The Accuracy of Australia's Geodetic Network

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Australia's network of well-established geodetic survey marks is the essential basis for the country's spatial data infrastructure. Until recently, the precision of these positions was only really understood in a relative sense and was generally represented by an Order (1st order, 2nd order, etc). In 2000 the Inter-governmental Committee on Surveying and Mapping (ICSM), adopted Positional Uncertainty as a simple method of indicating coordinate accuracy for all types of users

This paper briefly documents the process used in the GDA94 national adjustment and describes in more detail the calculation of the Positional Uncertainty. It presents the results and independently checks them against positions from Geoscience Australia's on-line GPS processing system (AUSPos).

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INTRODUCTION

A geodetic network traditionally consists of permanent survey marks on inter-visible hills, interconnected by observed directions and distances. The known positions (latitude and longitude) of one or more origin (datum) stations are then used along with these observations to propagate positions to all other stations, using a least squares adjustment process to ensure the best results. This set of positions is then used as the fundamental spatial framework for everything from mapping and navigation to asset management and environmental monitoring. However, in spatial activities a position is only fully useful if it includes a measure of its accuracy.

Australian Geodetic Datum

Australia's first continental geodetic network, computed in 1966, was a major achievement. Based on Johnston Origin it consisted of 2506 stations connected by more than 50 000 km of Tellurometer traversing, over 500 Laplace astro stations and many angular observations (Bomford, 1967). Although limited by the computers of the time, the Varycord least squares adjustment software used to compute the positions was leading edge technology and the process was an outstanding success (National Mapping, 1967). The resulting positions are known as Australian Geodetic Datum 1966 (AGD66) coordinates.

In 1984 this network was upgraded by additional observations and improved modelling of the data (Allman and Veenstra, 1984). Although still based on Johnston Origin, geoid-ellipsoid separations were included as were Geodimeter distances. The new Transit Doppler satellite system was used to better control the large and sometimes sparse network, as were baselines derived from Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI). The rigorous adjustment of the data used the CHAOS software that was a forerunner of the Newgan adjustment software (Allman, 1993). This process used the Canadian Section method (Pinch and Peterson, 1974) so that the 5 498 stations were contained in 35 sections. The resulting positions are known as Australian Geodetic Datum 1984 (AGD84) coordinates, but not all States adopted them.

Both AGD66 and AGD84 used the Australian National Spheroid (ANS) and the astronomically derived position of Johnston Origin, which meant that these datums were a best fit for Australia, but not globally. This was not critical at the time, but with the advent of the Global Positioning System (GPS), a globally compatible, earth-centred (geocentric) datum was soon to become necessary. This eventually resulted in the Geocentric Datum of Australia 1994 (GDA94).

Geocentric Datum of Australia

The 1997 readjustment of the Australian geodetic network in terms of GDA94 used all the data included in the AGD84 adjustment, as well as the many terrestrial observations and geodetic quality GPS baselines and networks observed since then. The origin for this datum was the positions of the eight continuous GPS stations known as the Australian Fiducial Network (AFN), which has since evolved into the Australian Regional GPS Network (ARGN) of continuous GPS stations (Twilley and Digney, 2001). Several GPS campaigns undertaken between 1992 and 1994 extended these positions to a further 78 stations of the geodetic network, with a typical spacing of about 500 km. These are known as the Australian National Network (ANN) (Manning and Harvey, 1994). The coordinates of the AFN and ANN were computed in terms of the International Terrestrial Reference Frame 1992 (ITRF92) at 1 January 1994, ensuring that GDA94 was a geocentric datum compatible with modern satellite positioning (Morgan *et al*, 1996).

The GDA94 adjustment held both the AFN and ANN positions fixed and was carried out using the NEWGAN software. Once again the Section method was used, so that the more than 7 000 stations and 71 390 observations were sub-divided, into twelve sections.

