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

Majuro, Marshall Islands, February 2020

GEOSCIENCE AUSTRALIA
RECORD 2023/22

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Geoscience Australia acknowledges the traditional custodians of the country where this work was undertaken. We also acknowledge the support provided by individuals and communities to access the country, especially in remote and rural Australia.

ISSN 2201-702X (PDF)
ISBN 978-1-922625-58-8 (PDF)
eCat 148871

Bibliographic reference: Lal, A., Rattan, V., Kalouniviti, M., Brown, N. J., Thomas, B. R., 2023 *Pacific Sea Level and Geodetic Monitoring Project: Levelling & GNSS Monitoring Survey Report: Majuro, Marshall Islands, February 2020.* Record 2023/22. Geoscience Australia, Canberra. https://dx.doi.org/10.26186/148871

Contents

1 Motivation

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

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

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

2 Introduction

This report provides the results of the GNSS monument monitoring survey & high precision level survey completed between the Sea Level Fine Resolution Acoustic Measuring Equipment (SEAFRAME) tide gauge and the GNSS Continuously Operation Reference Station (CORS) in Majuro, Marshall Islands from 4th – 11th February 2020. 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 the difference in height between the Tide Gauge and GNSS monument. The levelling route includes a deep driven benchmark array in Majuro, which runs a distance of approximately 3.0 km. Previous levelling surveys have been conducted along this route using the Total Station differential levelling technique in 2006, 2007, 2009, 2010, 2012, 2013, 2015, 2017 and 2018. This report contains an analysis of the 2020 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 Veenil Rattan, 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.

This survey was carried out in conjunction with the SPC Tide Gauge Maintenance Team. The tide gauge station was also upgraded. Maleli Turagabeci of the Pacific Community (SPC) was responsible to upgrade the Tide Gauge Station by uplifting the environment tube of the Tide Gauge Station in Majuro.

Tide Gauge Station height raised

On 05/02/2020, the environment tube of the Tide Gauge Station was raised by 0.3868 m. This was necessary due to high tide sea level values being unable to be observed by the tide gauge at its previous height (see Fig 3.3 and 3.4). The primary sea level sensor benchmark (MAR14) at the Tide Gauge Station is attached to top of the environment tube and was therefore also raised by 0.3868 m. In its new position the primary sea level sensor benchmark has been renamed, MAR14A.

2.1 Site Description and Contacts

The levelling benchmark array, GNSS CORS, and SEAFRAME is approximately 3.0 km long, running from the GNSS CORS pillar (MAJU) at the NTA compounds to the Tide Gauge Station (MAR13) at the Wharf and further onto the Catholic Church (MAR50).

Access to the site is generally unrestricted, contact the Meteorological office before commencing the survey.

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2.2 Survey Support

The survey team very much appreciate the support from the Marshall Islands Meteorological Office, who received the survey equipment freight on our behalf. Through their continued support for the past years makes all these project visits a success.

The PSLGMP Survey team would also like to acknowledge the continued support of the Marshall Islands Land and Survey Department and appreciate the continued working relationship that has been in place since 2004 and were able to make a staff member available to assist the survey team during the survey work. Mr Bill Labija, provided the valuable assistance and support in the field.

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
MAR 13	SEAFRAME project plaque benchmark
MAR 14	SEAFRAME sensor reference benchmark (old height)
MAR 14A	SEAFRAME sensor reference benchmark (new height)
MAR 3	Deep driven benchmark
MAR 15	Deep driven benchmark
MAR 50	Deep driven benchmark
MAR 51	Deep driven benchmark
MAR 52	Deep driven benchmark
MAR 100	Deep driven benchmark
MAR 107	Deep driven benchmark
RM1	GNSS CORS reference mark 1
RM2	GNSS CORS reference mark 2
RM3	GNSS CORS reference mark 3
MAJUBM	Reference benchmark in the base of 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; MAR31, MAR101, MAR102, MAR104, MAR106, MAR107, MAR108, MAR114 and MAR116 (Fig 3.5).

On 06/02/2020, the environment tube of the Tide Gauge Station was raised by 0.3868 m, due to some high tide sea level values being unable to be observed by the tide gauge at its previous height (see Fig 3.3 and 3.4). The SEAFRAME sensor reference benchmark on the tide gauge (MAR14) was therefore also raised by 0.3867 m and has been renamed, MAR14A. In future surveys, MAR14A will be used in the levelling analysis, as the SEAFRAME sensor reference benchmark

3.1.1 PSLGMP Vertical Reference Frame Wiring Diagram

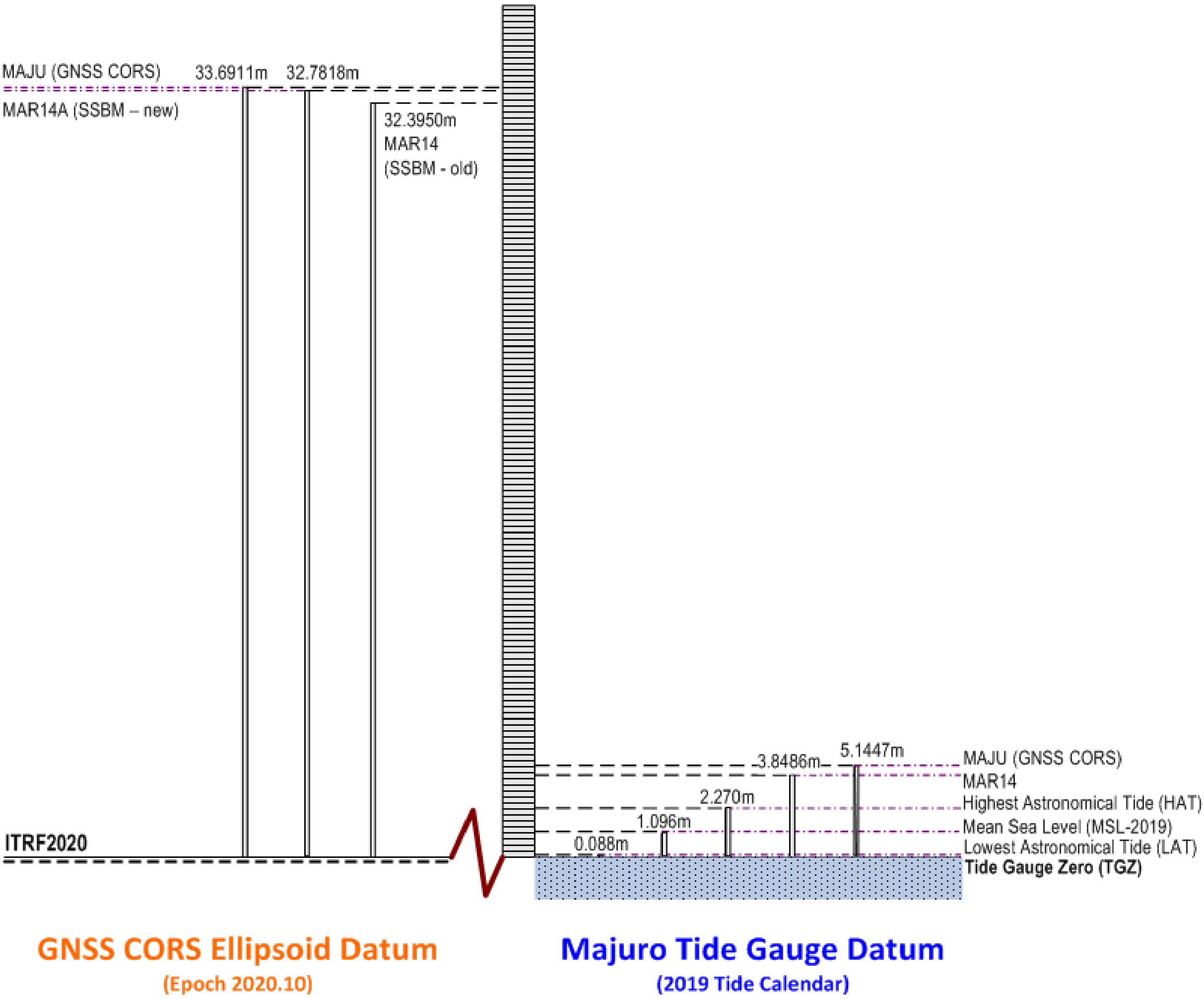


Figure 3.1 Wiring diagram depicting the offsets between surveyed marks. The left-hand side shows the height of the GNSS CORS pillar (MAJU), SEAFRAME sensor reference benchmark (old height; MAR14), SEAFRAME sensor reference benchmark (new height; MAR14A) with respect to the International Terrestrial Reference Frame 2020 at epoch 2020.10. The right-hand side shows the height of MAJU, MAR14, 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)

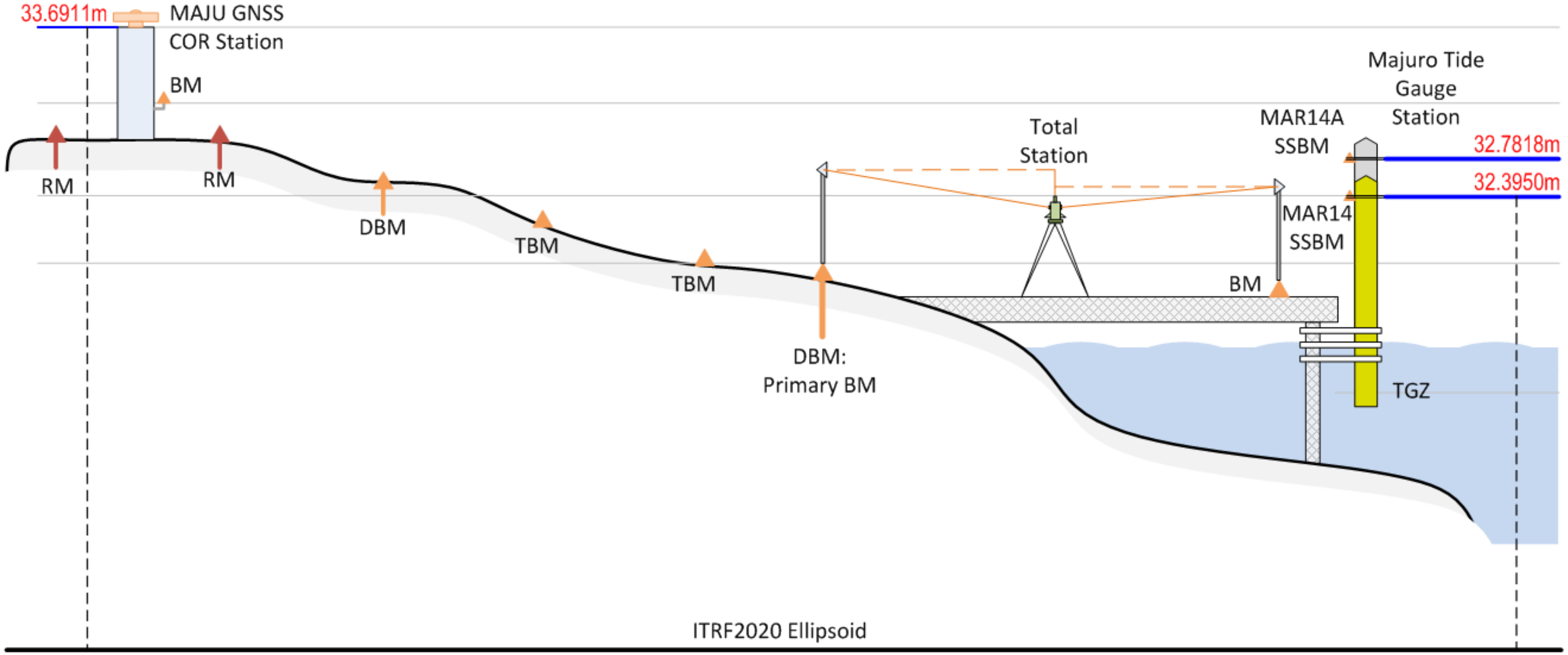


Figure 3.2 Simplified representation of the Total Station differential levelling survey carried out between the GNSS CORS and the SEAFRAME Tide Gauge.

Figure 3.3 Tide Gauge Station. The red circle denotes the location of the SEAFRAME sensor reference benchmark (old height; MAR14). Image from 2020.

Figure 3.4 Refurbished Tide Gauge Station. The red circle denotes the location of the SEAFRAME sensor reference benchmark (new height; MAR14A). Image from 2020.

Figure 3.5 GNSS CORS pillar. The red circle denotes the location of the GNSS CORS benchmark (MAJUBM). Image from 2020

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

3.1.2 GNSS CORS and Reference Marks

The GNSS CORS site is located within NTA compound in Majuro. The site consists of the existing national telecommunications building and the compound that is housing the technical equipment and a 2.0 m high antenna pillar. The pillar is approximately 30 metres from the building. Access to the compound is by arrangement with the Meteorological Office.

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 3.7). 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.

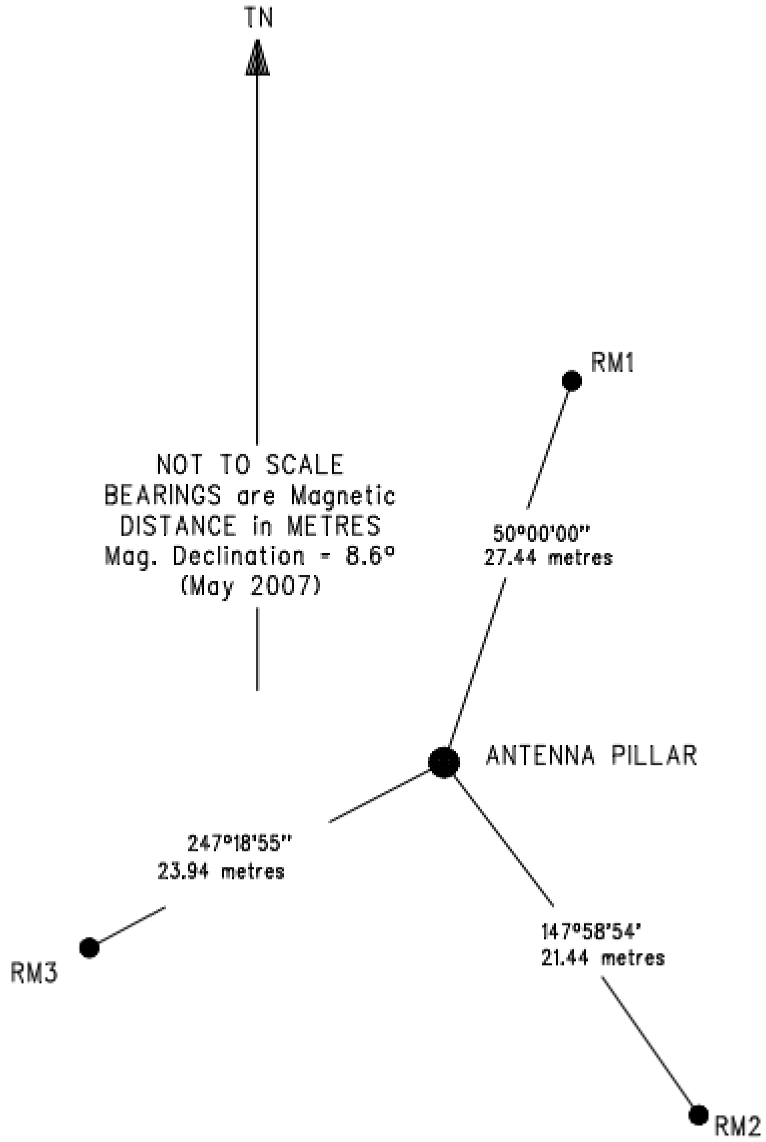


Figure 3.7 GNSS CORS site monitoring survey reference marks.

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 (MAJUBM).

3.2.2 Historical Survey Datum

In the past, the adopted reference point for the levelling survey was MAR3 fixed at 1.60834 metres.

The height of MAR3 was derived by:

> 1993 – Adopting the MSL height of USCG BM 4; RL = 1.91414m MSL (Nov 68 – May 69)
>
> 1994 – Adopting the height of MAR3 as derived in the 1993 survey.

