International Global Navigation Satellite Systems Society
IGNSS Symposium 2013

Outrigger Gold Coast, Qld Australia
16-18 July, 2013

Monitoring Station Movement using a State-Wide Simultaneous 'Adjustment of Everything'– Implications for a Next-Generation Australian Datum

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ABSTRACT

The establishment of a next-generation Australian datum is currently being investigated. Such datum update is required to accommodate the increasing accuracy and improved spatial and temporal resolution available from modern positioning technologies to an ever-broadening user base. While the spatial community debates the costs, benefits and optimum implementation of a new datum, each Australian state and jurisdiction is currently preparing a dataset containing all available geodetic measurements from their archives. New computing technologies mean that state-wide and even nation-wide adjustments are now routinely possible with an essentially unlimited number of stations and measurements, while new measurements can be incorporated immediately when they are available. This study discusses the opportunities and limitations of a simultaneous adjustment of all available GNSS measurements for monitoring the movement of geodetic survey stations. Two case studies in NSW are presented to highlight the different implications of land movement versus station instability on potential datum deformation models in the vicinity of these stations. Additional measurements via 'crowd-sourcing' methodologies would help to maintain the currency and relevance of the datum, while traditionally non-geodetic techniques such as DInSAR and LiDAR would be invaluable in defining the extent of any detected deformation. The results presented here are preliminary and aim to highlight areas of potential research, and promote discussion regarding datum update in the wider spatial community.

KEYWORDS: data-mining, Datum, deformation, geodesy, GNSS

1. INTRODUCTION

This study investigates the motivation for developing a more rigorous and explicit approach to measuring and modelling land deformation, driven by increases in measurement precision, increases in measurement density and an increasing desire for accurate four-dimensional coordinates. In the context of preparing for a new higher-accuracy, higher-density Australian datum two examples are given of deformation that has been detected during a state-wide adjustment of all available Global Navigation Satellite System (GNSS) measurements at Land and Property Information (LPI) in New South Wales (NSW). The implications of these deformation events on the development of this next-generation Australian datum and associated deformation models are discussed.

Advances in positioning technologies over the last few decades have resulted in easy access to high-accuracy and high-precision coordinates at ever-increasing spatial and temporal resolutions. For example, it is now routinely possible to use GNSS technologies to achieve quick centimetre-level positioning relative to a permanent Continuously Operating Reference Station (CORS) (Janssen *et al.,* 2011, 2013), or via Precise Point Positioning (Rizos *et al.*, 2012). Using real-time corrections to GNSS satellite and clock information, provided for example via the International GNSS Service (IGS, 2013), GIS single-frequency receivers can achieve decimetre-level positioning anywhere on the globe; other mass-market mobile GNSS receivers are likely not far behind.

In this context, the limitations of the current Australian datum are becoming apparent. The Geocentric Datum of Australia 1994 (GDA94) was cutting-edge when it was adopted. GDA94 was gazetted with coordinates determined for 8 Australian Fiducial Network (AFN) stations in the then global reference frame, the International Terrestrial Reference Frame 1992 (ITRF1992) at epoch 1994.0 (Dawson and Woods, 2010). However, since 1994, ITRF has seen significant improvements and refinements with seven new realisations culminating in the current ITRF2008, with the next ITRF2013 in preparation (Altamimi *et al.*, 2011; IGN, 2012). GDA94 has recently been re-gazetted for 21 AFN stations and with improved accuracy (Commonwealth of Australia, 2012), but still remains only indirectly linked to the current global reference frame via ITRF1992. GDA94 has also been literally 'left behind' because its plate-fixed coordinates are 'frozen' at the epoch 1994.0; meanwhile the Australian plate has moved and rotated by up to 1.3 metres. In contrast, ITRF can describe the current, historical or future position for any point on the earth by associating a time-stamp or 'epoch' with the coordinates, and also providing a reasonable estimate of that point's velocity.

Haasdyk and Watson (2013) demonstrate how improvements in quantity and quality of geodetic measurements, as well as a demand to accommodate changing technologies have driven improvements in Australian datums over the last several decades. Most recently, high-precision GNSS baselines have exposed significant distortions and deficiencies in the GDA94 datum. In day-to-day survey operations, practitioners are often forced to distort high-quality measurements to fit lesser-quality survey control, and must develop work-arounds and transformations to fit today's measurements to yesterday's datum (Janssen and McElroy, 2010; Haasdyk, 2012). In the meantime, Geoscience Australia has established (since 2009) the Asia-Pacific Reference Frame (APREF), a dense regional network of GNSS CORS which aims to provide an authoritative source of coordinates and velocities in the Asia-Pacific region (GA, 2012a).