The Section method of adjustment gives the same result as if the data were adjusted as a single data set, but has the advantage that the data can be verified and, where necessary, corrected in manageable quantities. Initially each block was adjusted as a *free network* known as the Stage 1 adjustment. This produced position equations for stations that were common to more than one section (Junction Stations). These were combined in a subsequent adjustment procedure (Stage 2) to give the final positions for the Junction Stations. They were then used as constrained positions in a re-adjustment of each of the sections (Stage 3) to give the final positions for all stations.

The GDA94 national adjustment did not include data from Western Australia as their GPS networks were not available at that time. However, their *Statefix* GPS networks were subsequently observed and adjusted holding the AFN and ANN positions fixed as for the rest of the GDA94 network (Stewart *et al*, 1997). These positions were then used to propagate the GDA94 coordinates to the terrestrial geodetic network in Western Australian, which included overlaps on the South Australian and Northern Territory borders with stations already adjusted in the national GDA94 adjustment. The South Australian and Northern Territory sections were

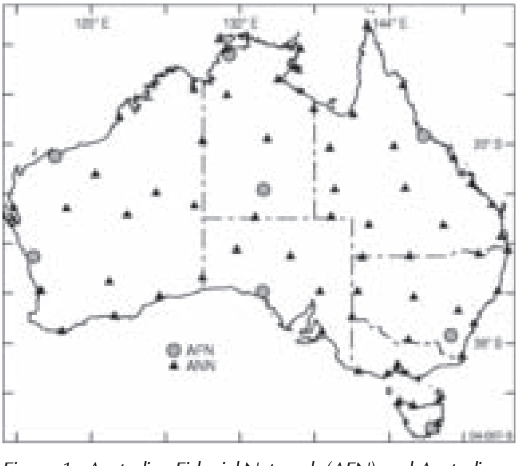

Figure 1. Australian Fiducial Network (AFN) and Australian National Network (ANN) stations

therefore readjusted to take advantage of the additional constraint in these sparse areas, improving the positions near the borders, but having no significant effect elsewhere. Some *fine-tuning* also took place in other States to make minor improvements to the observations and as a result, also to the positions.

GDA94 is now well established and has superseded the earlier AGD coordinates. The national geodetic adjustment was a major task in Australia's spatial history, but there was also a very significant effort involved in propagating these geocentric coordinates to the many subsidiary networks, databases and geographic information systems. Compiled data based on the AGD positions had to be transformed to the new datum and this presented its own challenges. Several transformation strategies were developed for this purpose (ICSM, 2001), the most accurate and consistent being the national transformation grids based on the common AGD and GDA94 positions at more than thirty thousand stations (Collier and Steed, 2001).

Station Order

With the advent of AGD66, the then National Mapping Council introduced a system to classify horizontal positions (latitude and longitude) according to their relative accuracy. This was the concept of *Order*, which was allocated on the basis of the fit of the survey to the existing survey control and was documented in *Standards and Practices for Control Surveys (SP1)* (ICSM, 2000a). Order readily indicates the hierarchy of the quality of positions (1st Order, 2nd Order, etc) but it is only a relative measure and does not immediately supply any quantitative information about the uncertainty of the position. At the time this value was best judged by the observation residuals in the least squares adjustment process.

The Newgan software used for the AGD84 adjustment provided full statistical information, including standard line and station error ellipses at the 39 percent confidence level. This meant that Order could be allocated based on the relative precision of the adjusted positions.

As survey measurement technology improved, the original Orders specified in SP1 became insufficient, as it was increasingly easy to achieve 1st Order results, which only required a relative accuracy of 7½ parts per million (at 39 percent confidence). Additional Orders of *0* and *00* were therefore added to manage this situation, but even the *00* Order only requires one part per million, which is now relatively easy to achieve with survey GPS observations.

