Using GNSS to establish a Height Datum on a Project

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Abstract

This paper explains in detail practical steps for establishing or extending a height datum on a project in PNG using GNSS Techniques, using recent surveys in PNG as examples. The following topics will be covered in the presentation:

1. An overview of the PNG, EGM96 and new EGM2008 geoid models
2. Preliminary tidal monitoring and determination of MSL, LAT and HAT
3. Using GNSS and PPP methods to estimate ellipsoid heights
4. Estimating the geoid zero-order term (correction)
5. Aligning a geoid profile with a pre-established height datum
6. Height datum conversions

Introduction

One of the most difficult technical challenges facing surveyors in PNG is establishing a height datum related to true Mean Sea Level (MSL) on a large project, particularly resource projects in remote highland or inland areas. Many of these resource projects that continue on to the construction and development phase have associated infrastructure works such as towns, airfields, pipelines, roads, ports and power supply connected to them.

It is essential that an accurate MSL height datum be established early on in a project, to ensure that there are no height datum offsets at different stages and locations of development. While an arbitrary height datum might seem expedient in the early stages of development (e.g. the exploration phase), problems occur with multiple height datums when a project enters the construction phase. The relatively small expense to the client of establishing a true MSL height datum ultimately pays dividends sometimes decades into the future.

Global Navigation Satellite Systems (GNSS) such as the US Global Positioning System (GPS), are particularly useful for establishing an accurate height datum in remote areas in PNG. This paper describes practical methods for surveyors to establish an MSL height datum on a project using GNSS. Some of the pitfalls resulting from misuse of this technology are also described.

An overview of height systems

The two main height systems used in surveying are geoidal (i.e. those related to MSL) and ellipsoidal (used by GNSS/GPS).

The **geoid** is a surface of equal gravitational potential which approximates **Mean Sea Level (MSL)** (Figure 1), even when extrapolated across land surfaces and mountain ranges. The geoid has significance for surveyors and engineers, as it is a reference surface for levelling, with plumb lines and the local astronomic zenith being normal (at right angles) to this surface.

An **ellipsoid** that best fits the earth's shape or geoidal surface is adopted as a basis for geodetic calculations, because it has a regular shape enabling simpler computational methods. With the advent of GNSS it has become necessary to develop a global best fit ellipsoid (e.g. the WGS84 and GRS80 ellipsoids which are practically identical in shape) to the global geoid. The difference in elevation between the geoid and the ellipsoid can be as low as -107 metres (near Sri Lanka) and as high as 85 metres (in Papua New Guinea) due to mass anomalies within the Earth. This means that ellipsoid heights of the sea level surfaces in PNG have values of up to 85 metres! The position of the reference ellipsoid to the Earth (e.g. the geocentre) is defined by the geodetic datum or reference frame.

Ellipsoids are often referred to as spheroids. The terms are interchangeable. A spheroid is defined as "a body like a sphere but not perfectly spherical" whereas an ellipsoid is defined as "the shape produced by rotating an ellipse about one of its axes", which is a more correct definition mathematically.

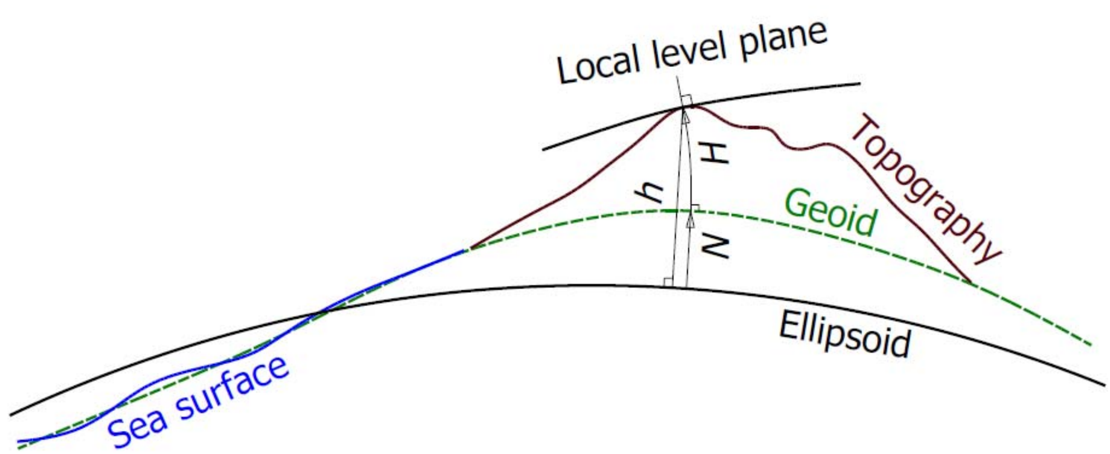


Figure 1. Surfaces, Orthometric Heights, Normal Heights and N values

Orthometric heights (H) are heights for a given position on the earth's surface above the geoid or approximate MSL following a curved plumb line (Figure 1). Surfaces of equal gravitational potential are generally not parallel to each other resulting in very small curvature of very long plumb lines. As a result, the orthometric height is greater than the height normal to the geoid. In reality this height difference is insignificant, rarely exceeding 0.3 m in even the highest mountain ranges.

