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

Funafuti, Tuvalu, October 2019

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Geoscience Australia acknowledges the traditional owners and custodians of Country throughout Australia and acknowledges their continuing connection to land, waters and community. We pay our respects to the people, the cultures and the elders past and present.

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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 the absolute movement of the tide gauge (managed by the 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 the 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 Vaiaku, Tuvalu from 9th to 15th October 2019. It also provides an updated height of the tide gauge derived from GNSS time series analysis and precise levelling observations.

GNSS Monitoring Survey

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

Levelling Survey

The Total Station differential levelling technique is used to observe differences in height between the Tide Gauge and the GNSS Monument. The levelling route includes a deep driven benchmark array in Funafuti, which runs approximately 3.7km. Previous levelling surveys have been conducted along this route using this technique in 2005, 2007, 2009, 2010, 2012, 2013, 2014, 2016, and 2018 This report contains an analysis of the 2019 Total Station differential levelling survey 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 Veenil Rattan 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.

2.1 Site Description and Contacts

The levelling benchmark array, GNSS CORS, and SEAFRAME Tide gauge are located north of the main Funafuti town area. The levelling run goes from tide gauge at the Funafuti wharf along the main road towards town commencing to the end of the Funafuti airport runway, along that adjacent road to the meteorology office where the GNSS CORS is located.

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2.2 Survey Support

The survey team very much appreciate the assistance from the Ministry of Lands and Natural Resources especially Mr. Sapolu Tetoa and Mr. Stanley Talataua for their assistance during the survey. Gratitude also goes to the senior management of the Ministry of Lands and Natural Resources for their continued support for the past years making all project visits a success.

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
BM22	Deep driven benchmark
BM23	Deep driven benchmark
BM24	Deep driven benchmark
BM26	Deep driven benchmark
BM27	Deep driven benchmark
BM28	Deep driven benchmark
TUV19	SEAFRAME sensor benchmark
TUV20	SEAFRAME Project plaque benchmark
TUVABM	Reference benchmark for the GNSS CORS pillar
TUV110	New SEAFRAME Tide gauge plaque
AQUA	New SEAFRAME sensor benchmark
RTGD	New Radar Gauge Reference Pin
RM4	GNSS CORS reference mark 4
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 temporary holding marks; 76, 106, 73, 74, 49, 48, 61, 60, 101, 104, 107, 108, 102, 42, and 109.

3.1.1 PSLGMP Vertical Reference Frame Wiring Diagram

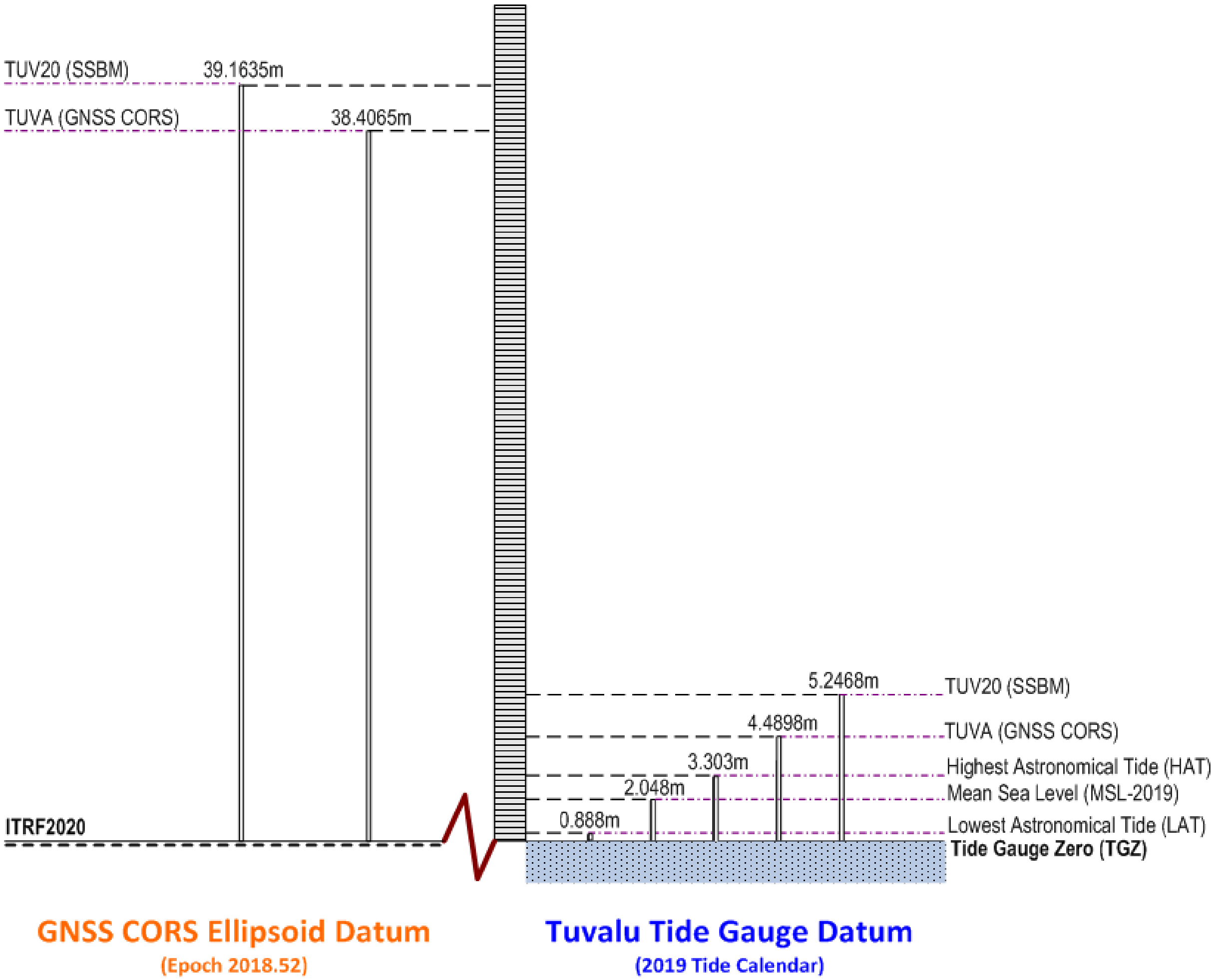


Figure 3.1 Wiring diagram depicting the offsets between surveyed marks. The left-hand side shows the height of the GNSS CORS pillar (TUVA), SEAFRAME sensor reference benchmark (TUV20) with respect to the International Terrestrial Reference Frame 2014 at epoch 2018.52. The right-hand side shows the height of TUVA, TUV20 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)

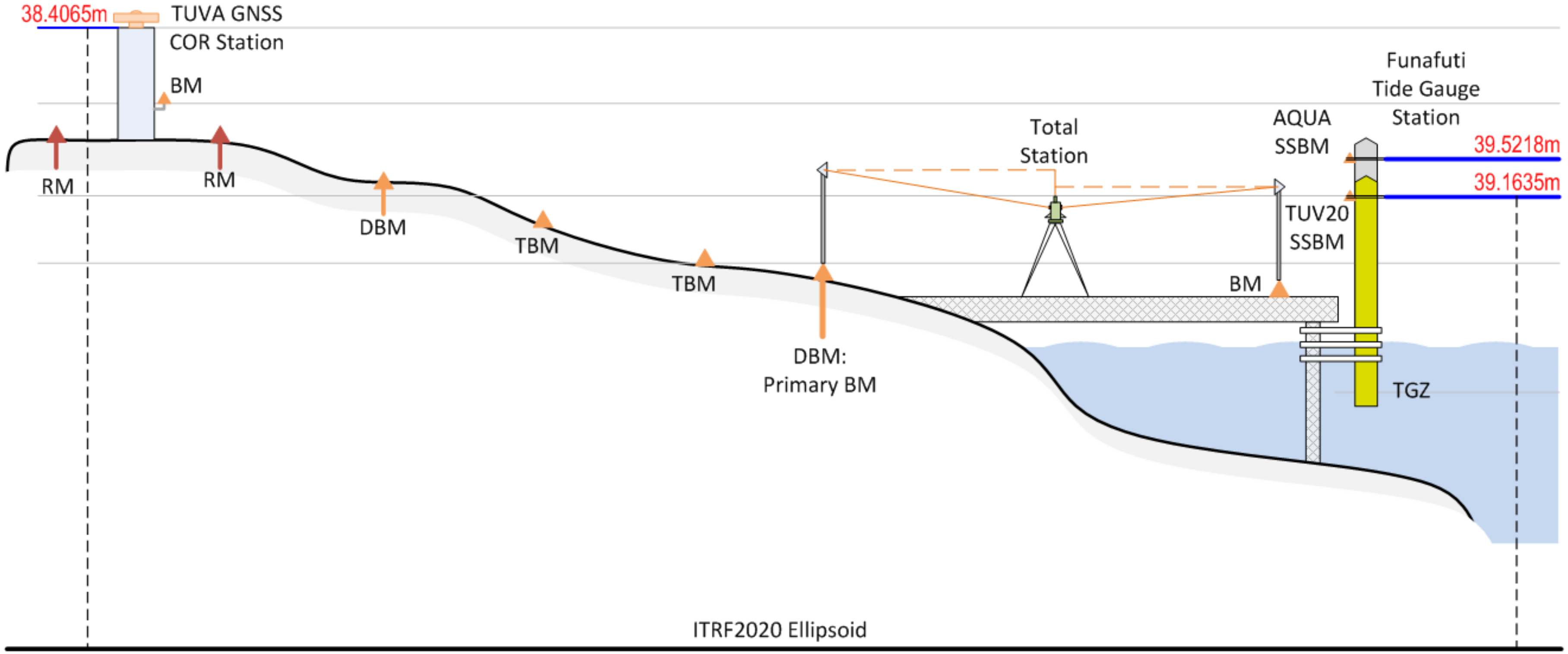


Figure 3.2 Simplified representation of the Total Station differential levelling survey carried out between the GNSS CORS and the SEAFRAME Tide Gauge.

Figure 3.2: Radar Gauge with RTGD sensor benchmark

Figure 3.4: Aqua track sensor. The red circle denotes the location of the SEAFRAME sensor reference benchmark (AQUA).

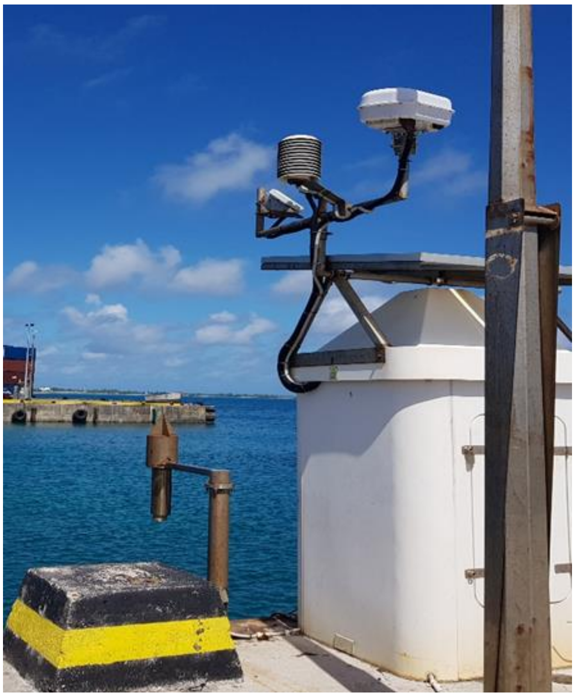


Figure 3.3: The old tide gauge facility in at the old jetty, overlooking the new Tide Gauge on the new jetty

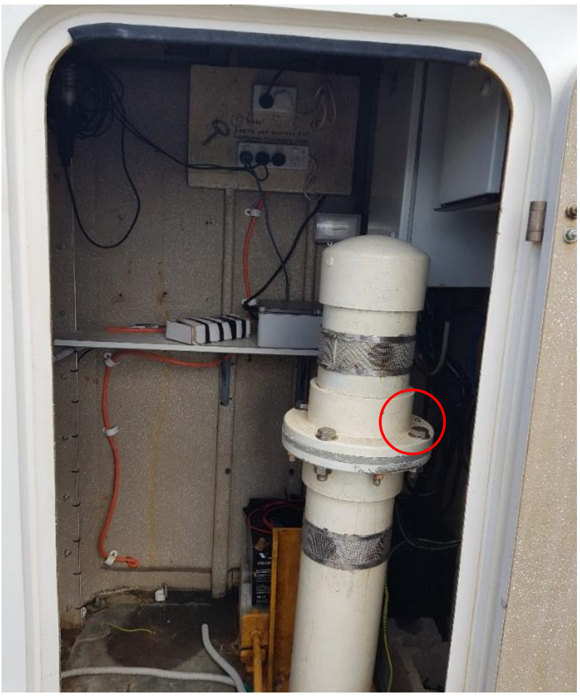


Figure 3.5: Aqua Track Sensor in the old tide gauge facility. The red circle denotes the SEAFRAME sensor survey benchmark (SSBM) – TUV20

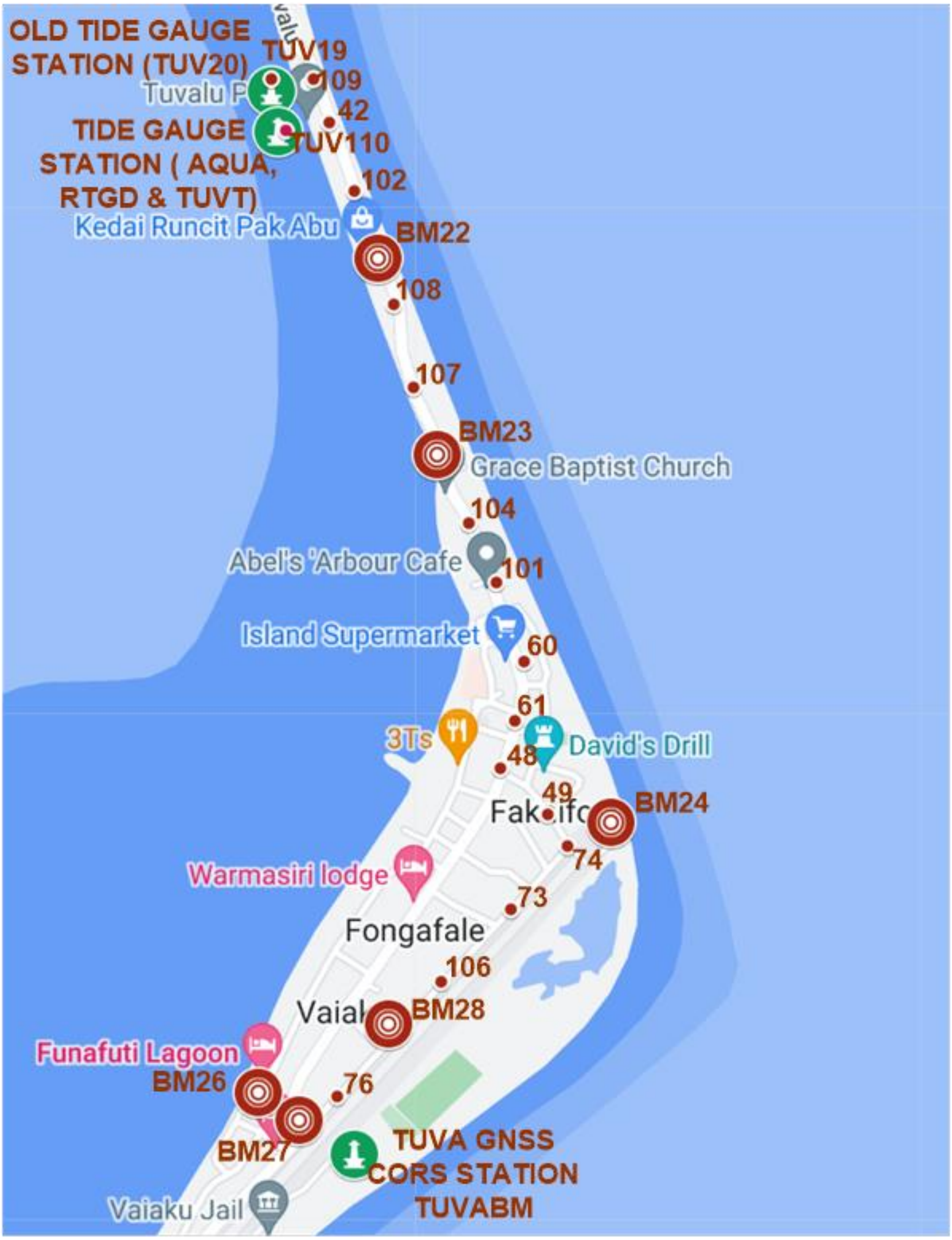


Figure 3.7 Levelling benchmark array. Source: Adopted from Google Maps.

3.1.2 GNSS CORS and Reference Marks

The GNSS CORS site is located within Tuvalu Metrological compound. The site consists of the weather office building that is housing the technical equipment and a 1.5 m GNSS CORS antenna pillar. The pillar is around 30 metres from the Meteorological Office. Access is unrestricted however prior visit to the weather office is advisable.

Three primary deep driven benchmarks were placed at the time of installation at 20m to 30m from the GNSS monument at approximately 120 degrees radial spacing from true north, where possible. The RM's consist of capped 20mm stainless steel rods driven to refusal and are protected by 150mm PVC pipe within circular poly carbonate boxes.

In 2015, it was discovered that the reference mark (RM1) was destroyed and needed to be replaced with a new one, that was installed as RM4.

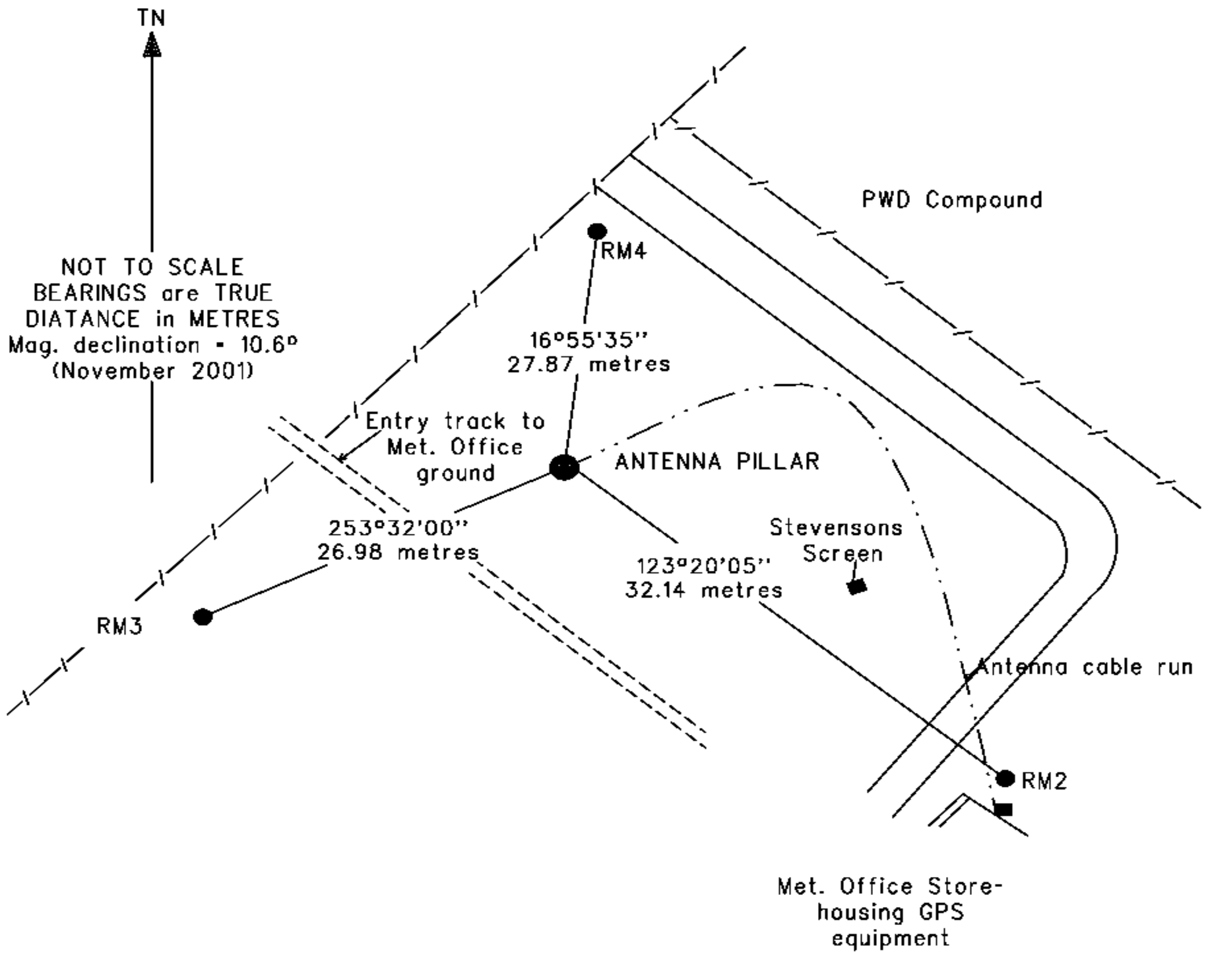


Figure 3.8 GNSS CORS site monitoring survey reference marks

3.2 Datum

3.2.1 Survey Datum

The adopted reference point for this survey is the levelling benchmark connected to the side of the GNSS CORS pillar (TUVABM).

