DATUMS IN THE PNG OILFIELDS - CONNECTING THE PAST WITH THE FUTURE

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Abstract
PNG is currently riding the kapul's back with increased global demand for petroleum products and minerals. Several major projects are in full operation, nearing production or are in an advanced stage of feasibility studies. This is a very challenging time for PNG's surveyors as new positioning techniques such as GPS are often being used on older exploration sites that use a multitude of earlier horizontal and height datums. Are surveyors expected to tie their state-of-the-art surveys to the earlier datum, or do they start afresh? How is earlier survey information related to these new surveys? The PNG Oilfields area near Kutubu is perhaps the most complex and difficult surveying environment anywhere on the planet. The extremely rugged nature of the terrain and long and chequered history of surveying there have produced several datums and associated problems. This paper presents the findings of recent geodetic surveys of the PNG oilfields and discusses how earlier datums have been related to PNG94. The paper also shows how GPS methods can be used to achieve best practice outcomes for surveyors, not just in the PNG Oilfields, but on any resource project in PNG.

Introduction

Papua New Guinea's unique geological setting has provided it with an extraordinary abundance of natural resources: gold, silver, copper, nickel, oil and gas, not to mention large tracts of fertile land and forests. Unfortunately, the same geological forces that are responsible for these riches have also created the practically inaccessible and rugged topography that have made exploitation of them such a difficult and costly exercise. Surveyors and exploration geologists are among the first groups of professionals to be seen on any project and their duties are particularly onerous due the difficult nature of the terrain, as well as issues of land ownership and relations with land owners unfamiliar with resource developments. The role of surveyors in finding, mining and transporting these resources is very much understated. This paper discusses what is happening with the largest resource projects in PNG's history, the PNG Oilfields projects and the associated LNG project.

New positioning technologies have made life considerably easier for surveyors, although new challenges are posed. Before the era of GPS, bringing geodetic control into remote areas of PNG was a very challenging enterprise, requiring considerable planning, labour, resources, time and money. Because many terrestrial surveying methods require line of sight (e.g. triangulation and trilateration), trigonometric stations had to be constructed on generally inaccessible high peaks, requiring strenuous efforts by clearing parties and helicopter pilots. Not only that, but windows of access and visibility were notoriously short and unpredictable due to inclement weather prevalent in many upland areas of PNG. Because of these factors, lots of waiting time was required. The difficulties didn't just stop there. Once the measurements were gathered, there ensued considerable reduction and analysis using basic computers to get a list of coordinates and levels. The computations were made especially difficult because of the very large variability in elevation, atmospheric conditions and geoidal undulation caused by the extreme topography, which impacted on distance measurement and astronomical observations. The accuracy achieved by these earlier surveys has proven to be quite exceptional in the circumstances and is a great credit to the earlier surveyors and their assistants, who have exemplified the highest professional standards in surveying.

It is not surprising that surveyors dealing constantly with these interminable difficulties in PNG have welcomed satellite surveying methods, albeit with some trepidation. All that is required is a clear view of the sky, usually found at most airstrips and helipads. Nowadays, it is possible to get an absolute accuracy of a centimetre anywhere in the world with a single day's dual-frequency carrier phase GPS observations. While coordinates derived by GPS may be precise at the level of 0.1 ppm, this precision brings to light other new problems that most surveyors are still unfamiliar with. The ease of coordinate acquisition comes at a cost. In surveying, there is no easy solution!

Resource surveying requirements

All phases of any resource project are crucially dependent upon an accurate and integrated survey control network or datum and the PNG Oil and Gas projects between Juha and Kikori are no exception. Typically the sequence of surveying in any large PNG project is as follows:

1. Aerial photography, satellite imagery, topographic mapping phase
2. Population mapping and customary land / freehold land surveys in areas of potential development
3. Geological mapping and geophysical surveys (e.g. gravity, seismic imaging, hyperspectral imaging, magnetic)
4. Environmental and heritage surveys
5. Lease boundary surveys
6. Exploration drilling and associated infrastructure (wells, camps, logistics depots, roads, airstrips etc..)
7. Construction phase (production facilities, pipelines and terminals)
8. Production and export phase
9. Site rehabilitation and alternate utilisation phase

All of these different stages of development require integrated survey control from the outset to ensure that all spatial data can be related harmoniously. In practice this is difficult to achieve, often due to a lack of integration and cooperation between spatial practitioners representing the different stakeholders. The absolute and relative accuracy (also referred to as the positional and local uncertainty) of the survey control requirements varies according to the tolerances of the different users. Positional uncertainty (PU) refers to the accuracy of surveyed locations with respect to the defining datum e.g. PNG94. The local uncertainty (LU) refers to the accuracy of locations with respect to nearby points and control.

Typical positional (PU) and local (LU) uncertainties for resource projects

- GIS & mapping surveys (e.g. clan boundaries, population mapping, geological mapping) environmental surveys
  PU 4 metres, LU 2 metres

- Geophysical surveys (gravity, seismic)
  PU 2 metres, LU 0.5 metres

- Topographic surveys, earthwork setout
  PU 0.5 metres, LU 0.1 metres

- Exploration wells, Construction setout and as-built surveys
  PU 0.15 metres, LU 0.02 metres (0.005 metres for pre-cast setout)

- Deformation monitoring and other high precision surveys
  PU 0.15 metres, LU 0.002 metres

- Secondary survey control (datum extension within project area)
  PU 0.1 metres, LU 0.015 metres

- Primary survey control (datum for each prospect or production area)
  PU 0.03 metres, LU 0.01 metres

- Fiducial control - geodynamic monitoring (PNG94 datum)
  PU 0.005 metres, LU 0.005 metres

Problems associated with large enduring projects such as the PNG Oilfields project
Unfortunately the importance of integrity and accuracy of spatial data is poorly understood by many stakeholders in resource projects. All too often, different surveyors and GIS operators from different firms will be contracted to support different companies conducting exploration and production during the lifetime of a project. Inevitably at each changeover critical information is lost or not passed on. The exigencies of many projects often do not allow surveyors sufficient scope or time to recover older survey information or complete due-diligence checks on existing surveys, requiring them to start afresh (particularly non-PNG based surveyors who are unfamiliar with existing local networks). When this occurs, differences of several metres or more can be introduced into spatial framework of the project, where data from different eras gets mixed up at different times in the spatial kitchen and the provenance of survey control for an area becomes lost. Exploration, construction and production managers often fail to appreciate the value of an accurate survey control network and the logistical requirements required to achieve it, and are often focussed on the more short-term visible and tangible requirements of drilling and output in order to maintain shareholder confidence.

