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

Apia, Samoa, July 2019

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Contents

1 Motivation

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

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

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

2 Introduction

This report provides the results of the GNSS monument monitoring survey & high precision level survey completed between the Sea Level Fine Resolution Acoustic Measuring Equipment (SEAFRAME) tide gauge and the GNSS Continuously Operation Reference Station (CORS) in Apia, Samoa from 30th July to 10th August 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 between the Tide Gauge and GNSS monument. The levelling route includes a deep driven benchmark array in Apia, which runs approximately 5.0 km. Previous levelling surveys have been conducted along this route using Total Station differential levelling technique in 2006, 2007, 2009, 2010, 2012, 2013, 2014, 2016, and 2017.This report contains an analysis of the 2019 Total Station differential levelling and GNSS monitoring results as well as a combined comparison of the previous levelling surveys.

Personnel

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

2.1 Site Description and Contacts

The levelling benchmark array, GNSS CORS, and SEAFRAME Tide Gauge are located approximately east of the Apia town centre. The levelling run goes from the Tide Gauge at the main port, along Matautu St, along Vaivase Rd and Plantation Rd to the Fagali'i airport, where the GNSS CORS is located.

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2.2 Survey Support

The survey team appreciated the assistance from the Lands & Survey Division especially Mr. Petania Tuala who always avail himself in discussing approvals to access the GNSS site at Fagalii Airport. He always provided a staff member for assistance with survey duties across the week and provided access to office space when required. For this survey Mr Frank Tuala assisted the team though out the entire field work. We acknowledge the support of the weather office in arranging for our clearance into the main port and tide gauge facility area. This must be done prior to the visit, and it is advisable that the weather office is the best to assist in this regard.

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
SAM16	SEAFRAME project plaque benchmark
SAM17	SEAFRAME sensor benchmark
BM201	Deep driven benchmark, located at the rear of the X Bar along the Apia Port Road.
BM210	Deep driven benchmark, along Matautu Street inside LDS Church grounds.
BM214	Deep driven benchmark, located corner of Vaivase and Fuaiupolu Roads.
BM213	Deep driven benchmark, located corner of Vaivase and Main East Coast Road
BM212	Deep driven benchmark, located inside Congregational Church, Main East Coast Road
BM215	Deep driven benchmark, located inside church grounds, Plantation Road.
BM220	Deep driven benchmark, located in front of Apia Park entrance gate
RM1	GNSS CORS reference mark 1
RM2	GNSS CORS reference mark 2
RM3	GNSS CORS reference mark 3
SAMOBM	Reference benchmark for the GNSS CORS pillar

Upon inspection, all the deep driven benchmarks were located, found in good order, and undisturbed. Included in the survey were the temporary holding marks; 330, 310, 139, 315, 305, 314, 304, 313, 303, 319, 318, 187, 301, 300, 321, 321, 320, 333, 104, 180, 331, 323 and 332 (Fig 3.6).

3.1.1 PSLGMP Vertical Reference Frame Wiring Diagram

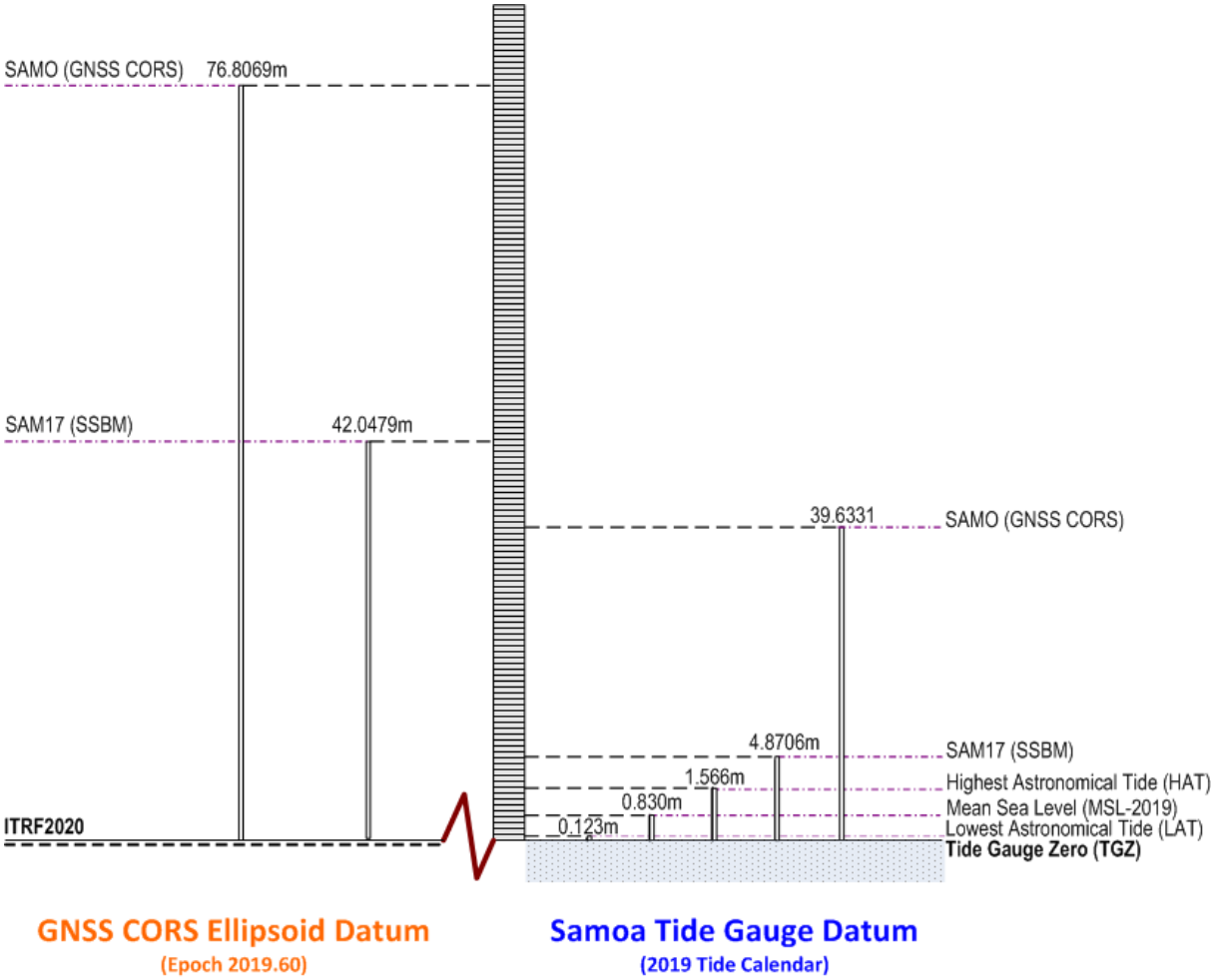


Figure 3.1 Wiring diagram depicting the offsets between surveyed marks. The left-hand side shows the height of the GNSS CORS pillar (SAMO), SEAFRAME sensor reference benchmark (SAM17), with respect to the International Terrestrial Reference Frame 2020 at epoch 2019.60. The right-hand side shows the height of SAMO, SAM17 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)

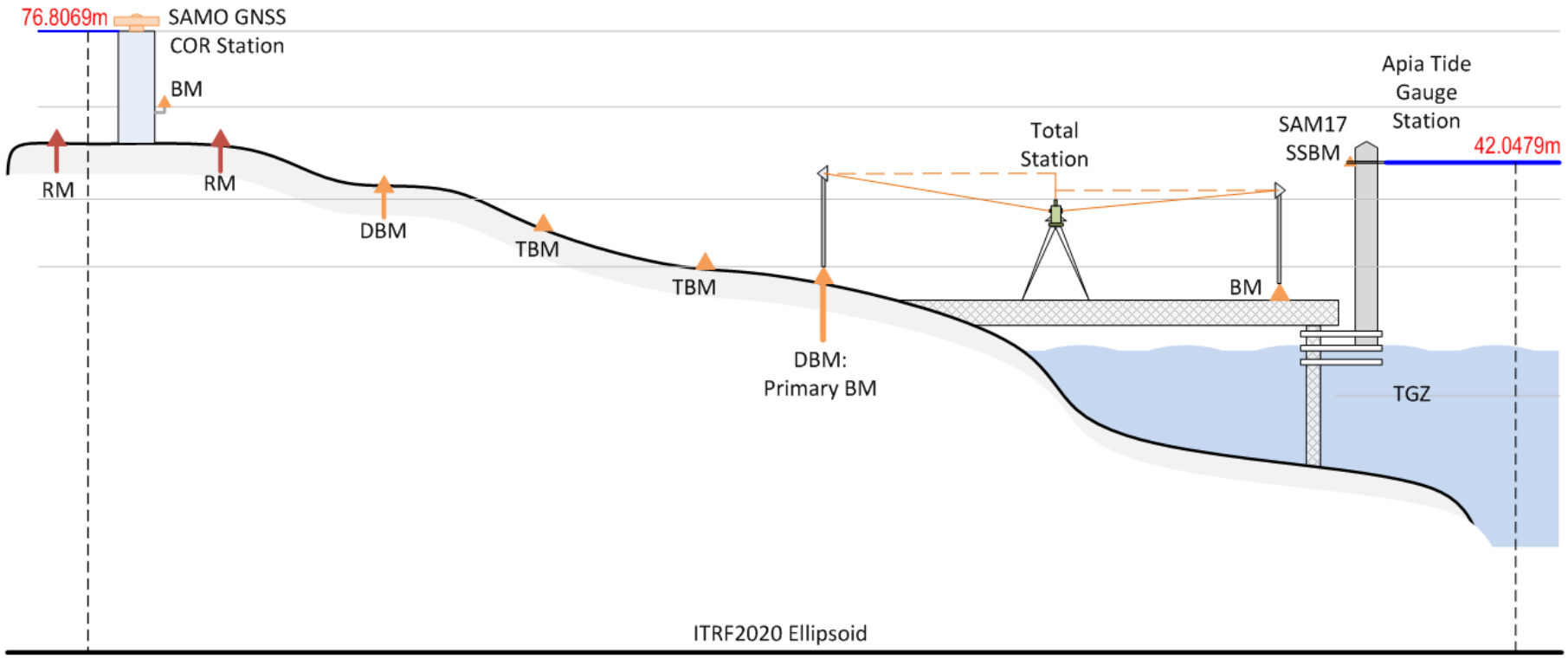


Figure 3.2 Simplified representation of the Total Station differential levelling survey carried out between the GNSS CORS and the SEAFRAME Tide Gauge.

Figure 3.3 Tide Gauge station. The red circle denotes the location of the SEAFRAME sensor reference benchmark. Image from 2017

Figure 3:4 GNSS CORS Pillar. The circle denotes the location of the location of the GNSS CORS Benchmark (SAMOBM). Image from 2017

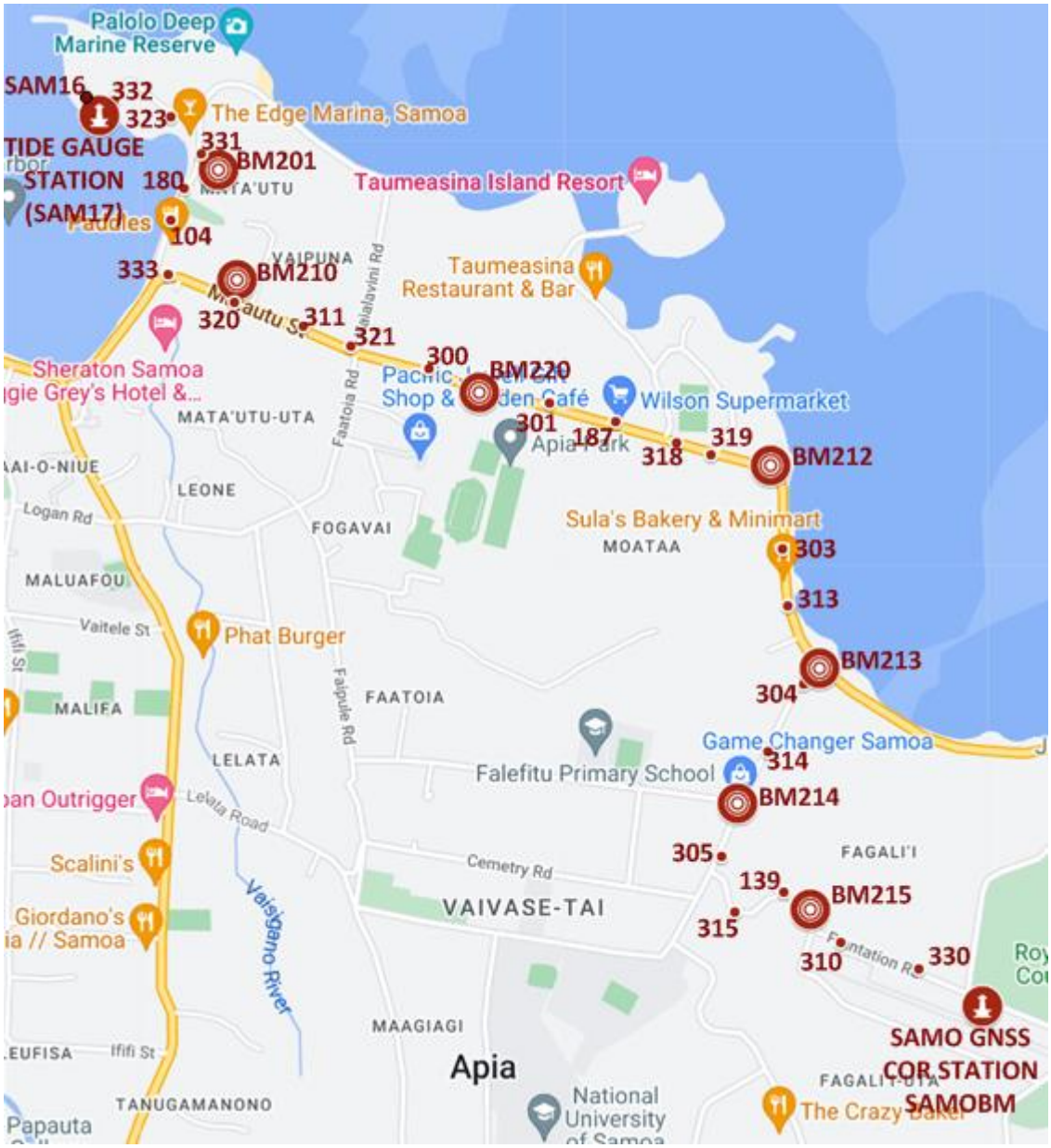


Figure 3.5 Levelling benchmark array. Source: Adopted from Google Maps.

3.1.2 GNSS CORS and Reference Marks

The GNSS CORS site is located within the Fagalii Airport grounds in Apia, Samoa. The site consists of a building to house the technical equipment and a 1.5 m GNSS CORS pillar. The pillar is approximately 30 metres from the building Access information and the key can be obtained from the Lands and Survey Department if required.

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

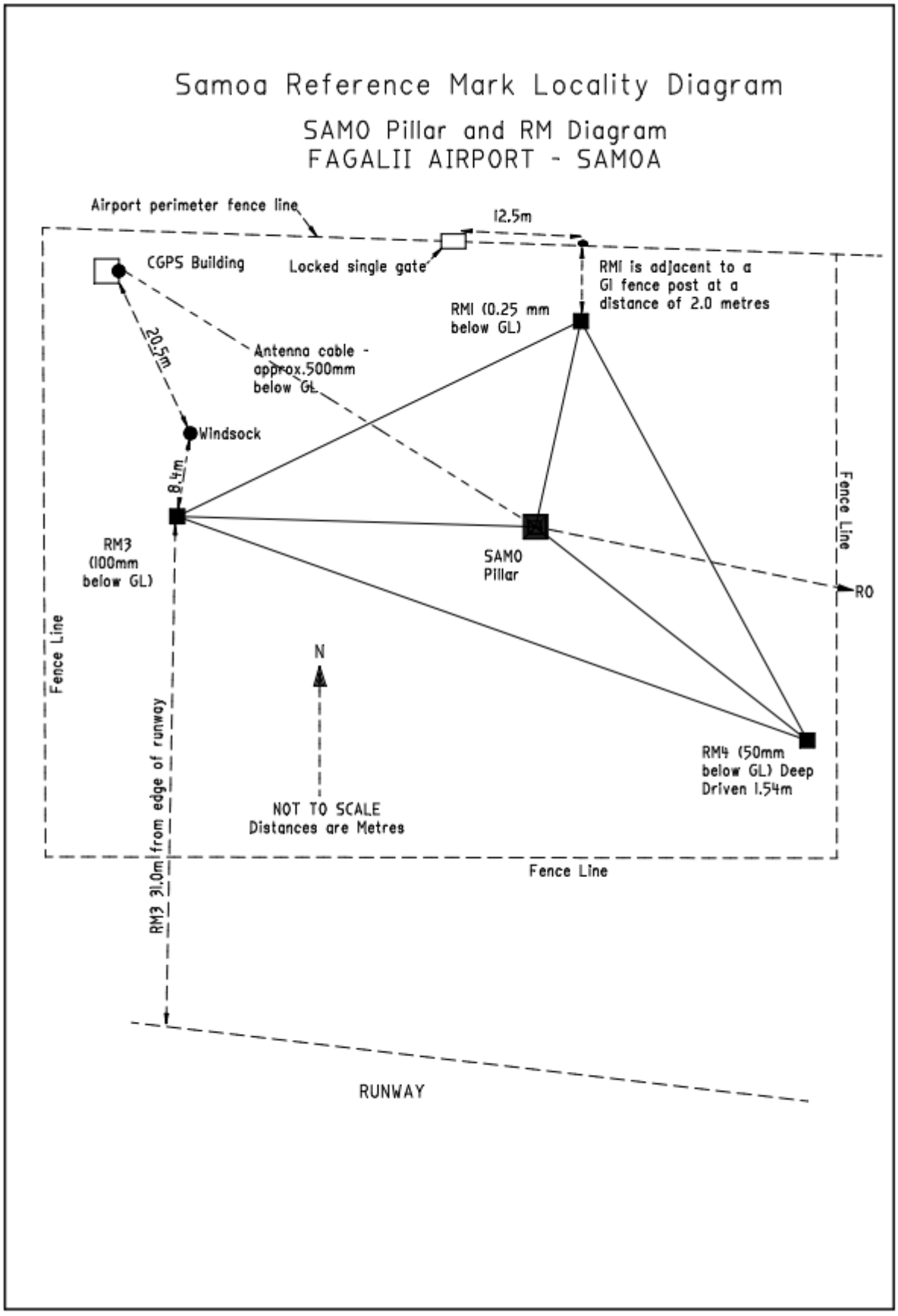


Figure 3.6 GNSS CORS site monitoring survey reference marks.

3.2 Datum

3.2.1 Survey Datum

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

3.2.2 Historical Survey Datum

The datum for the survey is Mean Sea Level (1993) and the adopted reference point for the levelling survey is BM201 fixed at RL of 1.3292m This value was determined by the National Tidal Centre Australia (NTCA).

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 30m of the GNSS pillar. We acknowledge that this monitoring does not account for any movement over the wider area – i.e., movements that might be consistent across all RM's.

4.1.1 Methodology

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

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

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

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

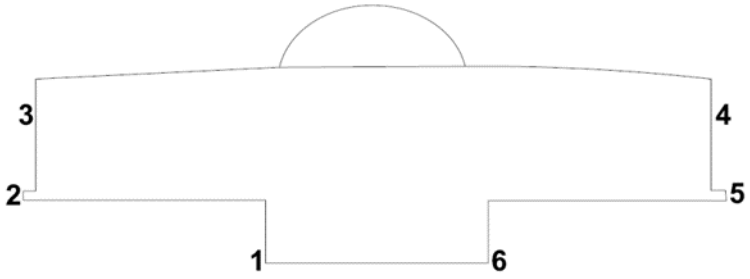


Figure 4.1.1 Symmetrical points on the antenna profile (TRM59800.00) observed from each RM.

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 square's 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 & ΔH, 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 Reporting

4.3.1 Levelling Survey

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

Table 4.3.1The Reduced Level (RL) shown is height relative to SAMOBM.