3.2.2 Historical Survey Datum

All survey reports preceding this report based on the following datum: University of Hawaii Tide Staff Zero (TSZ).

Reduction of the data has been calculated holding BM22 fixed at 3.22540 metres TSZ, this value was determined by the NTCA in 1993 by:

- Adopting the height of UH 1 (RL = 3.0072 metres TSZ)
- Adopting the height of BM22 as derived from the 1993 survey (RL = 3.22540 metres)

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.

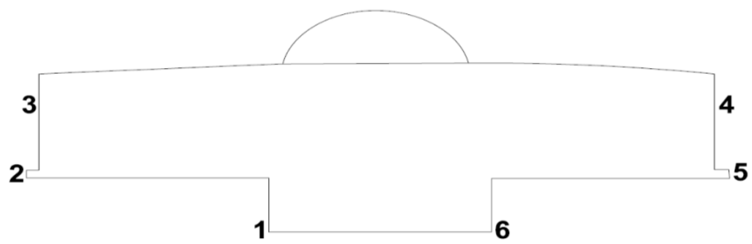


Figure 4.1 Symmetrical points on the antenna profile observed from each RM

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

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

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

4.2 Horizontal Observations

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

A horizontal control survey was conducted following the ICSM SP1 Guideline for Conventional Traverse Surveys (ICSM, 2021). Five sets of observations were completed at each standpoint; a set consists of a round of face left observations, followed by a round of face right observations to each of the visible survey marks. For each observation a horizontal direction, zenith angle and slope distance were 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 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 The Reduced Level (RL) shown is height relative to TUVABM.

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
TUVABM				0.0000	0.0000	0.0000
RM4	RM4	0.0000	-0.3760	-0.3760	0.0260	0.0260
RM2	RM2	0.0000	-0.2068	-0.5828	0.0483	0.0743
RM3	RM3	0.0000	-0.2272	-0.8100	0.0540	0.1280
RM2	RM2	0.2272	0.0000	-0.5828	0.054	
RM4	RM4	0.2068	0.0000	-0.3760	0.0498	
	TUVABM	0.3760	0.0000	-0.0001	0.026	
	Sum:	0.8100	-0.8100			
	Misclose:		-0.0001	-0.0001	0.258	(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)
TUVABM				0.0000		0.000
RM2	RM2	0.0000	-0.5830	-0.5830	0.033	0.033
	TUVABM	0.5829	0.0000	-0.0001	0.033	
	Sum:	0.5829	-0.5830			
	Misclose:		-0.0001	-0.0001	0.065	(Total Dist)
			ALLOWABLE (m):	0.0004	2 x Sqrt (km) test:	PASS

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
TUVABM				0.0000		0.000
RM3	RM3	0.0000	-0.8100	-0.8100	0.030	0.030
	TUVABM	0.8101	0.0000	0.0000	0.030	
	Sum:	0.8101	-0.8100			
	Misclose:		0.0000	0.0000	0.060	(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 (TUVA) was tightly constrained to its ITRF2020 coordinates and aligned to TUVA-RM3 with an azimuth of 253º 51’ 28.821” which had been determined in the 2016 survey by GNSS observation to RM3. The angular observations were given an uncertainty of 1.0” and the slope distances an uncertainty of 1.0 mm. The estimated coordinates and associated variance-covariance matrix were output in a SINEX file format and have been provided to Geoscience Australia.

The ITRF2020@2010.0 latitude and longitude coordinates adopted at TUVA 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 ITRF2020@2010.0 coordinates adopted at TUVA. 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)
TUVA	CCC	-8° 31' 31.04223"	179° 11' 47.6066"	38.4065
RM2	FFF	-8° 31' 31.62200"	179° 11' 48.4813"	36.8595
RM3	FFF	-8° 31' 31.28639"	179° 11' 46.7590"	36.6339
RM4	FFF	-8° 31' 30.36385"	179° 11' 47.6662"	37.068

Table 4.3.3 Earth Centred Cartesian coordinates and associated standard deviations (metres) for the GNSS & RM stations. ITRF2020@2010.0 coordinates adopted at TUVA (as per https://gnss.ga.gov.au/network). The ellipsoid height, we have adopted is taken from Brown et al. (2020) http://dx.doi.org/10.11636/Record.2020.003

Description	X	Y	Z	SD(e)	SD(n)	SD(up)
TUVA	-6307543.7735	88454.7107	-939277.9079	0.0000	0.0000	0.0000
RM2	-6307539.9785	88427.9049	-939295.2934	0.0004	0.0006	0.0004
RM3	-6307540.5452	88480.5850	-939285.0634	0.0004	0.0001	0.0004
RM4	-6307545.5648	88452.9132	-939257.0985	0.0004	0.0004	0.0004

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

Year	From	To	Δe	Δn	Δu
2019	TUVA	RM2	26.7503	-17.8108	-1.5464
2019	TUVA	RM3	-25.9165	-7.5010	-1.7725
2019	TUVA	RM4	1.8225	20.8404	-1.3394

4.4 Assessment of Results

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

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

YEAR	FROM	To	ΔE	ΔN	ΔU
2009	TUVA	RM2	26.7514	-17.8131	-1.5469
2010	TUVA	RM2	26.751	-17.8125	-1.5469
2012	TUVA	RM2	26.7507	-17.8131	-1.5454
2016	TUVA	RM2	26.7503	-17.8108	-1.5464
2018	TUVA	RM2	26.7503	-17.8114	-1.5458
2019	TUVA	RM2	26.7499	-17.8116	-1.5471
Ref RL	(as at 2016)		26.7509	-17.8124	-1.5464

YEAR	FROM	To	ΔE	ΔN	ΔU
2009	TUVA	RM3	-25.9175	-7.5013	-1.7728
2010	TUVA	RM3	-25.917	-7.5011	-1.7729
2012	TUVA	RM3	-25.9173	-7.5012	-1.7746
2016	TUVA	RM3	-25.9165	-7.501	-1.7725
2018	TUVA	RM3	-25.9167	-7.5011	-1.7730
2019	TUVA	RM3	-25.9171	-7.5012	-1.7727
Ref RL	(as at 2016)		-25.9171	-7.5012	-1.7732

YEAR	FROM	To	ΔE	ΔN	ΔU
2016	TUVA	RM4	1.8225	20.8404	-1.3394
2018	TUVA	RM4	1.8238	20.8415	-1.3390
2019	TUVA	RM4	1.8224	20.8412	-1.3385
Ref RL	(as at 2016)		1.8225	20.8404	-1.3394

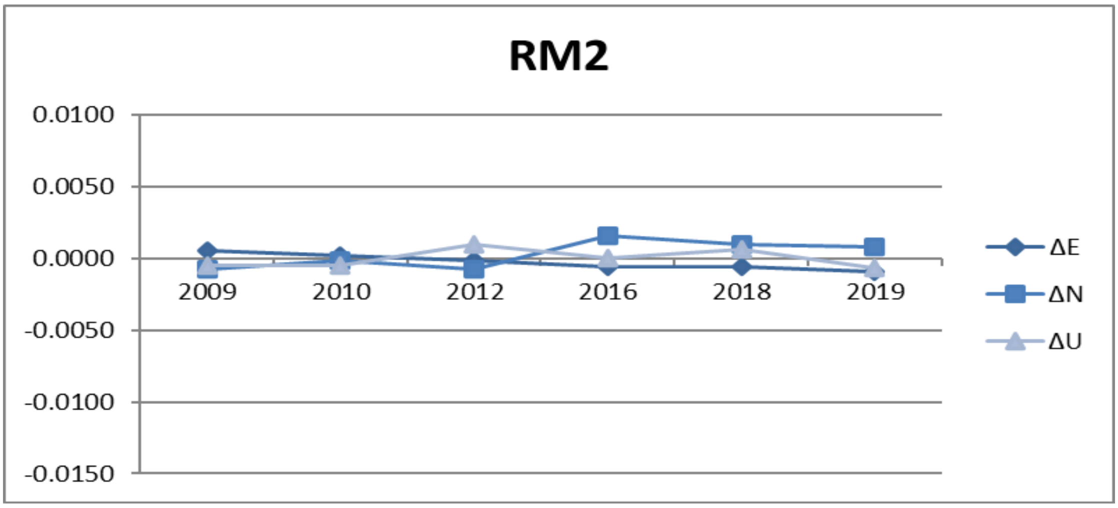


Figure 4.4.1 Time series of RM2 movement relative to GNSS (0 = REF pre 2016 mean)

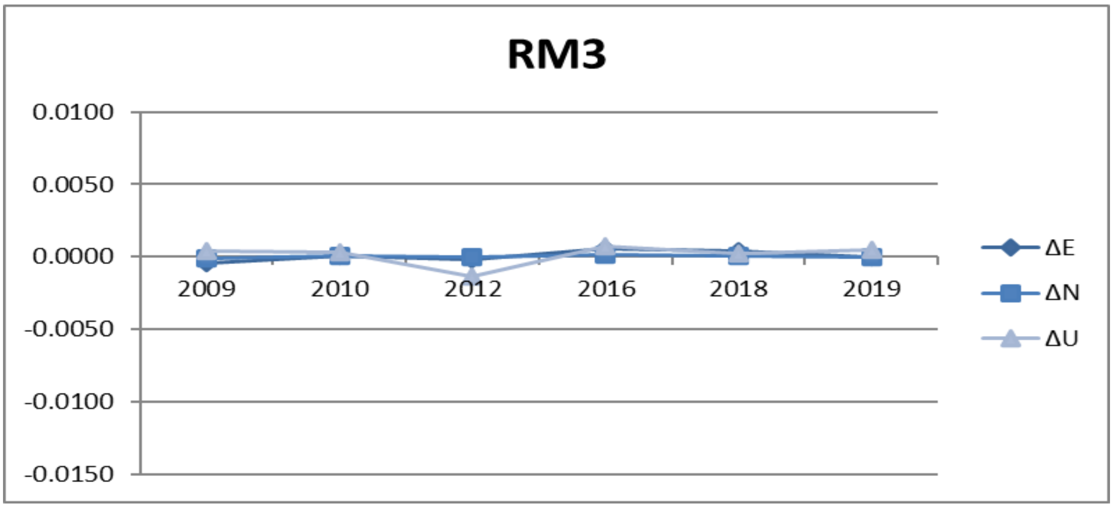


Figure 4.4.2 Time series of RM3 movement relative to GNSS (0 = REF pre 2016 mean)

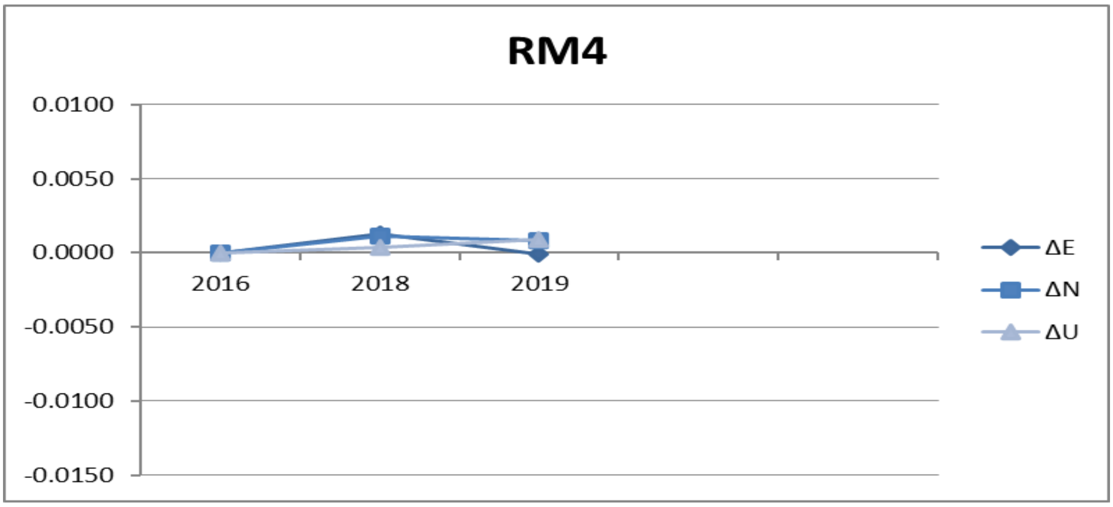


Figure 4.4.3 Time series of RM4 movement relative to GNSS (0 = REF pre 2016 mean)

5 Tide Gauge Level Connection

5.1 Background

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

5.2 Survey Methodology

The Total Station differential levelling technique was used for the Funafuti 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 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
TUVA (Ellipsoidal ht)	38.4065	Observed RL at the ARP of TUVA (Ellipsoidal) @ 2018.52
TUVA to TUVABM	-0.9631	Offset constant between BM at GNSS pillar plate
Primary Pole & 1/2m Pole	1.00337	Height difference between poles used (Calibrated September 2019)

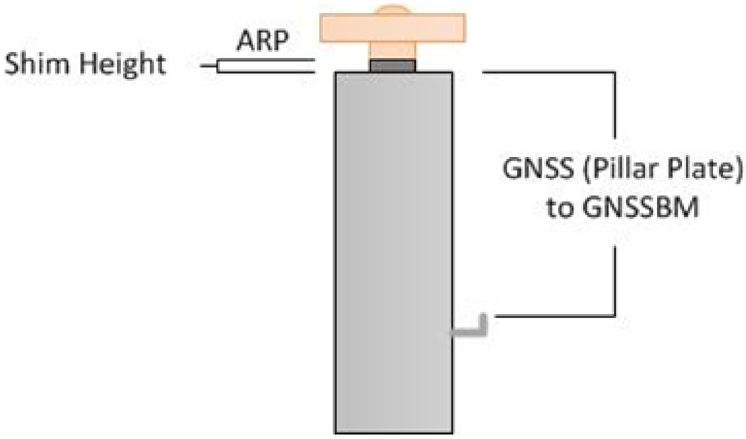


Figure 5.2.1 GNSS Pillar Offsets

5.3 Data Analysis and Results

Reduction of the digital data was computed using the Geoscience Australia levelling program "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 is shown in Table 5.3.1 below is the height relative to TUVABM (GNSS BM)

Table 5.3.1 Reduced level data – TUVA (GNSS CORS) to TUV19 (SEAFRAME Sensor Benchmark)

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
TUVA				0.9631		
TUVABM	TUVABM	0.0000	-0.9631	0.000	0.000	0.000
BM27	BM27	0.0000	-0.5252	-0.5252	0.144	0.144
76	76	0.0000	-0.0012	-0.5264	0.134	0.278
BM28	BM28	0.0027	0.0000	-0.5237	0.210	0.488
106	106	0.0000	-0.0089	-0.5326	0.213	0.701
73	73	0.0905	0.0000	-0.4421	0.199	0.899
74	74	0.2863	0.0000	-0.1558	0.205	1.104
BM24	BM24	1.2105	0.0000	1.0547	0.107	1.211
74B	74B	0.0000	-1.2105	-0.1559	0.107	1.319
49	49	0.6606	0.0000	0.5047	0.089	1.408
48	48	0.0000	-0.1836	0.3211	0.161	1.569
61	61	0.0000	-0.1834	0.1377	0.119	1.688
60	60	0.0434	0.0000	0.1811	0.138	1.826
101	101	0.1707	0.0000	0.3518	0.192	2.018
104	104	0.0000	-0.1081	0.2437	0.200	2.218
BM23	BM23	0.1547	0.0000	0.3984	0.178	2.396
107	107	0.0000	-0.4153	-0.0169	0.183	2.578
108	108	0.2714	0.0000	0.2546	0.145	2.723
BM22	BM22	0.2313	0.0000	0.4858	0.164	2.887
102	102	0.5358	0.0000	1.0217	0.209	3.096
42	42	0.0000	-0.0010	1.0207	0.121	3.217
109	109	1.0294	0.0000	2.0501	0.134	3.351
TUV19	TUV19	0.0000	-1.2978	0.7522	0.100	3.451
109	109	1.2980	0.0000	2.0502	0.100	

42	42	0.0000	-1.0291	1.0211	0.134	
102	102	0.0009	0.0000	1.0220	0.121	
BM22	BM22	0.0000	-0.5359	0.4862	0.209	
108	108	0.0000	-0.2314	0.2547	0.164	
107	107	0.0000	-0.2716	-0.0169	0.143	
BM23	BM23	0.4154	0.0000	0.3985	0.182	
104	104	0.0000	-0.1548	0.2437	0.178	
101	101	0.1079	0.0000	0.3516	0.200	
60	60	0.0000	-0.1711	0.1805	0.192	
61	61	0.0000	-0.0430	0.1375	0.139	
48	48	0.1833	0.0000	0.3209	0.123	
49	49	0.1839	0.0000	0.5048	0.161	
74B	74B	0.0000	-0.6606	-0.1558	0.090	
BM24	BM24	1.2105	0.0000	1.0547	0.107	
74	74	0.0000	-1.2105	-0.1558	0.107	
73	73	0.0000	-0.2862	-0.4420	0.204	
106	106	0.0000	-0.0904	-0.5324	0.199	
BM28	BM28	0.0086	0.0000	-0.5238	0.213	
76	76	0.0000	-0.0027	-0.5266	0.210	
BM27	BM27	0.0012	0.0000	-0.5254	0.131	
TUVABM	TUVABM	0.5256	0.0000	0.0002	0.144	
TUVA	TUVA	0.9631	0.0000	0.9633	0.000	
	Sum:	9.5856	-9.5854			
	Misclose:		0.0002	0.0002	6.901	(Total Dist)
			ALLOWABLE (m):	0.0037	2 x Sqrt (km) test:	PASS

Table 5.3.2 Reduced Level data – TUV19 (SSBM) to TUV20 (Old Tide Gauge Reference Benchmark)

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
TUV19				0.7522		3.451
TUV20	TUV20	0.9679	0.0000	1.7201	0.010	3.461
	TUV19	0.0000	-0.9679	0.7522	0.011	0.000
	Sum:	0.9679	-0.9679			
	Misclose:		0.0000	0.0000	0.021	(Total Dist)
			ALLOWABLE (m):	0.0002	2 x Sqrt (km) test:	PASS

Table 5.3.3 Reduced Level data – BM27 to BM26

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
BM27				-0.5253		0.144
BM26	BM26	0.8903	0.0000	0.3650	0.116	0.260
	BM27	0.0000	-0.8904	-0.5254	0.116	0.000
	Sum:	0.8903	-0.8904			
	Misclose:		-0.0001	-0.0001	0.232	(Total Dist)
			ALLOWABLE (m):	0.0007	2 x Sqrt (km) test:	PASS

Table 5.3.4 Reduced Level data – TUV42 to TUV110

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
42				1.0209		3.217
TUV110	TUV110	0.0197	0.0000	1.0406	0.181	3.397
	42	0.0000	-0.0197	1.0209	0.180	0.000
	Sum:	0.0197	-0.0197			
	Misclose:		0.0000	0.0000	0.361	(Total Dist)
			ALLOWABLE (m):	0.0008	2 x Sqrt (km) test:	PASS

Table 5.3.5 Reduced Level data – TUV110 (New Tide Gauge Benchmark) to AQUA (new SEAFRAME sensor benchmark)

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
TUV110				1.0406		3.397
AQUA	AQUA	1.0378	0.0000	2.0784	0.007	3.405
	TUV110	0.0000	-1.0379	1.0405	0.007	0.000
	Sum:	1.0378	-1.0379			
	Misclose:		-0.0001	-0.0001	0.015	(Total Dist)
			ALLOWABLE (m):	0.0002	2 x Sqrt (km) test:	PASS

Table 5.3.6 Reduced Level data – TUV110 to RTGD (Radar Tide Gauge Benchmark)

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
TUV110				1.0406		3.397
RTGD	RTGD	1.0503	0.0000	2.0909	0.010	3.408
	TUV110	0.0000	-1.0503	1.0406	0.010	0.000
	Sum:	1.0503	-1.0503			
	Misclose:		0.0000	0.0000	0.021	(Total Dist)
			ALLOWABLE (m):	0.0002	2 x Sqrt (km) test:	PASS