The Intergovernmental Committee on Surveying and Mapping (ICSM) is taking this opportunity to develop a next-generation national datum that is fundamentally different from previous Australian datums (Johnston and Morgan, 2010; ICSM, 2011). For the first time, computing power and new adjustment techniques will allow the simultaneous adjustment of all available geodetic measurements. The proposed datum would yield accurate and precise coordinates of all stations, seamless coordinates across state borders, and rigorous measures of uncertainty as required by newly updated survey control standards (ICSM, 2013b). More importantly, new measurements and new technologies can immediately contribute to this national adjustment to improve the accuracy and precision of the datum in perpetuity.

One consequence of creating a simultaneous adjustment of measurements gathered over several decades is that deformation can be detected for survey ground marks or 'stations' that have been repeatedly observed. Traditionally, a geodetic adjustment makes the assumption that all stations observed are stable and a single 'static' set of coordinates are estimated which best fits the provided measurements. However, if a station has moved, then measurements to that station before and after that movement will disagree. Previous studies have shown that the Australian plate, while generally stable, does suffer from local tectonic effects (e.g. earthquakes) and localised deformation (e.g. subsidence) (Ng *et al.*, 2008; Dawson and Woods, 2010).

This study examines two cases in NSW where the simultaneous adjustment of all available GNSS measurements has detected deformation of a given station. Upon further investigation it is apparent that one of these cases demonstrates highly localised deformation (the station itself is on an unstable structure), and the other demonstrates a sampling of a much larger deformation (due to ground subsidence attributed to underground mining). The implication of these findings is that the existing collection of geodetic measurements is of insufficient density (both spatially and temporally) to support the desired level of deformation modelling in the new datum.

Therefore, in order to realise and maintain a new datum through a high-density and centimetre-accurate network of permanent marks, the geodetic community needs to increase the quantity and relevance of geodetic data by fostering novel 'crowd-sourcing' methods. Additional techniques such as Differential Interferometric Synthetic Aperture Radar (DInSAR) and Light Detection and Ranging (LiDAR) and are also needed to better quantify and define the extents of any detected deformation, over a much larger area than point sampling can achieve. Finally, a comprehensive deformation model needs to be developed and applied universally with all measurements and coordinates time-stamped as part of their mandatory metadata (LINZ, 2003; Stanaway *et al.,* 2011).

2. Developing the Next-Generation Datum

2.1 Dynamic Phased-Adjustment Least Squares Methodology and DynaNet

A limiting factor in the simultaneous adjustment of large survey networks for previous datums has been the computing power available. Historically, large networks such as the most recent Australian national GDA94 adjustment (ICSM, 2013c) had to be segmented into separate 'sections' which were computed individually. For example, across NSW alone there were six sections of less than 1,000 stations each. This approach resulted in discrepancies across section boundaries, and the loss of relationships between stations in different sections.

However, Least Squares methods can be modified so that they are *not* limited by the number of stations or measurements. Leahy and Collier (1998) describe a 'dynamic phased-adjustment' which can perform a rigorous adjustment on a network of *any size*. As before, the network is divided it into smaller segments for adjustment, however those segments are then rigorously re-combined to return a correct assessment of the quality of the adjusted station coordinates and measurements. This allows the computation of absolute Positional Uncertainty (PU) of all observed stations across the network (ICSM, 2013b) as well as relative uncertainty between any nominated stations.

DynaNet, a program that can perform such a dynamic network adjustment has been developed at the former Department of Geomatics at the University of Melbourne (Collier, 2004), and is currently being modified to address the time-dependent requirements of the new datum (Fraser, Leahy & Collier, pers. comm.). Research has also begun towards incorporating deformation models into these adjustments. In this context, increases in computing power, in terms of both speed and memory, mean that the size of the network of measurements has become largely inconsequential. DynaNet can be implemented on a desktop computer, with adjustments of tens of thousands of stations and hundreds of thousands of measurements completed in a matter of minutes.

2.2 Constraint by Asia-Pacific Reference Frame (APREF)

Unlike the current datum, GDA94, which is constrained to a set of 'static' gazetted coordinates, any new national adjustment will be constrained to the best-available ITRF coordinates of GNSS CORS contributing to the Asia-Pacific Reference Frame (GA, 2012a; Figure 1a). In this way, the CORS become the new primary control and offer very high-precision and active monitoring of the stability of the datum at a density much greater than the 21 AFN stations of GDA94. Figure 1 shows the distribution of stations currently in APREF (several hundred across Australia) and demonstrates that the coordinates of the CORS can be continually monitored with a precision of several millimetres.

