GPS-geodetic deformation monitoring of the south-west seismic zone of Western Australia: review, description of methodology and results from epoch-one

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Abstract

The south-west seismic zone (SWSZ) is a northwest-southeast trending belt of intraplate earthquake activity that occurs in the south-western corner of Western Australia, and is one of the most seismically active areas in Australia. Since the SWSZ lies as close as ~150 km from the ~1.4 million population of the Perth region, it poses a distinct seismic hazard. Earthquake activity recorded by Geoscience Australia over the past three decades suggests that the SWSZ could be deforming by 0.5-5 mmy^{-1}. However, little is currently known about the magnitude and orientation of this deformation, and whether there is any associated surface expression. Previous geodetic studies of the SWSZ that used both terrestrial and Global Positioning System (GPS) techniques are inconclusive, due mainly to the imprecision of the technologies used in relation to the likely small amount of any surface deformation. Therefore, a new 48-point GPS-geodetic monitoring network has been established across the SWSZ to attempt to detect surface deformation, for which epoch-one episodic GPS-geodetic measurements were made in May 2002. This paper briefly reviews previous attempts to geodetically measure surface deformation across the SWSZ, summarises the scientific rationale for the new project, describes the network design and observations used, results of the May 2002 campaign (epoch-one) and discusses future work, including issues pertaining to the likely amount of surface deformation that can be detected.

Keywords: intraplate deformation, geodesy, GPS, south-west seismic zone

Introduction

The Australian continent, which lies entirely within the Australian tectonic plate, is subject to reasonably significant intraplate seismic activity (Wdowinski 1998). In Western Australia, a near-linear belt of such activity extends in an approximately northwest-southeast direction across the south-western corner of the State (Fig 1), which Doyle (1971) termed the south-west seismic zone (SWSZ). The SWSZ is one of the most seismically active areas in Australia (*e.g.* Everingham & Tilbury 1972), with the notable 1968 Meckering (magnitude 6.9), 1970 Calingiri (5.7), 1979 Cadoux (6.0), and more recently the 2001 Burakin (5.1) and 2002 Burakin (5.2) earthquakes. Since the SWSZ lies as close as ~150 km to the ~1.4 million people living in the Perth region, it poses a distinct seismic hazard (*e.g.* Gaull & Michael-Leiba 1987).

Knowledge of contemporary deformation is potentially an important component in understanding the earthquake activity in the SWSZ. However, little is currently known about the magnitude and orientation of any deformation. All that is presently known is that the western half of Australia is currently subject to an east-west-directed compressional stress regime (Reynolds & Hillis 2000; Zobak 1992). The expected association of surface expressions of deformation with seismic activity, though the two are not necessarily interdependent (*e.g.* Jackson & McKenzie 1988), has led to the use of terrestrial geodetic monitoring in parts of the SWSZ (discussed later). However, the amount of deformation in the SWSZ, as inferred from seismic monitoring conducted over the last three decades by Geoscience Australia, GA (formerly the Australian Geological Survey Organisation, AGSO), may be as small as 0.5 mm per annum, thus presenting a significant challenge to geodetic monitoring techniques in the SWSZ (*e.g.* Featherstone 1998). If the surface deformation were less than the proposed 0.5 mmy^{-1}, then this would suggest that the recent seismicity is atypical at a geological time scale.

Intraplate seismic activity has only received serious scientific attention in recent decades (*e.g.* Wdowinski 1998; Gaull & Michael-Leiba 1987; Snay *et al.* 1994). Due to the infrequent nature of intraplate earthquakes and extended recurrence periods for very large earthquakes in these zones (*e.g.* Weber *et al.* 1998), the inevitable extrapolation of data collected over the last few decades introduces a great deal of uncertainty in their analysis. Therefore, there is the need for independent, yet complementary, estimates of the rates of deformation in addition to those inferred from seismology.

The most effective means of quantifying contemporary surface deformation at discrete points over large areas is through high-precision geodetic measurements. In a deforming region, the amount of deformation can be quantified using repeated measurements of position, angles, distances, or a combination of these among a network of stable ground points. Historically, the measurements were made using conventional terrestrial surveying techniques (*i.e.* triangulation by measurement of angles, trilateration by measurement of distances, or a combination of both). Now, measurements from the Global Positioning System (GPS) have taken over as the primary means with which to quantify regional deformation (*e.g.* Bevis *et al.* 1997; Bock *et al.* 1997; Clarke *et al.* 1998; Weber *et al.* 1998; Pan *et al.* 2001).