POSITIONAL UNCERTAINTY

According to the ICSM standards, a 1st Order station should have an uncertainty of better than 7½ parts per million with respect to nearby stations. This amounts to 225 mm over a typical 30 km observed line. However if this station were near the coast it may in fact have an uncertainty with respect to the AGD Origin in the centre of Australia (Johnston Origin) of more than 15 metres (7½ ppm over 2,000 km). In terms of the GDA94 a 1st Order station could have an uncertainty of almost 2 metres with respect to the nearest ANN datum point (7½ ppm over 250 km). It is therefore apparent that while Order may adequately describe the relative merits of positions for those familiar with the underlying intricacies of SP1, it is not so informative for others in the spatial industry. This is particularly the case when they are trying to integrate and assess data from diverse sources.

This situation has been further exacerbated by recent developments in technology where very accurate positions can be achieved without apparent reference to surrounding geodetic control. Geoscience Australia's AUSPos on-line GPS processing system can give a position with an uncertainty of just a few centimetres (Dawson etal, 2001). For stations within Australia AUSPos gives both the latest ITRF position and the GDA94 position transformed from the ITRF value, using the known GDA94 and latest ITRF positions at the ARGN stations, in a process similar to that described by Dawson and Steed (2002). Also, systems such as Omnistar HP (Fugro, 2004) and Starfire (Sharpe *et al*, 2001) are promising real-time results with an uncertainty of about a decimetre. In these cases the concept of Order is irrelevant, as the coordinates are derived in a global reference frame (ITRF) and not from nearby GDA94 coordinates. A measure of the uncertainty is therefore needed in terms of the datum, rather than nearby control.

In 2000 the Inter-governmental Committee on Surveying and Mapping adopted *Positional Uncertainty* as a new method of indicating the