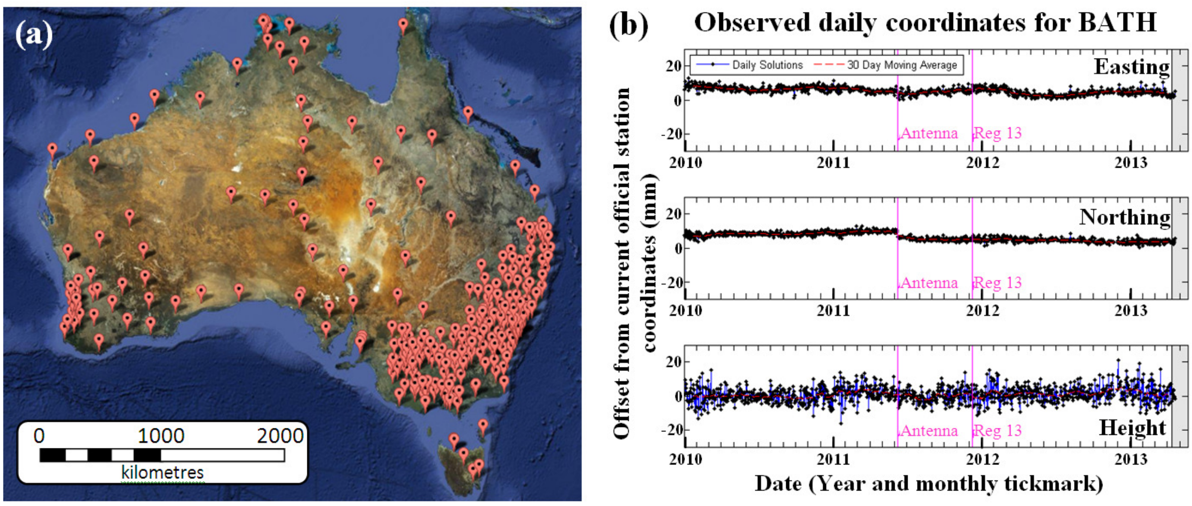

Figure 1: **(a)** APREF CORS across Australia (GA, 2013)
(b) CORS monitoring at Bathurst NSW (LPI, 2013). Apparent movement is a combination of atmospheric effects, equipment changes, station stability, local deformation, and more.

The variation shown in Figure 1b is a combination of real and apparent motion which can mostly be accounted for by equipment changes, regional and/or seasonal atmospheric effects and other 'loading' processes (e.g. Teferle *et al*., 2008; Tregoning and Watson, 2009). Any remaining (un-modelled) tectonic motion or local deformation can be quantified and incorporated into a deformation model at a resolution of several hundred kilometres or better.

Connections (measurements) between the CORS and the existing local geodetic infrastructure are necessary to transfer the constraints of the CORS coordinates to the rest of the adjustment. An example of this procedure is described by Gowans and Grinter (2013).

2.3 Collating All Geodetic Measurements

Each state and territory will still retain responsibility for its own geodetic infrastructure and measurements. Haasdyk and Watson (2013) give the example of collating and cleaning all available GNSS data within NSW, and demonstrate the simultaneous adjustment of 20,000+ stations and 66,000+ measurements. For this study, the CORS are constrained by their Regulation 13 certified values (GA, 2012b), which are essentially gazetted, 'static', GDA94 representations of the APREF coordinates.

The Permanent Committee on Geodesy (PCG) of the ICSM (ICSM, 2013a) is also collating these datasets, including all modern GNSS measurements as well as traditional terrestrial measurements (e.g. directions, distances) from all states and territories. This year the PCG will begin the testing of a simultaneous adjustment of all available geodetic measurements across Australia. The findings of the smaller NSW dataset can be directly applied to the tasks and methods employed in this larger national adjustment.

3. Identifying and Quantifying Deformation

3.1 The NSW Simultaneous Adjustment

As with any geodetic adjustment undertaken using Least Squares, the methodology includes gathering measurements and approximate starting coordinates, running the adjustment to estimate coordinates and corrections to the input measurements, and investigating outliers and adjustment statistics. Outliers in this context denote any measurement that needs to be significantly modified in order to 'fit' with the surrounding network of measurements and constraints. Since in this context, constraints are given by the highly precise Regulation 13 coordinates, all outliers are assumed to be due to disagreements between measurements.

Disagreements between measurements are quantified by their normalised residuals (NR) which is the ratio between the correction applied to make a measurement fit the network and the assumed uncertainty (expressed as one standard deviation) of that measurement. Note that the NR is only informative if the assumed uncertainty of the measurement is reliable. In the case of the NSW adjustment, these measurement uncertainties have been determined empirically over several decades of GNSS observations. It is assumed that this large measurement set has normally distributed errors and reliable uncertainties, and is therefore expected to have ~68%, ~95.5% and ~99.7% of the NR less than 1, 2, or 3 respectively. An NR greater than 3 is therefore quite unlikely, and flagged as an outlier.

The NSW adjustment is shown in Figure 2 with measurements coloured by their NR values. Note that outliers are often geographically clustered, because one outlying measurement will distort others nearby. The NSW adjustment has been undergoing an iterative cleaning process which includes classifying and correcting gross errors (e.g. incorrect height of instrument) or stations experiencing deformation, and then re-adjusting and re-analysing the network. At the time of writing (i.e. May 2013), 97% of measurements have an NR less than 3 (i.e. they fit well together), but a few localised issues remain with measurements of NR greater than 3.