Due to the small amount of expected deformation in the SWSZ (if indeed there is any surface expression of it) and the low precision of the terrestrial and *ad-hoc* GPS measurement methods then used, previous studies have proved inconclusive. Therefore, a more rigorous approach is required. Accordingly, a 48-ground-point GPS-geodetic deformation monitoring network has been established across the SWSZ (Fig 1), for which epoch-one GPS-geodetic measurements were made during May 2002. This collaborative venture involves funding and scientists from GA (Minerals and Geohazards, and National Mapping Divisions), the Western Australian Department of Land Information (DLI), the New Zealand Institute of Geological and Nuclear Sciences (GNS), Curtin University of Technology, and the University of Western Australia. This paper summarises the scientific rationale for this joint venture, describes the permanent network of ground monuments, gives results of the May 2002 GPS campaign and discusses the future work, including issues pertaining to the likely amount of surface deformation that could be detected using the GPS techniques described.

Previous geodetic deformation estimation in the SWSZ

There have been several attempts to geodetically measure surface deformation in various parts of Australia. Wellman (1981) presented an analysis and interpretation of repeat geodetic survey data for monitoring horizontal surface deformation throughout south-east and south-west Australia. In part of the SWSZ, he utilised results from a combination of first-order (Anon 2002) triangulation observations and resurvey trilateration observations. Note that the repeat survey used a different geodetic surveying technique than the initial survey, as well as different instrumentation.

Coleman & Lambeck (1983) seriously questioned the validity of Wellman's (1981) conclusions, arguing that the interpreted deformation is not significant because several critical factors were neglected. Clearly, this raises doubt as to the significance of any claimed crustal movement in the SWSZ, though admittedly Wellman (1981) states that 'it is irregular in magnitude and direction' in the SWSZ, which concurs with the later analysis performed by Featherstone (1998). Clearly, it is uncertain whether Wellman's (1981) estimates of horizontal surface deformation in the SWSZ are real or are simply an artefact of measurement, reduction and adjustment errors. This uncertainty is compounded by the inclusion of the same data in the least squares adjusted coordinates between measurement epochs (Coleman & Lambeck 1983).

Soon after the 1968 Meckering earthquake, DLI initiated a programme of episodic repeat-geodetic measurements to monitor surface deformation around the Meckering region, until 1995. This involved nine horizontal geodetic monitoring cells over parts of the SWSZ, and conducting second-order geodetic levelling over a large proportion of the SWSZ, which was used by Wellman & Tracey (1987). Changes in funding and advances in geodetic measurement technology dictated that the horizontal monitoring used both terrestrial-geodetic and GPS-geodetic techniques, which can exhibit scale differences (*cf* Savage *et al.* 1996). Featherstone (1998) analysed the horizontal DLI data and argued that these investigations of the SWSZ were also inconclusive (*cf* Coleman & Lambeck, 1983). Based on comparisons of the measured distances (*i.e.* the primary observations), no statistically significant changes were detected in relation to the expected precision of the measurement techniques used. Moreover, there were contradictory estimates of extension and compression for the same baselines. Although one of DLI's monitoring cells (to the west of Meckering) did show some significant differences, these could be simply attributed to instrumentation differences (Featherstone 1998).

In 2000, the first-named author reoccupied parts of this monitoring cell with Leica CRS1000 GPS receivers. Unfortunately, the GPS data collected were not of sufficient quality to resolve any motion. Nevertheless, the field survey was useful because it was discovered that several of the ground monuments were difficult to accurately centre over (*e.g.* 10 mm spikes set in concrete with no drill-hole; *cf* the monument to the right in Fig 2), and many of the monuments were not set on bedrock. At least one was demonstrably unstable, moving when kicked very gently. Therefore, the apparent statistically significant deformation observed in this area could simply be due to one or all of different GPS instruments, GPS-antenna centring errors over the ground marks, and disturbance of the marks between observation epochs.

From all these previous studies, there is clearly no consensus as to whether any surface deformation has actually been detected in the SWSZ, or whether observation and data reduction errors have been misinterpreted as deformation (*cf* Coleman & Lambeck 1983; Featherstone 1998). Accordingly, the consortium has taken a fresh approach to geodetic deformation monitoring in the SWSZ, as follows.

