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

Port Villa, Vanuatu, March 2019

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1 Motivation

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

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

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

2 Introduction

This report provides the results of the GNSS monitoring survey & high precision level survey completed between the Sea Level Fine Resolution Acoustic Measuring Equipment (SEAFRAME) tide gauge and the GNSS Continuously Operation Reference Station (CORS) in Port Vila, Vanuatu from 4th to 13th March 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 15 m from the GNSS monument.

Levelling Survey

The Total Station differential levelling technique is used to observe the difference in height between the Tide Gauge and GNSS monument. The levelling route includes a deep driven benchmark array in Port Villa, which runs approximately 2.5 km. Previous levelling surveys have been conducted along this route using the Total Station differential levelling technique in 2006, 2007, 2009, 2010, 2012, 2013, 2014, 2015, 2017 and 2018. This report contains an analysis of the 2019 Total Station differential levelling and GNSS monitoring results as well as a combined comparison of the previous levelling surveys.

Personnel

Personnel involved in the GNSS monitoring and levelling surveys were Andrick Lal and Marika Kalouniviti, from the Geodetic Survey at SPC. The GNSS time series analysis and derivation of the tide gauge ellipsoidal height 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 1.5kms Southwest of the Port Vila town centre. The levelling run goes from the Tide Gauge at the main cruise ship terminal, along Wharf Road and the Kumul Hwy, to the Vanuatu Meteorology Office where the GNSS CORS is located.

Local Project Contact:	Mr. Tony Kanas, Surveyor General
	Ministry of Lands and Natural Resources, Private Mail Bag 9007, George Pompidou Road, Port Vila.
Email	tonte_svy@yahoo.com
Phone	(678) 33120
GNSS Contact:	Bart Thomas – GNSS Networks Team, Geoscience Australia
Email:	Bart.Thomas@ga.gov.au
Phone:	+61 2 6249 9590
SEAFRAME Contact:	Jeff Aquilina – Bureau of Meteorology, Australia
Email:	J.Aquilina@bom.gov.au
Phone:	+61 8 8366 2621

2.2 Survey Support

The survey team appreciated the assistance from the Lands & Survey Division especially Mr. Tony Kanas and Mr Noel Naki who always avail themselves when assistance is required to access the GNSS site at Meteorological Office. Mr Tony Kanas always provided a staff member for assistance with survey duties across the week and provided access to office space when required. During the trip capacity building was important therefore Mr Tepi Jean Pascal a trainee survey technician was provided field training and assisted the team.

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
VAN2	Deep driven benchmark next to bus shelter along wharf road
VAN100	Deep driven benchmark within meteorology office compound
VAN16	SEAFRAME sensor benchmark
VAN14	Wall mounted benchmark on the corner of the Wharf Main Building Block
PTVL	Pin on GNSS COR Station base plate equipment mounted on concrete pillar
PTVLBM	Reference benchmark for the GNSS CORS pillar
RM4	GNSS CORS reference mark 4
RM2	GNSS CORS reference mark 2
RM3	GNSS CORS reference mark 3

Upon inspection, all the deep driven benchmarks were located, found in good order, and undisturbed. Included in the survey were the temporary holding marks; 202,154, 212, 204, 160, 210, 143, 211, 128, 207, and 208 (Fig 3.6). The temporary benchmark, 201, has been damaged, and therefore replaced with a new benchmark, 201A (masonry nail in concrete)

3.1.1 PSLGM Vertical Reference Frame Wiring Diagram

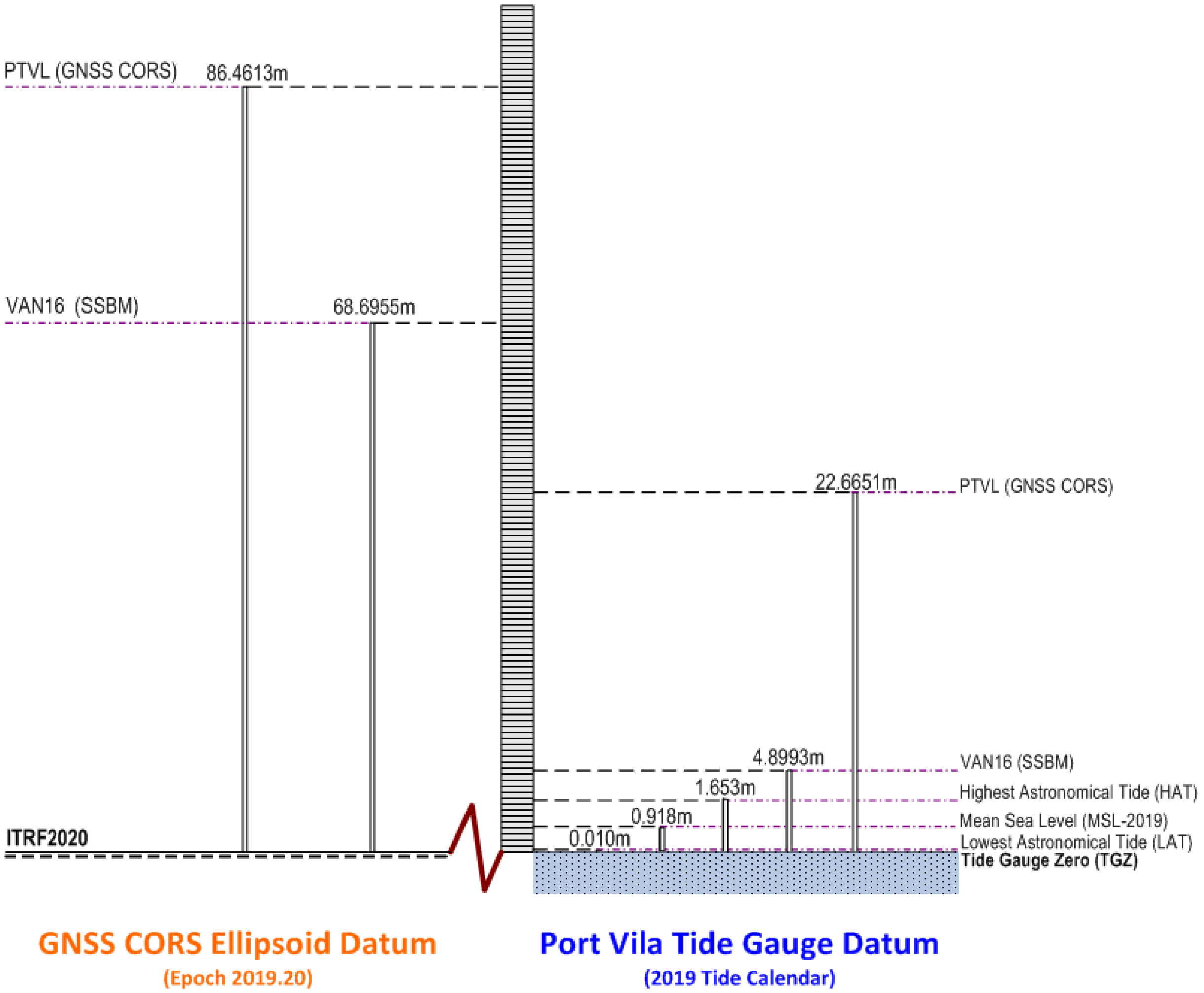


Figure 3.1 Wiring diagram depicting the offsets between surveyed marks. The left-hand side shows the height of the GNSS CORS pillar (PTVL), SEAFRAME sensor reference benchmark (VAN16) with respect to the International Terrestrial Reference Frame 2020 at epoch 2019.20. The right-hand side shows the height of PTVL, VAN16, 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)]

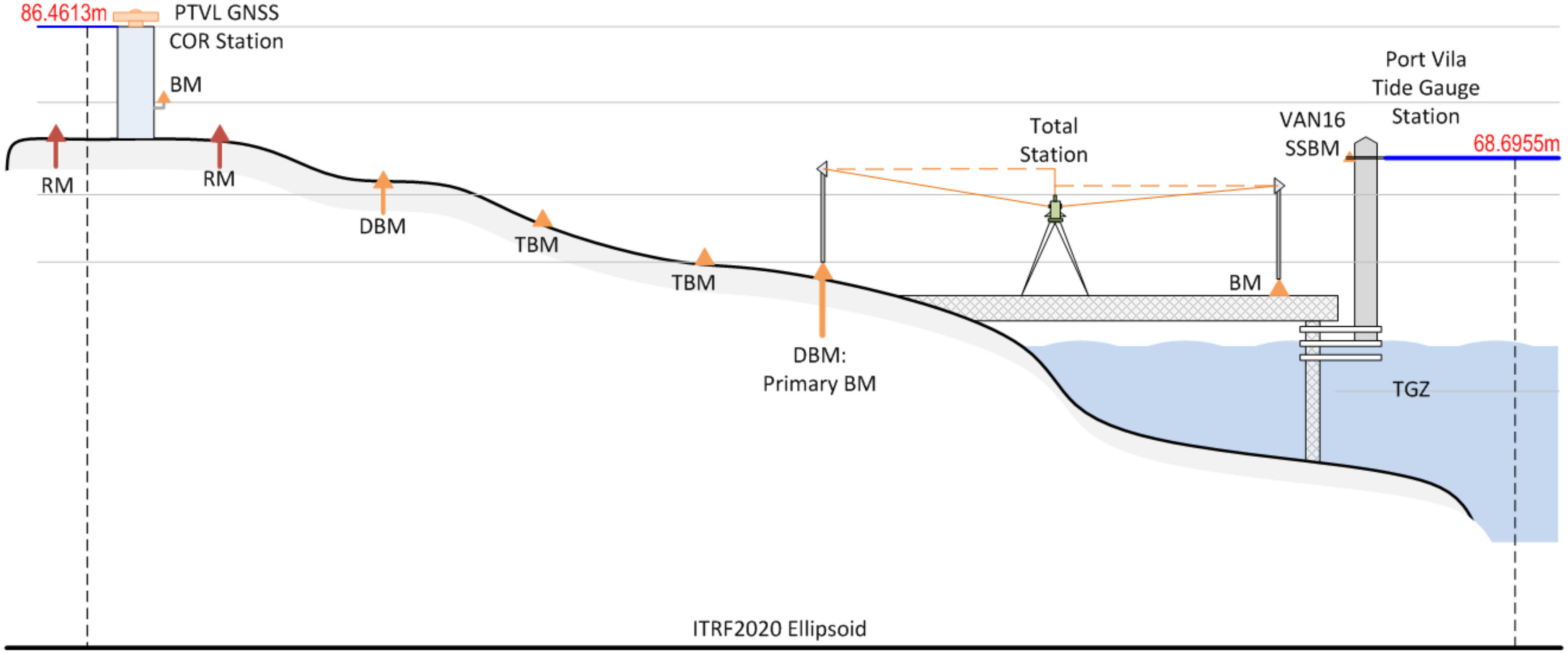


Figure 3.2 Simplified representation of the Total Station differential levelling survey carried out between the GNSS CORS and the SEAFRAME Tide Gauge.

Figure 3.3 Tide Gauge Station and the Radar tige gauge facility at the Port Vila Wharf

Figure 3.4 The red circle denotes the SEFRAME sensor benchmark location on the facility

Figure 3.5 GNSS CORS pillar. The red circle denotes the location of the GNSS CORS benchmark (PTVLBM). Image from 2019.

3.1.2 Levelling Benchmark Network

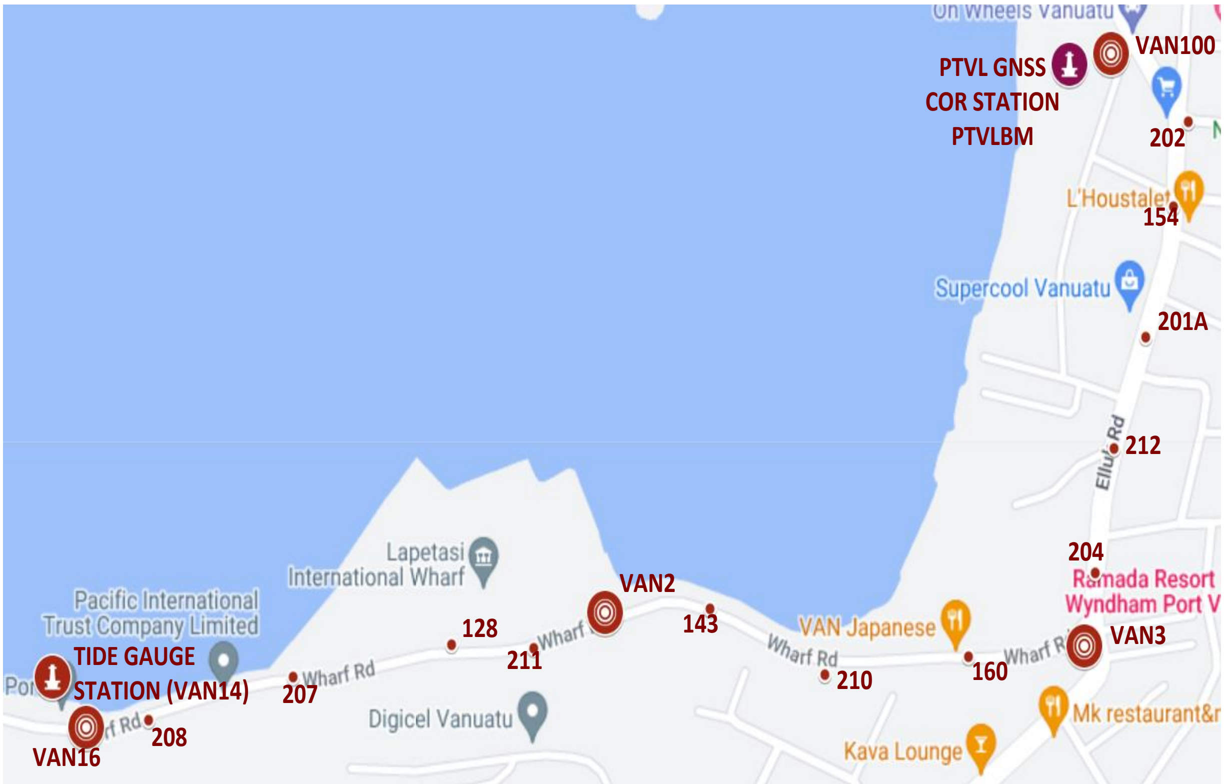


Figure 3.6 Levelling benchmark array. Source: Adopted from Google Maps.

3.1.3 GNSS CORS and Reference Marks

The GNSS CORS site is located within the Vanuatu Meteorological Office compound in Port Vila. 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 to the site is generally unrestricted during daylight hours, but the weather office should be notified, and access arranged before the survey is begun.

Three primary deep driven Reference Marks (RM) benchmarks were placed at the time of installation at a distance of 20m to 30m from the GNSS monument at approximately 120 degrees radial spacing from true north (Fig 3.7) 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.

Port Vila (PTVL) Continuous Operating Reference Station (CORS) & Reference Marks (RM1, RM2, RM3 & RM4)

The PTVL Station is a concrete pillar on a stainless steel plate with PTVLBM and the Reference Marks are capped 20mm stainless steel rods driven to refusal and protected by 150 mm PVC pipe within circular poly carbonate valve boxes. The valve box lids are approximately 50mm below ground level.