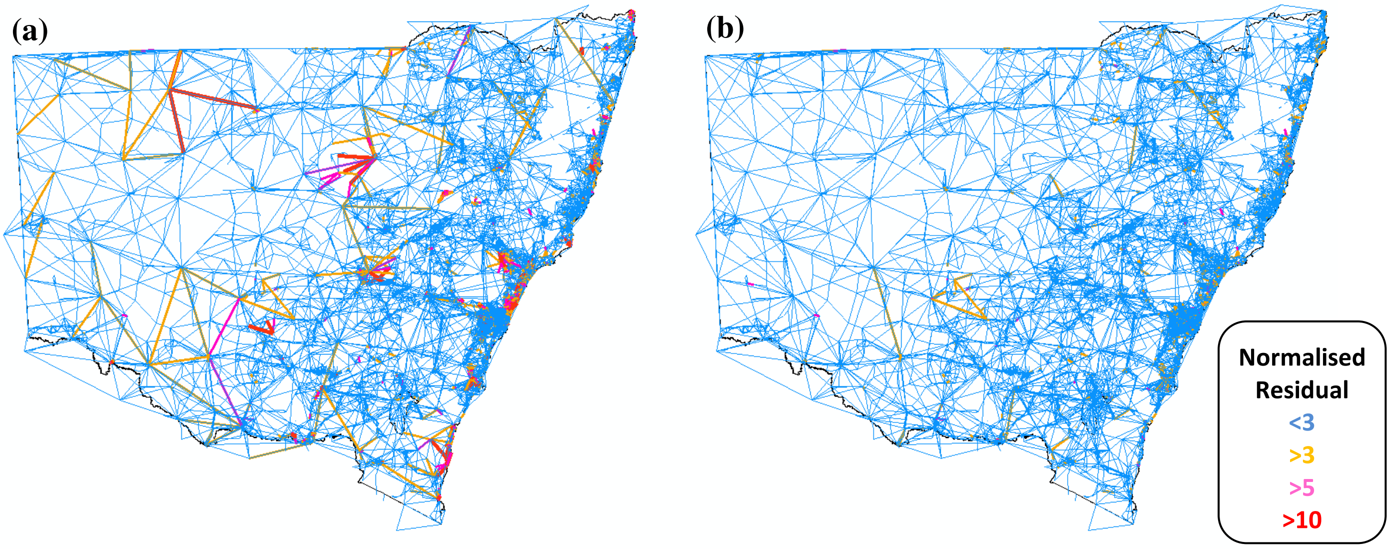

Figure 2: NSW GNSS network adjustment at various stages of cleaning

(a) Before cleaning 9% measurements with NR > 3 (and flagged as outliers), 1.7% with NR > 10

(b) As at May 2013 3% measurements with NR > 3 (and flagged as outliers), none with NR > 10

3.2 Deformation Case 1 (Ground Subsidence Attributed to Mining)

It is well known that underground long-wall coal mining can lead to deformation of the ground surface, both at the time of mining, and to a lesser extent in the period to follow as the ground settles into its new position (e.g. Ng *et al.*, 2010). As a result, stations in areas of known mining activity are immediately suspected of subsidence if measurements to those stations disagree over time.

TS5551 (a.k.a. Milbrodale Trigonometic Station) is one such station, and is shown in Figure 3. If this station is assumed to be stable over time, then there is significant tension in the adjustment, as shown by the many measurements that require significant correction in order to fit together (NR significantly greater than 3). If on the other hand, the adjustment is allowed to solve for different coordinates for each distinct GNSS campaign in which TS5551 was observed, then all the tension in network in the vicinity of TS5551 disappears. It is obvious therefore that a significant change in position of this single station has caused all nearby outliers in the adjustment. The few outliers which remain are related to a different station to the north-west in a separate area of subsidence.

Of particular note is the fact that TS5551 has only been measured (by GNSS) on two occasions, in 2002 and 2009. In this period TS5551 has dropped by 1.6 metres, and perhaps more surprisingly moved towards the north-east by more than 600 mm, as shown in Table 1. TS5551 is also the only station observed (by GNSS) in the entire area of possible subsidence shown in Figure 3, which is almost 10 km long. Even when terrestrial measurements are eventually included (they are not yet in the NSW simultaneous adjustment) there are only 15 coordinated stations in the mining area around TS5551 (not shown), most with only a single campaign of measurements prior to 2002.

