Deformation Modelling to Support the Papua New Guinea Geodetic Datum 1994 (PNG94)

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SUMMARY

The Papua New Guinea Geodetic Datum 1994 (PNG94) is the current gazetted datum used in Papua New Guinea (PNG). PNG94 is a realisation of the International Terrestrial Reference Frame 1992 (ITRF92) at epoch 1994.0. PNG has a very complex tectonic setting comprising of several rapidly moving microplates and deforming zones between the Australian and Pacific Plates. This paper describes how this rapid and complex deformation is modelled in the context of PNG94, considering that more than 20 years have elapsed since the realisation of the datum. Impacts of this deformation on different user groups are discussed with a view to a future update of the datum.

1. INTRODUCTION

PNG's current geodetic datum, PNG94, was realised at the same time as the Geocentric Datum of Australia 1994 (GDA94) as a realisation of the International Terrestrial Reference Frame 1992 (ITRF92) at epoch 1994.0 (1st January 1994). PNG is a very active country tectonically, due to its location in the collision zone between the Australian and Pacific plates along the Pacific "Ring of Fire". Within this collision zone there are also several smaller microplates and zones of diffuse deformation, which add to the complexity of the tectonic setting (Figure 1).

Significant internal deformation of the geodetic network makes it difficult for surveyors using GNSS/GPS positioning technology to connect their surveys to PNG94 with the required degree of precision unless tectonic deformation is modelled and a fixed reference epoch is formalised for users of spatial data products and for baseline combination in network adjustments (Stanaway, 2004). This is especially the case where GNSS surveyors access ITRF (currently realised by ITRF2008) and related reference frames such as the Asia Pacific Reference Frame (APREF), IGS08 and IGb08 (GPS only realisations of ITRF2008) directly through the use of precise point positioning (PPP) and the International GNSS Service (IGS) and regional CORS networks. In many other tectonically active jurisdictions e.g. New Zealand (Blick *et al.*, 2005), Japan and California, site velocity and deformation models have been implemented for use in conjunction with their geodetic datums to ensure that the relative precision of their geodetic networks are not degraded by unmodelled deformation. Use of a site velocity model enables site motion between the date (epoch) of measurement and a reference epoch to be estimated. In this way, computed coordinates can be related to the reference epoch to ensure that the framework and coordinates of spatial datasets remain "static" within a kinematic environment. Such datums are referred to as semi-dynamic or more correctly semi-kinematic datums, and are well suited for use in tectonically active countries. Continually changing coordinates related to arbitrary epochs are at present difficult to manage within spatial systems and require complex modelling algorithms to be embedded within GIS software applications (Stanaway and Roberts, 2013). These algorithms are currently being developed by GIS developers.