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
SAMOBM				0.0000		0.000
RM1	**RM1**	0.0000	-1.7311	-1.7311	0.0150	0.015
RM4	**RM4**	0.9489	0.0000	-0.7822	0.0284	0.0437
RM3	**RM3**	0.0000	-0.4401	-1.2222	0.0450	0.089
RM4	**RM4**	0.4400	0.0000	-0.7822	0.0450	
RM1	**RM1**	0.0000	-0.9488	-1.7310	0.0292	
	SAMOBM	1.7310	0.0000	0.0000	0.0150	
	Sum:	3.1199	-3.1200			
	Misclose:		0.0000	0.0000	0.178	(Total Dist)
			ALLOWABLE (m):	**0.0006**	**2 x Sqrt (km) test:**	**PASS**

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
SAMOBM				0.0000		0.0000
RM3	**RM3**	0.0000	-1.2222	-1.2222	0.0270	0.0270
	SAMOBM	1.2221	0.0000	-0.0001	0.0270	
	Sum:	1.2221	-1.2222			
	Misclose:		-0.0001	-0.0001	0.0540	(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)
SAMOBM				0.0000		0.0000
RM4	**RM4**	0.0000	-0.7822	-0.7822	0.0190	0.0190
	SAMOBM	0.7821	0.0000	-0.0001	0.0190	
	Sum:	0.7821	-0.7822			
	Misclose:		-0.0001	-0.0001	0.0390	(Total Dist)
			ALLOWABLE (m):	**0.0003**	**2 x Sqrt (km) test:**	**PASS**

4.3.1 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 (SAMO) was tightly constrained to its ITRF2014 coordinates and aligned to SAMO-RM1 with an azimuth of 13° 59' 22.610", which had been determined in the 2001 survey by GNSS observation to RM1. The angular observations were given an uncertainty of 1.0" and the slope distances an uncertainty of 1.0 mm. The estimated coordinates and associated variance-covariance matrix were output in a SINEX file format and have been provided to Geoscience Australia.

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

Table 4.3.2 Latitude, Longitude and Ellipsoidal Height (metres) for the GNSS & RM stations. ITRF2014@2010.0 Latitude, Longitude coordinates, and ITRF2020@2019.60 ellipsoidal height were adopted at SAMO. CCC means all 3 dimensions (in XYZ) are constrained and FFF means they were all free,

Station	Constraint	Latitude	Longitude	Ellipsoidal height(m)
SAMO	CCC	13° 50' 57.15078"	171° 44' 18.32496"	76.8069
RM1	FFF	13° 50' 56.67190"	171° 44' 18.20286"	74.3479
RM3	FFF	13° 50' 57.07076"	171° 44' 19.21314"	74.8633
RM4	FFF	13° 50' 57.49008"	171° 44' 17.78108"	75.2965

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@2019.60 ellipsoidal height were adopted at SAMO.

Description	X	Y	Z	SD(e)	SD(n)	SD(up)
SAMO	-6129702.3013	-890029.0930	-1516807.1331	0	0	0
RM1	-6129702.8980	-890033.8847	-1516792.2548	0.0001	0.0003	0.0003
RM3	-6129704.8421	-890002.5108	-1516804.2785	0.0005	0.0006	0.0003
RM4	-6129695.0330	-890045.6865	-1516817.8961	0.0004	0.0004	0.0003

Table 4.3.2.3 Difference in XYZ coordinates between the GNSS pillar and RMs (metres)

From	To	ΔE	ΔN	ΔU
SAMO	**RM1**	3.6667	14.7175	-2.4590
SAMO	**RM3**	-26.6714	2.4592	-1.9506
SAMO	**RM4**	16.3324	-10.4277	-1.5104

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

4.4 Assessment of Results

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

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

Year	From	To	ΔE	ΔN	ΔU
2001	**SAMO**	**RM1**	3.6672	14.7182	-2.4601
2002	**SAMO**	**RM1**	3.6669	14.7183	-2.4574
2004	**SAMO**	**RM1**	3.6669	14.7184	-2.4576
2006	**SAMO**	**RM1**	3.6670	14.7189	-2.4593
2008	**SAMO**	**RM1**	3.6670	14.7185	-2.4589
2010	**SAMO**	**RM1**	3.6668	14.7185	-2.4594
2014	**SAMO**	**RM1**	3.6669	14.7183	-2.4591
2016	**SAMO**	**RM1**	3.667	14.7176	-2.4608
2017	**SAMO**	**RM1**	3.667	14.7189	-2.4591
2019	**SAMO**	**RM1**	3.6667	14.7175	-2.4590
Ref RL	**(as at 2016)**		**3.6670**	**14.7183**	**-2.4591**

Year	From	To	ΔE	ΔN	ΔU
2001	**SAMO**	**RM3**	-26.6713	2.4623	-1.9509
2002	**SAMO**	**RM3**	-26.6704	2.4604	-1.949
2004	**SAMO**	**RM3**	-26.6718	2.4615	-1.9492
2006	**SAMO**	**RM3**	-26.6726	2.4596	-1.9506
2008	**SAMO**	**RM3**	-26.6715	2.4618	-1.9504
2010	**SAMO**	**RM3**	-26.6721	2.4611	-1.9507
2014	**SAMO**	**RM3**	-26.6717	2.4623	-1.9504
2016	**SAMO**	**RM3**	-26.6708	2.4619	-1.9474
2017	**SAMO**	**RM3**	-26.6716	2.4613	-1.9499
2019	**SAMO**	**RM3**	-26.6714	2.4592	-1.9506
Ref RL	**(as at 2016)**		**-26.6715**	**2.4614**	**-1.9498**

Year	From	To	ΔE	ΔN	ΔU
2008	**SAMO**	**RM4**	16.3306	-10.4285	-1.5101
2010	**SAMO**	**RM4**	16.3315	-10.4277	-1.5107
2014	**SAMO**	**RM4**	16.3307	-10.428	-1.5102
2016	**SAMO**	**RM4**	16.3308	-10.4275	-1.5118
2017	**SAMO**	**RM4**	16.3318	-10.4276	-1.511
2019	**SAMO**	**RM4**	16.3324	-10.4277	-1.5104
Ref RL	**(as at 2016)**		**16.3309**	**-10.4279**	**-1.5107**

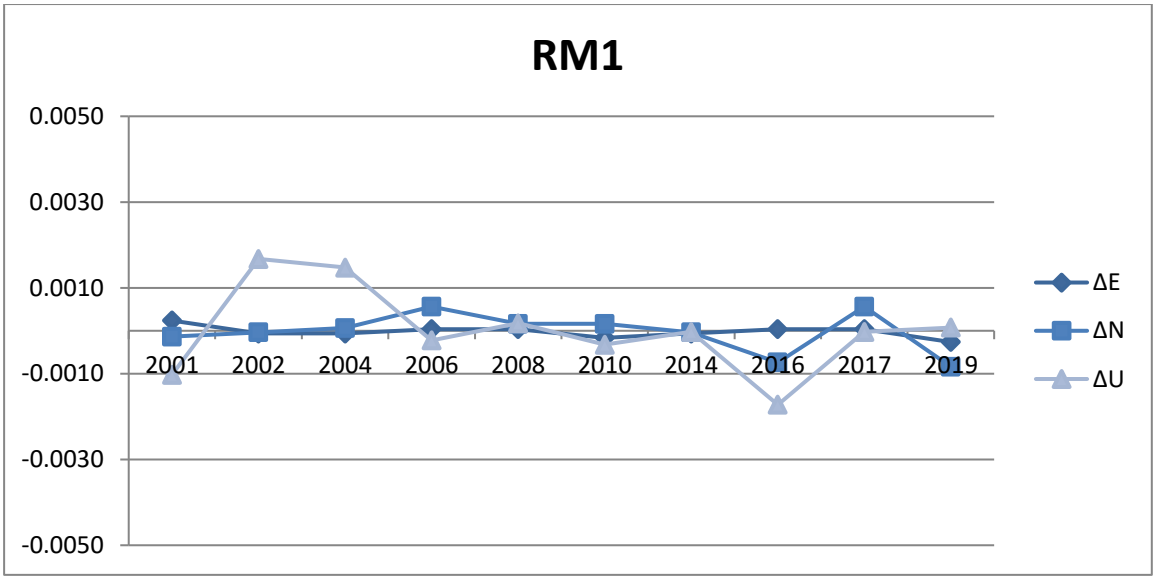


Figure 4.4.1 Time series of RM1 movement relative to GNSS (0 = REF pre 2016 mean)

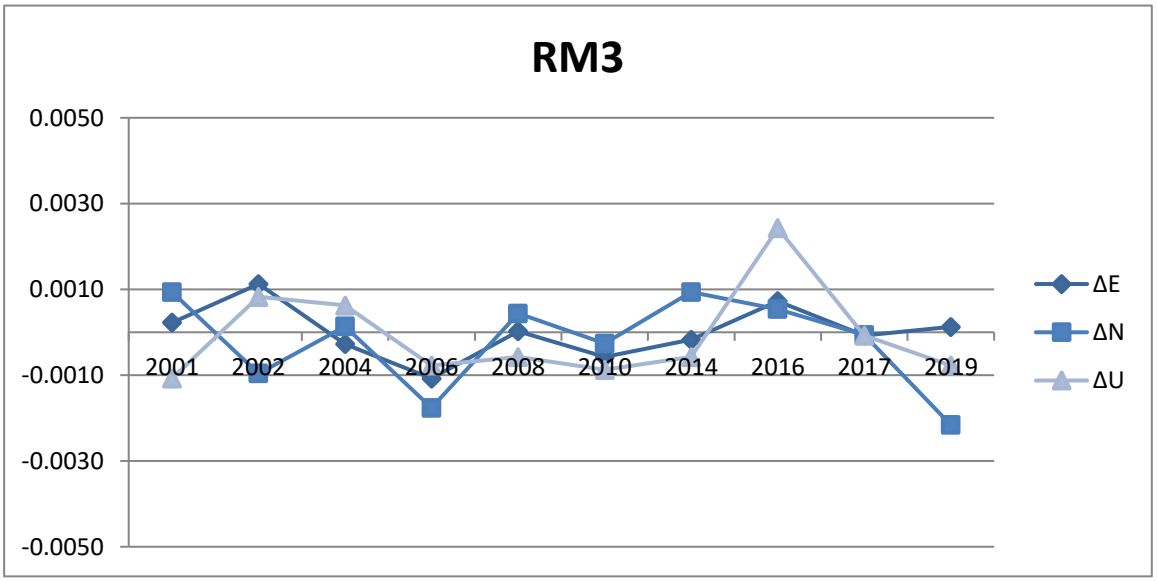


Figure 4.4.2 Time series of RM3 movement relative to GNSS (0 = REF pre 2016 mean)

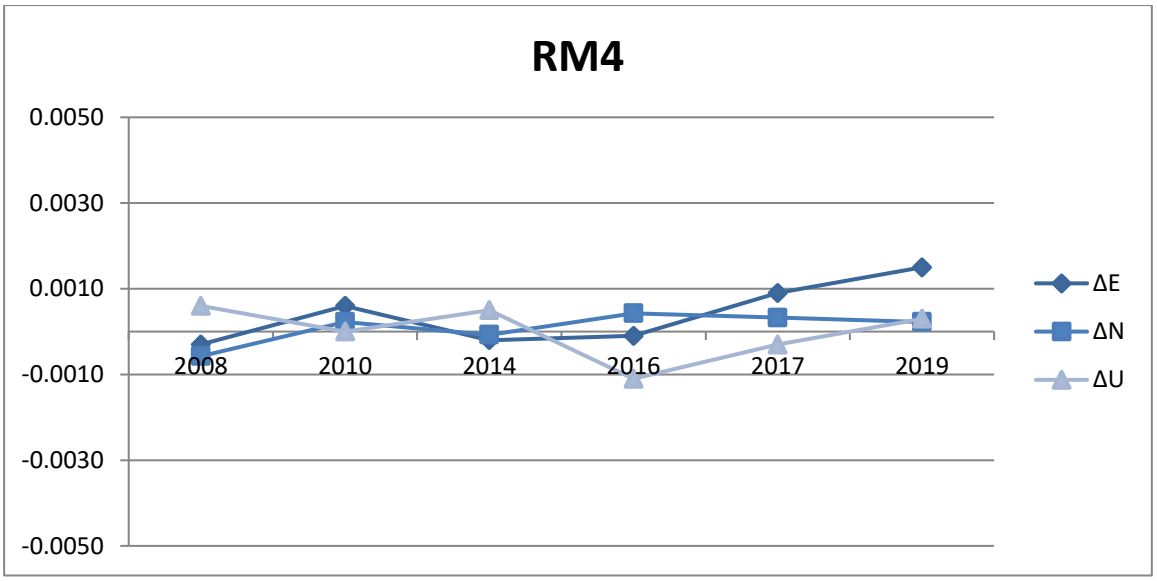


Figure 4.4.3 Time series of RM4 movement relative to GNSS (0 = REF pre 2016 mean)

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

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

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

In support of the slope distance observations, the ambient temperature, pressure and K 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
SAMO (Ellipsoidal ht)	76.8069	Observed RL at the ARP of SAMO (Ellipsoidal) @ 2019.60
SAMO - SAMOBM	-0.7282	Offset constant between GNSS pillar plate and GNSS BM
Primary Pole & 1/2m Pole	1.00061	Height difference between poles used (Calibrated August 2019)
Primary Pole & TG Pole	1.43252	Height difference between poles used (Calibrated September 2011)

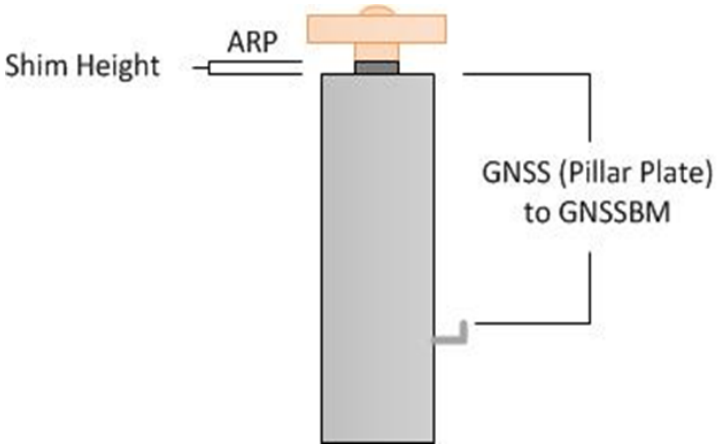


Figure 5.2.1 GNSS Pillar Offsets

5.3 Data Analysis and Results

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

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

Table 5.3.1 Reduced level data – SAMO (GNSS CORS) *to BM201(Deep Benchmark for the Apia wharf)*

From	To	Rise(m)	Fall(m)	RL(m)	Dist (Km)	Acc Dist (km)
SAMO				0.7282		
SAMOBM	**SAMOBM**	0.0000	-0.7282	0.000	0.0000	0.0000
330	**330**	0.0000	-7.7808	-7.7808	0.2138	0.2138
310	**310**	0.0000	-0.6410	-8.4218	0.2231	0.4369
BM215	**BM215**	0.0000	-8.1563	-16.5780	0.1648	0.6017
139	**139**	0.0000	-3.9438	-20.5218	0.0979	0.6996
315	**315**	0.0000	-7.7951	-28.3169	0.1562	0.8558
305	**305**	0.1363	0.0000	-28.1806	0.1827	1.0385
BM214	**BM214**	0.0000	-1.8883	-30.0688	0.1444	1.1829
314	**314**	0.0000	-4.4612	-34.5300	0.1712	1.3541
304	**304**	0.0000	-1.9598	-36.4898	0.2003	1.5544
BM213	**BM213**	0.0000	-0.5139	-37.0037	0.0755	1.6299
313	**313**	0.5801	0.0000	-36.4236	0.2043	1.8342
303	**303**	0.3269	0.0000	-36.0967	0.2076	2.0418
BM212	**BM212**	0.0000	-0.7053	-36.8020	0.2181	2.2599
319	**319**	0.0854	0.0000	-36.7166	0.1672	2.4271
318	**318**	0.0000	-0.1847	-36.9012	0.1025	2.5296
187	**187**	0.1883	0.0000	-36.7129	0.1811	2.7107
301	**301**	0.1419	0.0000	-36.5710	0.1948	2.9055
BM220	**BM220**	0.0000	-0.0960	-36.6670	0.2043	3.1098
300	**300**	0.0000	-0.0750	-36.7420	0.1878	3.2976
321	**321**	0.8086	0.0000	-35.9334	0.1994	3.4970
311	**311**	0.0000	-0.1688	-36.1022	0.1539	3.6509
BM210	**BM210**	0.0000	-0.8314	-36.9336	0.2058	3.8567
320	**320**	0.3567	0.0000	-36.5769	0.0171	3.8738
333	**333**	0.0236	0.0000	-36.5534	0.2004	4.0742
104	**104**	0.5019	0.0000	-36.0515	0.1547	4.2289
180	**180**	0.0574	0.0000	-35.9941	0.1016	4.3305
BM201	**BM201**	0.0000	-0.8658	-36.8599	0.1204	4.4509
180	**180**	0.8655	0.0000	-35.9944	0.1247	
104	**104**	0.0000	-0.0575	-36.0519	0.1015	

333	**333**	0.0000	-0.5017	-36.5535	0.1539	
320	**320**	0.0000	-0.0238	-36.5774	0.2004	
BM210	**BM210**	0.0000	-0.3567	-36.9340	0.0172	
311	**311**	0.8316	0.0000	-36.1025	0.2057	
321	**321**	0.1685	0.0000	-35.9340	0.1539	
300	**300**	0.0000	-0.8084	-36.7424	0.2033	
BM220	**BM220**	0.0749	0.0000	-36.6675	0.1885	
301	**301**	0.0958	0.0000	-36.5717	0.2042	
187	**187**	0.0000	-0.1416	-36.7132	0.1948	
318	**318**	0.0000	-0.1882	-36.9015	0.1811	
319	**319**	0.1848	0.0000	-36.7167	0.1026	
BM212	**BM212**	0.0000	-0.0853	-36.8020	0.1672	
303	**303**	0.7056	0.0000	-36.0964	0.2182	
313	**313**	0.0000	-0.3271	-36.4235	0.2075	
BM213	**BM213**	0.0000	-0.5803	-37.0038	0.2043	
304	**304**	0.5138	0.0000	-36.4900	0.0755	
314	**314**	1.9599	0.0000	-34.5301	0.2003	
BM214	**BM214**	4.4612	0.0000	-30.0689	0.1713	
305	**305**	1.8882	0.0000	-28.1807	0.1449	
315	**315**	0.0000	-0.1363	-28.3170	0.1818	
139	**139**	7.7950	0.0000	-20.5220	0.1563	
BM215	**BM215**	3.9439	0.0000	-16.5781	0.0977	
310	**310**	8.1560	0.0000	-8.4222	0.1650	
330	**330**	0.6411	0.0000	-7.7810	0.2231	
SAMOBM	**SAMOBM**	7.7808	0.0000	-0.0002	0.2137	
SAMO	**SAMO**	0.7282	0.0000	0.7280	0.0000	
	Sum:	44.0018	-44.0020			
	Misclose:		-0.0002	-0.0002	8.910	(Total Dist)
			ALLOWABLE (m):	**0.0042**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.2 Reduced level data – BM201 to SAM16(Tide Gauge Benchmark)

From	To	Rise (m)	Fall (m)	RL (m)	Dist (Km)	Acc Dist (km)
BM201				-36.8599	0.0000	4.4509
331	**331**	1.0058	0.0000	-35.8541	0.1042	4.5551
323	**323**	0.0000	-0.6340	-36.4881	0.1655	4.7206
332	**332**	0.2319	0.0000	-36.2562	0.1488	4.8694
SAM16	**SAM16**	0.4403	0.0000	-35.8159	0.0396	4.9090
332	**332**	0.0000	-0.4404	-36.2562	0.0396	
323	**323**	0.0000	-0.2321	-36.4884	0.1485	
331	**331**	0.6341	0.0000	-35.8543	0.1661	
BM201	**BM201**	0.0000	-1.0056	-36.8599	0.0997	
	Sum:	2.3121	-2.3121			
	Misclose:		0.0000	0.0000	0.912	(Total Dist)
			ALLOWABLE (m):	**0.0014**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.3 Reduced level data – SAM16 – SAM17 (Tide Gauge Sensor Benchmark)