The new 48-point SWSZ network

The most effective means of quantifying contemporary surface deformation at discrete points over large areas by GPS is through a network of continuously operating geodetic GPS receivers. Such an approach has been adopted in tectonically active regions such as Southern California (*e.g.* Bock *et al.* 1997), to obtain continuous coordinate time-series for the points occupied, from which velocities can be computed and surface deformation inferred. However, this would be an extremely costly undertaking across the reasonably remote SWSZ, with each station costing up to approximately A$70000 to install. A more economically efficient compromise is to establish a network of permanent ground monuments installed rigidly on bedrock, coupled with episodic repeat GPS surveys collected over several days per station, as was used by, for example, Clarke *et al.* (1998) and Pan *et al.* (2001). This episodic monitoring approach has been adopted in the SWSZ.

Unlike conventional terrestrial surveying methods, modern geodetic-GPS also offers the opportunity to directly measure both the absolute (*i.e.* in a global reference frame) and relative (*i.e.* between points in the local region of interest) deformation of the ground monuments. However, the small amount of deformation expected in the SWSZ still poses a technical challenge to continuous, and more so the episodic, GPS deformation monitoring. Based on the inconclusive results of the previous geodetic surveys over an approximate 30-year time span, the most important consideration is to determine if the new GPS-geodetic time-series will give an accurate representation of actual surface deformation, not simply an artefact of errors associated with the measurement and data processing techniques. As such, it is necessary to eliminate systematic errors from the episodic GPS-geodetic monitoring network as practically and economically possible.

Early in 2002, a 48-point network of permanent ground monuments was established by the consortium (Fig 1). For each of the 48 sites, GA selected potential granite rock sites from digital geological maps. DLI then used these to select the final site location and installed near-ground-level forced-centring pillars in bedrock. These ground monuments (Fig 2) were set using three epoxy-resined bolts set in drill-holes in the bedrock with nuts to level the stainless steel baseplate with respect to the local vertical. Once level, the screws and baseplate were set in more epoxy resin and fast-setting concrete, respectively. A standard 5/8-inch (Whitworth) thread had previously been set in each baseplate for the GPS antennas, or other geodetic instruments, to be re-centred exactly during each episodic occupation. Reference marks were also set at ~120-degree intervals and at ~3 m surrounding each mark, so that if disturbed or destroyed, the primary mark can be relocated to millimetre-precision.

Between 30 April and 22 May 2002, approximately 20 sites were simultaneously surveyed near-continuously (except for equipment failures at a few sites) for between 5 and 7 days. Each site used forced-centred GPS antennas, oriented as closely as possible to north using shims [washers of different diameter], on the permanent ground marks (Fig 3). Dual-frequency code and carrier-phase data were logged at a 30-second interval from all GPS satellites above a 5-degree elevation angle. The geodetic GPS receivers used were Ashtech Z Surveyor and Z12, Trimble 5700 and Leica CRS1000. The GPS antennas used were Ashtech [Dorne-Margolin-type] choke-ring, Trimble Zephyr (Fig 2), and Leica [Dorne-Margolin-type] choke-ring (Fig 3). The Dorne-Margolin-type antennas reduce multipath (reflected GPS signals) by the geometry and depth of the choke-rings, and the Zephyr antennas use advanced signal processing to reduce multipath (see Dawson 2002). Cost considerations and equipment availability among the consortium members precluded the preferable use of the same models of GPS receivers and antennas.

Five Ashtech Micro Z GPS receivers and antennas were operated continuously for the entire campaign (at newly established ground marks SZ07, SZ15, SZ20, SZ33 and SZ48 (Fig 1)). This provided a "backbone" of stations in order to precisely link the surveys. The remaining sites were occupied in three near-one-week phases (*i.e.* approximately 20 simultaneous occupations including the five continuous sites) from north to south with three survey teams moving and maintaining around five stations each. The mobile survey teams would periodically check the receivers, which in some cases proved essential because of power failures. At least 5 days of near-continuous dual-frequency GPS data were obtained from all but two of the sites.