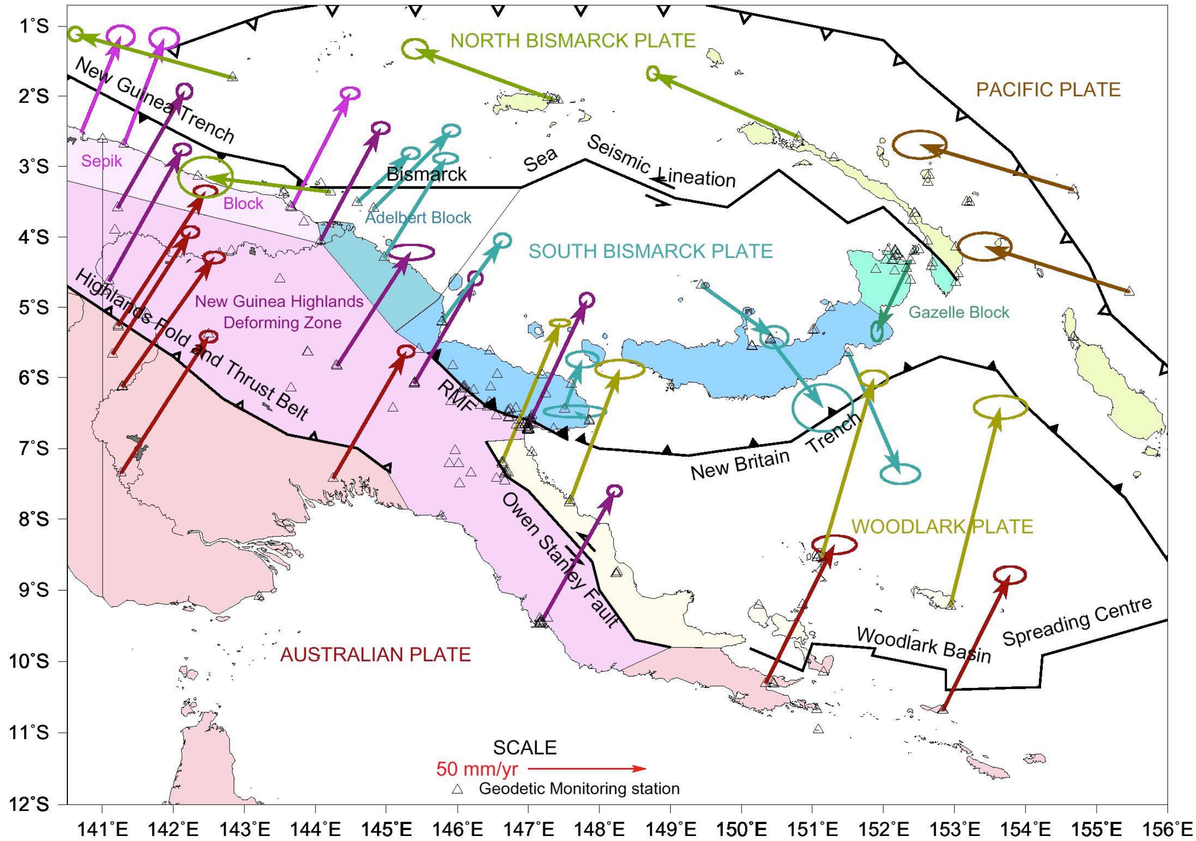

Figure 1. The tectonic setting in PNG, showing plate boundaries & ITRF/WGS84 site velocities

2. THE TECTONIC SETTING IN PAPUA NEW GUINEA

PNG is located in one of the most complex tectonic regions in the world. Over periods of millions of years, ancient islands, land masses and continents moving at up to several centimetres a year have collided, to raise great mountain ranges, or rifted apart, opening up great seas and wide valleys. Whole ocean floors have subducted beneath island arcs creating very deep ocean trenches, spawning destructive volcanoes. All of these forces have created the dramatic topography that characterises PNG and continues to this day. 7 centimetres a year may not seem to be very significant, but when viewed through the telescopic lens of time it does add up. The first human settlers in New Guinea some 50,000 years ago would have seen the Markham Valley 2 km wider than it is now. During this same period of time the Australian Plate has moved 1 km further into New Guinea like a continental scale bulldozer, raising the Highland ranges and ridges on the Papuan Fold and Thrust Belt by as much as 100 metres. PNG is caught in a massive continental scale jaw-like vice where the Australian and Pacific plates are closing together on the smaller microplates which form a large part of PNG (Figure 1).

What follows is a synopsis of recent research (Tregoning *et al.*, 1998, 1999, 2000; Stanaway, 2004; Wallace *et al.*, 2004). All types of plate boundary are represented in PNG, with relative motions between microplates some of the most rapid anywhere on the Earth. The Australian plate is moving in a north-northeasterly direction at about 60 mm/yr, colliding with the New Guinea Highlands (NGH) along the Papuan Fold and Thrust Belt (PFTB) where the main PNG Oilfields are located. The North Bismarck Plate (Manus Island and most of New Ireland) is being subducted obliquely beneath the Sepik Block along the New Guinea Trench (the source of the Aitape tsunami). Further to the east, the NGH are colliding with the Adelbert block and South Bismarck Plate along the Ramu-Markham Fault Zone (RMFZ). Here, the western part of the South Bismarck Plate (SBIS) is currently overthrusting the NGH. The collision is propagating towards the east-southeast along the RMFZ as the SBIS rotates clockwise and generates large earthquakes in the Lae area. This rotation is also opening up the Manus Basin with spreading and strike-slip motion along the Bismarck Sea Seismic Lineation (BSSL) to the north, and northwesterly subduction (up to 120 mm/yr) of the Solomon Sea Plate along the New Britain Trench (NBT) to the south. This very rapid subduction gives rise to the string of destructive volcanoes in New Britain. Southward subduction of the Solomon Sea Plate beneath the Woodlark Plate along the Trobriand trough is believed to be inactive, or very slow, and the two plates can be considered to be a single entity. The Woodlark Plate is rifting anti-clockwise away from the Australian Plate along the Woodlark Basin Spreading Centre (WBSC) with continental rifting occurring at the eastern end of the Papuan Peninsula. To the northeast, the Woodlark Plate is subducting northeasterly beneath the Pacific plate along the NBT and San Cristobal Trench south of the Solomon Island arc. To the west, the Woodlark Plate is moving northwest relative to the Australian Plate through strike-slip motion along the Owen Stanley Fault Zone (OFSZ), becoming transpressional closer to the RMFZ. The Pacific Plate is moving rapidly (at between 80 and 90 mm/yr) west-northwestwards across the northern margin of PNG, with a major left-lateral strike slip boundary with the SBIS along the Weitin Fault, and slow oblique subduction beneath the North Bismarck Plate along the Kilinailau and Manus Trenches. The Weitin Fault is possibly the fastest strike-slip boundary in the world and is associated with frequent and very significant earthquakes.