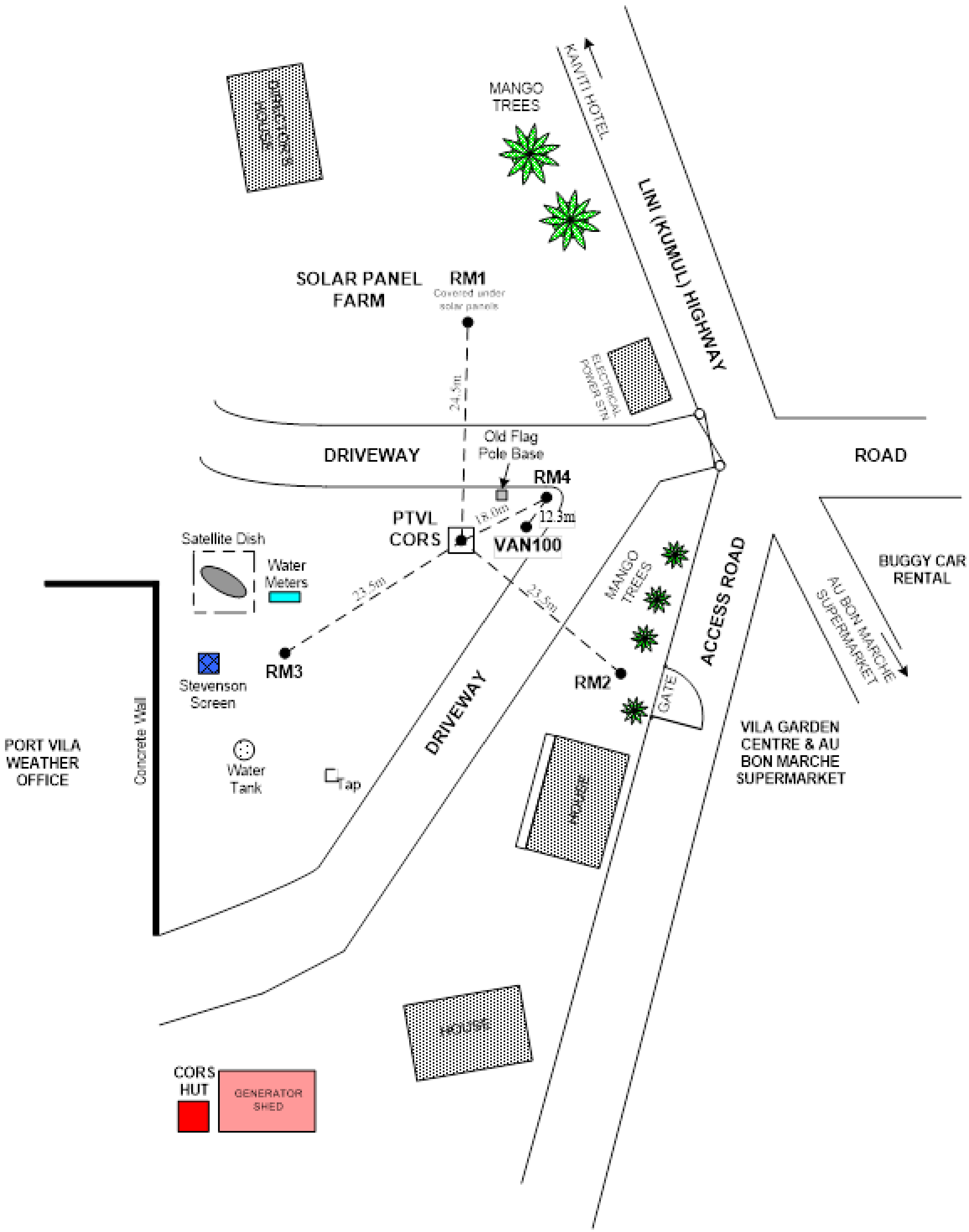


Figure 3.7 GNSS CORS site monitoring survey reference marks.

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 (PTVLBM) fixed at 0.0000m.

3.2.2 Historical Survey Datum

The datum for the survey is TGZ-ORSTOM and the adopted reference point for the levelling survey is VAN3 fixed at RL of 23.54630 m. This value was determined by the National Tidal Centre Australia (NTCA) in 1993 by adopting the height from the survey benchmark, BC1 (VAN14) with RL of 2.819m (MSL)

4 Monitoring Survey

4.1 Background

A local monitoring survey is undertaken routinely to monitor for any local horizontal or vertical movement of the GNSS pillar, relative to the RMs. The RMs are all located within 30 m of the GNSS pillar. We acknowledge that this monitoring does not account for any movement over the wider area – i.e., movements that might be consistent across all RM's.

4.1.1 Methodology

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

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

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

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

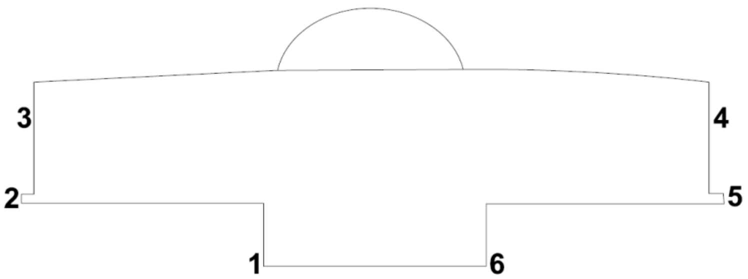


Figure 4.1. Symmetrical points on the antenna profile (TRM59800.00) observed from each RM

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

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

To avoid introducing any discontinuities into the GNSS time-series it is preferred, where possible, that the 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 was recorded. At each instrument set-up atmospheric conditions (temperature, pressure and relative humidity) were recorded. Atmospheric conditions were applied during the post-processing stage and not directly into the Total Station. Instrument and target heights were measured using an offset tape.

4.3 Data Analysis and Results

4.3.1 Levelling Survey

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

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

From	To	Rise	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
PTVLBM				0.0000		0.000
RM4	**RM4**	0.0000	-0.0059	-0.0059	0.018	0.018
RM2	**RM2**	0.0000	-0.9106	-0.9165	0.0235	0.0414
RM3	**RM3**	0.0000	-0.7250	-1.6415	0.039	0.080
RM2	**RM2**	0.7250	0.0000	-0.9165	0.039	
RM4	**RM4**	0.9106	0.0000	-0.0058	0.0235	
	PTVLBM	0.0058	0.0000	0.0000	0.018	
	Sum:	1.6414	-1.6415			
	Misclose:		0.0000	0.0000	0.160	(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)
PTVLBM				0.0000		0.000
RM3	**RM3**	0.0000	-1.6415	-1.6415	0.024	0.024
PTVLBM	**PTVLBM**	1.6415	0.0000	-0.0001	0.024	
	Sum:	1.6415	-1.6415			
	Misclose:		-0.0001	-0.0001	0.047	(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)
PTVLBM				0.0000		0.000
RM2	**RM2**	0.0000	-0.9165	-0.9165	0.023	0.023
	PTVLBM	0.9165	0.0000	0.0000	0.023	
	Sum:	0.9165	-0.9165			
	Misclose:		0.0000	0.0000	0.046	(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 (PTVL) was tightly constrained to its ITRF2014 coordinates and aligned to PTVL-RM3 with an azimuth of 248° 21' 07.00", which had been determined in the 2017 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 ITRF2014@2010.0 latitude and longitude coordinates adopted at PTVL 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@2019.20 ellipsoidal height were adopted at PTVL. CCC means all 3 dimensions (in XYZ) are constrained and FFF means they were all free,

Station	Constraint	Latitude	Longitude	Ellipsoidal Heights(m)
PTVL	**CCC**	-17° 44' 57.95814"	168° 18' 54.09350"	86.4613
RM2	**FFF**	-17° 44' 58.54828"	168° 18' 54.59641"	84.5766
RM3	**FFF**	-17° 44' 58.24067"	168° 18' 53.35061"	83.8520
RM4	**FFF**	-17° 44' 57.78881"	168° 18' 54.64689"	85.4872

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@2019.20 ellipsoidal height were adopted at PTVL.

Description	X	Y	Z	SD(e)	SD(n)	SD(up)
PTVL	-5950573.3050	1230677.0982	-1932016.9868	0.0000	0.0000	0.0000
RM2	-5950569.1313	1230661.1059	-1932033.6921	0.0004	0.0004	0.0002
RM3	-5950563.8457	1230697.4903	-1932024.4641	0.0004	0.0002	0.0002
RM4	-5950577.2525	1230661.2669	-1932011.7316	0.0004	0.0003	0.0002

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

FROM	To	ΔE	ΔN	ΔU
PTVL	**RM2**	14.8156	-18.1435	-1.8847
PTVL	**RM3**	-21.8853	-8.6862	-2.6094
PTVL	**RM4**	16.3027	5.2060	-0.9741

[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 ∆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
2012	**PTVL**	**RM2**	14.8161	-18.1432	-1.8849
2014	**PTVL**	**RM2**	14.8164	-18.1424	-1.8851
2019	**PTVL**	**RM2**	14.8156	-18.1435	-1.8847
Ref RL	**(as at 2014)**		**14.8163**	**-18.1428**	**-1.8850**

Year	From	To	ΔE	ΔN	ΔU
2012	**PTVL**	**RM3**	-21.8862	-8.6866	-2.6096
2014	**PTVL**	**RM3**	-21.8858	-8.6864	-2.6093
2019	**PTVL**	**RM3**	-21.8853	-8.6862	-2.6094
Ref RL	**(as at 2014)**		**-21.8857**	**-8.6873**	**-2.6095**

Year	From	To	ΔE	ΔN	ΔU
2019	**PTVL**	**RM4**	16.3027	5.2060	-0.9741
Ref RL	**(as at 2019)**		**16.3024**	**5.2071**	**-0.9741**

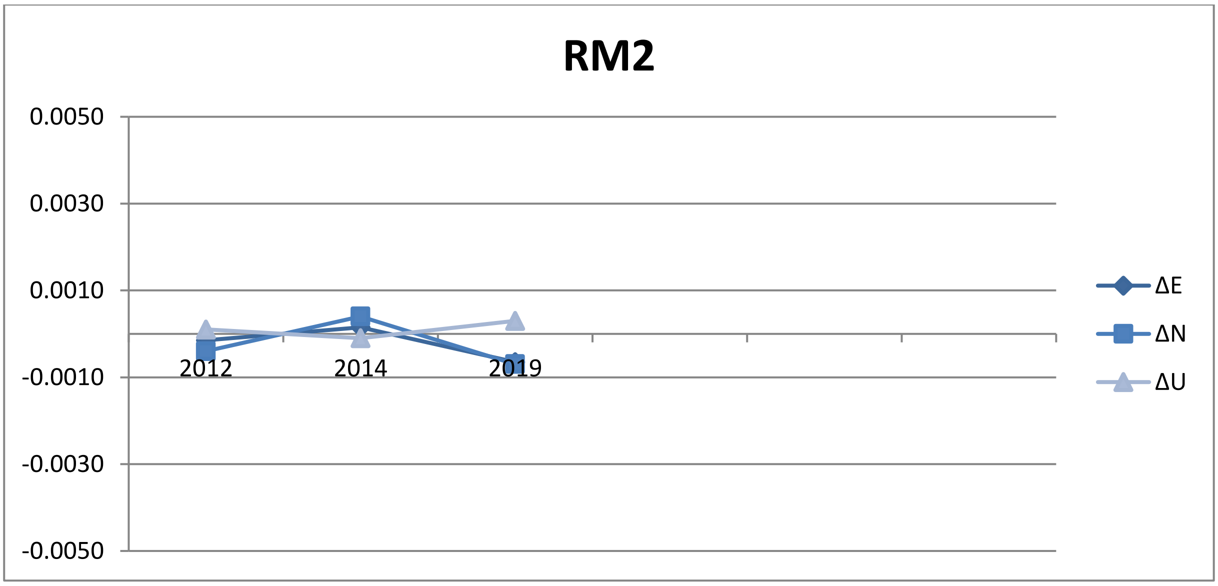


Figure 4.4.2 Time series of RM3 movement relative to GNSS (0 = REF pre 2014 mean)

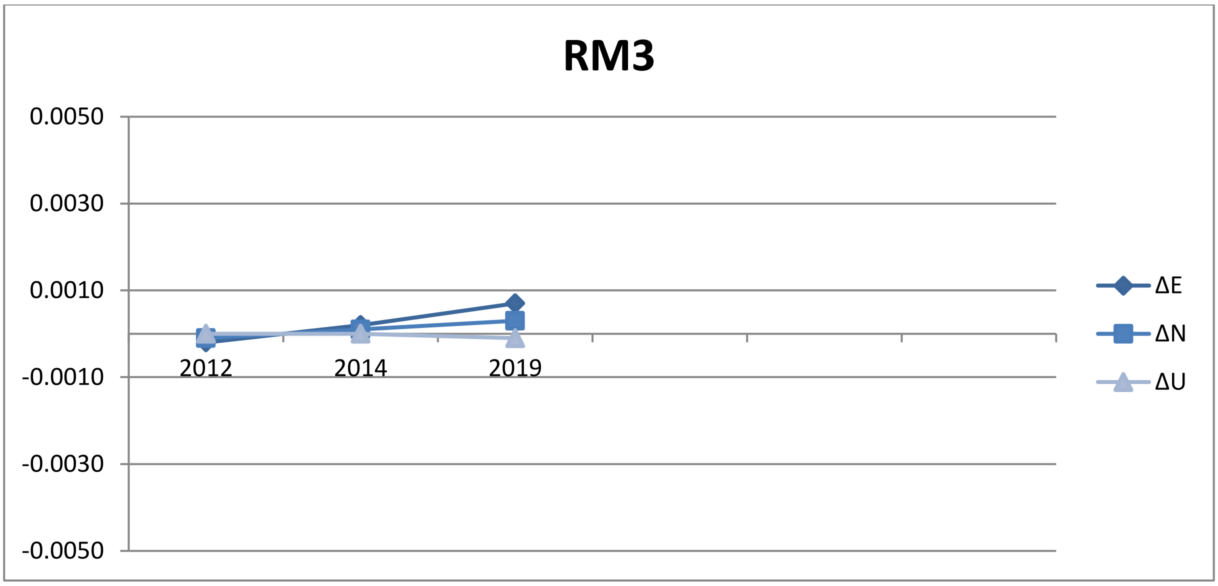


Figure 4.4.3 Time series of RM3 movement relative to GNSS (0 = REF pre 2014 mean)

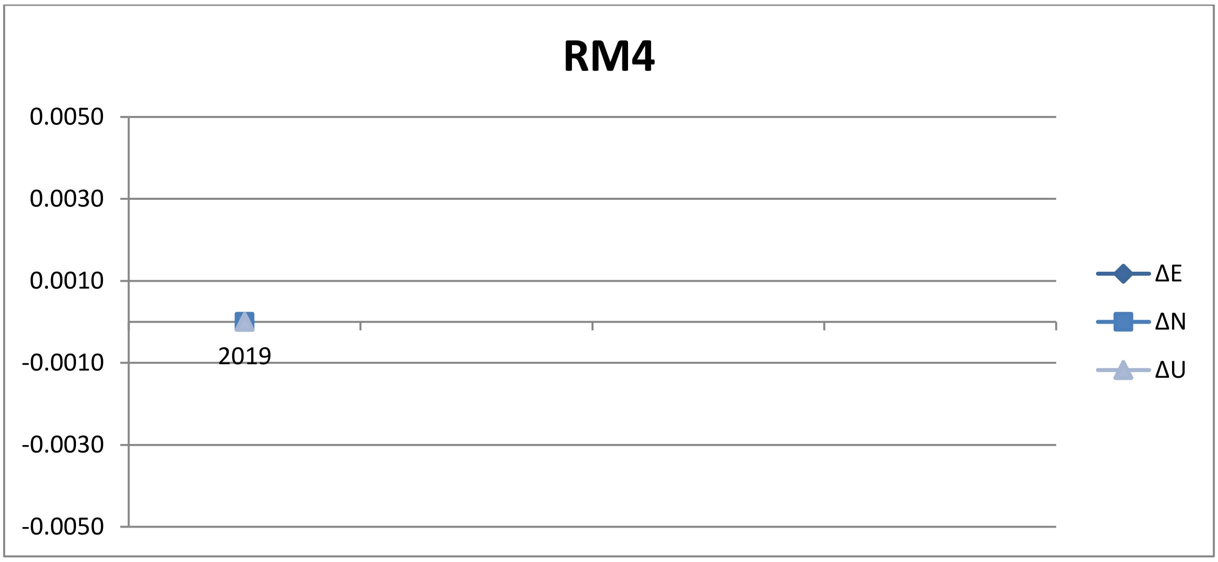


Figure 4.4.4 Time series of RM4 movement relative to GNSS (0 = REF pre 2019 mean)

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

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

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

In support of the slope distance observations, the ambient temperature, pressure and humidity are recorded (Kestral 4000 pocket weather tracker) and input into the instrument to apply the first velocity correction to the observed distances (Rüeger & Brunner, 1982). Five rounds of observations are taken to the backsight and foresight targets from each instrument setup. The instrument measures slope distances (±1mm) and vertical angle (1”) to derive height differences.