Initially, MAR2 was the reference point for the surveys, but this was found to be destroyed during the 2006 survey. To keep all the reduced levels consistent in reference to a unique benchmark, the RL of MAR3 as determined in the 1993 survey and was adopted as the datum for all the surveys.

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.

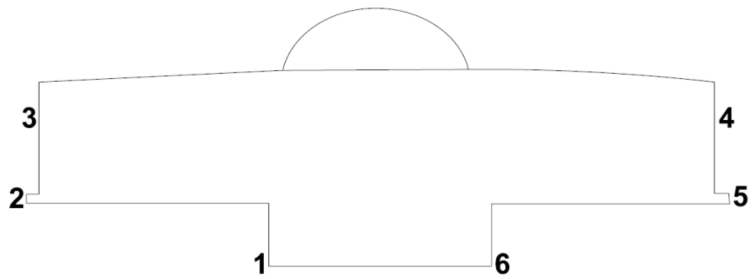


Figure 4.1 Symmetrical points on the antenna profile (TRM59800.00) observed from each RM.

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 also providing standard deviations and a misclose for the levelling loop. Refer to Section 5 for a detailed description of the levelling process.

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

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
MAJUBM				0.0000		0.0000
RM1	**RM1**	0.0000	-1.8145	-1.8145	0.0220	0.0220
RM2	**RM2**	0.0000	-0.14702	-1.9615	0.0346	0.0561
RM3	**RM3**	0.0000	-0.1851	-2.1466	0.0510	0.1070
RM2	**RM2**	0.1852	0.0000	-1.9613	0.0510	
RM1	**RM1**	0.14689	0.0000	-1.8144	0.0346	
	MAJUBM	1.8145	0.0000	0.0000	0.0220	
	Sum:	2.1466	-2.1466			
	Misclose:		0.0000	0.0000	0.2140	(Total Dist.)
			ALLOWABLE (m):	**0.0007**	**2 x Sqrt (km) test:**	**PASS**

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
MAJUBM				0.000		0.0000
RM1	**RM1**	0.0000	-1.8145	-1.8145	0.022	0.0220
MAJUBM	**MAJUBM**	1.8145	0.0000	0.0000	0.022	
	Sum:	1.8145	-1.8145			
	Misclose:		0.0000	0.0000	0.0430	(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)
MAJUBM				0.0000		0.0000
RM3	**RM3**	0.0000	-2.1466	-2.1466	0.0280	0.0280
	MAJUBM	2.1466	0.0000	0.0000	0.0280	
	Sum:	2.1466	-2.1466			
	Misclose:		0.0000	0.0000	0.0560	(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 (MAJU) was tightly constrained to its ITRF2014 coordinates and aligned to MAJU-RM3 with an azimuth of 317° 59’ 56.918”, which had been determined in the 2007 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 MAJU as GNSS constraint are taken from the Geoscience Australia GNSS portal[1]. The ellipsoidal height is the ITRF2020 height from the week of the survey. For more information on how this ellipsoidal height was computed, see Brown et al. (2020).

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

Table 4.3.2 Latitude, Longitude and Ellipsoidal Height (metres) for the GNSS & RM stations. ITRF2014@2010.0 Latitude, Longitude coordinates, and ITRF2020@2020.1 ellipsoidal height were adopted at MAJU. CCC means all 3 dimensions (in XYZ) were constrained in the adjustment FFF means they were all free.

Station	Constraint	Latitude	Longitude	Ellipsoidal height (m)
MAJU	**CCC**	7° 07' 08.93585"	171° 21' 52.2713"	33.6911
RM1	**FFF**	7° 07' 09.3256"	171° 21' 52.8494"	30.9317
RM2	**FFF**	7° 07' 08.22931"	171° 21' 52.5965"	30.7851
RM3	**FFF**	7° 07'09.59872"	171° 21' 51.6738"	30.6008

Table 4.3.3 Earth Centred Cartesian coordinates and associated standard deviations (metres) for the GNSS & RM stations. ITRF2014@2010.0 Latitude, Longitude coordinates (as per https://gnss.ga.gov.au/network), and ITRF2020@2020.1 ellipsoidal height were adopted at MAJU.

Description	X	Y	Z	SD(e)	SD(n)	SD(up)
MAJU	-6257572.2582	950332.8058	785215.2915	0	0	0
RM1	-6257570.7472	950314.6358	785226.8303	0.0002	0.0002	0.0002
RM2	-6257573.5647	950322.9129	785193.3939	0.0002	0.0003	0.0002
RM3	-6257563.9783	950350.0942	785235.1148	0.0002	0.0002	0.0002

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

From	To	ΔE	ΔN	ΔU
MAJU	**RM1**	17.7371	11.9731	-2.7594
MAJU	**RM2**	9.9769	-21.7048	-2.9060
MAJU	**RM3**	-18.3357	20.3632	-3.0904

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
2007.5	**MAJU**	**RM1**	17.7372	11.9730	-2.7586
2007.9	**MAJU**	**RM1**	17.7375	11.9733	-2.7595
2009	**MAJU**	**RM1**	17.7378	11.9741	-2.7594
2010	**MAJU**	**RM1**	17.7375	11.9733	-2.7592
2013	**MAJU**	**RM1**	17.7378	11.9729	-2.7592

2015	**MAJU**	**RM1**	17.7367	11.9733	-2.7593
2017	**MAJU**	**RM1**	17.7378	11.9731	-2.7593
2018	**MAJU**	**RM1**	17.7377	11.9738	-2.7593
2020	**MAJU**	**RM1**	17.7371	11.9731	-2.7594
Ref RL	**(as at 2013)**		**17.7376**	**11.9733**	**-2.7592**

YEAR	FROM	To	ΔE	ΔN	ΔU
2007.5	**MAJU**	**RM2**	9.9769	-21.7039	-2.9046
2007.9	**MAJU**	**RM2**	9.977	-21.7046	-2.9055
2009	**MAJU**	**RM2**	9.9769	-21.7039	-2.9056
2010	**MAJU**	**RM2**	9.977	-21.7047	-2.9057
2013	**MAJU**	**RM3**	9.9773	-21.704	-2.9058
2015	**MAJU**	**RM2**	9.977	-21.7034	-2.9059
2017	**MAJU**	**RM2**	9.9765	-21.7044	-2.906
2018	**MAJU**	**RM2**	9.9769	-21.7045	-2.9059
2020	**MAJU**	**RM2**	9.9769	-21.7048	-2.906
Ref RL	**(as at 2013)**		**9.9770**	**-21.7042**	**-2.9054**

YEAR	FROM	To	ΔE	ΔN	ΔU
2007.5	**MAJU**	**RM3**	-18.3355	20.3631	-3.0889
2007.9	**MAJU**	**RM3**	-18.336	20.3635	-3.0899
2009	**MAJU**	**RM3**	-18.3369	20.3645	-3.0899
2010	**MAJU**	**RM3**	-18.3359	20.3634	-3.0900
2013	**MAJU**	**RM3**	-18.3356	20.3631	-3.0901
2015	**MAJU**	**RM3**	-18.3356	20.3631	-3.0901
2017	**MAJU**	**RM3**	-18.3358	20.3633	-3.0907
2018	**MAJU**	**RM3**	-18.3362	20.3638	-3.0902
2020	**MAJU**	**RM3**	-18.3357	20.3632	-3.0904
Ref RL	**(as at 2013)**		**-18.3360**	**20.3635**	**-3.0898**

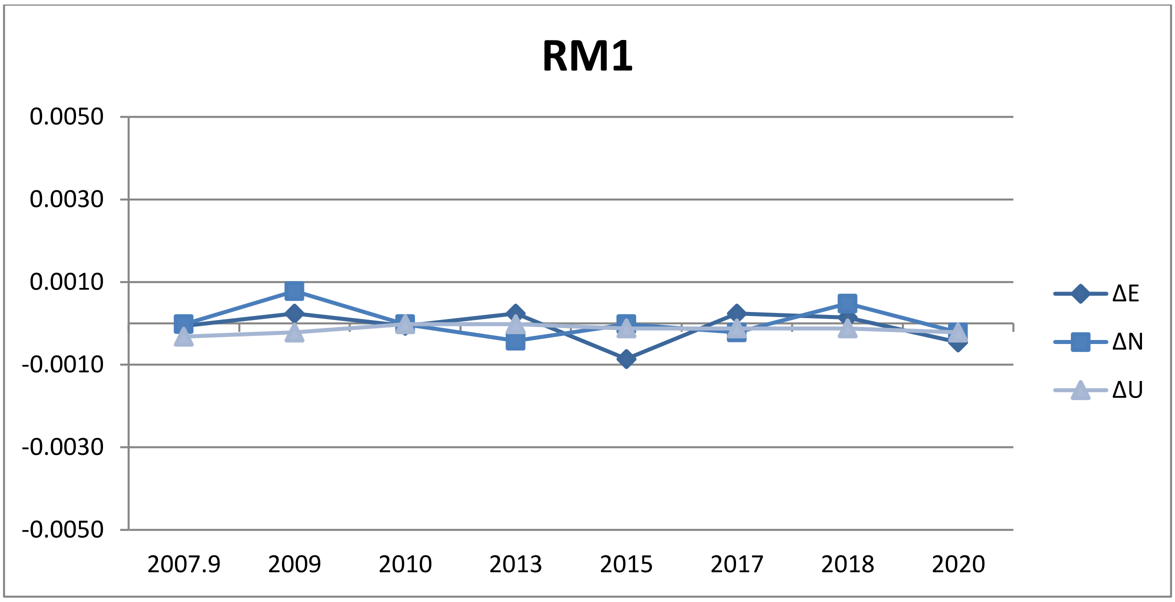


Figure 4.4.1 Time series of RM1 movement relative to GNSS pillar (0 = REF pre 2010 mean).

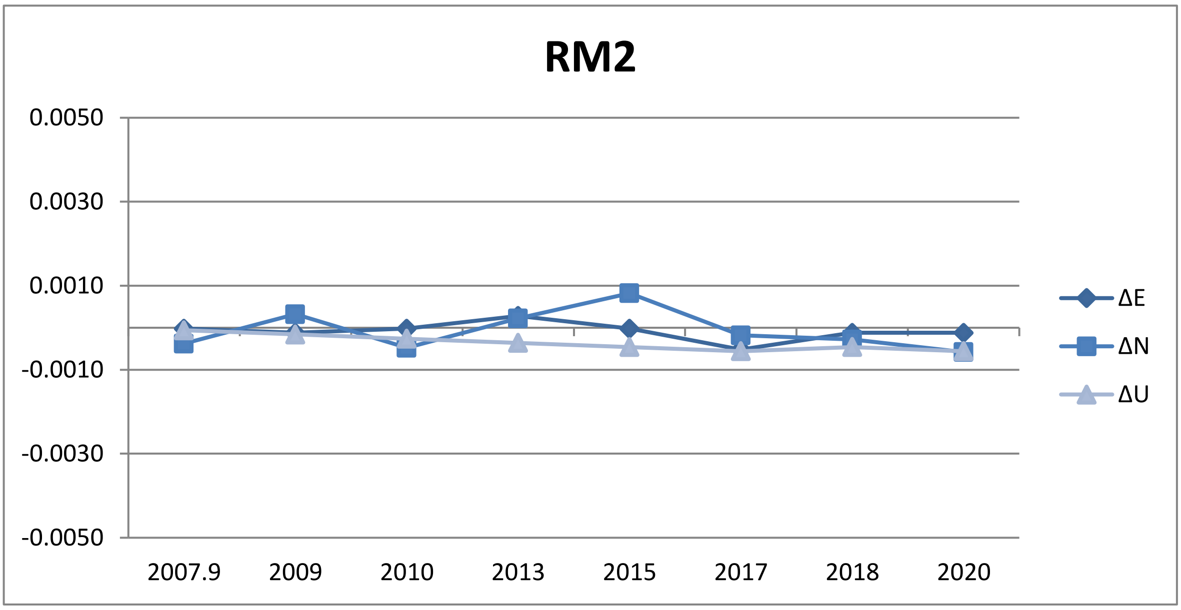


Figure 4.4.2 Time series of RM2 movement relative to GNSS pillar (0 = REF pre 2010 mean).

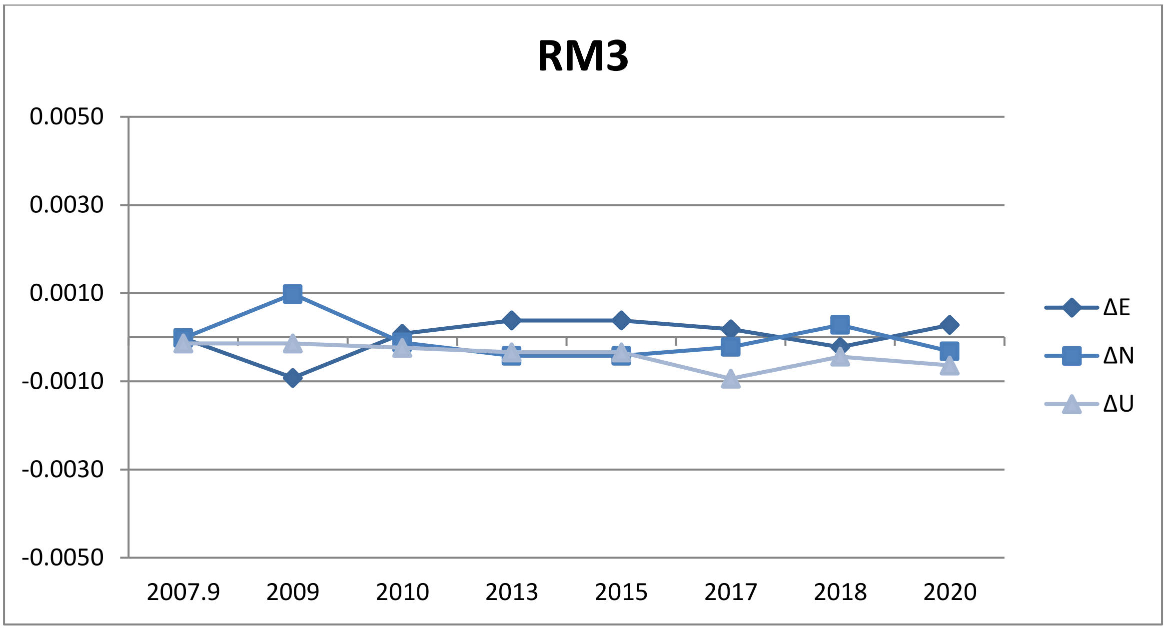


Figure 4.4.3 Time series of RM3 movement relative to GNSS pillar (0 = REF pre 2010 mean).

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 Majuro 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
MAJU (Ellipsoidal ht)	33.6911	Observed RL at the ARP of MAJU (Ellipsoidal) @ 2020.10
MAJU - MAJUBM	-0.9444	Offset constant between BM at GNSS pillar plate
Primary Pole & 1/2m Pole	1.00054	Height difference between poles used (Calibrated September 2019)

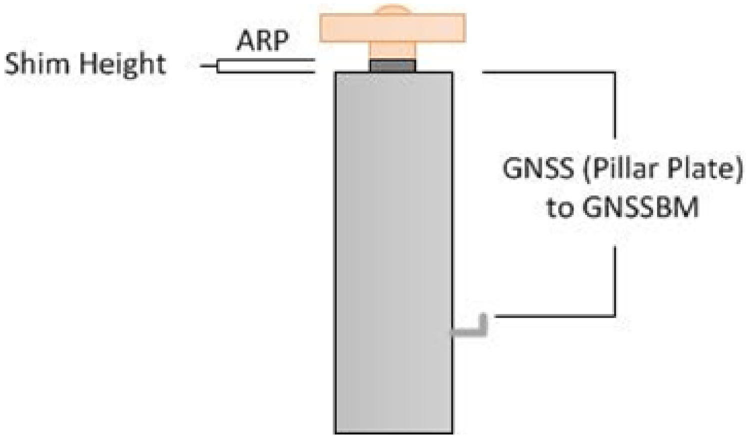


Figure 5.2.1 GNSS Pillar Offsets

5.3 Data Analysis and Results

Reduction of the digital data was computed using the Geoscience Australia levelling program "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 MAJUBM (GNSS BM)

Table 5.3.1 Reduced level data – MAJU (GNSS CORS) to MAR14 (Tide Gauge Benchmark).