3. EFFECTS OF TECTONICS ON GEODETIC INFRASTRUCTURE

Since the beginning of 1994, there have been more than 2,000 earthquakes above Magnitude 5 in PNG, including 20 above magnitude 7 (NEIC database). On the 17th July 1998 an undersea earthquake of M_w 7.1 along the New Guinea Trench near Aitape caused a devastating tsunami killing over 2,000 people in coastal villages nearby. On the 16th November 2000, severe earthquakes of M_w 7.9 and 8.0 were associated with a major rupturing of the Weitin Fault in Southern New Ireland over hundreds of kilometres. The earthquakes resulted in massive horizontal land movements of up to several metres in magnitude, landslides and some minor tsunami activity. Two years later, on the 8th September 2002, a M_w 7.8 earthquake struck off the Wewak coast, causing significant surface ruptures and minor tsunamis in the region. Subduction of oceanic plates and continental rifting result in the significant volcanic activity in PNG, especially in New Britain, Bougainville, along the Sepik Coast and in Oro Province. The twin volcanic eruptions of Tavurvur and Vulcan near Rabaul on 19th September 1994 destroyed much of the city and many other communities in PNG face the constant threat of renewed or nascent volcanic activity (e.g. Ulawun, Pago, Manam, Karkar, Bagana and Lamington). Twenty years of secular tectonic and seismic deformation have resulted in baseline changes of up to seven metres between many PNG94 geodetic stations in seismically affected areas.

Many low-lying coastal regions and islands in PNG are not only threatened by potential tsunamis, but are also subject to an increase in sea level as a result of climate change. The risk is magnified if tectonic subsidence is also occurring. The Pacific Sea Level Monitoring Project (PSLM) (http://www.bom.gov.au/pacific/projects/pslm/index.shtml) has been operational since 2002, formerly as the SPSLCMP. Continuous GNSS/GPS measurements are made in close proximity to tide gauges operated by the National Tidal Centre (NTC) of the Australian Bureau of Meteorology. Comparison of the vertical displacement of the tide-gauge with the actual tide data allows estimation of absolute sea-level change in the region without systematic bias resulting from tectonic uplift or subsidence at the monitoring site.

Volcano slope monitoring by geodetic techniques can be achieved by accurate measurements from a nearby stable network; however inter-seismic strain which often occurs over broad areas can really only be effectively monitored from a geophysically stable network such as the ITRF. A network of four GNSS CORS has been established around the Rabaul Caldera by the Rabaul Volcanological Observatory (RVO) to monitor volcanically related deformation, particularly uplift resulting from magma movement close to the surface.

4. MODELLING OF TECTONIC DEFORMATION IN PNG

PNG has been the subject of a number of crustal deformation surveys and plate tectonic studies. In the 1970s, two trilateration networks were established by the Australian National Mapping Division to measure tectonic movement in two areas in PNG suspected to be undergoing rapid deformation (Sloane & Steed, 1976). The first network was established across the Markham Valley near Kaiapit, west of Lae and the second across the St. Georges Channel between the Gazelle Peninsula and southern New Ireland. Massive pillars were constructed for these monitoring surveys but results were inconclusive, due largely to the short observation span of the surveys and also the fact that the pillars weren't deeply anchored to bedrock. In 1981, a network of stations around PNG was surveyed using the Transit Doppler satellite navigation system (Angus-Leppan *et al.*, 1983), and remeasured by GPS in 1990 by a team of geodesists from the University of New South Wales (UNSW) (Stolz, 1989). The first geodetic measurements of the rapid convergence across the New Britain Trench were made with this study. The network was extended and resurveyed in 1991 and 1992 by UNSW funded by ANU (McClusky *et al.*, 1994; Mobbs, 1997). From 1993 onwards, research groups from the Rensselaer Polytechnic Institute (RPI) (1993-1997), the University of California, Santa Cruz (UCSC) (1997-2001), the Research School of Earth Sciences (RSES) Australian National University (1996-2008), and GNS Science New Zealand (2003-2013) have undertaken extensive GPS monitoring campaigns in PNG in collaboration with local institutions. These surveys were designed to observe and densify the geodetic monitoring network, in order to define the large-scale tectonic framework and to investigate deformation in plate boundary zones in PNG. Local institutions involved in these campaigns have included the PNG National Mapping Bureau (NMB), the Office of the Surveyor-General (OSG) Geodetic Section, the Department of Surveying and Land Studies (DSLS) of the PNG University of Technology (UniTech), the Rabual Volcanological Observatory (RVO) and the PNG Geological Survey.

Since 1993, several GNSS CORS have been established by different geodetic agencies in PNG (Table 1). The four CORS in the Rabaul Network provide real time monitoring of the main active caldera. The Manus PSLM site was installed by the National Mapping Division of Geoscience Australia in 2002 to monitor vertical motion of the tide gauge site on Manus.

A substantial archive of campaign dual-frequency GPS observations has been formed since 1990 from an extensive network of sites around PNG (Figure 2). This archive is ideal for the geodetic estimation of the PNG site velocity field, deformation model and the computation of the PNG geodetic datum. The data quality and quantity vary significantly but approximately 160 sites in PNG have sufficient quality data to define their ITRF position with an accuracy of < 20mm.