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
SAM16				-35.8159		4.9090
SAM17	**SAM17**	1.7816	0.0000	-34.0343	0.0117	4.9207
	SAM16	0.0000	-1.7816	-35.8162	0.0118	
	Sum:	1.7816	-1.7816			
	Misclose:		0.0000	0.0000	0.024	(Total Dist)
			ALLOWABLE (m):	**0.0002**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.4 Measured height differences (in metres) between all BMs (ΔH_{2019})

	SAMOBM	BM215	BM214	BM213	BM212	BM220	BM210	BM201	SAM16	SAM17	RM1	RM3	RM4	SAMO
SAMOBM	-	-16.5781	-30.0689	-37.0037	-36.8020	-36.6672	-36.9338	-36.8599	-35.8159	-34.0343	-1.7310	-1.2222	-0.7822	0.7282
BM215	16.5781	-	-13.4908	-20.4257	-20.2239	-20.0892	-20.3557	-20.2818	-19.2378	-17.4562	14.8470	15.3559	15.7959	17.3063
BM214	30.0689	13.4908	-	-6.9349	-6.7331	-6.5984	-6.8649	-6.7910	-5.7470	-3.9654	28.3378	28.8467	29.2867	30.7971
BM213	37.0037	20.4257	6.9349	-	0.2018	0.3365	0.0699	0.1439	1.1879	2.9695	35.2727	35.7815	36.2216	37.7319
BM212	36.8020	20.2239	6.7331	-0.2018	-	0.1347	-0.1318	-0.0579	0.9861	2.7677	35.0709	35.5798	36.0198	37.5302
BM220	36.6672	20.0892	6.5984	-0.3365	-0.1347	-	-0.2666	-0.1926	0.8514	2.6330	34.9362	35.4450	35.8851	37.3954
BM210	36.9338	20.3557	6.8649	-0.0699	0.1318	0.2666	-	0.0739	1.1179	2.8995	35.2028	35.7116	36.1516	37.6620
BM201	36.8599	20.2818	6.7910	-0.1439	0.0579	0.1926	-0.0739	-	1.0440	2.8256	35.1289	35.6377	36.0777	37.5881
SAM16	35.8159	19.2378	5.7470	-1.1879	-0.9861	-0.8514	-1.1179	-1.0440	-	1.7816	34.0848	34.5937	35.0337	36.5441
SAM17	34.0343	17.4562	3.9654	-2.9695	-2.7677	-2.6330	-2.8995	-2.8256	-1.7816	-	32.3032	32.8121	33.2521	34.7625
RM1	1.7310	-14.8470	-28.3378	-35.2727	-35.0709	-34.9362	-35.2028	-35.1289	-34.0848	-32.3032	-	0.5088	0.9489	2.4592
RM3	1.2222	-15.3559	-28.8467	-35.7815	-35.5798	-35.4450	-35.7116	-35.6377	-34.5937	-32.8121	-0.5088	-	0.4400	1.9504
RM4	0.7822	-15.7959	-29.2867	-36.2216	-36.0198	-35.8851	-36.1516	-36.0777	-35.0337	-33.2521	-0.9489	-0.4400	-	1.5104
SAMO	-0.7282	-17.3063	-30.7971	-37.7319	-37.5302	-37.3954	-37.6620	-37.5881	-36.5441	-34.7625	-2.4592	-1.9504	-1.5104	-

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

YEAR	SAMOBM	BM215	BM214	BM213	BM212	BM220	BM210	BM201	SAM16	SAM17	RM1	RM3	RM4	SAMO
2002.9	0.000	-16.5793	-30.0697	-37.0043	-36.8023		-36.9334	-36.8577						
2004.7	0.000	-16.5786	-30.0700	-37.0047	-36.8025		-36.9351	-36.8597						
2006.8	0.000	-16.5796	-30.0703	-37.0052	-36.8042		-36.9380	-36.8634						
2006.8	0.000	-16.5793	-30.0702	-37.0044	-36.8022		-36.9363	-36.8622	-35.8163	-34.0287	-1.7313	-1.2226		0.7279
2008.0	0.000	-16.5788	-30.0705	-37.0059	-36.8039	-36.6682	-36.9377	-36.8627	-35.8175	-34.0305	-1.7309	-1.2224	-0.7820	0.7283
2010.0	0.000	-16.5791	-30.0695	-37.0048	-36.8029	-36.6692	-36.9377	-36.8622	-35.8172	-34.0303	-1.7311	-1.2224	-0.7823	
2011.5	0.000	-16.5776	-30.0676	-37.0028	-36.8008	-36.6638	-36.9299	-36.8526	-35.8082	-34.0235	-1.7312	-1.2222	-0.7821	
2013.4	0.000	-16.5796	-30.0711	-37.0060	-36.8034	-36.6686	-36.9362	-36.8609	-35.8173	-34.0331				
2015.9	0.000	-16.5796	-30.0700	-37.0059	-36.8152	-36.6795	-36.9452	-36.8694	-35.8258	-34.0403	-1.7307	-1.2223	-0.7820	
2016.4	0.000	-16.5764	-30.0671	-37.0021	-36.7997	-36.6658	-36.9327	-36.8574	-35.8149	-34.0317	-1.7305	-1.2217	-0.7819	0.7282
2017.4	0.000	-16.5785	-30.0696	-37.0046	-36.8029	-36.6667	-36.9339	-36.8583	-35.8159	-34.0342	-1.7309	-1.2222	-0.7822	0.7282
2019.6	0.000	-16.5781	-30.0689	-37.0037	-36.8020	-36.6672	-36.9338	-36.8599	-35.8159	-34.0343	-1.7310	-1.2222	-0.7822	0.7282

5.4 Comparison with previous surveys

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

5.4.1 Difference in Reference Height Values

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

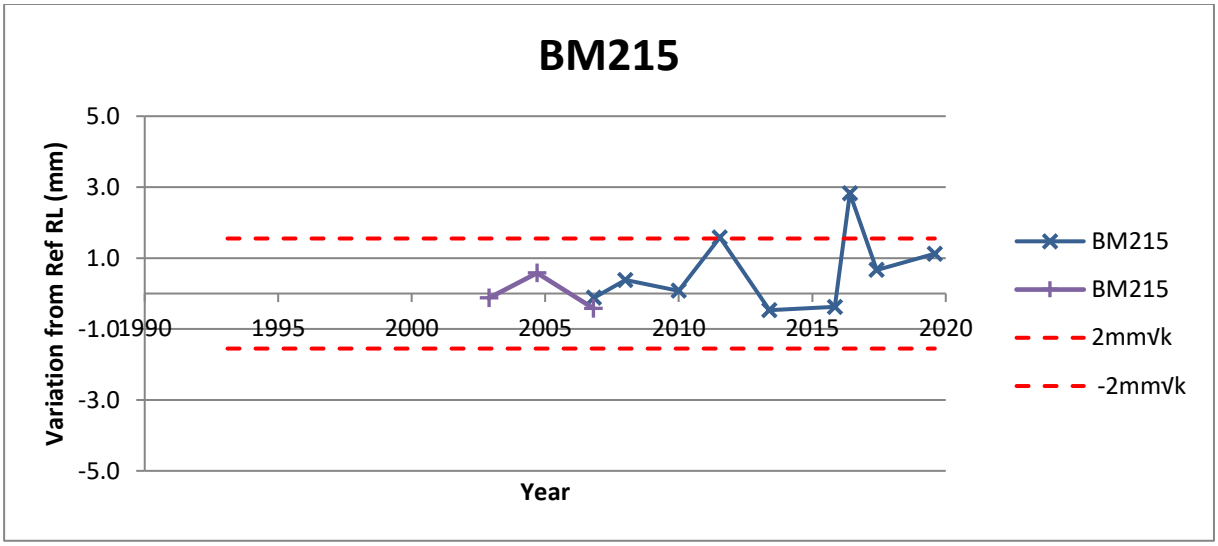
REF - 2019	SAMOBM	BM215	BM214	BM213	BM212	BM220	BM210	BM201	SAM16	SAM17	RM1	RM3	RM4	SAMO
SAMOBM	-	-0.0011	-0.0011	-0.0009	-0.0007	-0.0009	-0.0030	-0.0016	-0.0010	0.0034	0.0001	0.0000	0.0001	0.0000
BM215	0.0011	-	0.0000	0.0002	0.0004	0.0002	-0.0019	-0.0005	0.0002	**0.0045**	0.0012	0.0011	0.0012	0.0012
BM214	0.0011	0.0000	-	0.0002	0.0004	0.0002	-0.0019	-0.0005	0.0002	**0.0045**	0.0012	0.0011	0.0012	0.0011
BM213	0.0009	-0.0002	-0.0002	-	0.0002	0.0000	-0.0021	-0.0007	0.0000	0.0043	0.0010	0.0009	0.0010	0.0009
BM212	0.0007	-0.0004	-0.0004	-0.0002	-	-0.0002	-0.0023	-0.0009	-0.0002	0.0041	0.0009	0.0007	0.0009	0.0008
BM220	0.0009	-0.0002	-0.0002	0.0000	0.0002	-	-0.0021	-0.0007	0.0000	0.0043	0.0010	0.0009	0.0010	0.0009
BM210	0.0030	0.0019	0.0019	0.0021	0.0023	0.0021	-	0.0014	0.0021	**0.0064**	0.0032	0.0030	0.0032	0.0031
BM201	0.0016	0.0005	0.0005	0.0007	0.0009	0.0007	-0.0014	-	0.0007	**0.0051**	0.0018	0.0016	0.0018	0.0017
SAM16	0.0010	-0.0002	-0.0002	0.0000	0.0002	0.0000	-0.0021	-0.0007	-	0.0044	0.0011	0.0009	0.0011	0.0010
SAM17	-0.0034	**-0.0045**	**-0.0045**	-0.0043	-0.0041	-0.0043	**-0.0064**	**-0.0051**	-0.0044	-	-0.0033	-0.0034	-0.0033	-0.0034
RM1	-0.0001	-0.0012	-0.0012	-0.0010	-0.0009	-0.0010	-0.0032	-0.0018	-0.0011	0.0033	-	-0.0001	0.0000	-0.0001
RM3	0.0000	-0.0011	-0.0011	-0.0009	-0.0007	-0.0009	-0.0030	-0.0016	-0.0009	0.0034	0.0001	-	0.0002	0.0001
RM4	-0.0001	-0.0012	-0.0012	-0.0010	-0.0009	-0.0010	-0.0032	-0.0018	-0.0011	0.0033	0.0000	-0.0002	-	-0.0001
SAMO	0.0000	-0.0012	-0.0011	-0.0009	-0.0008	-0.0009	-0.0031	-0.0017	-0.0010	0.0034	0.0001	-0.0001	0.0001	-

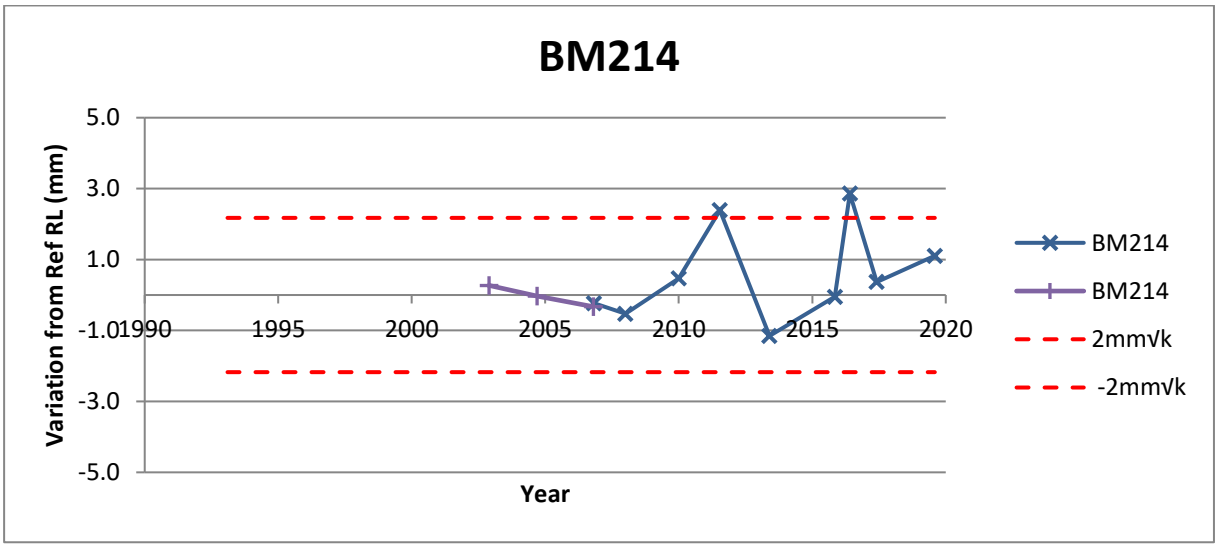
Table 5.4.1.1 values are calculated by subtracting the difference in height between RL_{2019} values (Table 5.3.4) from the difference in height between RL_{REF} values.

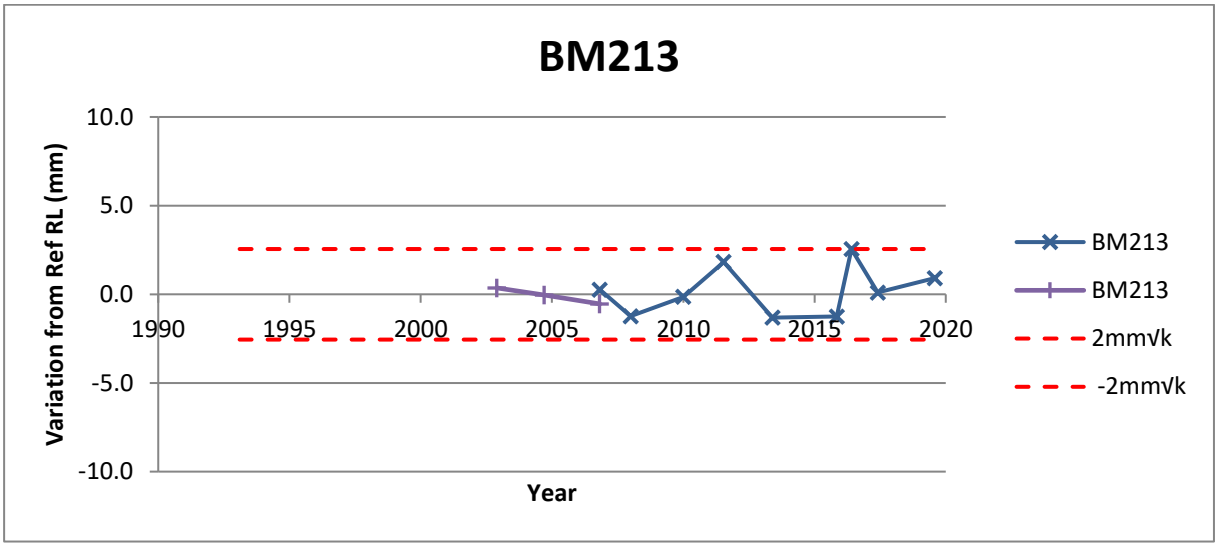
Comparing the change in relative heights between all benchmarks can help identify movement of a particular BM, inconsistency in survey, or even deformation between the GNSS pillar and levelling run BMs.

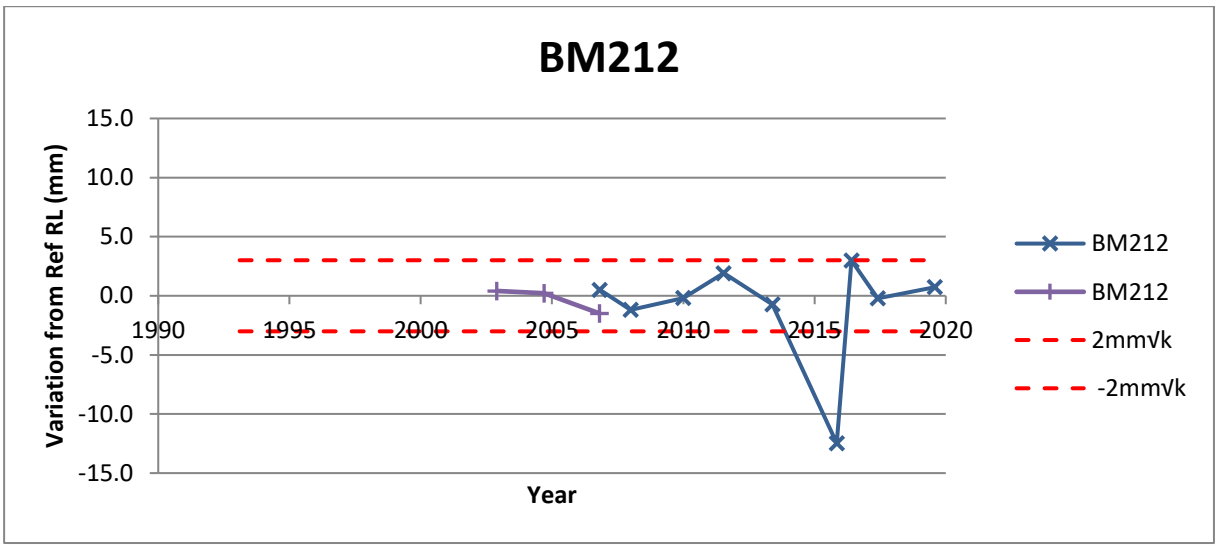
5.4.2 Time Series Charts for each BM

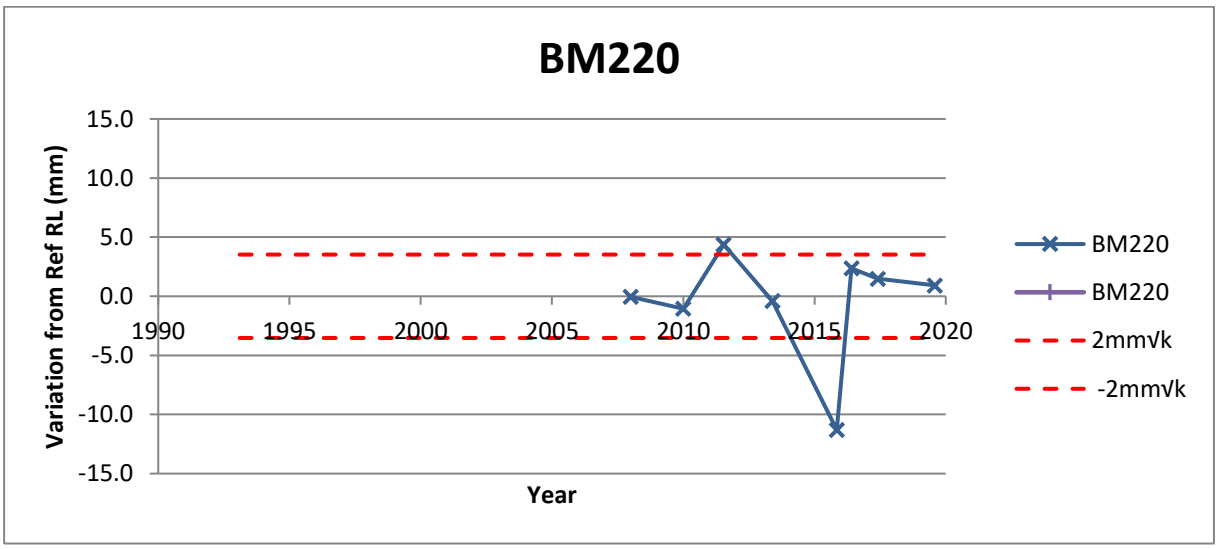
The change in RL over time can be used to detect trends of movement or survey errors. In the series of figures below, the red dashed lines represent the allowable error in height based on the levelling technique used and distance of the benchmark from the GNSS pillar ($2mm\sqrt{K}$). The purple line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