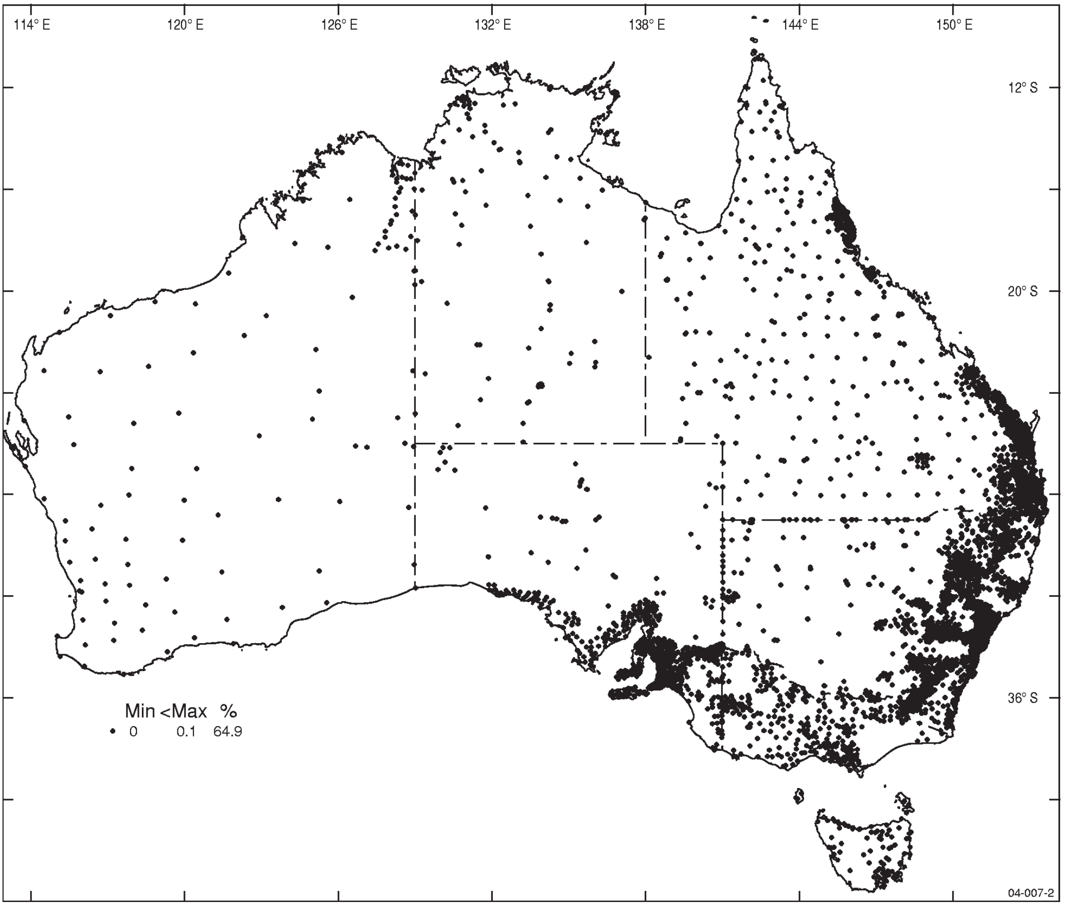

Figure 2. *Primary GDA94 stations with Positional Uncertainty less than 0.1 m*

accuracy of coordinates (ICSM, 2000b). The concept is similar to that used in the United States in that it uses a simple and meaningful value in metres to describe a circle of uncertainty (FGDC, 1998). It may be independent of the nearby survey network; is an easily understood value in metres and meets the requirements of the International Standards Organisation's (ISO) Technical Committee on Geographic Information and Geomatics.

ICSM's SP1 defines Positional Uncertainty as *the uncertainty of the coordinates, in metres, at the 95% confidence level, with respect to the defined reference frame*. In Australia, the defined reference frame for horizontal positions is GDA94, as realised by the adopted AFN and ANN positions. The recommended ISO 95 percent confidence level gives users a more realistic measure of the possible range of differences when comparing positions from different sources. However, it must be remembered that this measure is almost two and a half times larger than the one standard deviation (39 percent confidence) value often quoted.

Positional Uncertainty may be applied to any spatial information and can be derived from any appropriate information. For example, the Positional Uncertainty for positions derived from a hand-held GPS receiver may be taken from the manufacturer's specifications or for positions in a GIS or digitised from a map it may be the accumulated uncertainty from the various error sources during their production (Manning and Steed, 2001). However, for geodetic surveying, the Positional Uncertainty is generally computed from the station error ellipses produced during the least squares adjustment process.