Ellipsoidal heights (h) are the heights of the location, normal (at right angles) to the reference ellipsoid (Figure 2).

The height difference between the geoid and a specific ellipsoid is known as the **geoidal height or** the **geoid-ellipsoid separation (*N*)**. The 'N' value is the ellipsoid height minus the orthometric height (Equations 1 and 2).

$$N = h - H \qquad (1)$$

$$H = h - N \qquad (2)$$

GNSS natively uses ellipsoidal heights for data processing. These are converted to approximate MSL elevations using a geoid model which computes N values for any given location. These N values are subtracted from the ellipsoidal height to compute elevations above MSL using (2).

Hydraulic flow rates at very small gradients are very sensitive to changes in level as a result of undulation of the local level surface with respect to the ellipsoid. Although a geoid model has sufficient local precision for most engineering work, precise levelling methods should be used if high precision relative levels are required.

A pipeline is being laid to a high grade tolerance along a 2000 m section at a new development in Kandrian, WNB Province. A surveyor measures the height at both ends of the pipe with GPS and determines *the ellipsoidal height difference* to be 0.4 m. The surveyor then levels between both ends and finds that the *level height difference* is actually –0.1 m ! Of course the surveyor has to adopt the level difference. In an ellipsoidal height system it is theoretically possible for water to flow "uphill".

Vertical Datums in PNG

The rugged and undeveloped nature of much of the terrain in Papua New Guinea has hampered the development of a nationwide levelling network and a rigorous MSL based vertical datum. In some coastal areas, isolated regional levelling nets have been completed in some towns and cities, usually originating from a tide-gauge and related to MSL. Even within coastal cities, different authorities use different height datums, and so, many stations will have several reduced levels (RLs) as a consequence. Many inland areas have had MSL transferred by trigonometrical heighting, sometimes with reciprocal measurements, often without. Many stations such as photo-control points have had elevations computed by altimetry (differential barometry), or by relative gravity measurements. As a consequence of the fragmented nature of vertical datums in PNG, discrepancies of up to 10 metres exist between local MSL height datums.

MSL varies from the geoid at < 1m level due to local anomalies such as thermal expansion of the ocean, ocean currents, storm surges and atmospheric loading. Furthermore most geoid models are tide free and there is usually an offset between the geoidal surface and true MSL for any given location.

Geoid Models in PNG

Several different geoid models have been used in PNG to compute ***N*** values. The first geoid widely used with GNSS/GPS was the **PNG94 Geoid** developed by Prof. Bill Kearsley from UNSW in 1996 (Kearsley & Ahmad, 1996) (Figure 2). The model was derived from a combination of surface gravity measurements, geometric connections between conventional levelling and GPS/Doppler, and the Ohio State University gravimetric geoid 1991 (OSU91). The resolution of the model is 0.1° (6') and the accuracy of ***N*** values varies across PNG, typically 1-1.5 metres. An MS-DOS program is available from the PNG National Mapping Bureau and the Department of Surveying and Land Studies, Unitech, which computes the ***N*** value from the PNG94 Geoid model for any given location in PNG.