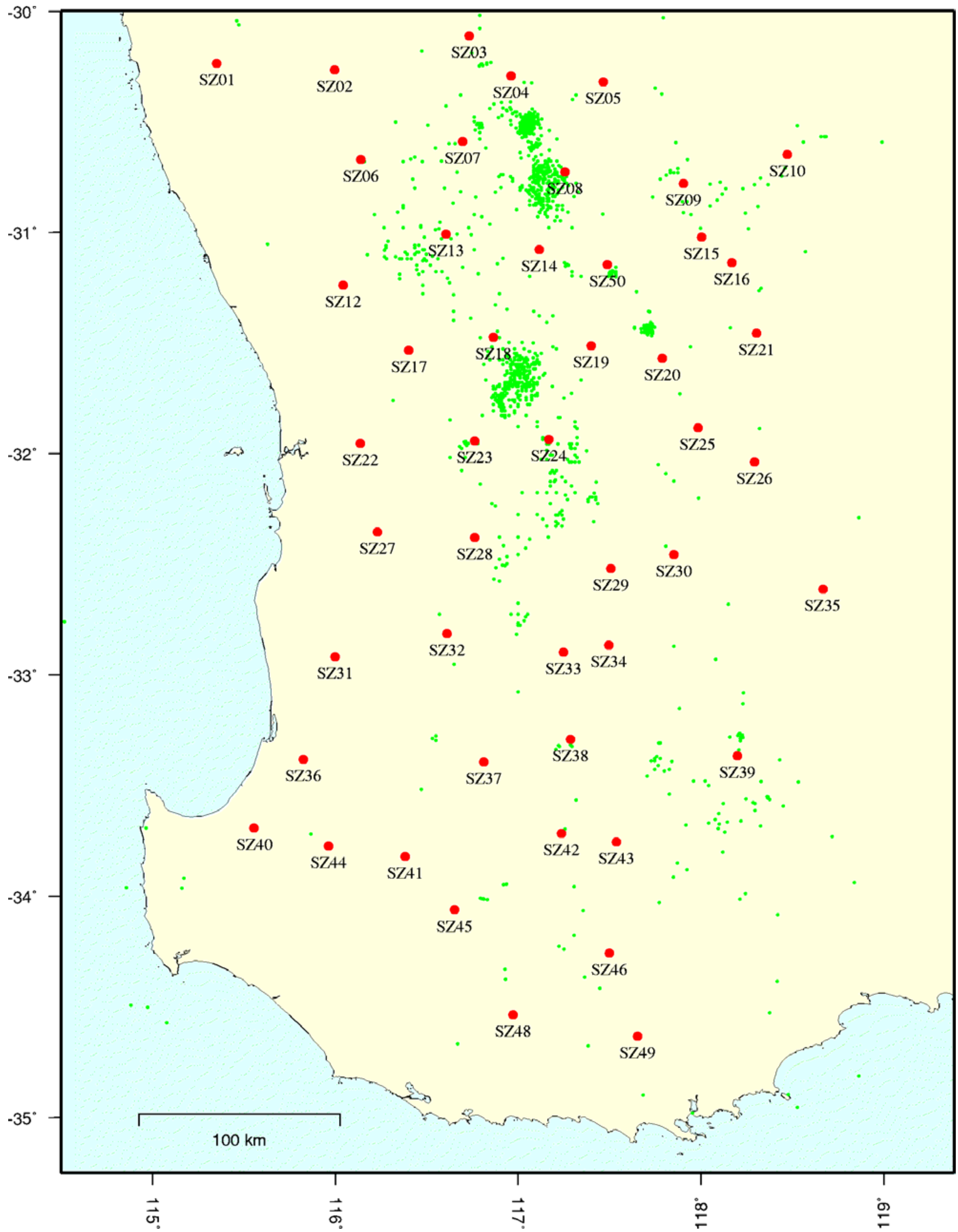

Figure 1. Distribution of the 48 GPS stations in the SWSZ, which were each surveyed for 5-7 days during May 2002 [SZ11 and SZ47 were not placed]. The dots show all the recorded earthquakes in this region (1970-2002).

Figure 2. A newly installed ground monument (left); the ground mark to the right is part of the existing Western Australian geodetic network maintained by DLI.

Figure 3. The GPS receiver was powered by a combination of solar panels and car batteries and left unattended (excepting checks) during each site occupation.

The 48-point GPS monitoring network will be used predominantly for monitoring horizontal deformation across the SWSZ, because GPS is inherently less precise in the vertical (shown later) due mainly to a combination of the geometry of the satellites (with them being only above the ground-based antennas) and imprecisely modelled atmospheric refraction of the GPS signals. Geodetic spirit levelling is the most precise means with which to monitor vertical deformation at discrete points. Therefore, if vertical deformation is sought over the SWSZ, it is probably best to reoccupy and extend the levelling network used by Wellman & Tracey (1988).