Table 5.3.7 Reduced Level data – TUV110 to TUVT (Tide Gauge GNSS CORS)

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
TUV110				1.0406		Acc Dist
TUVT	TUVT	0.9793	0.0000	2.0199	0.010	3.451
	TUV110	0.0000	-0.9793	1.0406	0.010	0.000
	Sum:	0.9793	-0.9793			
	Misclose:		0.0000	0.0000	0.020	(Total Dist)
			ALLOWABLE (m):	0.0002	2 x Sqrt (km) test:	PASS

Table 5.3.8 Measured height differences (in metres) between all BMs (ΔRL_{2019})

	TUVABM	BM27	BM26	BM28	BM24	BM23	BM22	TUV19	TUV20	TUV110	TUVT	AQUA	RTGD	TUVA
TUVABM	-	-0.5253	0.3650	-0.5238	1.0547	0.3984	0.4860	0.7522	1.7201	1.0406	2.0199	2.0784	2.0909	0.9631
BM27	0.5253	-	0.8903	0.0015	1.5800	0.9237	1.0113	1.2775	2.2454	1.5659	2.5452	2.6037	2.6162	1.4884
BM26	-0.3650	-0.8903	-	-0.8888	0.6897	0.0335	0.1210	0.3873	1.3551	0.6756	1.6550	1.7134	1.7260	0.5981
BM28	0.5238	-0.0015	0.8888	-	1.5785	0.9222	1.0098	1.2760	2.2439	1.5644	2.5437	2.6022	2.6147	1.4869
BM24	-1.0547	-1.5800	-0.6897	-1.5785	-	-0.6562	-0.5687	-0.3025	0.6654	-0.0141	0.9652	1.0237	1.0362	-0.0916
BM23	-0.3984	-0.9237	-0.0335	-0.9222	0.6562	-	0.0875	0.3538	1.3217	0.6422	1.6215	1.6800	1.6925	0.5647
BM22	-0.4860	-1.0113	-0.1210	-1.0098	0.5687	-0.0875	-	0.2663	1.2341	0.5546	1.5340	1.5924	1.6050	0.4771
TUV19	-0.7522	-1.2775	-0.3873	-1.2760	0.3025	-0.3538	-0.2663	-	0.9679	0.2884	1.2677	1.3262	1.3387	0.2109
TUV20	-1.7201	-2.2454	-1.3551	-2.2439	-0.6654	-1.3217	-1.2341	-0.9679	-	-0.6795	0.2998	0.3583	0.3708	-0.7570
TUV110	-1.0406	-1.5659	-0.6756	-1.5644	0.0141	-0.6422	-0.5546	-0.2884	0.6795	-	0.9793	1.0378	1.0503	-0.0775
TUVT	-2.0199	-2.5452	-1.6550	-2.5437	-0.9652	-1.6215	-1.5340	-1.2677	-0.2998	-0.9793	-	0.0585	0.0710	-1.0568
AQUA	-2.0784	-2.6037	-1.7134	-2.6022	-1.0237	-1.6800	-1.5924	-1.3262	-0.3583	-1.0378	-0.0585	-	0.0125	-1.1153
RTGD	-2.0909	-2.6162	-1.7260	-2.6147	-1.0362	-1.6925	-1.6050	-1.3387	-0.3708	-1.0503	-0.0710	-0.0125	-	-1.1278
TUVA	-0.9631	-1.4884	-0.5981	-1.4869	0.0916	-0.5647	-0.4771	-0.2109	0.7570	0.0775	1.0568	1.1153	1.1278	-

Table 5.3.9 Time-series of Reduced Levels (with respect to TUVABM)

YEAR	TUVABM	BM27	BM26	BM28	BM24	BM23	BM22	TUV19	TUV20	TUV110	TUVT	AQUA	RTGD	TUVA
1993.2					1.0568	0.3971	0.4840	0.7399	1.7185					
1994.5					1.0554	0.3980	0.4840	0.7412	1.7189					
1995.5					1.0558	0.3978	0.4840	0.7419	1.7195					
1998.0					1.0544	0.3973	0.4840	0.7420	1.7194					
1998.5					1.0539	0.3969	0.4840	0.7434	1.7201					
2000.1					1.0537	0.3972	0.4840	0.7428	1.7186					
2001.6					1.0538	0.3976	0.4840	0.7434	1.7185					
2003.4	0.0000	-0.5249	0.3685		1.0546	0.3977	0.4840	0.7437	1.7179					
2005.6	0.0000	-0.5249	0.3677		1.0534	0.3961	0.4829	0.7439	1.7167					
2005.6	0.0000	-0.5255	0.3667		1.0532	0.3961	0.4822	0.7435	1.7161					
2007.2	0.0000	-0.5250	0.3672		1.0555	0.3986	0.4847	0.7472	1.7189					
2009.1	0.0000	-0.5256	0.3664	-0.5247	1.0548	0.3979	0.4836	0.7459	1.7170					
2010.1	0.0000	-0.5258	0.3666	-0.5254	1.0534	0.3952	0.4812	0.7447	1.7150					
2012.4	0.0000	-0.5257	0.3659	-0.5257	1.0537	0.3963	0.4836	0.7463	1.7158					
2013.6	0.0000	-0.5259	0.3659	-0.5253	1.0542	0.3959	0.4841	0.7480	1.7172					
2015.5	0.000	-0.5246	0.3671	-0.5234	1.0546	0.3980	0.4850	0.7510	1.7205					0.9631
2016.8	0.000	-0.5261	0.3646	-0.5252	1.0522	0.3952	0.4824	0.7488	1.7180					0.9631
2017.5							0.4824	0.750	1.718		2.349	2.072	2.085	0.9631
2018.52	0.000	-0.5261	0.3643	-0.5258	1.0518	0.3937	0.4806	0.7461	1.7145	1.0347	2.0140	2.0684	2.0813	0.9631
2019.76	0.000	-0.5253	0.3650	-0.5238	1.0547	0.3984	0.4860	0.7522	1.7201	1.0406	2.0199	2.0784	2.0909	0.9631

5.4 Comparison with previous surveys

All historic data has been readjusted relative to the benchmark attached to the base of the GNSS pillar (TUVABM) (Table 5.3.9). 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.

1.1.1 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.

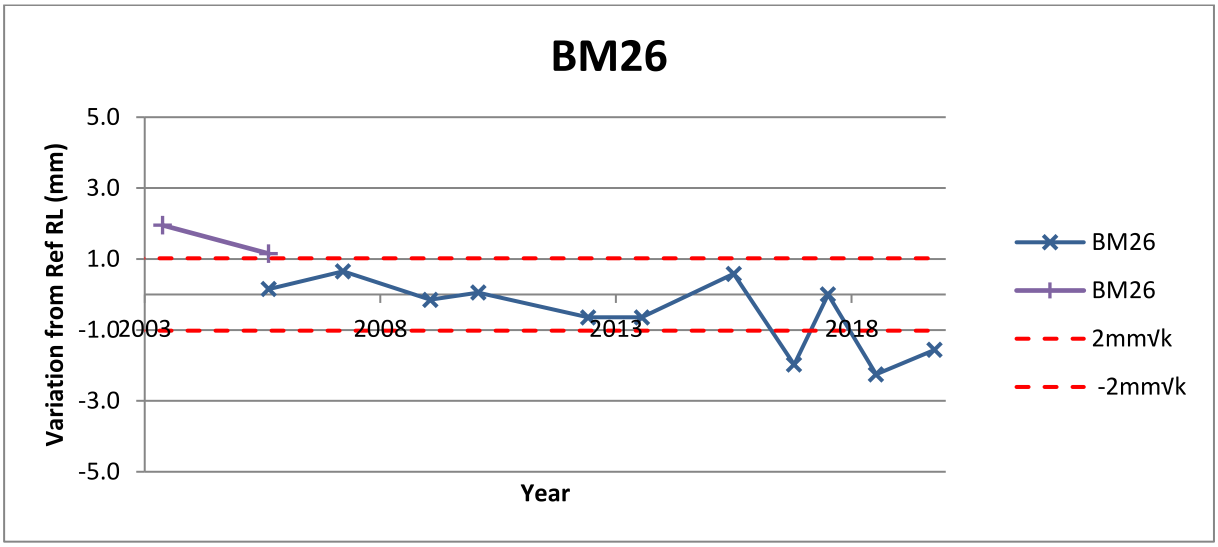
REF-2019	TUVABM	BM27	BM26	BM28	BM24	BM23	BM22	TUV19	TUV20	TUV110	TUVT	AQUA	RTGD	TUVA
TUVABM	-	-0.0003	0.0016	-0.0016	-0.0007	-0.0012	-0.0019	**-0.0055**	-0.0019	**-0.0059**	-0.0029	**-0.0082**	**-0.0078**	0.0000
BM27	0.0003	-	0.0018	-0.0013	-0.0005	-0.0010	-0.0017	**-0.0053**	-0.0016	**-0.0057**	-0.0027	**-0.0079**	**-0.0075**	0.0003
BM26	-0.0016	-0.0018	-	-0.0032	-0.0023	-0.0028	-0.0035	**-0.0071**	-0.0034	**-0.0075**	**-0.0045**	**-0.0097**	**-0.0094**	-0.0016
BM28	0.0016	0.0013	0.0032	-	0.0009	0.0004	-0.0003	-0.0039	-0.0003	-0.0044	-0.0013	**-0.0066**	**-0.0062**	0.0016
BM24	0.0007	0.0005	0.0023	-0.0009	-	-0.0005	-0.0012	**-0.0048**	-0.0012	**-0.0052**	-0.0022	**-0.0075**	**-0.0071**	0.0007
BM23	0.0012	0.0010	0.0028	-0.0004	0.0005	-	-0.0007	-0.0043	-0.0007	**-0.0047**	-0.0017	**-0.0070**	**-0.0066**	0.0012
BM22	0.0019	0.0017	0.0035	0.0003	0.0012	0.0007	-	-0.0036	0.0000	-0.0040	-0.0010	**-0.0063**	**-0.0059**	0.0019
TUV19	**0.0055**	**0.0053**	**0.0071**	0.0039	**0.0048**	0.0043	0.0036	-	0.0037	-0.0004	0.0026	-0.0027	-0.0023	**0.0055**
TUV20	0.0019	0.0016	0.0034	0.0003	0.0012	0.0007	0.0000	-0.0037	-	-0.0041	-0.0011	**-0.0063**	**-0.0059**	0.0019
TUV110	**0.0059**	**0.0057**	**0.0075**	0.0044	**0.0052**	**0.0047**	0.0040	0.0004	0.0041	-	0.0030	-0.0022	-0.0019	**0.0059**
TUVT	0.0029	0.0027	**0.0045**	0.0013	0.0022	0.0017	0.0010	-0.0026	0.0011	-0.0030	-	**-0.0052**	**-0.0049**	0.0029
AQUA	**0.0082**	**0.0079**	**0.0097**	**0.0066**	**0.0075**	**0.0070**	**0.0063**	0.0027	**0.0063**	0.0022	**0.0052**	-	0.0004	**0.0082**
RTGD	**0.0078**	**0.0075**	**0.0094**	**0.0062**	**0.0071**	**0.0066**	**0.0059**	0.0023	**0.0059**	0.0019	**0.0049**	-0.0004	-	**0.0078**

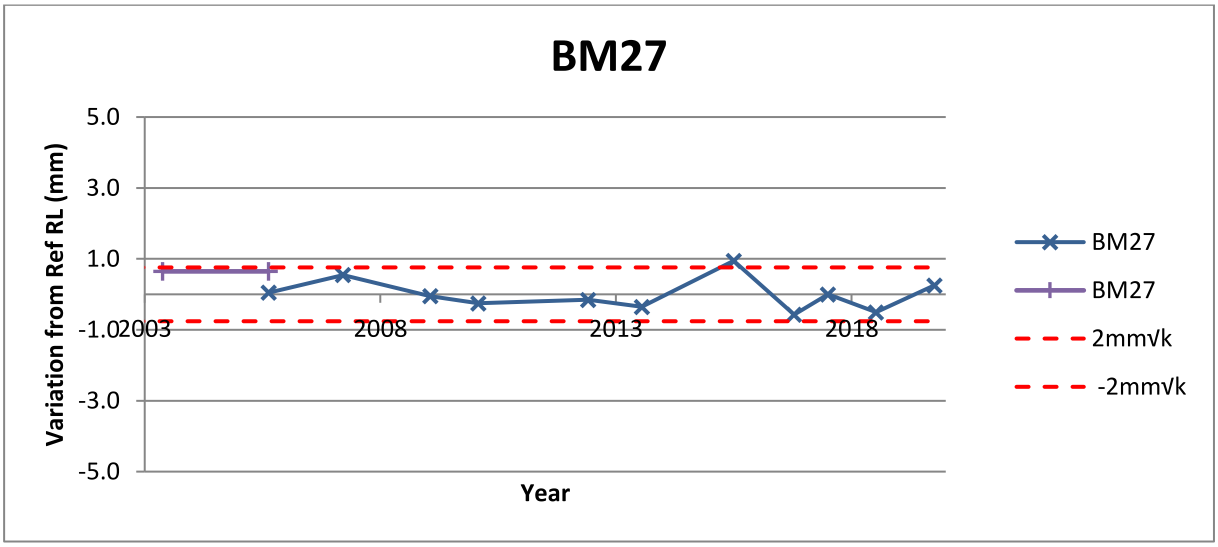
Table 5.4.1.1 values are calculated by subtracting the difference in height between RL_{2019} values (Table 5.3.8) from the difference in height between RL_{REF} values.

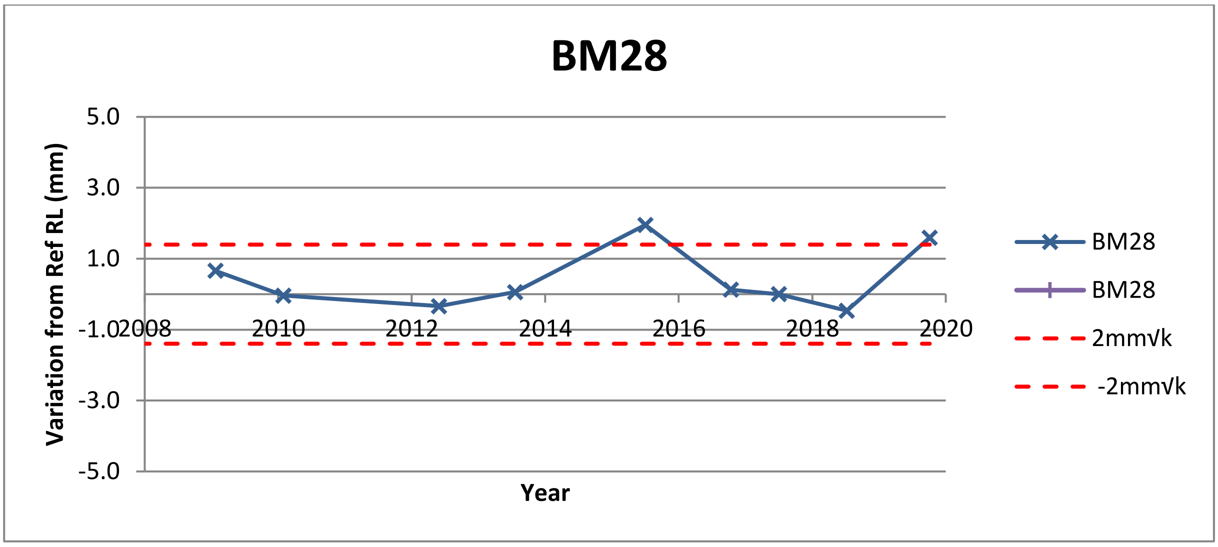
Comparing the change in relative heights between all benchmarks, will help identify the movement of a particular BM, inconsistency in the survey, or even deformation to the GNSS pillar and leveling run BM's.

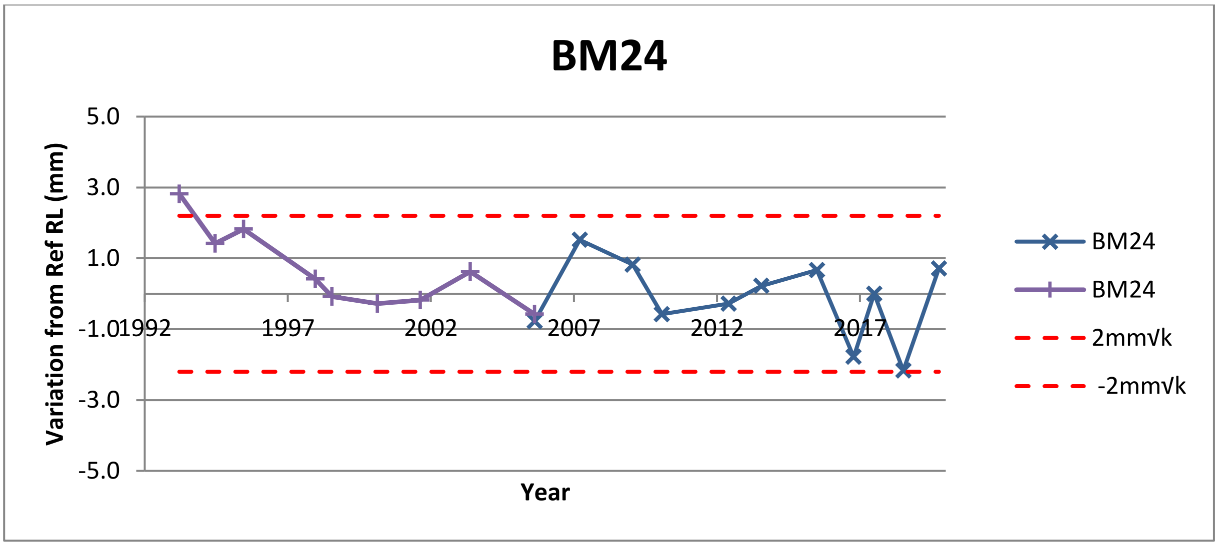
5.4.1 Time Series Charts for each BM

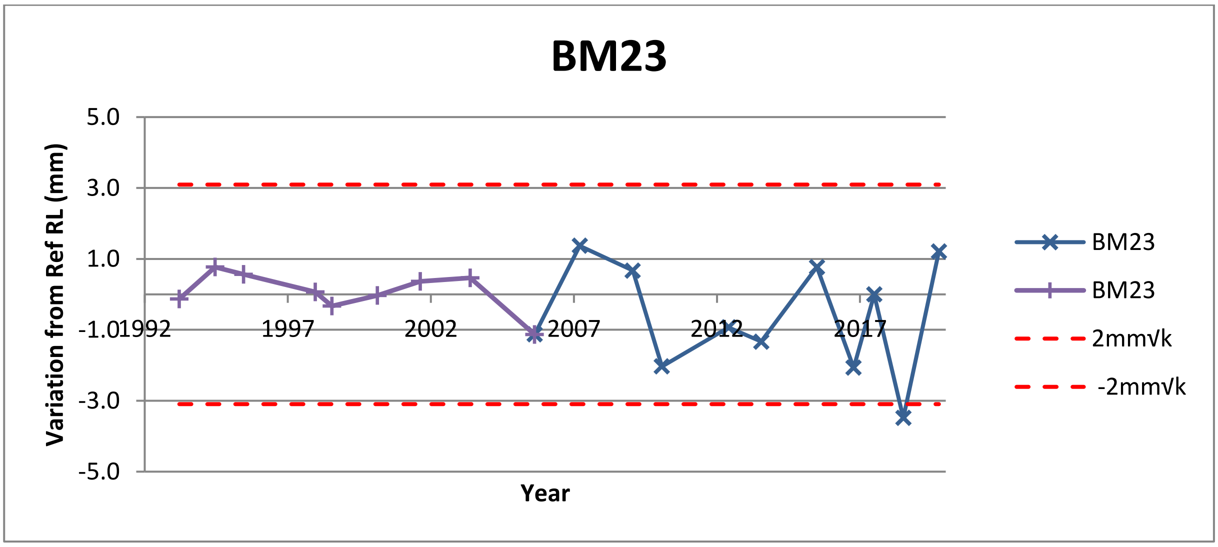
The change in RL over time can be used to detect trends of movement or survey errors. In the series of figures below, the red dashed lines represent the allowable error in height based on the levelling technique used and distance of the benchmark from the GNSS pillar (*2mm√k*). The purple line (with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

