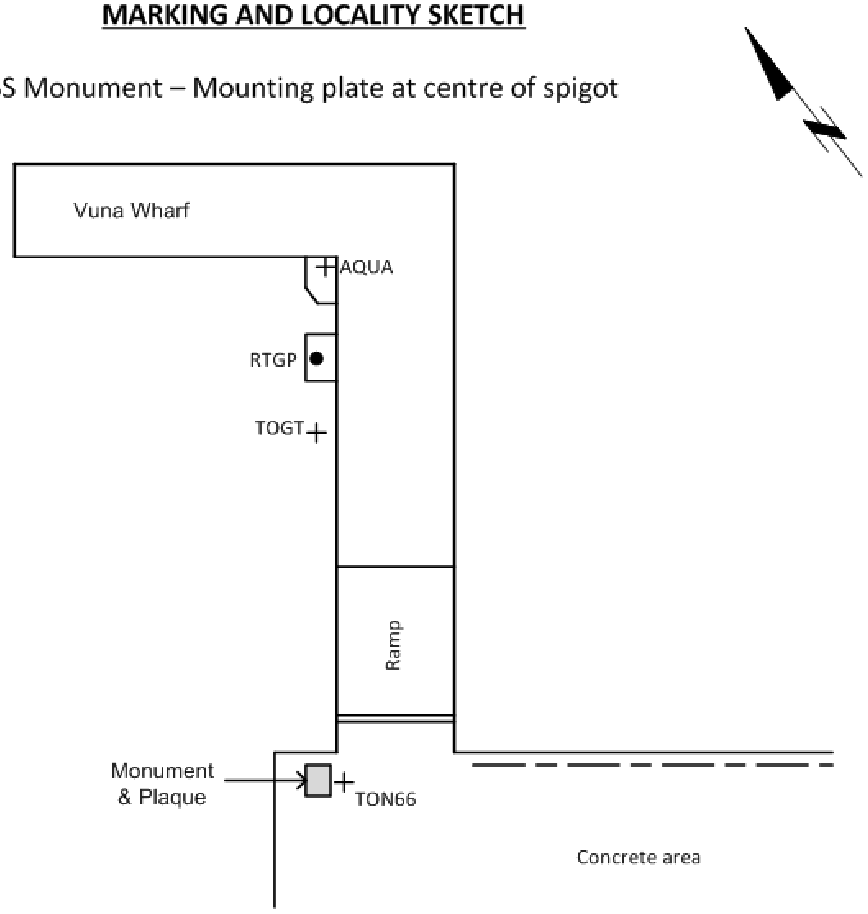
SURVEY BENCH MARK RECORD

Bench Mark Number: RTGP

Original Bench Mark Established by: Geodesy Section, Geoscience Australia & Applied Geoscience and Technology Division, SPC	*Date: 5/06/2018*
Existing Bench Mark Established by:	*Date:*
Notes / References: GNSS mount plate on Radar Tide Gauge structure; Centre and base of spigot	
Country: Tonga *Island:* Tongatapu	*City: Nuku'alofa*

MARKING AND LOCALITY SKETCH

Bench Mark: GNSS Monument – Mounting plate at centre of spigot



NOT TO SCALE | Distances in Metres | Magnetic Bearings

Approved by: Geoscience Australia / SPC | *Date: 30/6/2018*

PACIFIC SEA LEVEL MONITORING PROJECT

Australian Aid

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Geoscience Australia

SPC
Secretariat of the Pacific Community

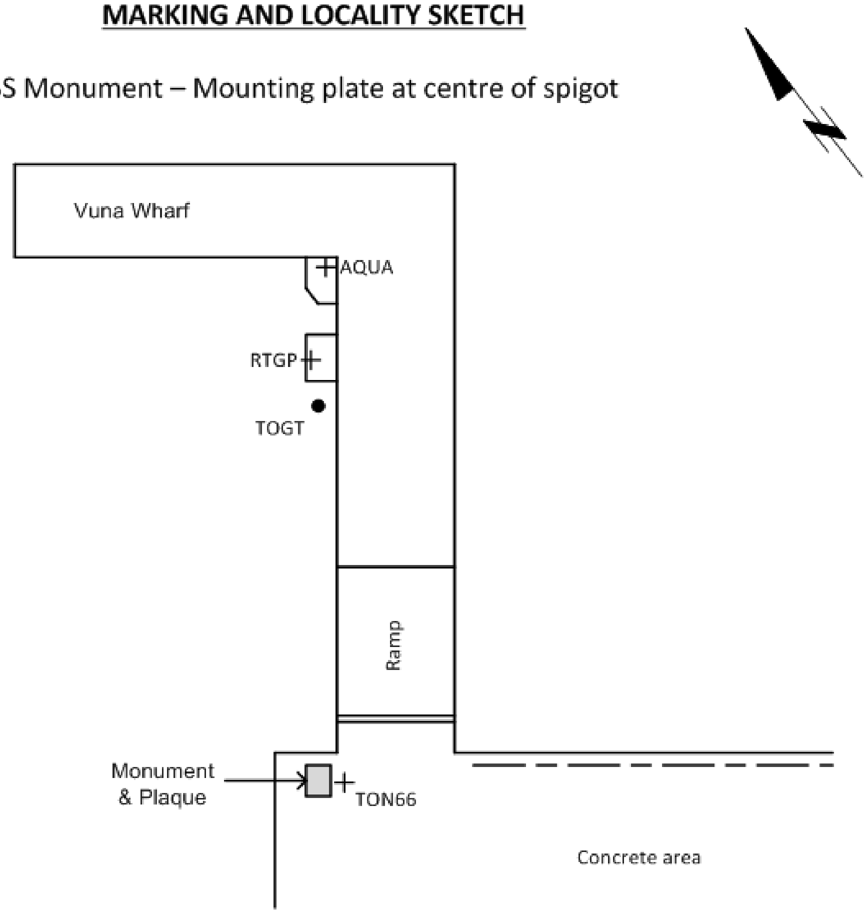
SURVEY BENCH MARK RECORD

Bench Mark Number: TOGT

Original Bench Mark Established by: Geodesy Section, Geoscience Australia & Applied Geoscience and Technology Division, SPC	*Date: 5/06/2018*
Existing Bench Mark Established by:	*Date:*
Notes / References: GNSS mount plate on Radar Tide Gauge structure; Centre and base of spigot	
Country: Tonga *Island:* Tongatapu	*City:* *Nuku'alofa*

MARKING AND LOCALITY SKETCH

Bench Mark: GNSS Monument – Mounting plate at centre of spigot



NOT TO SCALE Distances in Metres Magnetic Bearings

Approved by: Geoscience Australia / SPC *Date: 30/6/2018*

PACIFIC SEA LEVEL MONITORING PROJECT

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

SURVEY BENCH MARK RECORD

Bench Mark Number: AQUA

Original Bench Mark Established by: *Date: 5/06/2018*

Geodesy Section, Geoscience Australia & Applied Geoscience and Technology Division, SPC

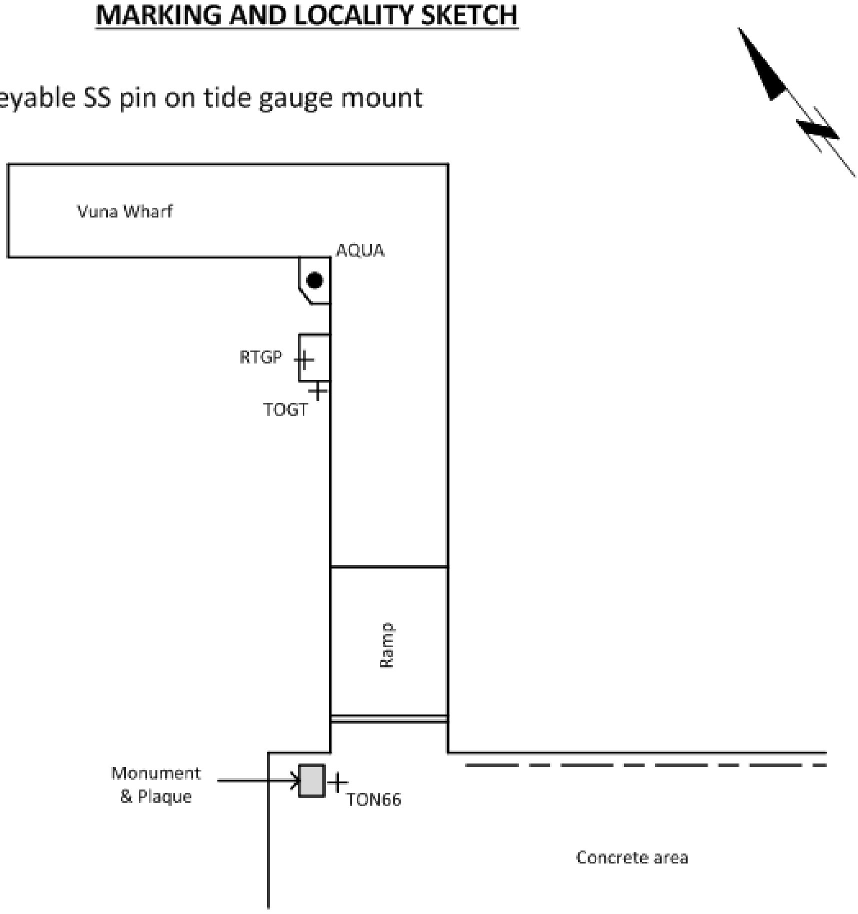
Existing Bench Mark Established by: *Date:*