GPS Data Processing and Results

Any geodynamic deformation monitoring campaign that uses GPS (episodic or continuous) requires sophisticated data processing and error modelling. Firstly, geodetic quality (*i.e.* dual-frequency code and carrier-phase) instruments and antennas that reduce the effects of multipath must be used. Secondly, scientific GPS data processing software must be used. Commercial GPS data processing software is inadequate because of its approximated algorithms and inability to model the small, yet important, biases that would obscure the small, if any, surface deformations in the SWSZ.

The National Mapping Division of GA processed the GPS data collected for epoch one (Dawson 2002) using the Bernese version 4.2 GPS software (Hugentobler *et al.* 2001), closely following the procedures adopted by the regional analysis centres of the International GPS Service (IGS; http://igscb.jpl.nasa.gov/). This data processing included the rigorous modelling of systematic errors, including variable ionospheric and tropospheric signal refraction, periodic solid-Earth- and ocean-tide effects, and antenna phase-centre variations. The GPS satellite orbit information used was that provided in the final IGS orbital product, which was held fixed together with Earth-orientation parameters. Carrier-phase ambiguity resolution was attempted on all baselines for all GPS data collected above an elevation angle of 10 degrees.

Besides the GPS data collected in the SWSZ, GPS data were also collated from continuously operating GPS receivers at Alice Springs, Karratha, Ceduna and Perth, whose 30-second (code and dual-frequency carrier-phase) data are made freely available through the IGS. These were included since their data are processed daily by IGS analysis centres and hence have extremely accurately (sub-cm) known coordinates in a global, dynamic, reference frame. When the position of a point is expressed in a dynamic reference frame, it is accompanied by the particular epoch to which it refers. This recognises the fact that the coordinates of the point will change due to global plate tectonic motion and hence the point also has an associated velocity (curiously, no mention is made of intraplate deformations in the models used). The estimates of coordinates and velocities for Alice Springs, Karratha, Ceduna and Perth are computed by the International Earth Rotation Service (IERS) using all available IGS GPS data and are updated approximately yearly in a solution termed the International Terrestrial Reference Frame (ITRF).

The latest realisation is ITRF2000 (http://lareg.ensg.ign.fr/ITRF/ITRF2000), which used all GPS and other space-based data up until the end of the year 2000 to compute the coordinates and velocity estimates for each point. Hence, including data from the IGS stations (with published ITRF2000 coordinates and associated velocities) in the GPS network solution has enabled the positions of the 48 SWSZ monitoring points to be computed relative to the four nearby IGS stations and to express their coordinates in the ITRF2000. The velocities of the 48 SWSZ monitoring points could then be subsequently computed from the coordinate estimates obtained at different epochs. For the epoch-one survey, the coordinates of the four IGS stations were fixed at their ITRF2000 values at the campaign mid-epoch 2002.37, therefore the coordinates of the SWSZ monitoring points also refer to ITRF2000 epoch 2002.37

While the GPS data were collected continuously at each monitoring point over the 5-7 day observation period (excepting the five stations that were occupied nearly continuously for 22 days), discrete three-dimensional position solutions were obtained using the data for each (Universal Time) day, which were then combined using least squares techniques to obtain the final ITRF2000 epoch 2002.37 coordinate estimates (Dawson 2002). This approach enables some internally estimated quality assurance of the solutions, via the computation of coordinate standard errors (1σ) from the variation of each daily solution from the mean. Importantly, such 1σ are only indicators of the internal precision of the solution, namely that there is a 68% probability that the position solution obtained from any given day will be equal to the mean value in each dimension. When these three dimensions are combined to form a horizontal ellipse or three-dimensional ellipsoid, the error magnitudes must be scaled for multivariate statistics (*e.g.* Anon. 1996).