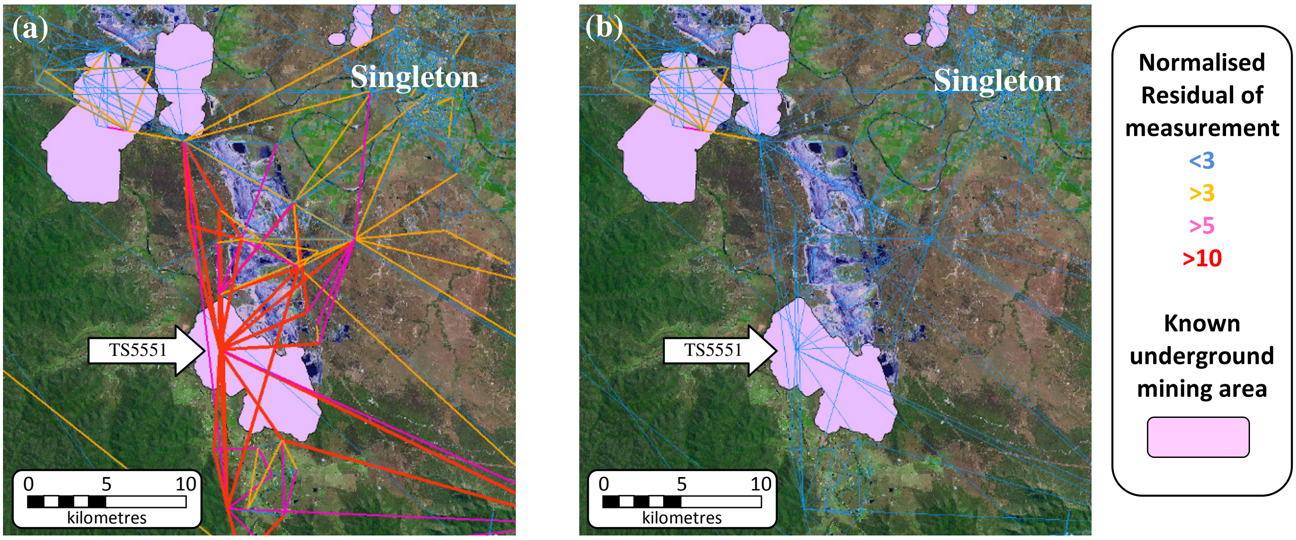

Figure 3: Effect of subsidence on adjustment around TS5551,
mining areas shown are approximate only (Mine Subsidence Board, pers. comm.)
(a) TS5551 is assumed to be stable over time
(b) TS5551 is solved for different coordinates in 2002 and 2009

Table 1: TS5551 coordinates when solved separately for each campaign, expressed in GDA94(2010)

	Epoch (yr)	**Easting (m)** (σ ≈ 10 mm)	**Northing (m)** (σ ≈ 10 mm)	**Zone**	**H(Ellipse) (m)** (σ ≈ 12 mm)
TS5551	2002	318038.322	6381436.133	56	199.030
TS5551	2009	318038.713	6381436.656	56	197.399
Difference (m)		**-0.391**	**-0.523**		**1.631**

3.3 Implications of Deformation Case 1 (Ground Subsidence Attributed to Mining)

Unfortunately the low spatial and temporal resolution of these measurements is not sufficient to say anything meaningful about the deformation experienced by other stations or landscape features in the vicinity of TS5551. Ng *et al.* (2010) clearly demonstrate that the actual deformation experienced during long-wall coal mining is complex both spatially and temporally, with surface deformation occurring within days of the underground mining. Nor do we have any real confidence in the coordinates of TS5551 itself, which could have moved at any time before, during, or after the dates observed.

Current practice in NSW is to simply 'red-flag' stations in such areas of possible subsidence, with an accompanying moratorium against their use, for example, in cadastral surveying. Further investigation into the nature and extents of any subsidence is only undertaken as required. Transects of levelling (for vertical deformation) or GNSS measurements (for 3D deformation) are sometimes repeated across such areas of suspected subsidence to monitor and quantify any subsidence. But these techniques are limited in the number of stations, occupations and transects employed, each of which is proportional to the cost of the project.

It would be far more useful if the deformation at these stations was determined with techniques such as DInSAR or LiDAR, which can measure at much higher spatial resolution, and with much higher frequency than traditional geodetic measurements.

DInSAR measures the relative ground displacement between two SAR image acquisitions, in the line-of-sight (LOS) from the satellite. Deformation can be detected at the centimetre-level with a resolution limited only by the pixel-size of the satellite imagery, and with frequent repeat measurements (e.g. ~45 days for repeat passes of ALOS PALSAR) (Ng *et al.*, 2010). Most studies have assumed that horizontal displacement was negligible, and the LOS displacement was therefore simply projected onto the vertical direction. Of course, our example of deformation at TS5551 demonstrates that there may be complex horizontal, as well as vertical deformation. Ng *et al.* (2010) demonstrate that a 3D deformation vector can be determined by combining at least three LOS measurements with different 'look' angles and satellite trajectory heading directions, as catered for in more modern satellites. Unfortunately limitations remain on the use of DInSAR such as the poor north-south precision due to current SAR satellite configurations, and the availability and cost of SAR images.