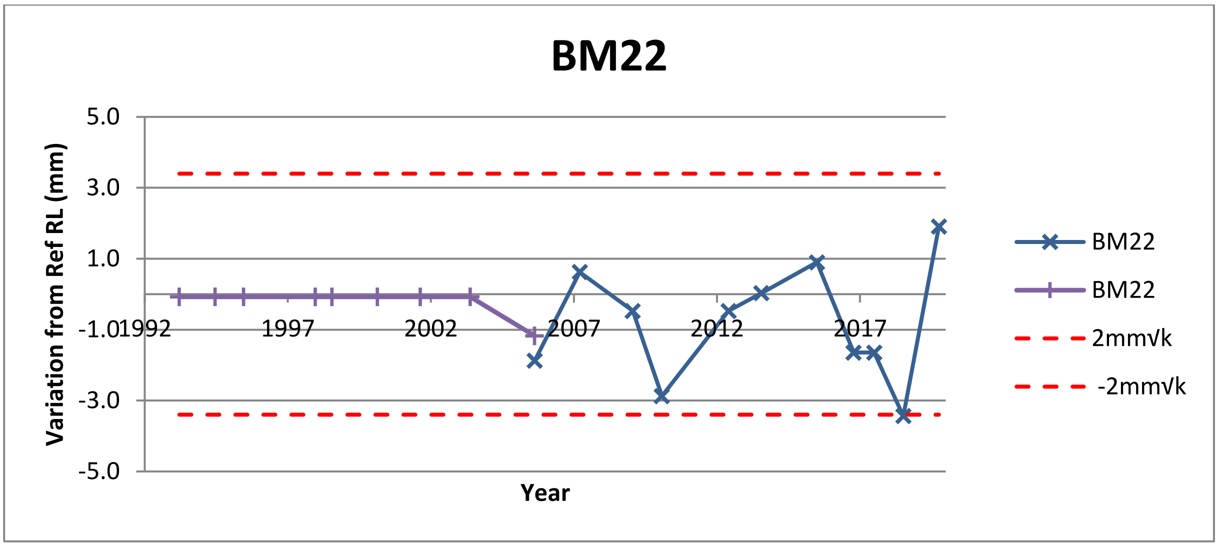


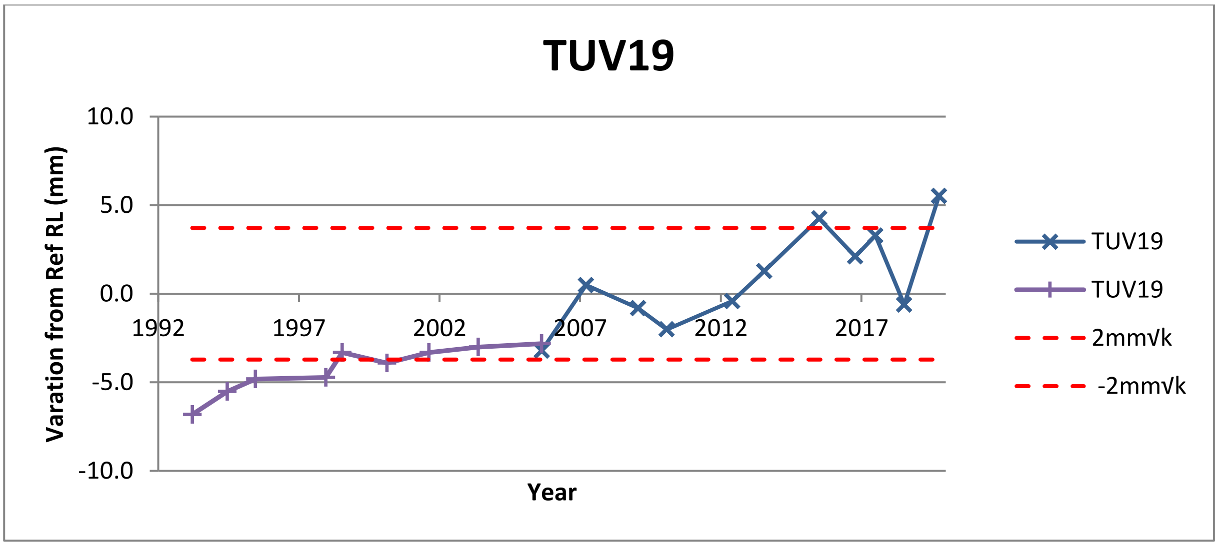


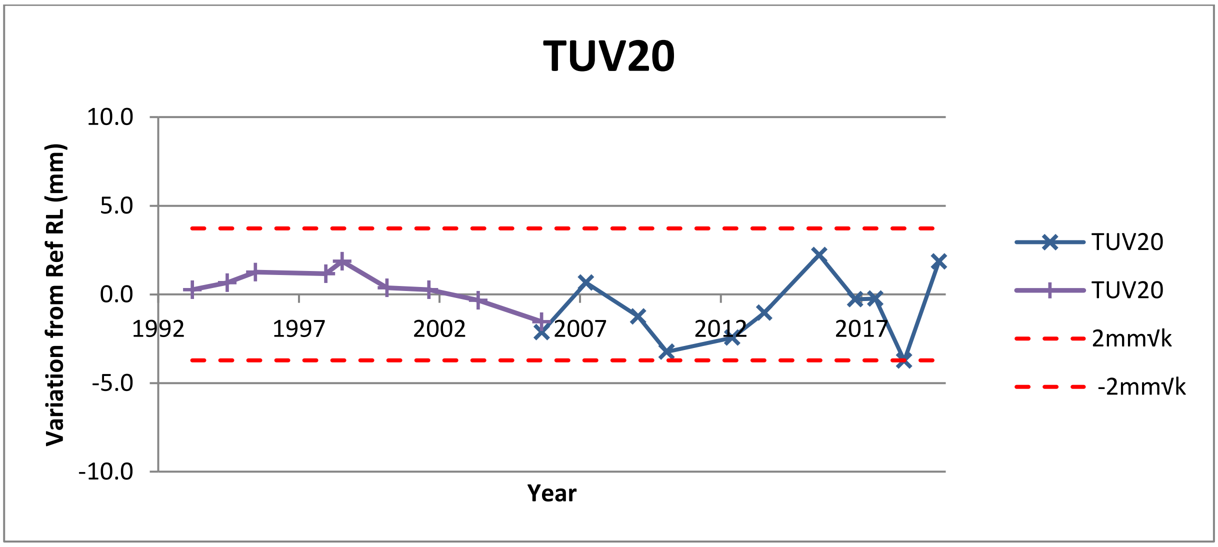

BM28
5.0
3.0
1.0
-1.0
-3.0
-5.0
2008
2010
2012
2014
2016
2018
2020
Variation from Ref RL (mm)
Year
BM28
BM28
2mm√k
-2mm√k

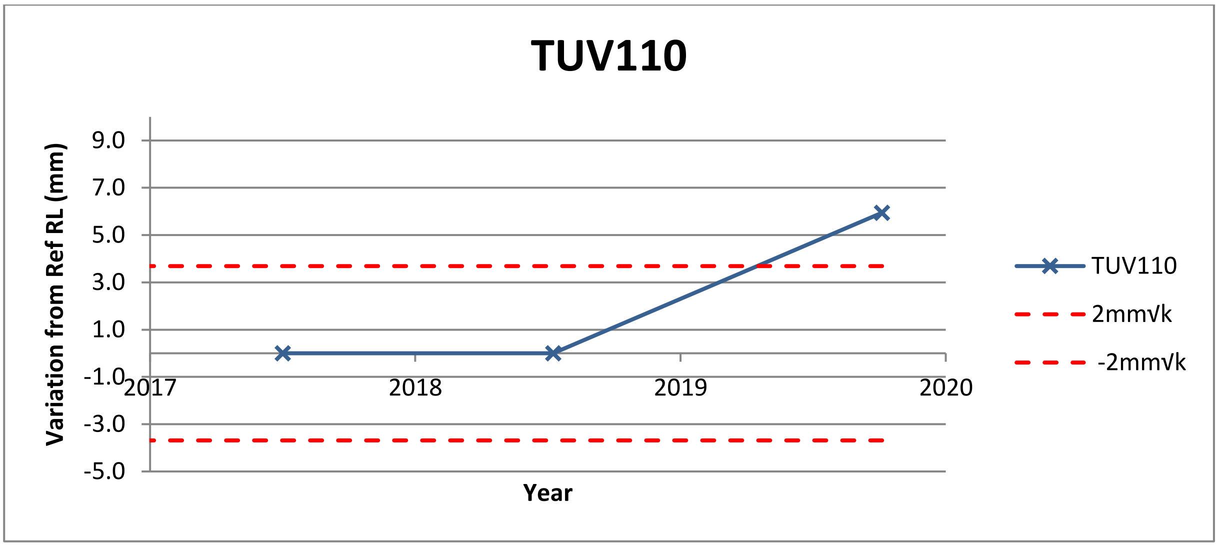

BM24
5.0
3.0
1.0
-1.0
-3.0
-5.0
1992
1997
2002
2007
2012
2017
Variation from Ref RL (mm)
Year
BM24
BM24
2mm√k
-2mm√k

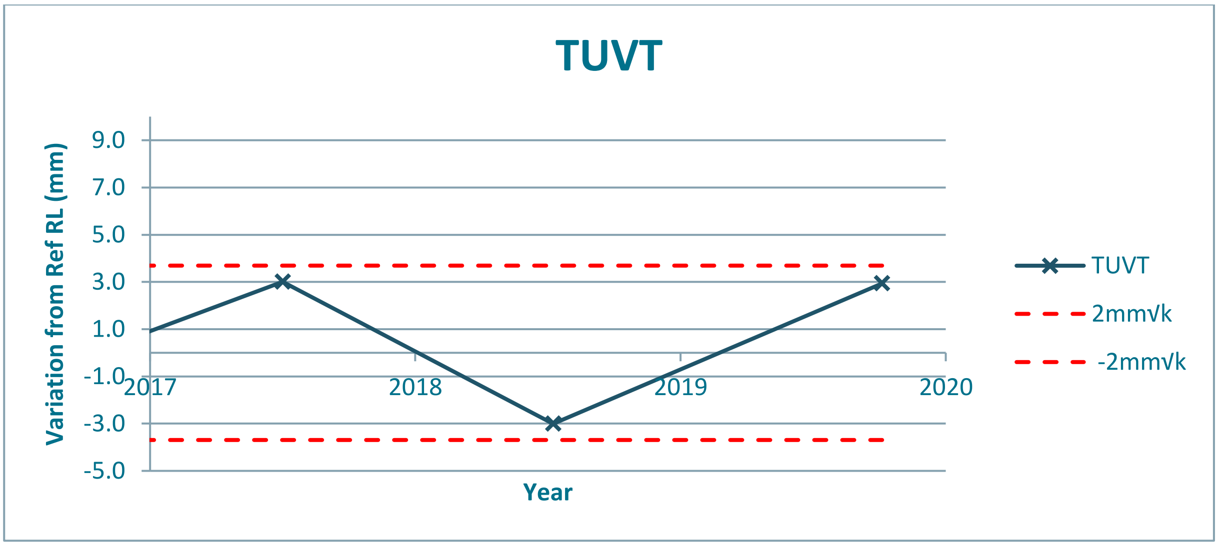

BM23
5.0
3.0
1.0
-1.0
-3.0
-5.0
1992
1997
2002
2007
2012
2017
Variation from Ref RL (mm)
Year
BM23
BM23
2mm√k
-2mm√k

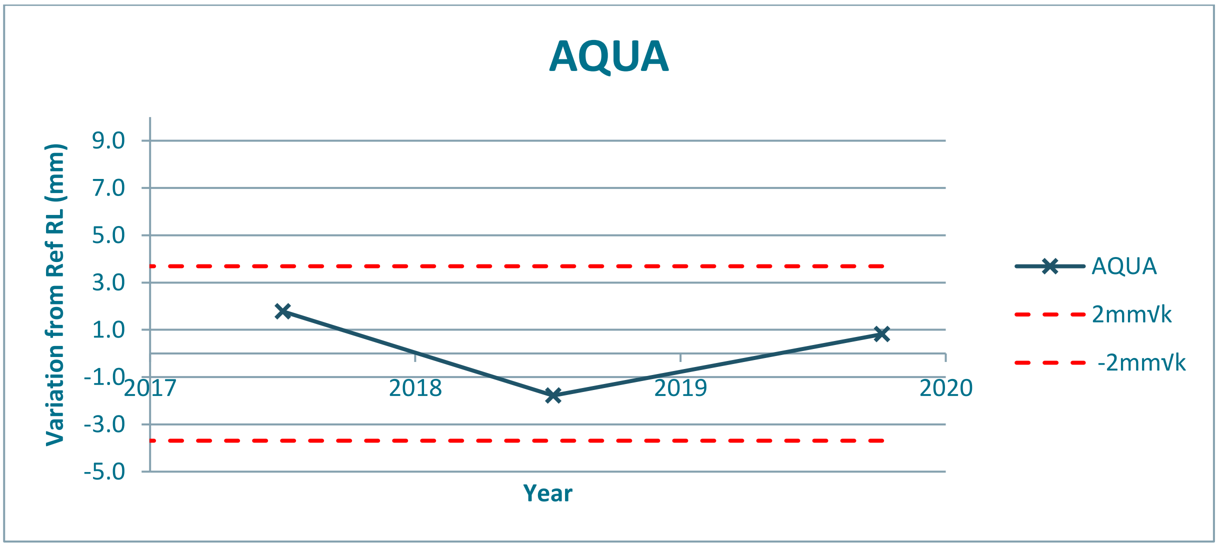

BM22
5.0
3.0
1.0
-1.0
-3.0
-5.0
1992
1997
2002
2007
2012
2017
Variation from Ref RL (mm)
Year
BM22
BM22
2mm√k
-2mm√k


TUV19
10.0
5.0
0.0
-5.0
-10.0
1992
1997
2002
2007
2012
2017
Varation from Ref RL (mm)
Year
TUV19
TUV19
2mm√k
-2mm√k


TUV20
10.0
5.0
0.0
-5.0
-10.0
1992
1997
2002
2007
2012
2017
Variation from Ref RL (mm)
Year
TUV20
TUV20
2mm√k
-2mm√k


TUV110
Variation from Ref RL (mm)
9.0
7.0
5.0
3.0
1.0
-1.0
-3.0
-5.0
2017
2018
2019
2020
Year
TUV110
2mm√k
-2mm√k


TUVT
Variation from Ref RL (mm)
9.0
7.0
5.0
3.0
1.0
-1.0
-3.0
-5.0
2017
2018
2019
2020
Year
TUVT
2mm√k
-2mm√k


AQUA
Variation from Ref RL (mm)
9.0
7.0
5.0
3.0
1.0
-1.0
-3.0
-5.0
2017
2018
2019
2020
Year
AQUA
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 above 0.003 m:

- TUV19, TUV110, AQUA, RTGD
    - localised movement of the mark is located at the wharf where there are heavy movement of vehicles.

The survey from the primary GNSS BM (TUVABM) to the TG Plaque (TUV19) shows some change. There is a high chance of deformation on the wharf structure when looking at the two past result of this benchmark.

Table 6.1 Comparison of results with Reference ^H

PT ID	Reference ^H (m)	2019.76 Value (m)	Difference
TUVABM - Primary BM (BM22)	0.4841	0.4860	0.0019
BM22 - TG Plaque BM (TUV110)	0.5506	0.5546	0.0040
BM22 - TG ref pin (AQUA)	1.5861	1.5924	0.0063
TUVABM - BM22	0.4841	0.4860	0.0019
BM22 - TUV110	0.5506	0.5546	0.0040
TUV110 - RTGD	1.0485	1.0503	0.0019

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

PT ID	Reference RL (m)	2019.76 Value (m)	Difference	ITRF2020	TGZ
TUVABM	0.000	0.000	0.0000	37.4434	3.5267
BM27	-0.5255	-0.5253	0.0003	36.9181	3.0014
BM26	0.3665	0.3650	-0.0016	37.8084	3.8917
BM28	-0.5254	-0.5238	0.0016	36.9196	3.0029
BM24	1.0540	1.0547	0.0007	38.4981	4.5814
BM23	0.3972	0.3984	0.0012	37.8418	3.9251
BM22	0.4841	0.4860	0.0019	37.9294	4.0127
TUV19	0.7467	0.7522	0.0055	38.1956	4.2789

TUV20	1.7182	1.7201	0.0019	39.1635	5.2468
TUV110	1.0347	1.0406	0.0059	38.4840	4.5673
TUVT	2.3460	2.3489	0.0029	39.7923	5.8756
AQUA	2.0702	2.0784	0.0082	39.5218	5.6051
RTGD	2.0831	2.0909	0.0078	39.5343	5.6176
TUVA	0.9631	0.9631	0.0000	38.4065	4.4898
TGZ	-3.5286	-3.5267	0.0019	33.9167	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 the 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).

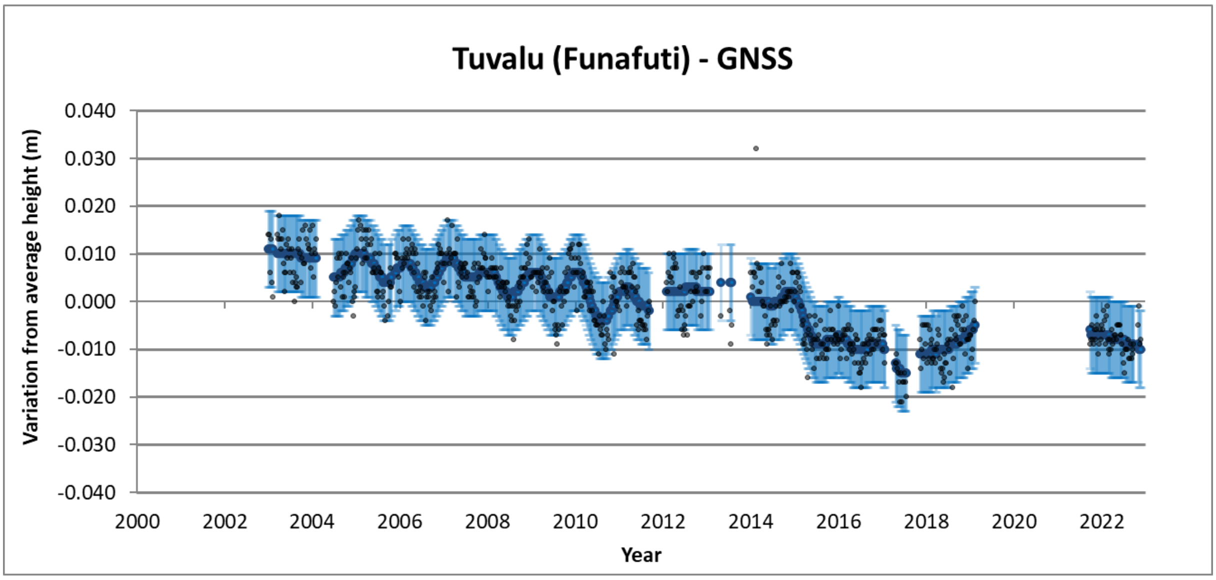


Figure 7.1 Time series of GNSS analysis (dark blue line) with 95% CI uncertainty (light blue lines).

[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.

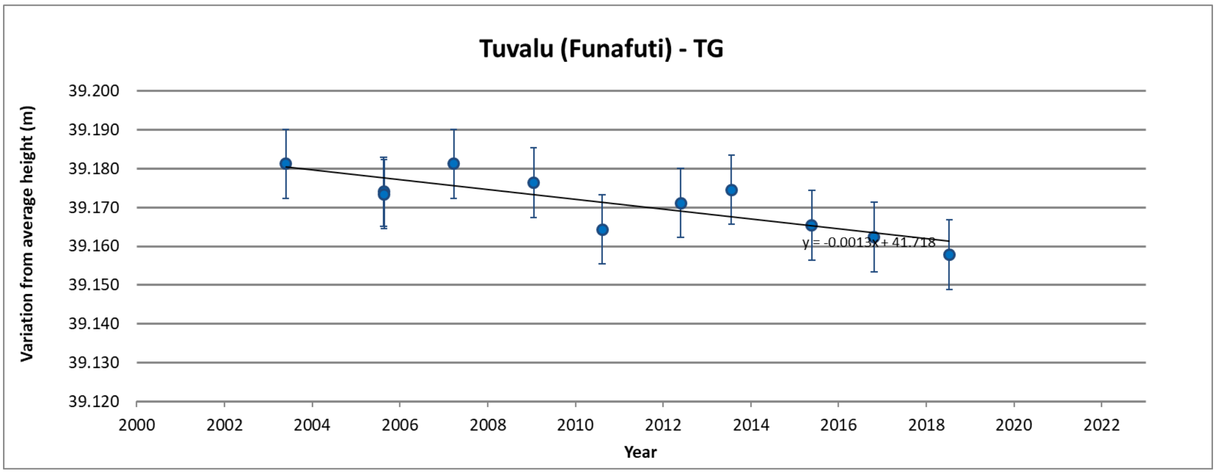


Figure 7.2 The height of the SEAFRAME sensor reference benchmark (with respect to ITRF2020).