Table 5.2.2 contains the values of the constants or calibrated heights used throughout the analysis

Table 5.2.2. Calibrations and constants

Name	Value (m)	Description
PTVL (Ellipsoidal ht)	86.4613	Observed RL at the ARP of PTVL (Ellipsoidal) @ 2019.20
PTVL - PTVLBM	-0.9681	Offset constant between BM at GNSS pillar plate
Primary Pole & 1/2m Pole	1.00043	Height difference between poles used (Calibrated February 2019)
Primary Pole & TG Pole	1.42958	Height difference between poles used (Calibrated February 2019)

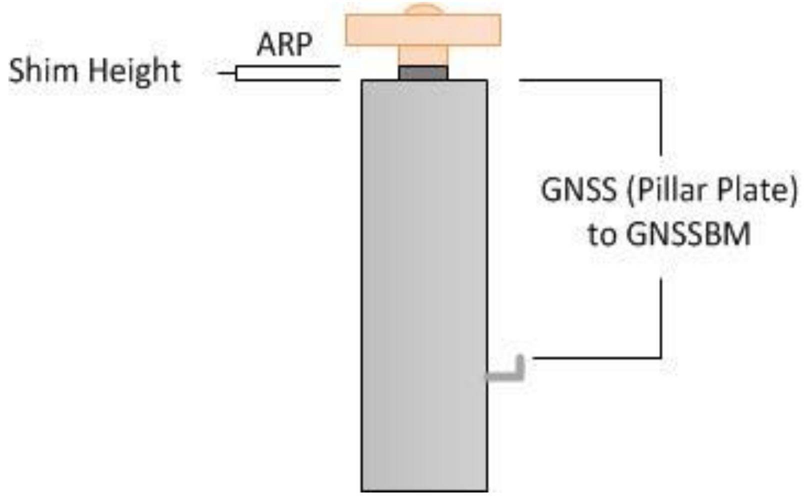


Figure 5.2.1 GNSS Pillar Offsets

5.3 Data Analysis and Results

Reduction of the digital data was computed using the Geoscience Australia levelling program “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 PTVLBM (GNSSBM)

Table 5.3.1 Reduced level data – PTVL (GNSS CORS) to VAN2 (Deep Driven Benchmark)

From	To	Rise(m)	Fall(m)	RL(m)	Dist (km)	Acc Dist (km)
PTVL				0.9681		
PTVLBM	**PTVLBM**	0.0000	-0.9681	0.000	0.000	0.000
VAN100	**VAN100**	0.0000	-0.5622	-0.5622	0.031	0.031
202	**202**	2.9442	0.0000	2.3820	0.120	0.152
154	**154**	0.0000	-4.0617	-1.6797	0.195	0.347
201A	**201A**	0.0000	-3.6665	-5.3462	0.170	0.517
132	**132**	0.5866	0.0000	-4.7596	0.151	0.668
204	**204**	5.5071	0.0000	0.7474	0.158	0.826
VAN3	**VAN3**	1.0251	0.0000	1.7726	0.098	0.924
160	**160**	0.0000	-4.5595	-2.7870	0.183	1.107
210	**210**	0.0000	-7.4394	-10.2264	0.209	1.316
143	**143**	1.5034	0.0000	-8.7231	0.162	1.478
VAN2	**VAN2**	0.0000	-3.0447	-11.7677	0.246	1.724
143	**143**	3.0444	0.0000	-8.7233	0.246	
210	**210**	0.0000	-1.5032	-10.2265	0.162	
160	**160**	7.4396	0.0000	-2.7869	0.209	
VAN3	**VAN3**	4.5599	0.0000	1.7730	0.184	
204	**204**	0.0000	-1.0252	0.7478	0.098	
132	**132**	0.0000	-5.5069	-4.7591	0.162	
201A	**201A**	0.0000	-0.5869	-5.3460	0.151	
154	**154**	3.6666	0.0000	-1.6794	0.170	
202	**202**	4.0614	0.0000	2.3819	0.195	
VAN100	**VAN100**	0.0000	-2.9444	-0.5624	0.120	
PTVLBM	**PTVLBM**	0.5621	0.0000	-0.0003	0.032	
PTVL	**PTVL**	0.9681	0.0000	0.9678	0.000	
	Sum:	35.8683	-35.8686			
	Misclose:		-0.0003	-0.0003	3.454	(Total Dist)
			ALLOWABLE (m):	**0.0026**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.2 Reduced level data – VAN2 to VAN16 (SEAFRAME sensor reference benchmark).

From	To	Rise(m)	Fall(m)	RL(m)	Dist (km)	Acc Dist (km)
VAN2				-11.7677		1.724
211	**211**	0.0000	-2.0111	-13.7788	0.107	1.831
128	**128**	0.0000	-3.5406	-17.3194	0.162	1.993
207	**207**	0.0000	-0.7723	-18.0918	0.226	2.219
208	**208**	0.0000	-0.6966	-18.7884	0.210	2.429
VAN16	**VAN16**	1.9907	0.0000	-16.7977	0.086	2.514
208	**208**	0.0000	-1.9908	-18.7885	0.086	
207	**207**	0.6967	0.0000	-18.0919	0.210	
128	**128**	0.7720	0.0000	-17.3199	0.226	
211	**211**	3.5405	0.0000	-13.7793	0.162	
	VAN2	2.0112	0.0000	-11.7681	0.107	
	Sum:	9.0110	-9.0114			
	Misclose:		-0.0004	-0.0004	1.580	(Total Dist)
			ALLOWABLE (m):	**0.0018**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.3 Reduced level data – VAN16 to VAN14 (Tide Gauge Benchmark)

From	To	Rise(m)	Fall(m)	RL(m)	Dist (km)	Acc Dist (km)
VAN16				-16.7977		2.514
VAN14	**VAN14**	0.0000	-1.4073	-18.2050	0.032	2.546
	VAN16	1.4072	0.0000	-16.7978	0.032	0.000
	Sum:	1.4072	-1.4073			
	Misclose:		-0.0001	-0.0001	0.064	(Total Dist)
			ALLOWABLE (m):	**0.0004**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.4 Reduced level data – VAN16 – Radar Tide Gauge Reference Point

From	To	Rise(m)	Fall(m)	RL(m)	Dist (km)	Acc Dist (km)
VAN16				-16.7977		2.514
RTGP	**RTGP**	0.0787	0.0000	-16.7190	0.012	2.527
	VAN16	0.0000	-0.0788	-16.7978	0.012	0.000
	Sum:	0.0787	-0.0788			
	Misclose:		-0.0001	-0.0001	0.024	(Total Dist)
			ALLOWABLE (m):	**0.0002**	**2 x Sqrt (km) test:**	**PASS**

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

	PTVLBM	VAN100	VAN3	VAN2	VAN14	VAN16	RM2	RM3	PTVL	RM4
PTVLBM	-	-0.5623	1.7728	-11.7677	-18.2050	-16.7977	-0.9165	-1.6415	0.9681	-0.0059
VAN100	0.5623	-	2.3351	-11.2054	-17.6427	-16.2354	-0.3542	-1.0792	1.5304	0.5564
VAN3	-1.7728	-2.3351	-	-13.5405	-19.9778	-18.5705	-2.6893	-3.4142	-0.8047	-1.7787
VAN2	11.7677	11.2054	13.5405	-	-6.4373	-5.0300	10.8513	10.1263	12.7358	11.7619
VAN14	18.2050	17.6427	19.9778	6.4373	-	1.4073	17.2885	16.5635	19.1731	18.1991
VAN16	16.7977	16.2354	18.5705	5.0300	-1.4073	-	15.8812	15.1563	17.7658	16.7919
RM2	0.9165	0.3542	2.6893	-10.8513	-17.2885	-15.8812	-	-0.7250	1.8846	0.9106
RM3	1.6415	1.0792	3.4142	-10.1263	-16.5635	-15.1563	0.7250	-	2.6095	1.6356
PTVL	-0.9681	-1.5304	0.8047	-12.7358	-19.1731	-17.7658	-1.8846	-2.6095	-	-0.9740
RM4	0.0059	-0.5564	1.7787	-11.7619	-18.1991	-16.7919	-0.9106	-1.6356	0.9740	-

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

YEAR	PTVLBM	VAN100	VAN3	VAN2	VAN14	VAN16	RM2	RM3	PTVL	RM4
1993.0	0.000		1.7723							
1994.0	0.000		1.7723							
1995.2	0.000		1.7723							
1997.1	0.000		1.7723							
1998.2	0.000		1.7723							
1999.6	0.000	-0.5604	1.7723							
2001.2	0.000	-0.5610	1.7723							
2002.7	0.000	-0.5607	1.7723	-11.7657	-18.2103	-16.7993				
2004.4	0.000	-0.5613	1.7723	-11.7653	-18.2098	-16.7980				
2006.7	0.000	-0.5596	1.7723	-11.7658	-18.2105	-16.8012				
2006.7	0.000	-0.5610	1.7723	-11.7652	-18.2112	-16.8027				
2008.3	0.000	-0.5611	1.7723	-11.7658	-18.2118	-16.7996				
2009.9	0.000	-0.5608	1.7723	-11.7654	-18.2104	-16.7998				
2011.2	0.000	-0.5620	1.7723	-11.7655	-18.2091	-16.7971				
2012.8	0.000	-0.5620	1.7723	-11.7653	-18.2074	-16.7990			0.9681	
2014.4	0.000	-0.5620	1.7734	-11.7626	-18.2056	-16.7984				
2015.9	0.000	-0.5622	1.7716	-11.7646	-18.2068	-16.8054	-0.9162	-1.6416	0.9681	-0.0058
2017.2	0.000	-0.5619	1.7719	-11.7691	-18.2062	-16.7925	-0.9162	-1.6411	0.9681	-0.0058
2019.2	0.000	-0.5623	1.7728	-11.7677	-18.2050	-16.7977	-0.9165	-1.6415	0.9681	-0.0059

5.4 Comparison with previous surveys

All historic data has been readjusted relative to the benchmark attached to the base of the GNSS pillar (PTVLBM) (Table 5.3.6). To investigate whether BMs have moved over time, the RLs from the 2019 survey (RL_{2019}) have been compared to a reference height (RH) defined as the average of all previously calculated RLs. In cases where a site has undergone known movement (e.g., BM removed and reinstalled), the RH is the latest measured RL

5.4.1 Difference in Reference Height values

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

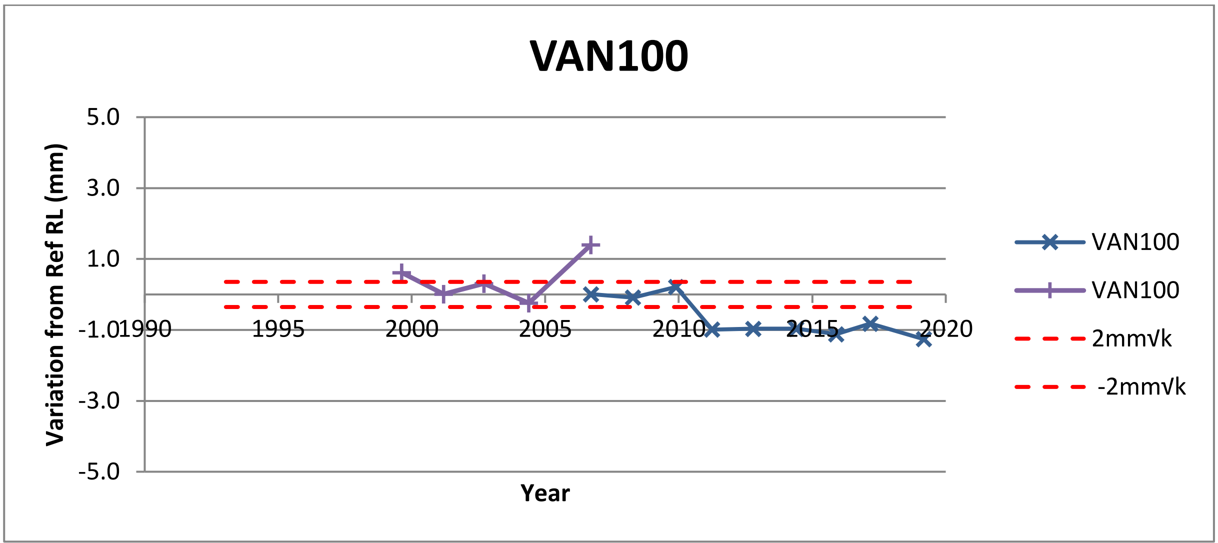
REF - 2019	PTVLBM	VAN100	VAN3	VAN2	VAN14	VAN16	RM2	RM3	PTVL	RM4
PTVLBM	-	0.0013	-0.0005	0.0023	-0.0055	-0.0013	0.0002	0.0001	0.0000	0.0000
VAN100	-0.0013	-	-0.0018	0.0010	-0.0067	-0.0026	-0.0010	-0.0012	-0.0013	-0.0012
VAN3	0.0005	0.0018	-	0.0028	-0.0050	-0.0008	0.0008	0.0006	0.0005	0.0005
VAN2	-0.0023	-0.0010	-0.0028	-	-0.0078	-0.0036	-0.0021	-0.0022	-0.0023	-0.0023
VAN14	0.0055	0.0067	0.0050	0.0078	-	0.0042	0.0057	0.0056	0.0055	0.0055
VAN16	0.0013	0.0026	0.0008	0.0036	-0.0042	-	0.0016	0.0014	0.0013	0.0013
RM2	-0.0002	0.0010	-0.0008	0.0021	-0.0057	-0.0016	-	-0.0001	-0.0002	-0.0002
RM3	-0.0001	0.0012	-0.0006	0.0022	-0.0056	-0.0014	0.0001	-	-0.0001	-0.0001
PTVL	0.0000	0.0013	-0.0005	0.0023	-0.0055	-0.0013	0.0002	0.0001	-	0.0000
RM4	0.0000	0.0012	-0.0005	0.0023	-0.0055	-0.0013	0.0002	0.0001	0.0000	-

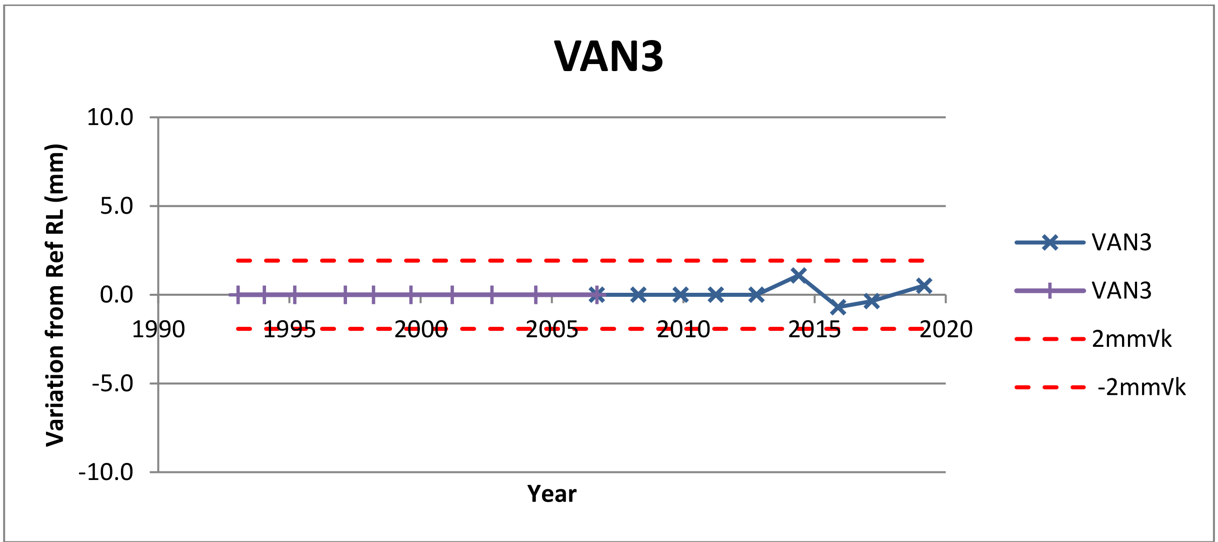
Table 5.4.1.1 values are calculated by subtracting the difference in height between RL_{2019} values (Table 5.3.5) from the difference in height between RL_{REF} values.