LiDAR involves a 3D laser scanner, usually airborne, which targets the area of interest with a sequence of LASER pulses from which distance and orientation are computed, a digital terrain model developed, and centimetre-level coordinates and deformation determined. Recent studies indicate that 1 cm vertical deformation, and 20 cm horizontal deformation can be detected at spatial resolutions of better than 15 metres, given sampling densities as low as 0.5 points / m^2 (Borsa & Minster, 2012; Meigs 2013). In airborne LiDAR, the kinematic location of the laser scanner can be accurately determined using CORS reference stations, even at the relatively low-densities shown in some areas of Australia in Figure 1 (Columbo *et al.*, 2010).

3.4 Deformation Case 2 (Survey Station Instability)

In contrast to the above case of land subsidence over a larger scale, there are many instances of discrete stations that move on much more local scales, purely due to station instability. Some examples include stations which have been manually disturbed by heavy vehicle traffic, stations removed and replaced during construction works, stations in unstable soils, etc. The case below describes the movement of a survey station located on a structure of questionable stability.

TS7350 (a.k.a. Euston Trigonometic Station) is one of many stations established on the top of existing structures (e.g. reservoirs and silos). These vantage points offered the height required for long-distance measurements in otherwise flat areas of NSW. Figure 4 clearly demonstrates that these measurements do not fit well together in the adjustment if TS7350 is considered to be stable. When the adjustment is allowed to solve for different coordinates for each distinct GNSS campaign in which TS7350 was observed, a significant horizontal movement of approximately 315 mm is detected, as shown in Table 2. The change in height is not statistically significant.

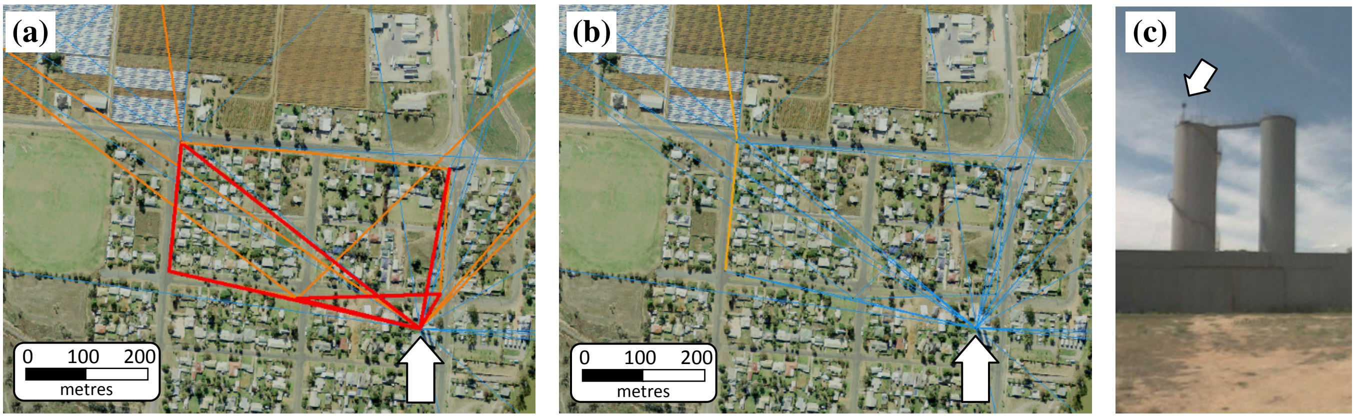

Figure 4: TS7350 Euston Reservoir Trigonometric Station
(a) TS7350 is assumed to be stable over time
(b) TS7350 is solved for different coordinates in 1991 and 2001
(c) TS7350 as viewed from the ground: Pillar and vanes are seen on the upper left

Table 2: TS7350 coordinates when solved separately for each campaign, expressed in GDA94(2010)

	Epoch (yr)	**Easting (m)** (σ ≈ 8 mm)	**Northing (m)** (σ ≈ 8 mm)	**Zone**	**H(Ellipse) (m)** (σ ≈ 10 mm)
TS7350	1991	659994.281	6172420.597	54	86.116
TS7350	2001	659994.531	6172420.410	54	86.102
Difference (m)		**-0.250**	**0.187**		**0.013**

3.5 Implications of Deformation Case 2 (Survey Station Instability)

As with the previous case of mine subsidence, the low spatial and temporal resolution of these measurements is not sufficient to say anything meaningful about the deformation experienced in the immediate vicinity of the station. As before, given the scarcity of GNSS measurements, we do not have confidence in the coordinates of TS7350 except at the time of each GNSS campaign, in 1991 and 2001. DInSAR and LiDAR would probably not be applicable to the scenario of station instability given that most survey stations have a very small footprint. Instead, such deformation can only be detected when the station itself is occupied during measurements.

An interesting distinction between these two cases is the initially *subjective* assessment that TS5551 has moved due to land subsidence, while TS7350 has moved due to station instability and not a larger land-movement. TS7350, for example, was suspected of movement after a local road survey noted discrepancies between contemporary measurements and published coordinates at TS7350. The measurements, however, do also give weight to this theory: Since other survey stations in the area still agree both locally and at greater distances, any movement of TS7350 is likely due solely to movement in the multi-storey reservoir.