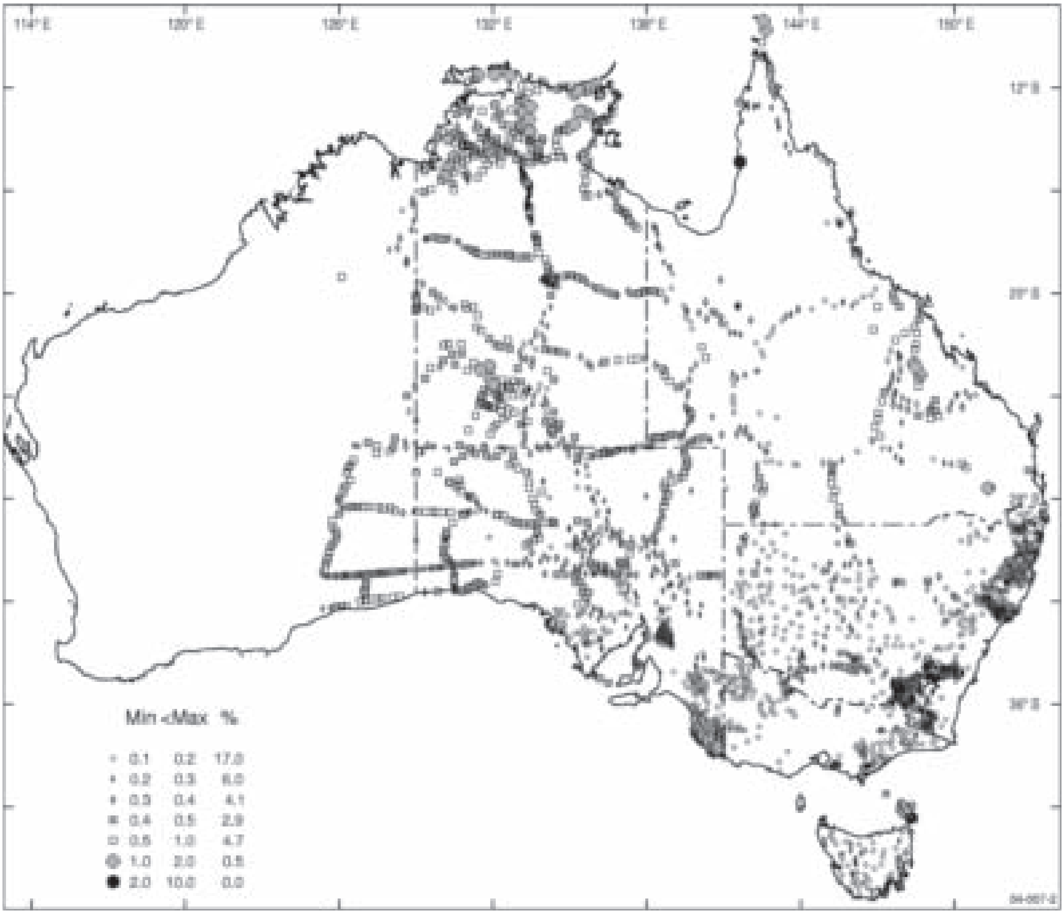

Figure 3. *Primary GDA94 stations with Positional Uncertainty of 0.1 m or more*

The error ellipses and other associated information from least squares adjustments will continue to be used by surveying specialists for further adjustments and analysis. However, the Positional Uncertainty for general use is a simple circular measure readily computed from the error ellipses using formulae proposed by Leenhouts (1985). This assumes that the error ellipses are in terms of the *defined datum*, but the Section method used for the GDA94 national adjustment only gives error ellipses in terms of the junction points in each section. To overcome this problem a statistically correct technique was developed to combine each station error ellipse with the nearest junction point error ellipse. The resulting combined error ellipses were then in terms of the GDA94 datum and were used with Leenhouts' formulae to produce the Positional Uncertainty for each station. This process was completed late in 2003 and produced the results shown in Figures 2 and 3. The Positional Uncertainty for the WA Statefix points was also computed directly from the 95 percent error ellipses produced by the Statefix *Geolab* adjustment.

The embedded tables in Figures 2 and 3 show the percentage of all stations with a Positional Uncertainty that falls within each of the range of values given (greater than or equal to *Min* metres and less than *Max* metres). They illustrate the influence of the substantial GPS networks, with more than 80 percent of the positions having a Positional Uncertainty less than 20 cm and, as separately shown in Figure 2, almost 65 percent less than 10 cm (about 8 cm and 4 cm respectively, when expressed at the 39 percent confidence level). It is also apparent that at least one station (the Hiran station on the eastern side of the Gulf of Carpentaria with a

Positional Uncertainty of almost 10 metres) was historically included in the network, but has a large uncertainty and these days adds little value to the geodetic network.

VERIFICATION OF GDA94 POSITIONAL UNCERTAINTY

Initially, the computed Positional Uncertainties were sorted and collated in terms of the previously allocated Order. It might be expected that stations with higher Order would have a better (smaller) Positional Uncertainty. However, this is not necessarily the case as the Positional Uncertainty is a function of the distance from the nearest datum point (AFN or ANN) which may be several hundred of kilometres away, while the Order is a function of nearby stations, perhaps only a few tens of kilometres away. Table 1 shows a tendency for the higher Orders to have a better Positional Uncertainty, but there is such a large range (possibly due to the varying distance from the datum points) that this cannot be taken as significant. It also indicates that some previous allocations of Order may have been unduly optimistic. In Table 1 over 90 percent of the stations are *0* Order, but the tables in Figures 2 and 3 show that the best 90 percent of the same stations have a Positional Uncertainty of up to 0.4 metres. It is therefore apparent that Order does not give a true indication of the quality of a coordinate with respect to the datum.