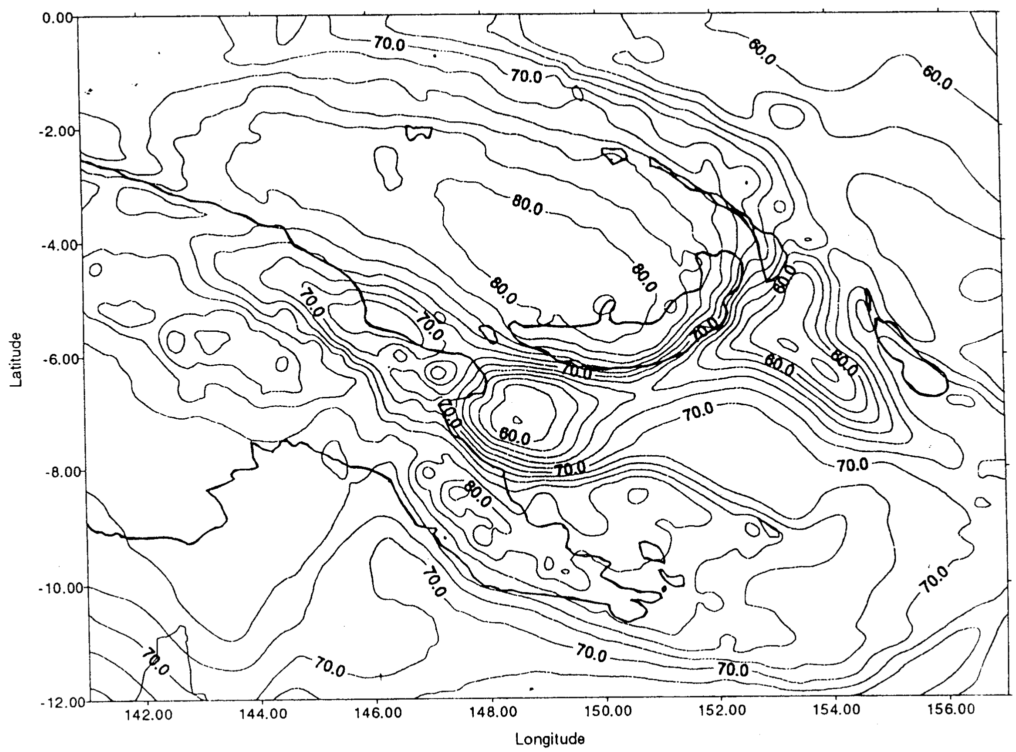


Figure 2. PNG94 Geoid geoid height (N value) (Kearsley, 1996)

Unfortunately, the MS-DOS executable won't run on most modern computer operating systems such as Windows-XP or Windows Vista without considerable effort.

The **Earth Gravity Model 1996 (EGM96)** WGS84 geoid, developed by NASA and the US National Geospatial Intelligence Agency, is a global model with a 15 minute grid size that is widely used for GNSS surveying and is usually incorporated into GNSS post-processing software. For this reason, EGM96 has been wisely used in PNG in preference to the PNG94 geoid in recent years. The precision of the model is similar to the PNG94 Geoid (+/- 1.5 metres). EGM96 ***N*** values can be computed online at
http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm96/intpt.html

Towards the end of 2008, the **Earth Gravity Model 2008 (EGM2008 or EGM08)** WGS84 geoid was released and represents a very significant improvement in precision over earlier geoid models (now +/- 0.2 m). The model is available in 1, 2.5 and 10

minute grid sizes. EGM2008 is gradually being implemented in GNSS post-processing software and most software providers have an EGM08 geoid file which can be downloaded and setup within an existing configuration. At present, there is no online calculator like there is for EGM96, however Hans-Gerd Duenck-Kerst of Brothersoft has released a free program ***AllTrans EGM2008*** which can be downloaded at
http://www.brothersoft.com/alltrans-egm2008-calculator-216023.html

The default *AllTrans* installation comes with a 10' grid file, however if possible, the 2.5' or 1' files should be downloaded and used with *AllTrans* to obtain more accurate interpolations. For most surveying purposes the 2.5' grid should be sufficiently accurate. as the 1' file is over 150MB in size and requires a good internet connection to download.

More information on EGM2008 and downloadable EGM2008 grid files can be found at
http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/egm08_wgs84.html

Provided that EGM96 hasn't been already established as a project geoid model, it is advisable to use the EGM2008 model where possible. EGM2008 was tested in May 2009 in the north of PNG and like EGM96 there is a 1.4-1.5m offset from true MSL. This offset needs to be determined in order for more precise MSL estimates to be made using the model. This process is discussed in more detail later in the paper.

The OmniStar geoid model

Users of ***OmniStar***, especially the HP service, need to be very careful how they interpret elevations from the service through client software such as ***SoloField***. By default, the service provides MSL estimated from a very inaccurate geoid model used by the receiver software, with model inaccuracies exceeding **18 metres** in many parts of PNG. Unless the user software allows the user to configure and use a proper geoid model such as EGM96, then elevations should be considered to be approximations only (even if the displayed precision is less than a metre). To overcome this problem, ellipsoidal heights should be logged (by turning the Add GGA-separation setting on) and the ellipsoid heights manually converted to MSL using a separate geoid model program or the EGM96 online calculator.

Establishing a height datum on a new project

In situations where there is no existing height control on a project, a new height datum point will have to be established within the project area. Either a true MSL datum, or an approximate MSL datum derived from a geoid model can be used to define the height datum. A true MSL height datum should be used if any coastal or river engineering works may be associated with the project in the future. If this isn't the case, then a geoid model derived MSL datum can suffice. If a true MSL is required, refer to sections later in the paper which describe this process in more detail.

To establish a new height datum just using a geoid model, 2-3 days of good quality dual-frequency GNSS observations are required on the datum point. The data from these observations can then be processed using AUSPOS or NRCan post-processing services to obtain a centimetre accurate ellispsoidal height. The approximate MSL value is then computed using the ***N*** value derived from a geoid model using equation (2).

Alternatively, if a PNG94 control point is located within 20 -30 km of the new station, then the baseline between the two stations can be observed using Static observations and then post-processed and the ellipsoid height computed this way. Using an arbitrary datum (e.g. from a handheld GPS, or from interpolating map contours) is strongly discouraged.