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
MAJU				0.9444		
MAJUBM	**MAJUBM**	0.0000	-0.9444	0.0000	0.000	0.000
999	**999**	0.0000	-1.3886	-1.3886	0.119	0.119
102	**102**	0.0247	0.0000	-1.3639	0.202	0.321
110	**110**	0.1524	0.0000	-1.2115	0.176	0.496
MAR100	**MAR100**	0.0000	-0.4488	-1.6603	0.205	0.701
101	**101**	0.3066	0.0000	-1.3537	0.240	0.942
116	**116**	0.1164	0.0000	-1.2373	0.209	1.150
108	**108**	0.0000	-0.1666	-1.4039	0.198	1.348
31	**31**	0.0589	0.0000	-1.3449	0.188	1.536
MAR107	**MAR107**	0.0000	-0.1339	-1.4788	0.243	1.779
MAR13	**MAR13**	0.0000	-0.0779	-1.5567	0.227	2.006
MAR107	**MAR107**	0.0779	0.0000	-1.4788	0.227	
31	**31**	0.1337	0.0000	-1.3451	0.243	
108	**108**	0.0000	-0.0592	-1.4043	0.188	
116	**116**	0.1664	0.0000	-1.2379	0.198	
101	**101**	0.0000	-0.1161	-1.3540	0.209	
MAR100	**MAR100**	0.0000	-0.3071	-1.6610	0.240	
110	**110**	0.4491	0.0000	-1.2120	0.205	
102	**102**	0.0000	-0.1521	-1.3641	0.176	
999	**999**	0.0000	-0.0251	-1.3892	0.202	
MAJUBM	**MAJUBM**	1.3888	0.0000	-0.0004	0.119	
MAJU	**MAJU**	0.9444	0.0000	0.9440	0.000	
	Sum:	5.0243	-5.0247			
	Misclose:		-0.0004	-0.0004	4.050	(Total Dist.)
			ALLOWABLE (m):	**0.0028**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.2 Reduced level data – MAR107 (Deep Driven Benchmark) to MAR50 (Deep Driven Benchmark).

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
MAR107				-1.4788	0.000	1.779
106	**106**	0.2663	0.0000	-1.2125	0.179	1.958
114	**114**	0.0000	-0.0366	-1.2491	0.197	2.155

MAR15	**MAR15**	0.0000	-0.1536	-1.4027	0.143	2.298
104	**104**	0.1996	0.0000	-1.2031	0.211	2.509
MAR50	**MAR50**	0.0000	-0.4309	-1.6340	0.050	2.559
104	**104**	0.4309	0.0000	-1.2031	0.050	
MAR15	**MAR15**	0.0000	-0.1997	-1.4028	0.211	
114	**114**	0.1538	0.0000	-1.2490	0.143	
106	**106**	0.0366	0.0000	-1.2124	0.197	
	MAR107	0.0000	-0.2662	-1.4786	0.179	
	Sum:	1.0872	-1.0870			
	Misclose:		0.0002	0.0002	1.562	(Total Dist.)
			ALLOWABLE (m):	**0.0018**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.3 Reduced level data – MAR13 (Tide Gauge Benchmark) to MAR14 (SEAFRAME sensor reference benchmark).

From	To	Rise (m)	Fall (m)	RL (m)	Dist (Km)	Acc Dist (km)
MAR13				-1.5567		2.006
MAR14	**MAR14**	1.2050	0.0000	-0.3517	0.019	2.025
	MAR13	0.0000	-1.2050	-1.5567	0.019	
	Sum:	1.2050	-1.2050			
	Misclose:		0.0000	0.0000	0.039	(Total Dist.)
			ALLOWABLE (m):	**0.0003**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.4 Reduced level data – MAR13 (Tide Gauge Benchmark) to MAR14A (new SEAFRAME sensor reference benchmark).

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
MAR13				-1.5567		2.006
MAR14A	**MAR14A**	1.5918	0.0000	0.0350	0.020	2.026
	MAR13	0.0000	-1.5918	-1.5567	0.020	
	Sum:	1.5918	-1.5918			
	Misclose:		0.0000	0.0000	0.041	(Total Dist.)
			ALLOWABLE (m):	**0.0003**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.5 Reduced level data – 108 to MAR3.

From	To	Rise (m)	Fall (m)	RL (m)	Dist (km)	Acc Dist (km)
108				-1.4041		1.348
MAR3	**MAR3**	0.0000	-0.1321	-1.5362	0.020	1.368
	108	0.1322	0.0000	-1.4040	0.020	
	Sum:	0.1322	-0.1321			
	Misclose:		0.0001	0.0001	0.040	(Total Dist.)
			ALLOWABLE (m):	**0.0003**	**2 x Sqrt (km) test:**	**PASS**

Table 5.3.6 Measured height differences (in metres) between all BMs (ΔRL_{2020}).

	MAJUBM	MAR100	MAR3	MAR107	MAR13	MAR14	MAR15	MAR50	RM1	RM2	RM3	MAJU
MAJUBM	-	-1.6607	-1.5362	-1.4788	-1.5567	-0.3517	-1.4028	-1.6340	-1.8145	-1.9614	-2.1466	0.9444
MAR100	1.6607	-	0.1244	0.1819	0.1039	1.3089	0.2579	0.0266	-0.1538	-0.3008	-0.4859	2.6051
MAR3	1.5362	-0.1244	-	0.0574	-0.0205	1.1845	0.1335	-0.0978	-0.2782	-0.4252	-0.6103	2.4806
MAR107	1.4788	-0.1819	-0.0574	-	-0.0779	1.1271	0.0760	-0.1552	-0.3357	-0.4826	-0.6678	2.4232
MAR13	1.5567	-0.1039	0.0205	0.0779	-	1.2050	0.1540	-0.0773	-0.2577	-0.4047	-0.5898	2.5011
MAR14	0.3517	-1.3089	-1.1845	-1.1271	-1.2050	-	-1.0510	-1.2823	-1.4627	-1.6097	-1.7948	1.2961
MAR15	1.4028	-0.2579	-0.1335	-0.0760	-0.1540	1.0510	-	-0.2313	-0.4117	-0.5587	-0.7438	2.3472
MAR50	1.6340	-0.0266	0.0978	0.1552	0.0773	1.2823	0.2313	-	-0.1805	-0.3274	-0.5125	2.5784
RM1	1.8145	0.1538	0.2782	0.3357	0.2577	1.4627	0.4117	0.1805	-	-0.1470	-0.3321	2.7589
RM2	1.9614	0.3008	0.4252	0.4826	0.4047	1.6097	0.5587	0.3274	0.1470	-	-0.1851	2.9058
RM3	2.1466	0.4859	0.6103	0.6678	0.5898	1.7948	0.7438	0.5125	0.3321	0.1851	-	3.0910
MAJU	-0.9444	-2.6051	-2.4806	-2.4232	-2.5011	-1.2961	-2.3472	-2.5784	-2.7589	-2.9058	-3.0910	-

Table 5.3.7 Time-series of Reduced Levels (with respect to MAJUBM).

YEAR	MAJUBM	MAR100	MAR3	MAR107	MAR13	MAR14	MAR15	MAR50	RM1	RM2	RM3	MAJU
1993.4			-1.5334		-1.5494	-0.3440						
1994.5			-1.5334		-1.5485	-0.3427						
1995.5			-1.5334		-1.5491	-0.3439	-1.3900					
1997.0			-1.5334		-1.5488	-0.3430	-1.3905					
1998.6			-1.5334		-1.5493	-0.3440	-1.3910					
2000.3			-1.5334		-1.5495	-0.3447	-1.3916					
2001.7			-1.5334		-1.5494	-0.3434	-1.3920					
2003.1			-1.5334		-1.5489	-0.3486	-1.3964	-1.6318				
2006.3			-1.5334		-1.5488	-0.3503	-1.3982	-1.6321				
2006.3			-1.5334		-1.5498	-0.3516	-1.3982	-1.6318				
2007.8	0.0000	-1.6591	-1.5334	-1.4769	-1.5495	-0.3481	-1.3993	-1.6326				0.9443
2009.2	0.0000	-1.6598	-1.5337	-1.4771	-1.5501	-0.3491	-1.3984	-1.6323				0.9443
2010.8	0.0000	-1.6590	-1.5345	-1.4769	-1.5494	-0.3494	-1.3975	-1.6313				0.9445
2012.5	0.0000	-1.6593	-1.5339	-1.4761	-1.5484	-0.3519	-1.3979	-1.6317				0.9445
2013.8	0.0000	-1.6609	-1.5378	-1.4804	-1.5525	-0.3509	-1.4041	-1.6354				0.9442
2015.6	0.000	-1.6593	-1.5342	-1.4771	-1.5538	-0.3484	-1.4007	-1.6326	-1.8145	-1.9611	-2.1459	0.9446
2017.2	0.000	-1.6588	-1.5340	-1.4768	-1.5557	-0.3532	-1.4015	-1.6331	-1.8147	-1.9616	-2.1464	0.9444
2018.4	0.000	-1.6593	-1.5341	-1.4769	-1.5557	-0.3495	-1.4013	-1.6330	-1.8145	-1.9613	-2.1462	0.9444
2020.1	0.000	-1.6607	-1.5362	-1.4788	-1.5567	-0.3517	-1.4028	-1.6340	-1.8145	-1.9614	-2.1466	0.9444

5.4 Comparison with previous surveys

All historic data has been readjusted relative to the benchmark attached to the base of the GNSS pillar (MAJUBM) (Table 5.3.7). To investigate whether BMs have moved over time, the RLs from the 2020 survey (RL_{2020}) 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_{2020} values (in metres). Shows the difference in height between two marks from the current survey compared to the reference height difference.

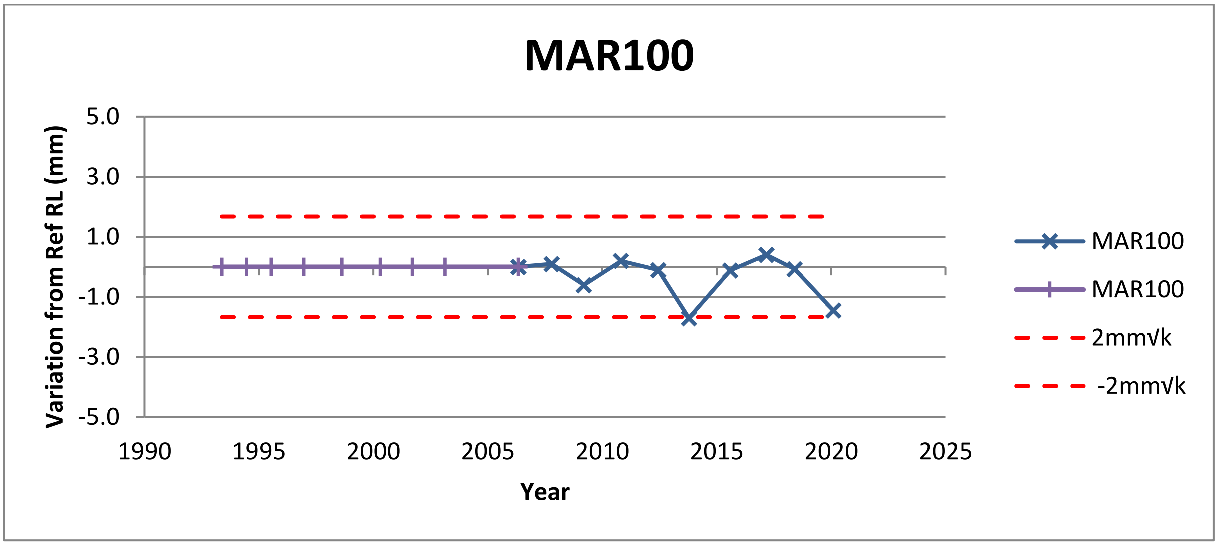
REF - 2020	MAJUBM	MAR100	MAR3	MAR107	MAR13	MAR14	MAR15	MAR50	RM1	RM2	RM3	MAJU
MAJUBM	-	0.0015	0.0028	0.0019	**0.0075**	0.0025	0.0048	0.0018	-0.0001	0.0003	0.0005	0.0000
MAR100	-0.0015	-	0.0013	0.0005	**0.0061**	0.0010	0.0033	0.0003	-0.0015	-0.0012	-0.0009	-0.0015
MAR3	-0.0028	-0.0013	-	-0.0009	0.0047	-0.0003	0.0020	-0.0010	-0.0028	-0.0025	-0.0022	-0.0028
MAR107	-0.0019	-0.0005	0.0009	-	0.0056	0.0006	0.0029	-0.0002	-0.0020	-0.0016	-0.0014	-0.0019
MAR13	**-0.0075**	**-0.0061**	-0.0047	-0.0056	-	-0.0050	-0.0027	**-0.0057**	**-0.0076**	**-0.0072**	**-0.0070**	**-0.0075**
MAR14	-0.0025	-0.0010	0.0003	-0.0006	0.0050	-	0.0023	-0.0007	-0.0025	-0.0022	-0.0019	-0.0025
MAR15	-0.0048	-0.0033	-0.0020	-0.0029	0.0027	-0.0023	-	-0.0030	-0.0048	-0.0045	-0.0042	-0.0048
MAR50	-0.0018	-0.0003	0.0010	0.0002	**0.0057**	0.0007	0.0030	-	-0.0018	-0.0015	-0.0012	-0.0018
RM1	0.0001	0.0015	0.0028	0.0020	**0.0076**	0.0025	0.0048	0.0018	-	0.0003	0.0006	0.0001
RM2	-0.0003	0.0012	0.0025	0.0016	**0.0072**	0.0022	0.0045	0.0015	-0.0003	-	0.0003	-0.0003
RM3	-0.0005	0.0009	0.0022	0.0014	**0.0070**	0.0019	0.0042	0.0012	-0.0006	-0.0003	-	-0.0005
MAJU	0.0000	0.0015	0.0028	0.0019	**0.0075**	0.0025	0.0048	0.0018	-0.0001	0.0003	0.0005	-

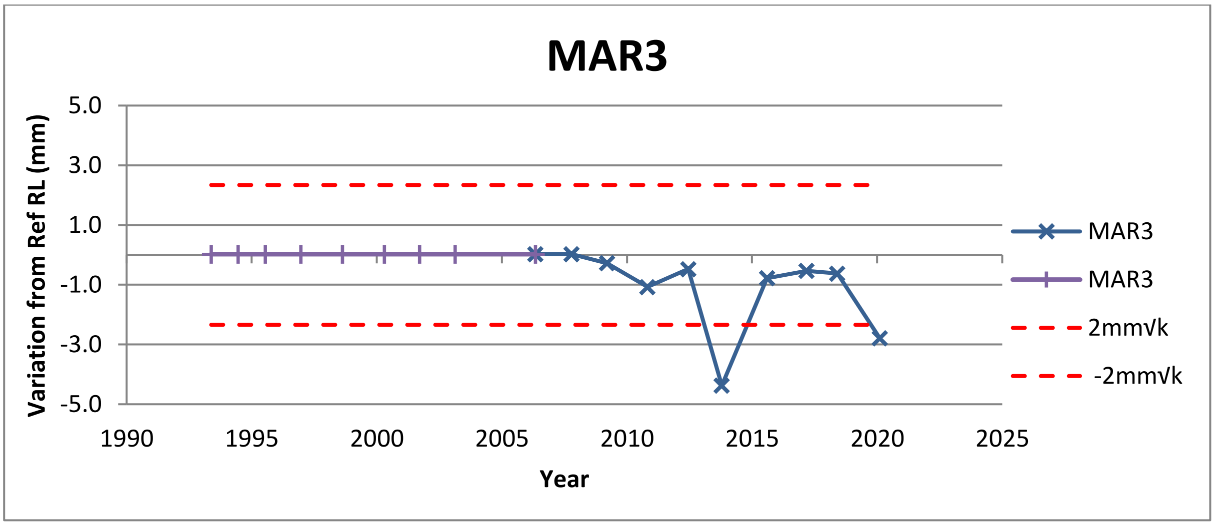
Table 5.4.1.1 values are calculated by subtracting the difference in height between RL_{20} values (Table 5.3.6) from the difference in height between RL_{REF} values.