4. Modelling Deformation

Historically transformations of coordinate sets have been focused on changes between datums either at the national level, where idealised rigid plate tectonic motion is modelled, or at the regional level where 'static' coordinates have been assumed. This approach was sufficient when the precision of measurements and transformations was at the decimetre-level. However, increases in measurement precision and the desire to map deformation with respect to time demands a more rigorous approach and explicit deformation modelling over time.

4.1 Historical Distortion / Transformation Modelling

Existing methodologies for transforming coordinates at the datum-level (e.g. between ITRF realisations or from ITRF to GDA94) have been generally restricted to the 14-parameter transformation, which is a conformal 7-parameter transformation that changes linearly with time (Dawson and Woods, 2010; Haasdyk and Janssen, 2011). These methods are insufficient to represent anything smaller than national-scale differences between datums.

To deal with distortions at smaller scales, a grid transformation can be effectively employed. For example, Collier (2002) describes the development and application of a grid transformation between coordinates expressed in the recent Australian datums AGD66/84 and GDA94. He particularly notes that "the provision of an otherwise complex transformation model on a regular grid is a convenient and widely accepted practice that satisfies the criteria of simplicity, efficiency and uniqueness". Note, however, that the precision of these AGD to GDA transformations are at the decimetre-level, and the transformation is defined between two nominally 'static' datums, where coordinates are expected not to change.

4.2 Modelling Deformation Over Time (e.g. Revised New Zealand Geodetic Datum 2000 Deformation Model)

In order to account for the deformation events noted by this study, consideration must be given not only to distortions and transformations *between* datums, but also deformations *within* datums over time. New Zealand, which sits astride two tectonic plates, has been employing a 'semi-dynamic' datum since the year 2000, in order to account for the complex land motions and deformations in their region. This model employs a deformation model, where velocities are interpolated from a regular grid of roughly 50 to 100 km spacing, to propagate contemporary measurements and coordinates back to their relative position at the epoch of 1 January 2000 (LINZ, 2013).

Many options were considered during development of the NZGD2000 deformation in order to account for discovery of imperfections in the model, the possibility of non-linear velocities, or discrete deformation events (e.g. earthquakes, landslips) that are not represented by the long-term trends (LINZ, 2003). While a simple constant velocity model was eventually adopted, it was always anticipated that a more complex treatment would be required to account for temporal changes and discrete events.

In mid-2013, Land Information New Zealand (LINZ) expects to publish its revised NZGD2000 Deformation Model. This revised model augments the existing national (constant) velocity model with several 'patches' to describe substantial deformation events that have affected New Zealand since 2000 (LINZ, pers. comm.). These 'patches' represent the measured distortion (and associated uncertainty values) that describe distinct deformation events such as the 2010 and 2011 Canterbury earthquakes.

In general, a 'patch' can contain a grid, a multi-resolution grid (where more information is available in some areas) or a triangular irregular network (TIN) of offsets or velocities to apply in a given area. A 'patch' will also be multiplied by a scalar which changes over time in a linear, ramp, step or exponential decay model. Using 'patches' in this way, a deformation model can be developed and updated at any resolution, to describe historical and recent deformation events to the maximum ability of the existing measurements.

It is important to note that the proposed New Zealand deformation model does not define point deformations; a 'patch' must be spatially continuous and evaluate to zero at its edges. This is required to ensure that any displacement must be 'uniquely invertible', or in other words, locations must transform uniquely back and forth between epochs, without the creation or destruction of any portion of the coordinate space. The consequence is that any deformation events must be modelled (and interpolated) between a grid of points. Station instability which explicitly affects a single station must therefore be handled by a different mechanism purely because no other local deformation information is available.

In New Zealand, station-specific movements are handled by nominating a new station name to recognise that the physical station no longer represents the same abstract location. In NSW, the coordinates of the existing station are updated, and a history of coordinates is maintained for that station. The presence (and ease of modification) of physical naming or numbering on the monument itself likely plays a large part in designing these protocols on a jurisdiction by jurisdiction basis.

4.3 To Model, or Not to Model, That is the Question

One salient difference between the deformation scenarios described above is the scale of the deformation. Starting with the APREF CORS coordinates (in ITRF at the current epoch), tectonic motion and deformation at a regional scale of hundreds of kilometres are monitored daily. This continuous CORS monitoring can quite easily detect the predictable tectonic movement of the Australian plate (approximately 70 mm/yr to the NNE; Dawson and Woods, 2010) and any deviations from the assumptions of a rigid Australian tectonic plate.

However, as the scale of deformation decreases, the monitoring difficulties increase, mostly due to the economics of deploying personnel and hardware for the task. At a local scale of several tens of kilometres, the effects of man-made subsidence, landslips and even earthquakes causing notable surface deformation (Dawson and Tregoning, 2007, study 19 such events since 1968 in Australia) can be monitored with DInSAR, LiDAR or other high-resolution techniques, but at greater cost and lower frequency. Slow moving landslides (e.g. as detected in New Zealand's Dunedin area) can have such irregular deformation patterns that even geodetic stations at 200 metre spacing are inadequate to model the deformation to desired accuracies (Donnelly, pers. comm.).