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.

[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.

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

Date	Height (m)	Uncertainty (95%CI) (m)
2003.40	39.1813	0.009
2005.63	39.1741	0.009
2005.64	39.1735	0.009
2007.23	39.1813	0.009
2009.05	39.1764	0.009
2010.61	39.1644	0.009
2012.40	39.1712	0.009
2013.56	39.1746	0.009
2015.39	39.1655	0.009
2016.81	39.1625	0.009
2018.52	39.1579	0.009

8 References

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

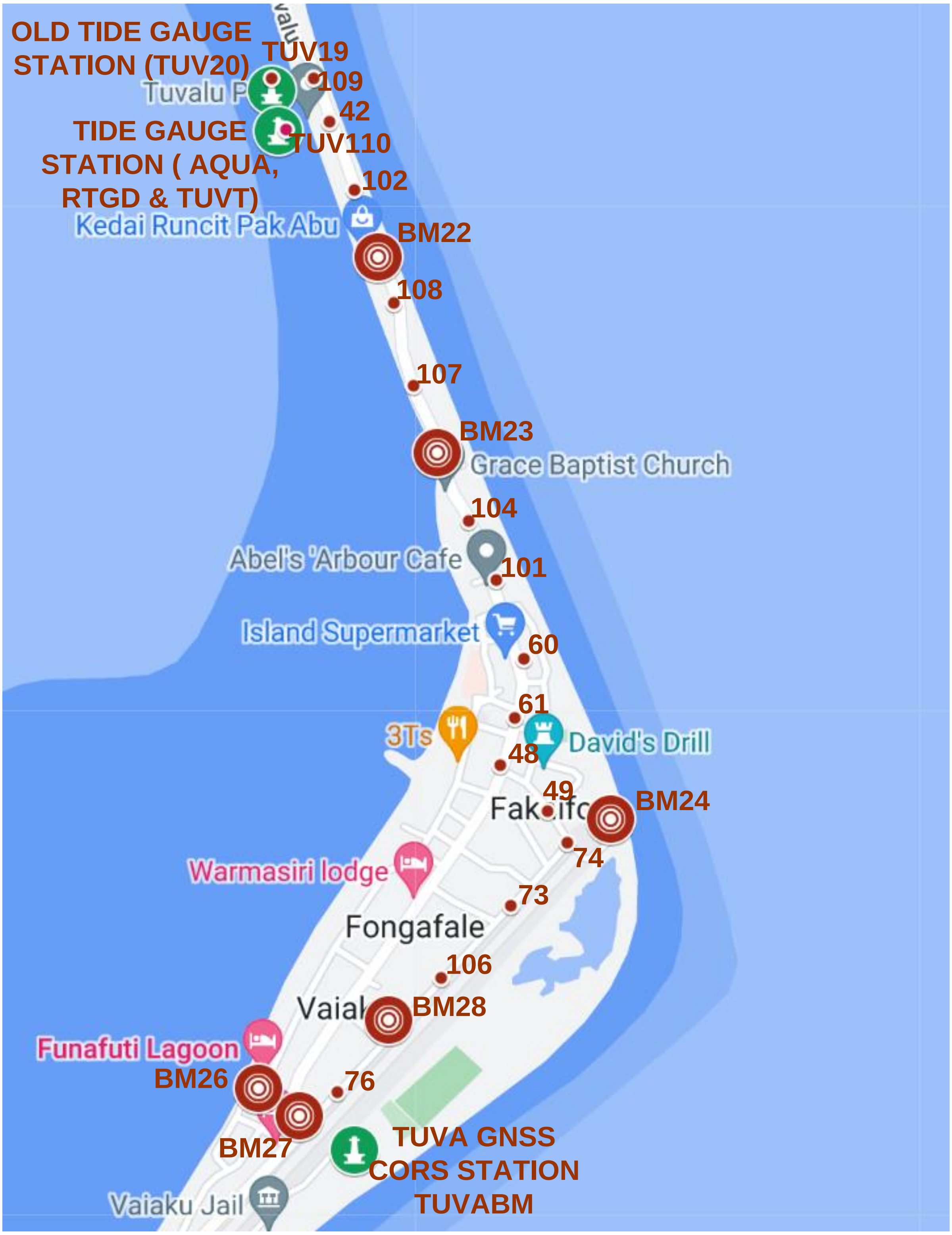
Fraser, R., Leahy, F., Collier, P., 2018. *DynAdjust User's Guide Version 3.0*. Dynamic Network Adjustment Software.

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

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

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

Appendix A Locality Diagrams



Source: Google Maps

A 1. Deep Benchmarks

PACIFIC SEA LEVEL MONITORING PROJECT

SURVEY BENCH MARK RECORD

Bench Mark Number: **BM22**

Original Bench Mark Established by: *Date: 29/03/2007*

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

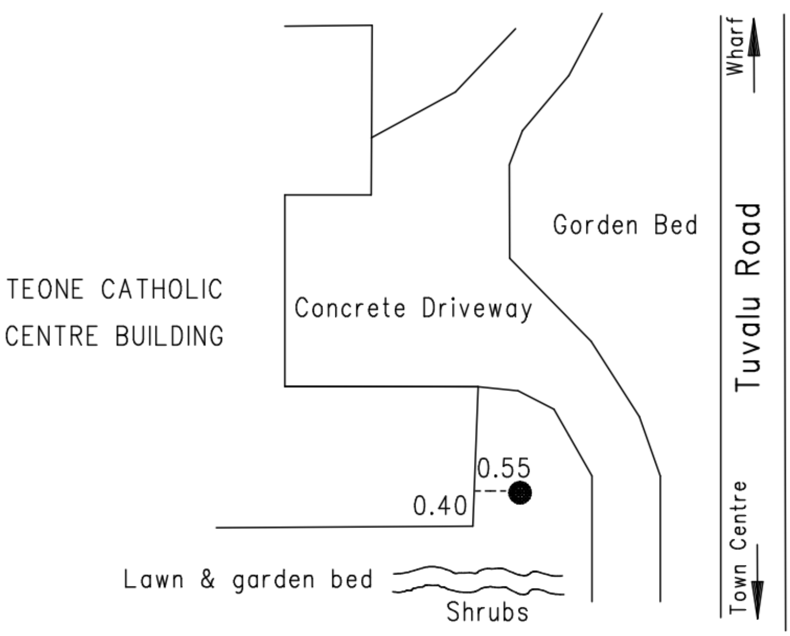
Existing Bench Mark Established by: S. Yates & A. Lal *Date:* 29-03-07

Notes / References: Deep driven bench mark, covered by plastic housing. Good location for GNSS obs.

Country: Tuvalu
Island: Funafuti *City:*Fongafale

MARKING AND LOCALITY SKETCH

Bench Mark: 2.2m 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 0.25m below ground level. Locality sketch Mark approximately 500m from the tide gauge station. Not to scale distances in meters & Magnetic bearing



NOT TO SCALE Distances in Metres Magnetic Bearings

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

PACIFIC SEA LEVEL AND GEODETIC MONITORING PROJECT

Australian Government
Geoscience Australia

Pacific Community
Communauté du Pacifique

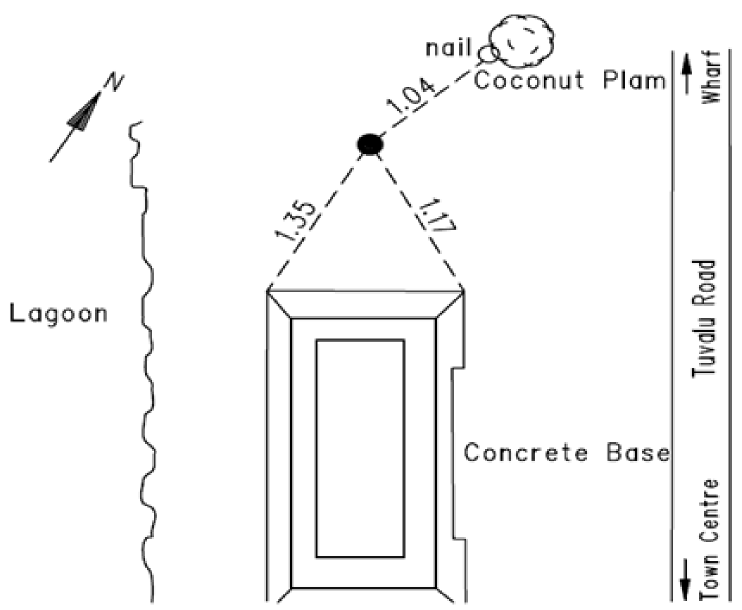
SURVEY BENCH MARK RECORD

Bench Mark Number: **BM23**

Original Bench Mark Established by: Geodesy Section, Geoscience Australia & Applied Geoscience and Technology Division, SPC	*Date: 18/01/2007*
Existing Bench Mark Established by: S. Yates & A. Lal	*Date:* 18-01-07
Notes / References: Deep driven bench mark, covered by plastic housing. Good location for GNSS obs.	
Country: Tuvalu *Island: Funafuti*	*City:*Fongafale

MARKING AND LOCALITY SKETCH

Bench Mark: 2.2m 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 1000m from the tide gauge station. Not to scale distances in meters & Magnetic bearing



NOT TO SCALE   Distances in Metres   Magnetic Bearings

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

PACIFIC SEA LEVEL AND GEODETIC MONITORING PROJECT

Australian Aid

Australian Government
Geoscience Australia

Pacific Community
Communauté du Pacifique

SURVEY BENCH MARK RECORD

Bench Mark Number: **BM24**

Original Bench Mark Established by: *Date: 18/01/2007*

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

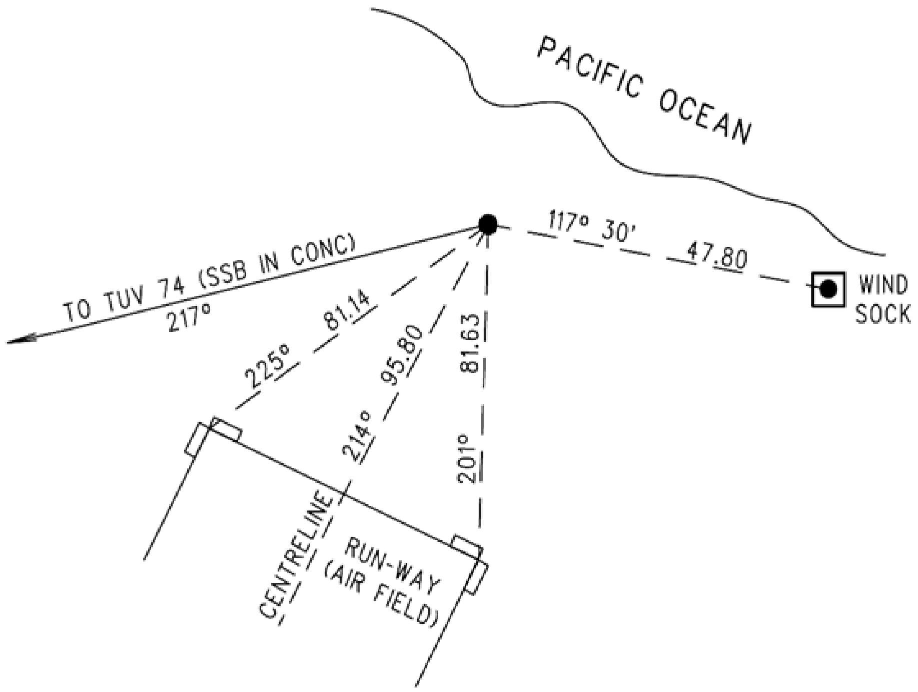
Existing Bench Mark Established by: S. Yates & A. Lal *Date:* 18-01-07

Notes / References: Deep driven bench mark, covered by plastic housing. Good location for GNSS obs.

Country: Tuvalu
Island: Funafuti
*City:*Fongafale

MARKING AND LOCALITY SKETCH

Bench Mark: 2.2m of 19mm diameter stainless steel capped rod driven until refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite, for 0.8m top of mark 0.15m below ground level. Locality sketch Mark approximately 2000m 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: 2/9/2014*

PACIFIC SEA LEVEL AND GEODETIC MONITORING PROJECT

Australian Aid | Australian Government Geoscience Australia | Pacific Community Communauté du Pacifique

SURVEY BENCH MARK RECORD

Bench Mark Number: BM26

Original Bench Mark Established by: *Date: 18/01/2007*

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

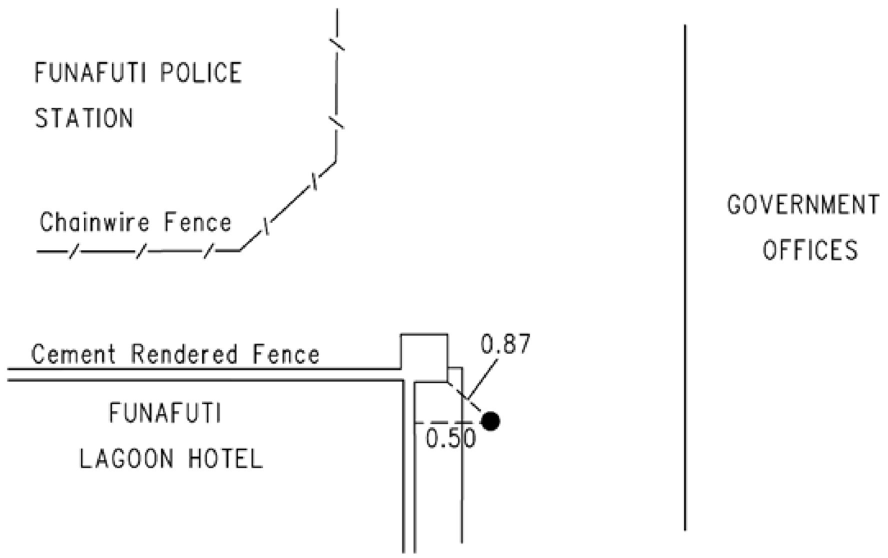
Existing Bench Mark Established by: S. Yates & A. Lal *Date:* 29-01-07

Notes / References: Deep driven bench mark, covered by plastic housing. Good location for GNSS obs.

Country: Tuvalu
Island: Funafuti *City:*Fongafale

MARKING AND LOCALITY SKETCH

Bench Mark: 2.2m of 19mm diameter stainless steel capped rod driven until refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite, for 0.5m top of mark 0.1m below ground level. Locality sketch Mark approximately 3100m 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: 2/9/2014*

PACIFIC SEA LEVEL AND GEODETIC MONITORING PROJECT

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Communauté du Pacifique

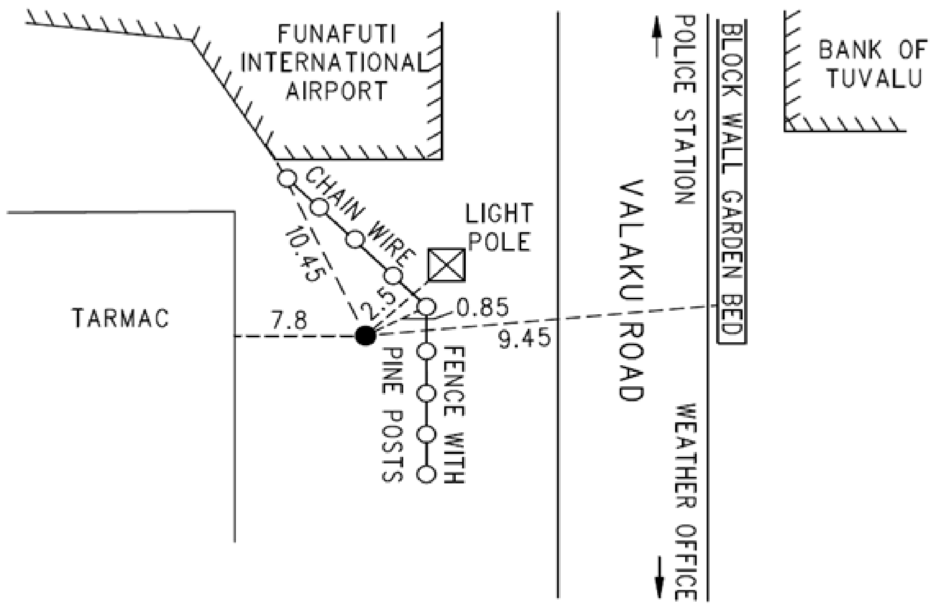
SURVEY BENCH MARK RECORD

Bench Mark Number: BM27

Original Bench Mark Established by: Geodesy Section, Geoscience Australia & Applied Geoscience and Technology Division, SPC	*Date: 18/01/2007*
Existing Bench Mark Established by: S. Yates & A. Lal	*Date:* 29-01-07
Notes / References: Deep driven bench mark, covered by plastic housing. Good location for GNSS obs.	
Country: Tuvalu *Island: Funafuti*	*City:*Fongafale

MARKING AND LOCALITY SKETCH

Bench Mark: 2.2m of 19mm diameter stainless steel capped rod driven until refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite, for 0.5m top of mark 0.1m below ground level. Locality sketch Mark approximately 3200m 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: 2/9/2014*

PACIFIC SEA LEVEL MONITORING PROJECT

Australian Aid

Australian Government
Geoscience Australia

SPC Secretariat of the Pacific Community

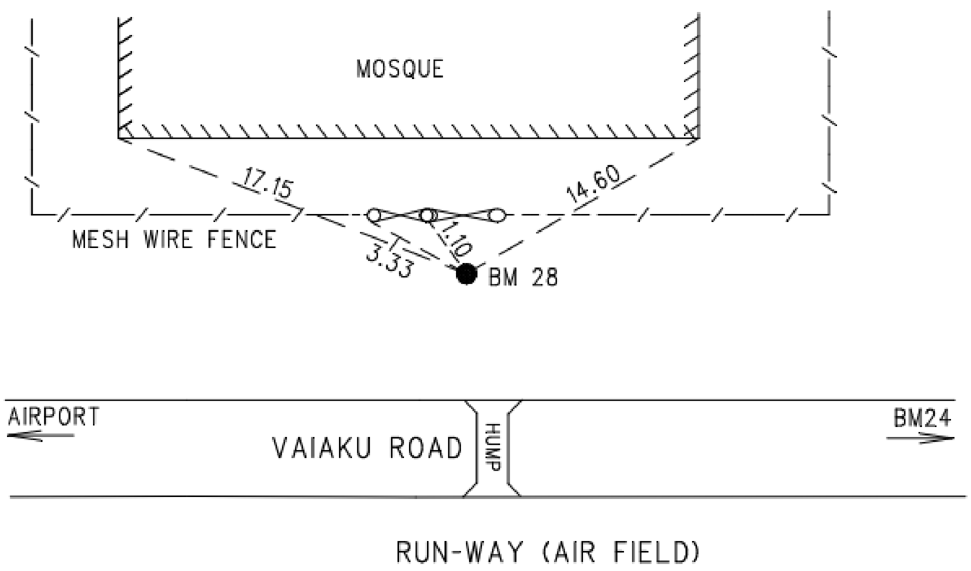
SURVEY BENCH MARK RECORD

Bench Mark Number: BM28

Original Bench Mark Established by: Geodesy Section, Geoscience Australia & Applied Geoscience and Technology Division, SPC	*Date: 18/01/2007*
Existing Bench Mark Established by: S. Yates & A. Lal	*Date:* 22-01-09
Notes / References: Deep driven bench mark, covered by plastic housing. Good location for GNSS obs.	
Country: Tuvalu *Island: Funafuti*	*City:*Fongafale

MARKING AND LOCALITY SKETCH

Bench Mark: 2.2m 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 0.1m below ground level. Locality sketch Mark approximately 600m from the GNSS station. Not to scale distances in meters & Magnetic bearing