Surveyors often have themselves to blame for this situation as they often don't reinforce the critical importance of their role at the highest level of management of the project. Surveyors need to take a far more proactive role with their clients to ensure that the importance of survey quality is understood at all levels and not be seen as mere technicians.

In recent years there has also been some confusion arising from the requirement to adopt WGS84 as a datum for new PNG surveys. This is a potentially dangerous situation for practical and legal reasons. PNG94 has been gazetted as the official “legal” datum in PNG. PNG94 is realised by a network of 14 stations with coordinates defined by their ITRF92 values at epoch 1994.0. WGS84 is related to PNG94 and their reference ellipsoids are similar at less than 1mm, however since 1994 coordinates between the systems have diverged due to tectonic motion of the different plates in PNG by as much as 1.3 metres between 1994 and 2008. Because WGS84 is a dynamic datum and unless a local realisation of the datum and epoch is defined it can have no relevance in high precision or legally certifiable surveys in PNG. WGS84 remains a datum for navigation and positioning at the level of 2-5 metres.

Unfortunately, many precise point positioning (PPP) services do not have the complexity of the PNG tectonic setting setup in their systems and produce coordinates only in ITRF2000/WGS84 at the epoch of observation. These are not PNG94 coordinates!

Another issue is the lack of use or understanding of plane datums. Map grid coordinate systems are often used for local plane surveys with a scale factor of 1. In the PNG oilfields highland areas this assumption can lead to errors of 600 ppm (0.6m in every kilometre)! Construction plane grids do not appear to be used in the PNG Oilfields. A 40 km road or pipeline in AGD66 or PNG94 could in fact be 40.024 km in local Plane (i.e. 24 metres difference between the two)!

Legacy issues also plague surveyors. Because most of the development of the Oil Fields was completed on AGD66 many current surveys still need to be related to it e.g. well-location reporting, lease boundaries, mapping, GIS etc. Current PNG Oil and Gas legislation stipulates the definition of lease boundaries and reporting of well locations in AGD66. Some surveyors unwittingly use the default NGA parameters to transform from WGS84 to AGD66. These are known to be inaccurate to 7-8 metres in the Oil Fields and do not relate to existing AGD66.

A brief history of surveying in the PNG Oilfields

Fred Pratt's "*Report on the existing survey systems in use on the Gobe, Kutubu and Hides Oil Fields*" and James Sinclair's "*Mastamak*" have been the primary sources for the historical study summarised here.

During the early 1960s, the precursor to the National Mapping Bureau's geodetic section established the first nationwide geodetic network including those within the main PNG oil and gas fields (the T and NM/J series marks). This was done by classical triangulation and trilateration using the newly available MRA101 tellurometers. The survey also included the US Department of Defense HIRAN network (e.g. HIRAN 23 at Aird Hills near Kikori). The relative uncertainty of this network consisting mostly of trig stations on remote and high mountain tops is generally sub-metre. Elevations derived by trig heighting could be up to 4 metres in error resulting from uncertainties in atmospheric modelling and deflection of the vertical due to the ruggedness of the topography. According to Fred Pratt, observations in the Oilfields area weren't closed off to a tide gauge, presumably because tides are strongly influenced by seasonal river flows in the Gulf region.

By the late 1960s significant exploration was underway in the Kutubu area and two surveyors, Alan Mail and Brian Wigley densified the existing NMB network in the Kutubu area (AM stations) to support this. During the late 1960s and early 1970s, the Royal Australian Survey Corps of the Australian Army established an extensive network of stations (AA series) to provide control for the current 1:100,000 topographic map series. The use of aircraft (AERODIST) initially and later the TRANSIT satellite doppler system used to augment the trilateration and triangulation process, improved efficiency considerably and an accuracy of 0.5-2 metres was achieved for the ground control, sufficiently acceptable for the scale of mapping.

Seismic surveys requiring high relative accuracy were conducted in the area and a company, SSL established a network of stations to support it. Unfortunately, SSL did not initially tie into the existing network and scaled the datum off a 1:100,000 map resulting in significant differences with existing control. During the 1980s Carson Pratt Surveys (CPS) established an extensive control network from Gobe to Hides (CP stations), tied in to the existing network. During their surveys a heighting error of 15m was found in the primary network. This accounts for the large difference between the older height datum still used for well reporting and true MSL. During the late eighties doppler satellite surveying methods with a relative accuracy of 0.2-0.4m were used by SSL and a Canadian company, Nortech to support seismic and laser profiling surveys. Relative heighting accuracy was improved by these surveys to 1 metre by using an early geoid model to compute orthometric heights (close to MSL). The absolute accuracy (agreement with true MSL) of heights is at the level of 4-5 metres.

By the late 1980s the new GPS system was being used by Nortech to establish control along the proposed export pipeline. Relative heighting was improved with the new OSU86 geoid model, however errors in earlier surveys were not rectified. A metre error in the Nortech network was identified by Fred Pratt and confirmed by later validation. Agreement between most of these different surveys is at the level of 1.5 metres. In practice the accuracy of the survey network should be sub 0.3m. Arman Larmer Surveys (ALS) densified the datum in the Kutubu and Gobe areas in the early 1990s and these surveys form the basis for much of the construction work in these areas. Unfortunately the 14 metre discrepancy still exists between the construction height datum and the old height datum upon which earlier geophysical work and current petroleum reporting is still based.

In 2005, surveys were conducted to support the GAS FEED survey for the PNG-QLD Gas pipeline and associated infrastructure. Asia Pacific Surveys, Arman Larmer Surveys and geodetic surveyors from UniTech completed a high precision GPS survey connected to PNG94 (Datum PSM 5583 Kikori). *Quickclose* was contracted to validate the processing and transform the results using a tectonic velocity model. MSL elevations were derived using the EGM96 derived geoid model. EGM96 derived elevations were corrected by tidal observations made at the Kumul offshore platform, far enough offshore not to be influenced by seasonal fluvial discharge from rivers in the Gulf area. Fugro Spatial Solutions provided a high accuracy digital elevation model using Airborne Laser Scanning techniques over sections of Oil Fields based upon this survey control.