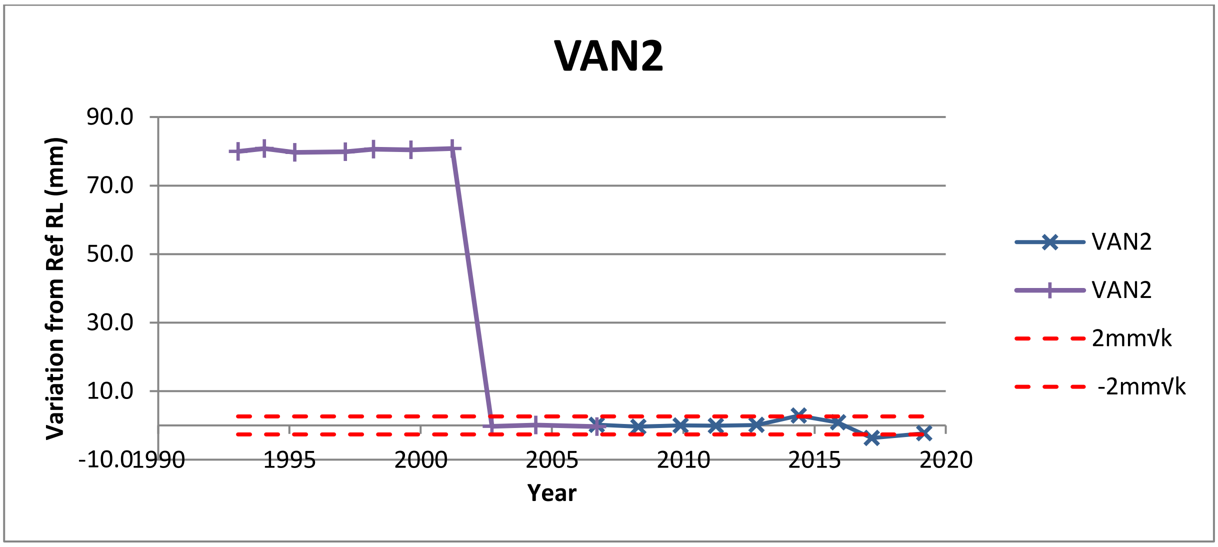
Comparing the change in relative heights between all benchmarks can help identify movement of a particular BM, inconsistency in survey, or even deformation between the GNSS pillar and levelling run BMs

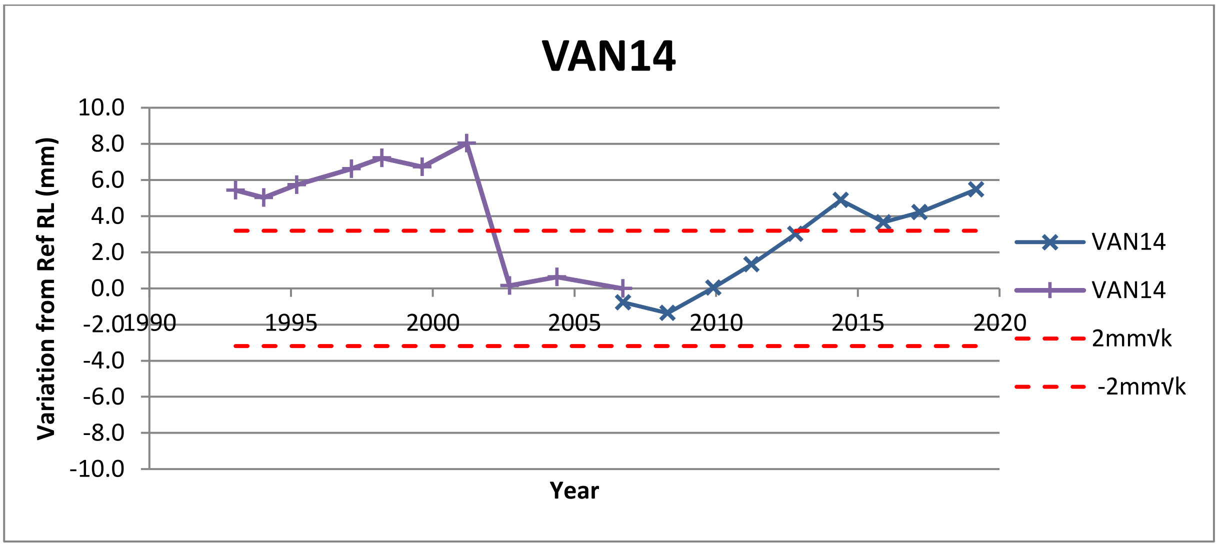
5.4.2 Time Series Charts for each BM

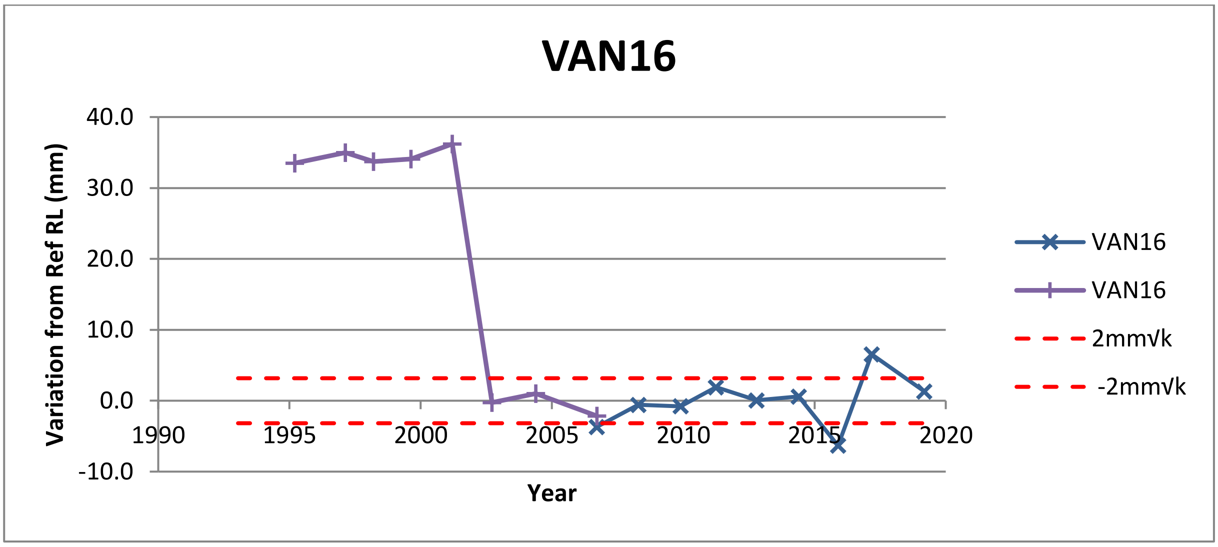
The change in RL over time can be used to detect trends of movement or survey errors. In the series of figures below, the red dashed lines represent the allowable error in height based on the levelling technique used and distance of the benchmark from the GNSS pillar ($2mm\sqrt{K}$). The purple line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






VAN2
90.0
70.0
50.0
30.0
10.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Variation from Ref RL (mm)
Year
VAN2
VAN2
2mm√k
-2mm√k


VAN14
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Variation from Ref RL (mm)
Year
VAN14
VAN14
2mm√k
-2mm√k


VAN16
40.0
30.0
20.0
10.0
0.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Variation from Ref RL (mm)
Year
VAN16
VAN16
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:

- VAN16, which is likely due to:
    - localised movement on the wharf, that is located at the tide gauge station as the sensor benchmark, where there are heavy movements.
    - the combined impact is a relative height difference of 0.0036 m with VAN2.
- VAN14, which is likely due to:
    - localised movement on the wharf, that is located on the side of the building at the wharf where there are heavy movements and may be from the effects of the building movements.
    - the combined impact is a relative height difference of 0.0067 m with VAN100.

The survey from the primary GNSS BM (PTVLBM) to the TG Plaque (VAN14) shows significant change. There is a high chance of deformation to the wharf structure when looking at the two past surveys of this benchmark.

The survey from the primary GNSS BM (PTVLBM) to the TG Sensor Benchmark (VAN16) show that the tide gauge is stable, and no deformation has occurred since the previous survey.

The tide gauge facility is experiencing local movements mainly due to the wharf structure's reaction to berthing ships and heavy movements of trucks.

Table 6.1 Comparison of results with Reference ^H.

PT ID	Reference ^H (m)	2019.18 Value (m)	Difference
PTVLBM - Primary BM (VAN2)	-11.7654	-11.7677	0.0023
VAN2 - TG Plaque BM (VAN14)	-6.4450	-6.4373	-0.0078
VAN2 - TG ref pin (VAN16)	-5.0336	-5.0300	-0.0036
PTVLBM - VAN3	1.7723	1.7728	0.0005
VAN3 - VAN14	-19.9827	-19.9778	-0.0050
VAN14 - VAN16	1.4114	1.4073	-0.0042

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

PT ID	Reference RL (m)	2019.18 Value (m)	Difference	TGZ	ITRF2020
PTVLBM	0.000	0.000	0.0000	21.6970	85.4932
VAN100	-0.5610	-0.5623	-0.0013	21.1347	84.9309
VAN3	1.7723	1.7728	0.0005	23.4698	87.2660
VAN2	-11.7654	-11.7677	-0.0023	9.9293	73.7255
VAN14	-18.2105	-18.2050	0.0055	3.4920	67.2882
VAN16	-16.7990	-16.7977	0.0013	4.8993	68.6955
RM4	-0.0058	-0.0059	0.0000	21.6912	85.4873
RM2	-0.9162	-0.9165	-0.0002	20.7805	84.5767
RM3	-1.6413	-1.6415	-0.0001	20.0556	83.8518
PTVL	0.9681	0.9681	0.0000	22.6651	86.4613
TGZ	-21.6983	-21.6970	0.0013	0.0000	63.7962

7 Absolute height of the tide gauge

When combined, the GNSS and levelling data provide information about the absolute movement of the tide gauge. This information can be used by Bureau to translate relative sea level into absolute sea level.

7.1 GNSS time series analysis

The ellipsoidal height of the GNSS pillar is computed using Geoscience Australia's weekly cumulative GNSS solution and modelled using Chebyshev polynomials[2] (Figure 7.1). Uncertainty regions (95% confidence) were determined using the residuals with respect to the polynomial model. Large outliers (>50cm) were removed manually as they have a significant impact on the estimated uncertainties. The ellipsoidal heights are with respect to the International Terrestrial Reference Frame 2020 (ITRF2020).

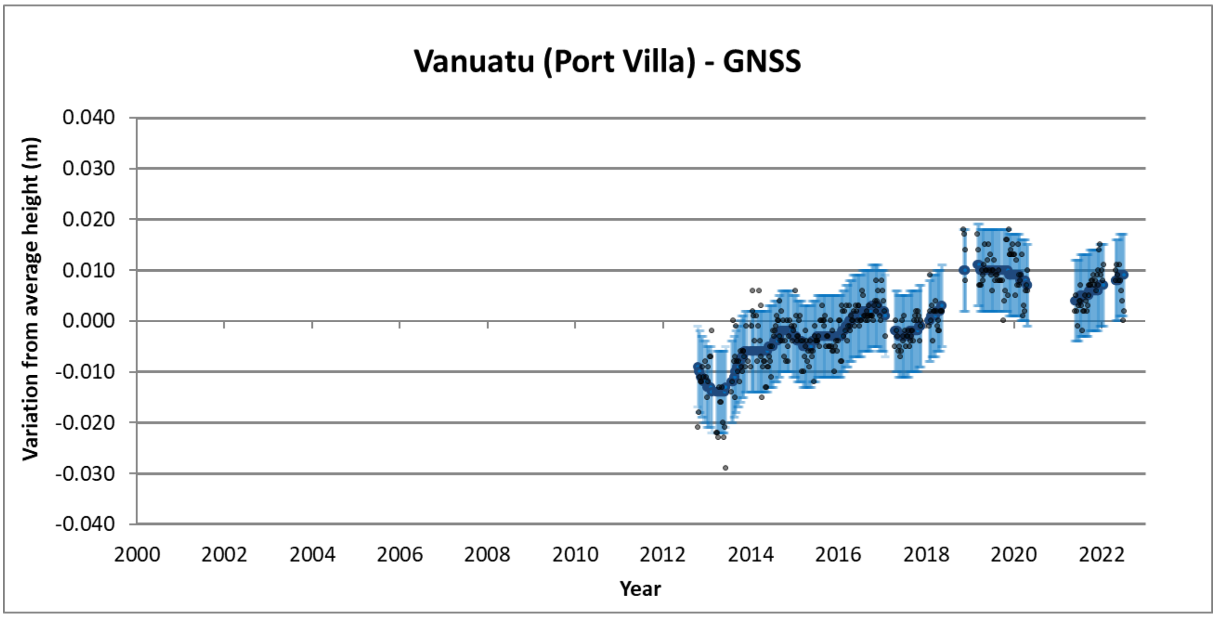


Figure 7.1 Time series of GNSS analysis (dark blue line) with 95%CI uncertainty (light blue lines).

[2] The order of the polynomial was determined iteratively by evaluating the significance of the improvement in model misfit Chi-Squared by an F test. The number of terms used in the preferred models ranged from 2 (i.e. linear) to 10 across the analysed time series and depends on the complexity of the observed signal.

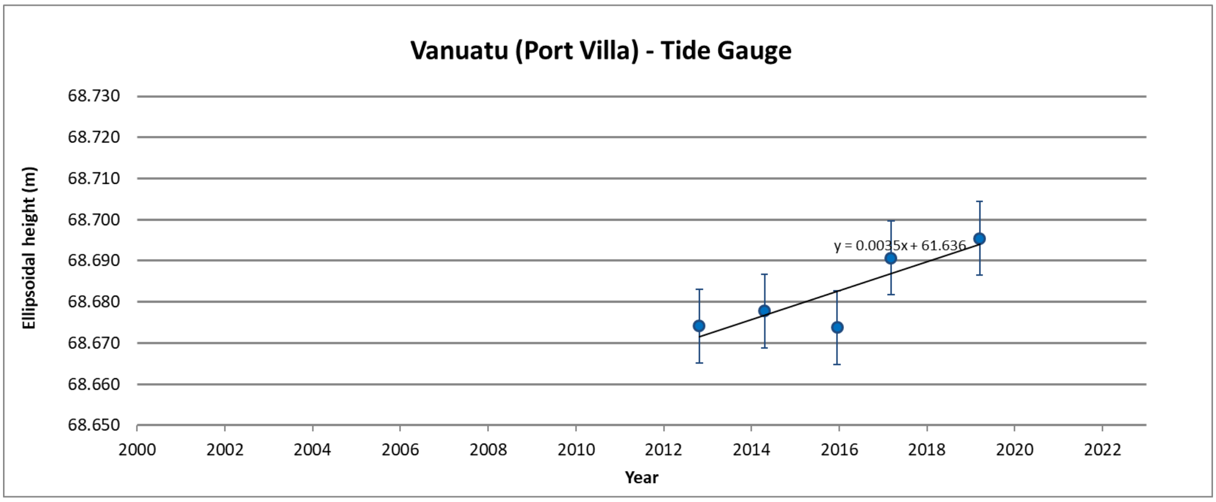


Figure 7.2 The height of the SEAFRAME sensor reference benchmark (with respect to ITRF2020).

The height of the SEAFRAME sensor reference benchmark is the sum of the ellipsoidal height of the GNSS pillar plate and the levelled height difference between the GNSS pillar plate and SEAFRAME sensor reference benchmark (Figure 7.2; Table 7.1))[3]. The height uncertainty is the combined uncertainty from the GNSS analysis and the levelling.

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

Date	Height (m)	Uncertainty (95%CI) (m)
2012.81	68.6742	0.009
2014.30	68.6778	0.009
2015.95	68.6738	0.009
2017.18	68.6907	0.009
2019.20	68.6955	0.009

[3] It is recognised that the height of the SEAFRAME sensor reference benchmark is the sum of the geometric GNSS ellipsoidal height and the physical orthometric levelling height. No geoid corrections were applied to the levelling data because of the short distance of the levelling run and the lack of high resolution gravity data in this region.

8 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

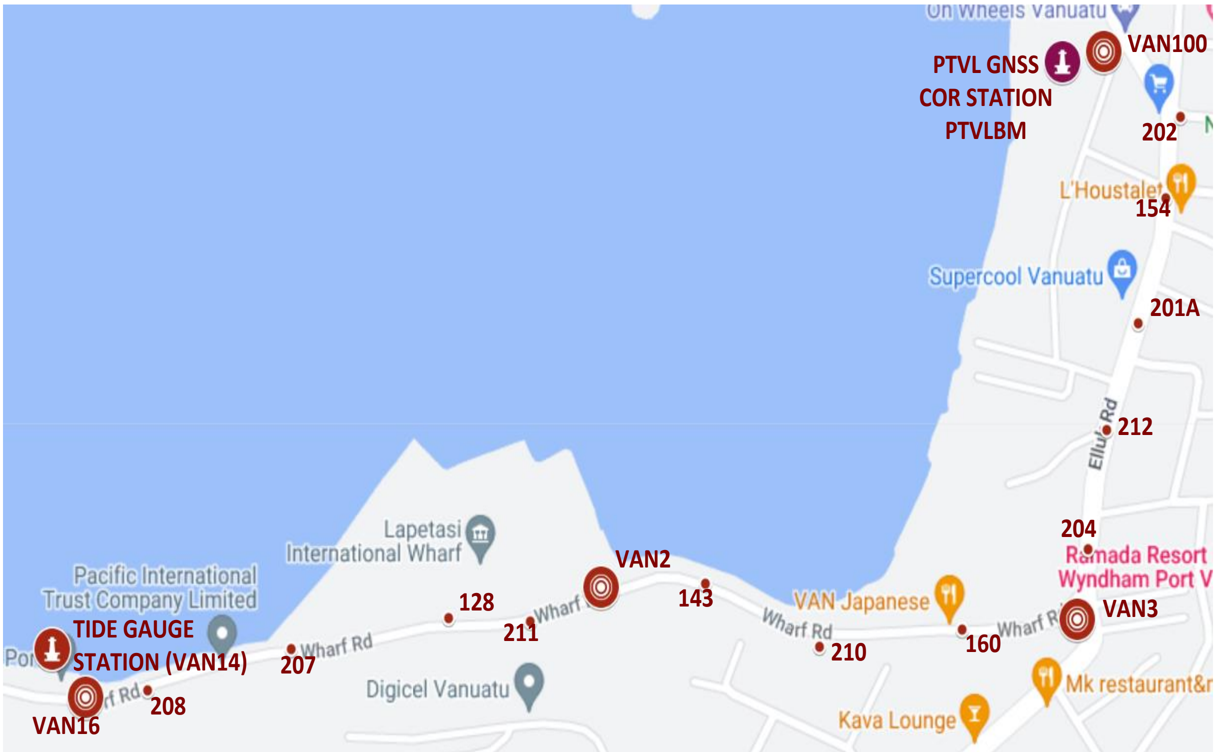
Fraser, R., Leahy, F., Collier, P., 2018. *DynAdjust User's Guide Version 3.0*. Dynamic Network Adjustment Software.