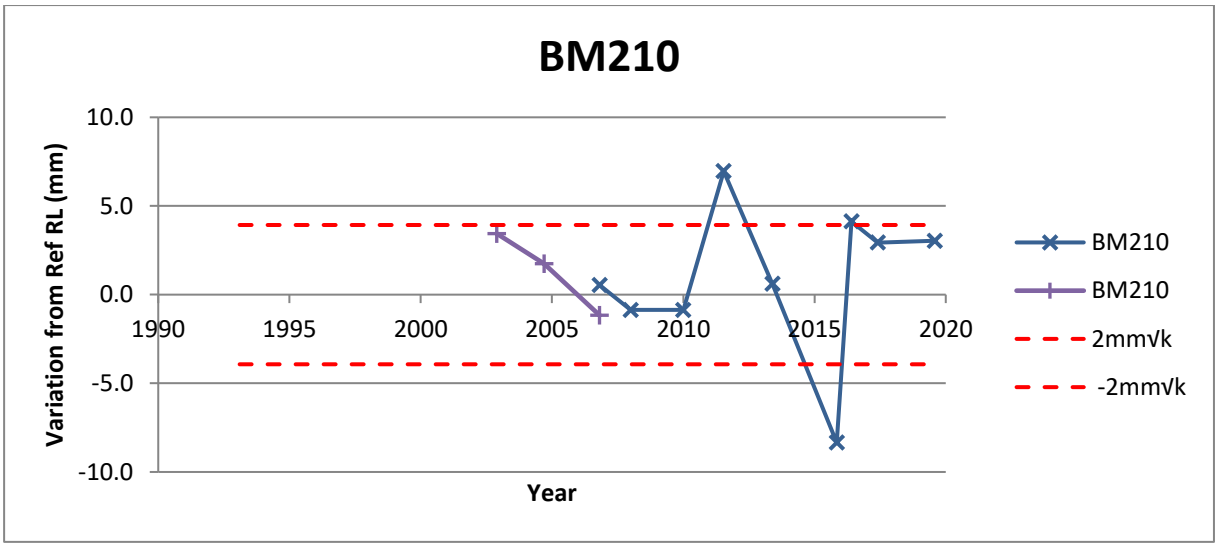


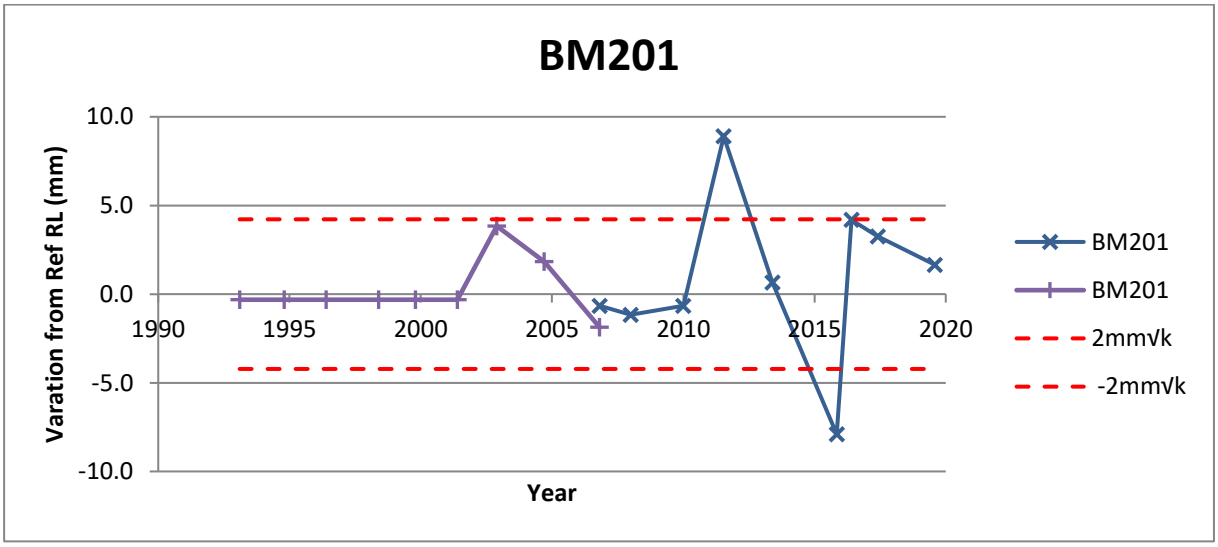


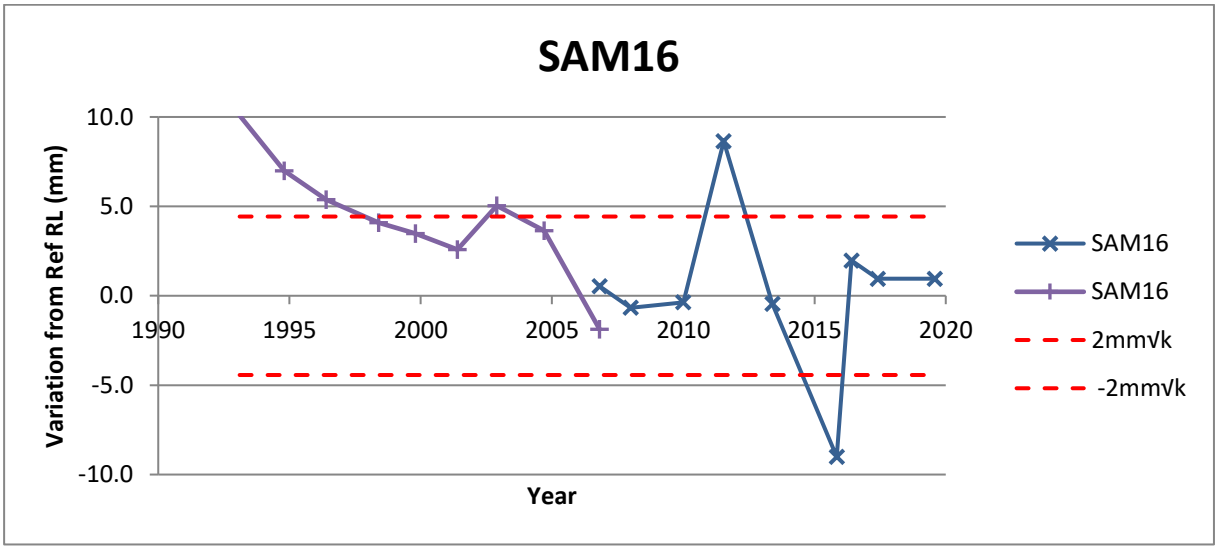

BM213
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Variation from Ref RL (mm)
Year
BM213
BM213
2mmvk
-2mmvk

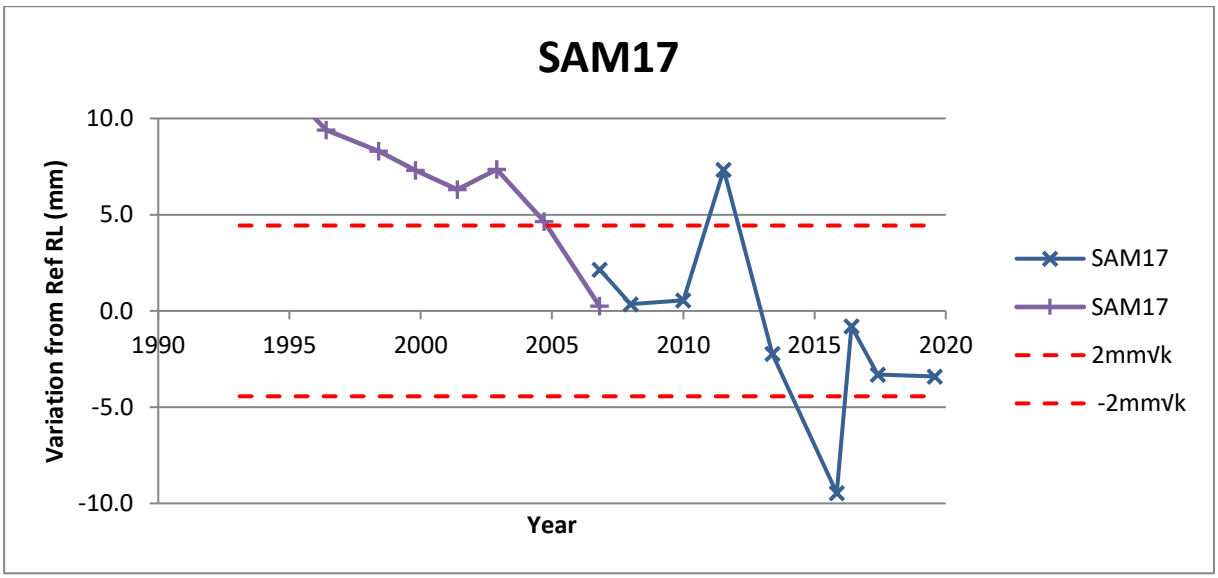

BM212
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
1990
1995
2000
2005
2010
2015
2020
Variation from Ref RL (mm)
Year
BM212
BM212
2mmvk
-2mmvk


BM220
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
1990
1995
2000
2005
2010
2015
2020
Variation from Ref RL (mm)
Year
BM220
BM220
2mmvk
-2mmvk


BM210
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Variation from Ref RL (mm)
Year
BM210
BM210
2mmVk
-2mmVk


BM201
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Varation from Ref RL (mm)
Year
BM201
BM201
2mmVk
-2mmVk


SAM16
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Variation from Ref RL (mm)
Year
SAM16
SAM16
2mmvk
-2mmvk


SAM17
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Variation from Ref RL (mm)
Year
SAM17
SAM17
2mmvk
-2mmvk

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 0.003m:

- SAM17 had movements prior with this survey indicating there are still movements of the wharf structure. This maybe is an indicator that the tide gauge facility reinforcements are fragile. The wharf structure itself has proven otherwise as there is no concern at all with regards to its stability.

Variation to all other ΔH measured are within specification, so no change to the Fixed ΔH_{ref} will be made for future comparisons.

Table 6.1 Comparison of results with Reference ^H.

PT ID	Reference ^H (m)	2019.60 Value (m)	Difference
SAMOBM - Primary BM (BM201)	-36.8615	-36.8602	0.0013
BM201 - TG Plaque BM (SAM16)	1.0447	1.0440	-0.0007
BM201 - TG ref pin (SAM17)	2.8307	2.8256	-0.0051
SAMOBM - BM201	-36.8615	-36.8602	0.0013
BM201 - SAM16	1.0447	1.0440	-0.0007
SAM16 - SAM17	1.7860	1.7816	-0.0044
SAMO - TG Plaque	-36.5451	-36.5444	0.0007
SAMO - TG BM	-34.7591	-34.7628	-0.0037

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

PT ID	Reference RL (m)	2019.60 Value (m)	Difference	TGZ	ITRF2020
SAMOBM	0.0000	0.0000	0.0000	38.9049	76.0787
BM215	-16.5792	-16.5781	0.0011	22.3268	59.4995
BM214	-30.0700	-30.0689	0.0011	8.8360	46.0087
BM213	-37.0047	-37.0037	0.0009	1.9011	39.0740
BM212	-36.8027	-36.8020	0.0007	2.1029	39.2760
BM220	-36.6682	-36.6672	0.0009	2.2376	39.4105
BM210	-36.9368	-36.9338	0.0030	1.9711	39.1419
BM201	-36.8615	-36.8599	0.0016	2.0450	39.2172
SAM16	-35.8168	-35.8159	0.0010	3.0890	40.2619
SAM17	-34.0308	-34.0343	-0.0034	4.8706	42.0479
RM1	-1.7309	-1.7310	-0.0001	37.1738	74.3477
RM3	-1.2222	-1.2222	0.0000	37.6827	74.8565
RM4	-0.7820	-0.7822	-0.0001	38.1227	75.2967
SAMO	0.7282	0.7282	0.0000	39.6331	76.8069
TGZ	-38.9014	-38.9049	-0.0034	0.0000	37.1773

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).

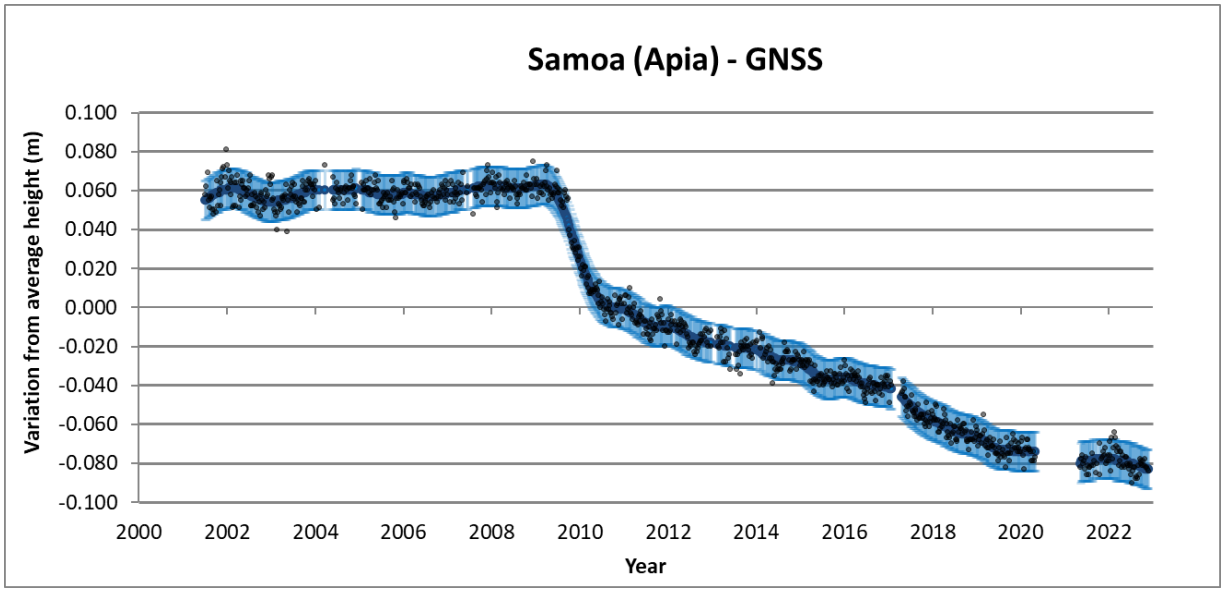


Figure 7.1 Time series of GNSS analysis (dark blue line) with 95%CI uncertainty (light blue lines).

[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.

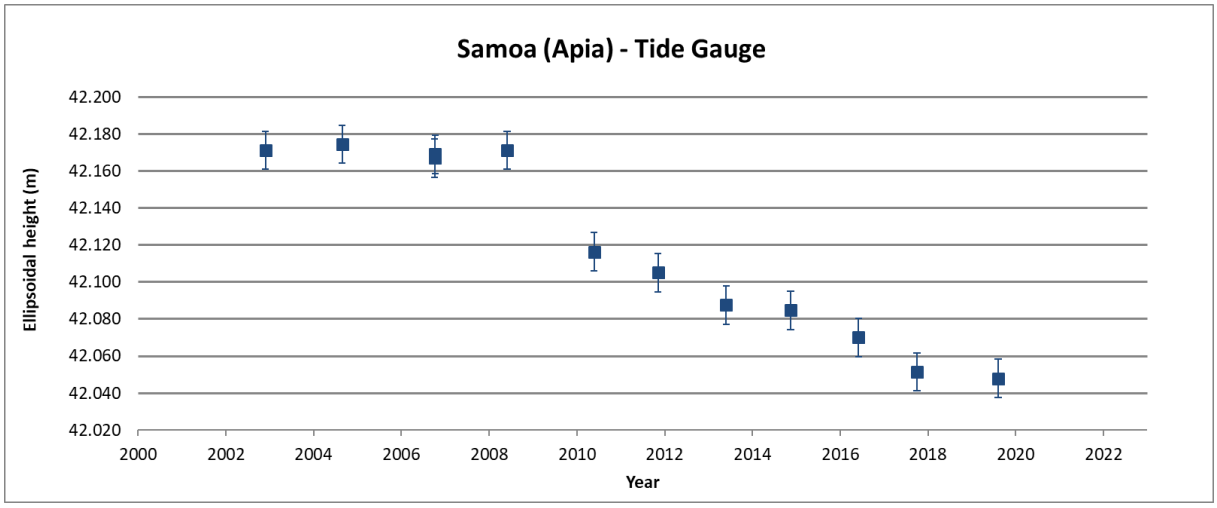


Figure 7.2 The height of the SEAFRAME sensor reference benchmark (with respect to ITRF2020).

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 Ellipsoidal height of the tide gauge along with the 95%CI uncertainty derived from GNSS time series analysis and levelling. Ellipsoidal height is with respect to the International Terrestrial Reference Frame 2014.

Date	Height(m)	Uncertainty (95%CI) (m)
2002.90	42.1712	0.0103
2004.65	42.1745	0.0103
2006.76	42.1671	0.0103
2006.77	42.1690	0.0103
2008.41	42.1712	0.0103
2010.39	42.1164	0.0103
2011.85	42.1052	0.0103
2013.40	42.0876	0.0103
2014.87	42.0847	0.0103
2016.42	42.0701	0.0103
2017.75	42.0515	0.0103
2019.60	42.0479	0.0103

[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

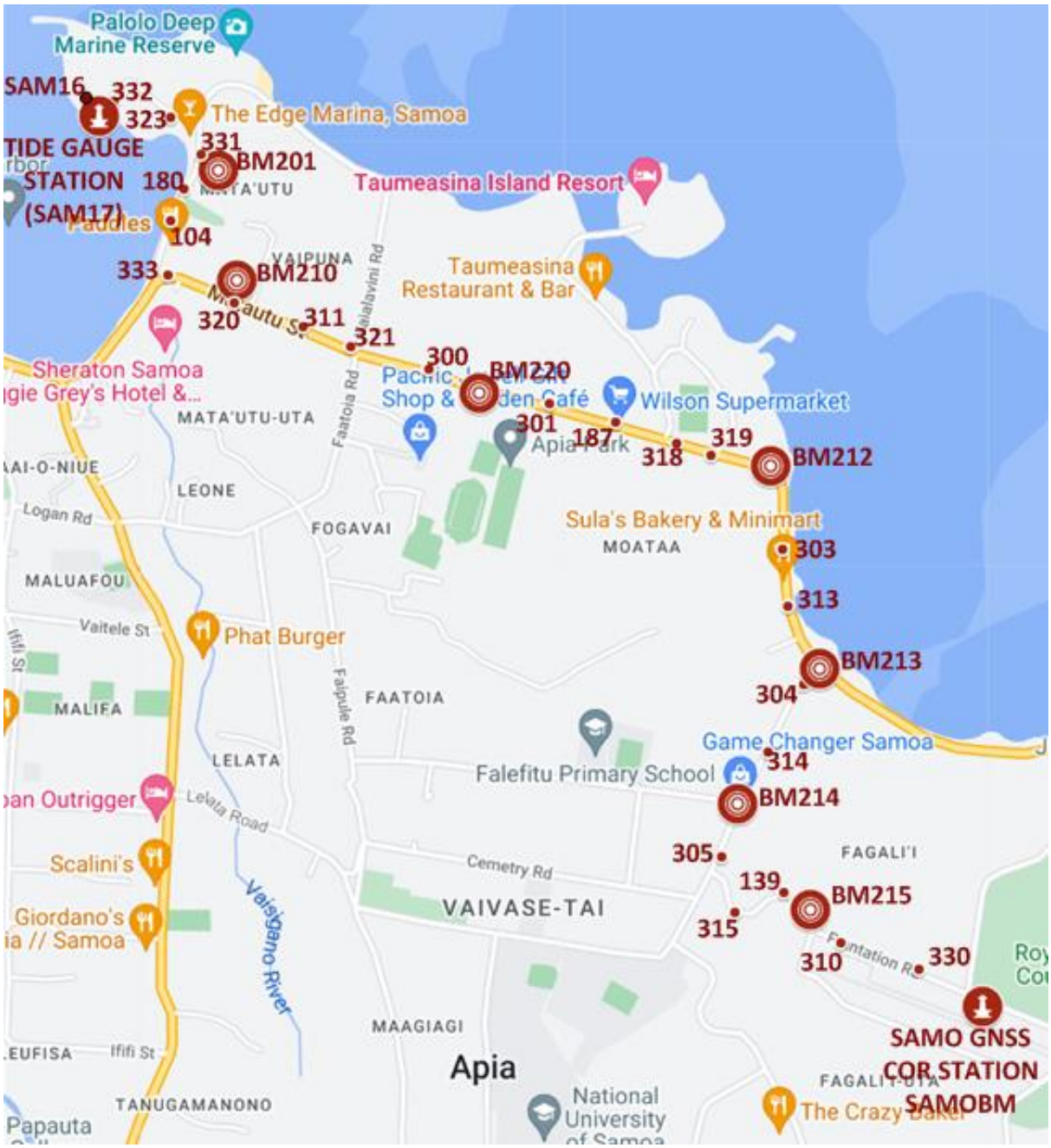
Fraser, R., Leahy, F., Collier, P., 2018. *DynAdjust User's Guide Version 3.0*. Dynamic Network Adjustment Software.