In 2007, Quickclose was contracted by Oil Search to completely review their survey requirements and specifications for their operations, complete a validation of the Oil Fields primary survey network and compute accurate transformation parameters between AGD66, PNG94 and ITRF2000/WGS84 network in the Oil Fields and LNG pipeline areas. After a two year hiatus and change in direction, the LNG FEED survey is now under way again with the development of a pipeline from the oil and gas fields to an LNG processing and export facility near Port Moresby.

Results from the 2007 validation survey in the PNG Oilfields

The GAS FEED datum stations coordinated in 2005 were reobserved and validated in 2007 and the accuracy of the primary control network was improved from 0.15 m to 0.08 m or better as a result of refinements in the regional tectonic velocity model. Secondary stations and other stations were also included in the validation. A full listing of station coordinates and their positional uncertainties is set out (Tables 4 & 5 at end of this paper) and a plot of the stations in shown in Figure 1.

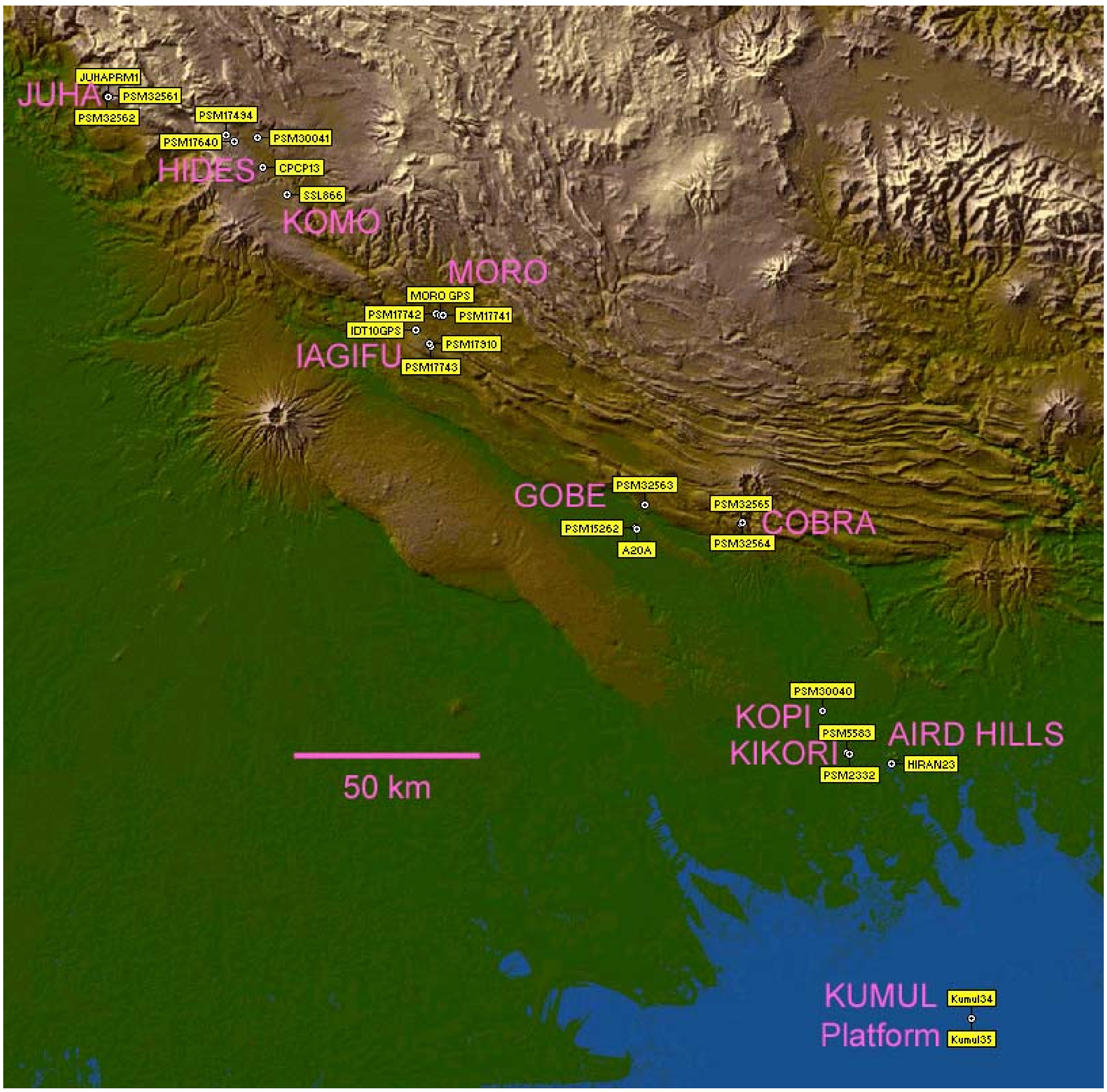

Figure 1: PNG Oilfields - Network of primary, secondary & tertiary control stations

Tectonic stability of the Oilfields geodetic network

Precise point positioning technology using modern GNSS techniques such as GPS has advanced to the extent that plate tectonics can significantly influence the accuracy of precise positions if the tectonics are not modelled correctly. As the PNG Oilfields lie in a tectonically active area it is necessary to relate positions to a specific time or reference epoch, so that coordinates of survey marks do not change continuously and also so that baseline network adjustments are not influenced by tectonic deformation. The PNG Oilfields lie at the northern edge of the Australian Plate. During the last 8 million years the collision between the Australian Plate and terranes in the New Guinea Highlands has resulted in the exhumation of the Papuan Foreland to form the Papuan Fold and Thrust Belt (PFTB) within which the principal PNG petroleum fields are located. This collision is still active with shortening across the PFTB estimated to be between 6 and 15 mm/yr.

Geodetic techniques such as GPS can now measure tectonic deformation directly and there is a network of geodetic monitoring stations around the PFTB that were used as part of the validation to monitor this deformation. These stations are: PSM 5583 Kikori, PSM 17001 Kopiago, PSM 3507 Mendi and PSM 3419 Mt. Hagen. The stations were first observed between 1993 and 1997 and repeat observations have been made at all stations except Mendi. The following ITRF2000 velocities have been estimated for the stations:

Kikori	East 34 mm/yr	North 54 mm/yr
Mt. Hagen	East 30 mm/yr	North 48 mm/yr
Kopiago	East 31 mm/yr	North 55 mm/yr

Baseline changes between 1993 and 2007 indicate insignificant changes (< 1 mm/yr) between Kikori-Kopiago and Mt. Hagen-Kopiago, however shortening between Kikori and Mt. Hagen is 5 +/- 1 mm/yr. The majority of this shortening is predicted to occur to the NE of the principal oilfields. Assuming that there is no significant anomalous deformation within the area, the following site velocities have been estimated for the following locations within the PNG Oilfields:

Kopi, Kikori, Kumul, Gobe	East	34 mm/yr	North	54 mm/yr
Kutubu, Moro, Iagifu, Moran	East	33 mm/yr	North	54 mm/yr
Hides, Juha	East	32 mm/yr	North	54 mm/yr

These velocities can be used to estimate ITRF2000/WGS84 at any epoch and PNG94.