Recent test adjustments of a combined New South Wales data set (four GDA94 sections in a single data set) using the GHOST adjustment software (Canadian Geodetic Survey, 1988) held fourteen AFN and ANN stations fixed. The uncertainties obtained directly from this adjustment *agree fairly well* (at the few millimetre level) with the indirectly computed values from the GDA94 national adjustment (Watson, 2004). Further analysis of these data is expected, but these initial results provide evidence that the method used to combine the national adjustment error ellipses is sound.

Similarly, Western Australia has carried out tests propagating GDA94 error ellipses through their hierarchical network adjustments. The Positional Uncertainties produced by these limited tests in areas common to the GDA94 national adjustment agree at the millimetre level with the Positional Uncertainties produced from the GDA94 network (Morgan, 2004).

The most independent test of the GDA94 Positional Uncertainties comes from AUSPos results. At the time of these tests there were 200 stations in the GDA94 geodetic network, which also had AUSPos solutions (86 in the National Network, and 114 in the later computed supplementary networks). After initial comparison of the AUSPos and published GDA94 positions, eight of these with very large differences were discarded. These discarded points were all from GDA94 supplementary adjustments well down the hierarchy, with an as yet unknown, but probably large, accumulated uncertainty. In several cases the geometry of the conventional observations used to coordinate these points was also found to be very poor.

For the remaining 192 points, the GDA94 coordinates produced by the good quality AUSPos results (which are independent of the GDA94 network) have an expected accuracy of a few centimetres. When these are compared with the published GDA94, an alternative indication of the GDA94 Positional Uncertainty is produced. Figure 4 shows the magnitude, orientation and distribution of the difference in position for all 192 points and it is apparent that the AUSPos

ORDER	Stations		Positional Uncertainty		Range	
	No.	%	Average (m)	Std. Dev. (m)	Max (m)	Min (m)
0^{th}	7133	90.3	0.119	0.158	1.4	0.0
1^{st}	518	6.6	0.277	0.293	9.1	0.03
2^{nd}	92	1.2	0.317	0.941	1.9	0.01
3^{rd}	28	0.4	0.290	0.236	1.2	0.26
4^{th}	2	0.03	0.110	0.014	0.12	0.1
5^{th}	4	0.05	0.273	0.111	0.41	0.14
Unallocated	126	1.6	0.101	0.157	0.58	0.01