The aim of the earlier GPS campaigns was to obtain the first geodetic measurements across the larger plate boundaries in PNG, between the South Bismarck, Woodlark, Pacific and Australian Plates and also to realise the PNG94 Datum. Subsequent campaigns have increasingly focused on identifying smaller microplates, rigid blocks and measuring strain rates in deforming zones near plate boundaries. The campaigns have necessarily been collaborative in nature, due to the logistical difficulties operating in PNG and the mutual interests of many of the participating institutions. Many of the GPS data collected by campaigns conducted by NMB and OSG for cadastral mapping and land development purposes have also been useful for geodynamics studies. The GPS base station at the Department of Surveying and Land Studies at UNITECH, Lae has been part of the IGS tracking network since 2002 and is an important contribution by PNG to global geodynamic and geodetic studies. Since 2006, internet issues at Unitech have meant that availability of LAE1 data has been intermittent, but it is still operating. In addition to these major survey campaigns, a significant amount of GPS data have also been provided to the OSG from private survey firms, exploration and mining companies operating in PNG. For example, Oil Search Ltd. has funded extensive surveys of their PNG geodetic network since 2007.

SITE	Network	Method	Installed	Location	Responsible Agencies
LAE1	IGS & IGS Reference Frame Site	GPS	1996	Sandover Building, Papua New Guinea University of Technology, Lae	UNITECH, PNG
MORE	WING W. Pacific Integrated Network	GPS	1993 to 2011	NMB Tower at Waigani, Port Moresby	ERI (Earthquake Research Institute), University of Tokyo and NMB, then OSG since 2001
NMB2	APREF	GNSS	2011 to 2014	NMB Tower at Waigani, Port Moresby (to be removed in 2014)	PNG Office of the Surveyor-General (OSG)
WAIG	APREF	GNSS	2014	Eda Tano Haus at Waigani (replaces NMB2)	PNG Office of the Surveyor-General (OSG)
MORB	IDS	DORIS	2002 to 2012	NMB, Waigani, Port Moresby	Centre national d'études spatiales (CNES) / NMB and OSG
MOSB	IDS	DORIS	2012	NMB, Waigani, Port Moresby (on same site as MORB)	Centre national d'études spatiales (CNES) / NMB and OSG
RVO_	Rabaul Caldera Network	GPS	1998	Rabaul Volcanological Observatory	PNG Department of Mineral Policy and Geohazards Management - RVO
SPT_	Rabaul Caldera Network	GPS	1998	Sulphur Point, Rabaul	PNG Department of Mineral Policy and Geohazards Management - RVO
SDA_	Rabaul Caldera Network	GPS	1998	Matupit SDA Church, Rabaul	PNG Department of Mineral Policy and Geohazards Management - RVO
VIS_	Rabaul Caldera Network	GPS	1998	Vulcan Island, Rabaul	PNG Department of Mineral Policy and Geohazards Management - RVO
PNGM	PSLM	GPS	2002	Lombrum Naval Base, Manus	Geoscience Australia (GA)

Table 1. Continuous GNSS/GPS/DORIS sites in PNG between 1993 and 2014

These studies, together with other seismological and geological studies, have collectively formed the basis for the current understanding of plate kinematics and crustal deformation in PNG (Tregoning *et al.*, 1998; Wallace *et al.*, 2004; Stanaway, 2004). The campaigns have enabled sub-centimetre accurate ITRF coordinates and site velocities, euler poles of microplates, and fault locking parameters to be estimated. An increasingly dense network of stations and results from these studies has already resulted in very significant improvements to PNG's geodetic datum.