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: Google Maps

A1. Deep Benchmarks

PACIFIC SEA LEVEL MONITORING PROJECT

Australian Aid — Australian Government, Geoscience Australia — Pacific Community / Communauté du Pacifique

SURVEY BENCH MARK RECORD

Bench Mark Number: VAN2

Original Bench Mark Established by: *Date:04.11.91*

National Tidal Centre Australia, Oceanographic Services,
Bureau of Meteorology, 25 College Road, Kent, S.A

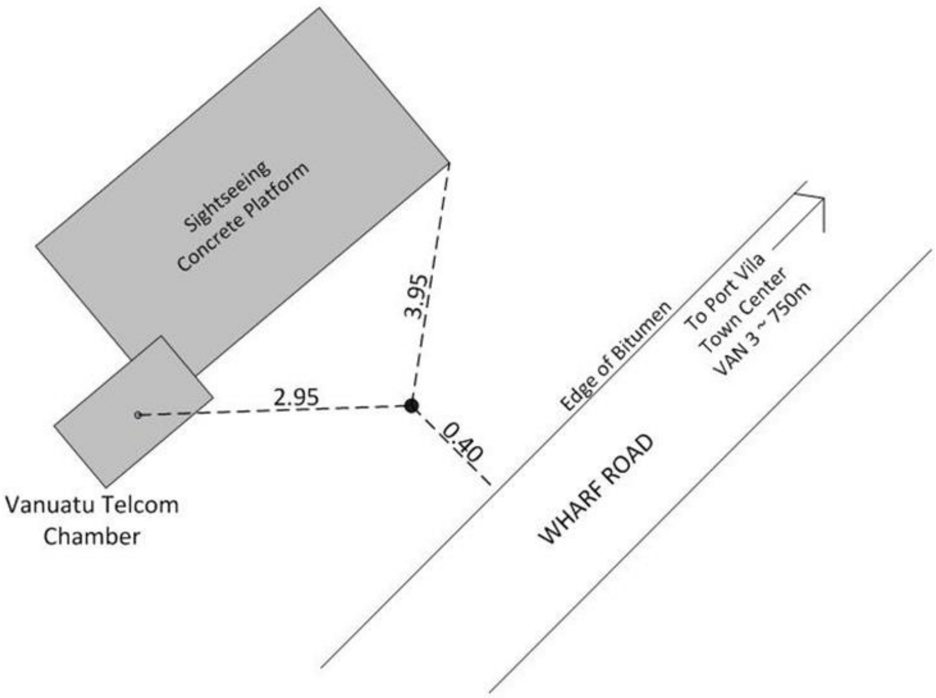
Existing Bench Mark Established by: *Date:*

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

Country: Vanuatu
Island: Efate *City: Port Vila*

MARKING AND LOCALITY SKETCH

Bench Mark: 7.3m of 19mm diameter stainless steel capped rod driven until refusal. Rod sheathed with PVC tube filled with bentonite for 0.5m. Top of mark 0.30 below ground level. Mark is approximately 800m from the tide gauge station



NOT TO SCALE Distances in Metres Magnetic Bearings

Approved by: Geoscience Australia/SOPAC *Date: December 2006*

PACIFIC SEA LEVEL MONITORING PROJECT

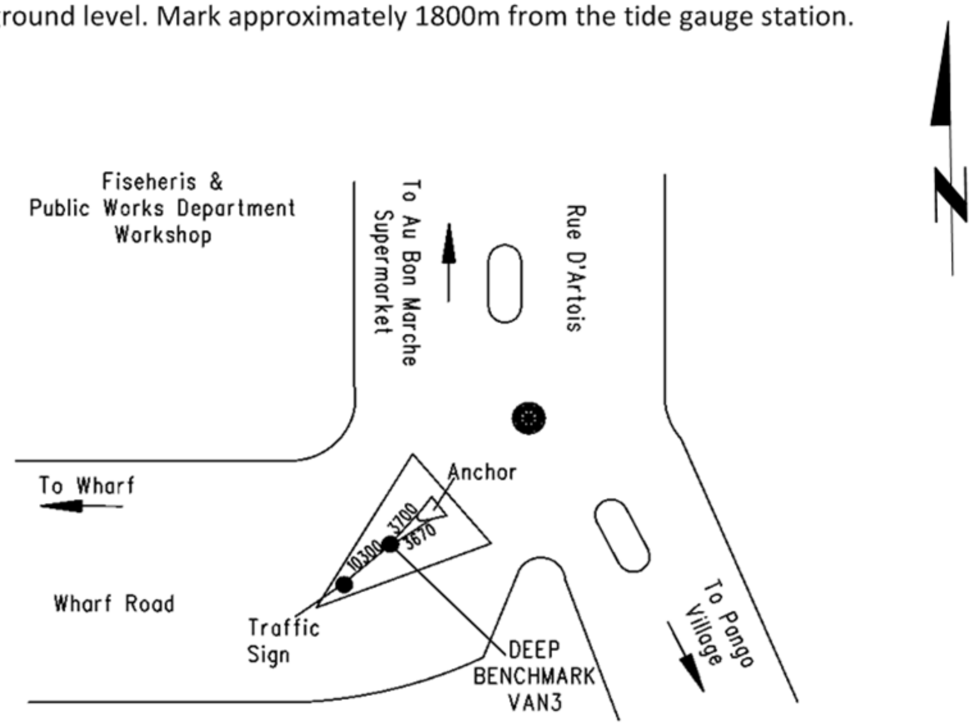
SURVEY BENCH MARK RECORD

Bench Mark Number: VAN3

Original Bench Mark Established by: National Tidal Centre Australia, Oceanographic Services, Bureau of Meteorology, 25 College Road, Kent, S.A	*Date: 05.11.91*
Existing Bench Mark Established by:	*Date:*
Notes / References: Deep driven bench mark, covered by plastic housing. Good location for GNSS obs.	
Country: Vanuatu *Island:* Efate	*City:* *Port Vila*

MARKING AND LOCALITY SKETCH

Bench Mark: 3.3m of 19mm diameter stainless steel capped rod driven until refusal. Rod sheathed with 50mm PVC tube filled with bentonite for 0.5m. Top of mark 0.2m below ground level. Mark approximately 1800m from the tide gauge station.



NOT TO SCALE   Distances in Metres   Magnetic Bearings

Approved by: Geoscience Australia / SOPAC   *Date: December 2006*

PACIFIC SEA LEVEL & GEODETIC MONITORING PROJECT

SURVEY BENCH MARK RECORD

Bench Mark Number: VAN100

Original Bench Mark Established by: *Date: August 1999*
National Tidal Centre Australia, Oceanographic Services,
Bureau of Meteorology, 25 College Road, Kent, S.A

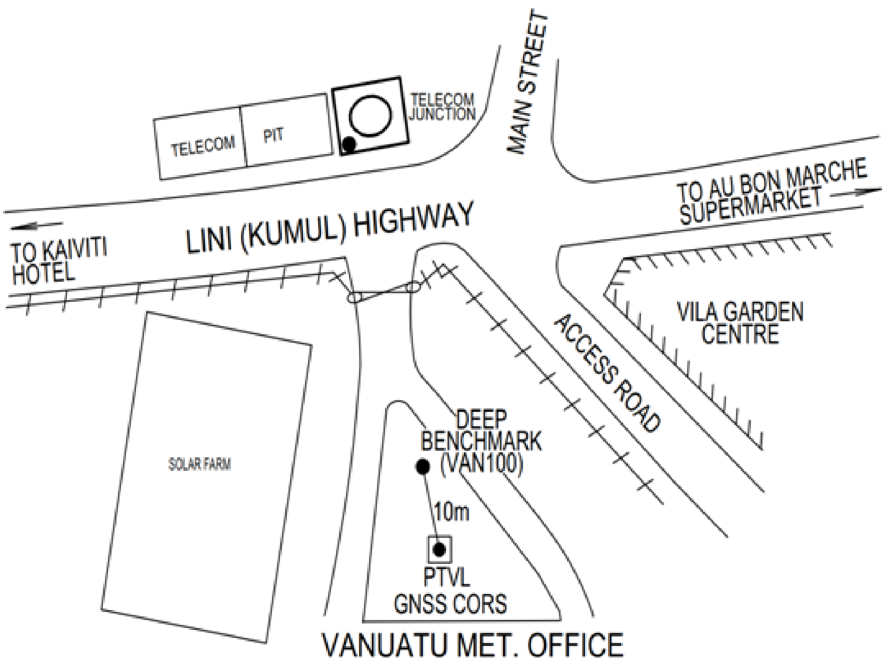
Existing Bench Mark Established by: *Date:*

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

Country: Vanuatu
Island: Efate *City:* *Port Vila*

MARKING AND LOCALITY SKETCH

Bench Mark: 19mm diameter stainless steel capped rod driven until refusal. Rod sheathed with 50mm PVC tube. Top of mark on ground level. Mark approximately 2500m from the tide gauge station.

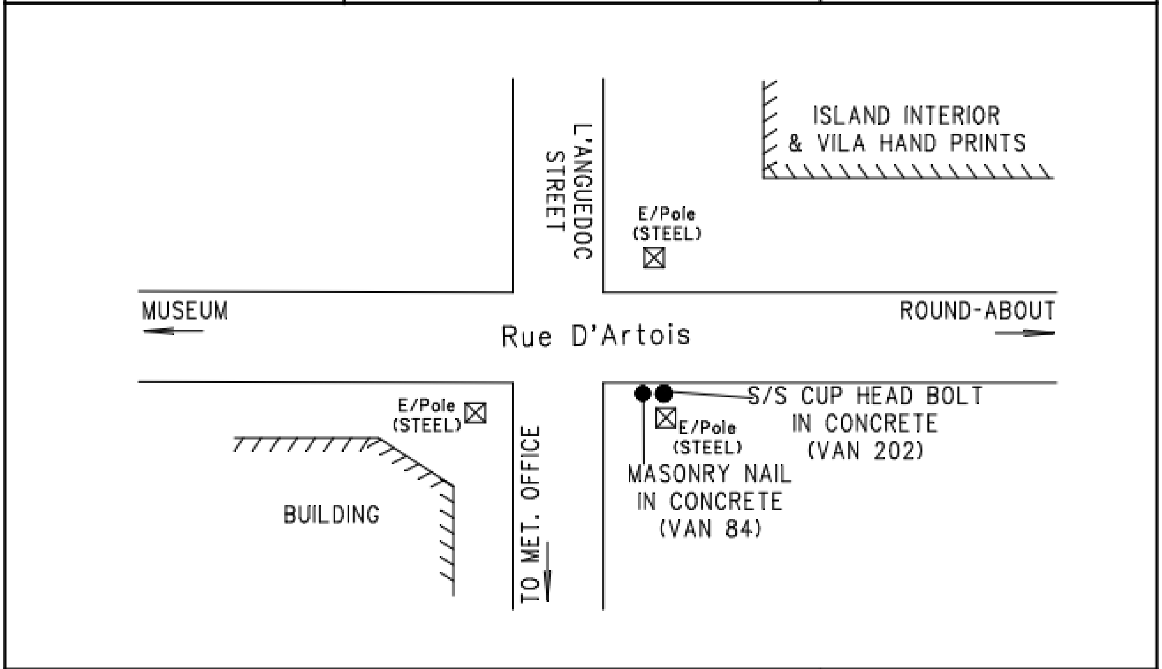


NOT TO SCALE Distances in Metres Magnetic Bearings

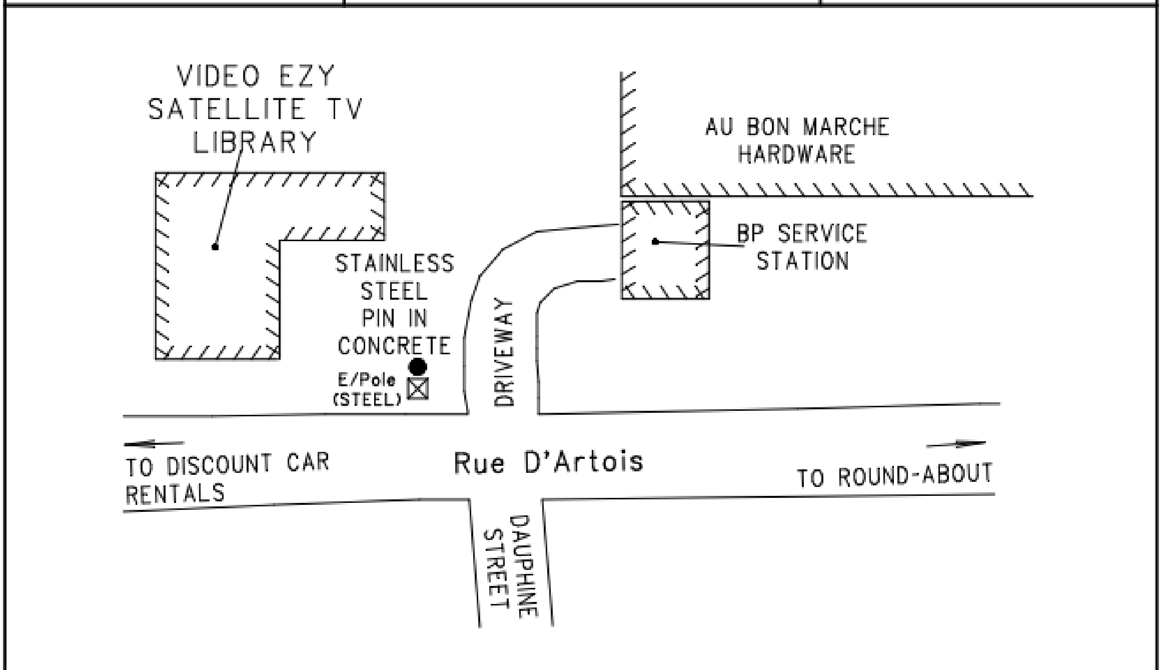
Approved by: Geoscience Australia / SOPAC *Date: December 2006*

A2 Temporary Benchmarks

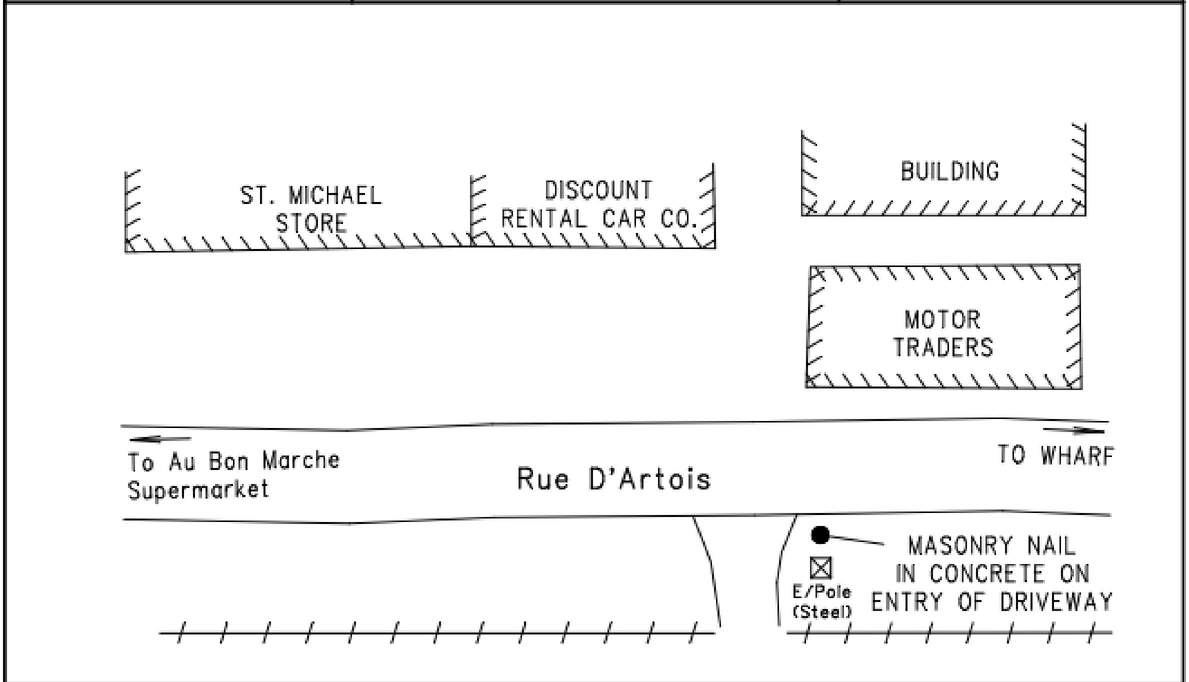
COUNTRY: Vanuatu	ISLAND: Efate CITY: Port Vila	L. D. P. 815 POINT NO. 202
PROJECT:S PSLGM	SURVEYOR: S Yates & A Lal	DATE: 05-08-12