There is insufficient data to estimate uplift rates at this stage, however it is likely to be less than 3 mm/yr. Repeat observations in 2009 at infield primary stations first observed in 2005 will verify these estimates and identify any anomalous tectonic activity.

Conversion of ITRF2000/WGS84 coordinates to PNG94

The ITRF2000 coordinates of stations in the validation survey were determined by AUSPOS and baseline post-processing and adjusted back to epoch 1994.0 using the site velocities described above. The 1994.0 epoch coincides with the epoch of realisation of PNG94. A comparison between the gazetted PNG94 and computed coordinates for Kikori and Mt. Hagen fiducial stations showed agreement of less than 15 mm horizontal and less than 30 mm in ellipsoidal heights. This indicates that the epoch adjusted coordinates for other stations in the network are also aligned with PNG94 at a similar level of accuracy.

Differences between height datums and geoid models in the Oilfields

As mentioned previously, there are several variations in locally realised MSL depending upon historically accepted values of height datum points. Gravity models have been used to compute geoid models (in general terms, the separation between MSL and a reference ellipsoid used by GPS). These models have improved significantly in recent years from 1-2 metre accuracy to better than 0.5 metres such as the current Earth Gravity Model 1996 (EGM96). It is anticipated that EGM07 will have an accuracy of approximately 0.2 metres but this has not yet been released. The PNG geoid model developed by Prof. Kearsley from the University if New South Wales, is based on the OSU91 model and is accurate to 0.5m in the Oil Fields area due to the inclusion of BP Gravity data. EGM96 is available online at http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm96/intpt.html while the PNG geoid is available on request from NMB or UniTech as an MS-DOS executable running on Windows 98, Windows 96 or MS-DOS Operating Systems.

The geoid-WGS84 ellipsoid separation is significant in PNG (between 76 m at Kikori and 82 metres at Hides) The large geoid-ellipsoid separation, high geoidal gradients, mass anomalies and high elevation of many locations in the PNG Oilfields impacts on the accuracy of GPS heighting. The geoid-ellipsoid separation (*n* value) is considered to be normal to the ellipsoid, when in fact the true orthometric height difference is greater due to curvature of the normal path (plumb line) when integrated across the geopotential field. The difference between the normal and orthometric heights could be as much as 0.2 m in the PNG Oilfields.

EGM96 was used to compute the ellipsoid-geoid separation (n value) for each of the stations in validation survey. The EGM96 derived MSL elevations were compared with existing tabulated data in order to estimate local height datum offsets from the EGM96 derived geoid. EGM96 *n* values were compared with those computed by the PNG geoid calculator and agreement was usually found to be better than 0.7 m. Without geometric levelling ties across the network, it is difficult to say which geoid model is more accurate.

Determination of MSL by tidal monitoring
GPS observations were collected at Kumul 34 on the Kumul Platform in order to verify the accuracy of geoid models at a tidal monitoring station not influenced by river flows. The Kumul platform is sufficiently far offshore not be significantly influenced by seasonal changes in fluvial discharge from the Kikori River. Five hours of observations were made at Kumul 34 with a tie made to Kumul 35. Tidal monitoring data were collected from the platform's tidal monitoring system and several measurements were made during the period of measurement from the GPS stations down to the sea surface (by tape). These measurements were correlated with data from the tidal monitoring system. The Lowest Astronomic Tide (LAT) elevations of the sea surface output from the monitoring were also compared with the National Tidal Facility (NTF) predictions for the platform. The difference between the predicted and measured LAT was 0.25 m with a consistent offset. The tidal range for the location is predicted to be 3.8 m indicating that MSL is approximately 1.9 m LAT. On the basis of 5 hours tidal observations, the computed *n* value (geoid-ellipsoid separation) at Kumul is 75.4 m . The computed *n* value based on 2 months tidal observations in 2003 is 75.33 m (Kumul 34 ellipsoid ht 103.30m, LAT height 29.81 m and MSL height 27.97m) which is in agreement with the short period validation at 0.1 m.

The measured *n* value differs from the EGM96 n value of 74.46 m by 0.87 m indicating a bias in EGM96 over the area. The PNG Geoid model *n* value is 76.41 which is significantly different. PNG Geoid *n* values differ from EGM96 *n* values by up to 1 metre over the PNG Oilfields area.

Until a better geoid model over the PNG Oilfields becomes available (e.g. EGM07 or from precise levelling observations), it is recommended that EGM96 *n* values with a 0.87m correction applied be used to estimate MSL elevations from GPS methods.

Double-run precise levelling along the pipeline and road corridors between Hides and Kikori could be conducted to enable a more accurate model of the orthometric geoid-ellipsoid separation in the PNG Oilfields to be computed. For any engineering projects where elevation and gradient control is critical, control stations used should be levelled by precise geometric levelling techniques. The EGM96 geoid gradient may be insufficiently accurate.

Summary of Height Datums and reference systems used

Mean Sea Level (MSL)

Origin:	Mean Sea Level / Geoid
Applications:	engineering, mapping and surveying
Remarks:	Different definitions depending upon method of survey, tide gauge origin and geoid model.