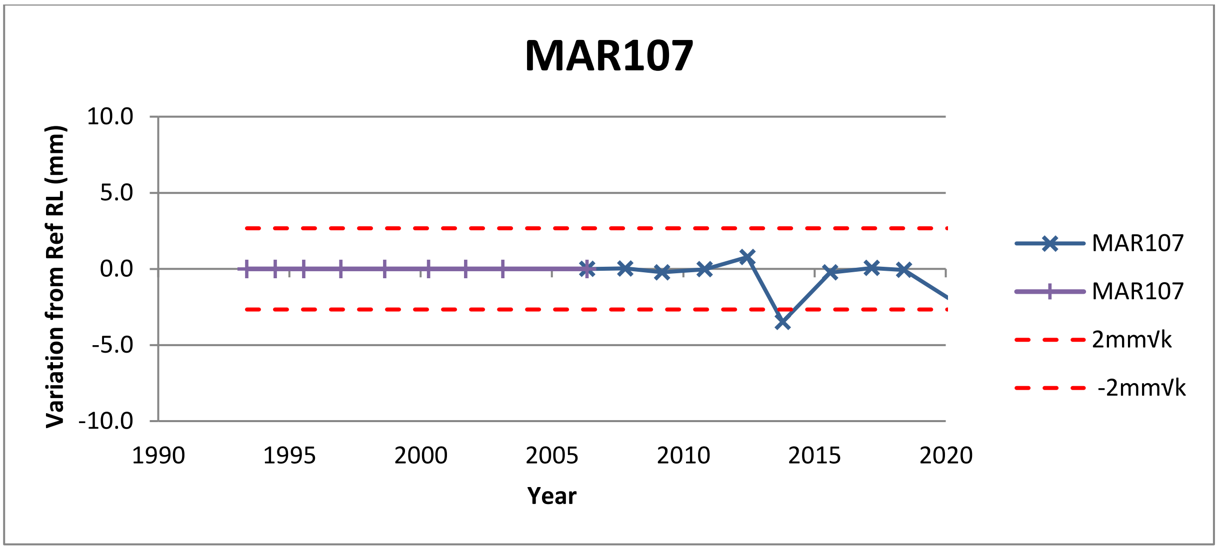
Comparing the change in relative heights between all benchmarks can help identify movement of a particular BM, inconsistency in survey, or even deformation between the GNSS pillar and levelling run BMs.

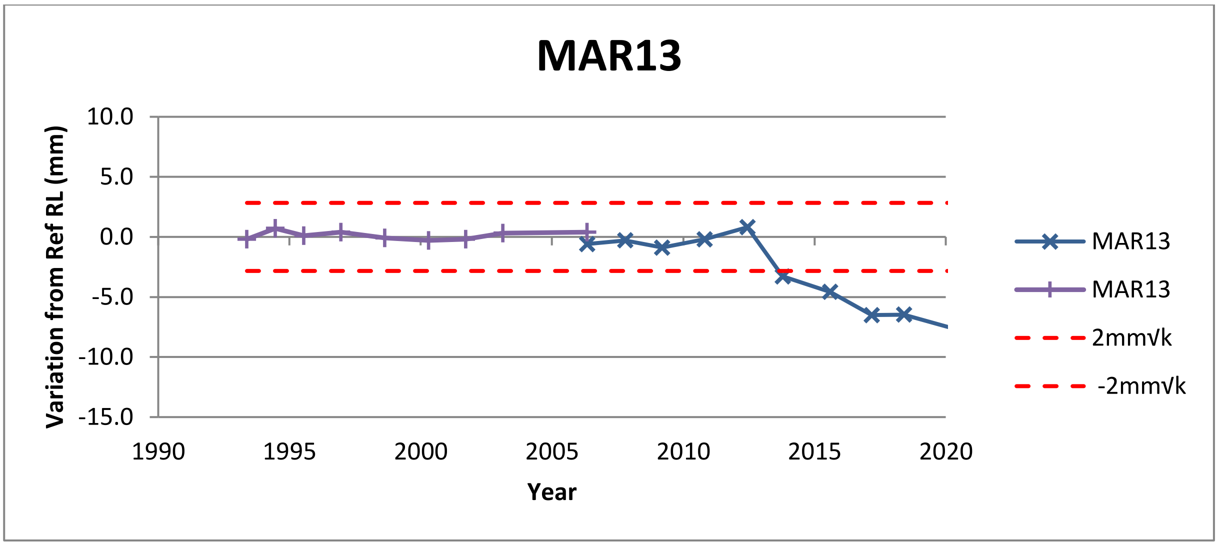
5.4.2 Time series charts for each BM

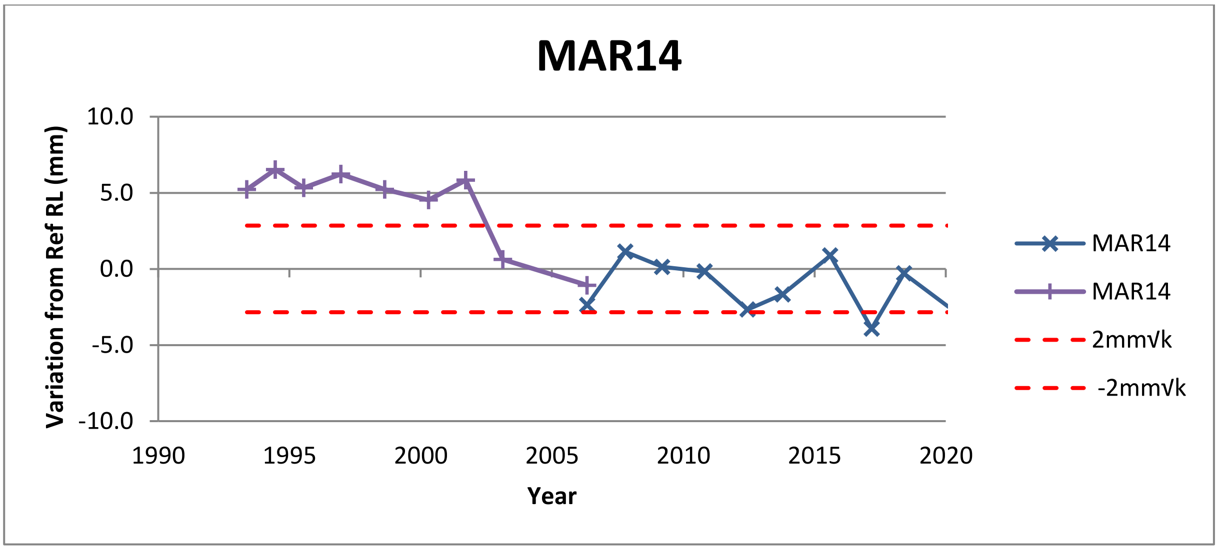
The change in RL over time can be used to detect trends of movement or survey errors. In the series of figures below, the red dashed lines represent the allowable error in height based on the levelling technique used and distance of the benchmark from the GNSS pillar ($2mm\sqrt{K}$). The purple line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

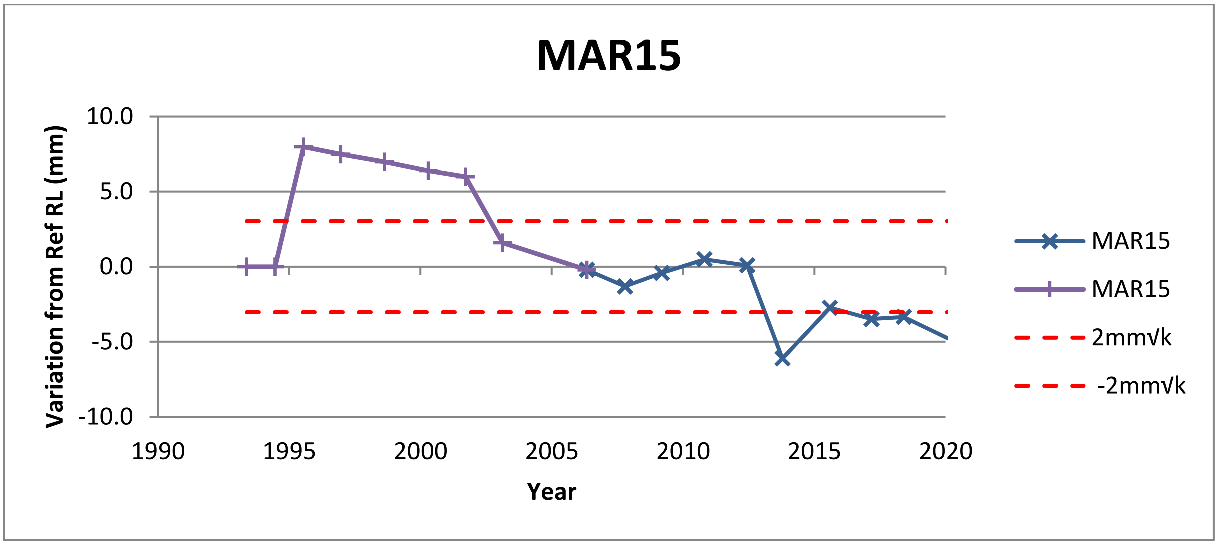




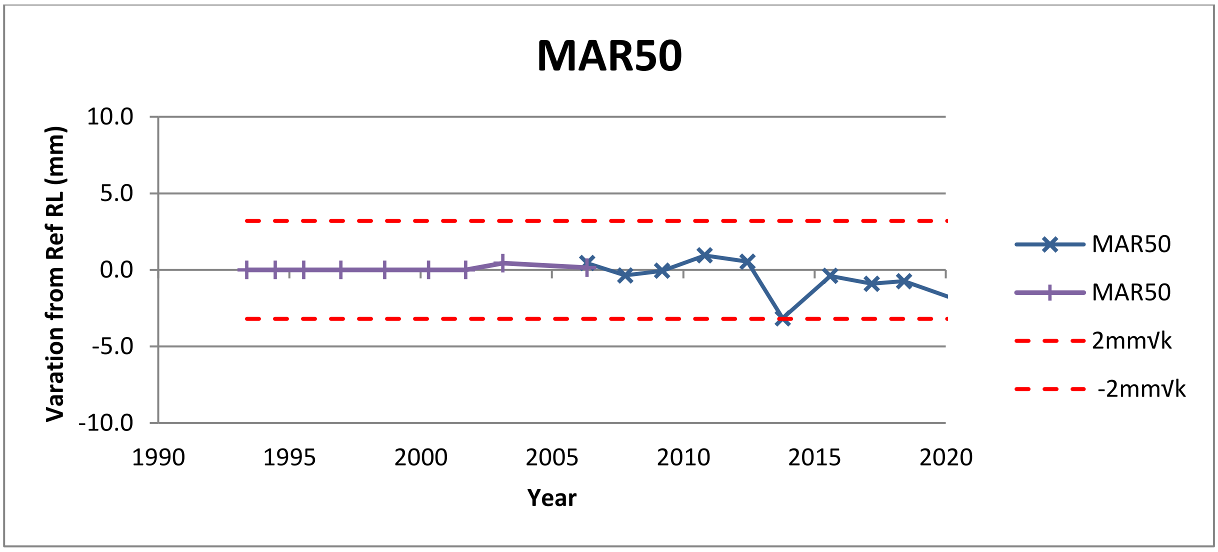

MAR107
Variation from Ref RL (mm)
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Year
MAR107
MAR107
2mm√k
-2mm√k


MAR13
Variation from Ref RL (mm)
10.0
5.0
0.0
-5.0
-10.0
-15.0
1990
1995
2000
2005
2010
2015
2020
Year
MAR13
MAR13
2mm√k
-2mm√k


MAR14
Variation from Ref RL (mm)
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Year
MAR14
MAR14
2mm√k
-2mm√k



MAR15
Variation from Ref RL (mm)
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Year
MAR15
MAR15
2mm√k
-2mm√k



MAR50
Varation from Ref RL (mm)
10.0
5.0
0.0
-5.0
-10.0
1990
1995
2000
2005
2010
2015
2020
Year
MAR50
MAR50
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 couple of differences above 0.003 m:

- MAR13 and MAR15, which is likely due to
  - localised movement of MAR13 – which is located on a concrete block at the Uliga dock where there is a high chance of deformation of this part of the wharf structure.
  - localised movement of MAR15 – which is located within the Mobil fuel depot compound, where there is frequent movement of heavy vehicles around this benchmark.

The survey was completed within project specification. Small variation of individual RLs are expected within this value, but outliers and deformation can therefore be identified if they exist beyond this.

The survey from the primary GNSS BM (MAJUBM) to the TG Plaque (MAR13) shows significant changes. There is a high chance of deformation on the wharf structure (concrete block where MAR13 is installed) when looking at the two past result of this benchmark.

The SEAFRAME sensor reference benchmark in its old location (MAR14) is 3.8486 m above the Tide Gauge Zero of the Tide Gauge Station (refer to Table 6.2).

The SEAFRAME sensor reference benchmark in its new location (MAR14A) is 4.2354 m above the Tide Gauge Zero of the Tide Gauge Station (refer to Table 6.2).

Table 6.1 Comparison of results with Reference ^H (m

PT ID	Reference ^H (m)	2020.1 Value (m)	Difference
MAJUBM - Primary BM (MAR107)	-1.4769	-1.4788	0.0019
MAR107 - TG Plaque BM (MAR13)	-0.0723	-0.0779	0.0056
MAR107 - TG ref pin (MAR14)	1.1276	1.1271	-0.0006
MAJUBM - MAR3	-1.5334	-1.5362	0.0028
MAR3 - MAR13	-0.0158	-0.0205	0.0047
MAR13 - MAR14	1.2000	1.2050	0.0050
MAJU - TG Plaque	-2.4936	-2.5011	0.0075
MAJU - TG BM	-1.2936	-1.2961	0.0025
MAJU - TGZ	-5.1422	-5.1447	0.0025

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

PT ID	Reference RL (m)	2020.1 Value (m)	Difference	TGZ	ITRF2020
MAJUBM	0.000	0.000	0.0000	4.2003	32.7467
MAR100	-1.6592	-1.6606	-0.0014	2.5397	31.0861
MAR3	-1.5334	-1.5362	-0.0028	2.6641	31.2105
MAR107	-1.4769	-1.4788	-0.0019	2.7215	31.2679
MAR13	-1.5492	-1.5567	-0.0075	2.6436	31.1900
MAR14	-0.3492	-0.3517	-0.0025	3.8486	32.3950
MAR15	-1.3980	-1.4027	-0.0048	2.7976	31.3440
MAR50	-1.6322	-1.6340	-0.0018	2.5663	31.1127
RM1	-1.8145	-1.8145	0.0001	2.3859	30.9322
RM2	-1.9611	-1.9614	-0.0003	2.2389	30.7853
RM3	-2.1460	-2.1466	-0.0005	2.0538	30.6002
MAJU	0.9444	0.9444	0.0000	5.1447	33.6911
MAR14A		0.0351		4.2354	32.7818
TGZ	-4.1978	-4.2003	-0.0025	0.0000	28.5464

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).