COUNTRY: Vanuatu	ISLAND: Efate CITY: Port Vila	L. D. P. 725 POINT NO. 154
PROJECT: PSLGM	SURVEYOR: S Yates & A Lal	DATE: 07-09-06



COUNTRY: Vanuatu	ISLAND: Efate CITY: Port Vila	L. D. P. 814 POINT NO. 201A
PROJECT:S PSLGM	SURVEYOR: S Yates & A Lal	DATE: 02-04-08



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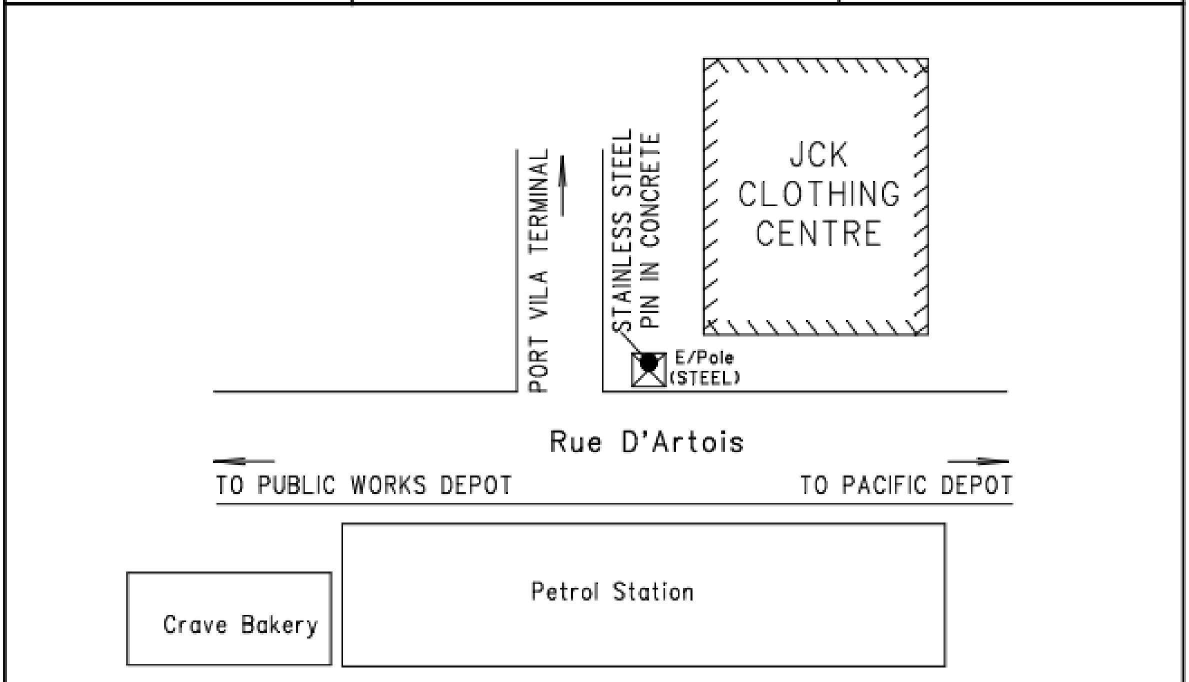
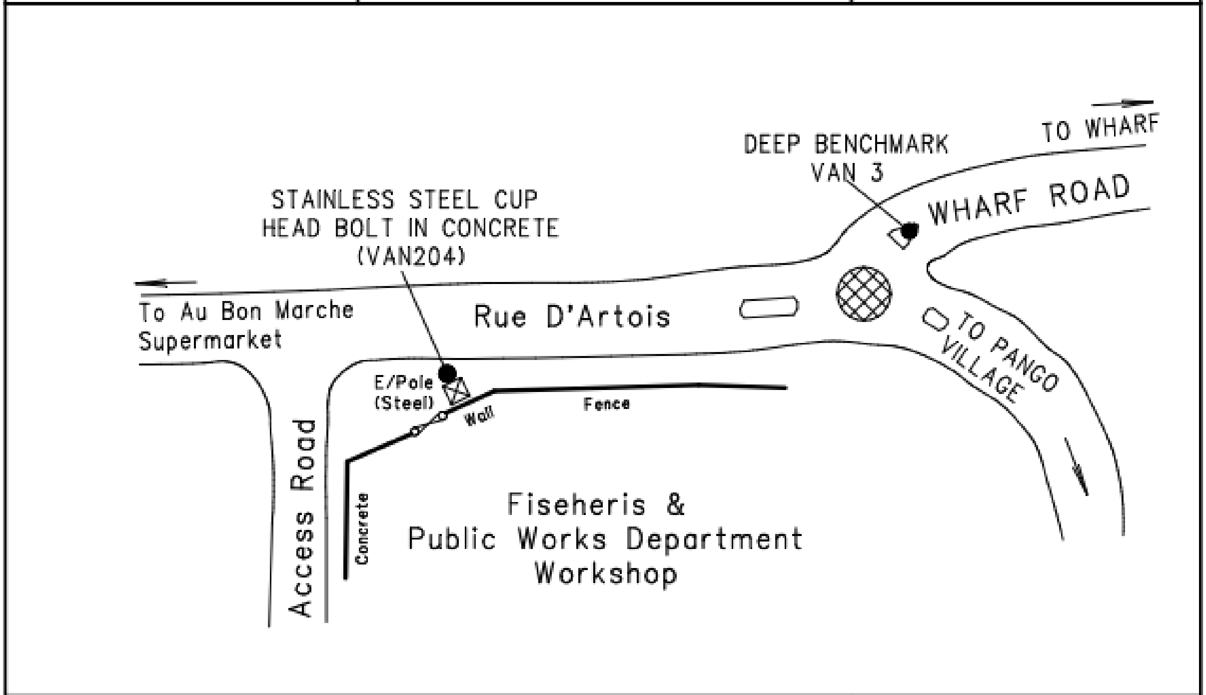
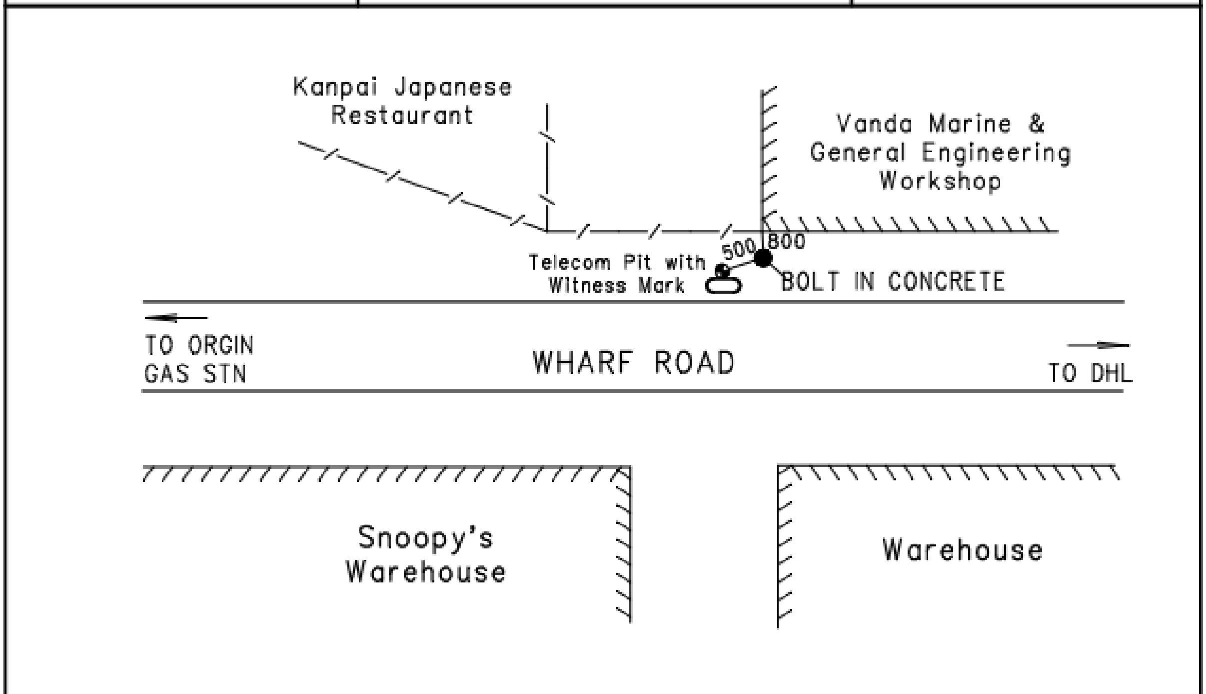
PROJECT: PSLGM	SURVEYOR: AL & MK	DATE: 06-03-19



COUNTRY: Vanuatu	ISLAND: Efate CITY: Port Vila	L. D. P. 910 POINT NO. 204
PROJECT:S PSLGM	SURVEYOR: A Woods & A Lal	DATE: 29-09-09



COUNTRY: Vanuatu	ISLAND: Efate CITY: Port Vila	L. D. P. 713 POINT NO. 160
PROJECT: PSLGM	SURVEYOR: S Yates & A Lal	DATE: 07-09-06



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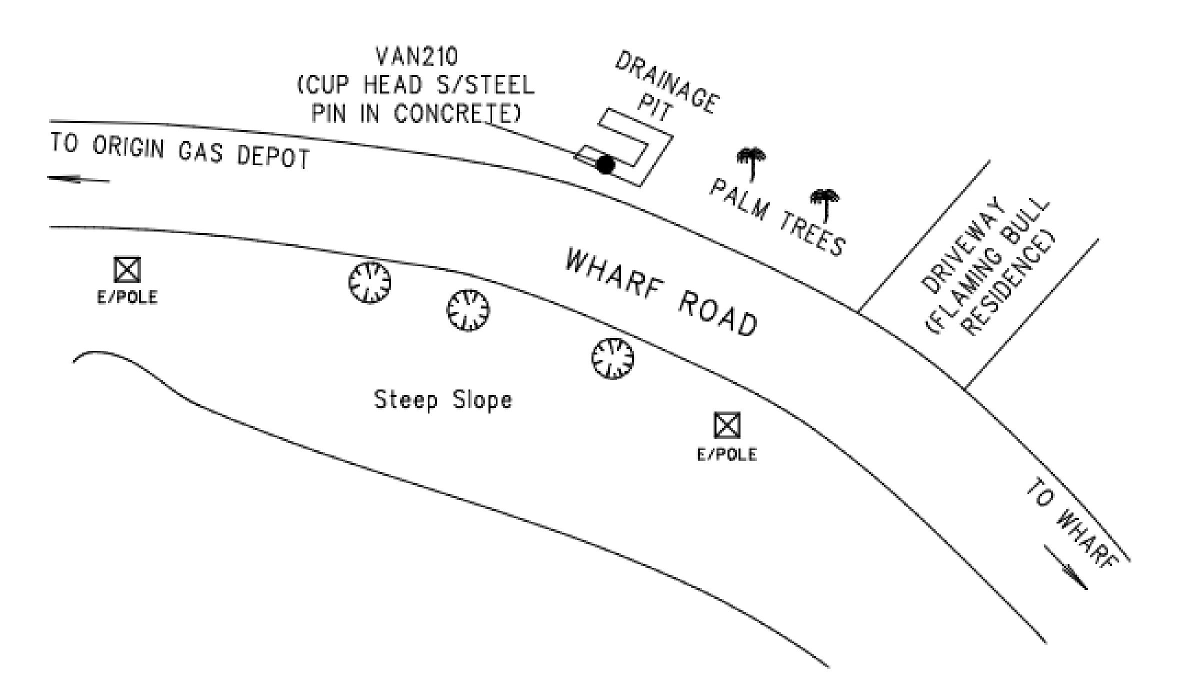
PROJECT:PSLGM	SURVEYOR: S Yates & A Lal	DATE: 19-10-12



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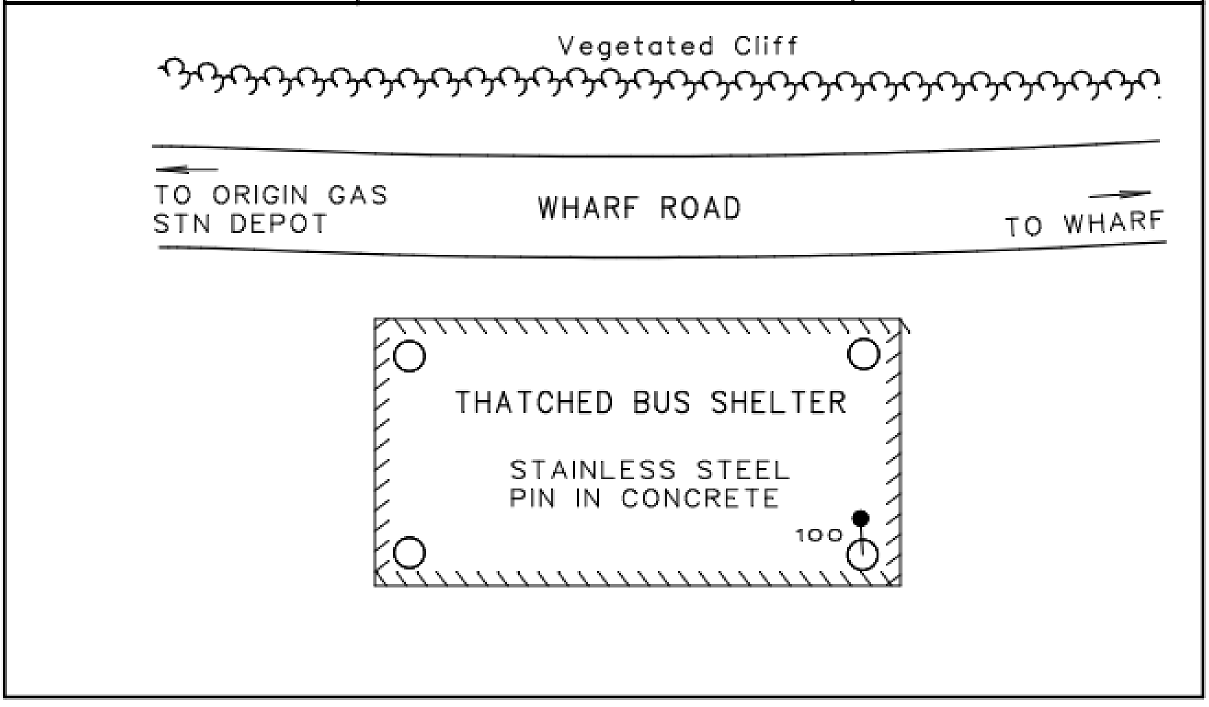
PROJECT: PSLGM	SURVEYOR: S Yates & A Lal	DATE: 07-09-06