Mean Sea Level (by EGM96)

Origin:	Geoid derived from EGM96 (Earth Gravity Model)
Applications:	Remote sites in the exploration phase
Remarks:	Accurate to 0.5 m in most areas. EGM96 is currently the standard geoid model used globally. An improved model EGM07 to be released during 2008. Offset from MSL at Kumul platform by 0.87 m RL(EGM96)=RL(Kumul34)+0.87

Mean Sea Level (Kumul 34)

Origin:	Kumul 34 on Kumul Platform (RL 27.97) and EGM96
Applications:	engineering, mapping and surveying
Remarks:	Based on the EGM96 model corrected to fit MSL measurements made at the Kumul Platform. Accurate to 0.5 m in most areas. Should be used as initial height datum for large scale engineering projects. RL(Kumul34)=RL(EGM96)-0.87

Lowest Astronomic Tide (LAT Kumul)

Origin:	Kumul 34 on Kumul Platform (LAT RL 29.81)
Applications:	Marine and coastal surveying, tidal monitoring
Remarks:	1.84 m below MSL. RL(Kumul34)=RL(LAT)-1.84

Mean Sea Level (PNG Geoid)

Origin:	Geoid derived from OSU91 geoid model and local gravity
Applications:	PNG National Mapping Bureau / Department of Lands
Remarks:	Accurate to 0.7 m in most areas. Software to compute separations has limited distribution and has not been updated to run on current operating systems. Up to 1 m variation with respect to EGM96

Mean Sea Level (Chevron Datum)

Origin:	AM57 (PSM 9293) Kutubu R.L. 1304.05
Applications:	drilling reports in the Kutubu area, old drilling datum
Remarks:	Relative accuracy of 0.4 m in most areas. MSL(Chevron)=MSL(EGM96) - 15.9

Mean Sea Level (Kutubu Datum)

Origin:	PSM17910 Iagifu RL 1363.79 (Local transformation origin)
Applications:	Construction surveys in the Kutubu area. Accurate to 0.3 m MSL(Kutubu)=MSL(EGM96)+2.6 MSL(Kutubu)=MSL(Chevron)+18.5

Mean Sea Level (Hides Datum)

Origin:	PSM17640 RL 2465.95 (Local transformation origin)

Mean Sea Level (Juha Datum)

Origin:	Juha PRM1 RL 966.5 (Local transformation origin)

Mean Sea Level (Gobe Datum)

Origin:	PSM15262 Gobe RL 53.68 (Local transformation origin)

WGS84 Ellipsoid Height (WGS84)

Origin:	Geocentre	Ellipsoid: World Geodetic System 1984 (WGS84)
Applications:	Not used. Differs from MSL by up to 80 metres	

ITRF2000 Ellipsoid Height (ITRF2000)

Origin:	Geocentre	Ellipsoid: Geodetic Reference System 1980 (GRS80)
Applications:	Tectonic monitoring, high precision surveys. Differs from MSL by up to 80 m	

PNG94 Ellipsoid Height (PNG94)

Origin: Geocentre & Coordinates of PNG Fiducial Network
Ellipsoid: Geodetic Reference System 1980 (GRS80)
Applications: High precision surveys. Differs from MSL by up to 80 metres

To→ From↓	EGM96	Kumul34	LAT Kumul	Chevron	Kutubu	Hides	Juha	Gobe
EGM96	0	-0.87	0.97	-15.9	2.6	0.55	5.3	2.3
Kumul34	0.87	0	1.84	-15.03	3.47	1.42	6.17	3.17
LAT Kumul	-0.97	-1.84	0	-16.87	1.63	-0.42	4.33	1.33
Chevron	15.9	15.03	16.87	0	18.5	16.45	21.2	18.2
Kutubu	-2.6	-3.47	-1.63	-18.5	0	-2.05	-2.7	-0.3
Hides	-0.55	-1.42	0.42	-16.45	2.05	0	4.75	1.75
Juha	-5.3	-6.17	-4.33	-21.2	-2.7	-4.75	0	-3.0
Gobe	-2.3	-3.17	-1.33	-18.2	0.3	-1.75	3.0	0

Table 1: Conversion reckoner between different height datums in PNG Oilfields

Validation of the AGD66 network in the PNG Oilfields

A selection of primary control stations were resurveyed in 2007 as part of the validation process in order to compute regional and local transformation parameters between PNG94 and AGD66. Many primary stations were recovered, often with great difficulty, as regrowth since last occupation has been quite significant.

A least squares estimate of the best fit between the AGD66 network of recovered stations and their PNG94 coordinates indicates homogeneity across the network of ~1.5 m, which is quite remarkable considering the difficult nature of the terrain and survey management problems discussed earlier. Within each development area agreement is usually at the 0.2 m level. The misfit of ~1.5 m within the Kutubu control network between Iagifu and Moro identified by Fred Pratt was verified. Fred Pratt's report suggests that the error has arisen from incorrect GPS ambiguity fixing with the Nortech survey at PM Y22. PM Y22 is the AGD66 datum station in the Iagifu area. An ALS station PSM 17910 was found in the same location and it appears that the surveyor who established it adopted Y22 as a reference mark (Star picket in concrete) 1.684m 165°29' from PSM17910.

PSM15271 above the Ai'io River was not found despite an extensive search. The area has dense secondary regrowth and no PSM sketch, witness post or other monumentation could be found. The location of PSM 15265 near Kantobo was found to be completely overgrown and a helicopter could not be landed within a reasonable distance in order to gain access by foot within the timeframe of the validation survey. Fred Pratt has indicated that neither reference narks nor witness posts for these PSMs were established by Nortech.

Hiran-23 at Aird Hills was found after extensive clearing of a dense thicket of bamboo, however the original Aird Hills trig station and monument have both been destroyed by local villagers. As this important datum station has now been tied to the network at Kikori airport, there is no requirement to return to this location, as access is very arduous. There is also a long standing dispute in the nearby village about ownership of the site which may prevent access in the future. The site is no longer accessible by helicopter.

PM CG14 at Gobe is completely overgrown and will require several hours clearing to gain access from the GOBE SE Ridge Road.

A listing of AGD66 control stations is shown in Table 5 at the end of the paper.

Transformation Parameter Estimation

Transformation parameters and grid distortions (block-shifts) have been estimated by a robust least-squares analysis of the AGD66 station coordinates and their equivalent PNG94 coordinates. A standard three parameter transformation model has been estimated for medium accuracy transformations (up to 0.5 m) and a localised block-shift adjustment can also be implemented for higher accuracy transformations (up to 0.1 m). For mapping and GIS purposes (accuracy ~3 metres) a three (origin shift) has been estimated. In localised areas (< 10 km x 10 km) a two parameter block shift (ΔEastings & ΔNorthings) is sufficiently accurate for AMG66 to PNGMG conversions at the sub 0.2 m level. These parameters can be implemented by use of spreadsheets and other computer software to relate AGD66 data to PNG94 and ITRF2000 anywhere in the PNG Oilfields.