Using GNSS on projects with a pre-existing height datum

There are many instances in PNG where MSL Reduced levels have been derived from more imprecise methods such as trigonometric heighting and barometric altimetry. Trigonometric heighting was often computed from single ray observations with an assumed refraction index, or indeed no correction at all. This has resulted in discrepancies of up to 5 metres in the realisation of MSL in PNG. The discrepancies are particularly noticeable in inland areas such as the Highlands.

Surveyors using GNSS techniques on existing projects are usually required to continue providing elevations with respect to the existing height datum to their clients. Changing a height datum (even if to a more accurate one) is not to be undertaken lightly, unless there are serious problems with it. It is unlikely that any project manager would agree to a change in height datum, as the ramifications are usually very serious if the differences between the two datums is large, the tolerances small, and one datum is mistaken for another. In these instances the offset between the geoid model used and the existing height datum may need to be determined. In most projects in PNG, the geoid gradient is an acceptable representation of the local gravity field, so that the local height datum offset can be used in conjunction with a geoid model over quite large projects.

Computing the local height datum offset from a geoid model

The local height datum offset (o) can be computed using equation (3) if the ellipsoid height (h), the existing RL (RL_{LOCAL}) of the datum station and N values are known:

$$o = RL_{LOCAL} - h + N \qquad (3)$$

Once the offset is computed, reduced levels in the local height datum can then be computed from the geoid model using equation (4).

$$RL_{LOCAL} = h - N + o \qquad (4)$$

Alternatively, if the ellipsoidal height for the existing height datum station is unknown, irrelevant, or to simplify RTK survey workflows, a false ellipsoid height (h_{FALSE}) can be computed and used in the system using equation (5).

$$h_{FALSE} = RL_{LOCAL} + N \qquad (5)$$

For example:

The height datum of a gold exploration project in has always been PSM123456 with an RL of 1450.25 m (from a 1995 survey report) and subsequently used all over the prospect for exploration and mining feasibility studies. The ellipsoidal height is also known for PSM123456 and is given as 1537.01 m. The EGM96 ***N*** value is computed as 82.45 m. Wantok surveyors have been engaged by the operators to survey a series of new drill holes. GNSS methods will be used to complete the survey.

To ensure that any new survey work is aligned with the existing height datum, the surveyor has three options:

1. Compute the correction to be applied to the geoidal model using (3),

$$o = 1450.52 - 1537.01 + 82.45 = -4.04 \text{ m}$$

This is a good strategy if both ellipsoidal heights and local RLs need to be computed over the project area (e.g. for LiDar control), but is cumbersome for automated surveys such as RTK as there is usually no allowance made in these systems for constant height offsets.

2. Compute a false ellipsoidal height for the datum station (especially if the ellipsoidal height is not known) using (5).

$$h_{FALSE} = 1450.52 + 82.45 = 1532.97 \text{ m}$$

This strategy is ideal for automated surveying using a geoid model (e.g. RTK), however all ellipsoidal heights should be discarded, or labelled as arbitrary. This is a useful technique for RTK surveys.

3. Use the RL provided as the datum <u>and a geoid model</u> using inbuilt software (provided that the entered data is not assumed to be an ellipsoid height) and workflows. Some care and skill is required to do this successfully, as poor geometry of the calibration has been known to result in significant errors on projects.

In all instances, the system should be checked and calibrated by comparing results with other existing control points on the network.

Another option which isn't recommended is to not use a geoid model at all. Because of the very high geoidal undulations in PNG, this assumption can result in significant heighting errors on even small projects.

Establishing an MSL datum from Tidal Observations.

Tidal height datums are usually established using measurements from a specially constructed tide gauge. MSL is computed by modelling the tide gauge measurements over a considerable period of time, from months to years. MSL is generally defined as being approximately halfway between the Lowest Astronomical Tide (LAT) and Highest Astronomical Tide (HAT). These are the lowest and highest tides than can be expected over a full range of lunar and solar configurations (over a 19 year Metonic cycle). Access to a rigorous tidal datum isn't always possible, so this paper describes a rudimentary method for surveyors to measure tides in a local project area in order to estimate MSL with a precision of 10 cm.

Where a project height datum is required to be aligned with true Mean Sea Level (MSL), or Lowest Astronomical Tide (LAT), for example for coastal engineering, construction, or bathymetric surveys, it is necessary to measure sea level from a benchmark in a location close to the project area.

Location of tidal monitoring station considerations

Sea level should be measured at a location where wave amplitudes are reduced. Sheltered bays and harbours are ideal. River mouths should be avoided as high river flows adversely affect sea level measurements. Solid wharves and jetties (preferably concrete, or pile driven) provide reasonably stable locations for temporary benchmarks from which direct sea level observations can be made. If a wharf or jetty is used, it is advisable to locate benchmarks away from where boats and ships will be berthed.

The monitoring benchmark network

Wharves and jetties may be subject to localised subsidence or disturbance over longer periods of time, so a local benchmark network should be established within 1-2 km of where the tidal monitoring will be undertaken, to provide redundancy and to monitor stability of the network.