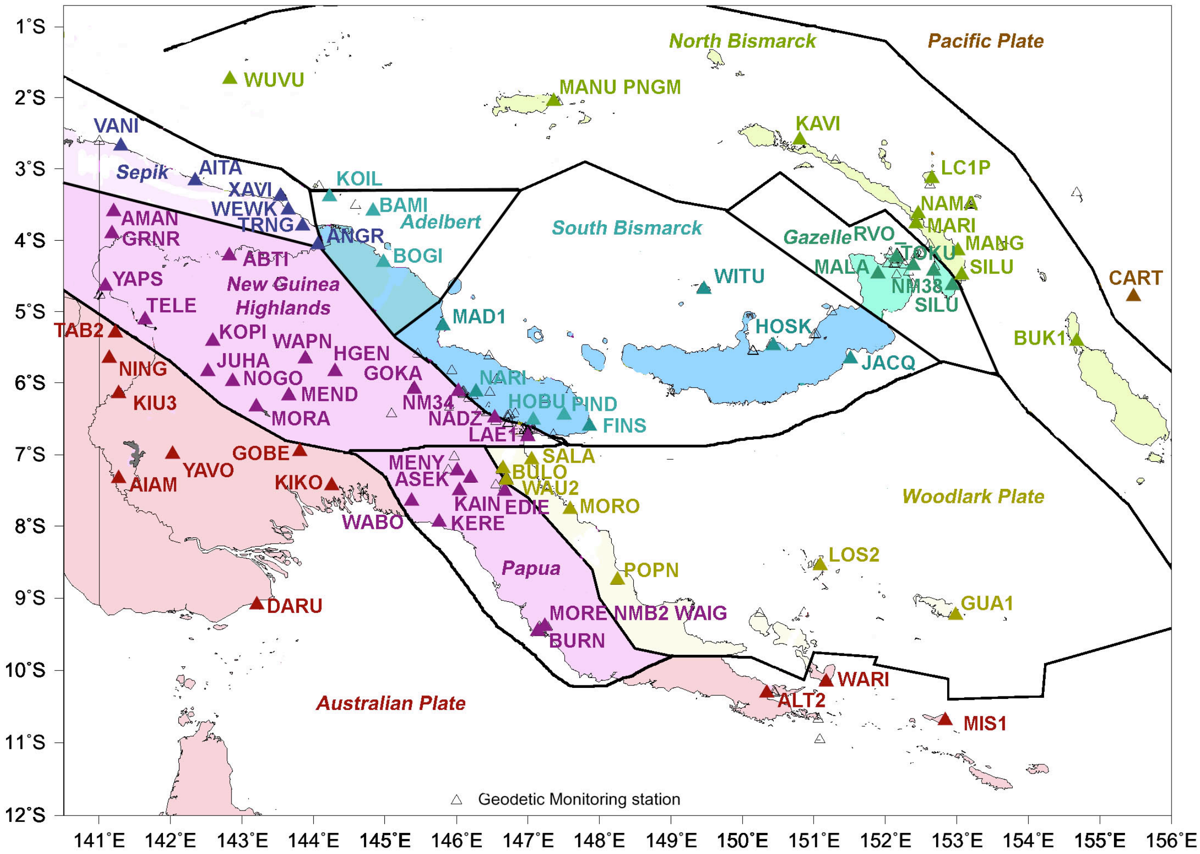

Figure 2. PNG geodetic monitoring network (primary stations) and plate zones

1-5 days of continuous GPS dual-frequency carrier-phase observations are typically collected at a widespread network of monitoring marks usually Permanent Survey Marks (PSM) or pillars spanning known tectonic plate boundaries. One day of observations typically achieves an accuracy of 5 mm, while five days of observations improves the accuracy to 2 mm. Software packages such as GAMIT/GLOBK, Bernese, Gipsy and online processing services such as AUSPOS derive mm-cm accurate positions using precise GPS orbits determined from the global IGS tracking network. The same site is observed over several epochs and a time-series is computed, showing any station movement between epochs within ITRF. From these time-series, site velocities can be estimated. Vertical movement of sites is inherently more difficult to measure due to much lower magnitudes in this direction. The precision of the vertical component of a position solution is an order of 2-3 times weaker than the horizontal component due to poorer satellite geometry, unmodelled phase centre variations in both GPS sensor and satellite antennas and temporal variation due to unmodelled ocean tide loading, tropospheric delay and groundwater changes as well as draconitic effects. Vertical motion is difficult to model with any level of confidence for epoch intervals of less than 10 years.

5. IMPROVEMENTS MADE TO PNG94

PNG94 was initially realised by the ITRF92 coordinates at epoch 1994.0 of 14 primary (fiducial) stations surveyed during regional GPS campaigns between 1992 and 1994. These coordinates have positional uncertainties of between 3-10 cm at 95% CI. This fiducial network has formed the basis for adjustment of secondary and tertiary geodetic networks comprising mostly of Transit Doppler and terrestrial observations (Allman, 1996). As a consequence, many 2nd and 3rd order geodetic stations in PNG94 have uncertainties of a few metres derived from the initial adjustment.

The acquisition of a substantial archive of long-period static GPS observations since the initial realisation of PNG94 has enabled significant improvements to the datum both in terms of reduced positional uncertainty and densification. A major readjustment of the fiducial and first order network was undertaken in 2008 and included many new stations with an observation history of at least three years in order for site velocities to be estimated from analysis of ITRF time series for each site. The 2008 adjustment defined PNG94 as a realisation of ITRF2005 at epoch 1994.0. During 2011, a provisional geoid model PNG08 was developed for PNG (Figure 3) by computing the offsets between the EGM2008 derived geoid model and observed MSL across a network of tide-gauges in PNG. Due to the effects of Mean Dynamic Topography (MDT), the EGM2008 equipotential surface is offset from MSL by between 0.7 and 1.5 metres, largely as a result of thermal expansion of oceans in tropical regions. The precision of the PNG08 model is 0.2 m at 68% CI due to both the sparsity of the tidal observations used and inherent imprecision in the EGM2008 geoid model.

Because of the absence of any extensive and interconnected levelling networks across PNG, and the multitude of different local realisations of MSL, often with uncertainties of several metres in the Highlands, adoption of PNG08 as a national vertical datum has been advantageous for GNSS heighting.

Another major national observation campaign and readjustment is currently underway, utilising static observations on zero and first order survey control at 29 of PNG's major airports. Depending upon the timing of the completion of the survey and adjustment, PNG94 will be redefined with ITRF2008 or ITRF2013 at epoch 1994, should ITRF2013 be released by the conclusion of the survey.

The positional uncertainties at 95% CI of the fiducial network have reduced from 10 cm in 1996, down to 2 cm in the latest realisation. The improvements have resulted in cm level changes to the originally gazetted coordinates at epoch 1994.0 so that for higher precision surveys it is necessary to suffix the realisation to account for the small differences at the reference epoch of 1994. PNG94(1996) is the initial realisation, PNG94(2011) is the current realisation and PNG94(2014) is currently being realised.