ITRF2000 coordinates are computed by precise point positioning techniques such as OmniStar-HP and by many post-processing methods such as AUSPOS. Coordinates computed by these methods need to be related to a common reference epoch so that the effects of tectonic deformation do not degrade the solution. It is also important that the epoch is standardised so that surveys conducted at different times in ITRF2000 can be related to each other. In both PNG and Australia the reference epoch is 1st January 1994 (1994.0) which is also the epoch of realisation of both PNG94 and GDA94.

The following strategies can be used to transform ITRF2000 and WGS84 coordinates to PNG94 (ITRF92 at epoch 1994.0) in the PNG Oilfields

GIS Molodensky & 3-parameter Shifts

The following parameters can be entered into most GIS and coordinate transformation packages:

Transformation	Accuracy	DX(m)	DY(m)	DZ(m)	Ellipsoid
ITRF2000/WGS84 to PNG94 **2008**	0.05	0.35	0.32	-0.76	WGS84/GRS80
ITRF2000/WGS84 to PNG94 **2009**	0.05	0.38	0.34	-0.81	WGS84/GRS80
ITRF2000/WGS84 to AGD66(Oil)	2.0	124	60	-154	ANS
PNG94 to AGD66(Oil)	2.0	124	60	-153	ANS
PNG94 to ITRF2000/WGS84 **2008**	0.05	-0.35	-0.32	0.76	WGS84/GRS80
PNG94 to ITRF2000/WGS84 **2009**	0.05	-0.38	-0.34	0.81	WGS84/GRS80
AGD66(Oil) to ITRF2000/WGS84	2.0	-124	-60	154	WGS84/GRS80
AGD66(Oil) to PNG94	2.0	-124	-60	153	WGS84/GRS80

Table 2: Molodensky/3 parameter shifts between datums in the PNG Oilfields

Ellipsoids:
ANS (Australian National Spheroid) a= 6378160 m, inverse flattening 298.25
WGS84 a = 6378137 m, inverse flattening 1/298.257223563
GRS80 a = 6378137m, inverse flattening 1/298.257222101
WGS84 is the same as GRS80 at sub 0.2mm

UTM/PNGMG94/AMG66 Map Grid Coordinate Transformation

ITRF2000, WGS84 and ITRF2005 UTM grid coordinates obtained by precise point positioning (e.g. AUSPOS, OmniStar-HP) can be converted to PNG94 grid coordinates (PNGMG94) using the following expressions:

50 mm accuracy in the PNG Oilfields

$$\text{Easting}_{PNG94} = \text{Easting}_{ITRF2000/WGS84} + (1994-y)*0.033$$

$$\text{Northing}_{PNG94} = \text{Northing}_{ITRF2000/WGS84} + (1994-y)*0.054$$

20 mm accuracy at Juha, Hides, Mananda, Moran, Agogo, Iagifu, Usano & Hedinia

$Easting_{PNG94} = Easting_{ITRF2000/WGS84} + (1994-y)*0.032$

$Northing_{PNG94} = Northing_{ITRF2000/WGS84} + (1994-y)*0.054$

20 mm accuracy at Gobe, Cobra, Barikewa, Kopi, Kikori & Kumul

$Easting_{PNG94} = Easting_{ITRF2000/WGS84} + (1994-y)*0.034$

$Northing_{PNG94} = Northing_{ITRF2000/WGS84} + (1994-y)*0.054$

where y is epoch in decimal year format (e.g. 1st March 2009 would be 2009 + (31+28+1)/365 = 2009.164)

The following table can be used for straightforward 50mm accurate conversions of coordinates in the PNG Oilfields by applying the following corrections for each year indicated:

	2008	**2009**	**2010**	**2011**	**2012**	**2013**
Easting	-0.48	-0.51	-0.54	-0.58	-0.61	-0.64
Northing	-0.78	-0.84	-0.89	-0.95	-1.00	-1.05

Table 3 - Correction applied to ITRF2000 / WGS84 UTM coordinates to get PNGMG94

1 metre accuracy AMG66 to PNGMG94 block shift

AMG66 Easting = PNGMG Easting - 122
AMG66 Northing = PNGMG Northing - 161

0.3 metre accuracy AMG66 to PNGMG94 block shifts

Juha
AMG66 Easting = PNGMG94 Easting - 121.9
AMG66 Northing = PNGMG94 Northing - 162.3

Hides
AMG66 Easting = PNGMG94 Easting - 121.9
AMG66 Northing = PNGMG94 Northing - 161.6

Moro
AMG66 Easting = PNGMG94 Easting - 121.5
AMG66 Northing = PNGMG94 Northing - 160.1

Iagifu
AMG66 Easting = PNGMG94 Easting - 123.0
AMG66 Northing = PNGMG94 Northing - 160.9

Gobe
AMG66 Easting = PNGMG94 Easting - 122.5
AMG66 Northing = PNGMG94 Northing - 160.7

Kikori
AMG66 Easting = PNGMG94 Easting - 121.6
AMG66 Northing = PNGMG94 Northing - 161.9

Guidelines for surveyors working in the PNG Oilfields

Equipment and capability

For control surveys over longer distances suitable GNSS/GPS equipment should be used. Ideally dual-frequency receivers should be used as these can measure baselines up to 50 km to an accuracy of a few centimetres using a broadcast ephemeris. Receiver Independent Exchange Format (RINEX) data can be extracted from dual frequency raw data and submitted to online processing services such as AUSPOS to obtain centimetre accurate ITRF coordinates. These coordinates need to be subsequently converted to PNG94 using a tectonic velocity model. Single-frequency receivers can measure lines accurately up to 10 km. Beyond 10 km, single frequency accuracy diminishes rapidly. The OmniSTAR HP service can be used to obtain 10 cm accurate positions in ITRF, but these positions need to be converted to PNG94 in much the same way as AUSPOS. There is a 10% chance that the HP solution can be incorrect by up to 0.9m so repeat observations should be made on different days if possible, to verify accuracy.

Control

The nearest control station listed in Table 4 should be used as the reference or base station for any surveys, with checks made from auxilliary base stations using other adjacent stations. It is unwise to use LAE1 and MORE GPS stations as they are located on different tectonic plates from the Oilfields.