NOT TO SCALE | Distances in Metres | Magnetic Bearings

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

PACIFIC SEA LEVEL AND GEODETIC MONITORING PROJECT

Australian Government
Geoscience Australia

Pacific Community
Communauté du Pacifique

SURVEY BENCH MARK RECORD

Bench Mark Number: Funafuti Tide Gauge

Original Bench Mark Established by: *Date: 19/04/18*

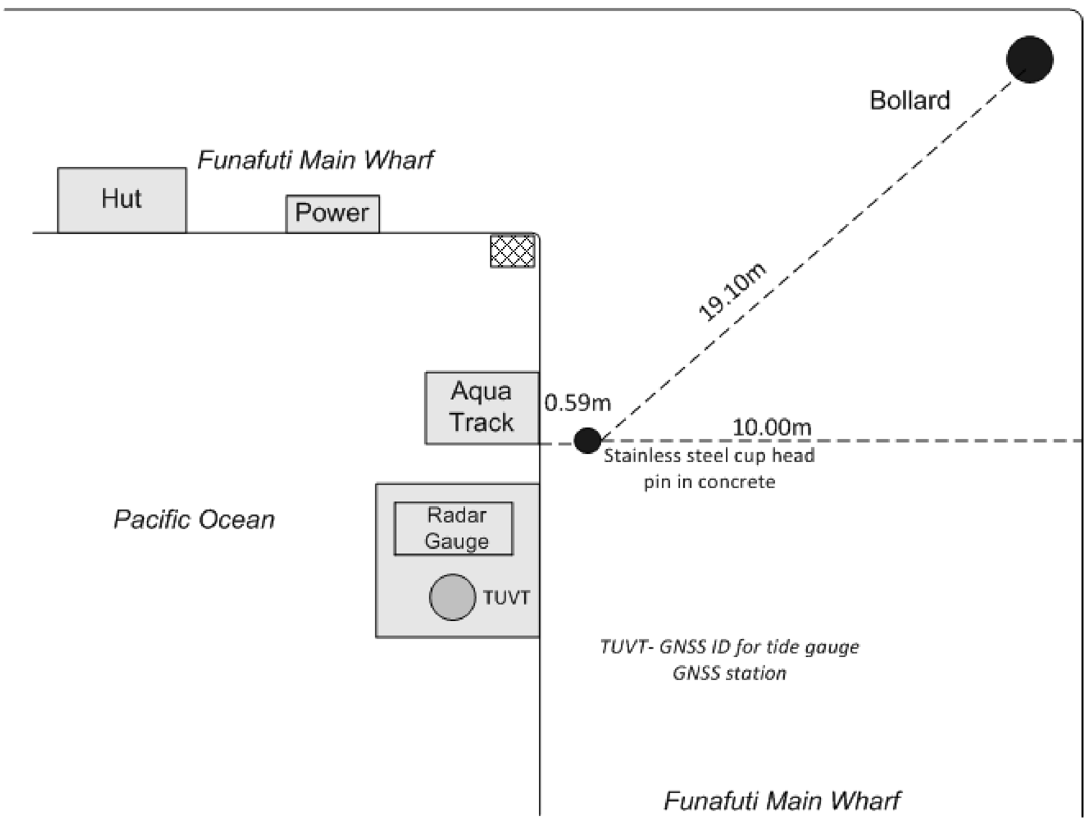
Pacific Community – SPC Geoscience, Energy, Maritime Division
Bureau of Meterology, 25 College Rd, Kent Town, SA, & Geoscience Australia

Existing Bench Mark Established by: *Date:*

Notes / References: Tide gauge reference benchmarks and GNSS Station

Country: Tuvalu
Island: Funafuti
City: Funafuti

MARKING AND LOCALITY SKETCH

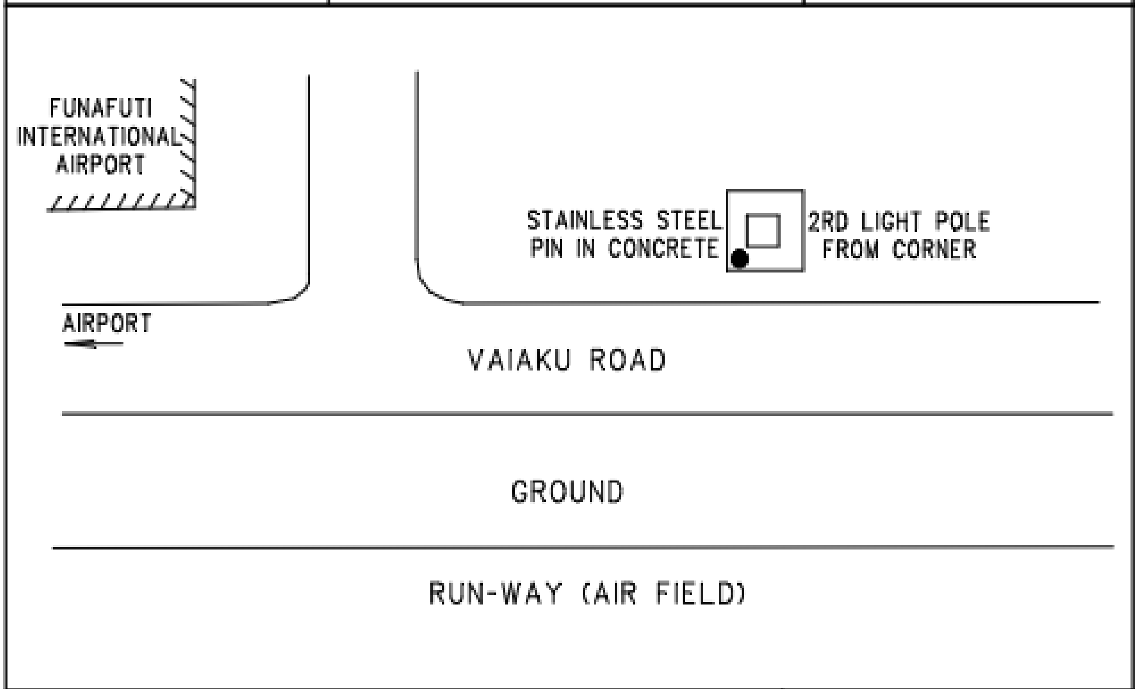


NOT TO SCALE Distances in Metres Magnetic Bearings

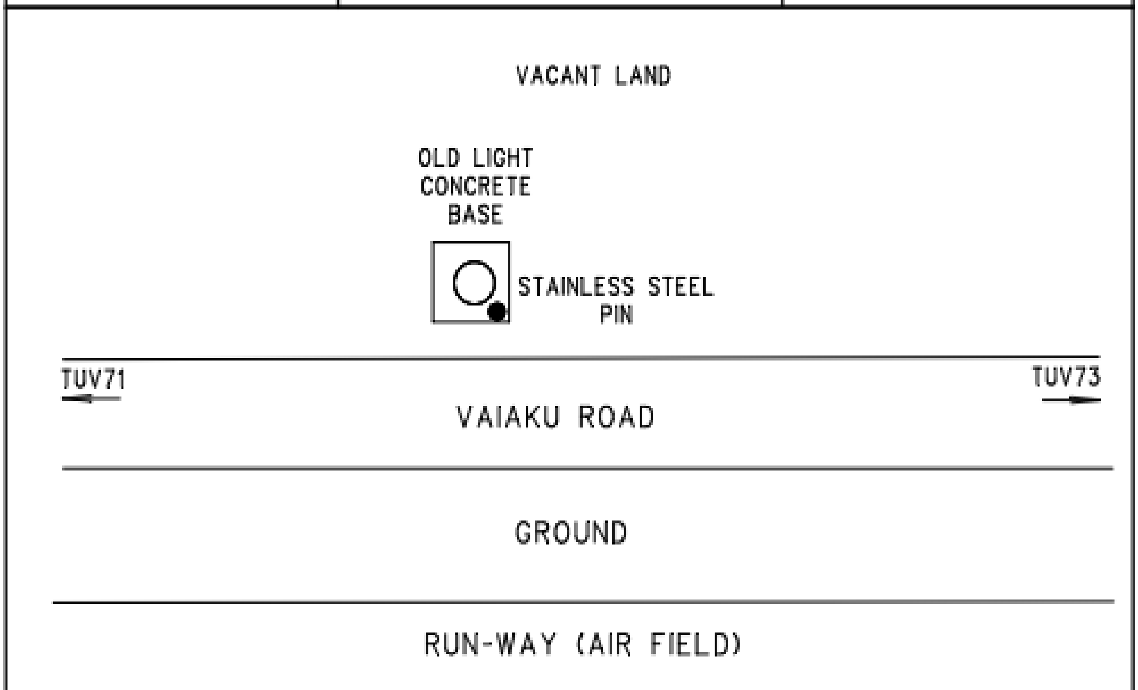
Approved by: Geoscience Australia / SPC *Date: 28/01/2019*

A 2 Temporary Benchmarks

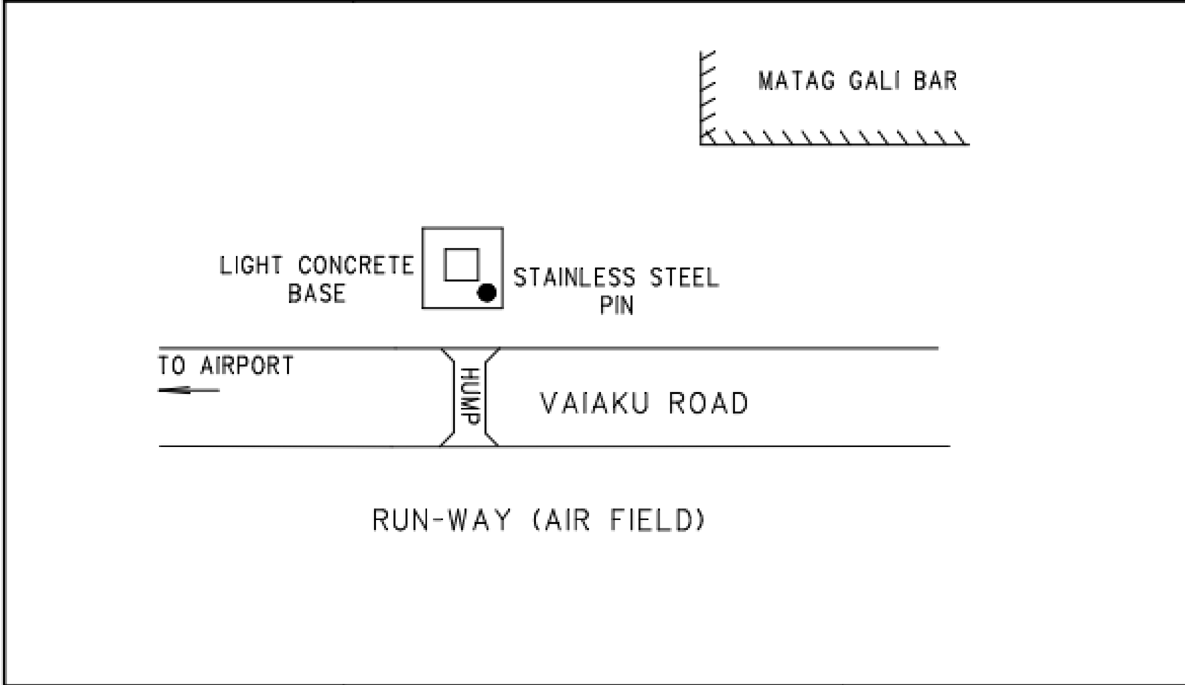
COUNTRY: Tuvalu	ISLAND: Funafuti CITY: Fongafale	L. D. P. 893 POINT NO. 76
PROJECT: PSLGMP	SURVEYOR: M. Kalouniviti	DATE: 02-10-19



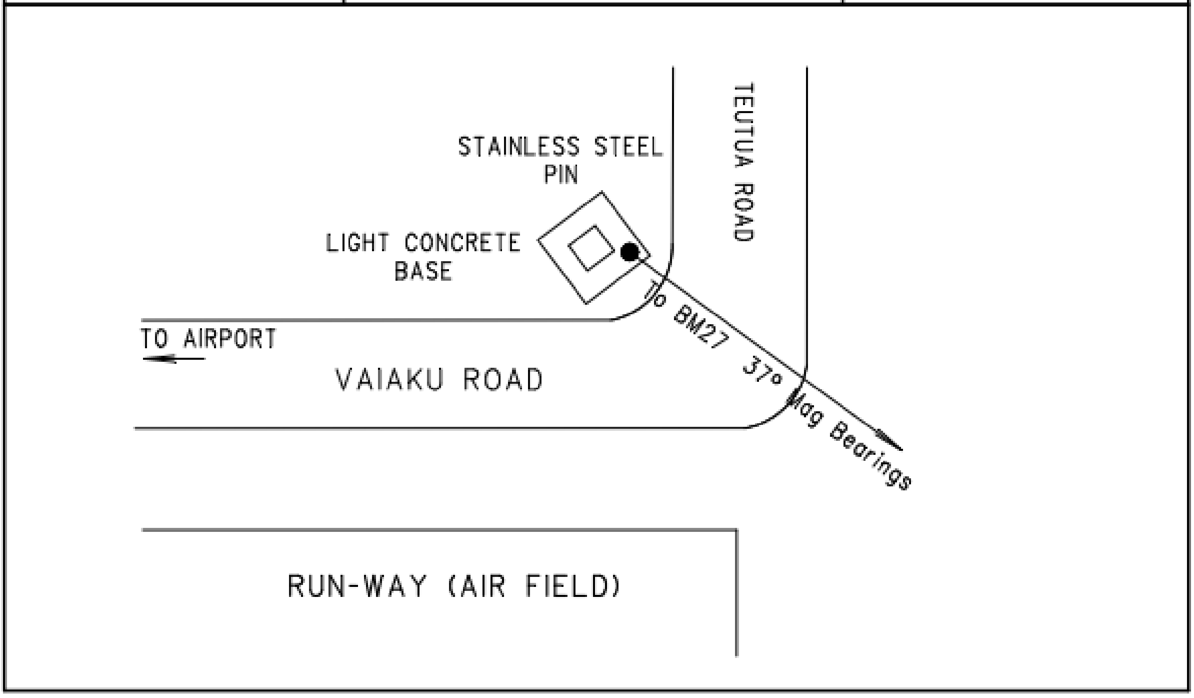
COUNTRY: Tuvalu	ISLAND: Funafuti CITY: Fongafale	L. D. P. 898 POINT NO. 106
PROJECT: PSLGMP	SURVEYOR: S. Yates & A. Lal	DATE: 23-05-12



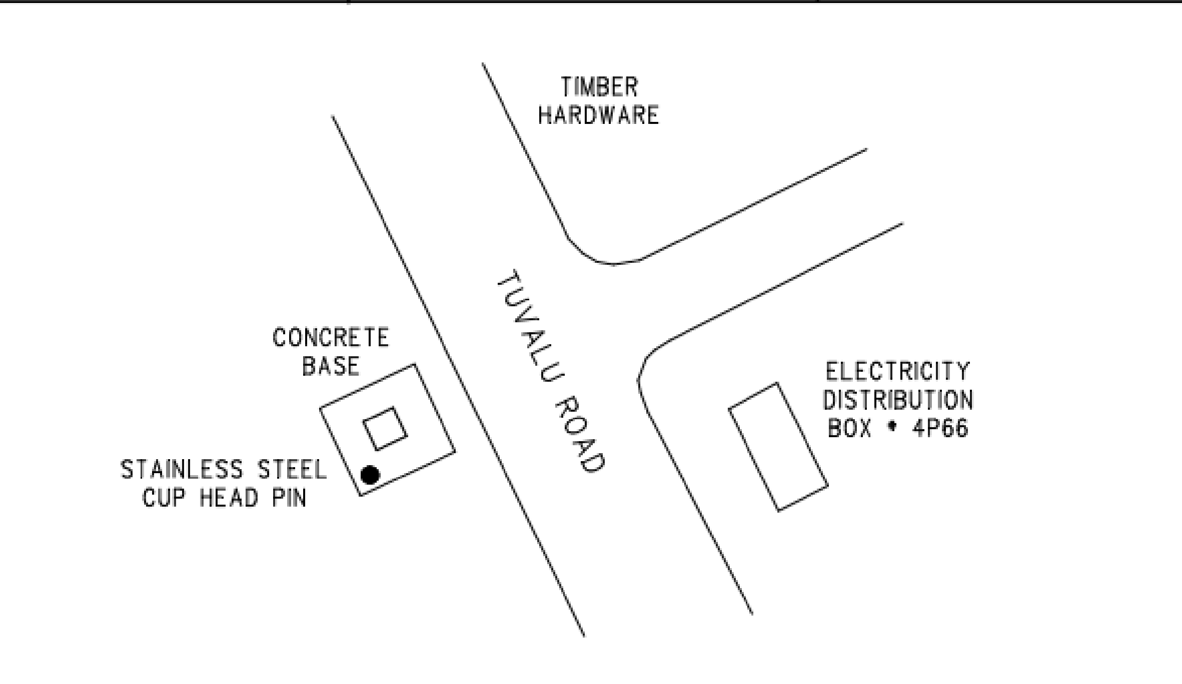
COUNTRY: Tuvalu	ISLAND: Funafuti CITY: Fongafale	L. D. P. 779 POINT NO. 73
PROJECT: PSLGMP	SURVEYOR: S. Yates & A Lal	DATE: 29-03-07



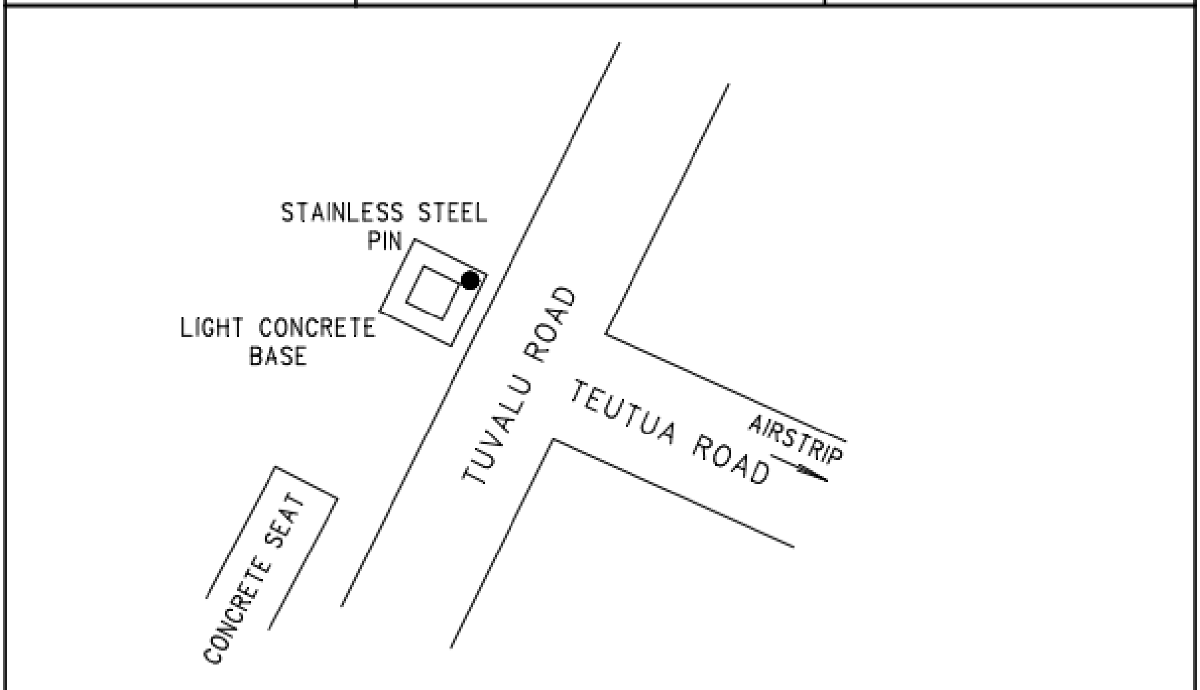
COUNTRY: Tuvalu	ISLAND: Funafuti CITY: Fongafale	L. D. P. 780 POINT NO. 74
PROJECT: PSLGMP	SURVEYOR: S. Yates & A Lal	DATE: 18-01-07



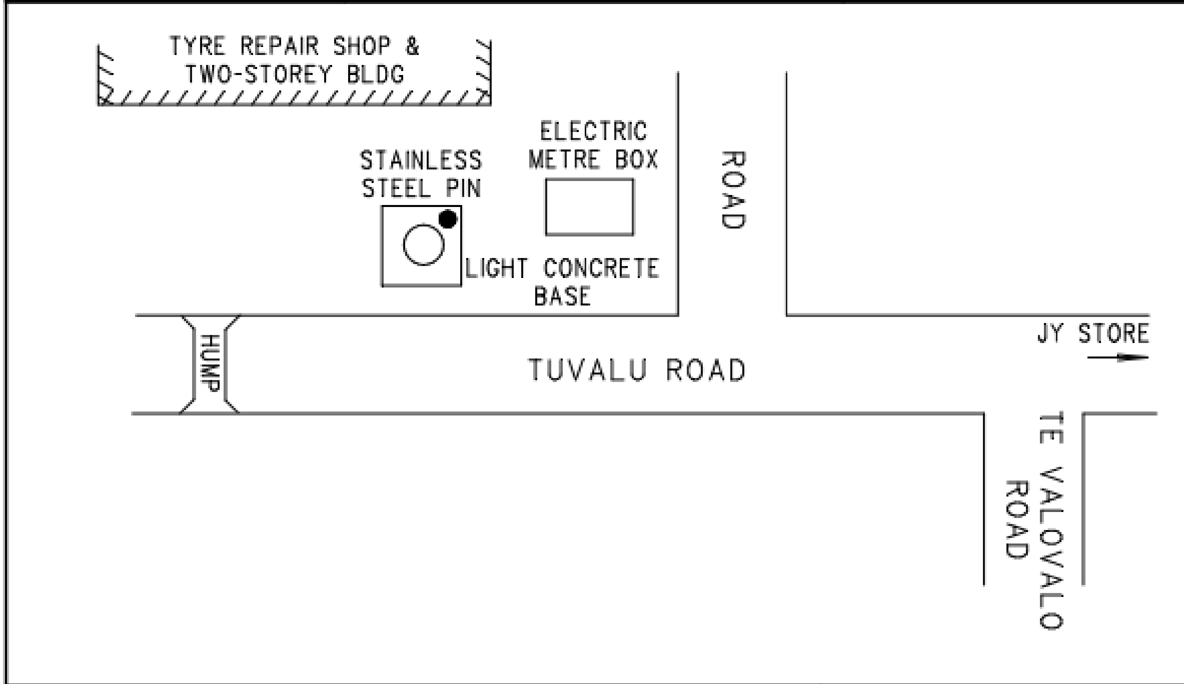
COUNTRY: Tuvalu	ISLAND: Funafuti CITY: Fongafale	L. D. P. 892 POINT NO. 49
PROJECT: PSLGMP	SURVEYOR: S. Turner	DATE: 24-08-01