Notes / References: Surveyable Stainless Steel Pin on Aquatrack collar

Country: Tonga
Island: Tongatapu *City: Nuku'alofa*

MARKING AND LOCALITY SKETCH

Bench Mark: Surveyable SS pin on tide gauge mount

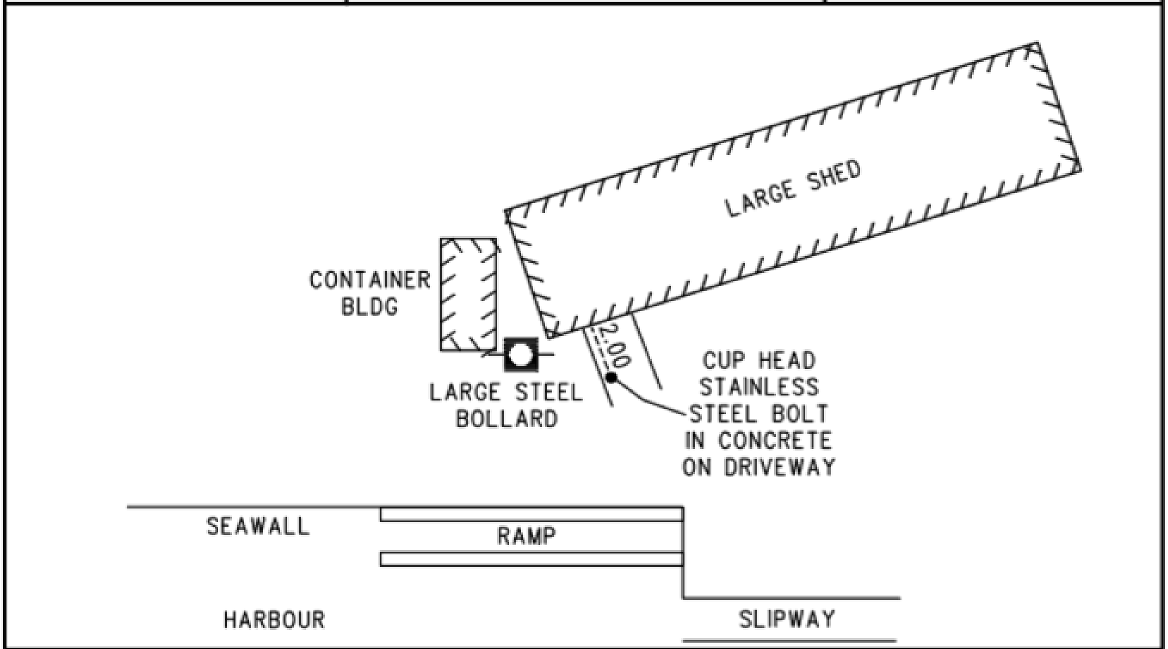


NOT TO SCALE Distances in Metres Magnetic Bearings

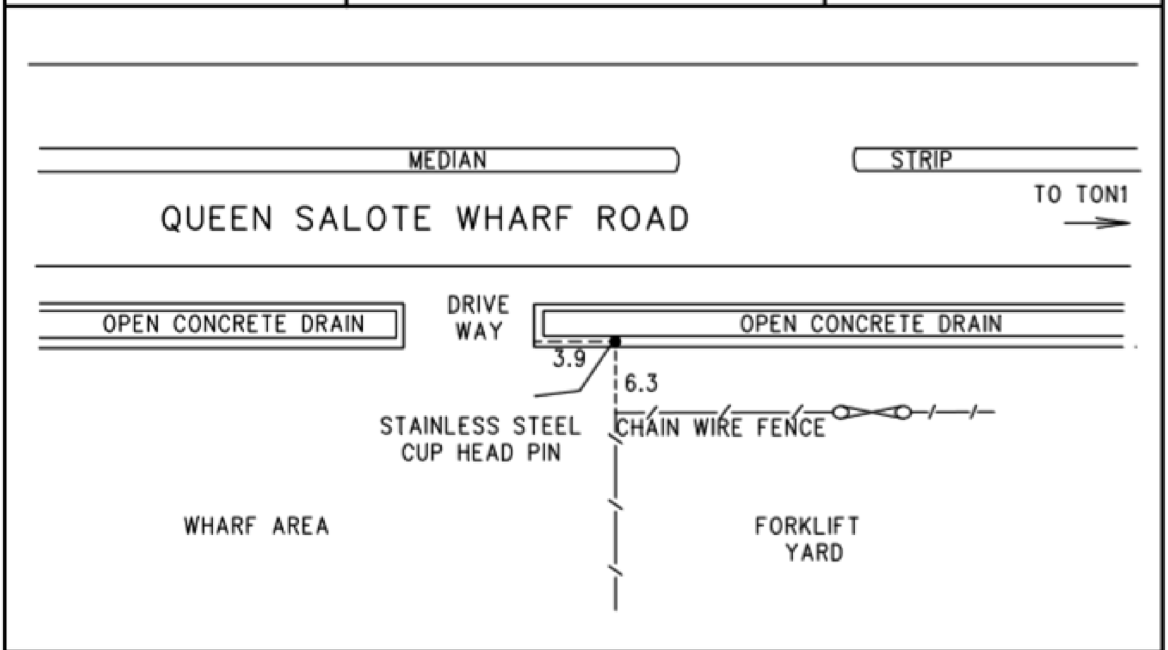
Approved by: Geoscience Australia / SPC *Date: 30/6/2018*

A 2 Temporary Benchmarks

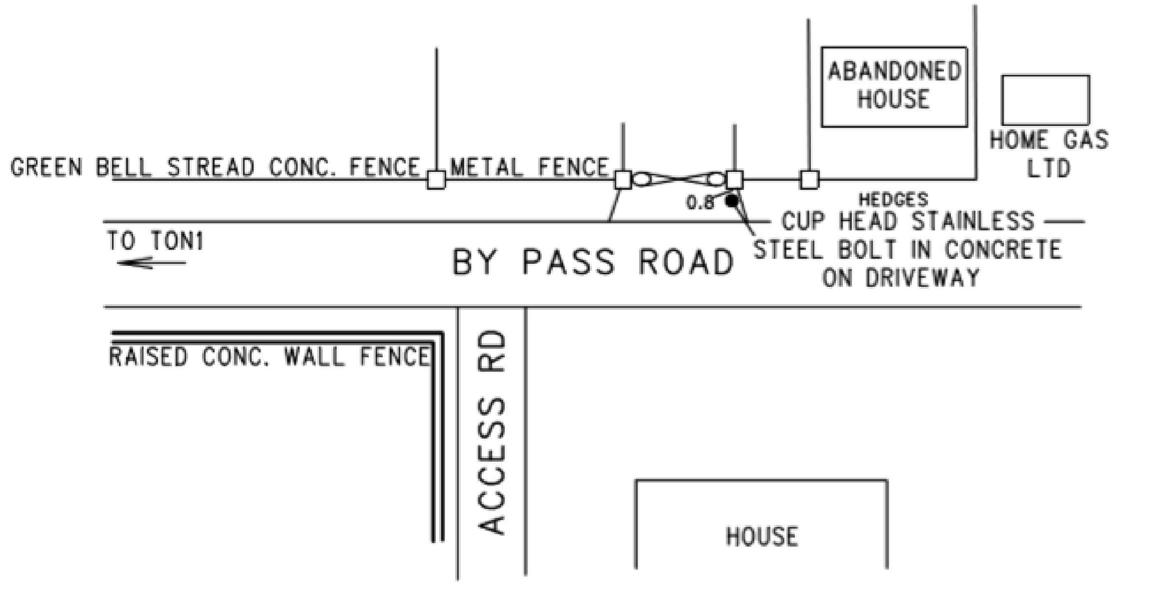
COUNTRY: Tonga	ISLAND: Tongatapu CITY: Nuku'alofa	L. D. P. 873 POINT NO.TON102
PROJECT: SPSLCMP	SURVEYOR: S Yates & A Lal	DATE: 10-10-08