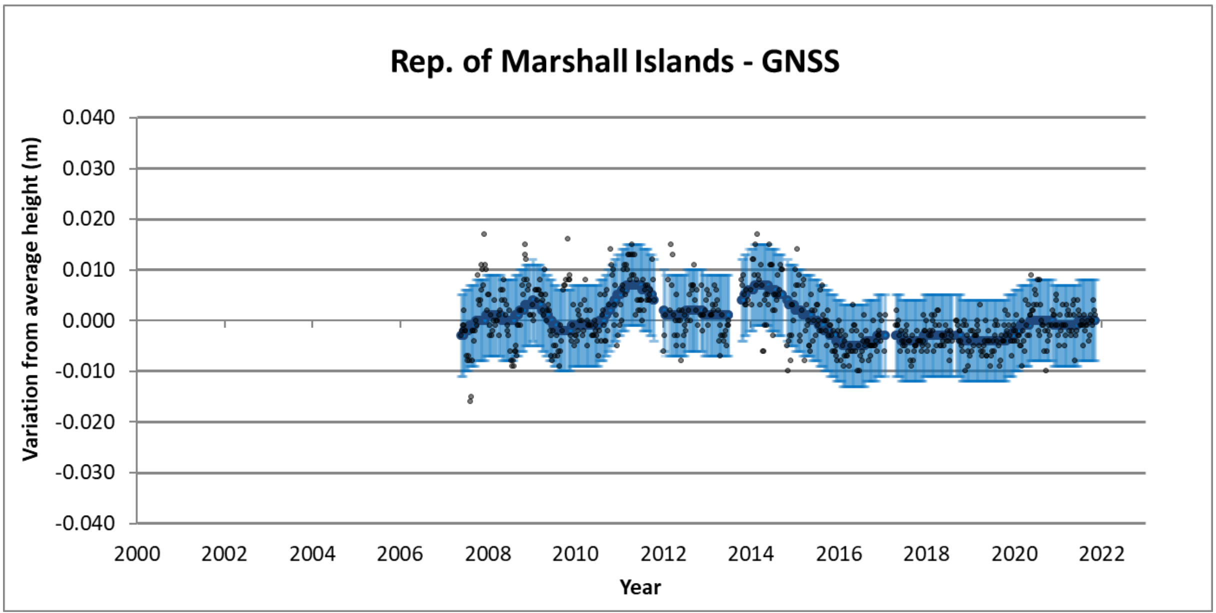


Figure 7.1 Time series of GNSS analysis (dark blue line) with 95%CI uncertainty (light blue lines).

[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.

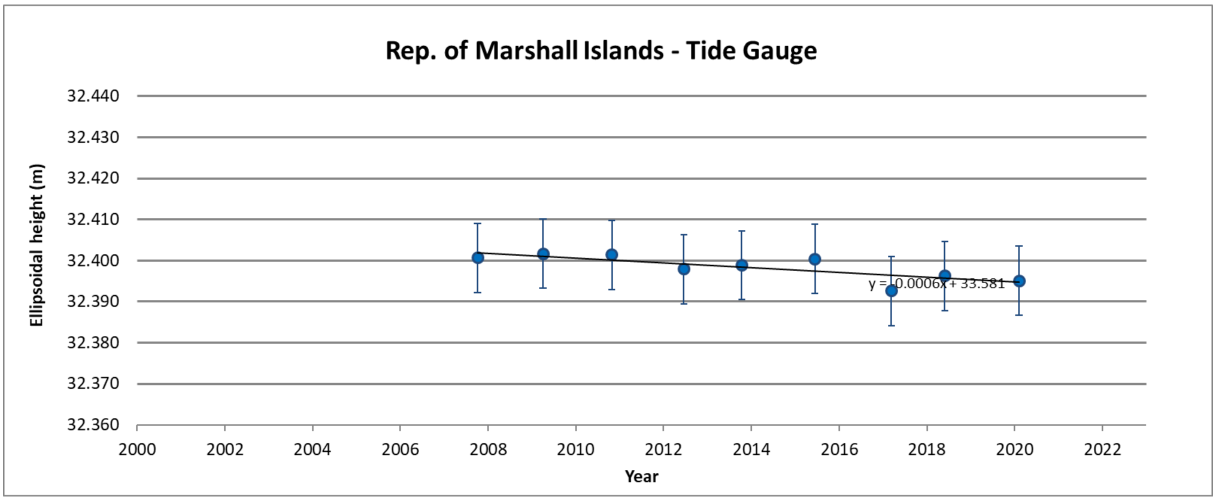


Figure 7.2 The height of the SEAFRAME sensor reference benchmark (with respect to ITRF2020).

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)
2007.76	32.4007	0.008
2009.25	32.4017	0.008
2010.82	32.4014	0.008
2012.46	32.3979	0.008
2013.78	32.3989	0.008
2015.45	32.4004	0.008
2017.19	32.3926	0.008
2018.41	32.3963	0.008
2020.10	32.3951	0.008

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

8 References

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Appendix A Locality Diagrams

Source: Google Maps

A 1 Deep Benchmarks

PACIFIC SEA LEVEL MONITORING PROJECT

Australian Aid

Australian Government
Geoscience Australia

Pacific Community
Communauté du Pacifique

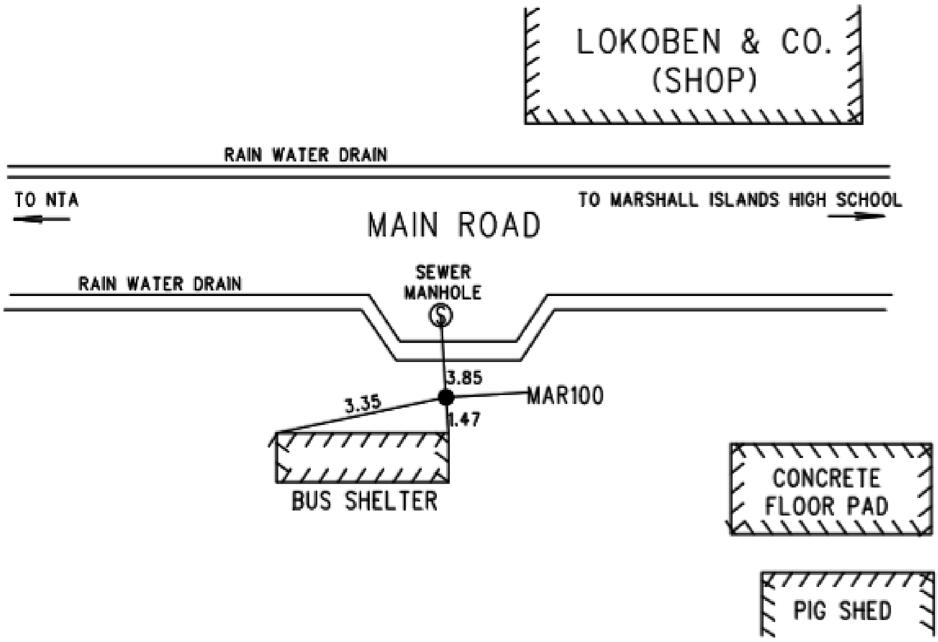
SURVEY BENCH MARK RECORD

Bench Mark Number: **MAR100**

Original Bench Mark Established by: The Pacific Community (SPC), with Geoscience Australia	*Date: 28.04.06*
Existing Bench Mark Established by:	*Date:*
Notes / References: Deep driven bench mark, covered by plastic housing. Good location for GNSS obs.	
Country: Marshall Island *Island: Majuro*	

MARKING AND LOCALITY SKETCH

Bench Mark: 19mm diameter stainless steel capped rod driven until refusal. Rod sheathed with PVC tube for top 0.2m. Top of mark 0.10 above ground. (mound built around valve box)



NOT TO SCALE | Distances in Metres | Magnetic Bearings

Approved by: *Date:*

PACIFIC SEA LEVEL MONITORING PROJECT

Australian Government
Geoscience Australia

SPC
Secretariat of the Pacific Community

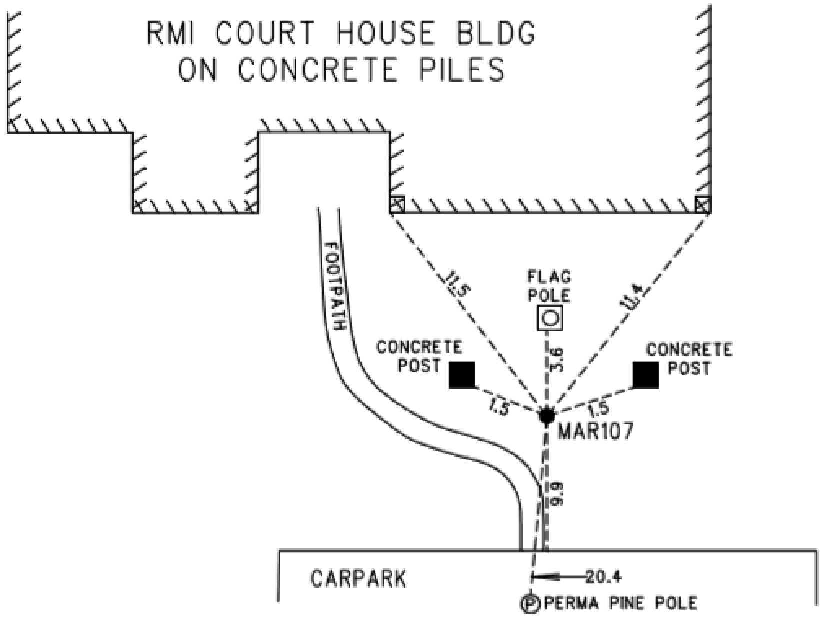
SURVEY BENCH MARK RECORD

Bench Mark Number: MAR107

Original Bench Mark Established by: Geodetic Unit of The Pacific Community (SPC), Department with Geoscience Australia	*Date: 04.04.09*
Existing Bench Mark Established by:	
Notes / References: Deep driven bench mark, covered by plastic housing. Good location for GNSS obs.	
Country: Marshall Islands *Island:* Majuro	*City:* *Uliga*

MARKING AND LOCALITY SKETCH

Bench Mark: 19mm diameter stainless steel capped rod driven until refusal. Rod sheathed with PVC tube for top 0.2m. Top of mark 0.10 above ground. (mound built around valve box)



NOT TO SCALE Distances in Metres Magnetic Bearings

Approved by: Geoscience Australia / SPC *Date:14.04.18*

PACIFIC SEA LEVEL MONITORING PROJECT

SURVEY BENCH MARK RECORD

Australian Government
Geoscience Australia

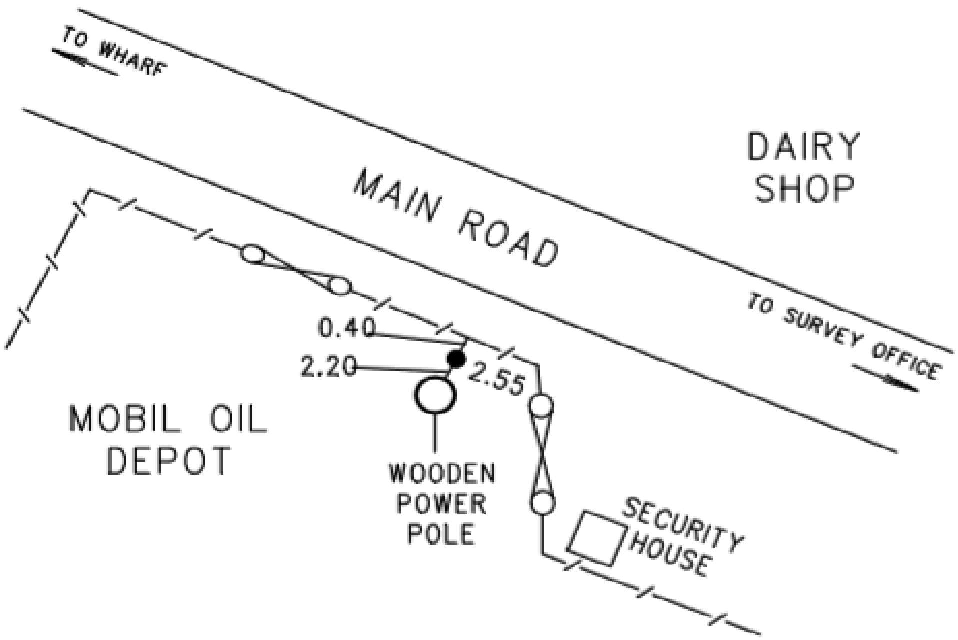
SPC
Secretariat of the Pacific Community

Bench Mark Number: MAR15

Original Bench Mark Established by: Geodetic Unit of The Pacific Community (SPC), Department with Geoscience Australia	*Date: 04.04.09*
Existing Bench Mark Established by:	
Notes / References: Deep driven bench mark, covered by plastic housing. Good location for GNSS obs.	
Country: Marshall Islands *Island:* Majuro	*City:* *Uliga*

MARKING AND LOCALITY SKETCH

Bench Mark: 19mm diameter stainless steel capped rod driven until refusal. Rod sheathed with PVC tube for top 0.2m. Top of mark 0.10 above ground. (mound built around valve box)



NOT TO SCALE | Distances in Metres | Magnetic Bearings

Approved by: Geoscience Australia / SPC *Date:14.04.18*

PACIFIC SEA LEVEL MONITORING PROJECT

Australian Government
Geoscience Australia

SPC Secretariat of the Pacific Community

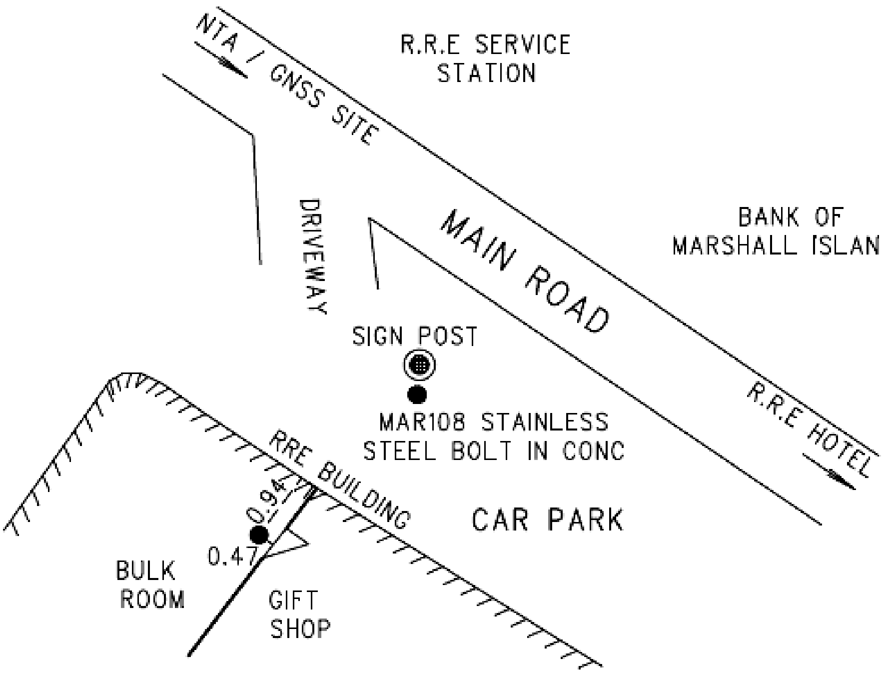
SURVEY BENCH MARK RECORD

Bench Mark Number: MAR3

Original Bench Mark Established by: Geodetic Unit of The Pacific Community (SPC), Department with Geoscience Australia	*Date: 04.04.09*
Existing Bench Mark Established by:	
Notes / References: Deep driven bench mark, covered by plastic housing. Good location for GNSS obs.	
Country: Marshall Islands *Island:* Majuro	*City:* Uliga

MARKING AND LOCALITY SKETCH

Bench Mark: 19mm diameter stainless steel capped rod driven until refusal. Rod sheathed with PVC tube for top 0.2m. Top of mark 0.10 above ground. (mound built around valve box)



NOT TO SCALE — Distances in Metres — Magnetic Bearings

Approved by: Geoscience Australia / SPC — *Date:14.04.18*

PACIFIC SEA LEVEL MONITORING PROJECT

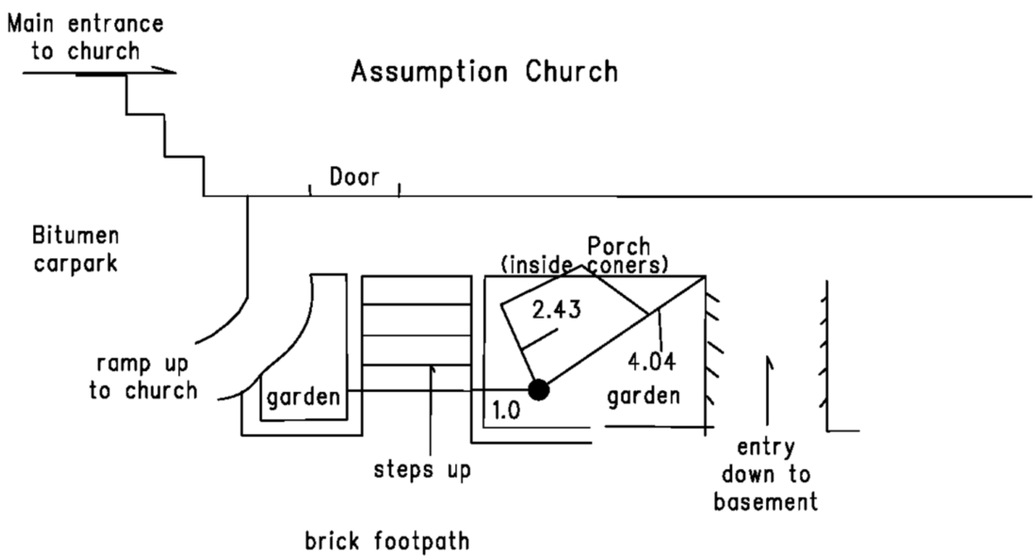
SURVEY BENCH MARK RECORD

Bench Mark Number: MAR50

Original Bench Mark Established by: National Tidal Centre Australia, Oceanographic Services, BoM, 25 College Rd, Kent Town, SA	*Date: 20/02/2003*
Existing Bench Mark Established by: S. Turner & A. Lal	*Date:*
Notes / References: Deep driven bench mark, covered by plastic housing. Good location for GNSS Occupation.	
Country: Republic of Marshall Island *Atoll: Majuro*	*City: Uliga*