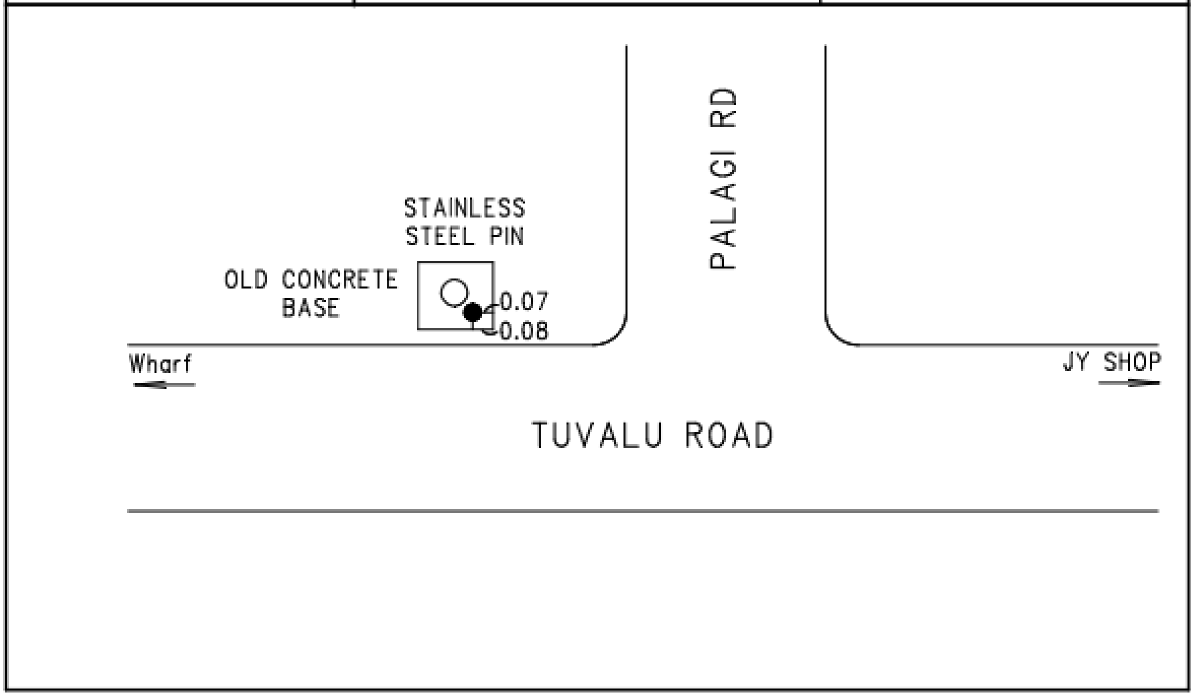
COUNTRY: Tuvalu	ISLAND: Funafuti CITY: Fongafale	L. D. P. 777 POINT NO. 48
PROJECT: PSLGMP	SURVEYOR: S. Yates & A Lal	DATE: 29-03-07



COUNTRY: Tuvalu	ISLAND: Funafuti CITY: Fongafale	L. D. P. 778 POINT NO. 61
PROJECT: PSLGMP	SURVEYOR: S. Yates & A Lal	DATE: 18-01-07



COUNTRY: Tuvalu	ISLAND: Funafuti CITY: Fongafale	L. D. P. 717 POINT NO. 60
PROJECT: PSLGMP	SURVEYOR: S. M. Turner	DATE: 12-05-03



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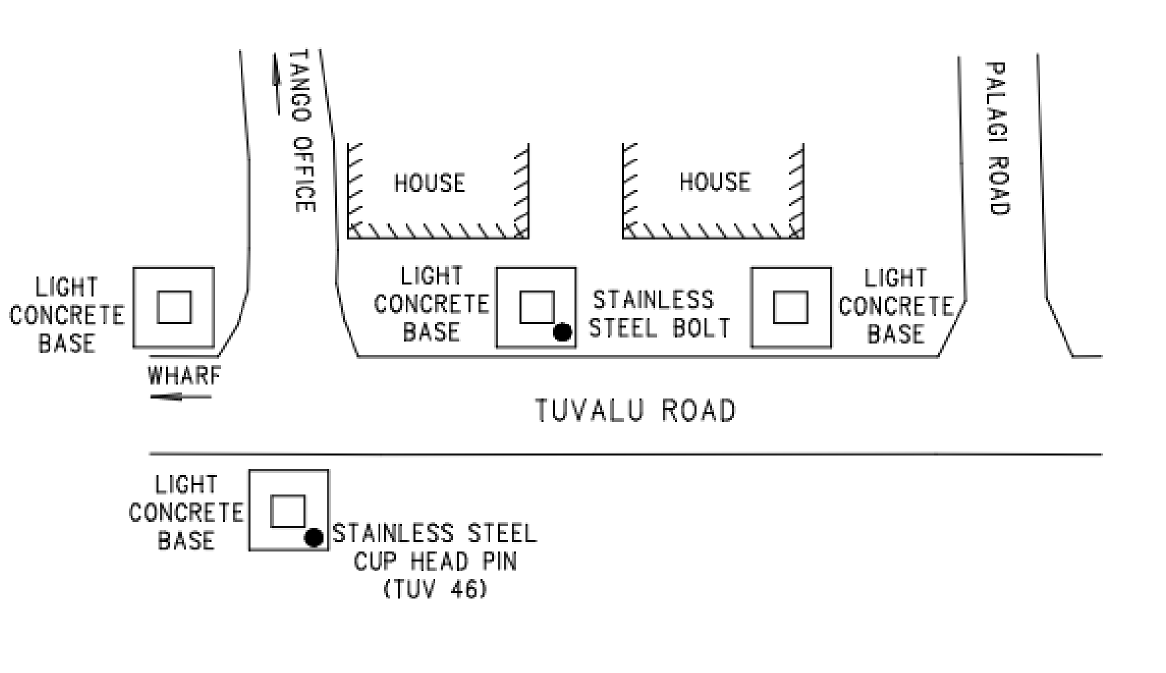
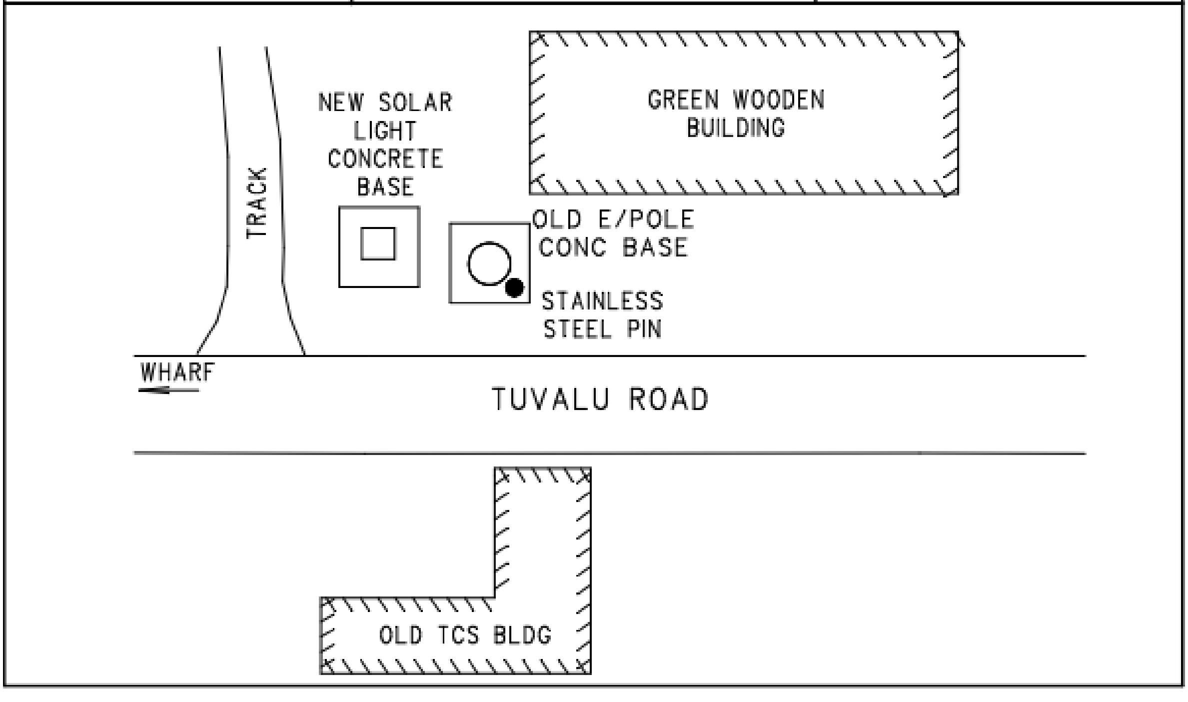
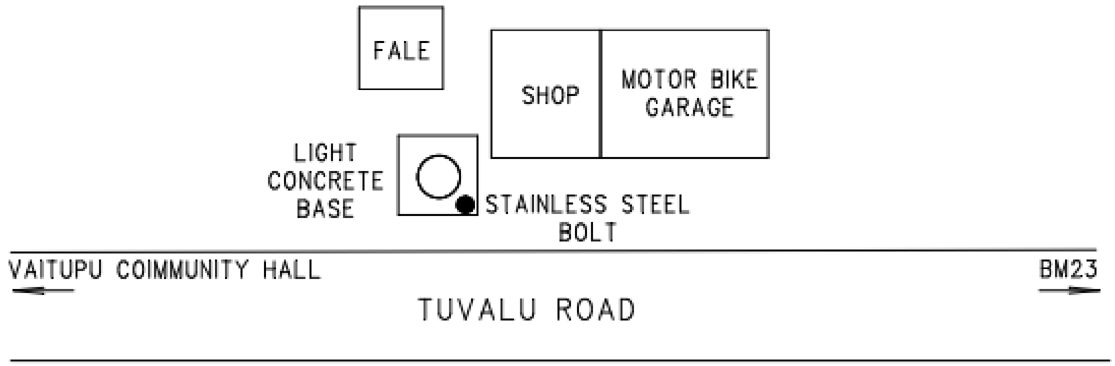
PROJECT: PSLGMP	SURVEYOR: S. Yates & A Lal	DATE: 18-01-07



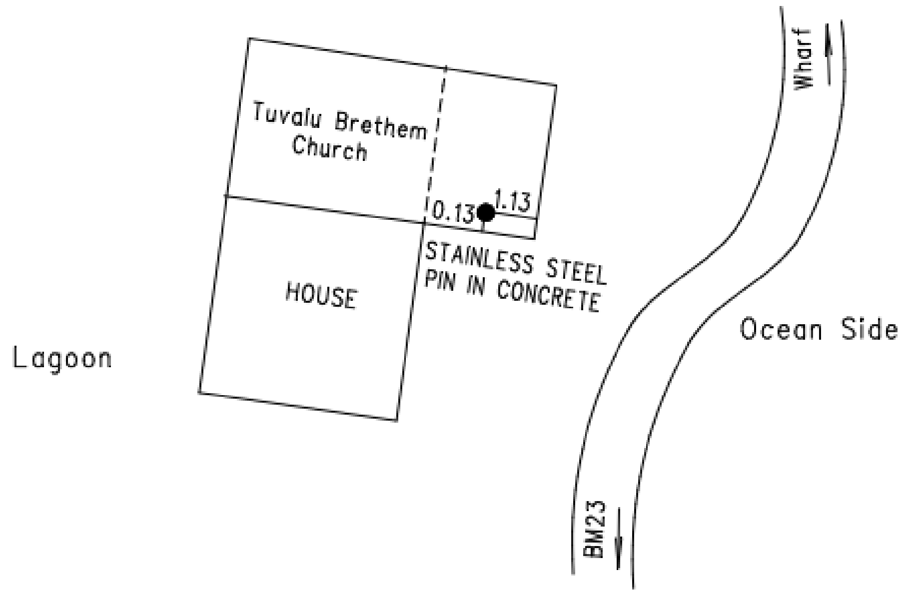
COUNTRY: Tuvalu	ISLAND: Funafuti CITY: Fongafale	L. D. P. 781 POINT NO. 104
PROJECT: PSLGMP	SURVEYOR: S. Yates & A Lal	DATE: 29-03-07



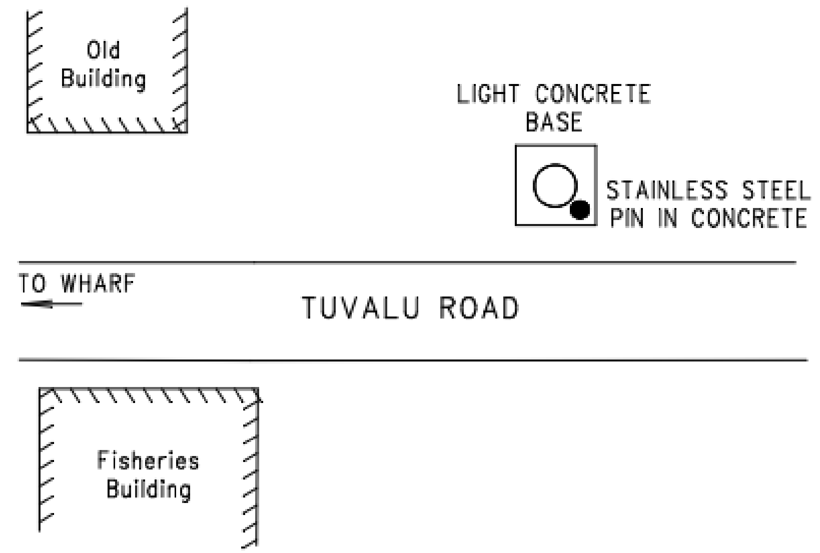
COUNTRY: Tuvalu	ISLAND: Funafuti CITY: Fongafale	L. D. P. 899 POINT NO. 107
PROJECT: PSLGMP	SURVEYOR: S. Yates & A. Lal	DATE: 20-07-13



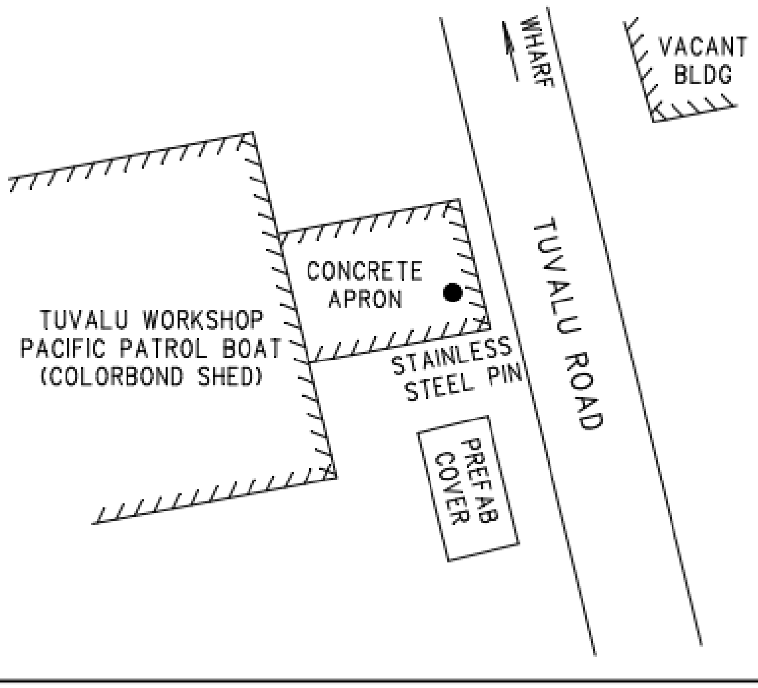
COUNTRY: Tuvalu	ISLAND: Funafuti CITY: Fongafale	L. D. P. POINT NO. 108
PROJECT: PSLGMP	SURVEYOR: AL, MK & VR	DATE: 29-09-16



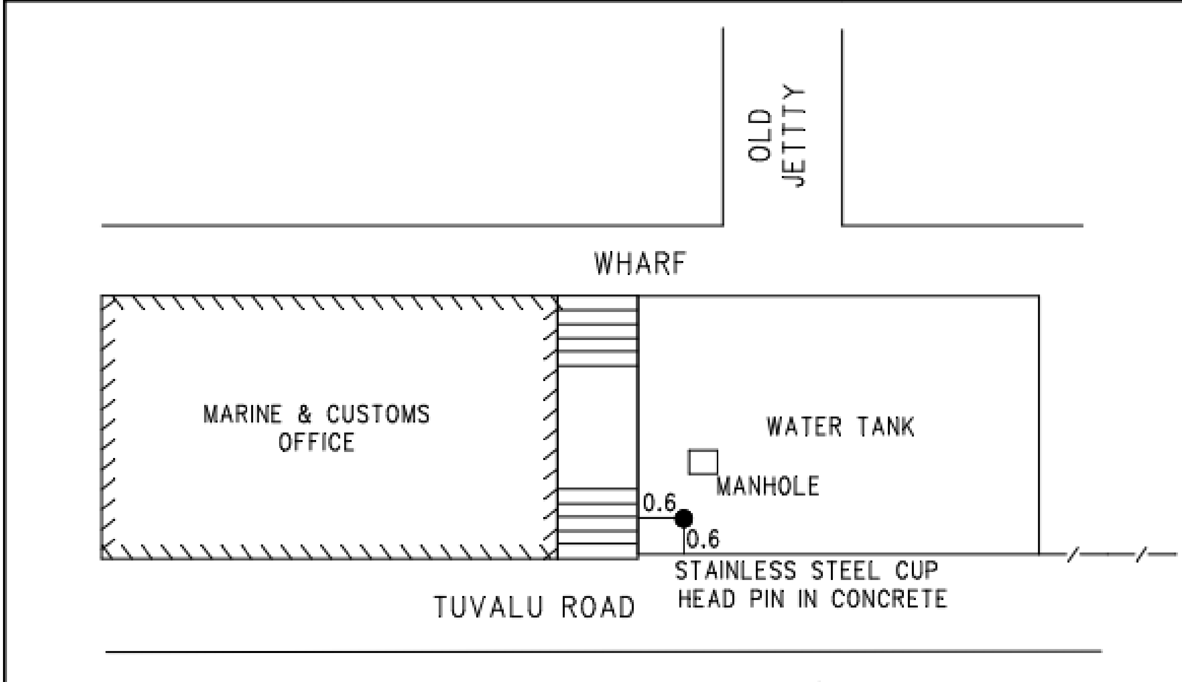
COUNTRY: Tuvalu	ISLAND: Funafuti CITY: Fongafale	L. D. P. 894 POINT NO. 102
PROJECT: PSLGMP	SURVEYOR: S. Yates & A. Lal	DATE: 23-05-12