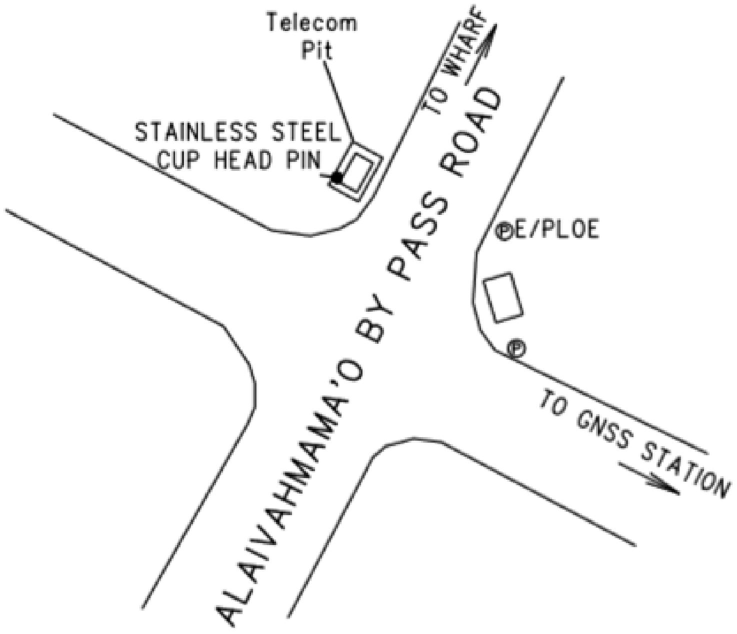
COUNTRY: Tonga	ISLAND: Tongatapu CITY: Nuku'alofa	L. D. P. 874 POINT NO. TON103
PROJECT: SPSLCMP	SURVEYOR: S Yates & A Lal	DATE: 10-10-08



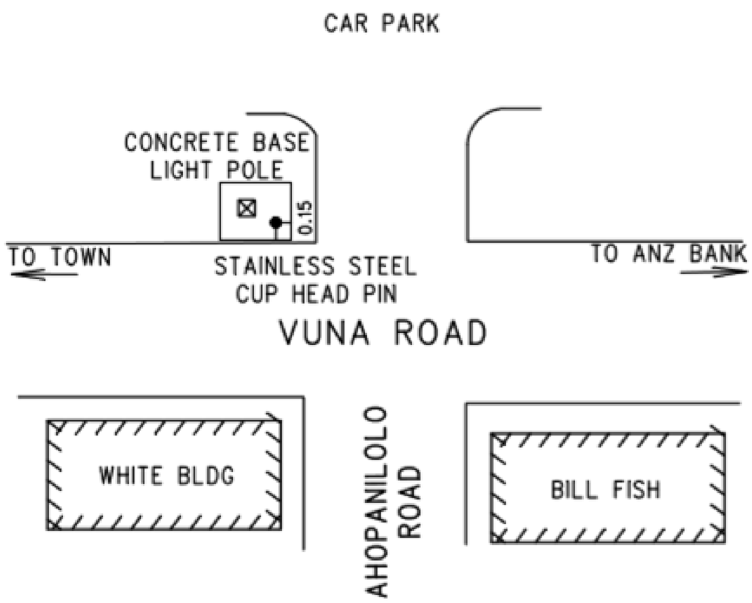
COUNTRY: Tonga	ISLAND: Tongatapu CITY: Nuku'alofa	L. D. P. 875 POINT NO.TON110
PROJECT: SPSLCMP	SURVEYOR: S Yates & A Lal	DATE: 10-10-08



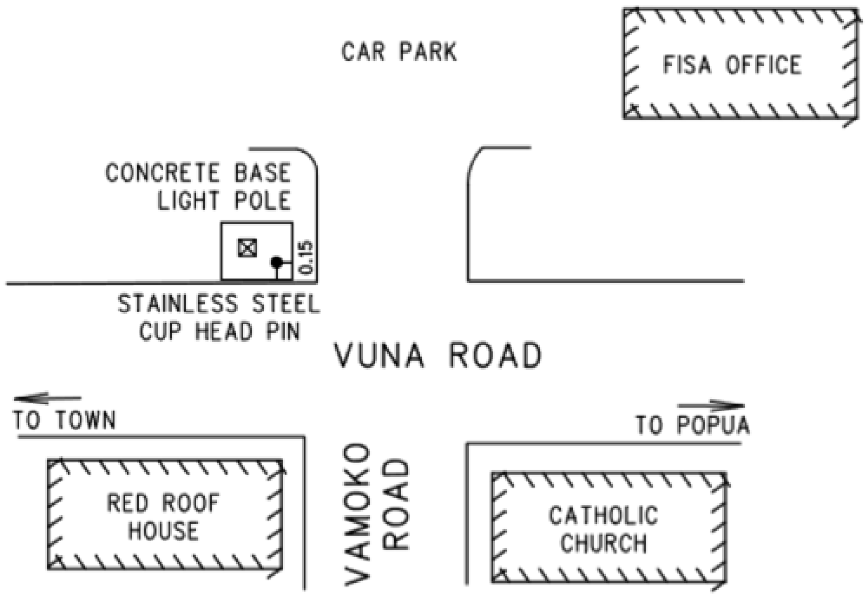
COUNTRY: Tonga	ISLAND: Tongatapu CITY: Nuku'alofa	L. D. P. 876 POINT NO. TON111
PROJECT: SPSLCMP	SURVEYOR: S Yates & A Lal	DATE: 10-10-08



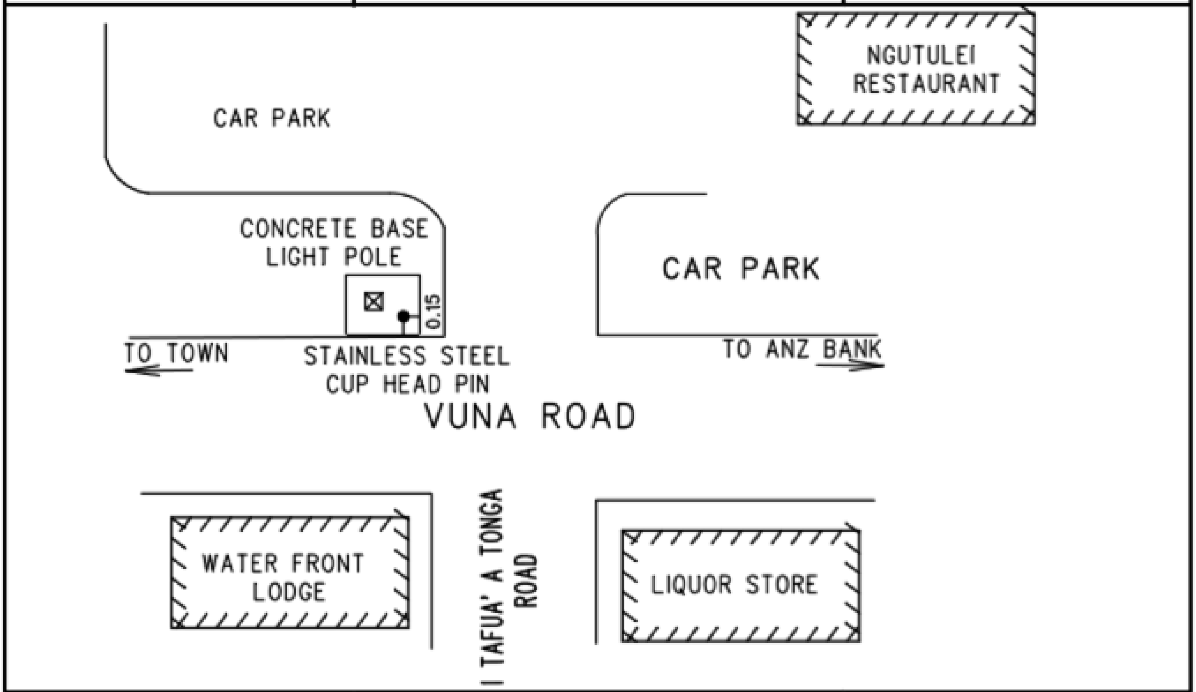
COUNTRY: Tonga	ISLAND: Tongatapu CITY: Nuku'alofa	L. D. P. POINT NO. 120
PROJECT: PSLGMP	SURVEYOR: A.L,V.R,M.K	DATE:18-04-18