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 Diagram



Source: Adopted from Google Map

A1. Deep Benchmarks

PACIFIC SEA LEVEL & GEODETIC MONITORING PROJECT

SURVEY BENCH MARK RECORD

Bench Mark Number: BM201

Original Bench Mark Established by: *Date: 27-11-91*
National Tidal Centre Australia, Oceanographic Services,
Bureau of Meteorology, 25 College Rd, Kent Town SA.

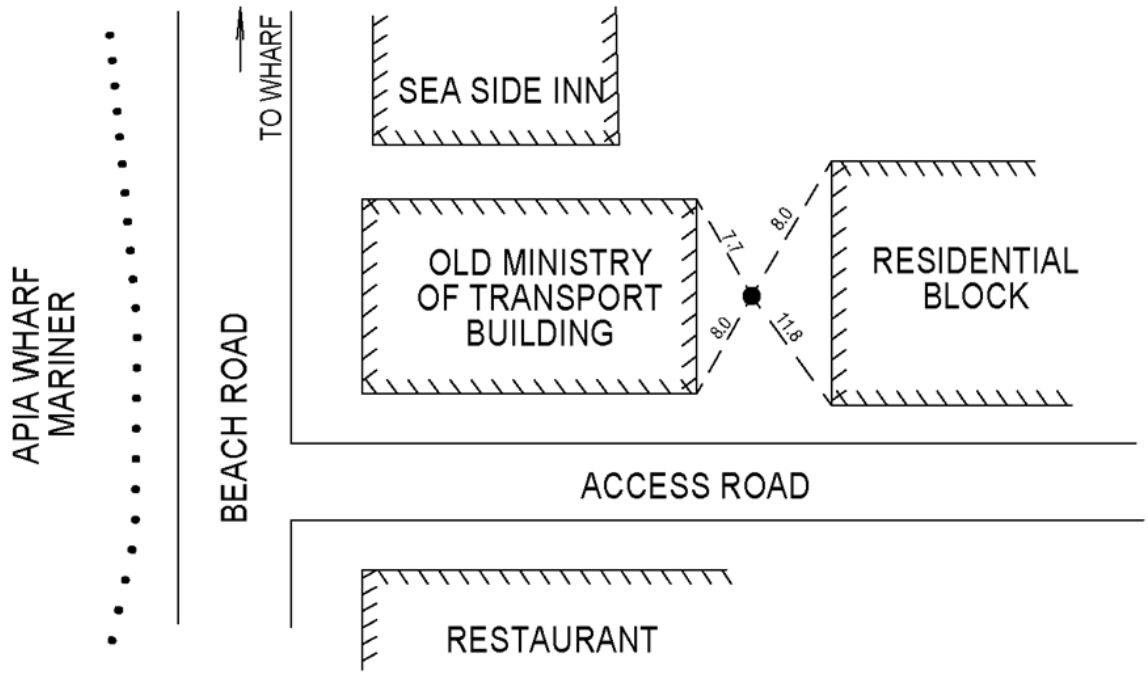
Existing Bench Mark Established by: *Date:*

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

Country: Samoa
Island: Upolu
City: Apia

MARKING AND LOCALITY SKETCH

Bench Mark: 7.4m of 19mm diameter stainless steel capped rod driven to refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite, for 1.2m. Top of mark 0.1m below ground level. Locality sketch Mark approximately 400m from the tide gauge station.



NOT TO SCALE Distances in Metres Magnetic Bearings

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

PACIFIC SEA LEVEL MONITORING PROJECT

Australian Government
Geoscience Australia

Pacific Community
Communauté du Pacifique

SURVEY BENCH MARK RECORD

Bench Mark Number: BM210

Original Bench Mark Established by: *Date: November2002*

National Tidal Centre Australia, Oceanographic Services,
Bureau of Meteorology, 25 College Rd, Kent Town SA.

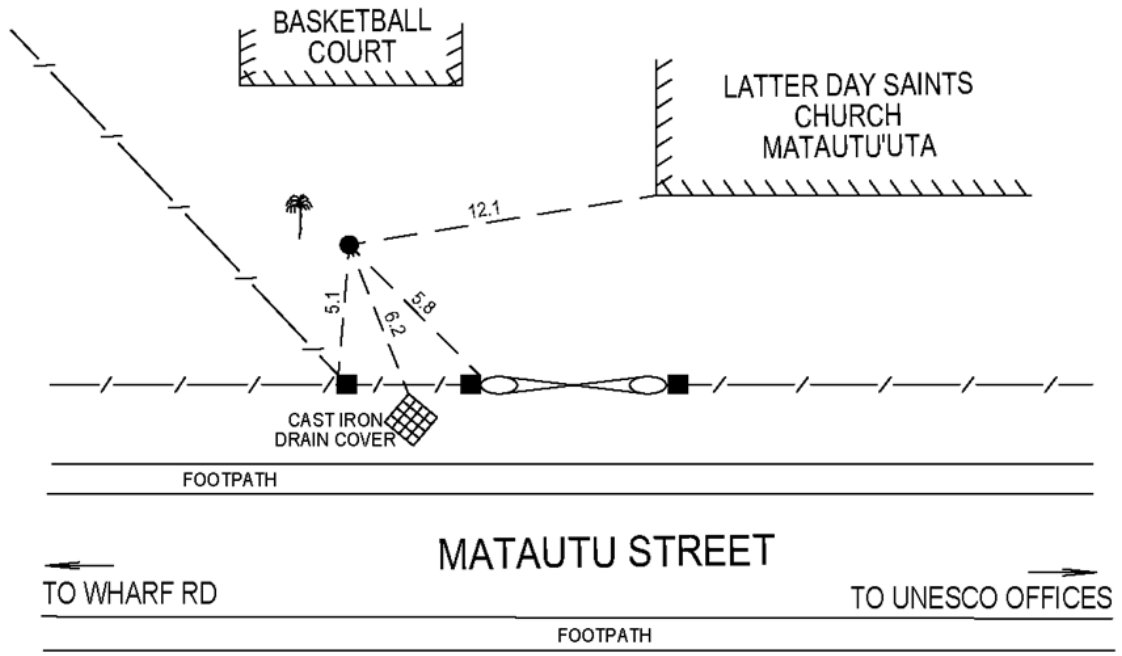
Existing Bench Mark Established by: *Date:*

Notes / References: Deep driven Benchmark
This survey mark is a good locality for GPS occupation

Country: Samoa
Island: Upolu
City: Apia

MARKING AND LOCALITY SKETCH

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



NOT TO SCALE Distances in Metres Magnetic Bearings

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

PACIFIC SEA LEVEL MONITORING PROJECT

Australian Government
Geoscience Australia

Pacific Community
Communauté du Pacifique

SURVEY BENCH MARK RECORD

Bench Mark Number: BM212

Original Bench Mark Established by: *Date: November2002*

National Tidal Centre Australia, Oceanographic Services,
Bureau of Meteorology, 25 College Rd, Kent Town SA.

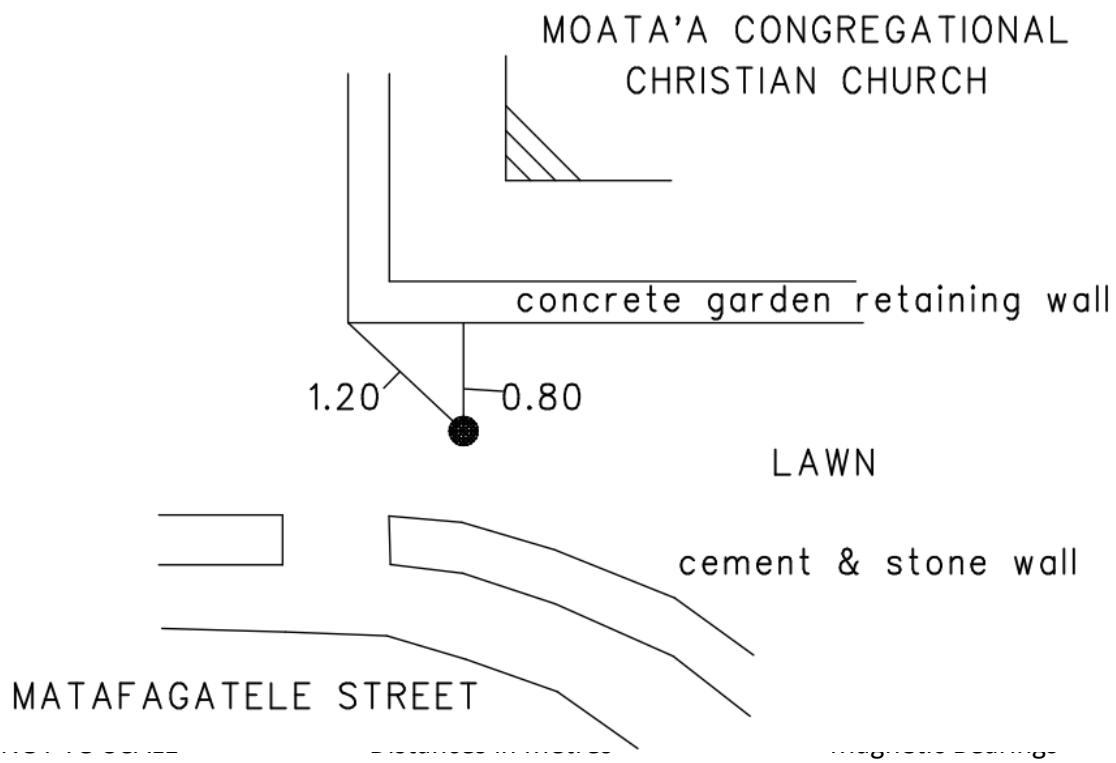
Existing Bench Mark Established by: *Date:*

Notes / References: Deep driven Benchmark
This survey mark is not in a good locality for GPS occupation

Country: Samoa
Island: Upolu
City: Apia

MARKING AND LOCALITY SKETCH

Bench Mark: 19mm diameter stainless steel capped rod driven to refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite. Top of mark 0.1m below ground level. Locality sketch Mark approximately 2800m from the tide gauge station.



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

PACIFIC SEA LEVEL MONITORING PROJECT

Australian Government
Geoscience Australia

Pacific Community
Communauté du Pacifique

SURVEY BENCH MARK RECORD

Bench Mark Number: BM213

Original Bench Mark Established by: *Date: November 2002*

National Tidal Centre Australia, Oceanographic Services,
Bureau of Meteorology, 25 College Rd, Kent Town SA.

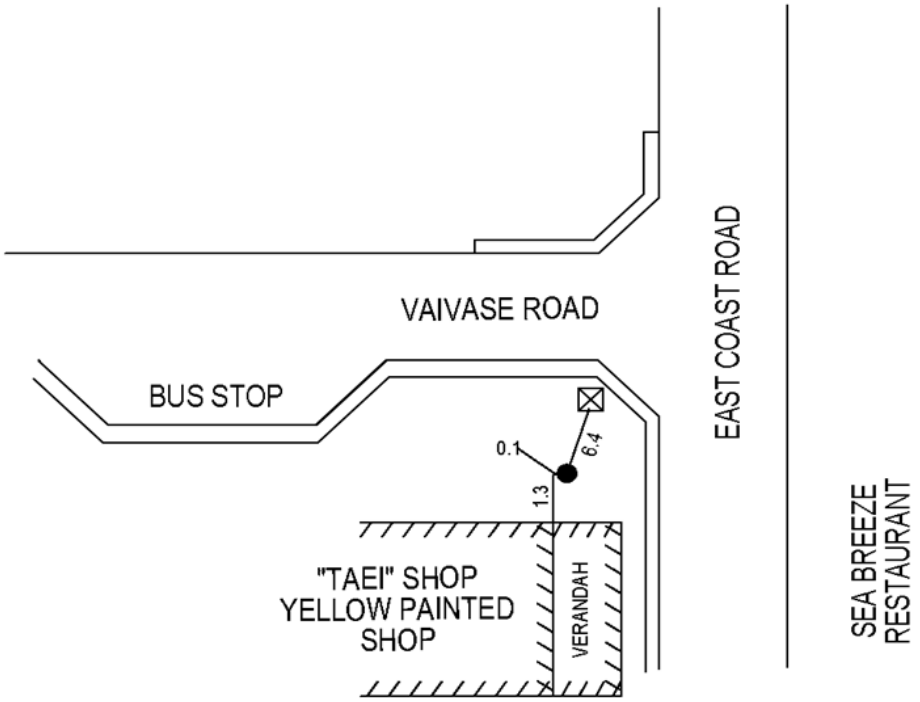
Existing Bench Mark Established by: *Date:*

Notes / References: Deep driven Benchmark
This survey mark is not in a good locality for GPS occupation

Country: Samoa
Island: Upolu
City: Apia

MARKING AND LOCALITY SKETCH

Bench Mark: 19mm diameter stainless steel capped rod driven to refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite for 1.2m. Top of mark is ground level. Locality sketch Mark approximately 3450m from the tide gauge station.



NOT TO SCALE Distances in Metres Magnetic Bearings

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

PACIFIC SEA LEVEL MONITORING PROJECT

Australian Government
Geoscience Australia

Pacific Community
Communauté du Pacifique

SURVEY BENCH MARK RECORD

Bench Mark Number: BM214

Original Bench Mark Established by: *Date: November 2002*

National Tidal Centre Australia, Oceanographic Services,
Bureau of Meteorology, 25 College Rd, Kent Town SA.

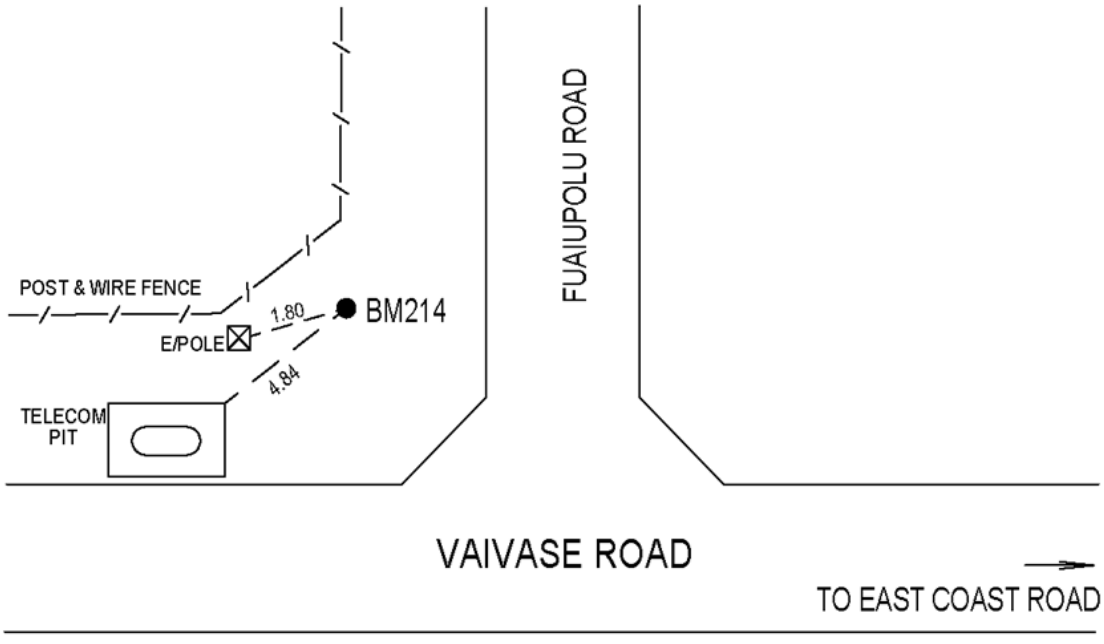
Existing Bench Mark Established by: *Date:*

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

Country: Samoa
Island: Upolu
City: Apia

MARKING AND LOCALITY SKETCH

Bench Mark: 19mm diameter stainless steel capped rod driven to refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite for 1.2m. Top of mark is ground level. Locality sketch Mark approximately 3900m from the tide gauge station.



NOT TO SCALE Distances in Metres Magnetic Bearings

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

PACIFIC SEA LEVEL MONITORING PROJECT

Australian Government
Geoscience Australia

Pacific Community
Communauté du Pacifique

SURVEY BENCH MARK RECORD

Bench Mark Number: BM215

Original Bench Mark Established by: *Date: November 2002*

National Tidal Centre Australia, Oceanographic Services,
Bureau of Meteorology, 25 College Rd, Kent Town SA.

Existing Bench Mark Established by: *Date:*

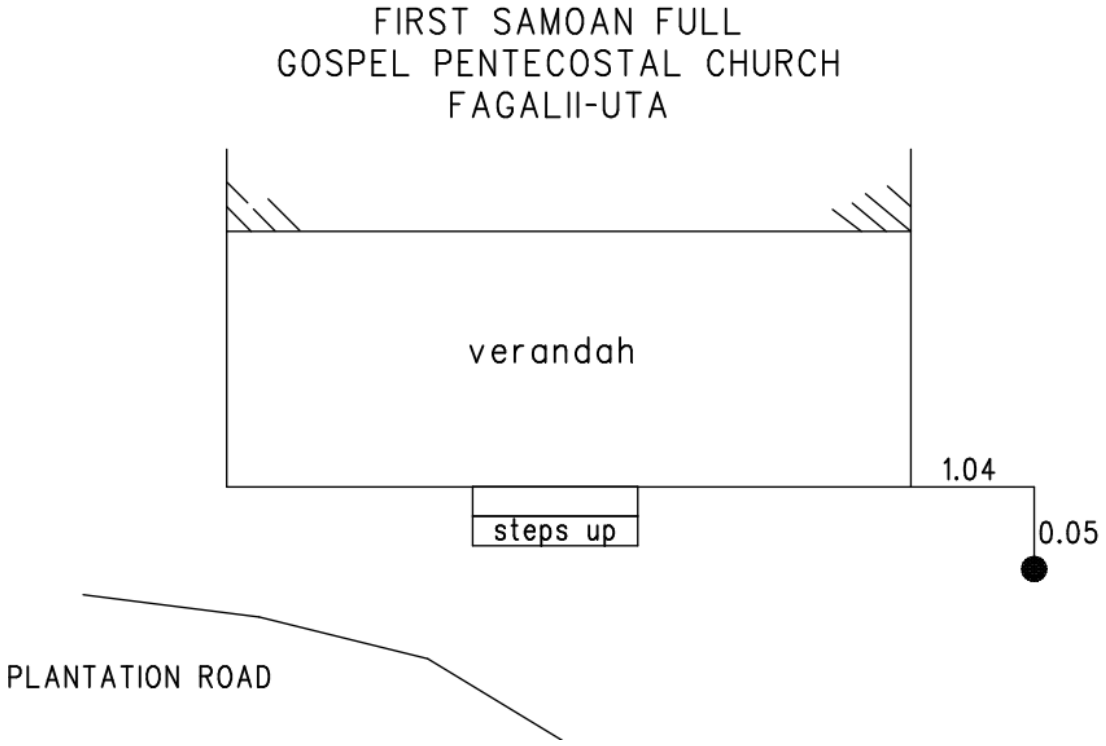
Notes / References: Deep driven Benchmark
This survey mark is not in a good locality for GPS occupation

Country: Samoa
Island: Upolu

City: Apia

MARKING AND LOCALITY SKETCH

Bench Mark: 19mm diameter stainless steel capped rod driven to refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite for 1.2m. Top of mark is ground level. Locality sketch Mark approximately 2500m from the tide gauge station.