Table 1. *Order compared to GDA94 Positional Uncertainty*

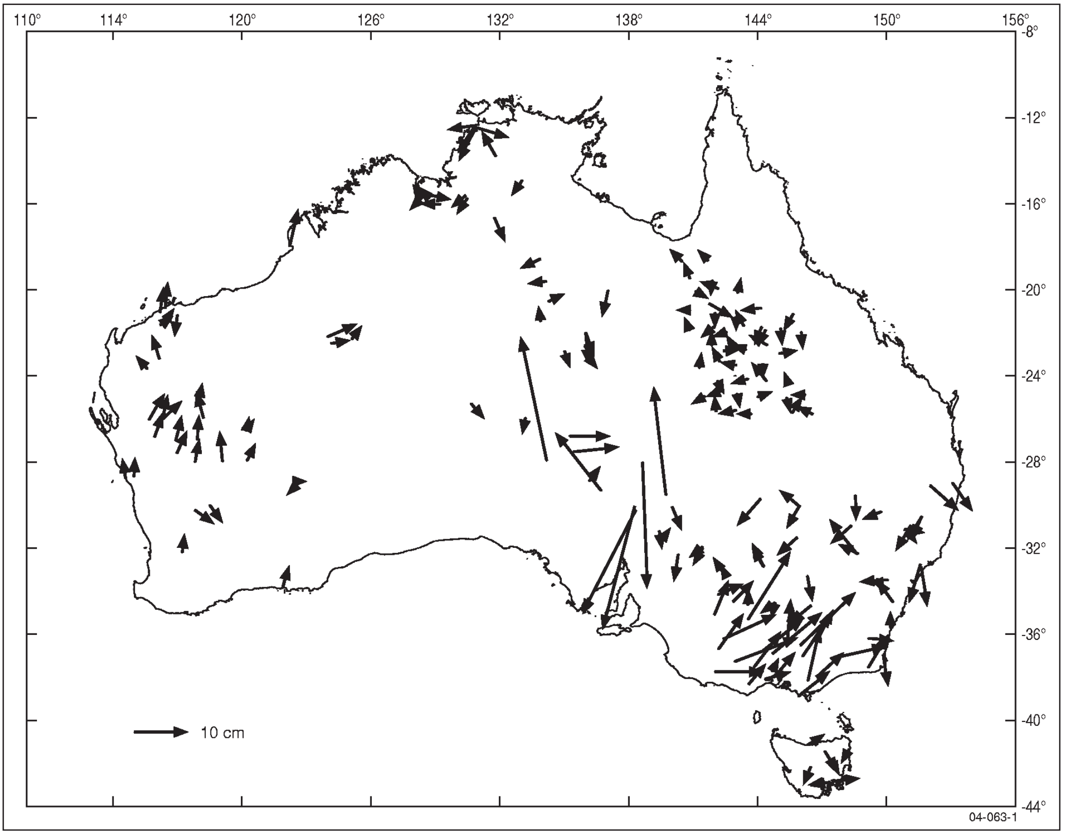

Figure 4. *Vectors of the difference in position from published GDA94 positions to AUSPos GDA94 positions*

GDA94 and published GDA94 results generally agree at the level of a few centimetres - but there are some large values.

The excellent comparisons in Queensland are indicative of the dense, high quality GPS networks that were included in the national GDA94 adjustment. Good comparisons in other areas also reflect the effect of the GPS networks.

The comparisons in South Australia are largely in sparse areas where the GPS control is of 1988 vintage, as is the GPS reduction software used (Sandford, 2004). This has resulted in a sometimes large Positional Uncertainty that is matched by the magnitude of the comparisons in Figure 4. Figure 5, which compares the differences with the computed Positional Uncertainty, further illustrates this situation.

Figures 5 and 6 show similar information as Figure 4, but displayed in a different way. In both cases the data are grouped by State and within each of these State groups the data are sorted by increasing magnitude of the position difference. Figure 5 includes both the size of the position difference and the derived GDA94 Positional Uncertainty for the 86 points in the National Network, while Figure 6 includes only the 106 points in the supplementary GDA94 networks (for which the Positional Uncertainty is not yet available).

It is apparent from Figure 5 that, not only is the comparison of coordinates generally very good, but the stations with larger differences generally have larger Positional Uncertainties, thus supporting the magnitude of the derived Positional Uncertainties. Although a few of the Positional Uncertainties are large compared to the position difference, no obvious explanation has been found, though these points are in sparse areas of the network and most are part of conventional Tellurometer traverses. In any case it is better for the Positional Uncertainty to be

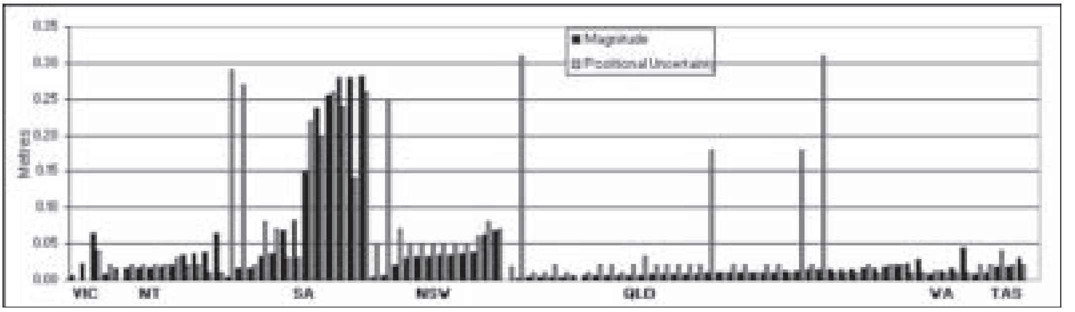

Figure 5. *Difference between published GDA94 and AUSPos GDA94 positions in the primary geodetic network (sorted by State) with computed GDA94 Positional Uncertainty*