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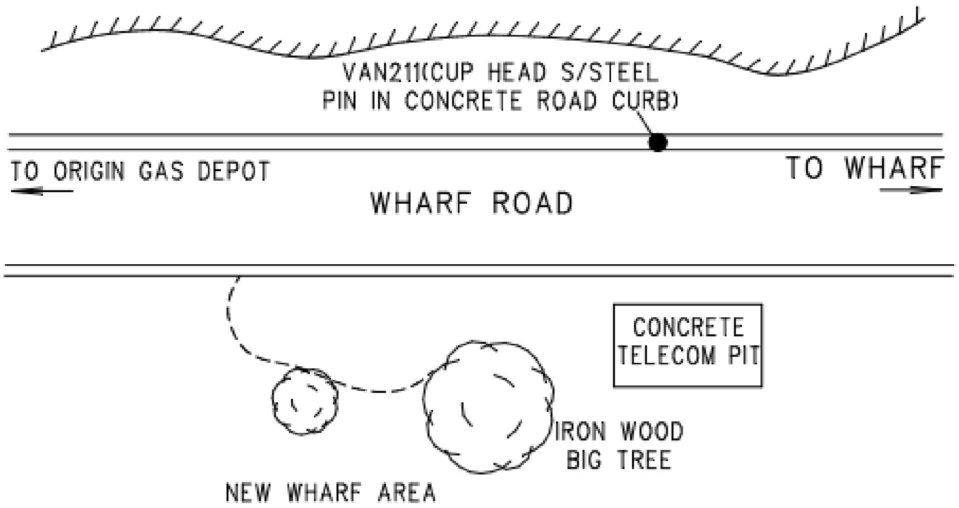
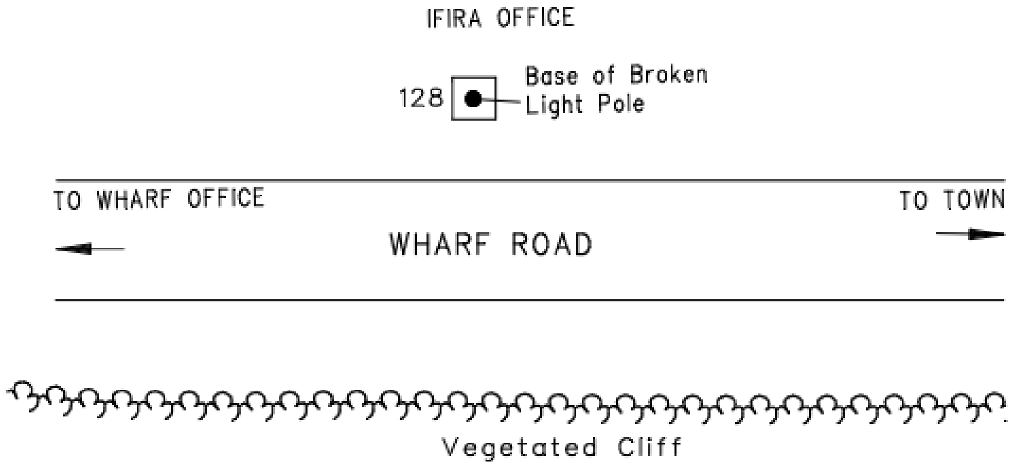
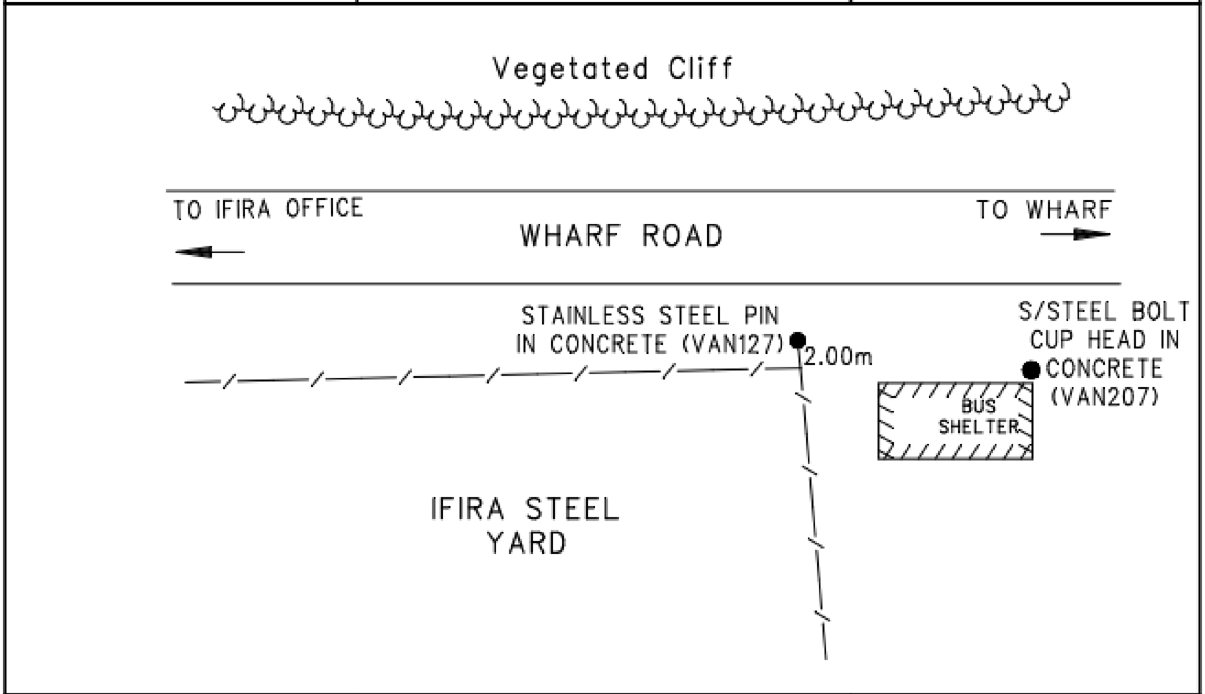
PROJECT:S PSLGM	SURVEYOR: S Yates & A Lal	DATE: 19-10-12



COUNTRY: Vanuatu	ISLAND: Efate CITY: Port Vila	L. D. P. 720 POINT NO. 128
PROJECT: PSLGM	SURVEYOR: AL & MK	DATE: 01-04-19



COUNTRY: Vanuatu	ISLAND: Efate CITY: Port Vila	L. D. P. 720 POINT NO. 207
PROJECT: PSLGM	SURVEYOR: S Yates & A Lal	DATE: 01-04-11



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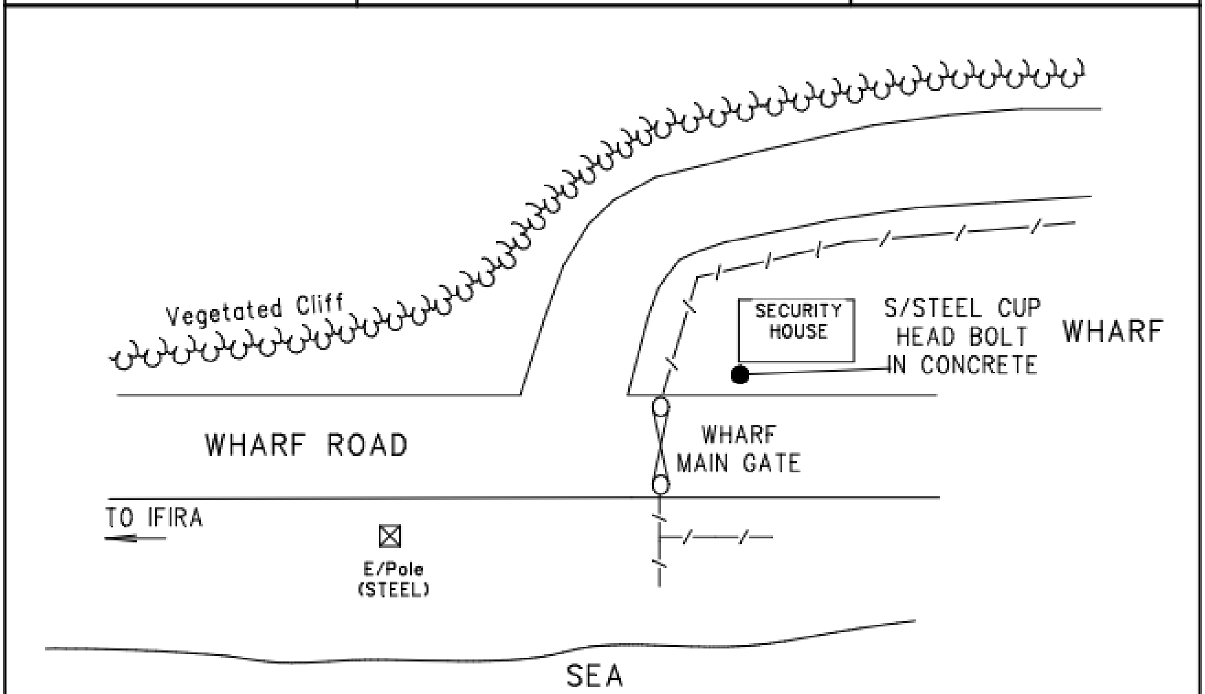
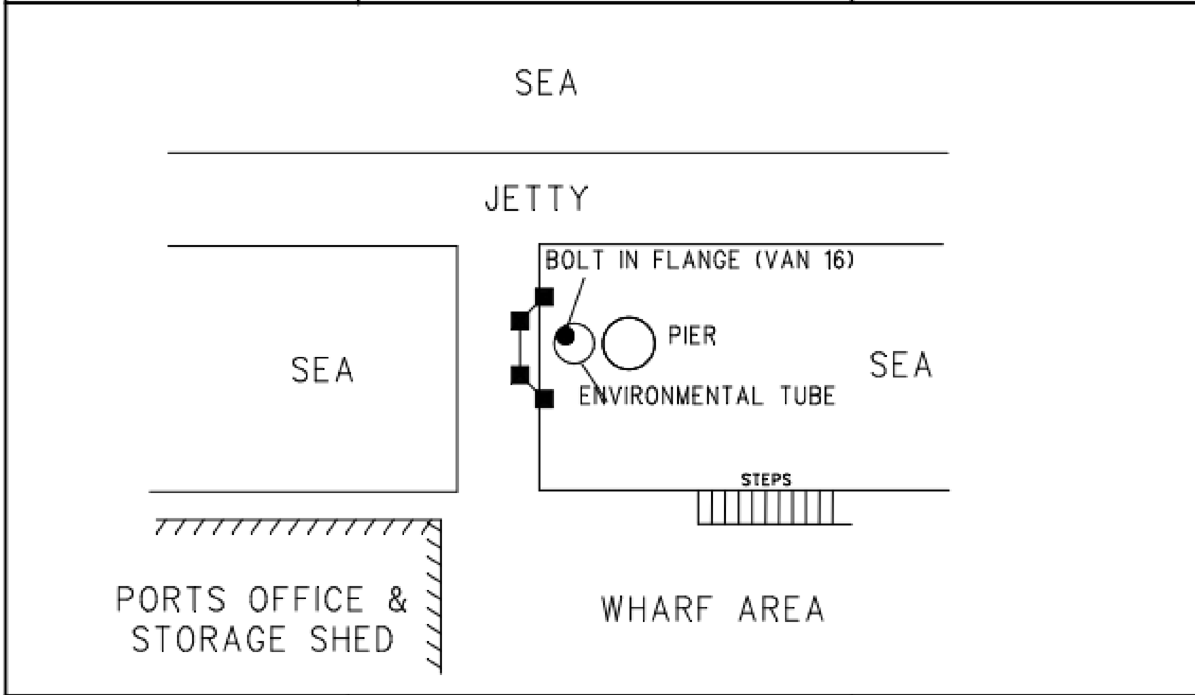
PROJECT: PSLGM	SURVEYOR: A Woods & A Lal	DATE: 01-04-11



COUNTRY: Vanuatu	ISLAND: Efate CITY: Port Vila	L. D. P. 816 POINT NO. VAN16
PROJECT: PSLGM	SURVEYOR: S Yates & A Lal	DATE: 07-04-08



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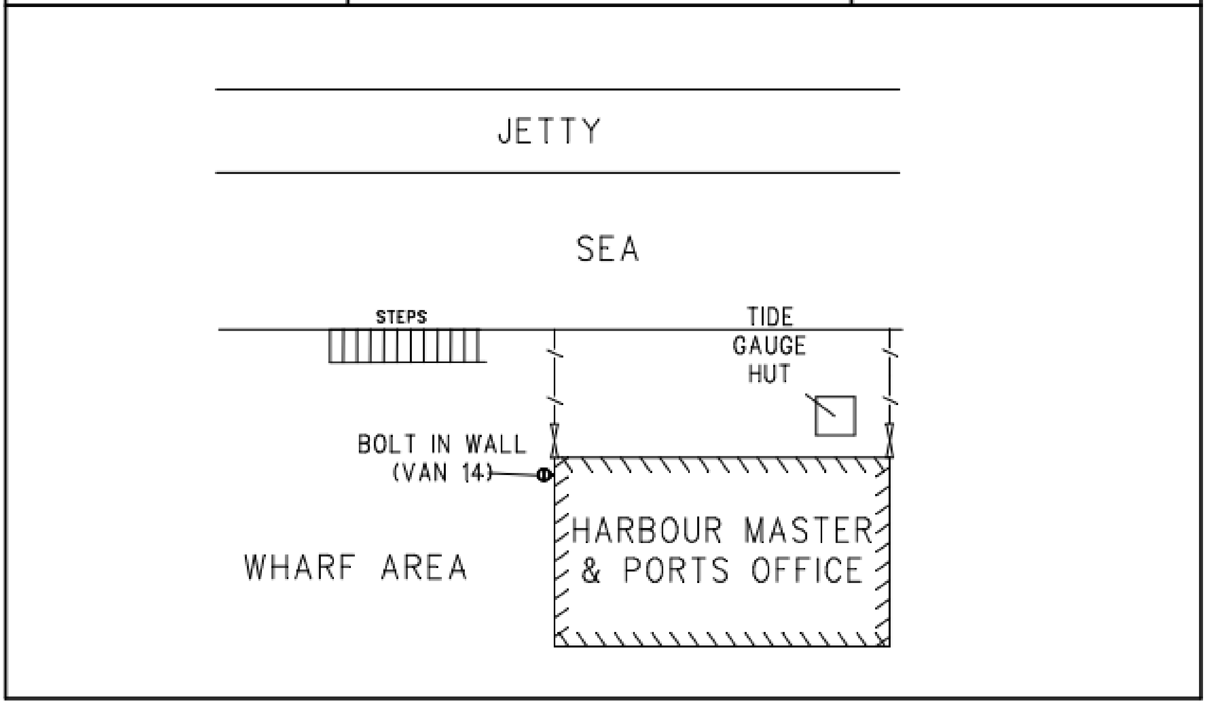
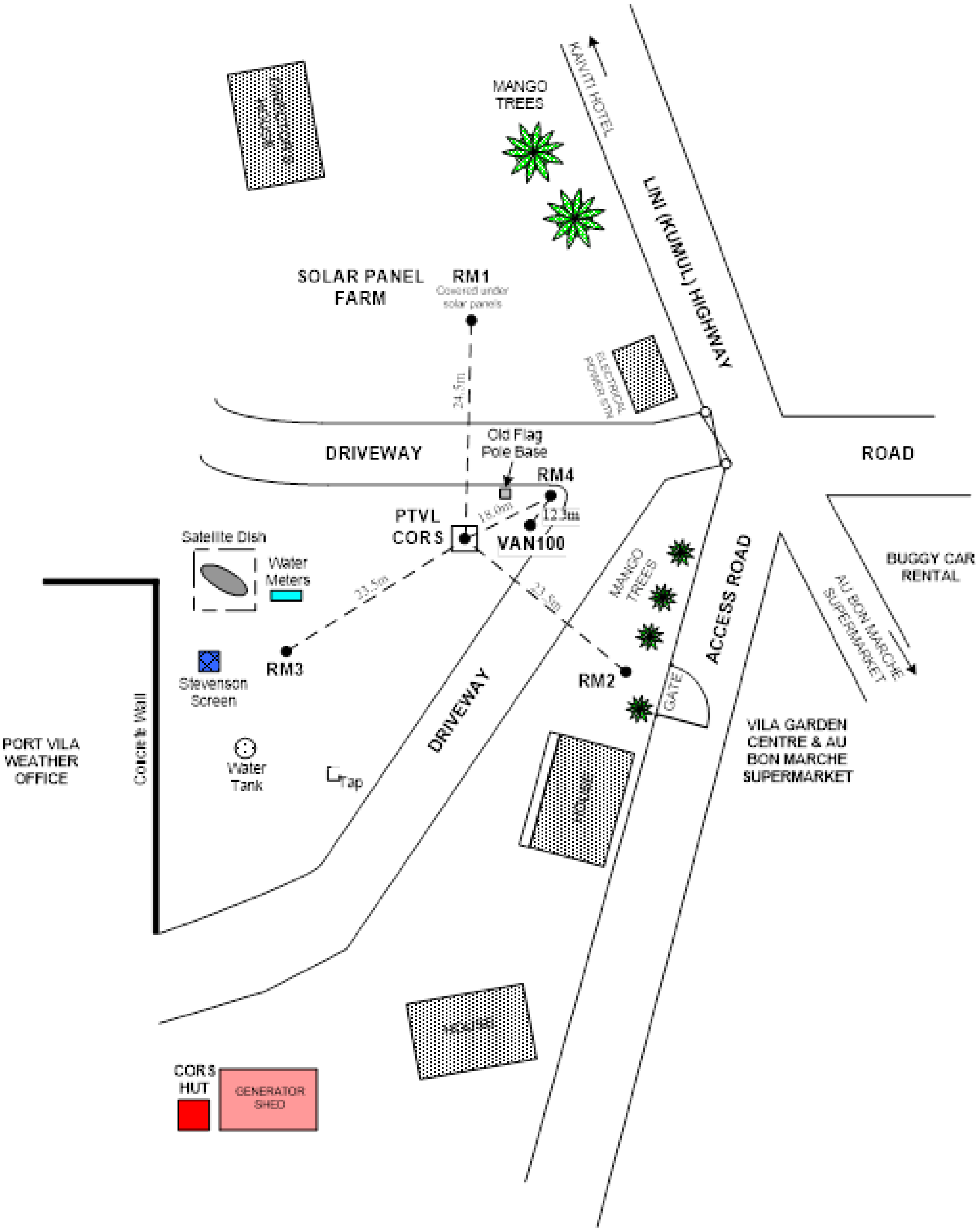
PROJECT: PSLGM	SURVEYOR: S Yates & A Lal	DATE: 07-04-08