The following marks should constitute the network (Figure 3):

A **secure GNSS benchmark, or CORS station** (a stable monument with good sky visibility in a secure location such as a government, company or hotel compound) should be established within 5 km of the tidal monitoring location. This is used to get 3 or more days of GNSS base data (72 hours or more observations) in order to estimate the ITRF absolute ellipsoidal height for the mark.

A **bedrock benchmark** or other highly stable monument that isn't sensitive to localised subsidence due to ground water changes and landslips. This station is used to verify the stability of the primary GNSS base station, particularly if the GNSS antenna is on potentially unstable ground, or built on clay soils subject to seasonal variations in height.

Secondary benchmarks near the monitoring benchmark. Ideally two, preferably three benchmarks in stable locations within 100 metres of the monitoring benchmark (Figure 5). These are used to verify local stability by means of conventional levelling. One of the benchmarks should be a PSM and have good sky visibility for GNSS observations.

The **tidal monitoring benchmark** should be at a location where a levelling staff can be lowered directly to the sea surface and measurements read off the staff (i.e. the edge of a jetty, wharf or pier, Figure 4). Alternatively, it can also be a benchmark from which direct readings can be made to the sea surface by conventional levelling using rise/fall or height of collimation methods.

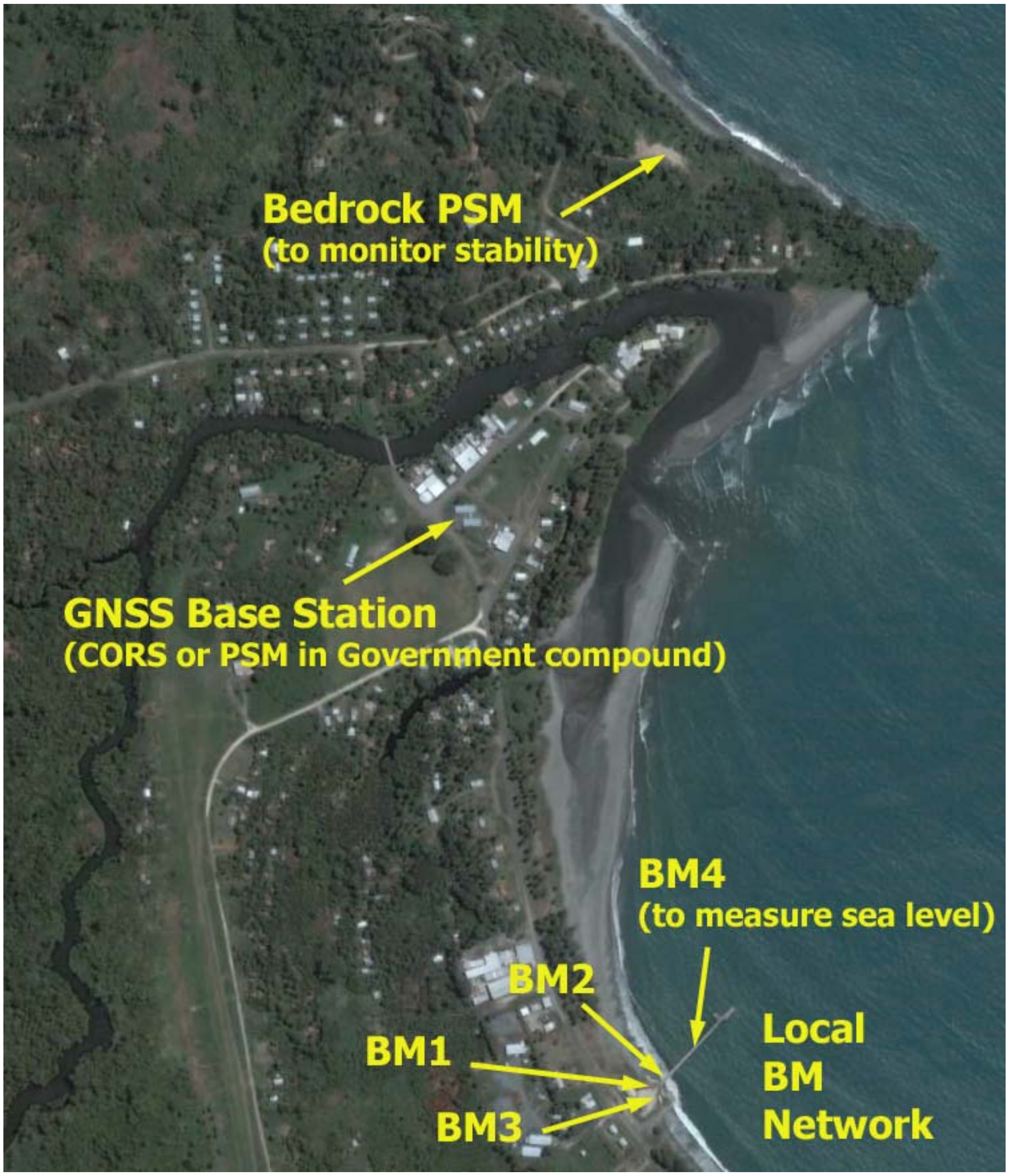


Figure 3. A typical PNG tidal BM network (Aitape, Sandaun Province)