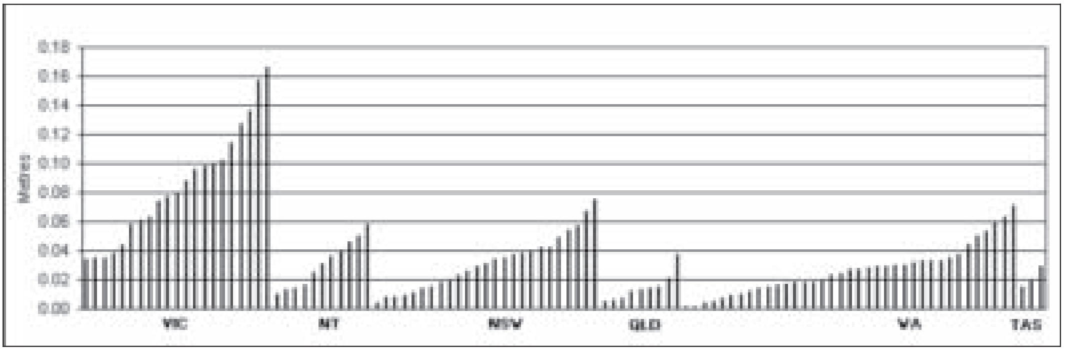

Figure 6. *Difference between published GDA94 and AUSPos GDA94 positions in the subsidiary geodetic network*

pessimistic, rather than optimistic and it could be argued that the published and AUSPos GDA94 positions may occasionally agree closely, even when the Positional Uncertainty of the published value is large.

While the Victorian comparisons in Figure 4 seem generally larger than others, Figure 5 shows that the comparisons at the national network stations are actually very acceptable and compatible with the computed Positional Uncertainty. Figure 6 however shows that while many of the comparisons for supplementary points are still very acceptable, a few are larger than expected. Some of these are Victorian GPSnet base stations (Roberts *et al*, 2003) with published GDA94 coordinates computed from nearby supplementary GDA94 positions, which have an accumulated, but as yet undetermined, uncertainty through the adjustment hierarchy. Recent investigations by Land Victoria indicate that improvements can be made in the reduction of some of the GPS observations used in the national adjustment in this region, by using more modern software (2000 vs 1993) and these improvements would flow down to the supplementary positions, improving the published GDA94 for at least some of them. This would bring them into closer agreement with the AUSPOS derived GDA94 coordinates. Other areas are still under investigation, but the intention is to increase the amount of GPS baselines in the control network, together with the number of AusPos solutions obtained as part of Geoscience Australia's investigations into the National Levelling Network (Ross, 2004).

CONCLUSIONS

Positional Uncertainty has been computed for all positions in the GDA94 National Geodetic Network and indicates a high quality set of coordinates, with the vast majority less than 20 cm and many less than 10 cm, at 95 percent confidence. These computed Positional Uncertainties correlate well with a comparison of published GDA94 positions and those produced independently from AUSPos, confirming the computed Positional Uncertainties as a good measure of the accuracy of GDA94 positions.

It is anticipated that Positional Uncertainty will be further propagated through the subsidiary GDA94 networks, enhancing their general use for spatial applications. This understanding of the accuracy of the GDA94 coordinates, along with the ability to accurately transform from ITRF positions to GDA94, will support the continued use of GDA94 for the foreseeable future.

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