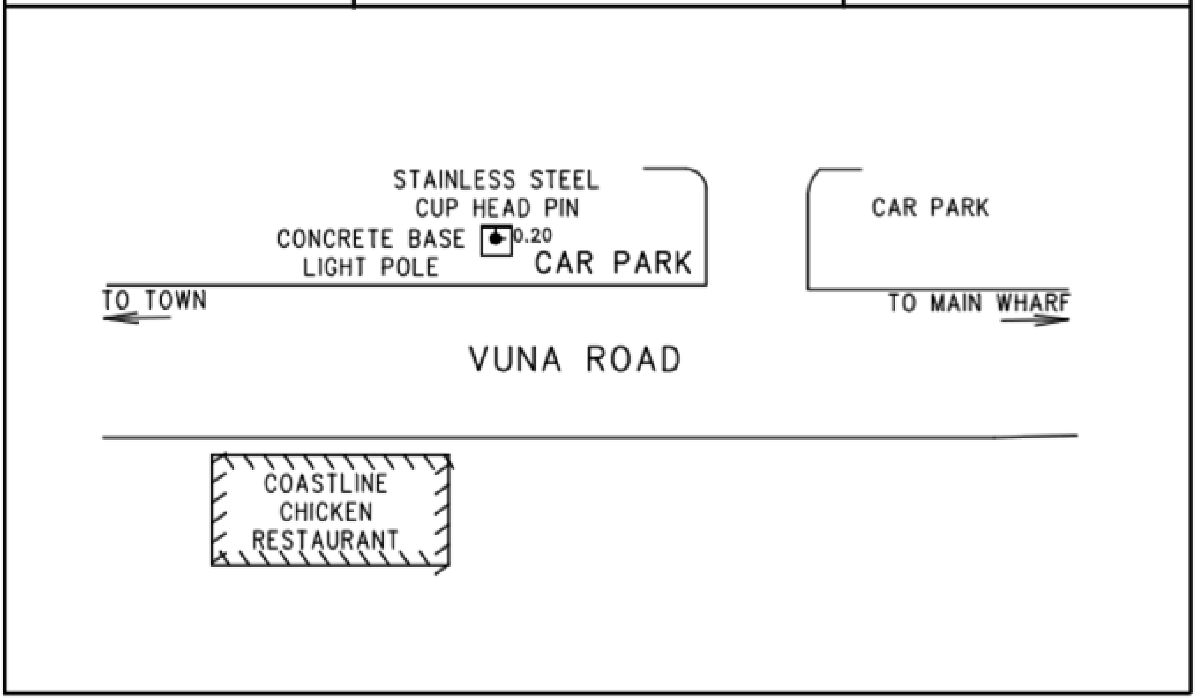
COUNTRY: Tonga	ISLAND: Tongatapu CITY: Nuku'alofa	L. D. P. POINT NO. 121
PROJECT: PSLGMP	SURVEYOR: A.L,V.R,M.K	DATE:18-04-18



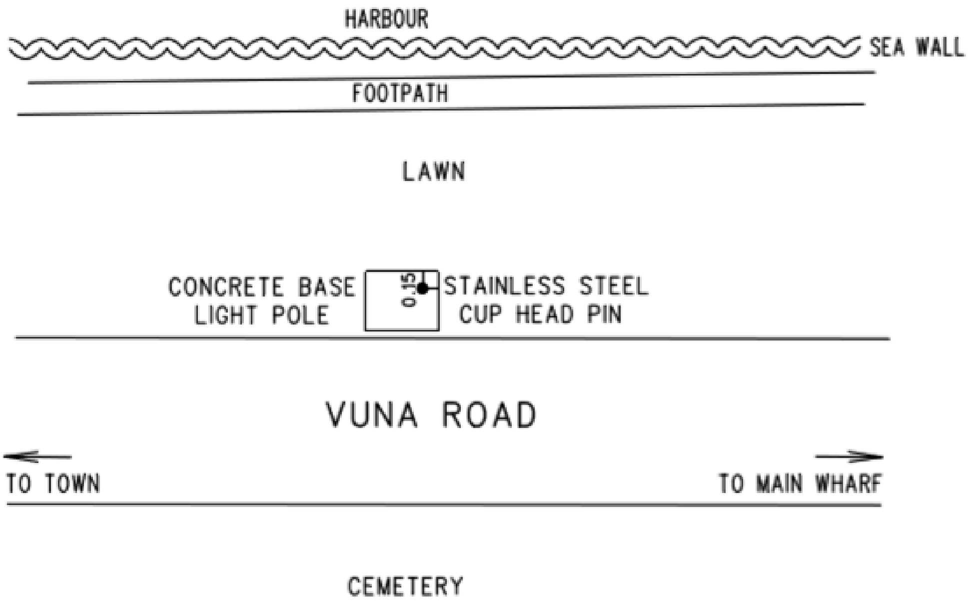
COUNTRY: Tonga	ISLAND: Tongatapu CITY: Nuku'alofa	L. D. P. POINT NO. 122
PROJECT: PSLGMP	SURVEYOR: A.L,V.R,M.K	DATE:18-04-18



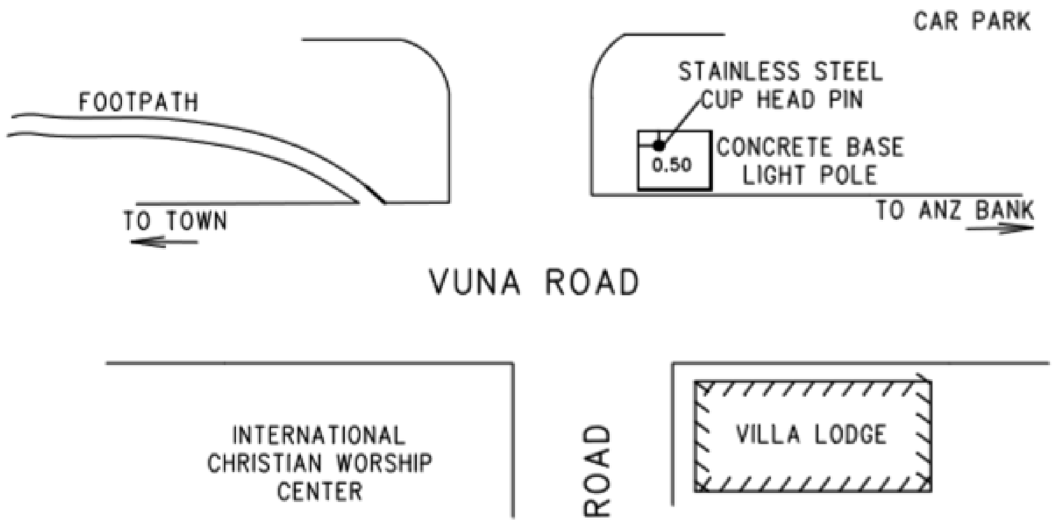
COUNTRY: Tonga	ISLAND: Tongatapu CITY: Nuku'alofa	L. D. P. POINT NO. 123
PROJECT: PSLGMP	SURVEYOR: A.L,V.R,M.K	DATE:18-04-18



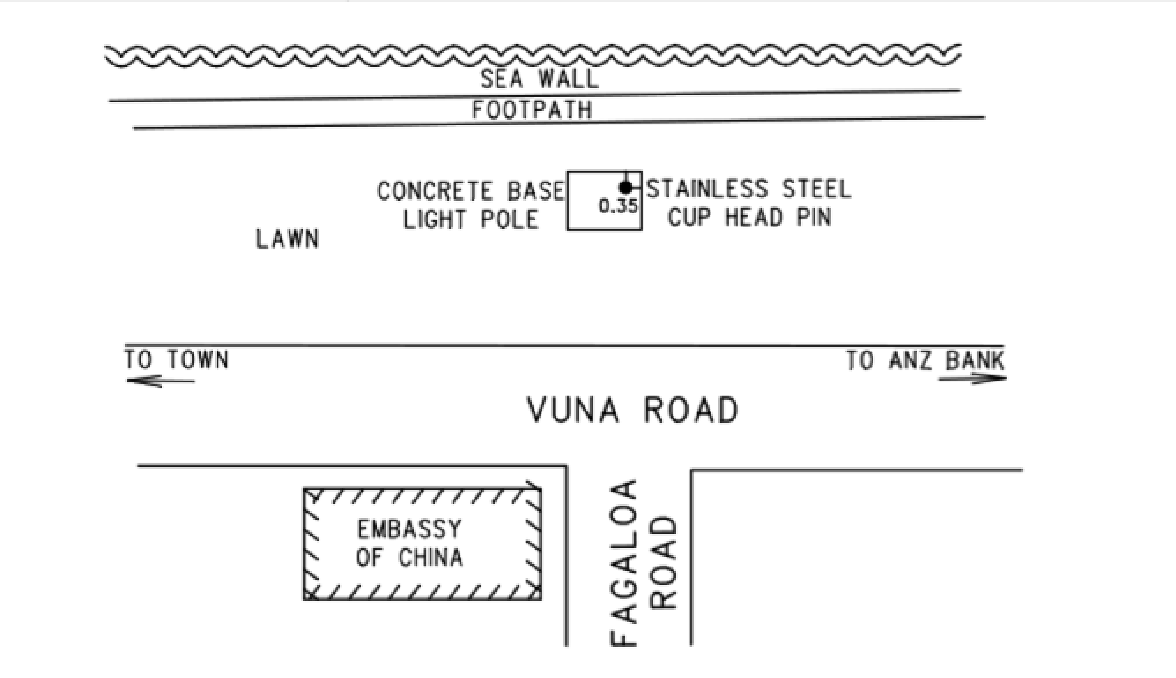
COUNTRY: Tonga	ISLAND: Tongatapu CITY: Nuku'alofa	L. D. P. POINT NO. 124
PROJECT: PSLGMP	SURVEYOR: A.L,V.R,M.K	DATE:18-04-18