Observing times

For AUSPOS the following occupation times are required for the given accuracy (if observing conditions are bad, double the time):

20 cm accuracy - observe for 1 hour (minimum time for AUSPOS)
10 cm accuracy - observe for 2 hours
5 cm accuracy - observe for 3 hours
2 cm accuracy - observe for 6 hours
1 cm accuracy - observe for 12 hours
0.5 cm accuracy - observe for 2 x 24 hour periods

Surveyors should wait 2 days before submitting the GPS data to AUSPOS in order to get a solution using the IGS Rapid orbit and two weeks to get the IGS Final Orbit (most reliable). Note: AUSPOS uses UT for submitted data files, so ensure that the observation start time is after 10 am PNG Time to ensure continuity of AUSPOS processing required for accurate solutions.

For static GPS surveys using dual-frequency enabled receivers, the following observation times are recommended in order to obtain a fixed solution (assuming 30 second epoch rate):

0-5 km	15 minutes	(30 minutes for single frequency receivers)
5-10 km	20 minutes	(40 minutes for single frequency receivers)
10-20 km	30 minutes	
20-30 km	40 minutes	
30-40 km	50 minutes	
40-50 km	60 minutes	

If observing conditions are not optimal (e.g. poor coverage, satellite availability, tree or building nearby) then the times above should be doubled.

For OmniSTAR-HP observations, convergence of less than 10cm should be attained before logging any data, and measurements on different days, or at least 3 hours apart, from a cold startup should be compared and meaned. Occasionally, the position converges incorrectly. Ellipsoid heights should be logged (by adding GGA sep.) as the geoid model generated by the host receiver can be in error by up to 18 metres. The EGM96 geoid calculator should be applied to obs.

Processing

For AUSPOS, raw data files from the receiver need to be converted to RINEX format using ***teqc*** or software provided with the GPS receiver. Submitted files are sent to AUSPOS at http://www.ga.gov.au/bin/gps.pl . A pdf report showing ITRF2000/2005 coordinates is emailed back within an hour or so.

For Static surveys, any reliable baseline post-processing software can be used to compute baselines between GPS antennas. The base station coordinates should be held fixed using Table 4 data and a fixed carrier-wave solution is required (either L1 narrow-lane, or L1/L2 ionospheric error free fixed). Use ellipsoidal heights and use a geoid model and other necessary corrections to compute MSL. All surveyed stations should be checked by baseline measurement from a different station if possible. Network adjustment can be performed on interconnected baselines, but this is not essential provided independent checks are done and sub 2 cm agreement is found.

Transformation

AUSPOS & OmniSTAR-HP solutions should be transformed to PNG94 using the strategies described above. PNG94 to AGD66 conversions should be done using the methods described above.

Table 4 - PNG Oilfields - Geodetic Datum PNG94 (ITRF92 Epoch 1994.0)

(To be used for primary survey control from 2008)

		PNG94 (ITRF92 Epoch 1994.0)		Ellipsoid	MSL Ht.	PNGMG94 Zone 54		Pos. Uncertainty			Vel. (m/yr)	
Station	**Location**	**Latitude**	**Longitude**	**Height**	**(Kumul)**	**Easting**	**Northing**	**σ E**	**σ N**	**σ Ht**	**East**	**North**
Fiducial Control												
LAE1	Lae IGS Base station	-6° 40' 25".3664	146° 59' 35".4670	140.33	68.28			0.01	0.01	0.010	0.026	0.052
PSM5583	Kikori Airstrip (Apron)	-7° 25' 24".6532	144° 14' 55".7667	88.93	12.00	858689.78	9178117.65	0.02	0.02	0.010	0.035	0.054
PSM17001	Kopiago Airstrip (Apron)	-5° 23' 09".0852	142° 29' 42".1907	1412.79	1327.67	665650.98	9404480.51	0.02	0.02	0.030	0.031	0.055
Primary Control												
PSM32561	Juha 4 (above)	-5° 50' 03".2869	142° 25' 10".2087	1041.18	958.31	657158.18	9354920.22	0.07	0.06	0.040	0.032	0.054
PSM30041	Nogoli Helipad	-5° 56' 02".4348	142° 47' 16".7455	1340.20	1257.54	697930.59	9343770.78	0.07	0.06	0.040	0.032	0.054
IDT10GPS	Iagifu IDT10 camp	-6° 23' 59".1002	143° 10' 43".5263	1192.81	1112.64	740997.39	9292094.93	0.07	0.06	0.040	0.033	0.054
PSM17742	Moro Airstrip (W End)	-6° 21' 44".9072	143° 13' 46".0940	917.86	837.42	746627.49	9296194.53	0.07	0.06	0.030	0.033	0.054
PSM32563	Gobe (Operations Camp)	-6° 49' 20".1261	143° 44' 42".7931	565.21	486.15	803439.28	9245035.88	0.07	0.06	0.040	0.034	0.054
PSM30040	Kopi (Valve station)	-7° 19' 19".7114	144° 11' 08".2790	84.44	7.24	851786.20	9189391.84	0.04	0.03	0.030	0.035	0.054
Secondary Control												
PSM32562	Juha 4	-5° 50' 04".8669	142° 25' 04".6812	1026.35	943.48	656988.03	9354872.12	0.07	0.06	0.040	0.032	0.054
CPCP13	Hides 4	-6° 00' 20".1417	142° 48' 05".7727	1757.65	1675.58	699412.77	9335848.86	0.09	0.06	0.040	0.032	0.054
PSM17743	Iagifu Ridge Camp (above)	-6° 26' 28".7380	143° 13' 00".6218	1470.84	1390.77	745191.88	9287478.65	0.07	0.06	0.050	0.033	0.054
MORO GPS	Fofari Camp (Senior)	-6° 21' 55".8294	143° 14' 26".7368	913.14	832.68	747875.54	9295853.49	0.07	0.06	0.060	0.033	0.054
PSM15262	Gobe Airstrip (W side)	-6° 52' 45".5701	143° 43' 21".3500	129.24	50.52	800901.00	9238734.50	0.08	0.06	0.060	0.034	0.054
A20A	Gobe Airstrip (S side)	-6° 52' 57".6856	143° 43' 36".0904	130.08	51.38	801351.74	9238359.46	0.08	0.06	0.040	0.034	0.054
PSM2332	Kikori Airstrip (S End)	-7° 25' 36".4929	144° 15' 11".8089	89.91	12.99	859179.61	9177749.89	0.03	0.03	0.040	0.035	0.054
Tertiary Control												
JUHAPRM1	Juha 4 (above)	-5° 50' 06".3449	142° 25' 11".2763	1043.23	960.36	657190.78	9354826.21	0.08	0.08	0.060	0.032	0.054
PSM17494	Hides 1 (above)	-5° 55' 42".2240	142° 42' 43".9756	2839.30	2756.68	689542.29	9344418.15	0.07	0.06	0.060	0.032	0.054
PSM17640	Hides 2 (above)	-5° 56' 44".2401	142° 43' 57".3569	2547.04	2464.54	691793.48	9342506.01	0.07	0.07	0.060	0.032	0.054
SSL866	Komo Airstrip	-6° 04' 17".1716	142° 51' 41".7762	1624.88	1543.28	706031.42	9328544.56	0.07	0.07	0.060	0.032	0.054
PSM17910	Iagifu 2 (above)	-6° 26' 02".9002	143° 12' 42".7950	1440.09	1360.00	744647.35	9288275.00	0.08	0.07	0.050	0.033	0.054
PSM17741	Moro Airstrip (E end)	-6° 21' 49".2971	143° 14' 47".5885	907.02	826.54	748517.47	9296051.44	0.07	0.06	0.040	0.033	0.054
PSM32565	Cobra 1	-6° 52' 08".3625	143° 59' 01".8200	1130.06	1051.11	829804.95	9239706.05	0.10	0.06	0.060	0.034	0.054
PSM32564	Cobra 1 (above)	-6° 52' 02".4674	143° 59' 04".6413	1136.14	1057.18	829892.78	9239886.77	0.10	0.07	0.060	0.034	0.054
Height Datum Stations												
HIRAN23	Aird Hills	-7° 26' 50".9425	144° 21' 25".6535	397.78	320.89	870639.93	9175374.19	0.04	0.03	0.030	0.035	0.054
Kumul34	Kumul platform	-8° 03' 51".3913	144° 33' 38".3558	103.30	27.96	892563.96	9106883.55	0.05	0.04	0.040	0.035	0.054
Kumul35	Kumul platform (Helipad)	-8° 03' 52".1178	144° 33' 38".8321	104.59	29.26	892578.36	9106861.08	0.05	0.04	0.040	0.035	0.054