MARKING AND LOCALITY SKETCH

Bench Mark: 2.0m of 19mm diameter stainless steel capped rod driven until refusal. Rod sheathed with 50mm diameter PVC pipe, filled with bentonite, for 0.6m, top of mark 0.1m below ground level. Locality sketch Mark approximately 1050m from the tide gauge station. Not to scale distances in meters & Magnetic bearing

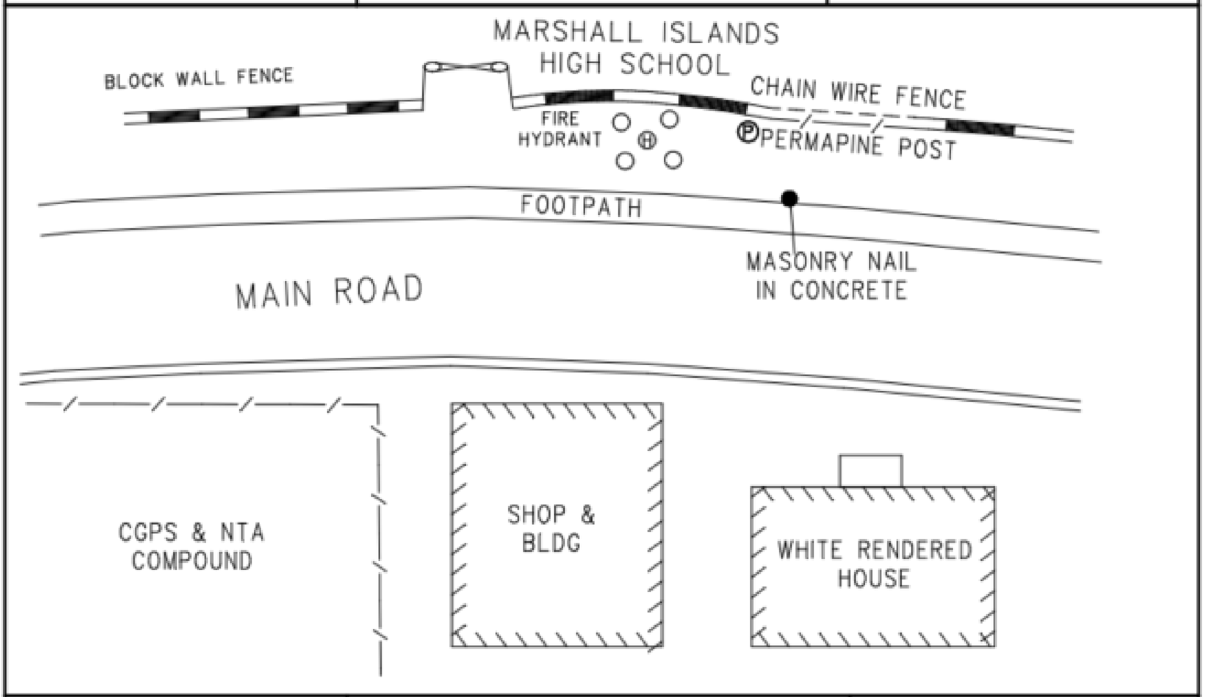


NOT TO SCALE Distances in Metres Magnetic Bearings

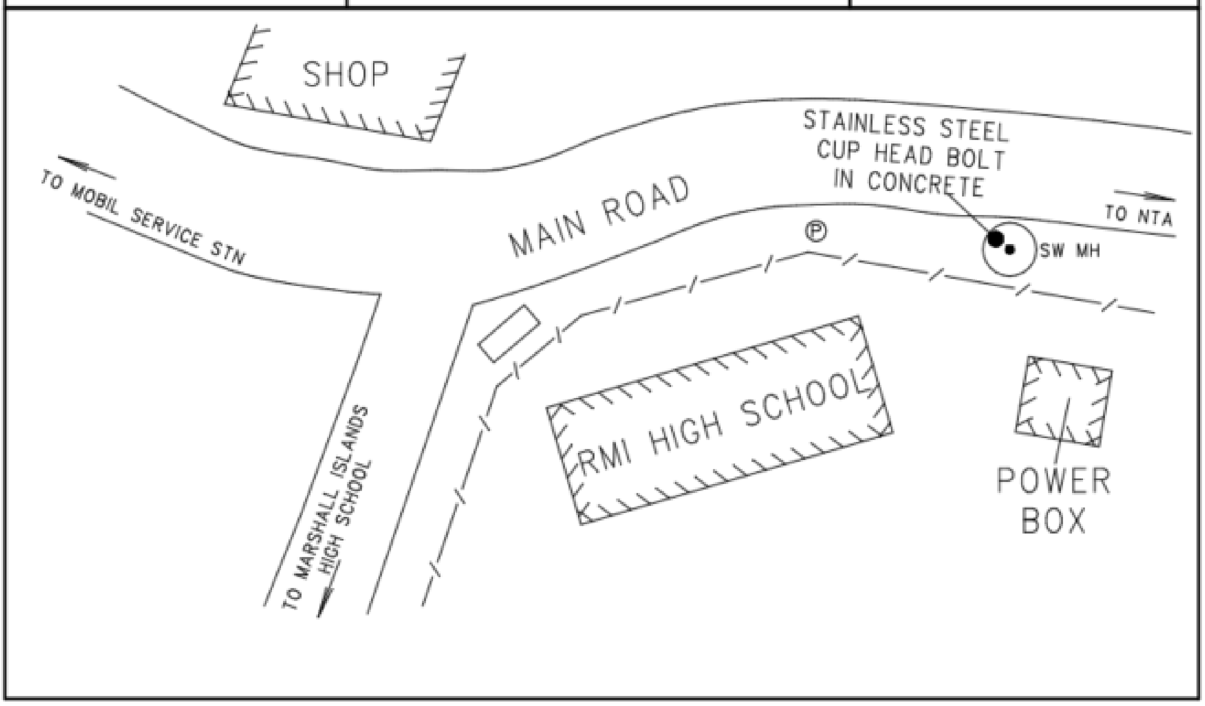
Approved by: Geoscience Australia / SPC *Date: Nov 2007*

A 2 Temporary Holdings Marks

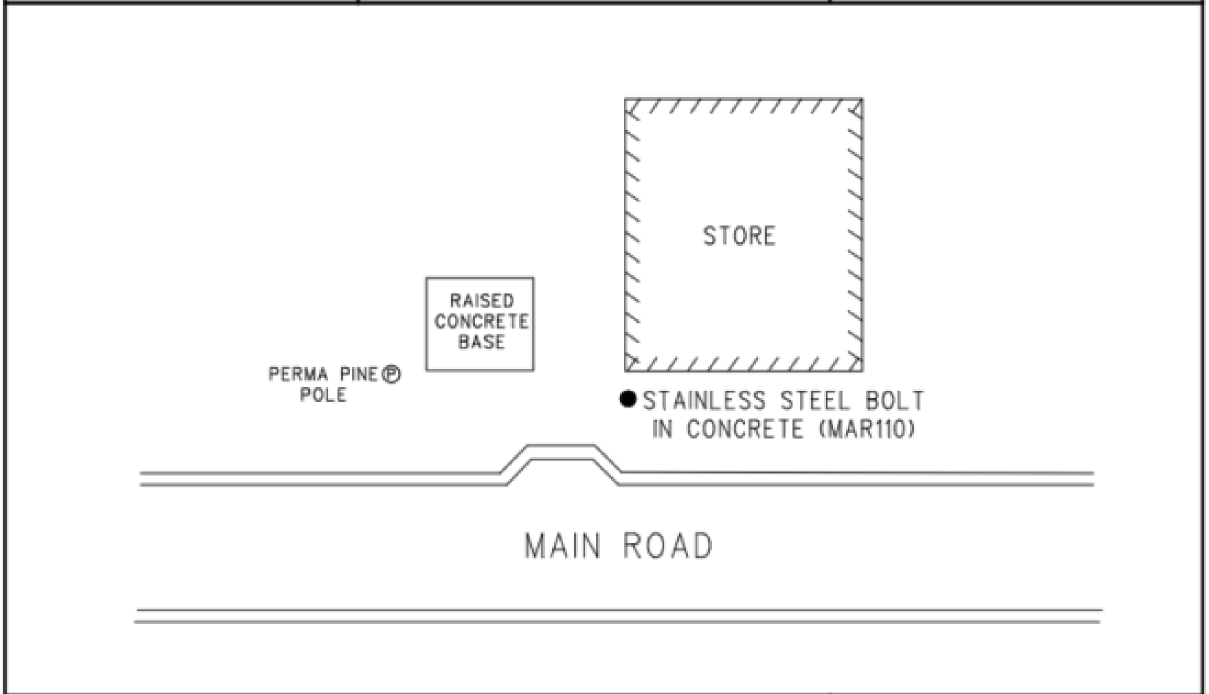
COUNTRY: Marshall Islands	ATOLL: Majuro CITY: Uliga	L. D. P. New Mark POINT NO. 999
PROJECT: SPSLCMP	SURVEYOR: A Lal & V Rattan	DATE: 8-02-20



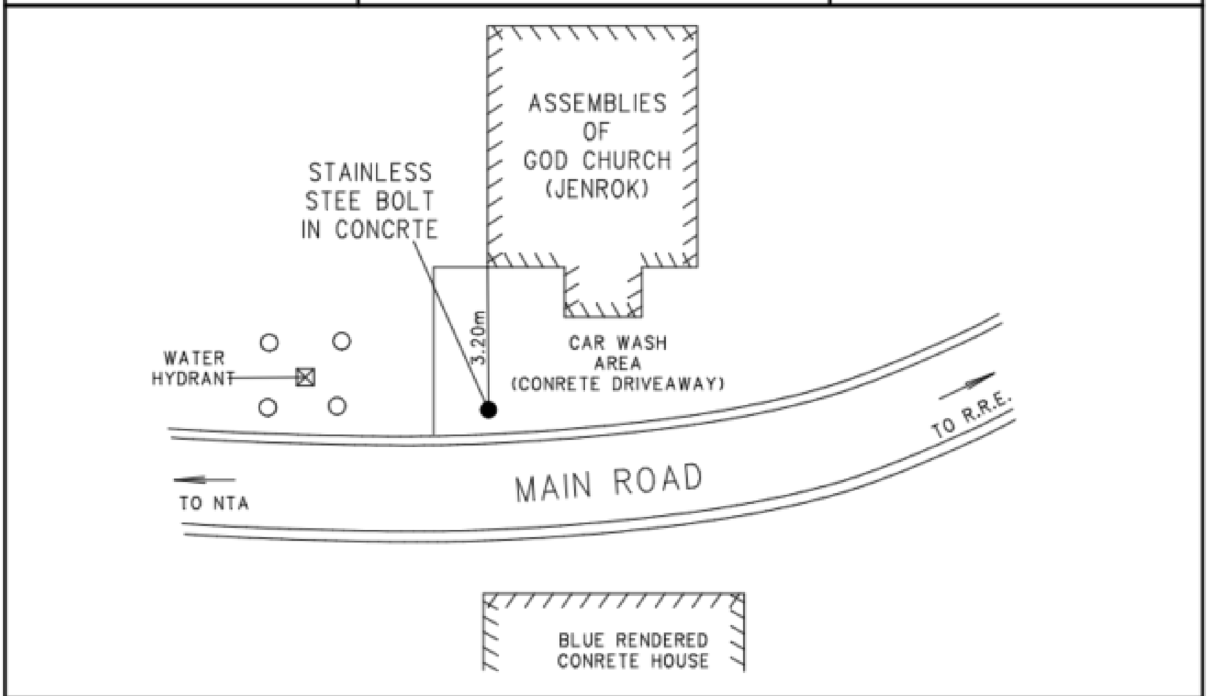
COUNTRY: Marshall Islands	ATOLL: Majuro CITY: Uliga	L. D. P. 799 POINT NO. MAR 102
PROJECT: SPSLCMP	SURVEYOR: M Deo & A Lal	DATE: 30-09-07



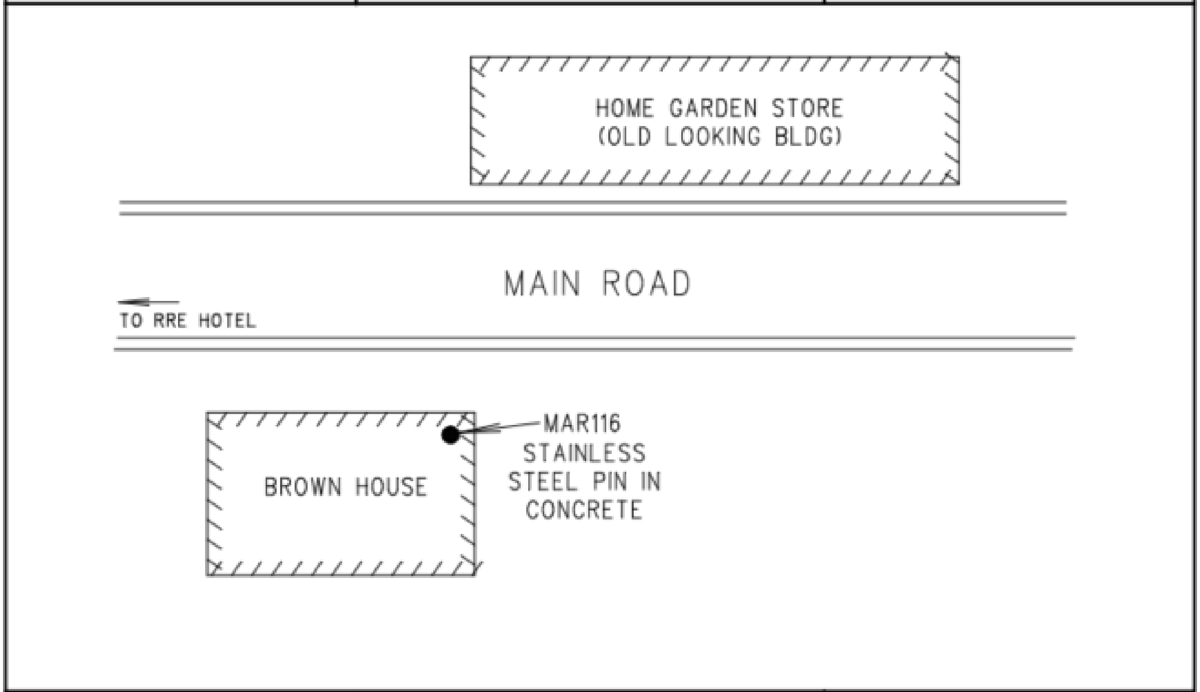
COUNTRY: Marshall Islands	ATOLL: Majuro CITY: Uliga	L. D. P. 898 POINT NO. MAR 110
PROJECT: SPSLCMP	SURVEYOR: M Deo & A Lal	DATE: 04-04-09