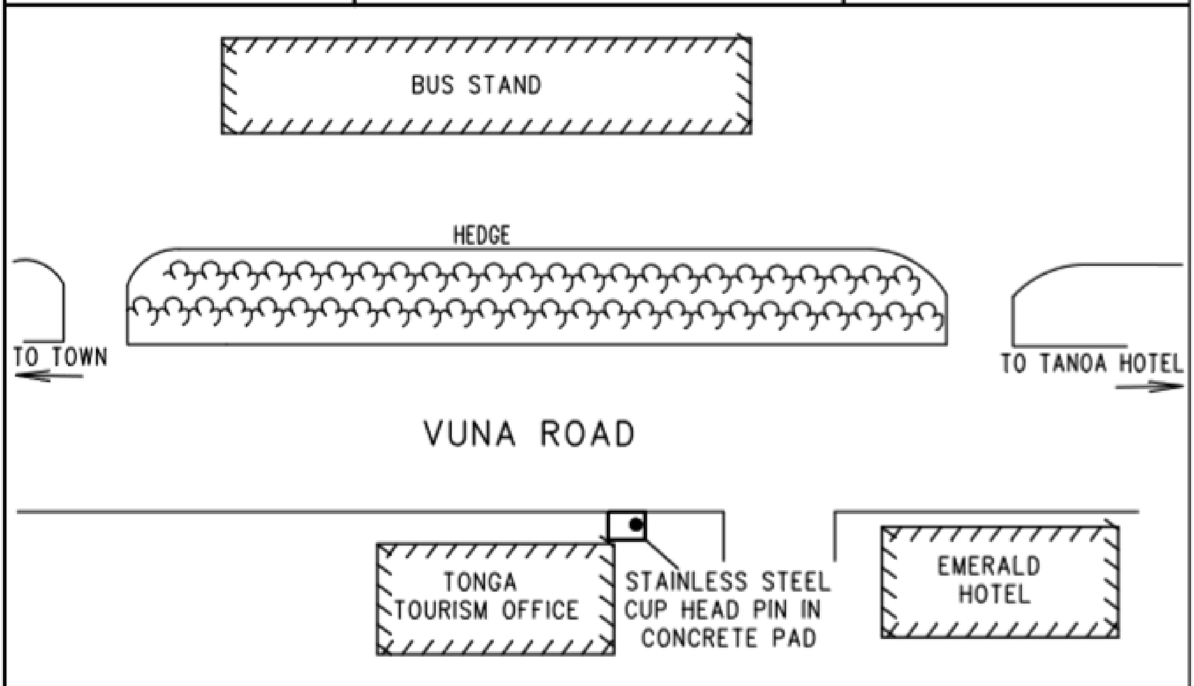
COUNTRY: Tonga	ISLAND: Tongatapu CITY: Nuku'alofa	L. D. P. POINT NO. 125
PROJECT: PSLGMP	SURVEYOR: A.L,V.R,M.K	DATE:18-04-18



COUNTRY: Tonga	ISLAND: Tongatapu CITY: Nuku'alofa	L. D. P. POINT NO. 126
PROJECT: PSLGMP	SURVEYOR: A.L,V.R,M.K	DATE:18-04-18



COUNTRY: Tonga	ISLAND: Tongatapu CITY: Nuku'alofa	L. D. P. POINT NO. 127
PROJECT: PSLGMP	SURVEYOR: A.L,V.R,M.K	DATE:18-04-18



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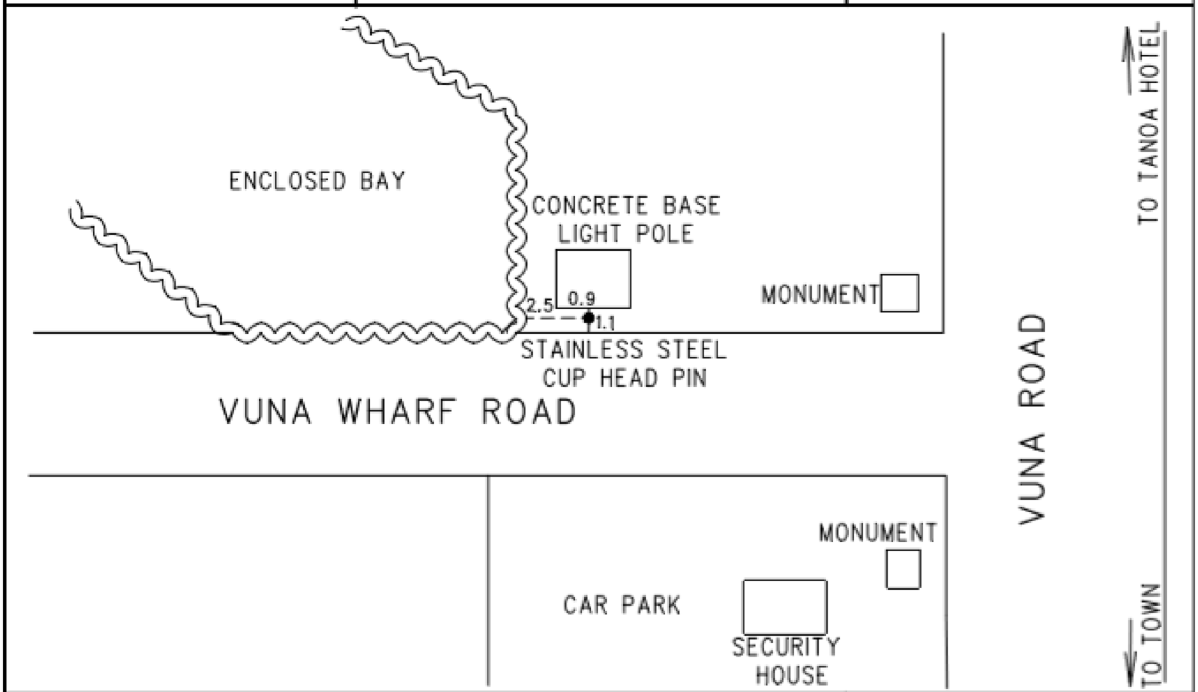
PROJECT: PSLGMP	SURVEYOR: A.L,V.R,M.K	DATE:18-04-18