Table 5 - PNG Oilfields - Geodetic Datum AGD66

(For reference only)

		AGD66		MSL Ht.	AMG66 Zone 54		Pos. Uncertainty		
Station	**Location**	**Latitude**	**Longitude**	**(EGM96)**	**Easting**	**Northing**	**σ E**	**σ N**	**σ Ht**
Primary Control									
HIRAN23	Aird Hills	-7°26'56.145"	144°21'21.690"	321.76	870518.36	9175212.25	0.10	0.10	0.30
SSL86/6	Komo Airstrip	-6°04'22.370"	142°51'37.814"	1544.15	705909.77	9328382.96	0.15	0.10	0.30
PSM15262	Gobe Airstrip (W side)	-6°52'50.736"	143°43'17.358"	51.39	800778.55	9238573.77	0.15	0.15	0.30
Secondary Control (from tabulated AGD66 data)									
JUHAPRM1	Juha 4 (above)	-5°50'11.565"	142°25'07.308"	961.23	657068.87	9354663.96	0.15	0.15	0.30
PSM17494	Hides 1 (above)	-5°55'47.425"	142°42'40.000"	2757.55	689420.20	9344256.50	0.15	0.10	0.30
PSM17640	Hides 2 (above)	-5°56'49.437"	142°43'53.388"	2465.41	691671.59	9342344.49	0.15	0.10	0.30
CPCP13	Hides 4	-6°00'25.340"	142°48'01.801"	1676.45	699290.81	9335687.28	0.15	0.10	0.30
PSM17910	Iagifu 2 (above)	-6°26'08.076"	143°12'38.785"	1360.87	744524.27	9288114.02	0.10	0.20	0.30
PSM17743	Iagifu Ridge Camp (above)	-6°26'33.909"	143°12'56.615"	1391.64	745068.90	9287317.84	0.10	0.20	0.30
PSM17742	Moro Airstrip (W End)	-6°21'50.054"	143°13'42.132"	838.29	746505.88	9296034.48	0.30	0.10	0.30
PSM17741	Moro Airstrip (E end)	-6°21'54.445"	143°14'43.635"	827.41	748396.14	9295891.36	0.30	0.10	0.30
Tertiary Control (by transformation)									
PSM32562	Juha 4	-5°50'10.089"	142°25'00.713"	944.35	656866.13	9354709.82	0.15	0.15	0.30
PSM32561	Juha 4 (above)	-5°50'08.509"	142°25'06.241"	959.18	657036.28	9354757.92	0.15	0.15	0.30
PSM30041	Nogoli Helipad	-5°56'07.634"	142°47'12.776"	1258.41	697808.69	9343609.18	0.15	0.10	0.30
IDT10GPS	Iagifu IDT10 camp	-6°24'04.274"	143°10'39.519"	1113.51	740874.39	9291934.03	0.10	0.20	0.30
MORO GPS	Fofari Camp (Senior)	-6°22'00.978"	143°14'22.778"	833.55	747754.04	9295693.39	0.30	0.10	0.30
A20A	Gobe Airstrip (S side)	-6°53'02.851"	143°43'32.097"	52.25	801229.24	9238198.76	0.15	0.15	0.30
PSM32563	Gobe (Operations Camp)	-6°49'25.292"	143°44'38.800"	487.02	803316.78	9244875.18	0.15	0.15	0.30
PSM32565	Cobra 1	-6°52'13.541"	143°58'57.840"	1051.98	829682.85	9239544.95	0.20	0.20	0.30
PSM32564	Cobra 1 (above)	-6°52'07.646"	143°59'00.662"	1058.05	829770.68	9239725.67	0.20	0.20	0.30
PSM30040	Kopi (Valve station)	-7°19'24.913"	144°11'04.314"	8.11	851664.60	9189229.94	0.15	0.15	0.30
PSM5583	Kikori Airstrip (Apron)	-7°25'29.854"	144°14'51.802"	12.87	858568.18	9177955.75	0.10	0.10	0.30
PSM2332	Kikori Airstrip (S End)	-7°25'41.694"	144°15'07.844"	13.86	859058.01	9177587.99	0.10	0.10	0.30
Height Datum Stations									
Kumul34	Kumul platform	-8°03'56.588"	144°33'34.389"	28.83	892442.36	9106721.65	0.15	0.15	0.30
Kumul35	Kumul platform (Helipad)	-8°03'57.315"	144°33'34.865"	30.13	892456.76	9106699.18	0.15	0.15	0.30