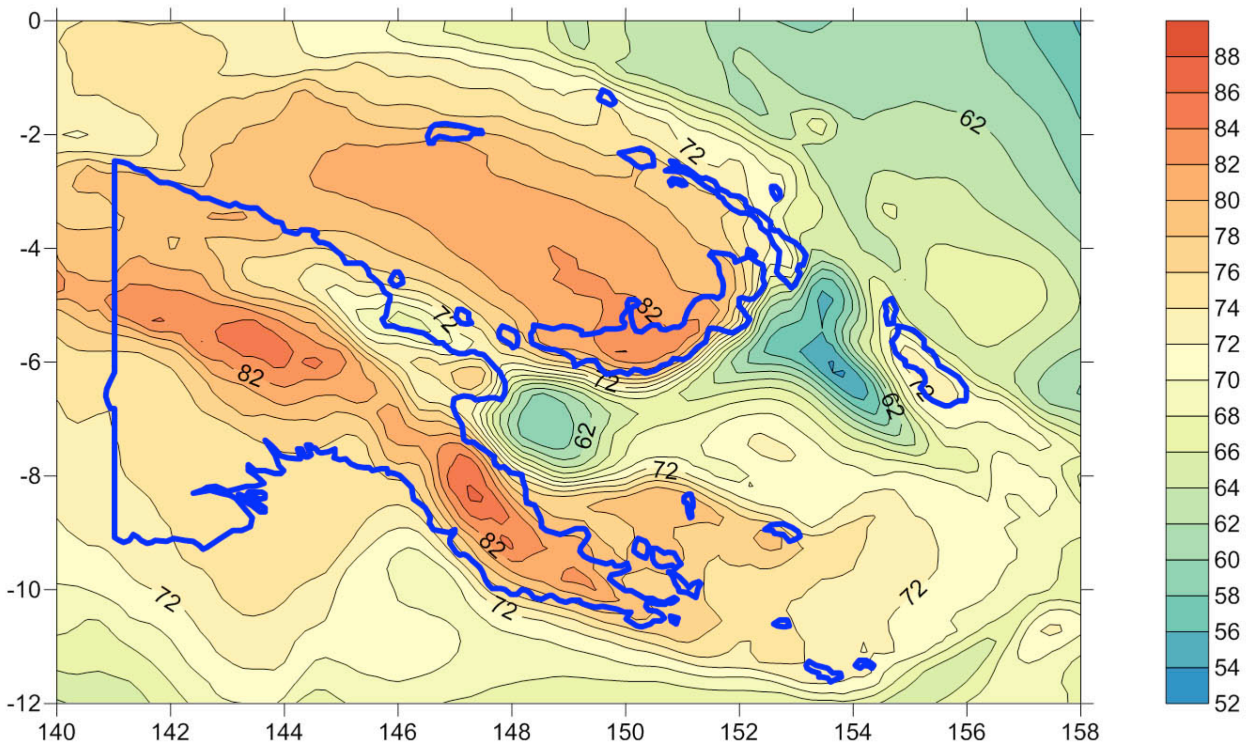

Figure 3. PNG08 Geoid Model - ellipsoid-geoid separation (N value) in metres

6. WHAT ARE THE REQUIREMENTS AND BENEFITS OF USING A SEMI-KINEMATIC DATUM?

Uses of spatial data in PNG are increasingly diverse: Cadastral surveys (including customary land and DCDB surveys), exploration and mining, engineering (bridges, dams, power, roads, pipelines), mapping, imagery, LiDar, navigation (air, land and sea), hazard monitoring (volcanoes, earthquakes, landslides, sea-level change) all require a homogenous spatial reference system or datum. For some users of spatial data, an absolute accuracy or positional uncertainty of several metres magnitude maybe acceptable for personal navigation or coarse mapping. Increasingly though, positional uncertainties of better than 10 cm are required to support most other surveys, such as LiDar, high-precision imagery control, and integration of different survey data at a common reference epoch. Smaller relative uncertainties (better than 5 mm) are also required, e.g. for deformation monitoring, engineering surveys and cadastral surveys. The requirements for absolute positioning accuracy and repeatability underpin any GIS which in its current form assumes that all data are of a consistent epoch (e.g. 1994). In order for these positional uncertainties to be achieved in a complex tectonic environment, a deformation model of site velocities and episodic deformation becomes an essential component of the PNG semi-kinematic datum definition (Stanaway *et al*., 2012 and 2014).