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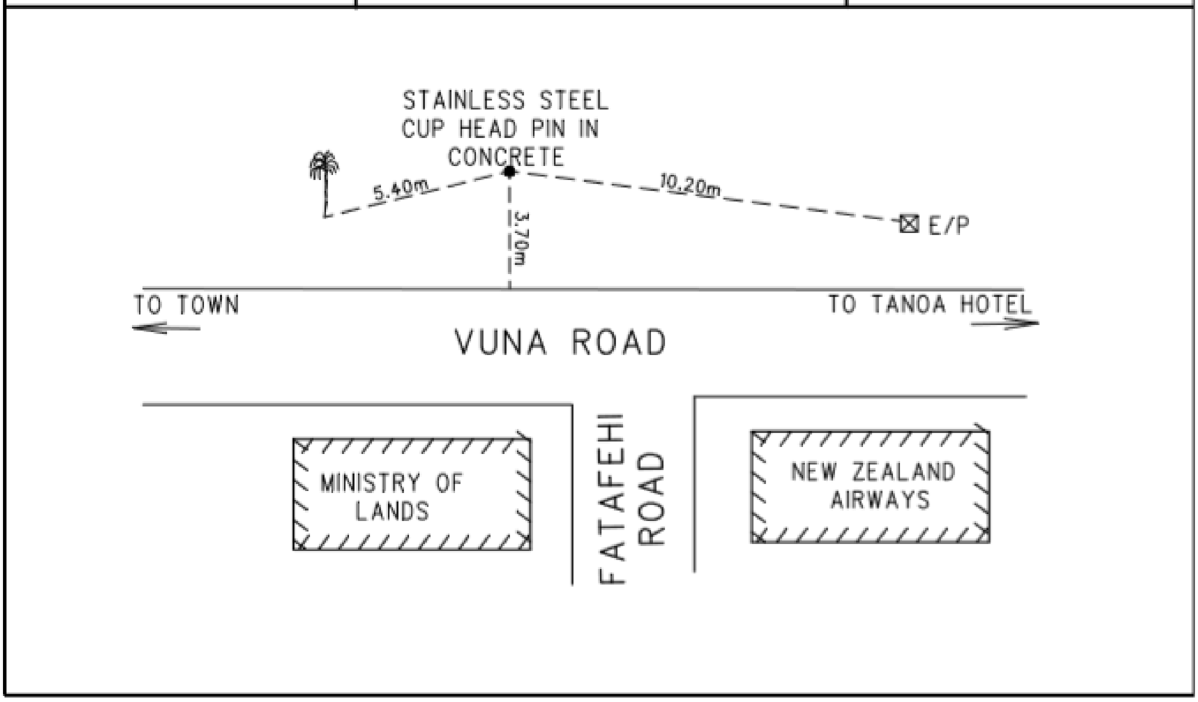

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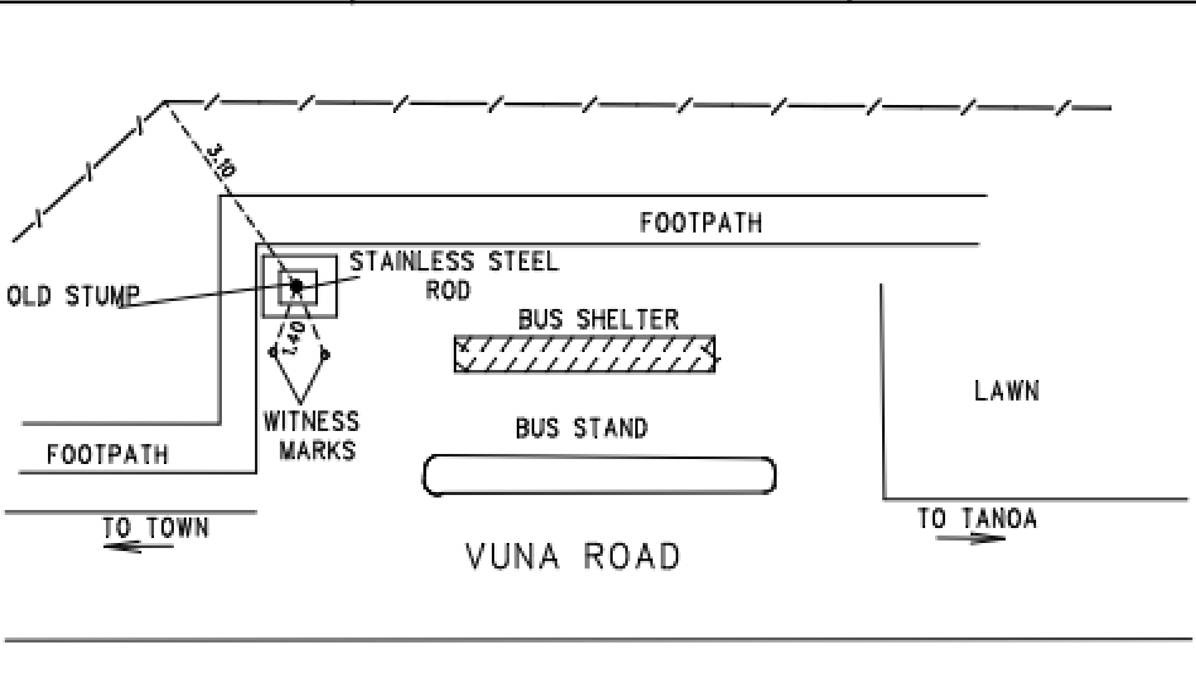