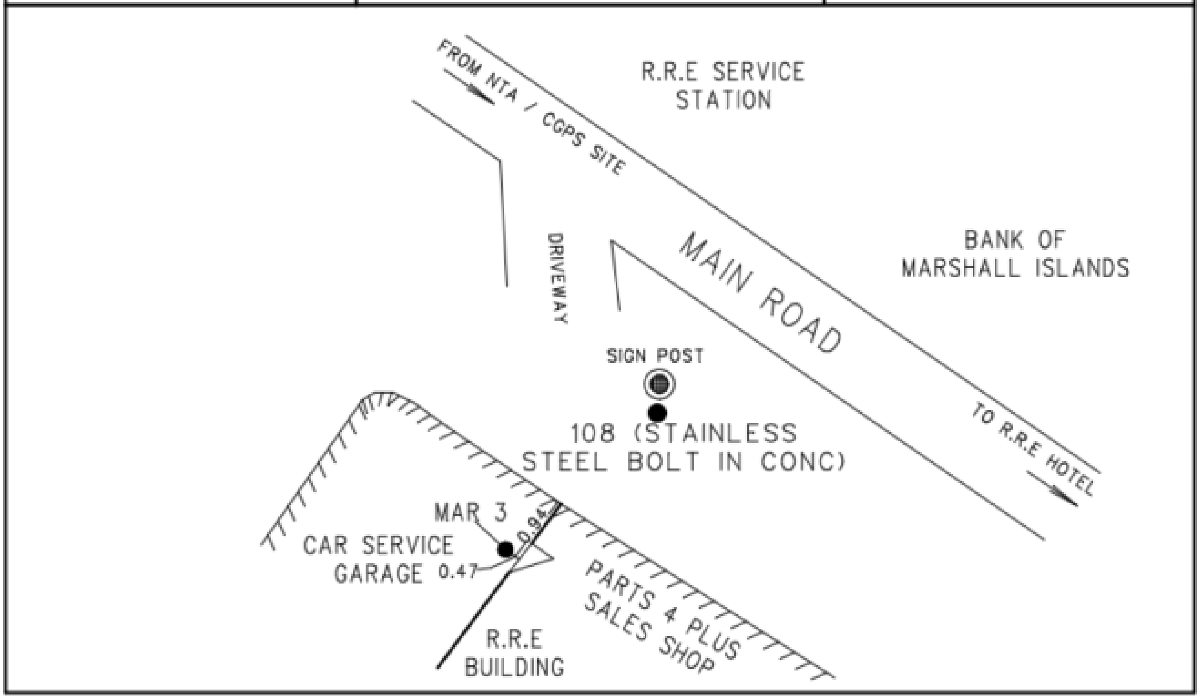
COUNTRY: Marshall Islands	ATOLL: Majuro CITY: Uliga	L. D. P. 798 POINT NO. MAR 101
PROJECT: SPSLCMP	SURVEYOR: M Deo & A Lal	DATE: 30-09-07



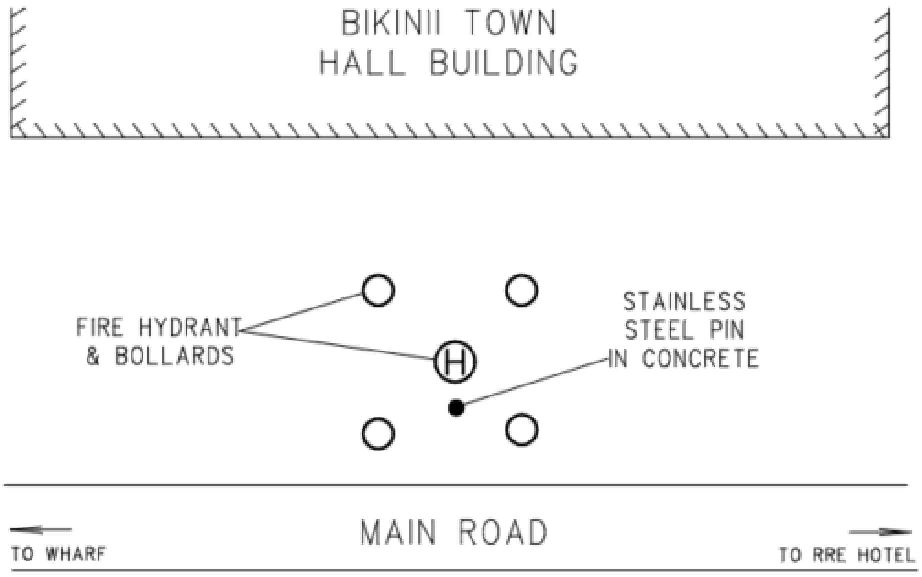
COUNTRY: Marshall Islands	ATOLL: Majuro CITY: Uliga	L. D. P. 897 POINT NO. MAR 116
PROJECT: SPSLCMP	SURVEYOR: R Ruddick & A Lal	DATE: 10-10-13



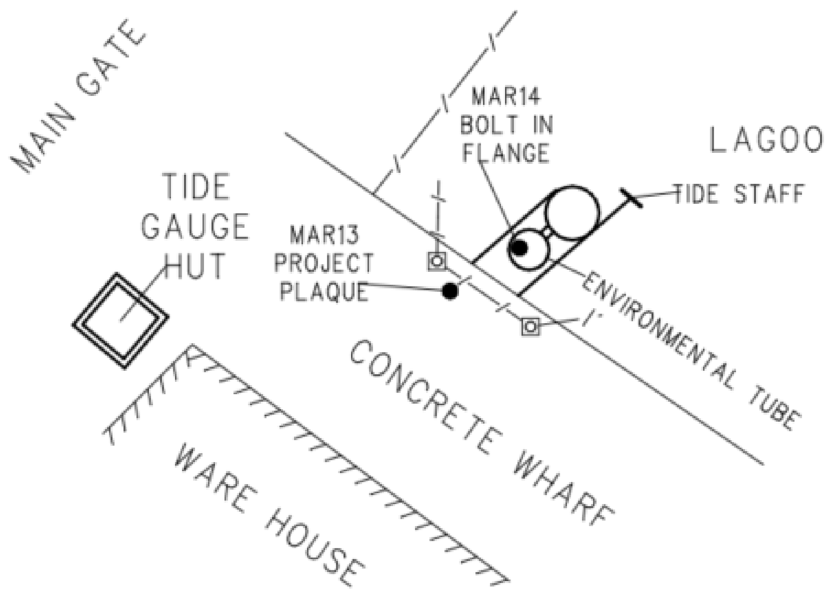
COUNTRY: Marshall Islands	ATOLL: Majuro CITY: Uliga	L. D. P. 791 POINT NO. 108
PROJECT: SPSLCMP	SURVEYOR: M Deo & A Lal	DATE: 04-04-09



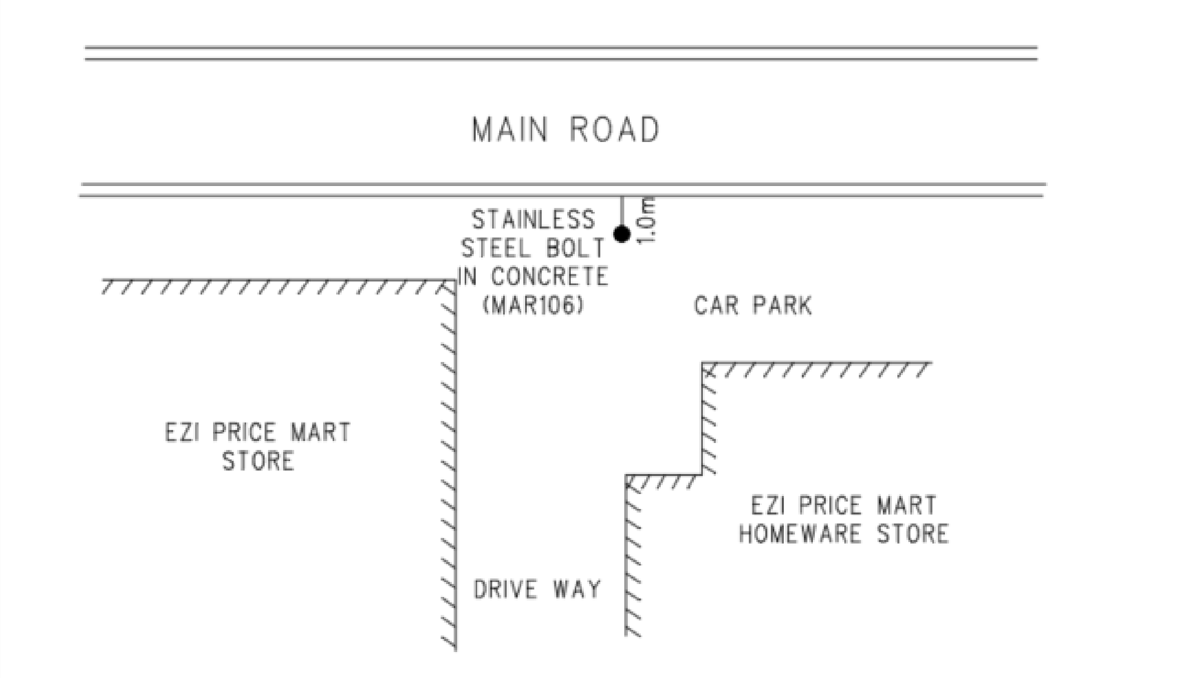
COUNTRY: Marshall Islands	ATOLL: Majuro CITY: Uliga	L. D. P. 793 POINT NO. MAR 31
PROJECT: SPSLCMP	SURVEYOR: M Deo & A Lal	DATE: 04-09-01



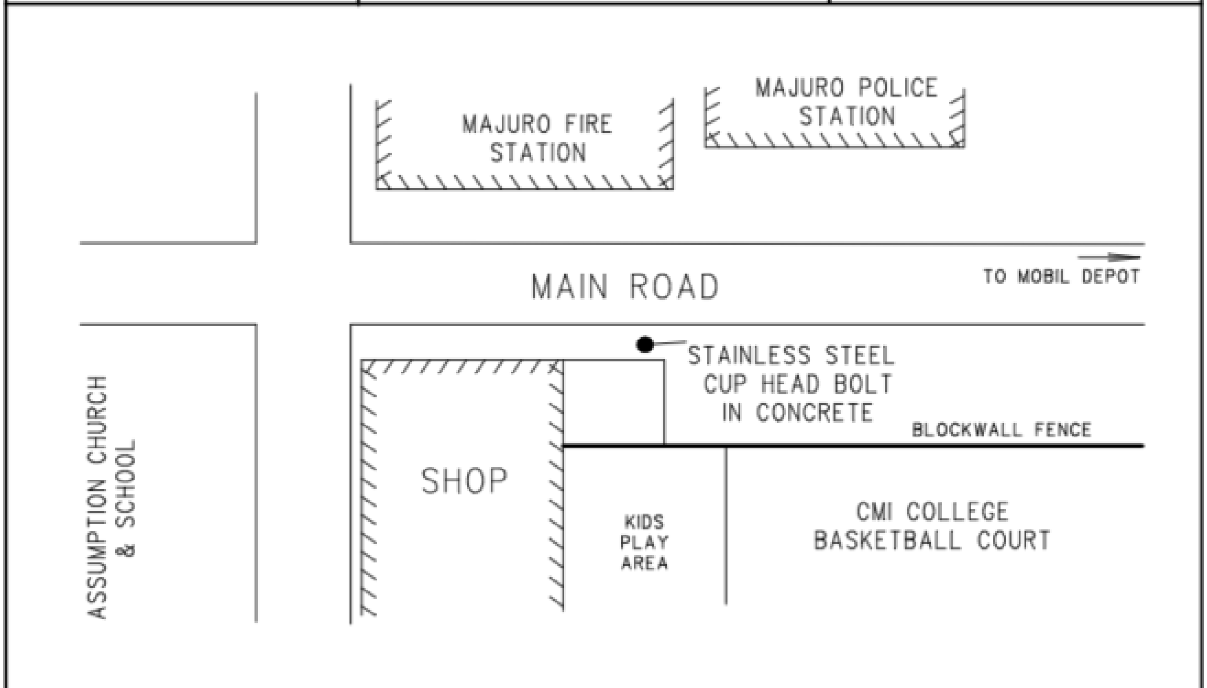
COUNTRY: Marshall Islands	ATOLL: Majuro CITY: Uliga	L. D. P. 792 POINT NO. MAR 13 & 14
PROJECT: SPSLCMP	SURVEYOR: M Deo & A Lal	DATE: 20-05-93



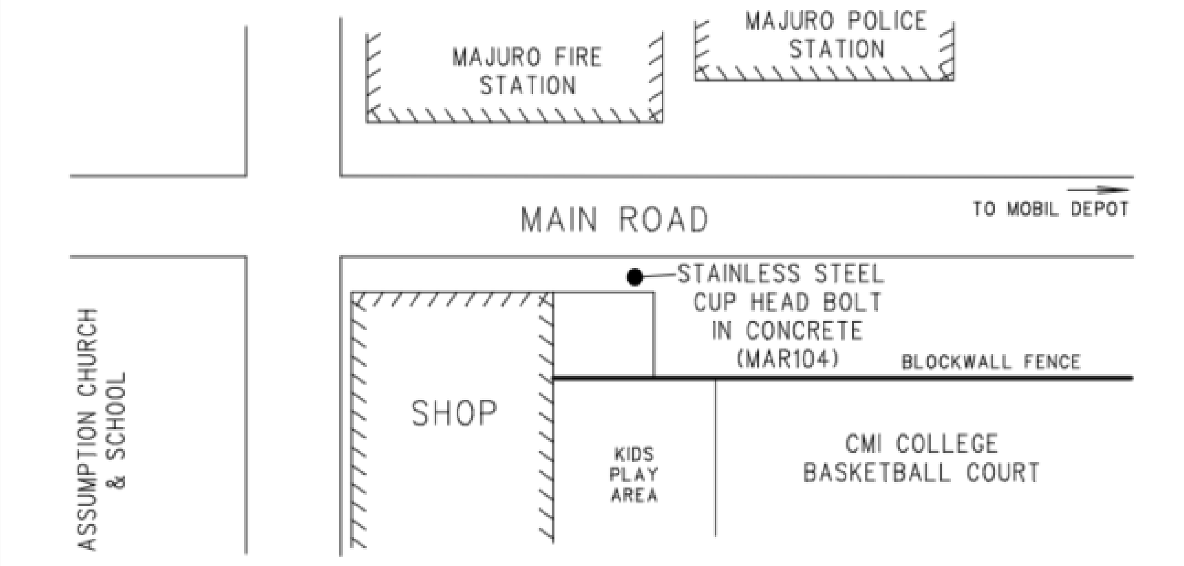
COUNTRY: Marshall Islands	ATOLL: Majuro CITY: Uliga	L. D. P. 896 POINT NO. MAR 106
PROJECT: SPSLCMP	SURVEYOR: M Deo & A Lal	DATE: 04-04-09