7. ISSUES WITH ADOPTING WGS84 AND ITRF AT ARBITRARY EPOCHS IN PNG

It is often assumed that PNG94 is identical to WGS84 and ITRF with a precision of 10 cm (as is often the case with any geocentric datum). This assumption was true for PNG94 in 1994, but since that time coordinates in the different systems have diverged because of ongoing tectonic deformation and the differences are now almost two metres in PNG (and several metres where significant coseismic deformation has occurred). Although the reference ellipsoids used by these three datums are similar at the sub-millimetre level, actual differences in station coordinates are now significant and the difference is increasing by several centimetres a year. By fixing the PNG94 reference epoch (1st January 1994), coordinates of PNG's datum can become traceable to a physical network within PNG by means of a site velocity model or deformation model. WGS84 and ITRF (currently ITRF2008) coordinate precision is meaningless unless measurement epochs are assigned to WGS84 and ITRF spatial data. Nevertheless it is recommended that baseline processing of long (> 20 km) GNSS baselines and network adjustments be accomplished using the latest ITRF or IGb08 solution for the reference station and IGS final orbits in order to minimise the effects of unmodelled deformation between the 1994 and the epoch of measurement. However, any coordinate solution should be propagated back to epoch 1994.0 using a site velocity model or by aligning the adjustment with the nearest zero or first order PNG94 control by applying a block shift (smaller networks), three parameter transformation (translation and rotation) or site transformation. It is also recommended to use ITRF for geodynamic monitoring (e.g. geological hazards such as volcanic activity, island subsidence and sea-level change) as this approach is insensitive to localised constraints when the constraint station itself maybe undergoing localised deformation.

Before the widespread acceptance of PNG94 until c.2010, one of the major sources of error and confusion has been the adoption of arbitrary epochs of ITRF (and WGS84) for different major projects in PNG. There have been numerous cases of reported misalignments of important datasets such as LiDar, cadastral and engineering surveys resulting from misinterpretation or assumption of the epoch of ITRF used as the survey origin. The difference has resulted in professional indemnity claims against surveyors by clients who have believed that the coordinate differences have been due to surveyor error rather than undocumented secular tectonic displacement between measurement and reference epochs. In many instances tender specifications for many major PNG resource projects have stipulated WGS84 as the project datum without specifying an epoch or coordinated monument to be used as the survey origin. This situation has been exacerbated by the lack of publically available detailed information on PNG94 and also by the widespread use of free online positioning services such as AUSPOS and NRCan's PPP service. These services deliver precision ITRF coordinates to users at the epoch of measurement, and not the 1994 epoch consistent with PNG94. The publication of PNG94 coordinates, datum and projection parameters on the Association of Surveyors of PNG (ASPNG) web-site at http://www.aspng.org/techinfopng94.htm and the inclusion of these parameters in the EPSG database and GeoRepository.com accessed by GIS software developers, have improved this situation substantially. In recent years PNG94 has become the standard datum requirement in PNG tenders.

8. WHAT PROBLEMS CAN SURVEYORS EXPERIENCE WITH PNG94 AT PRESENT?

Surveyors using GNSS/GPS methods to establish control in PNG will find coordinates changing significantly over periods of a few years if their base stations are located on different tectonic plates from their survey area. For example, where the APREF Port Moresby Lands CORS (WAIG) and the IGS CORS at UniTech Lae (LAE1) are used to coordinate stations in East New Britain or New Ireland.

ITRF positioning services such as AUSPOS, NRCan-PPP, Starfire, Trimble RTX and OmniStar currently deliver centimetre to decimetre accurate kinematic coordinates in ITRF2008. Coordinates computed for locally stable survey stations using these services will change by several centimetres a year in PNG to reflect the magnitude of tectonic motion of the site. Users of these systems will notice repeat measurements of stations changing even over an interval of several months. For example, if AUSPOS or OmniStar were used to establish geodetic control for a new mining operation in the PNG Highlands in 2002, a surveyor reobserving these stations in 2014 would notice that the ITRF coordinates would be 70 cm different! A local correction has to be applied to convert new measurements back to epoch used in the 2002 survey. If the surveyor in 2002 had known what the site velocity was, they would have converted the 2002 coordinates back to an epoch 1994 to be coincident with PNG94, so that the survey could be related to other surveys in the area and for spatial data to be harmonised at survey accuracy.

Within defined stable plate zones (Figure 1), away from plate boundaries (mostly south of the Highlands and Owen Stanley Range), baseline changes are likely to be small in magnitude and it is usually safe to use base stations up to 100km from a survey area within the same zone without significant degradation of relative accuracy. In broadly deforming zones that are relatively aseismic, such as the PNG Highlands, West New Britain and Milne Bay Province, baseline changes may be evident for baselines longer than 100km so that the closest geodetic station should be used. Rapidly deforming plate boundary zones: e.g. North of Nadzab and Lae, the entire Gazelle Peninsula and Southern New Ireland are very seismically active and also have rapid aseismic (slow creep) deformation with baseline changes of a few centimetres each year even over a few kilometres. The baseline from Unitech Lae to Hobu a few kilometres north is currently shortening aseismically at 5 cm/yr. Volcanic activity and large earthquakes also result in significant surface deformation. Geodetic surveyors at RVO use a real-time GPS monitoring system to provide early warnings of uplift associated with imminent eruptions. The November 2000 earthquake swarm (up to Magnitude 8.0) near southern New Ireland resulted in lateral displacements of 5-6 metres, with Tokua some 80 km from the epicentre of the lateral strike-slip event being displaced by 1 m.