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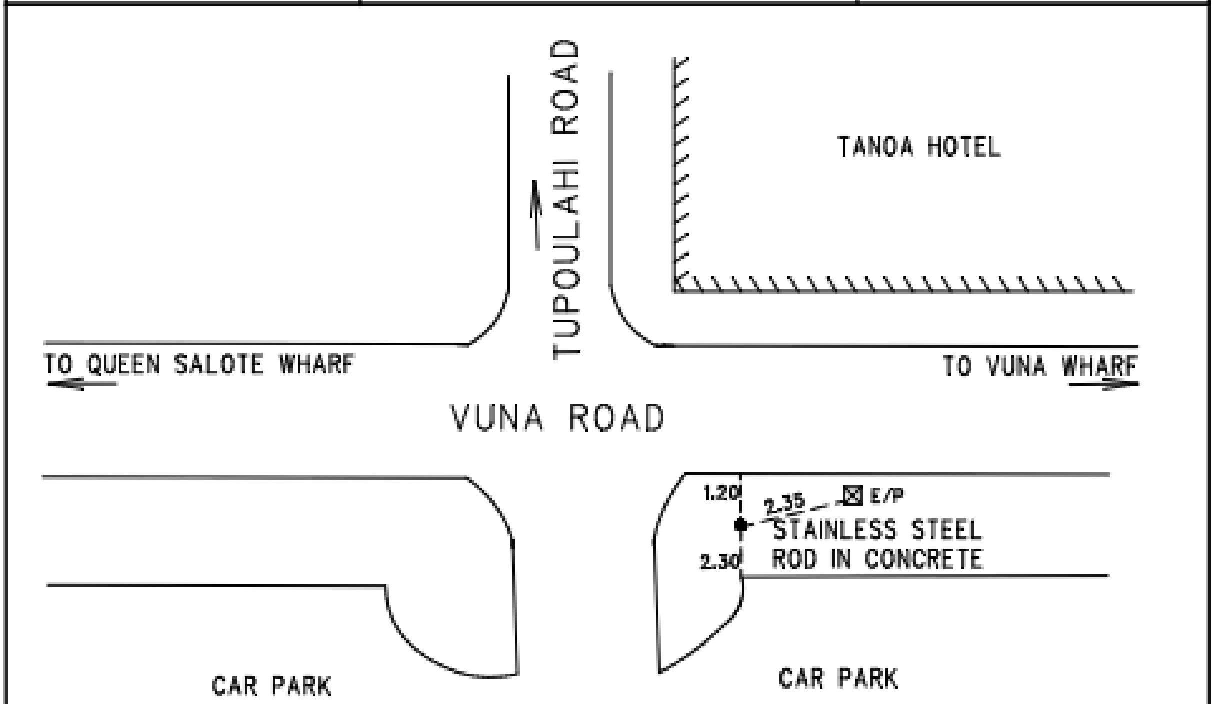
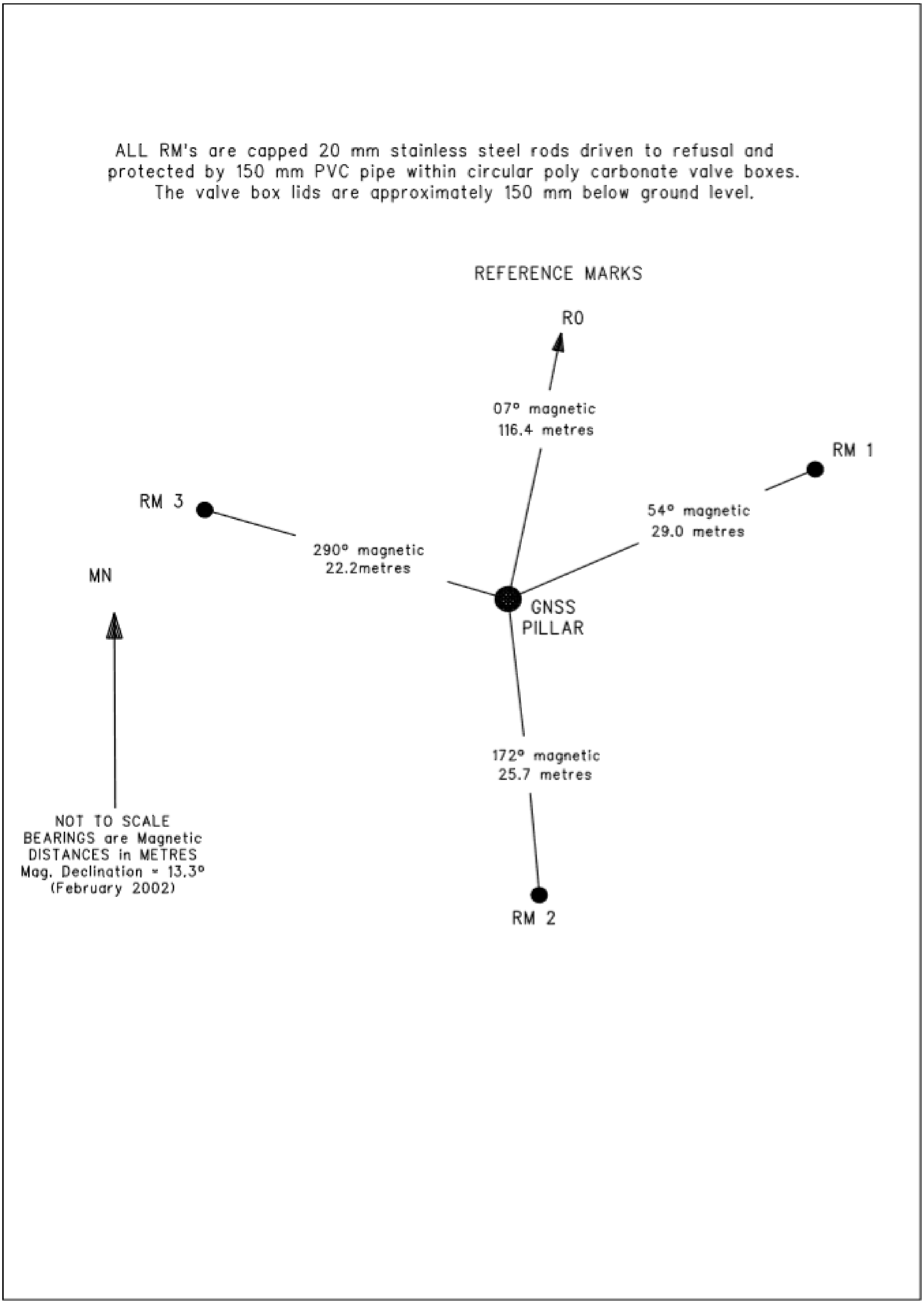
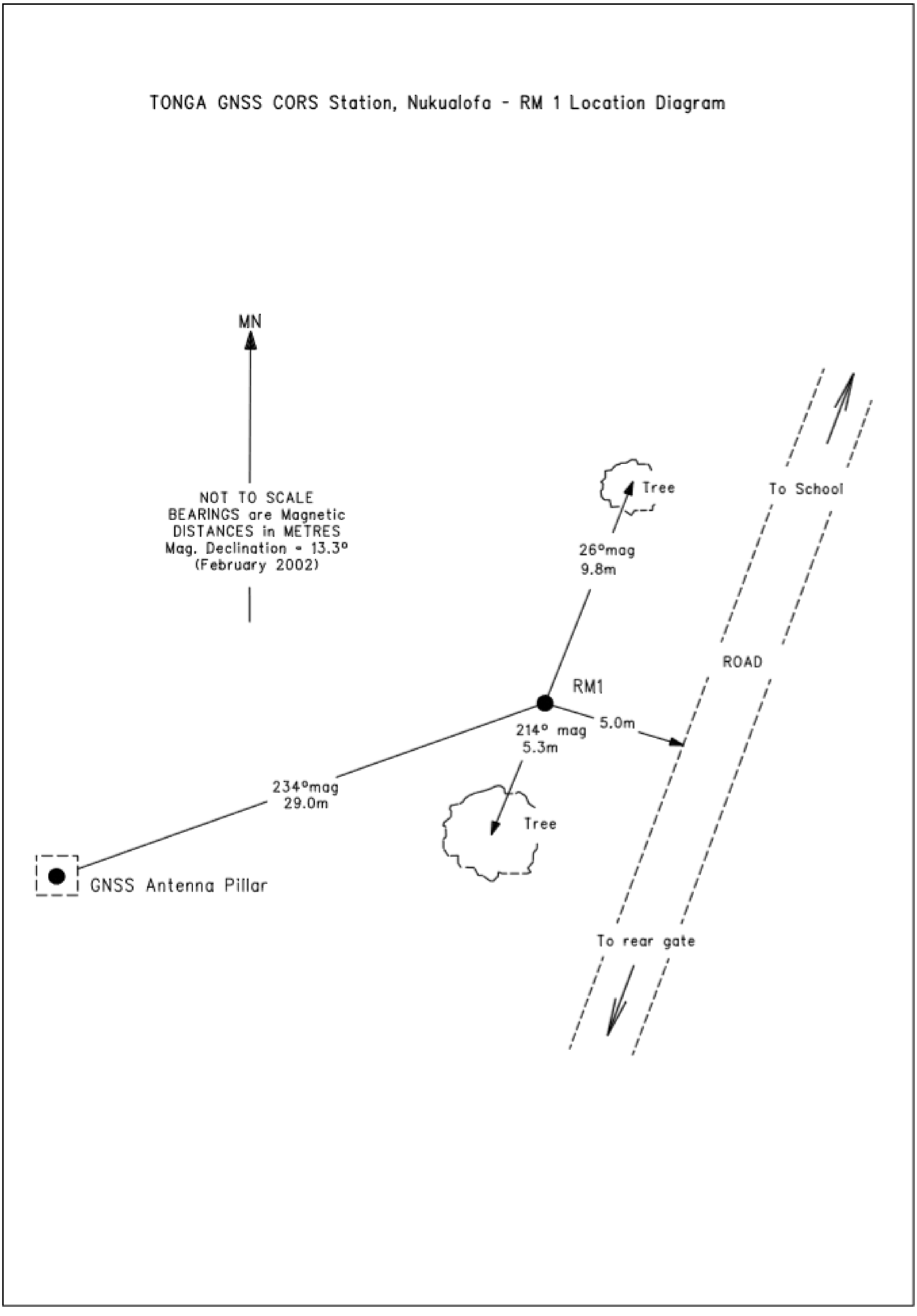
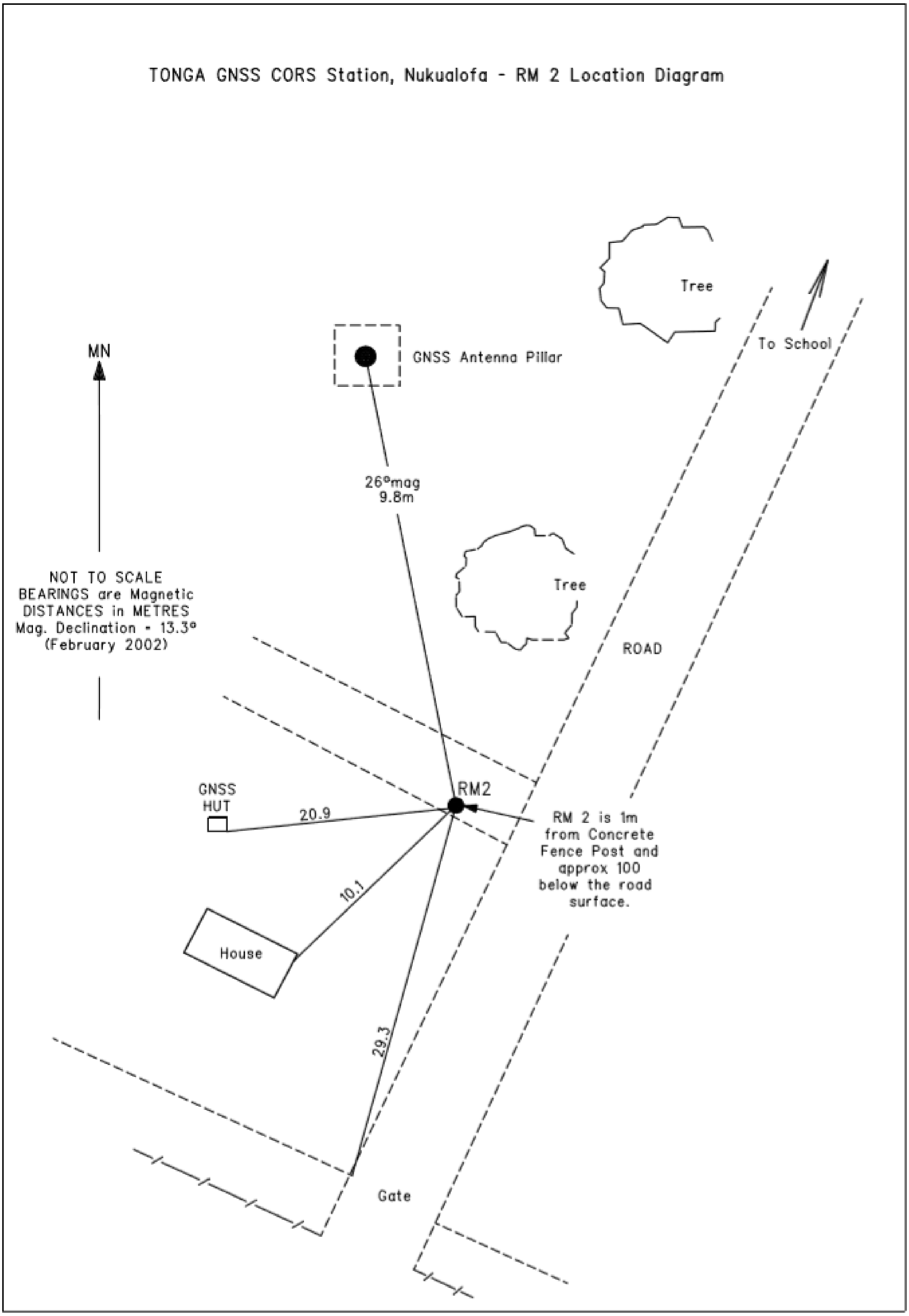