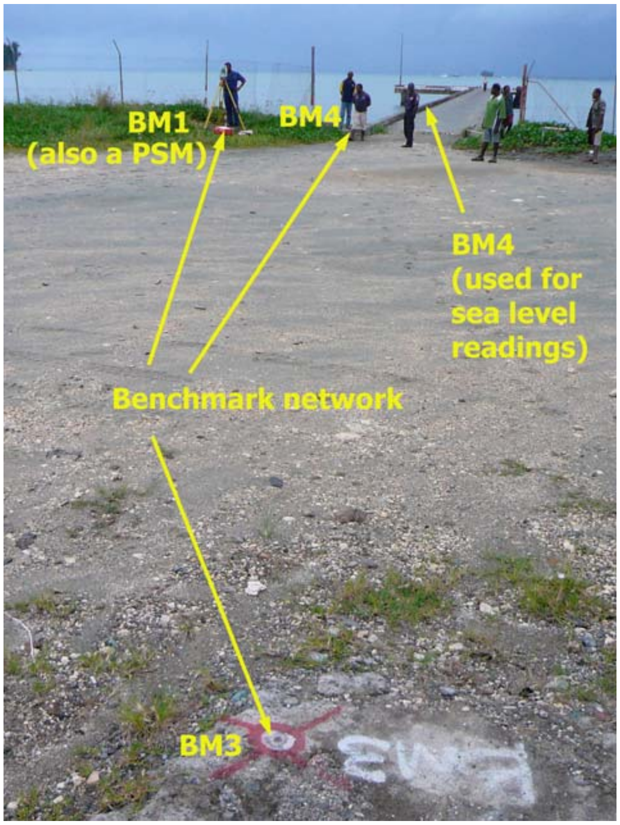


Figure 4. Local BM network (left) and monitoring BM (right)

Procedure for measuring and modelling local tides

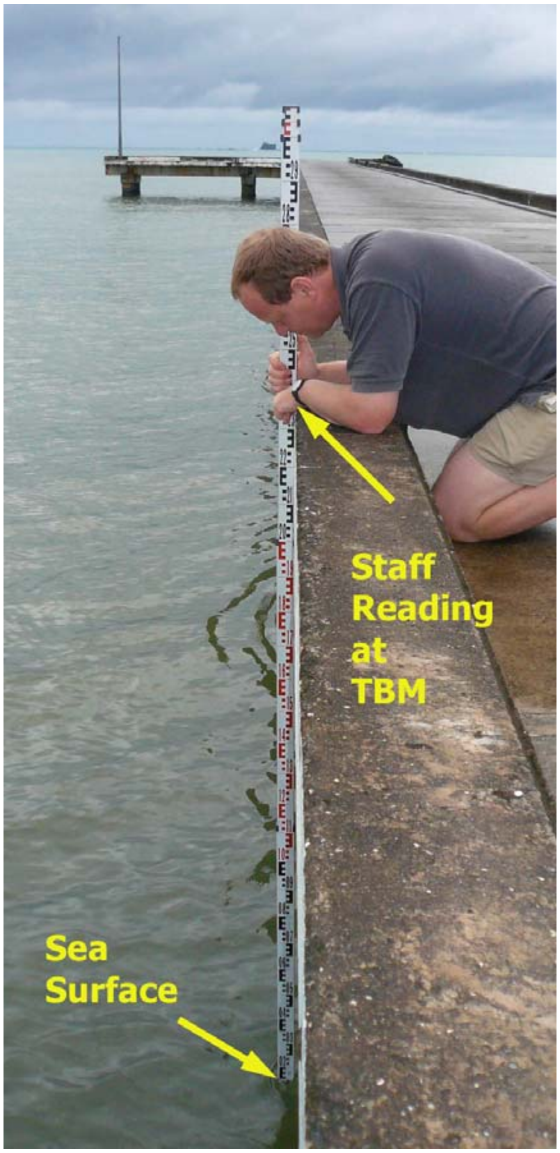
Tidal Predictions

The first step is to obtain tidal predictions for the site. This is necessary in the most usual case where tides cannot be measured over a tidal season. Michael Hopper has developed a free software program ***WZTide32*** to compute tidal predictions. The software can be downloaded at http://www.wxtide32.com

Once the software has been installed and is running, select the location for the tidal prediction: (*File, Location*). If the location to be monitored isn't in the location table, the coordinates of the tidal monitoring point can be entered manually (*File, User station*). To generate a tidal calendar showing times and heights of Low and High tides:
select (*File, Tide Calendar*) and select the start date from the calendar. A monthly tidal table is generated showing times (in PNG Time) and predicted heights (sea levels on the prediction datum) of Low and High Tides. Other useful information shown at the top of the table include the predicted Historical Low and High levels which broadly speaking equate to Lowest Astronomical Tide (LAT) and Highest Astronomical Tide (HAT).