NOT TO SCALE Distances in Metres Magnetic Bearings

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

PACIFIC SEA LEVEL MONITORING PROJECT

Australian Government
Geoscience Australia

Pacific Community
Communauté du Pacifique

SURVEY BENCH MARK RECORD

Bench Mark Number: BM220

Original Bench Mark Established by: *Date: May 2008*

National Tidal Centre Australia, Oceanographic Services,
Bureau of Meteorology, 25 College Rd, Kent Town SA.

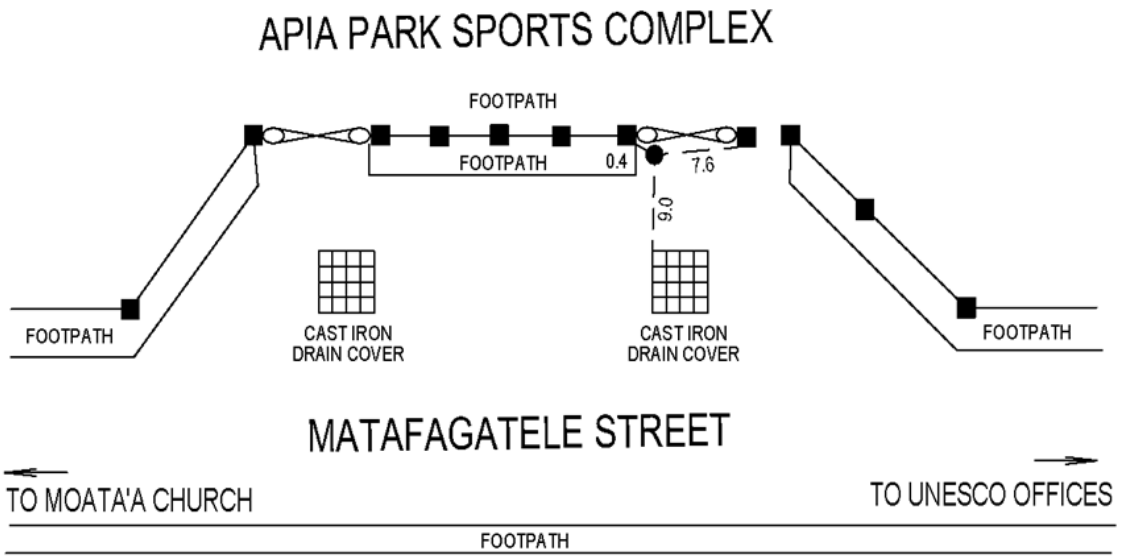
Existing Bench Mark Established by: *Date:*

Notes / References: Deep driven Benchmark
This survey mark is not in a good locality for GPS occupation

Country: Samoa
Island: Upolu
City: Apia

MARKING AND LOCALITY SKETCH

Bench Mark: 5.3m of 19mm diameter stainless steel capped rod driven to refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite for 0.5m. Top of mark is 0.1m below ground level. Locality sketch Mark approximately 2000m from the tide

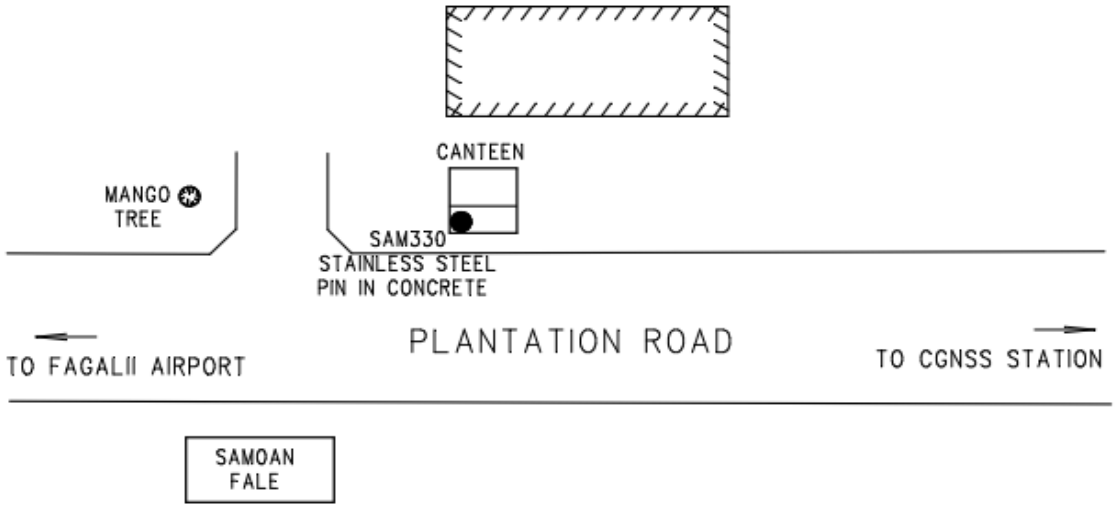


NOT TO SCALE Distances in Metres Magnetic Bearings

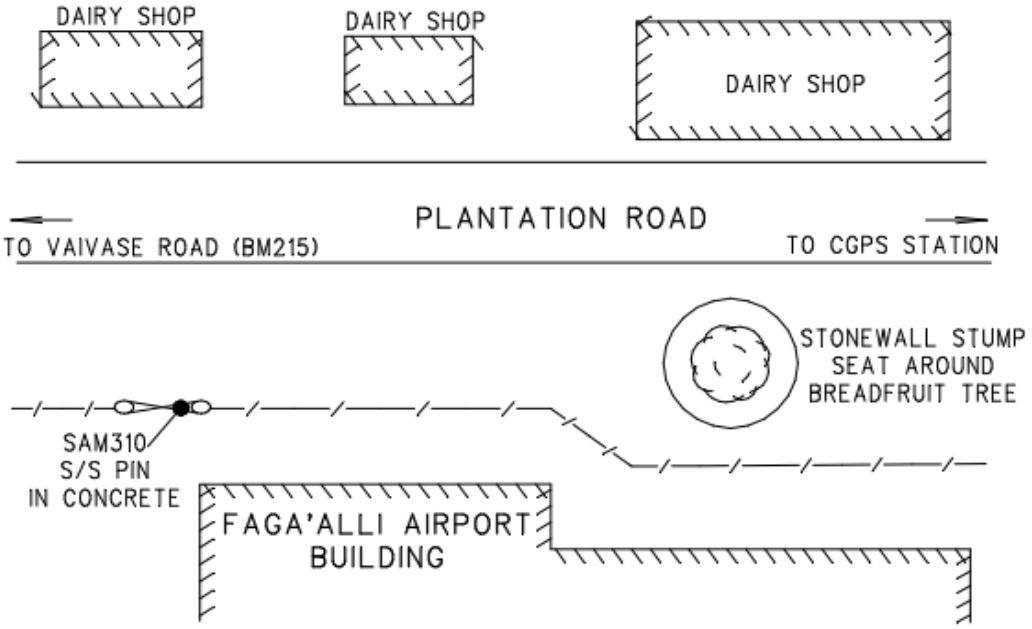
Approved by: Geoscience Australia / SPC *Date: November 2006*

A2. Temporary Holding Marks

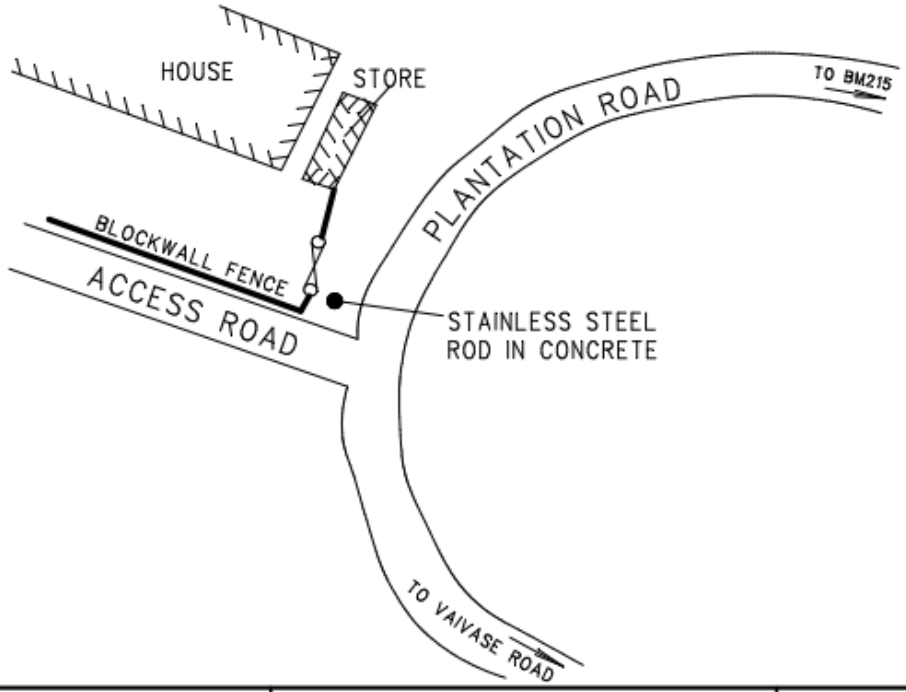
COUNTRY: Samoa	ISLAND: Upolu CITY: Apia	L. D. P. POINT NO. 330
PROJECT: PSLGM	SURVEYOR: A.Lal, V.Rattan, M.Kalouniviti	DATE: 28-10-17



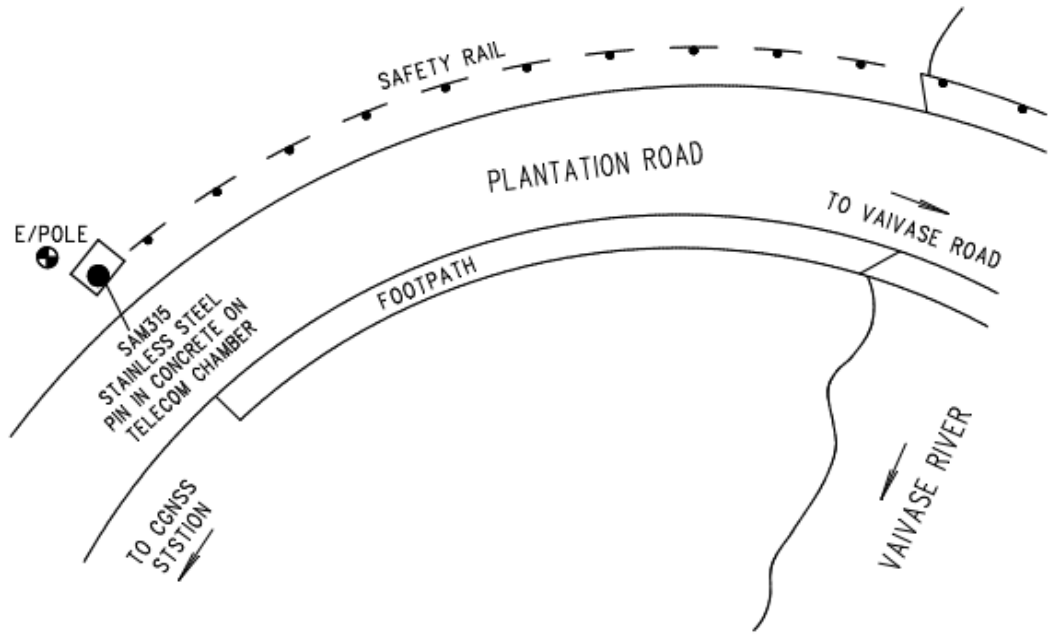
COUNTRY: Samoa	ISLAND: Upolu CITY: Apia	L. D. P. 902 POINT NO. 310
PROJECT: PSLGM	SURVEYOR: N Brown & A Lal	DATE: 25-05-10



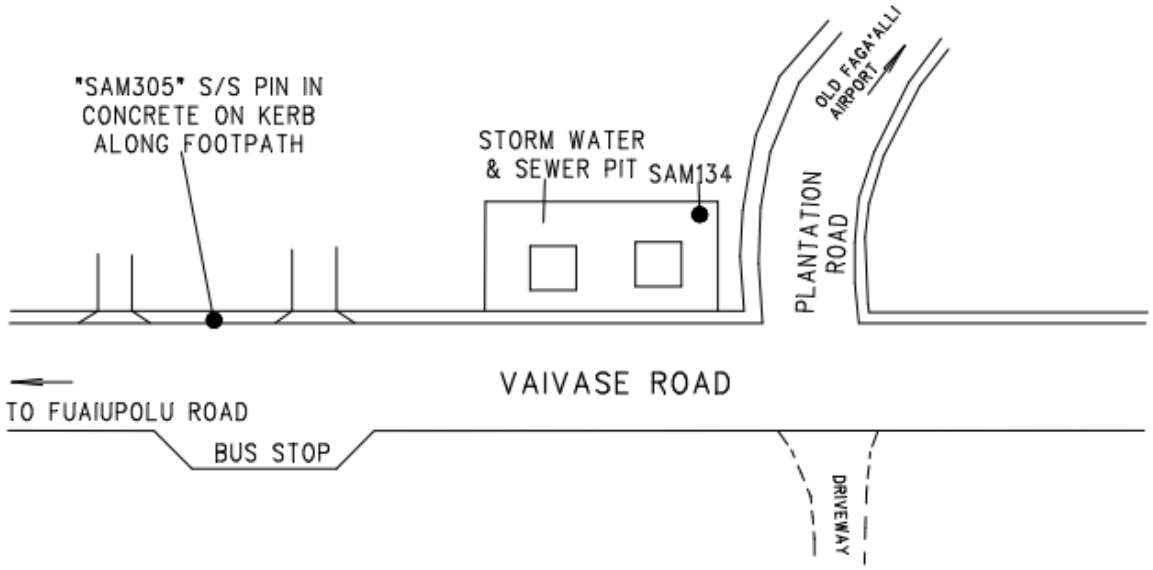
COUNTRY: Samoa	ISLAND: Upolu CITY: Apia	L. D. P. 762 POINT NO. 139
PROJECT: PSLGM	SURVEYOR: S Yates & A Lal	DATE: 15-10-06



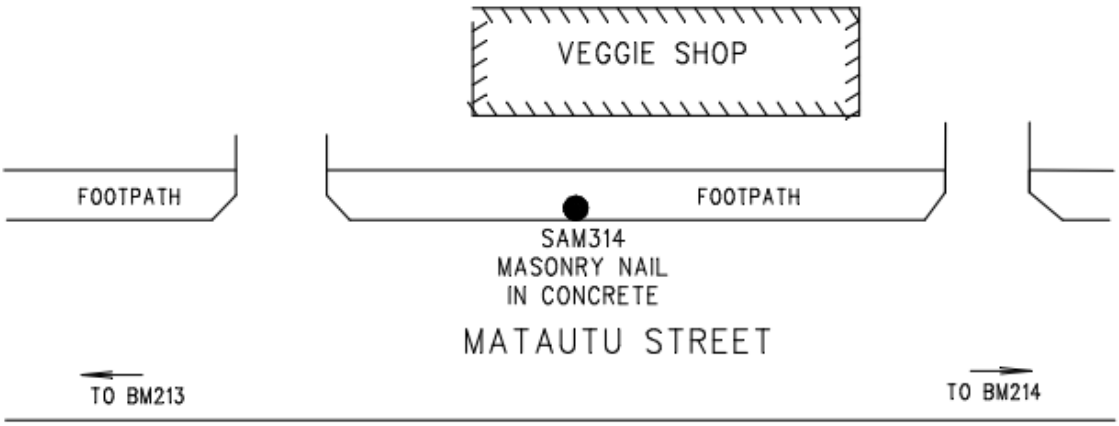
COUNTRY: Samoa	ISLAND: Upolu CITY: Apia	L. D. P. POINT NO. 315
PROJECT: PSLGM	SURVEYOR: N Brown & A Lal	DATE: 25-05-10



COUNTRY: Samoa	ISLAND: Upolu CITY: Apia	L. D. P. 825 POINT NO. 305
PROJECT: PSLGM	SURVEYOR: M Deo & A Lal	DATE: 25-05-08



COUNTRY: Samoa	ISLAND: Upolu CITY: Apia	L. D. P. POINT NO. 314
PROJECT: PSLGM	SURVEYOR: N Brown & A Lal	DATE: 25-05-10



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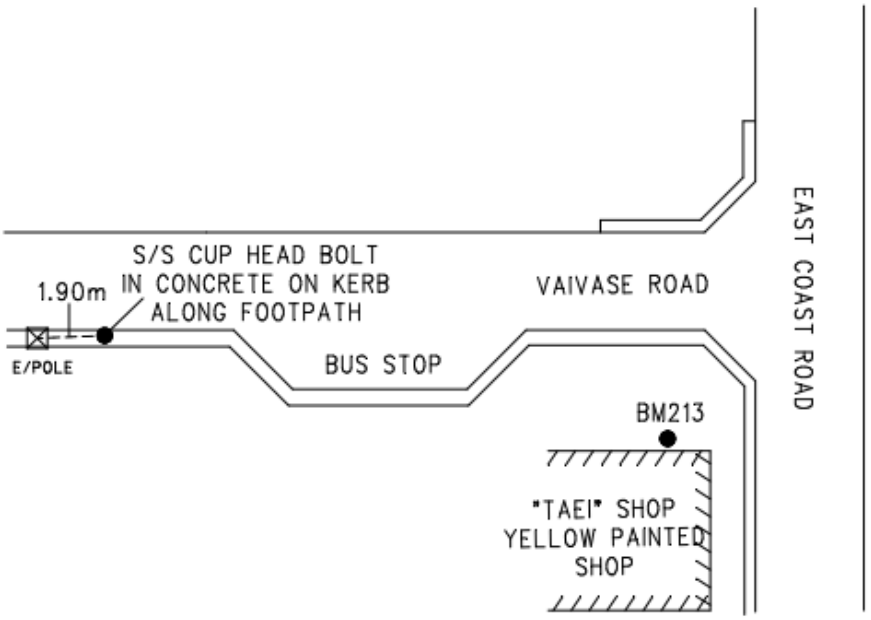
PROJECT: PSLGM	SURVEYOR: M Deo & A Lal	DATE: 25-05-08