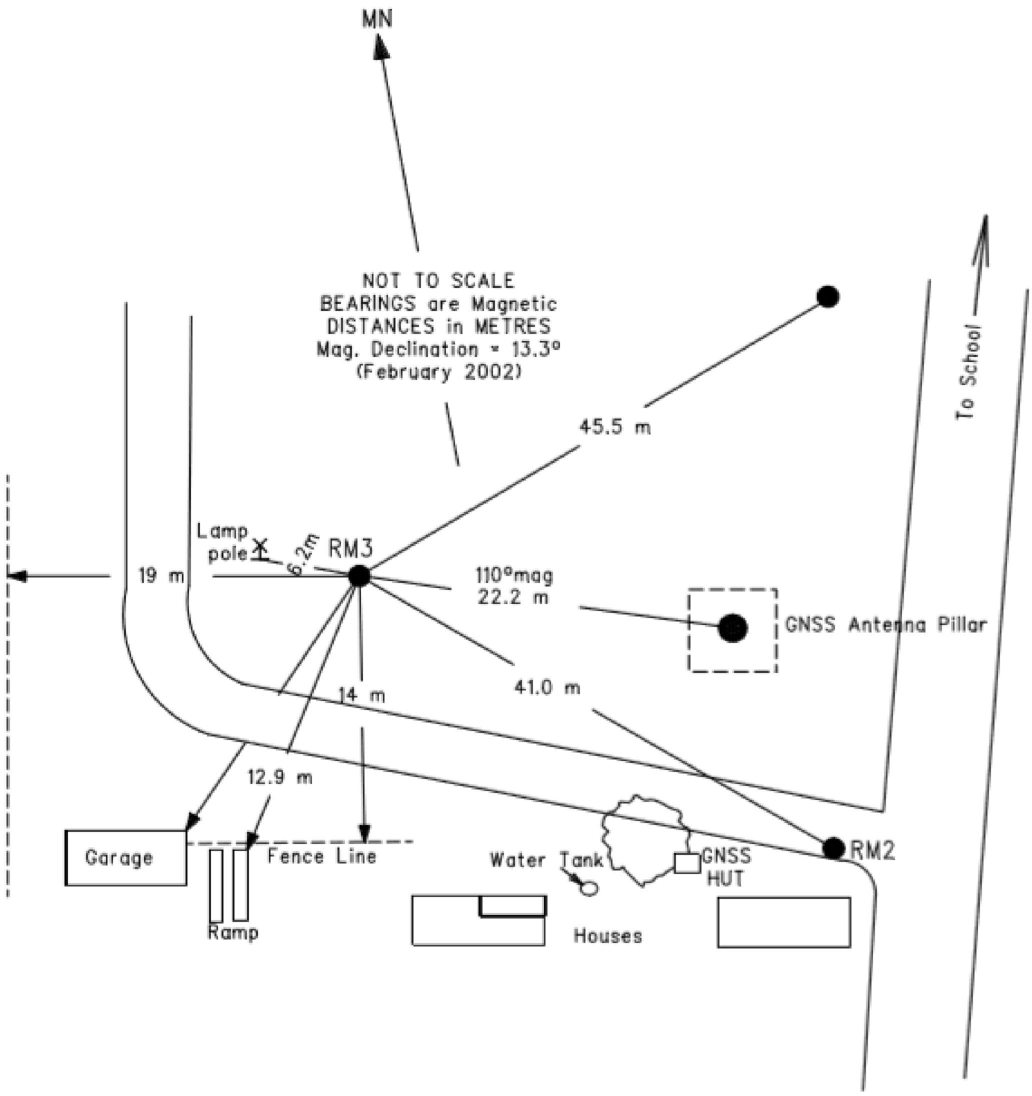
A 3 GNSS Reference Marks




TONGA GNSS CORS Station, Nukualofa - RM 1 Location Diagram
MN
NOT TO SCALE
BEARINGS are Magnetic
DISTANCES in METRES
Mag. Declination = 13.3°
(February 2002)
Tree
26°mag
9.8m
To School
ROAD
RM1
5.0m
214° mag
5.3m
234°mag
29.0m
Tree
GNSS Antenna Pillar
To rear gate


TONGA GNSS CORS Station, Nukualofa - RM 2 Location Diagram
Tree
To School
MN
GNSS Antenna Pillar
26°mag
9.8m
Tree
NOT TO SCALE
BEARINGS are Magnetic
DISTANCES in METRES
Mag. Declination = 13.3°
(February 2002)
ROAD
GNSS
HUT
RM2
20.9
RM 2 is 1m
from Concrete
Fence Post and
approx 100
below the road
surface.
10.1
House
29.3
Gate

TONGA GNSS CORS Station, Nukualofa - RM 3 Location Diagram



Appendix B Planning Aspects and Notes

Upon arranging travel to Tonga, contact 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.

Access to the GNSS CORS site at the college has been granted to maintain the equipment and is generally unrestricted during daylight hours, being mindful of school activities and the usual working restrictions on weekends.

Before accessing the tide gauge and conducting works in the wharf area, a courtesy call should be made to the ports authority to advise on working times and intent.

The survey equipment sent to Tonga was via DHL Express and returned. Note that when the shipment arrives in Tonga, the local focal point of contact should be notified to plan for freight clearances and note that there are additional charges for clearance, which are reimbursed on the visit.

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	*Multi-grip pliers*	
1	*Set of Screw Drivers*	
1	**PVC Pipe (1.2m)**	Api Fo'ou College GNSS COR Station Hut
1	*Aluminium GST6 tripod with Feet*	
1	**PVC Pipe (1.7m)**	Api Fo'ou College 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**	Api Fo'ou College GNSS COR Station Hut
1	**Green Bag - Leica GST40 Rigid Tripod**	Api Fo'ou College GNSS COR Station Hut
1	**Spade**	Api Fo'ou College GNSS COR Station Hut
1	**Crow Bar**	Api Fo'ou College GNSS COR Station Hut

Appendix C Equipment Specifications

B.1: Tachymeters, EDM, and Theodolites

A Leica TM50 (S/N 361441) Total Station was used to record all angles and distance measurements.

B.1.2 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°).

B.1.3 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.

B.2 Meteorological Sensor

B.2.1 Description

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

B.2.2 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%.

B.3 Forced Centring

B.3.1 Description

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

B.3.2 Specification

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

B.4 Targets and Reflectors

B.4.1 Description

The standard target kit includes:

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

B.4.2 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.

B.5 Precision Levelling

B.5.1 Levelling Instruments

Refer to section 2.1 for a description of the Leica TM50 Total Station.

B.5.2 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 1.00337 m.

B.6 Tripods

B.6.1 Description

Leica GST20 heavy-duty timber tripods with adjustable legs were used on all marks, except for the pillars, during the monitoring survey.

A Leica rigid timber tripod was used to mount the TM50 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.

B.7 GNSS Equipment

B.7.1 Description

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

TONG - Trimble Choke Ring antenna (TRM59800.00) - S/N 4844A59860

- Septentrio GNSS receiver SEPT POLARX5 Firmware Version 5.2.0 (S/N 3013233)

TOGT - Javad Choke Ring antenna (JAVRINGANT_DM SCIS) - S/N 02100

- Septentrio GNSS receiver SEPT POLARX5 Firmware Version 5.1.2 (S/N 3013249)