For each day of monitoring, *WxTide* can compute incremental predictions (e.g. every 30 minutes) (*File, Incremental Tides*) and select the date. Predicted sea levels above the prediction datum are shown in tabular format. This table can be printed off and used as a log sheet for tidal measurements.

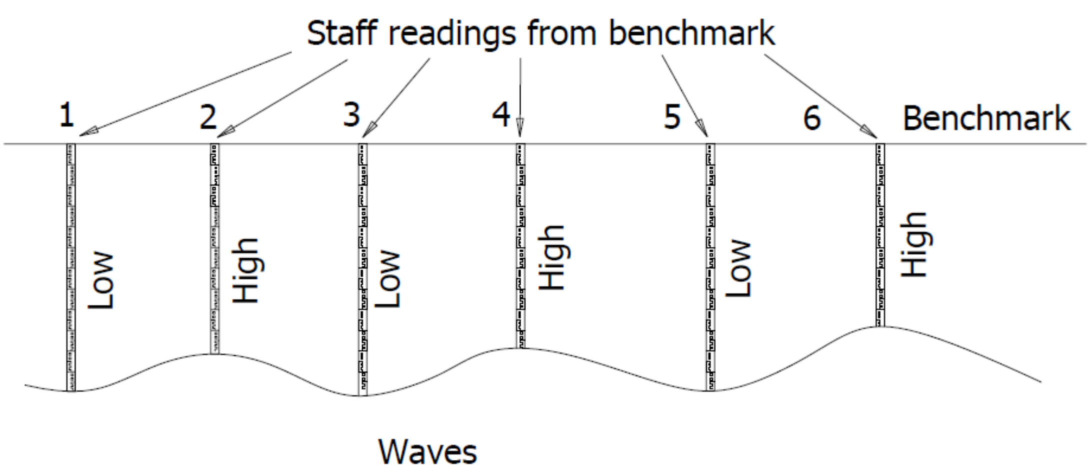
Tidal measurements



Measurements of sea level should be made so that they can be related to the incremental tidal predictions (i.e. on the hour, or 30 minutes past the hour). It is important to get measurements before and after High and Low tides, to capture the full scale of each tidal cycle, however measurements should be made as often as practicable. The more measurements that are made the better the MSL estimation will be. In general, seas are calmer in the early morning and late evening.

Even during calm periods, there will inevitably be some wave action. Several readings should be averaged to get a single observation
(e.g. 3 wave crests and 3 wave troughs)
(Figure 5).

Figure 5. Staff Readings for sea level measurements



Estimating the Ellipsoidal Height of the Monitoring Location.

If the ITRF ellipsoidal height of the GNSS base station isn't known, or verified, then RINEX data files for each day of observations should be submitted to AUSPOS (http://www.ga.gov.au/bin/gps.pl) or NRCan (http://www.geod.nrcan.gc.ca/online_data_e.php) a few days after the observations have been made (in order to use the IGS Precise Rapid Orbits). It is important to ensure that the antenna heights are measured correctly. Within an hour or so, these processing services email the ITRF coordinates and ellipsoidal heights for the stations. By submitting several days observations, a more precise height can be estimated by averaging the ellipsoidal heights for each day.

Local GNSS static baseline observations are used to compute the short baselines between the GNSS base station and observed benchmarks using GNSS post-processing software, holding the ellipsoidal height of the base station fixed. All baselines should be L1 Fixed (not L1 float) with a Reference Variance below 5, a Ratio higher than 5 and an RMS of less than 1 cm. It is important to form a closed loop for the observing network and also to repeat observations on different days to get an averaged solution. It is also important to ensure that antenna height measurements are consistent for all observations (e.g. using the same antenna type and measuring point), as this eliminates errors arising from mismodelling of the antennas' phase centres.

Computing approximate values using a Geoid Model

Once the ellipsoidal height of one of the benchmarks (BMs) has been estimated and checked, the approximate MSL elevation for the BM should be computed using a geoid model. Most post-processing software packages have geoid models built into them and the approximate MSL is computed automatically. Once the approximate MSL elevation has been estimated for one of the BMs, then a conventional levelling run should be completed to estimate the approximate MSL of all other BMs in the local network including the tidal monitoring BM.

Using the approximate MSL value of the monitoring BM computed from the geoid model, the approximate MSL value for each sea level measurement should be computed by subtracting the staff reading from the approximate MSL value of the BM (e.g. Table 1).