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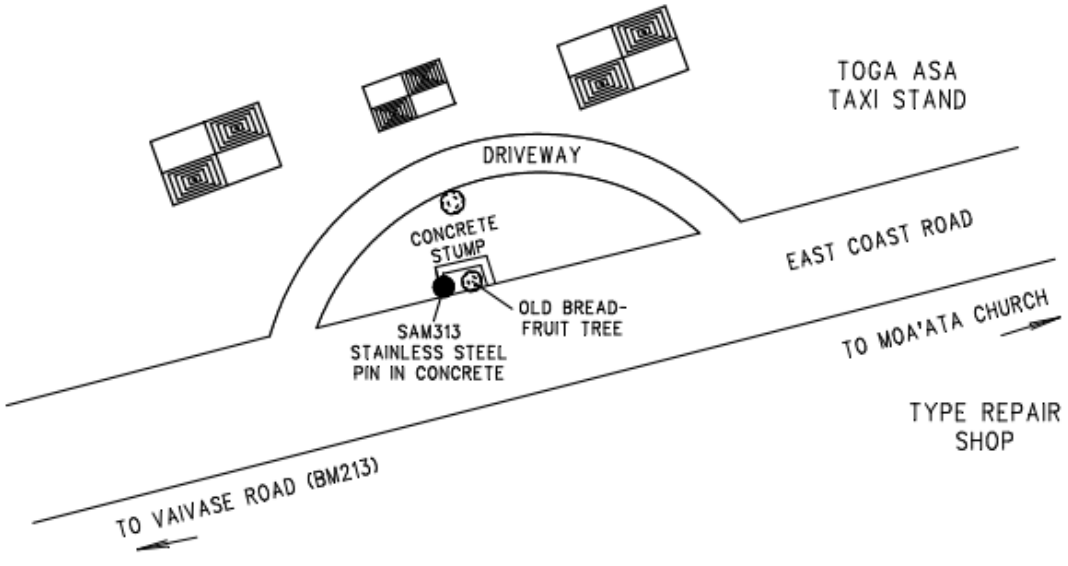
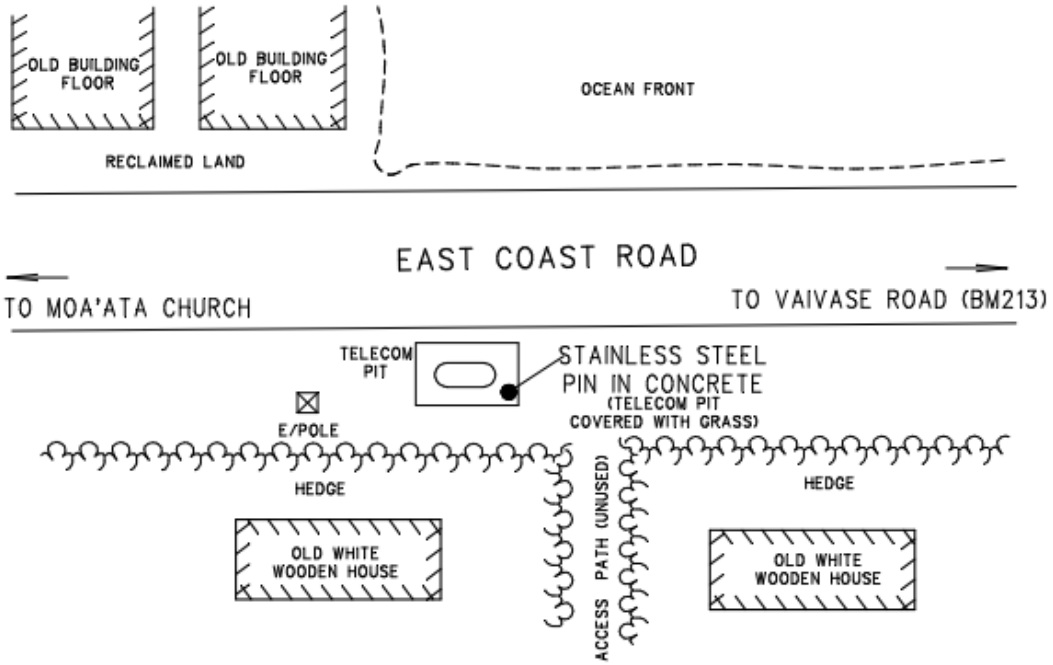
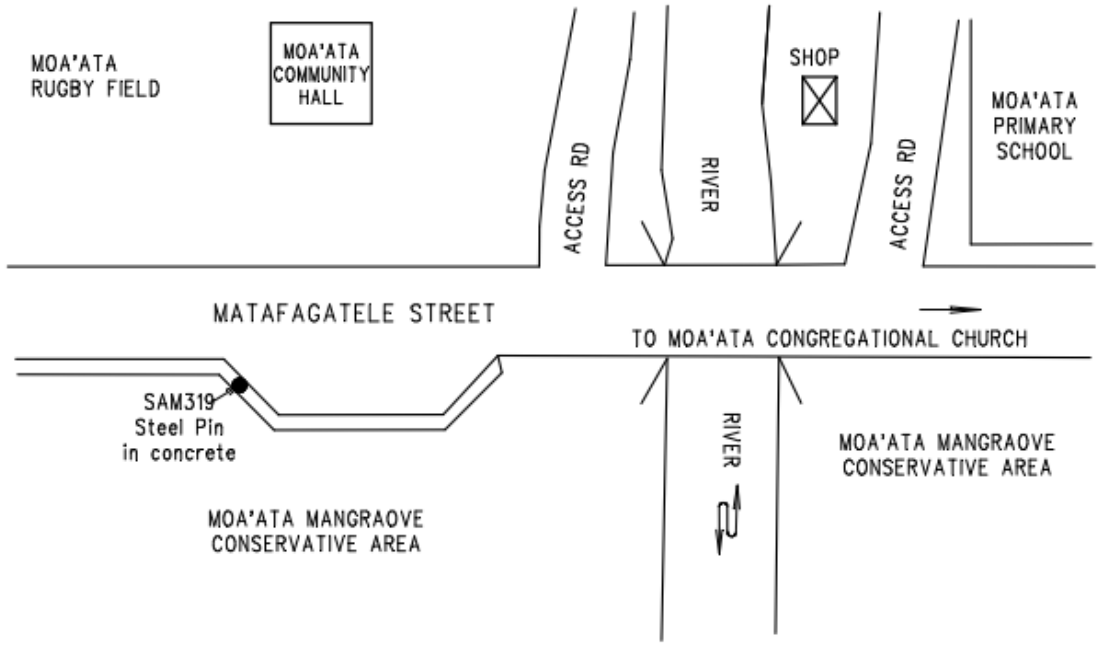
PROJECT: PSLGM	SURVEYOR: N Brown & A Lal	DATE: 25-05-10



COUNTRY: Samoa	ISLAND: Upolu CITY: Apia	L. D. P. 823 POINT NO. 303
PROJECT: PSLGM	SURVEYOR: M Deo & A Lal	DATE: 25-05-08



COUNTRY: Samoa	ISLAND: Upolu CITY: Apia	L. D. P. POINT NO. 319
PROJECT: PSLGM	SURVEYOR: N Brown & A Lal	DATE: 25-05-10



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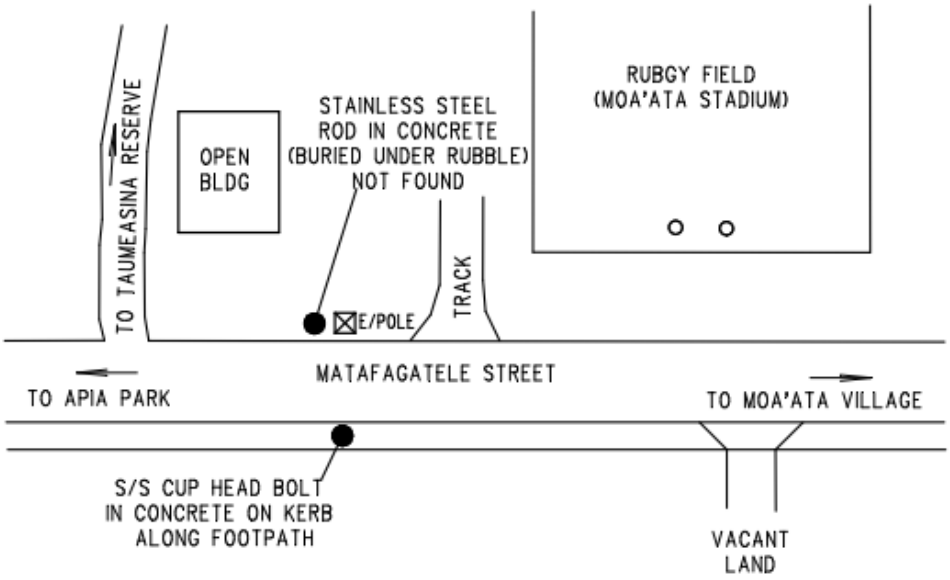
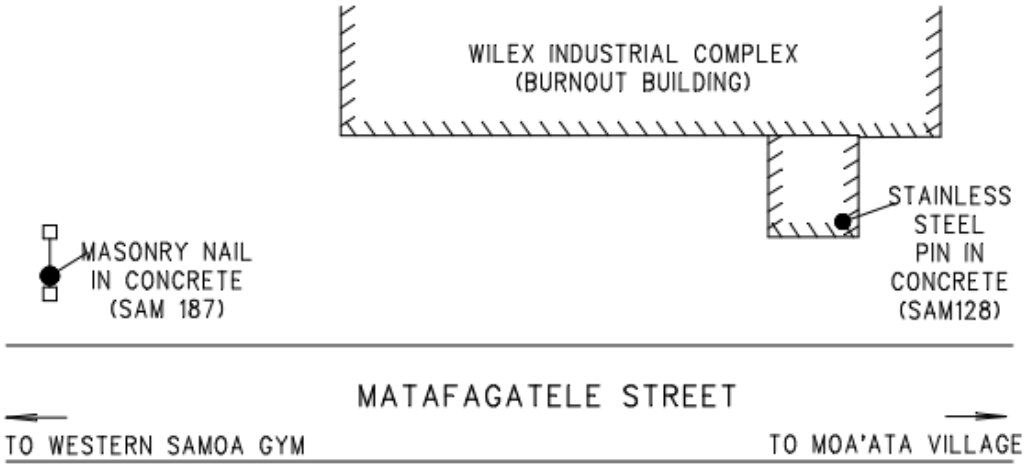
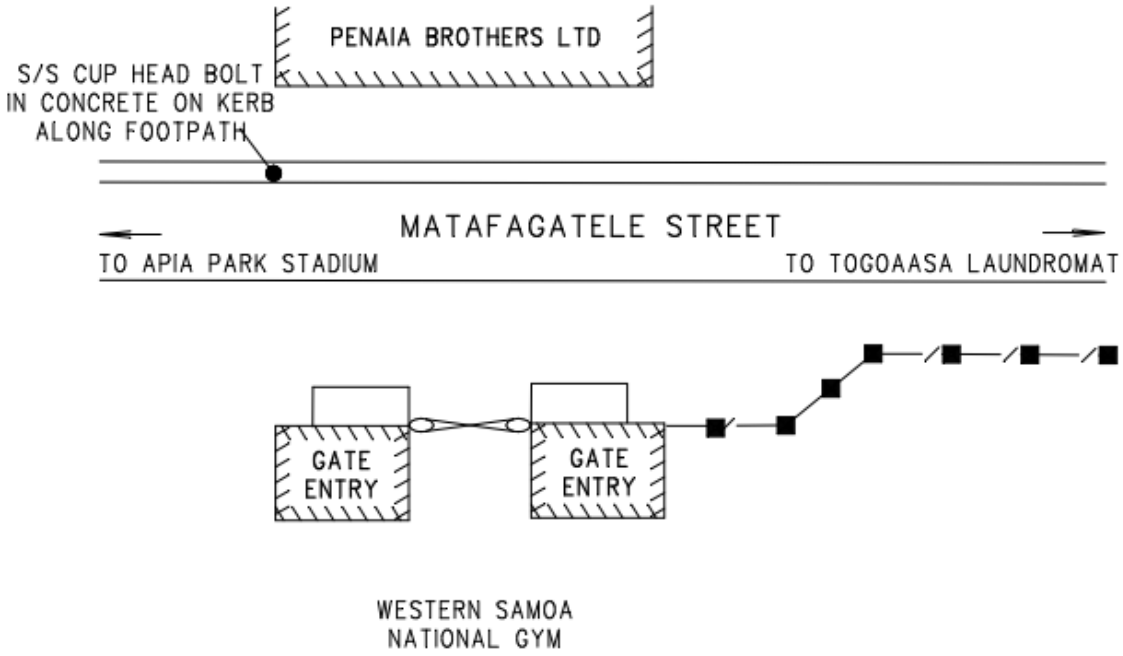
PROJECT: PSLGM	SURVEYOR: N Brown & A Lal	DATE: 25-05-10



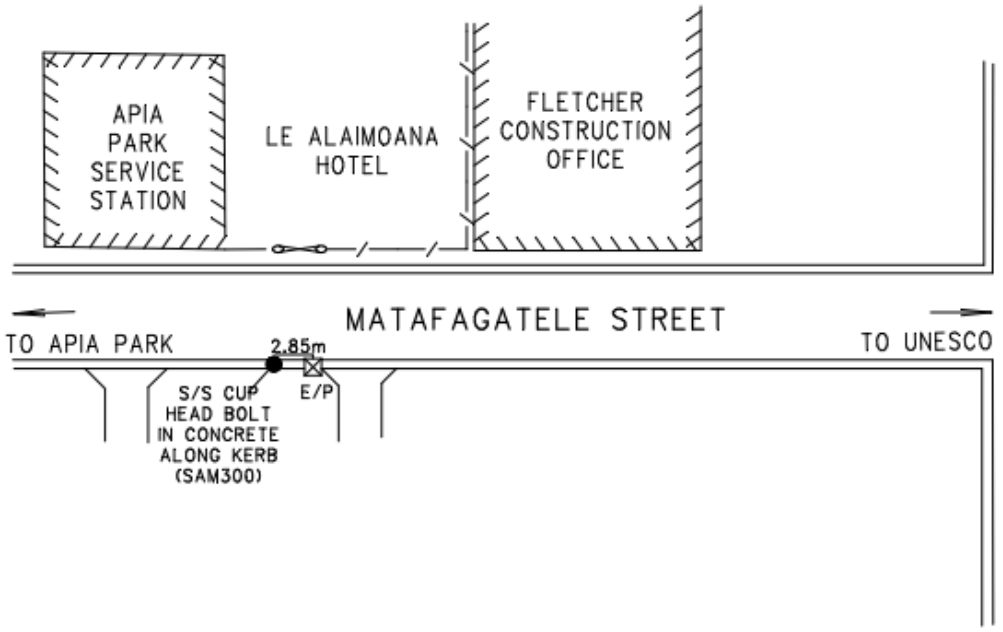
COUNTRY: Samoa	ISLAND: Upolu CITY: Apia	L. D. P. 749 POINT NO. 187
PROJECT: PSLGM	SURVEYOR: S Yates & A Lal	DATE: 14-10-06



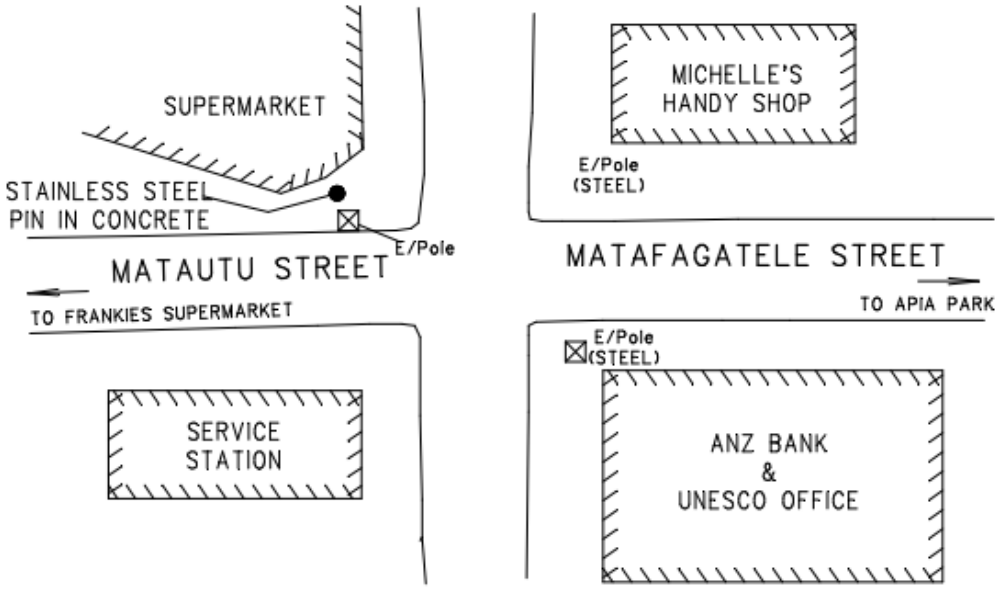
COUNTRY: Samoa	ISLAND: Upolu CITY: Apia	L. D. P. 821 POINT NO. 301
PROJECT: PSLGM	SURVEYOR: M Deo & A Lal	DATE: 25-05-08



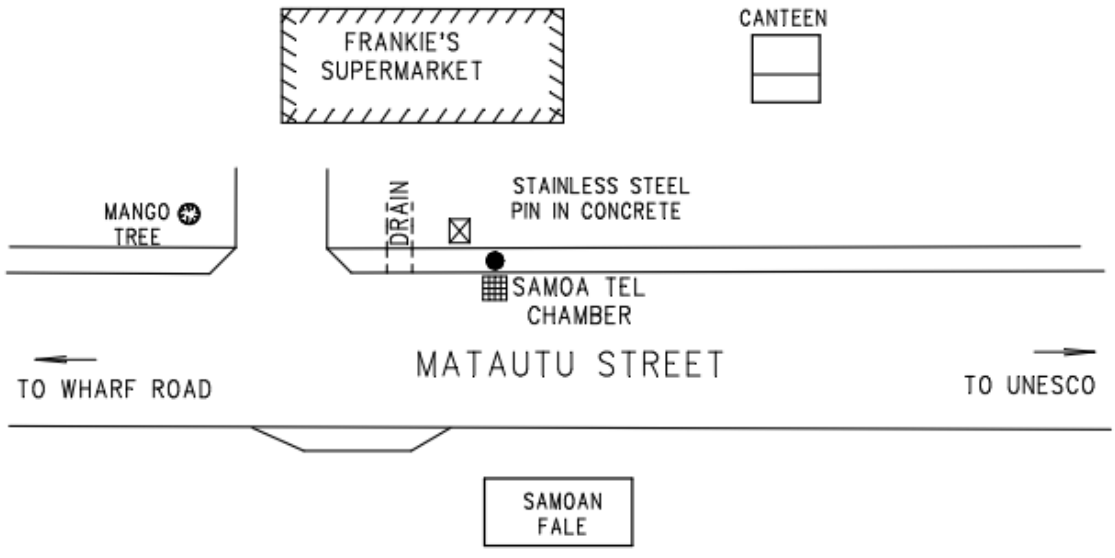
COUNTRY: Samoa	ISLAND: Upolu CITY: Apia	L. D. P. 820 POINT NO. 300
PROJECT: PSLGM	SURVEYOR: M Deo & A Lal	DATE: 27-05-08



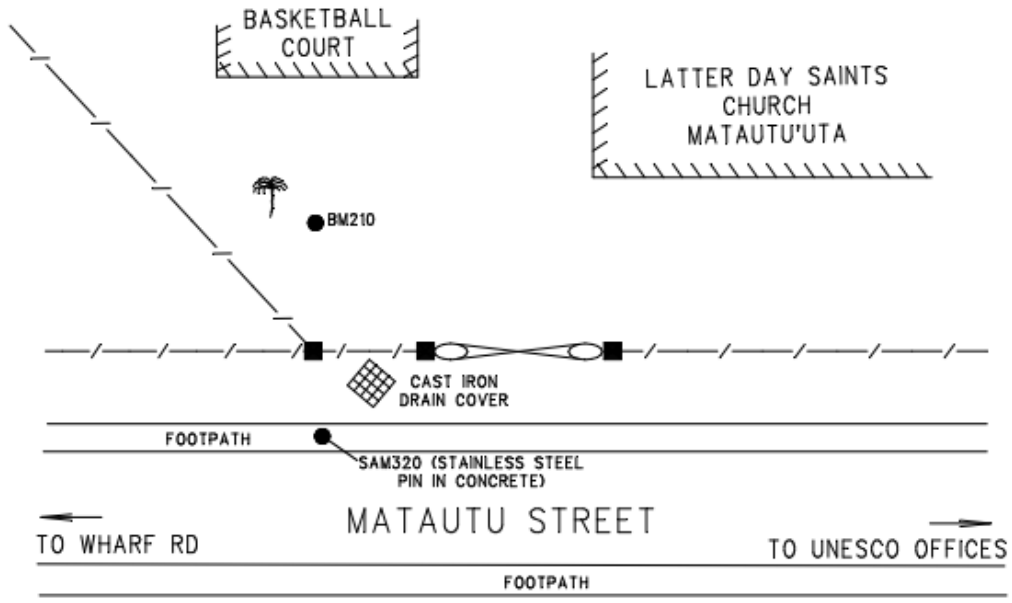
COUNTRY: Samoa	ISLAND: Upolu CITY: Apia	L. D. P. 745 POINT NO. 321
PROJECT: PSLGM	SURVEYOR: S Yates & A Lal	DATE: 14-10-06