9. WHAT STRATEGIES CAN SURVEYORS USE TO CONNECT TO PNG94?

Static GNSS/GPS and PPP (AUSPOS, OmniStar-HP etc.) are two of the principal methods (other than classical terrestrial methods) that surveyors in PNG can use to connect their surveys to PNG94. Dual-frequency GNSS/GPS receivers can typically measure baselines of up to 50 km with a precision of less than 20 mm using a broadcast ephemeris. Baselines measured by single-frequency receivers and RTK methods are typically limited to 10 km or less. For GNSS/GPS surveys in PNG the base station and rover station should be on the same tectonic plate (i.e. the baseline between them should not cross a plate boundary as shown in Figures 1 and 2). In areas of rapid relative deformation such as East New Britain, Southern

New Ireland and the Huon Peninsula, surveyors should use the closest PNG94 geodetic station available to them as use of stations even 10 km from the project area will have undergone significant relative deformation between 1994 and the epoch of measurement.

If a baseline measurement has to be made across a plate boundary or deforming zone, the ITRF coordinates at the epoch of measurement of the base station should be computed first using the site velocity. The coordinates of the rover station are then converted back to PNG94 using the site velocity computed from the plate motion model. A gridded site velocity model for PNG will be made available as part of the 2014 readjustment.

ITRF coordinates derived by AUSPOS or OmniStar also need to be converted to PNG94 using the site velocity computed from a PNG plate motion model, or by comparing current ITRF coordinates with the closest primary PNG94 station in order to estimate any corrections in the local area

The following expressions can be used to compute PNG94 coordinates from ITRF at different epochs:

$$\phi_{PNG94} = \phi_{ITRF} + V_N \cdot (1994 - t)$$
$$\lambda_{PNG94} = \lambda_{ITRF} + V_E \cdot (1994 - t)$$

Where;

t = Epoch of measurement in decimal years
(e.g. 31st July (day of year 213) 2008 is 2008 + 213/366 = 2008.582)
ϕ_{ITRF} is the ITRF2008 Latitude at the epoch of measurement (at time t)
λ_{ITRF} is the ITRF2008 Longitude at the epoch of measurement (at time t)
V_N and V_E are the ITRF site velocities converted to decimal degrees per year.

In regions where coseismic displacements are significant, the PNG94 coordinates would be shifted by the magnitude of the coseismic and postseismic deformation to ensure that localised networks maintain conformity after significant localised deformation. Should pre-earthquake coordinates be required, a patch model will be required.

10. CONCLUSIONS - THE FUTURE OF PNG94.

The network of PNG geodetic monitoring sites will continue to be densified. In order to make PNG94 more accessible to surveyors, geodetic stations will continue to be established in more secure areas with good sky visibility such as airports, helipads and the grounds and roofs of government or commercial offices. Stations located on remote mountain tops, gardens and public areas are generally unsuitable because of the high risk of destruction, lack of security, difficulty of access and lack of maintenance. Fortunately most airstrips in PNG already have at least one geodetic station within their perimeters, although many of the stations on lesser used airstrips do not yet have sufficiently accurate PNG94 coordinates. To facilitate RTK surveying, base stations and antenna masts can be established at offices with power supply, referenced to the local geodetic network of ground stations.

A gridded deformation model for PNG is being developed as a current research project at RSESA ANU and UNSW with support from the PNG OSG. The deformation model will enable spatial professionals to extract site velocities using PNG plate and fault locking models together with a database of historical earthquake displacements, by entering site coordinates (either ellipsoidal or UTM) or to compute coordinates at a specific epoch. As PNG currently does not have the resources and budget to manage and maintain an online positioning system, it is proposed to build site velocity models into Geoscience Australia's AUSPOS service, so that users who submit RINEX data within PNG territorial limits will receive a report of both ITRF and PNG94 coordinates for the submitted data.

The significant seismic activity that has occurred in PNG over the last twenty years is nevertheless introducing increasing uncertainty into site velocity and seismic deformation models due to the sparsity of monitoring stations in many seismically active regions. In the future it may be advantageous to update the reference epoch of the PNG geodetic datum in order to minimise the effects of these unmodelled deformation effects on the geodetic datum.

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BIOGRAPHICAL NOTES

Richard Stanaway is a part-time PhD student at UNSW. His research project is developing deformation models to support geodetic datum modernisation in Australia and Papua New Guinea. Richard is also the Director of the geodetic consultancy Quickclose, supporting the PNG Office of the Surveyor-General and also a wide private-sector client base in PNG including many of the major petroleum and mining companies operating in PNG. He is a Member of the Australian Surveying and Spatial Sciences Institute and a Fellow of the Association of Surveyors PNG. After completing his undergraduate studies at QUT in Brisbane, Richard was employed in PNG as a geodetic surveyor until 2001. He completed a Master of Philosophy at ANU in Canberra in 2004 researching the PNG geodetic datum and geodynamics. He currently chairs the IAG working group 1.3.2 on deformation modelling to support Regional Reference Frames and is a contributing member of FIG Commission 5 WG 5.2 on Reference Frames.

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