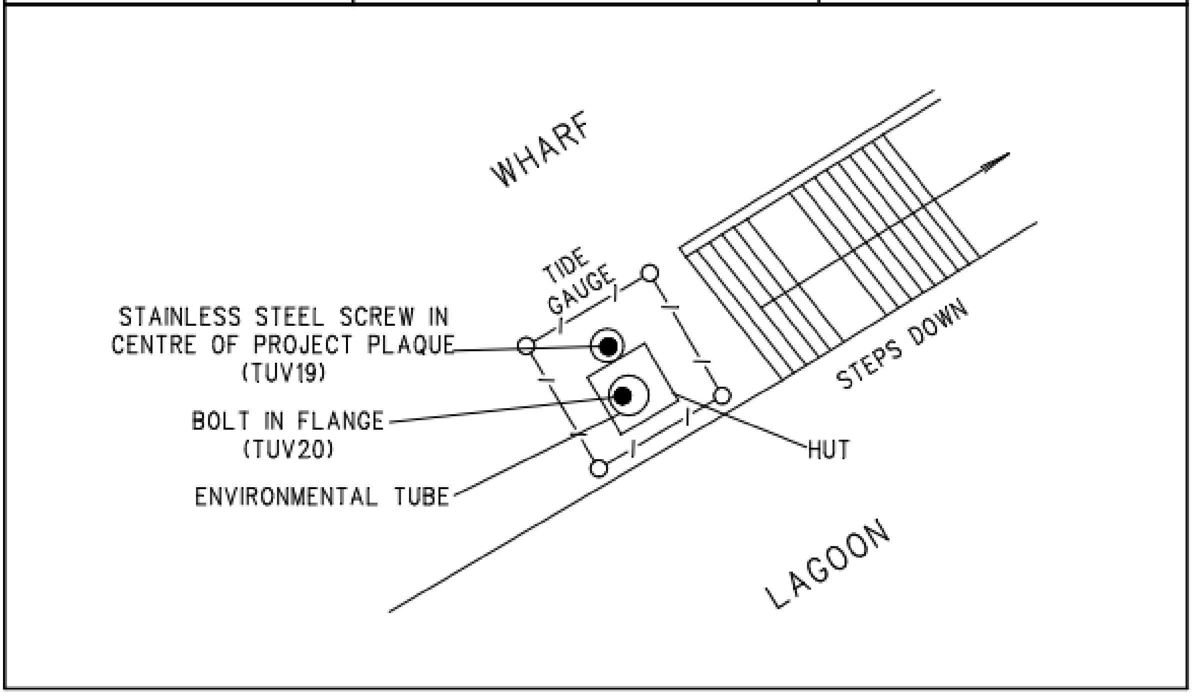
COUNTRY: Tuvalu	ISLAND: Funafuti CITY: Fongafale	L. D. P. 776 POINT NO. 42
PROJECT: PSLGMP	SURVEYOR: S. Yates & A Lal	DATE: 18-01-07



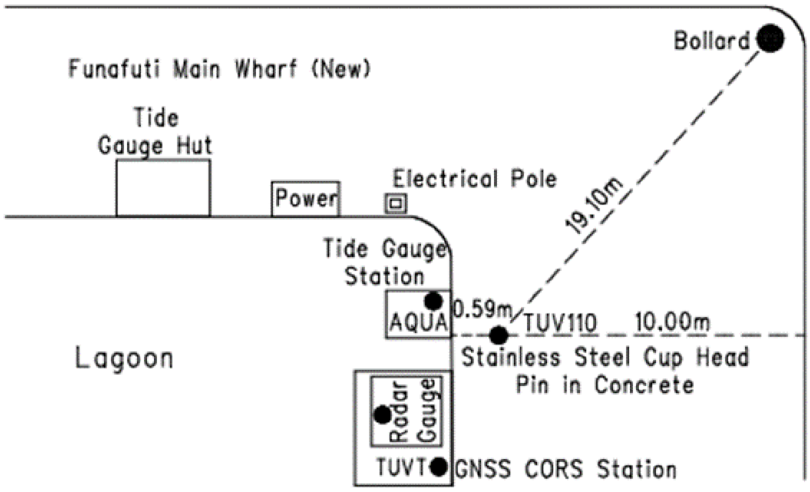
COUNTRY: Tuvalu	ISLAND: Funafuti CITY: Fongafale	L. D. P. POINT NO. 109
PROJECT: PSLGMP	SURVEYOR: AL, MK & VR	DATE: 02-10-16



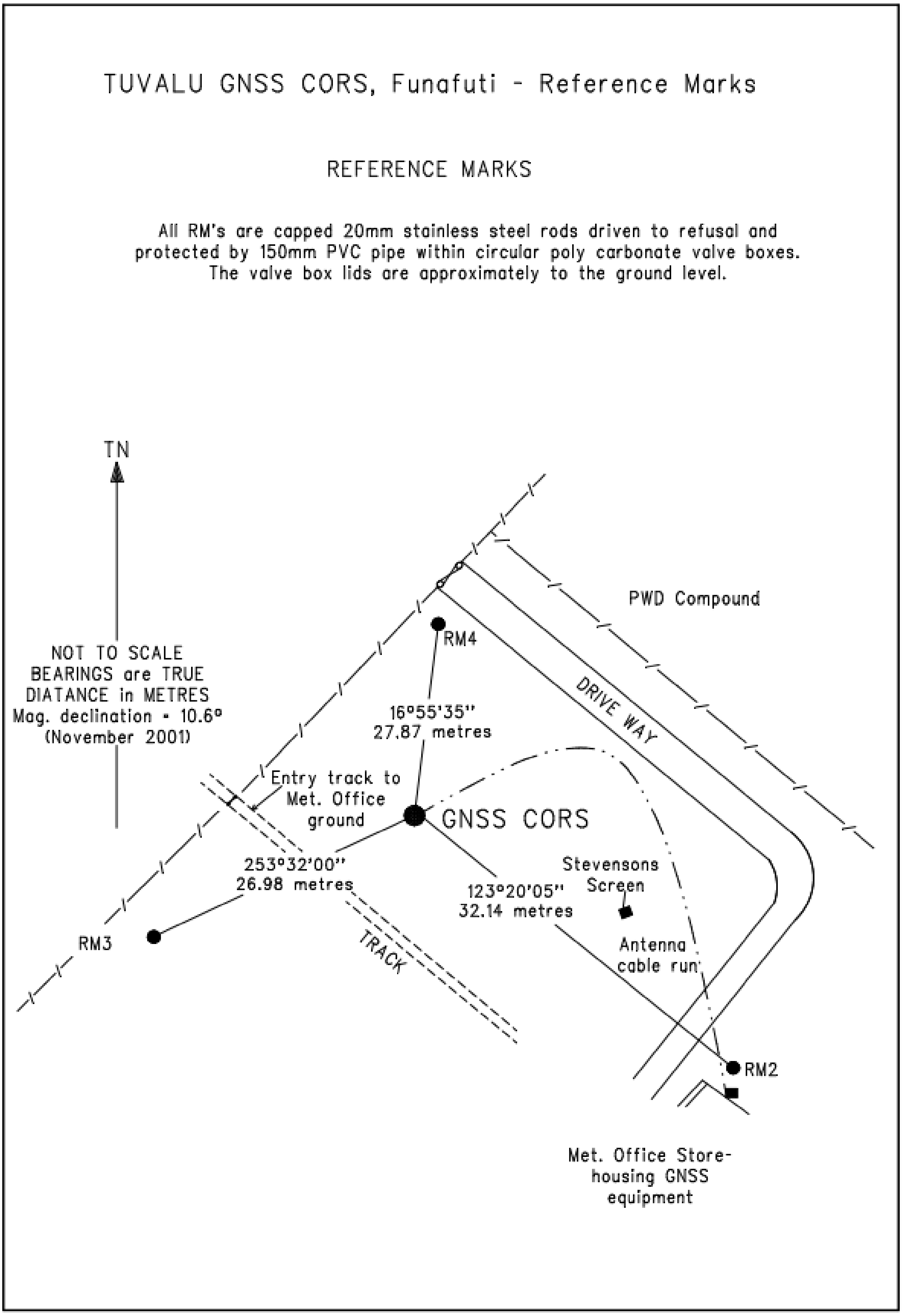
COUNTRY: Tuvalu	ISLAND: Funafuti CITY: Fongafale	L. D. P. 775 POINT NO. TUV 19 & 20
PROJECT: PSLGMP	SURVEYOR: S. Yates & A Lal	DATE: 29-03-07



COUNTRY: Tuvalu	ISLAND: Funafuti CITY: Fongafale	L. D. P. POINT NO. TUV110
PROJECT: PSLGMP	SURVEYOR: AL, MK & VR	DATE: 19-07-18



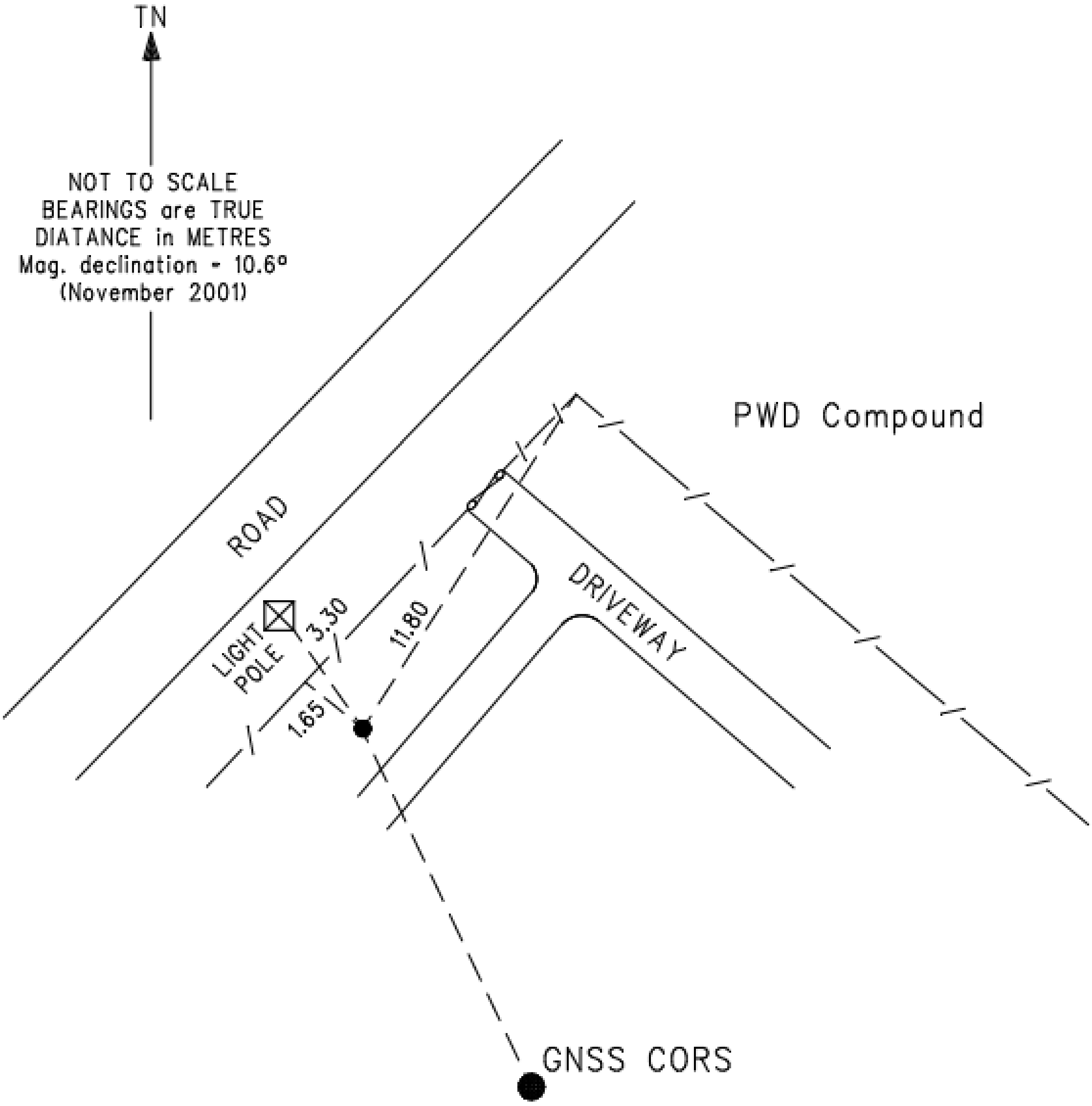
A 3 GNSS Reference Marks



TUVALU GNSS CORS, Funafuti - RM 4

REFERENCE MARKS

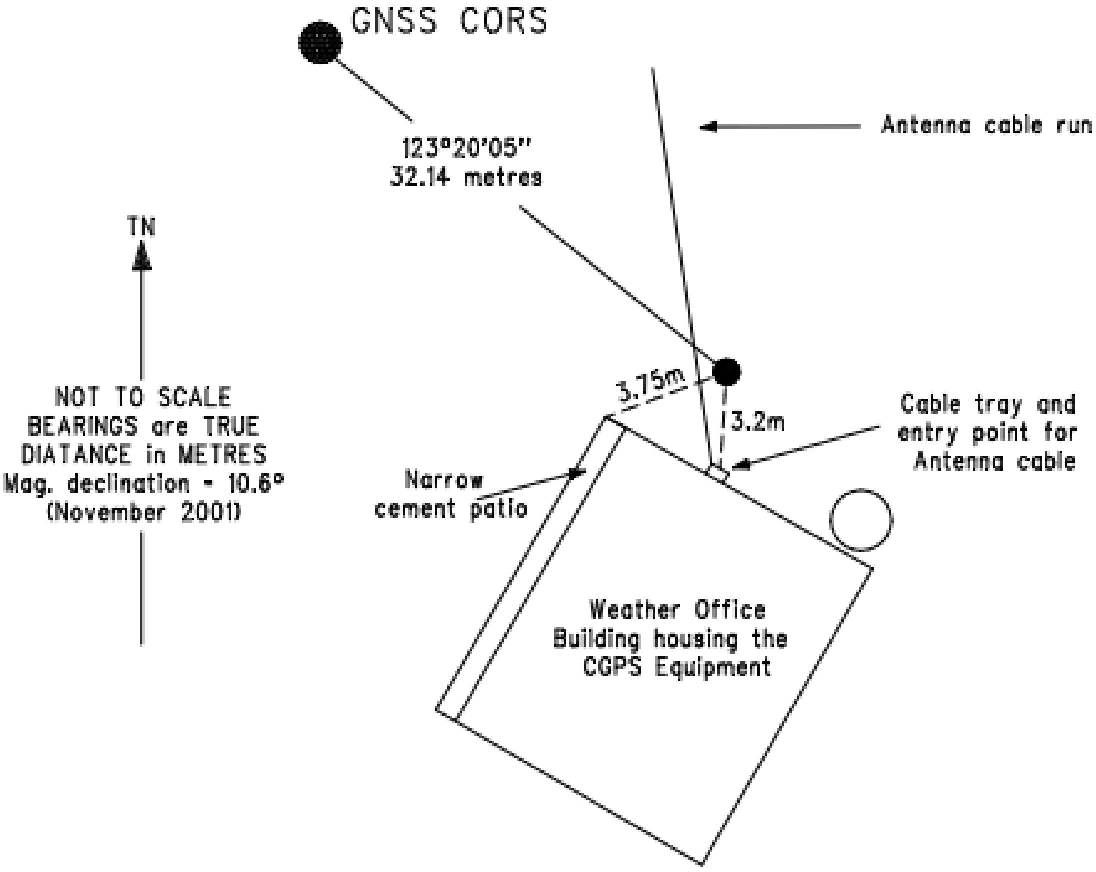
All RM's are capped 20mm stainless steel rods driven to refusal and protected by 150mm PVC pipe within circular poly carbonate valve boxes. The valve box lids are approximately to the ground level.



TUVALU GNSS CORS, Funafuti - RM 2

REFERENCE MARKS

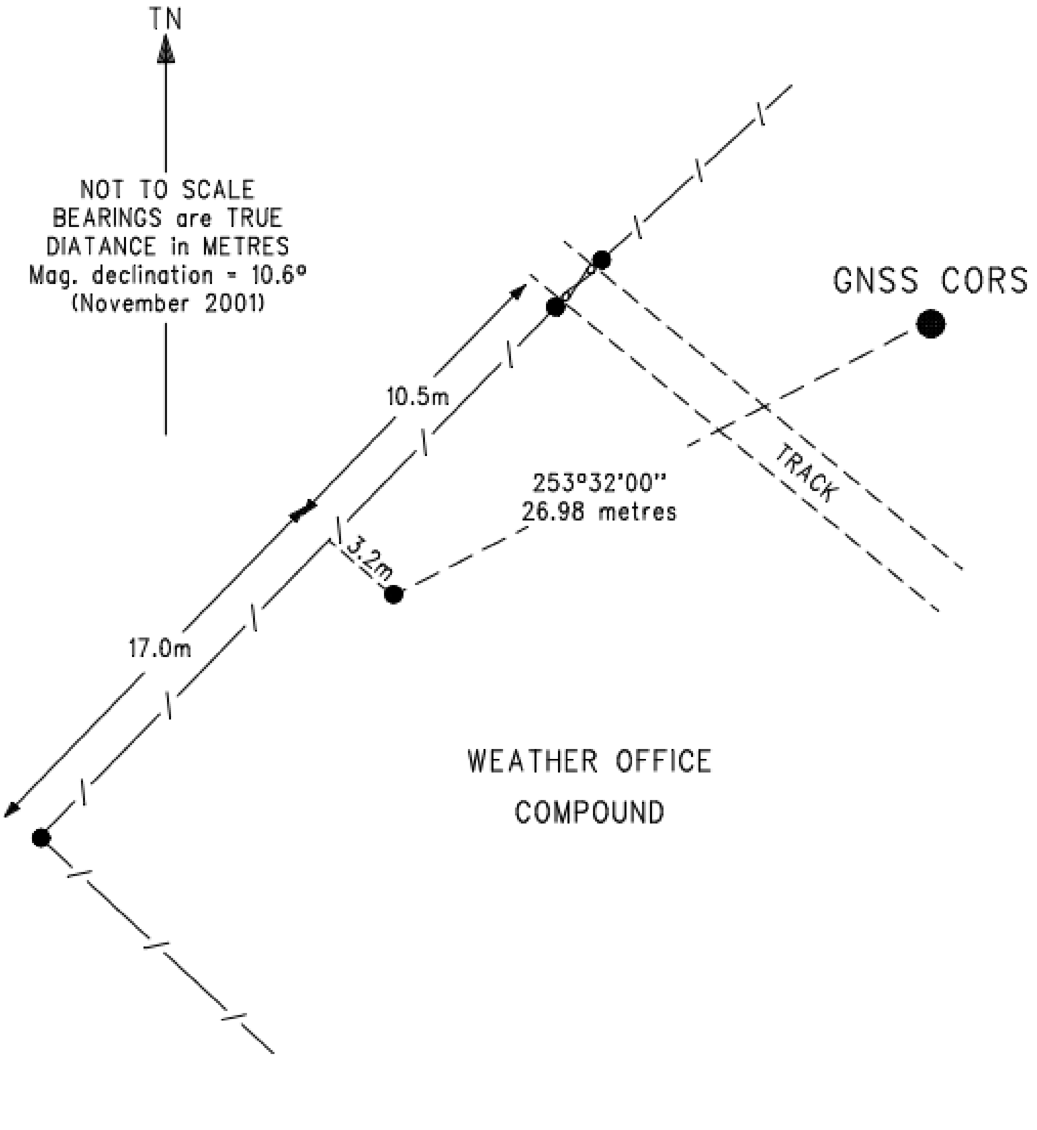
All RM's are capped 20mm stainless steel rods driven to refusal and protected by 150mm PVC pipe within circular poly carbonate valve boxes. The valve box lids are approximately to the ground level.



TUVALU GNSS CORS, Funafuti - RM 3

REFERENCE MARKS

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



Appendix B Planning Aspects and Notes

Upon arranging travel to Tuvalu, contact the project focal point at the Survey Office and The Weather Office in-country at least one month in advance.

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 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)	Tide Gauge Station Hut
1	*Aluminium GST6 tripod with Feet*	
1	PVC Pipe (1.7m)	Tide Gauge 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	Tuvalu Weather Office
1	Green Bag - Leica GST40 Rigid Tripod	Tide Gauge Station Hut
1	Spade	Tuvalu Weather Office
1	Crow Bar	Tuvalu Weather Office

Appendix C Equipment Specifications

Tachymeters, EDM and Theodolites

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

Specification

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

Calibration

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

Meteorological Sensor

Description

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

Specification

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

Forced Centring

Description

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

Specification

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

Targets and Reflectors

Description

The standard target kit includes:

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

Calibration

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

Precision Levelling

Levelling Instruments

Refer to section 2.1 for a description of the Leica TM30 total station.

Levelling Rods

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

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

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

Tripods

Description

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

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

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

GNSS Equipment

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

TUVA

- Trimble NETR9 GNSS receiver (S/N 5041K71023) (firmware: 5.37)
- Javad Choke Ring antenna (JAVRINGANT_DM NONE) - S/N 00688

TUVT

- Septentrio GNSS receiver SEPT POLARX5 Firmware Version 5.1.1 (S/N 3013248)
- Javad Choke Ring antenna (JAVRINGANT_DM SCIS) - S/N 02048