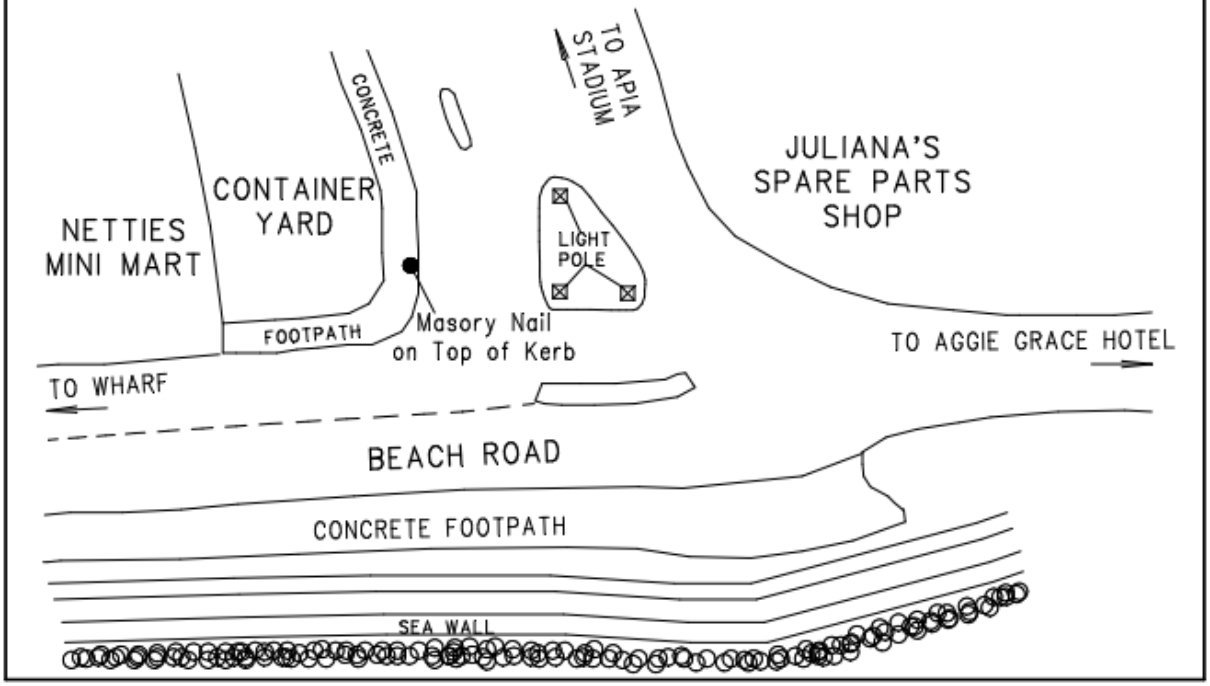
COUNTRY: Samoa	ISLAND: Upolu CITY: Apia	L. D. P. POINT NO. 311
PROJECT: PSLGM	SURVEYOR: N Brown & A Lal	DATE: 01-11-11



COUNTRY: Samoa	ISLAND: Upolu CITY: Apia	L. D. P. POINT NO. 320
PROJECT: PSLGM	SURVEYOR: N Brown & A Lal	DATE: 25-05-10



COUNTRY: Samoa	ISLAND: Upolu CITY: Apia	L. D. P. 741 POINT NO. 333
PROJECT: PSLGM	SURVEYOR: S Yates & A Lal	DATE: 14-10-06



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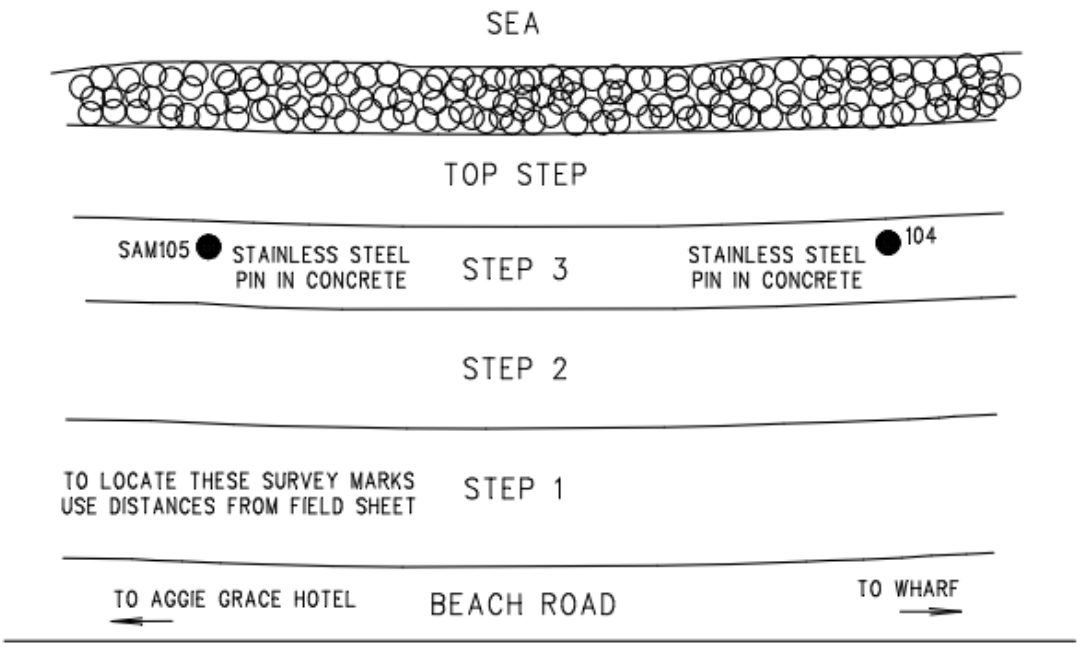
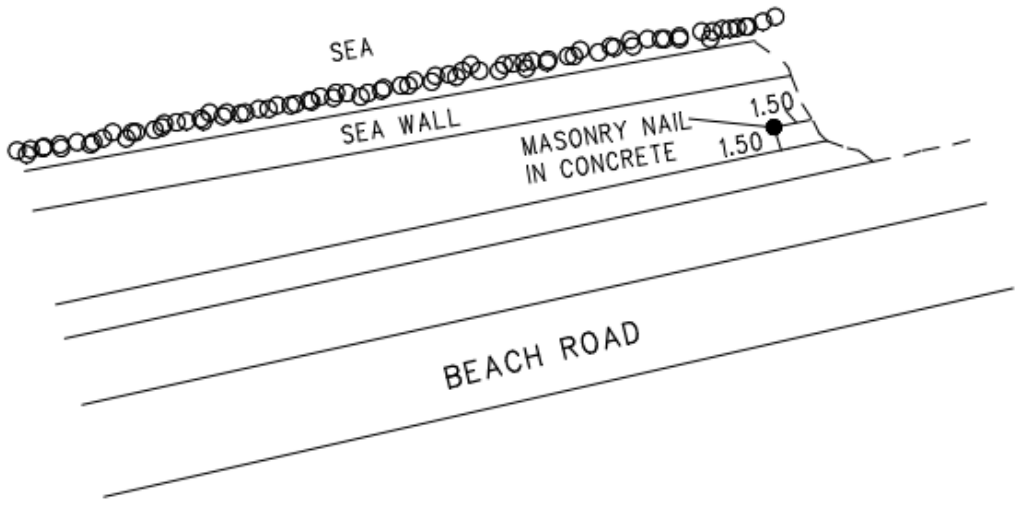
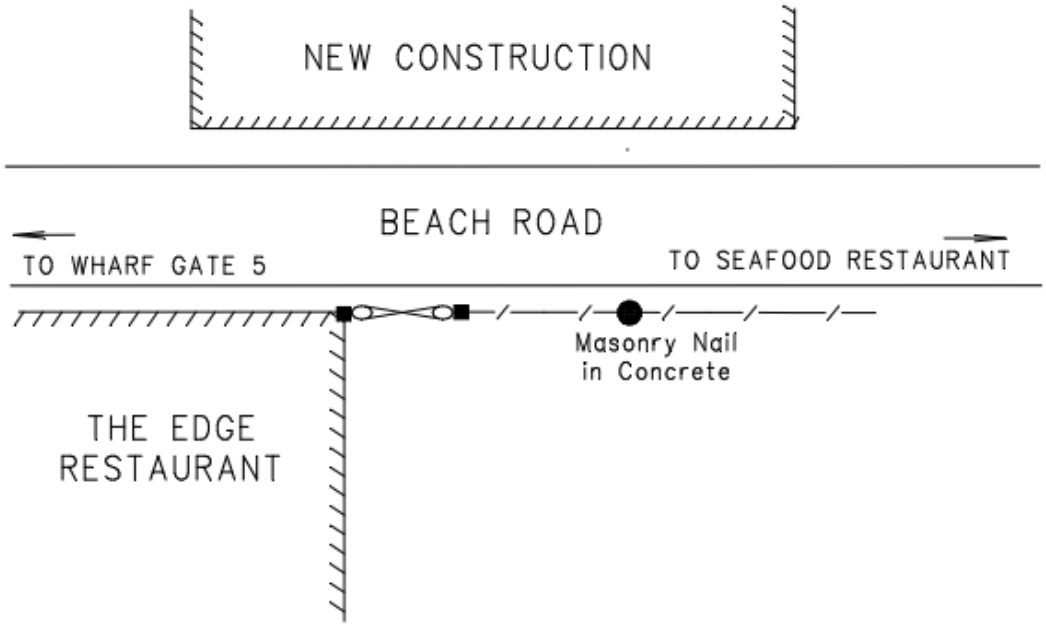
PROJECT:PSLGM	SURVEYOR: N Brown & A Lal	DATE: 25-05-10



COUNTRY: Samoa	ISLAND: Upolu CITY: Apia	L. D. P. 739 POINT NO. 180
PROJECT: PSLGM	SURVEYOR: S Yates & A Lal	DATE: 14-10-06



COUNTRY: Samoa	ISLAND: Upolu CITY: Apia	L. D. P. POINT NO. 331
PROJECT: PSLGM	SURVEYOR: N Brown & A Lal	DATE: 25-05-10



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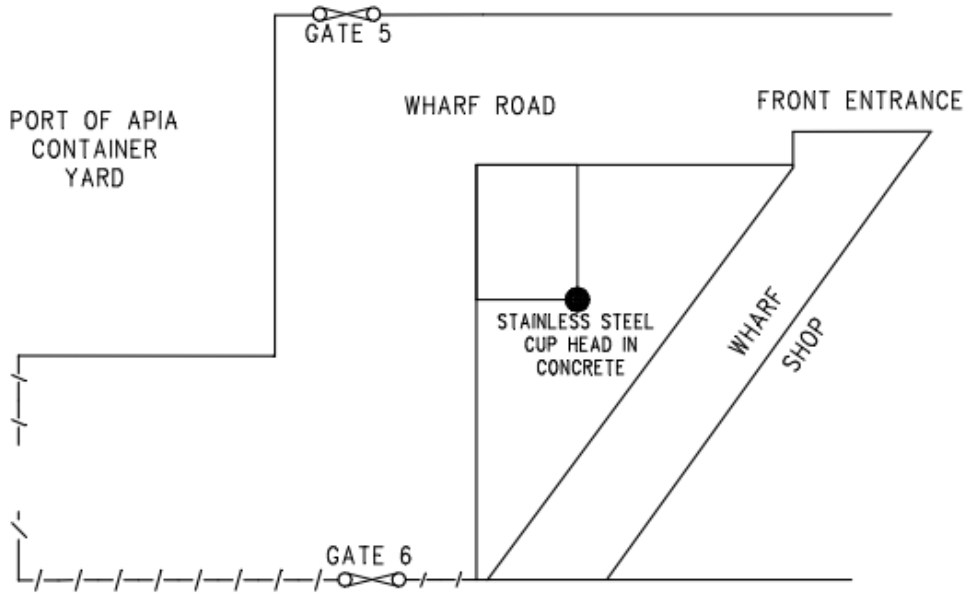

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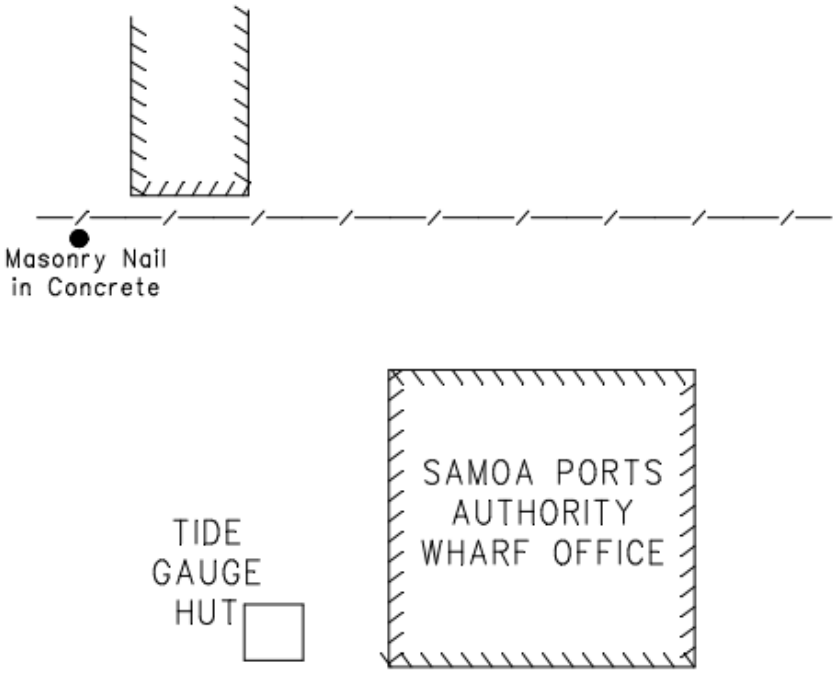
PROJECT: PSLGM	SURVEYOR: A.Lal, V.Rattan, M.Kalouniviti	DATE: 09-08-17



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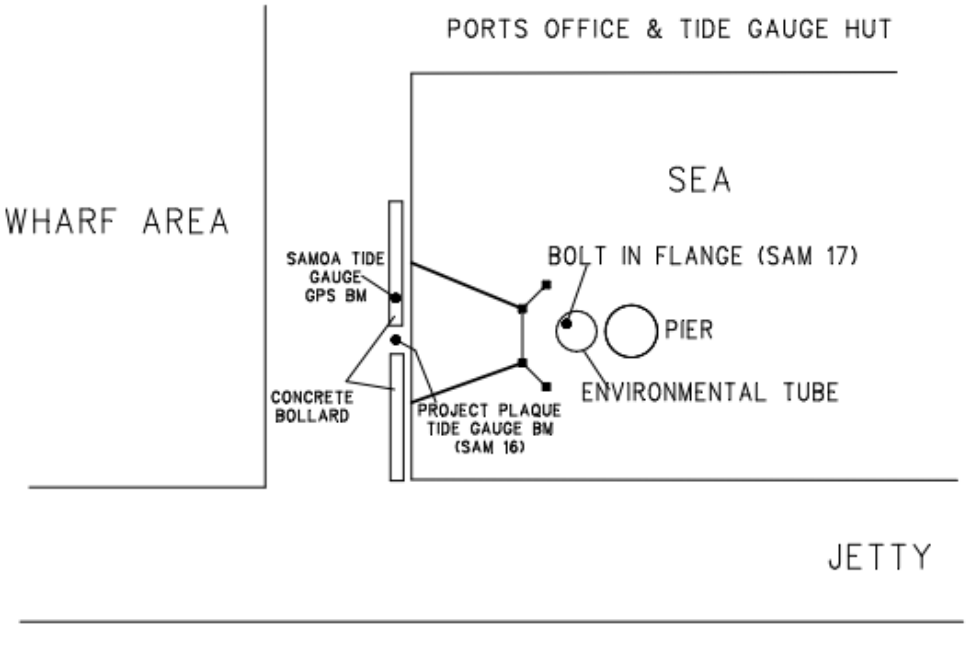
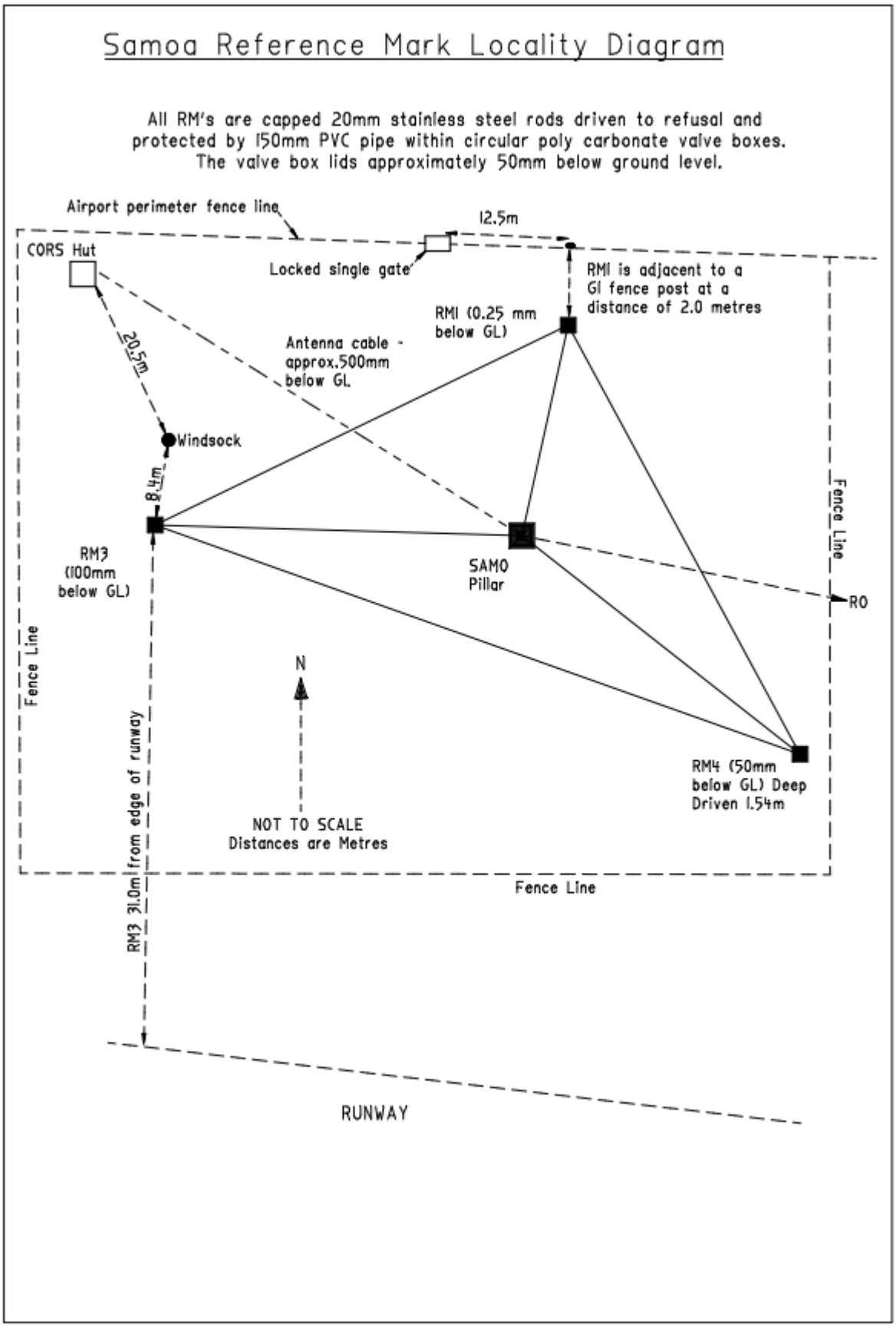


A3. GNSS Site Reference Marks



Appendix B Planning Aspects and Notes

Upon arranging travel to Samoa, 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 rapid clearance of the survey equipment from the Customs Authority when shipped across. Special thanks to the Director of Meteorological Services for the efficient clearance of the survey equipment from the customs bond. This survey equipment was sent for future field surveys for this project.

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

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)**	Fagali'i GNSS COR Station Hut
1	*Aluminium GST6 tripod with Feet*	
1	**PVC Pipe (1.7m)**	Fagali'i 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**	Fagali'i GNSS COR Station Hut
1	**Green Bag - Leica GST40 Rigid Tripod**	Fagali'i GNSS COR Station Hut
1	**Spade**	Fagali'i GNSS COR Station Hut
1	**Crowbar**	Fagali'i GNSS COR Station Hut

Appendix C Equipment Specifications

Tachymeters, Total Station, 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 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 1.00054m.

Tripods

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 TM30 on for the purpose of this levelling survey.

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

GNSS Equipment

Description

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

- Trimble NETR9 Serial Number:5038K70445, Firmware Vers:5.37
- Javad Choke Ring Antenna – JAVRINGANT_DM_NONE. Serial Numbe:958