Converting geoid model elevations to Prediction Datum

The approximate MSL sea level measurement for each readings are subtracted from the predicted heights from the tidal predictions. If the measurements have been made carefully and the tidal prediction is accurate, then the differences should be consistent at better than a few centimetres. The differences (Predicted - EGM) are averaged ($\boldsymbol{D}$) and the prediction datum RL ($\boldsymbol{RL_{PRED}}$) of the monitoring BM can be estimated using Equation (6).

$$\boldsymbol{RL_{PRED} = RL_{EGM} + D} \qquad (6)$$

Computing LAT, HAT and MSL

The next step is to compute approximate LAT and HAT for the BM. If the *WXtide* program is used, the predicted historical ***low*** and ***high*** levels in the prediction datum are shown at the top of the tide table (refer to previous section). HAT and LAT RLs for the monitoring BM can be computed using equations (7) and (8).

$$RL_{LAT} = RL_{PRED} - low \qquad (7)$$

$$RL_{HAT} = RL_{PRED} - high \qquad (8)$$

(where ***low*** and ***high*** are the predicted historical low and high indicated in the header of the prediction table)

The Mean Sea Level is computed by meaning the RL_{LAT} and RL_{HAT} (9)

$$RL_{MSL} = (RL_{HAT} + RL_{LAT}) / 2 \qquad (9)$$

Computing the geoid MSL correction (zero order term)

The correction (or zero order term) (c) to be applied to the geoid model to align the geoidal surface with local MSL is computed by (10).

$$c = RL_{MSL} - RL_{EGM} \qquad (10)$$

This correction can be applied over large areas to align the geoid model with true MSL.

Example:

Three days of GNSS dual frequency static measurements were made at PSM 32586 located in the Aitape Government compound. The RINEX data were submitted to AUSPOS and NRCan three days after the measurements were made. ITRF2005 ellipsoidal heights computed by these services for the PSM were averaged to be 81.200 m +/- 5 mm.

GNSS static observations were then made between PSM 32586 and PSM 32587 (BM 1) constructed near the Aitape jetty, and the observations repeated on a different day. The ellipsoidal height of PSM 32586 was held fixed in the post-processing of each baseline and the averaged ellipsoidal height for PSM 32587 computed as 82.225 m. Both baselines were L1 Fixed with small RMS, high ratio and small reference variance, indicating good quality observations.

The coordinates of PSM 32587 (BM 1) were entered into the EGM2008 model and an N value of 78.33 was computed.

The approximate MSL RL ($RL_{EGM2008}$) of BM1 was computed as 82.225 - 78.33 = 3.898 m using (2).

Three other benchmarks including the one used to measure sea levels from (BM4) were levelled twice and EGM2008 RLs of the local BM network were computed.

$$RL_{EGM2008} \text{ of BM4} = 3.766 \text{ m}$$

Staff readings from BM4 down to the sea surface were measured over the course of several tidal cycles and the staff readings booked (Table 1). The EGM2008 levels of the sea surface were computed by subtracting the staff readings from the EGM2008 level of BM4 (3.766 minus staff reading). The EGM2008 height for each observation from WXTide was subtracted from the Predicted Height from WXTide and the differences shown.

PNG Date (2009)	PNG Time (UT +10 hr)	Predicted Height (from WXTide)	Staff Reading (from BM4)	EGM08 RL (3.766 - staff reading)	Predicted minus EGM2008 (D)
May-20	03:00 PM	0.87	2.30	1.47	-0.60
May-20	04:00 PM	0.91	2.28	1.49	-0.58
May-21	09:00 AM	0.57	2.53	1.24	-0.67
May-21	12:00 PM	0.44	2.68	1.09	-0.65
May-21	01:00 PM	0.53	2.67	1.10	-0.57
May-21	05:00 PM	0.95	2.16	1.61	-0.66
May-21	06:00 PM	0.96	2.13	1.64	-0.68
May-21	10:30 PM	0.74	2.34	1.43	-0.69
May-22	04:30 AM	1.21	1.98	1.79	-0.58
May-22	08:00 AM	0.79	2.41	1.36	-0.57
May-22	10:00 AM	0.42	2.78	0.99	-0.57

Table 1. Sample measurements from Aitape tidal monitoring

From the table, the mean difference (D) is -0.62 m (σ = 0.05 m)

The Prediction Datum RL of BM 4 is computed as 3.766 + -0.62 = 3.15 m (Equation 6)

WxTide computes a historical low of -0.20 and historical high of 1.80 on the prediction datum, so:

LAT RL of BM4 = 3.15 - -0.20 = 3.35 m (from Equation 7)
HAT RL of BM4 = 3.15 - 1.80 = 1.35 m (from Equation 8)

The MSL RL is computed as the mean of HAT and LAT
MSL RL of BM4 = (1.35 + 3.35) / 2 = 2.35 m (from Equation 9)
The computed offset from EGM2008 = 2.35 - 3.766 = -1.42 m (Equation 10)

To convert EGM2008 derived MSL values in the Aitape area to true MSL (based on local tidal observations) 1.42 m needs to be subtracted.

References

Kearsley, W., and Ahmad, Z., *Report on the Geoid Computation for Papua New Guinea*, Australian Component of the Land Management Project for Papua New Guinea, 1996.