A3 GNSS Reference Marks

Port Vila (PTVL) Continuous Operating Reference Station (CORS) & Reference Marks (RM1, RM2, RM3 & RM4)

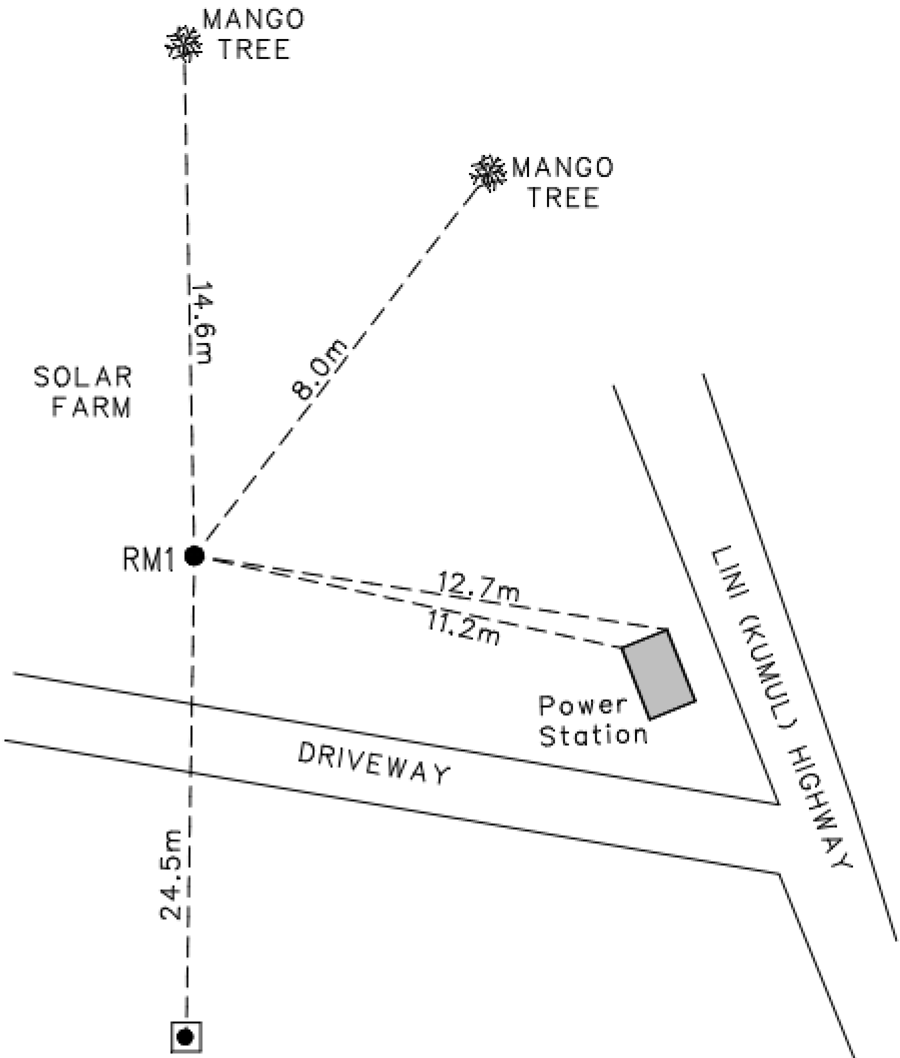
The PTVL Station is a concrete pillar on a stainless steel plate with PTVLBM and the Reference Marks are capped 20mm stainless steel rods driven to refusal and protected by 150 mm PVC pipe within circular poly carbonate valve boxes. The valve box lids are approximately 50mm below ground level.



VANUATU GNSS Station, Port Vila - RM1

REFERENCE MARK

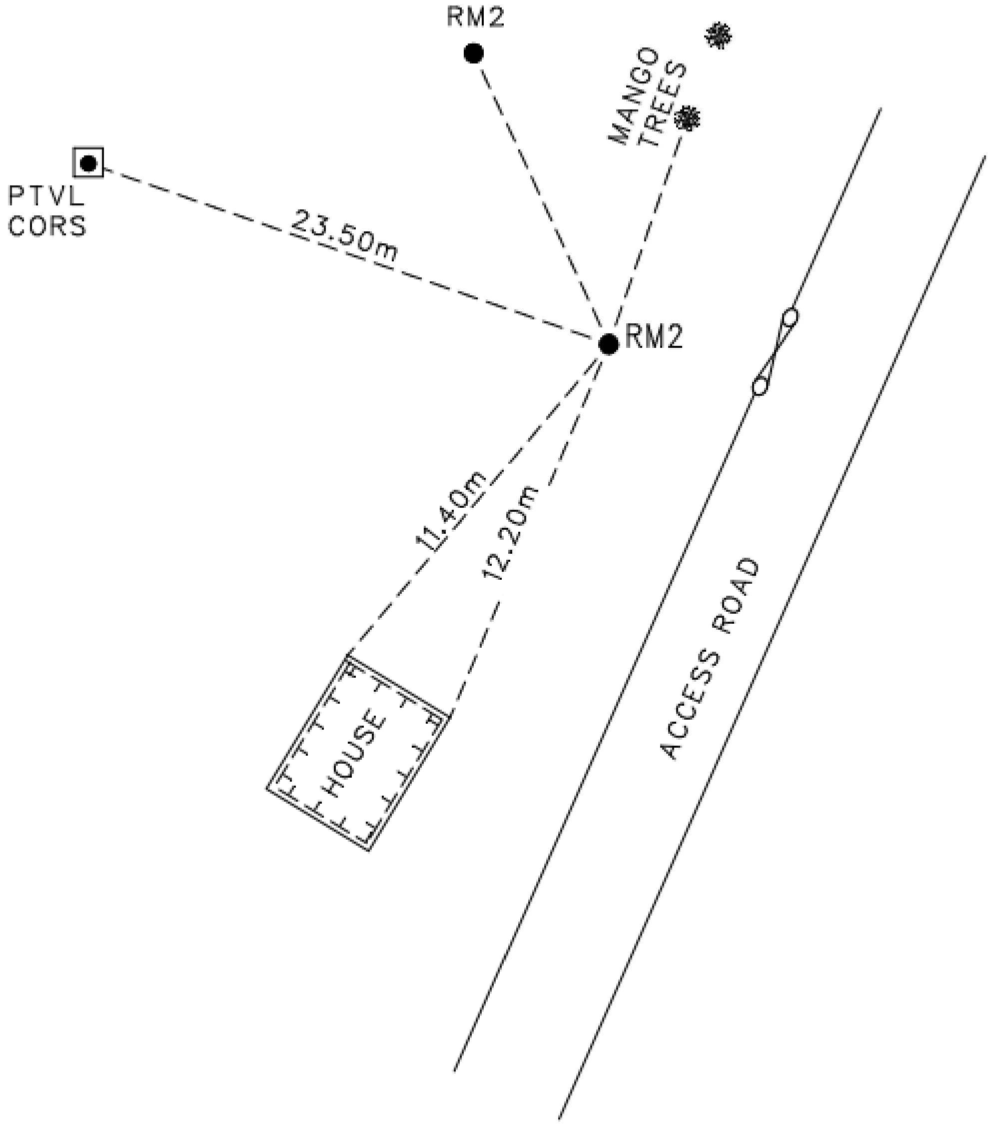
All RM's are capped 20.00mm stainless steel rods driven to refusal and protected by 150mm PVC pipe within circular poly carbonate valve boxes. The valve box lids are approximately 50mm below ground level



VANUATU GNSS Station, Port Vila - RM2

REFERENCE MARK

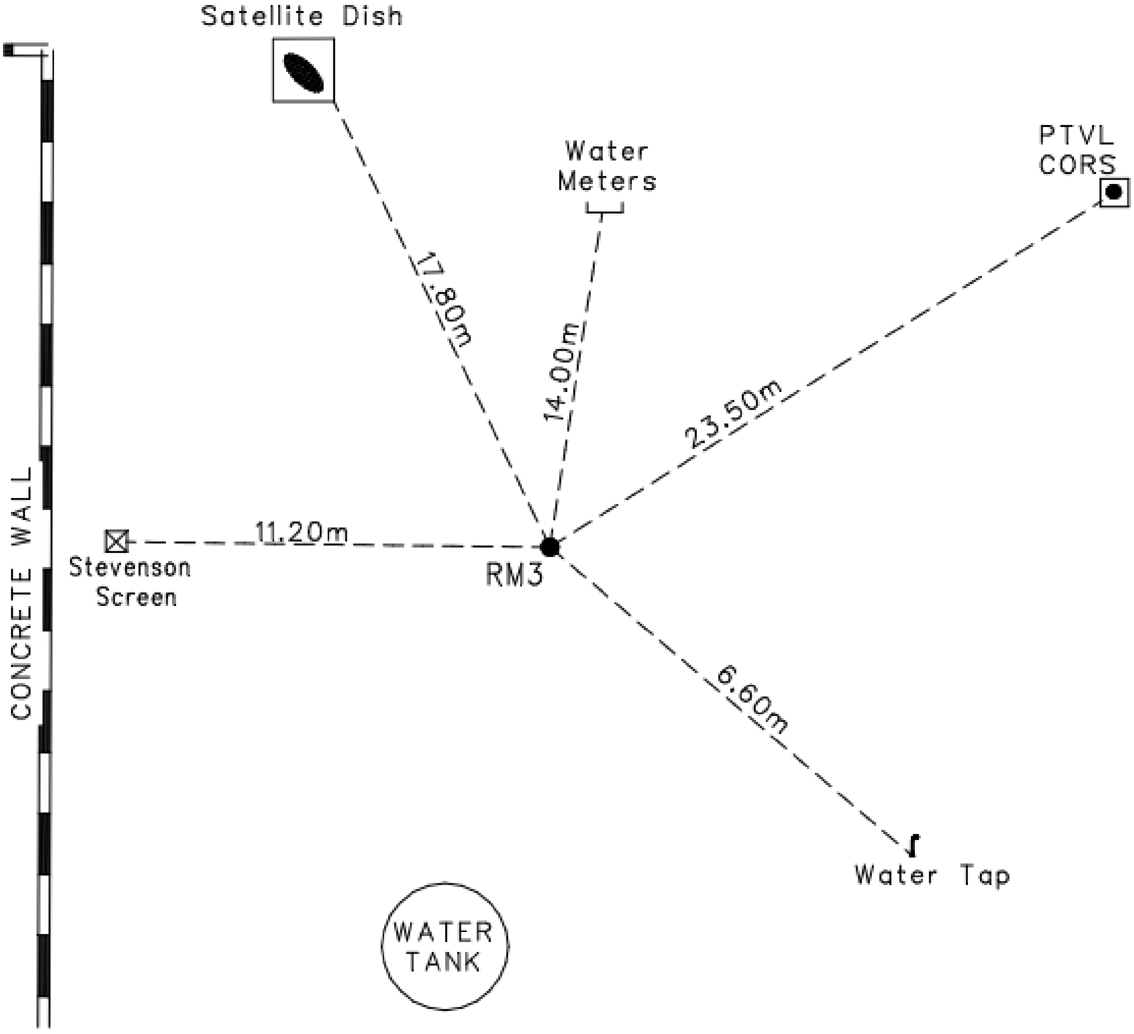
All RM's are capped 20.00mm stainless steel rods driven to refusal and protected by 150mm PVC pipe within circular poly carbonate valve boxes. The valve box lids are approximately 50mm below ground level



VANUATU GNSS Station, Port Vila - RM3

REFERENCE MARK

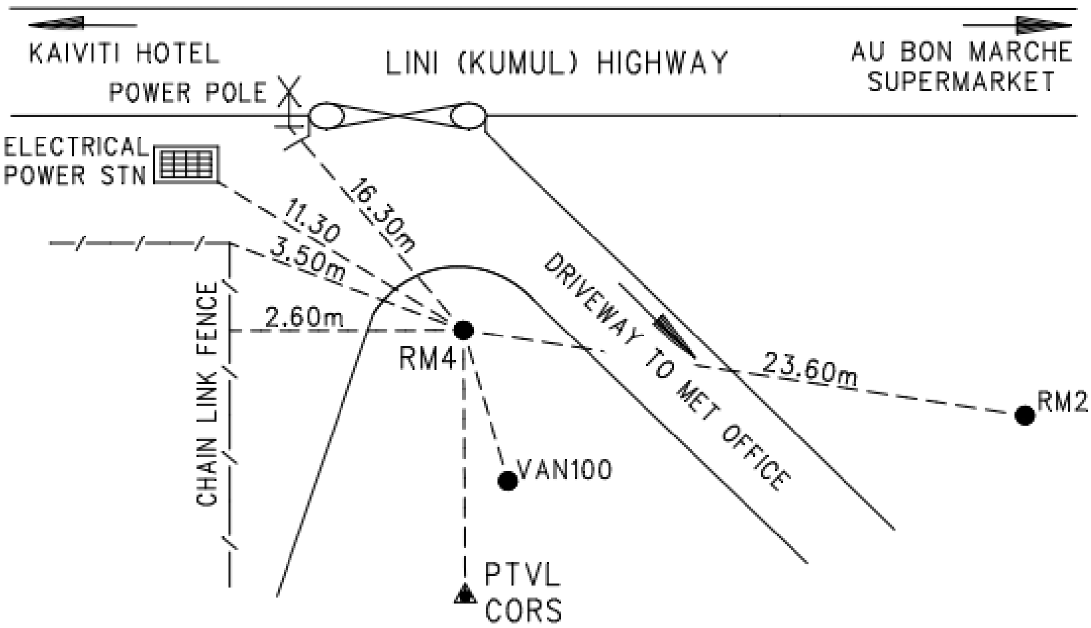
All RM's are capped 20.00mm stainless steel rods driven to refusal and protected by 150mm PVC pipe within circular poly carbonate valve boxes. The valve box lids are approximately 50mm below ground level



VANUATU GNSS Station, Port Vila - RM4

REFERENCE MARK

All RM's are capped 20.00mm stainless steel rods driven to refusal and protected by 150mm PVC pipe within circular poly carbonate valve boxes. The valve box lids are approximately 50mm below ground level



Appendix B Planning Aspects and Notes

Upon arranging travel to Vanuatu, make contact with the project focal point at the Survey Office and the Weather Office in country at least one month in advance.

Prior arrangements with the local counterpart should be made for rapid clearance of the survey equipment from the Customs Authority when shipped across. Special thanks to the Director of Land Management Division for the efficient clearance of the survey equipment from the customs bond.

The local Land and Survey office has been very helpful in receiving and storing the equipment until the survey team arrives. Daily allowance for food and water was provided to Local Surveyor

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

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

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

Quantity	Item & description	Locations
1	**Tool Box**	Tide Gauge Station Hut.
2	*Prism Pole Clamps*	*Tools used by C&M Teams (BoM & SPC)*
1	*50m Measuring Tape*	
1	*Engineers Hammer*	
1	*Carpenters Hammer*	
1	*Set of Allen Keys*	
1	*Torx Drivers*	
2	*Multigrips pliers*	
1	*Set of Screw Drivers*	
1	**PVC Pipe (1.2m)**	GNSS COR Station Hut
1	*Aluminium GST6 tripod with Feet*	
1	**PVC Pipe (1.7m)**	GNSS COR Station Hut
1	*Ground Base Plate*	
4	*Telescopic-Bi-pods*	
2	*Stainless-steel levelling prism poles*	
1	*Half Stainless-steel levelling prism pole*	
3	**Black Bags - Leica GST20 Telescopic Tripods**	GNSS COR Station Hut
1	**Green Bag - Leica GST40 Rigid Tripod**	GNSS COR Station Hut
1	**Spade**	GNSS COR Station Hut
1	**Crow Bar**	GNSS COR Station Hut

Appendix C Equipment Specifications

Tachymeters, EDM and Theodolites

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

Specification

1. EDM (infrared) distance standard deviation of a single measurement (DIN 18723, part 6): 0.6 mm ± 1 ppm.
2. 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

3. Temperature is accurate to 1.0°C between -29.0°C and 70.0°C.
4. Pressure is accurate to 1.5 mb at 25°C between 750 mb and 1100 mb.
5. 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:

6. 4 x Leica GDF21 tribrachs.
7. 4 x Leica GZR3 prism carriers with optical plummet.
8. 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:

- Trimble NETR9 GNSS receiver (S/N 5041K71020) (firmware: 5.44)
- JAVRINGANT_DM NONE (S/N 00931)