Finally, extremely local deformation due to station instability can only really be monitored by occupation of the station during a visit on-site. As demonstrated with the NSW dataset, it is entirely possible that subsequent measurements might be decades apart. Unfortunately, even defining station instability as point-specific (versus a point sampling of a larger deformation) requires a subjective and pragmatic judgement, which may simply occur because the deformation is small-scale and/or no additional sampling of the immediately vicinity is available.

The question that remains to be answered is which deformation events should be accounted for in the realisation of the datum, and which should be left out? It seems to be widely accepted that continental tectonic motion and deformation should be modelled, along with large-scale natural deformation events such as earthquakes. At smaller scales it is feasible that those running a mining operation, for example, would/should want to measure any subsequent deformation themselves, and not have these quantities modelled out of the datum. In contrast, a cadastral surveyor working in an area of possible subsidence probably only wants to confirm that new measurements agree with expected coordinates, and not be forced to chase any discrepancies due to subsidence which has probably already been quantified by others.

Due to such different demands from different users, it is possible that different 'patches' within a deformation model could be applied at the user's discretion. Unfortunately, while this approach is technically quite simple, the danger of potential mismanagement of metadata may require more strict application of any deformation model.

4.4 'Crowd-Sourcing' of Geodetic Data.

As implied above, the decision about what constitutes a deformation event (or process) worth measuring and monitoring depends on the roles and requirements of different organisations. Historically however, the responsibility of datum maintenance has been left solely in the hands of the often under-funded public sector. If this pattern continues, there is likely to be little impetus for monitoring deformation over small areas, or in unpopulated regions, except where monitoring is easy and/or automated, or the information is otherwise shown to be highly desirable.

As a case in point, even though the current NSW GNSS adjustment contains 60,000+ measurements, only 21% of those measurements represent a repeated measurement between the same two stations over the last 20 years. Of the 20,000+ stations involved, most have four or fewer GNSS measurements in total (not considering any terrestrial measurements). In order to detect deformation more comprehensively, and at smaller scales, smaller magnitudes and higher-precision, a significantly larger dataset will need to be gathered.

In the end, the currency and the resolution of the datum and deformation model will depend directly on the resources available for data collection and processing. In regions where there is an economic or scientific incentive, there is no reason why private and public organisations cannot pool their geodetic information for the benefit of all. Practical experience in Queensland has demonstrated the significant benefits in organising and 'crowd-sourcing' geodetic measurements from multiple organisations, each of which have a vested interest in developing the datum in a given region (Todd, pers. comm.).

It can be argued that the primary role of the geodesist is changing from data-capture to data-management. We have entered an era in which it is no longer difficult to obtain high-quality measurements using techniques such as GNSS, and to share those measurements using universal formats and automated data management (e.g. via eGeodesy; Donnelly *et al.* 2013). New measurements can and should be contributed by any suitable party, and the geodetic technical experts will ensure the proper adjustment and analysis of this data for the improvement of the datum and deformation model.

5. CONCLUSIONS

Australia currently has the opportunity to create a next-generation datum of high-precision, with rigorously quantified positional and relative uncertainty. With currently available computing power and adjustment methods, this datum can be responsive to change by incorporating new measurements and technologies immediately as they become available, essentially 'future-proofing' the datum. Gone are the days of fitting high-quality measurements to lesser-quality control. Instead, the next-generation datum can be a product created by its users, offering the accuracy and precision required by its users in perpetuity.

Some of the difficulties in maintaining a coordinated passive ground station infrastructure are demonstrated in this study, with the obvious conclusion that new measurement techniques offering higher spatial and temporal resolution are required to achieve the accuracy, precision, and currency desired. Additionally, 'crowd-sourcing' of high-quality geodetic information is likely to become the norm instead of the exception as the number of organisations capable of observing geodetic quality measurements increase, and project requirements drive the provision and maintenance of survey control.

An important consideration at this stage is the adoption of a deformation model to account for changes at national, regional, and local levels, as well as handling station instability. Australia and New Zealand are already working closely together through the ICSM. Close collaboration and attention to the application of the revised NZGD2000 Deformation Model will be imperative as Australia decides whether to adopt or extend this model. The case studies presented demonstrate that significant deformation is readily detectable within NSW. In order to provide accurate coordinates even at the decimetre level requires the collection and maintenance of time-stamp metadata on all coordinates and measurements.

This study aims to foster discussion regarding the development and implementation of the next-generation Australian datum, and its associated deformation model(s). It is the desire of the authors to engage the widest possible audience and feedback will be gratefully received.

ACKNOWLEDGEMENTS

Many thanks are given to the geodetic survey staff involved in data collection and analysis over many decades. These measurements provide the foundation to our past, present and future datums.

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