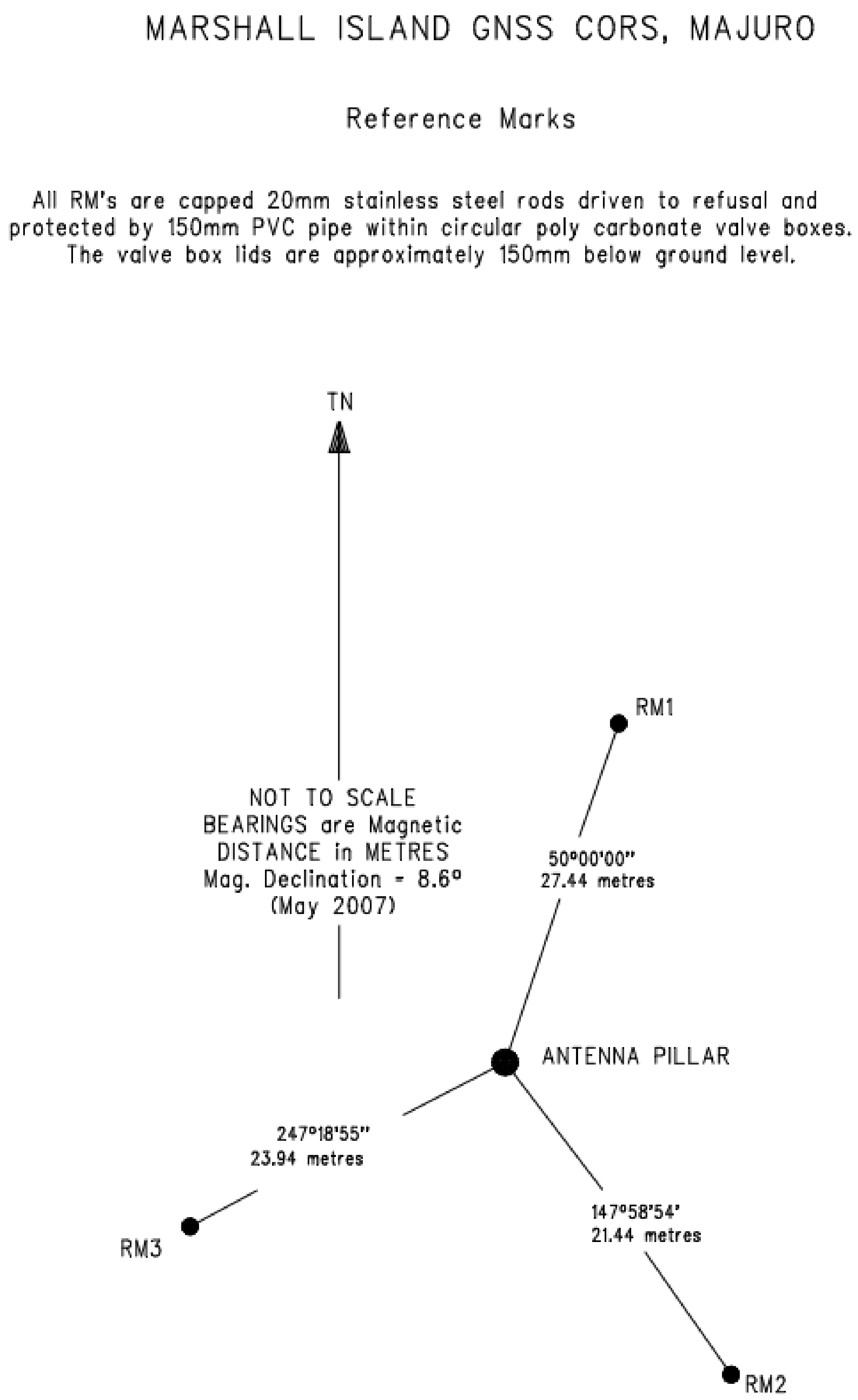
COUNTRY: Marshall Islands	ATOLL: Majuro CITY: Uliga	L. D. P. 594 POINT NO. MAR 114
PROJECT: SPSLCMP	SURVEYOR: M Deo & A Lal	DATE: 04-04-09



COUNTRY: Marshall Islands	ATOLL: Majuro CITY: Uliga	L. D. P. 594 POINT NO. MAR 104
PROJECT: SPSLCMP	SURVEYOR: M Deo & A Lal	DATE: 04-04-09



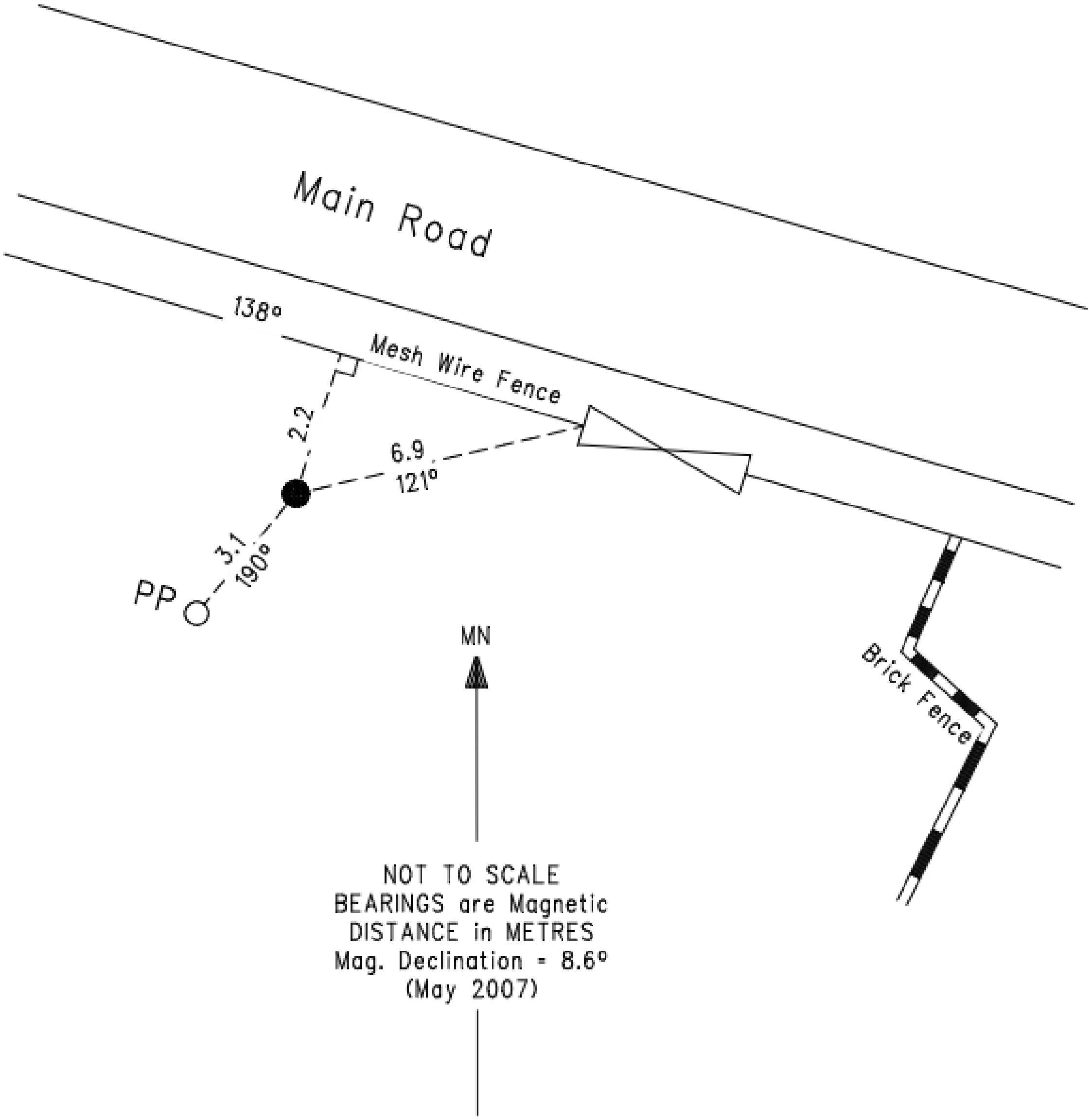
A 3 GNSS Site Reference Marks



MARSHALL ISLAND GNSS CORS, MAJURO - RM1

Reference Marks

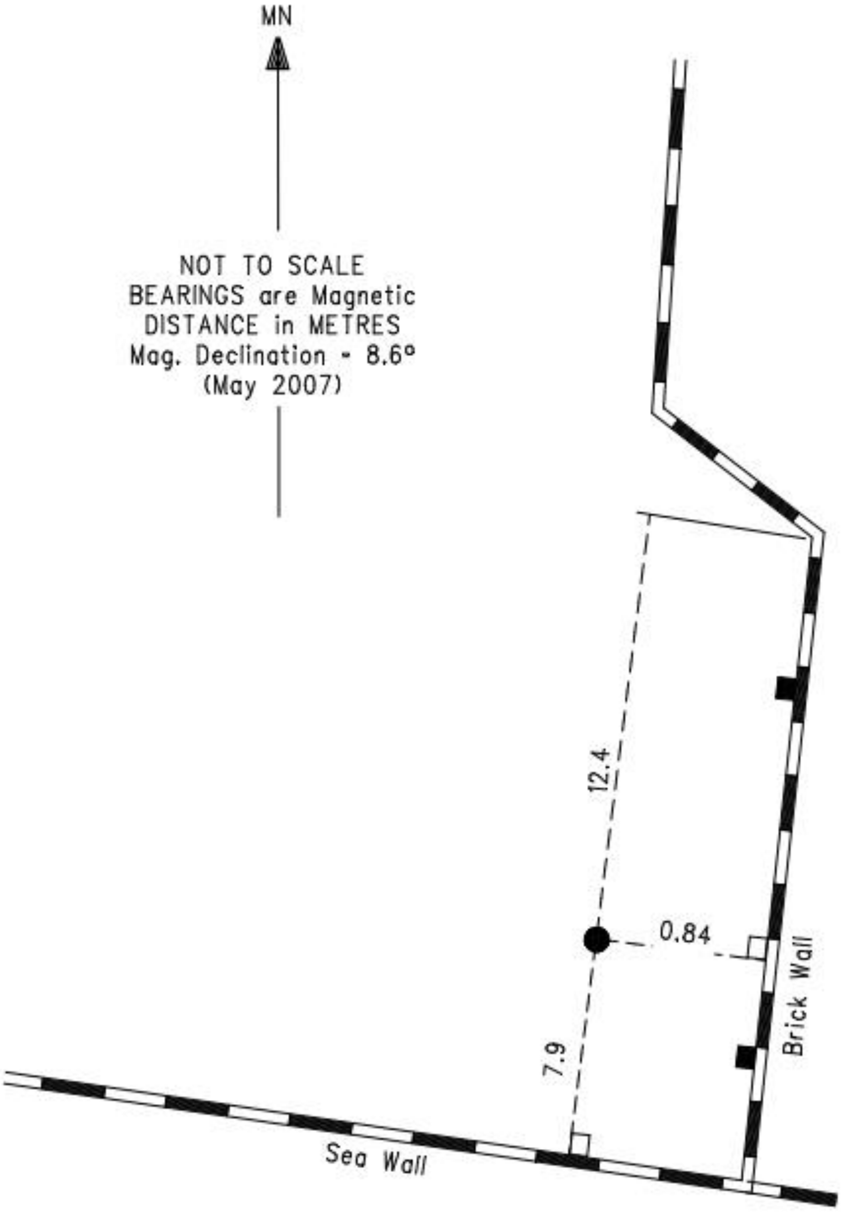
All RM's are capped 20mm stainless steel rods driven to refusal and protected by 150mm PVC pipe within circular poly carbonate valve boxes. The valve box lids are approximately 150mm below ground level.



MARSHALL ISLAND GNSS CORS, MAJURO - RM2

Reference Marks

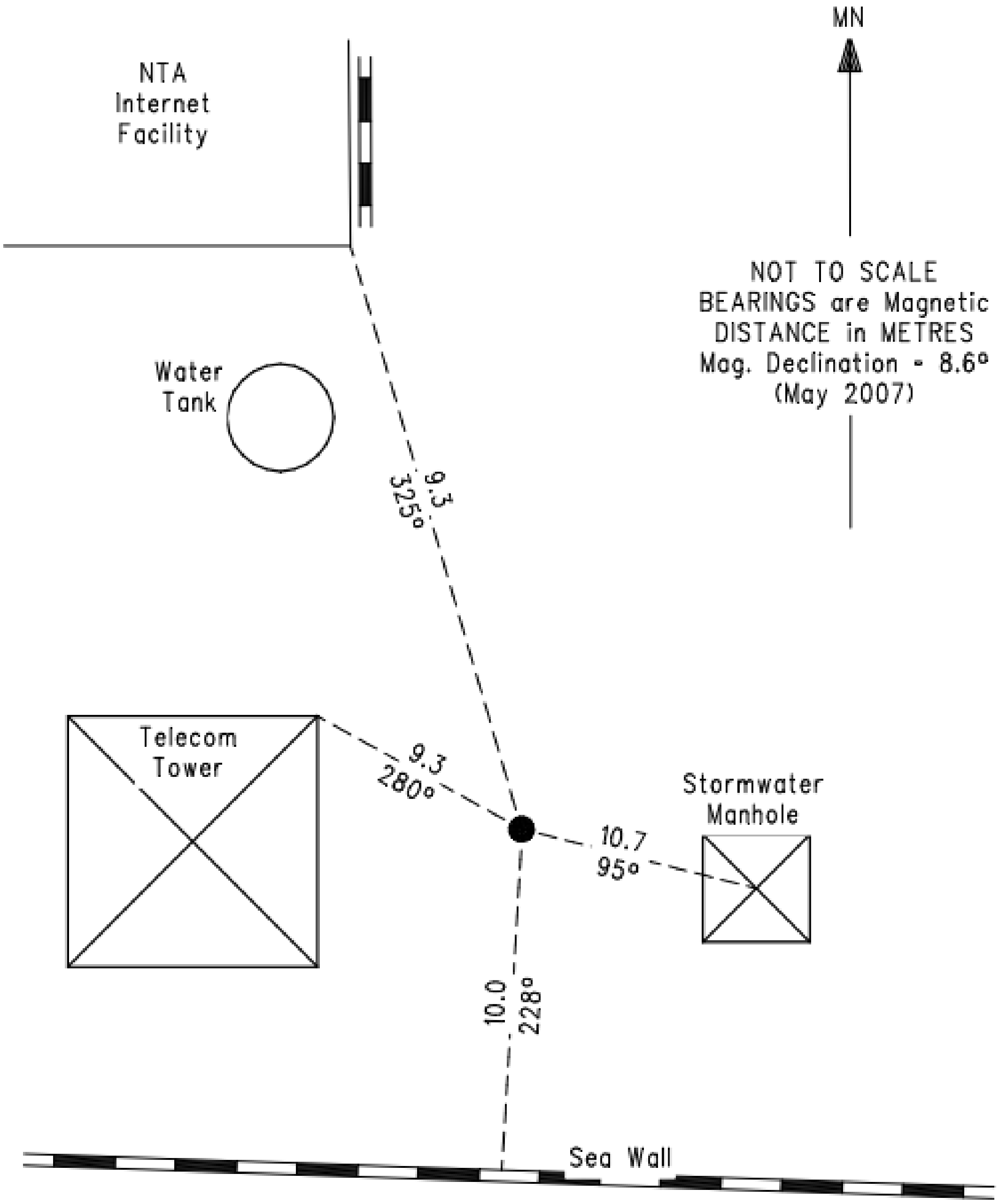
All RM's are capped 20mm stainless steel rods driven to refusal and protected by 150mm PVC pipe within circular poly carbonate valve boxes. The valve box lids are approximately 150mm below ground level.



MARSHALL ISLAND GNSS CORS, MAJURO - RM3

Reference Marks

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



Appendix B Planning Aspects and Notes

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

Prior arrangements with the local counterpart should be made for rapid clearance of the survey equipment from the Customs Authority when shipped across. Special thanks to the Director Meteorological Office for the efficient clearance of the survey equipment from the customs bond. These survey equipment was sent for future field surveys for this project.

The Meteorological 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

DHL Express is commonly used for the delivery of the survey equipment into and out of Marshall Islands.

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

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

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

Quantity	Item & description	Locations
1	**Tool Box**	Tide Gauge Station Hut.
2	*Prism Pole Clamps*	*Tools used by C&M Teams (Bureau & SPC)*
1	*50m Measuring Tape*	
1	*Engineers Hammer*	
1	*Carpenters Hammer*	
1	*Set of Allen Keys*	
1	*Torx Drivers*	
2	*Multigrips pliers*	
1	*Set of Screw Drivers*	
1	**PVC Pipe (1.2m)**	Lands & Survey Office
1	*Aluminium GST6 tripod with Feet*	
1	**PVC Pipe (1.7m)**	Lands & Survey Office
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**	Lands & Survey Office
1	**Green Bag - Leica GST40 Rigid Tripod**	Lands & Survey Office
1	**Spade**	Tide Gauge Station Hut.
1	**Crow Bar**	Tide Gauge Station Hut.

Appendix C Equipment Specifications

Tachymeters, EDM and Theodolites

A Leica TM50 (S/N 369132) 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 was used on all marks, with the exception of the pillars, during the monitoring survey.

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

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

GNSS Equipment

Description

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

- GNSS receiver SEPT POLARX4TR (S/N 3007661) (firmware:2.9.6)
- Javad Choke Ring antenna (JAVRINGANT_DM NONE (S/N 01513)