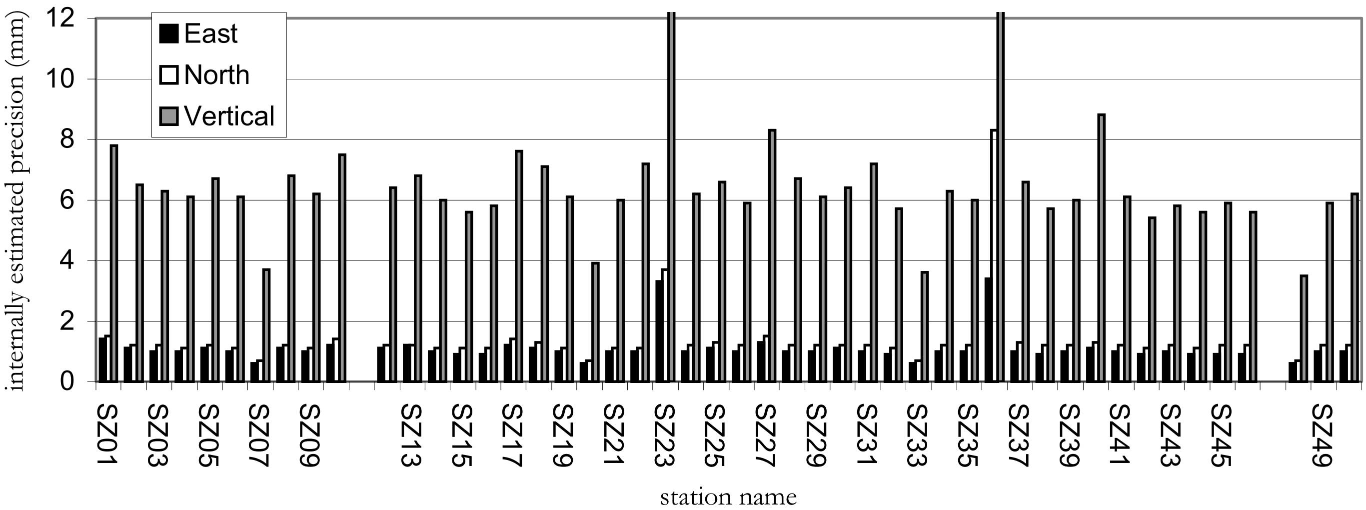

Figure 4. Internally estimated precision (1σ) of the epoch-one GPS-derived coordinates (ITRF2000 epoch 2002.37) of the 48-point network across the SWSZ (units in mm) [SZ11 and SZ47 were not placed]

Fig 4 and Table 1 summarise the internally estimated precision of the ITRF2000 (epoch 2002.37) coordinates of the 48 SWSZ stations. The geodetic coordinates (*i.e.* latitude, longitude and ellipsoidal height) are given by Dawson (2002). From Fig 4, 46 of the 48 occupied stations have an internally estimated precision of 1.5 mm in the horizontal [43 have a precision of 1 mm]; the vertical precision was generally better than 7 mm. Two stations (SZ23 and SZ36) gave very poor results due to Leica CRS1000 equipment failure (Fig 4). Therefore, Table 1 includes a summary of the results excluding these two outliers.

	1σ East	1σ North	1σ Vertical
Maximum	3.4 (1.4)	8.3 (1.5)	21.8 (8.8)
Minimum	0.6 (0.6)	0.7 (0.7)	3.5 (3.5)
Mean	1.09 (0.99)	1.36 (1.16)	6.80 (6.18)
STD	0.50 (0.16)	1.10 (0.17)	3.20 (1.06)

Table 1. Descriptive statistical summary of the internally estimated precision (1σ in mm) of the epoch-one GPS-derived coordinates (ITRF2000, epoch 2002.37) of the 48-point network across the SWSZ (values in parentheses exclude the two outliers at SZ23 and SZ36)

The internal precision estimates summarised in Table 1 and Fig 4 provide an indication of the consistency of the solution and suggest that the GPS data were generally of high quality and there were no major signal interference or reception problems, plus that systematic error effects that vary over the duration of the epoch-one campaign, such as atmospheric delays, were well mitigated by sophisticated modelling during the data processing. Nevertheless, the figures above are by no means an indication of coordinate accuracy. Inter-instrumental and site-dependent biases, notably un-modelled multipath, (*i.e.* systematic errors) will result in different coordinates being computed for the same station when surveyed with different GPS antennas and receivers. For instance, the electrical phase centres of the antenna at which the GPS signals are received are not necessarily coincident with the physical/geometric centre of the antenna due to mechanical imperfections, and also vary depending on the antenna make and model. Therefore, future surveys should endeavour to use the same receivers and antennas at the same ground marks. If not, great care will be exercised to account for the above-mentioned systematic errors so that any coordinate differences are not misinterpreted as surface motion in the SWSZ (cf. Lambeck & Coleman 1983; Featherstone 1998).

Discussion and Future Work

Previous geodetic surface deformation monitoring studies of the SWSZ remain inconclusive due to errors in the data collection and reduction techniques used. Therefore, a 48-point network of dedicated permanent ground monuments, with forced-centring apparatus, has been established to quantify any surface deformation associated with the seismic activity across the central part of the SWSZ with a view to long-term GPS-geodetic monitoring of their deformation. The consortium first occupied (epoch-one) this network during May 2002 using four different types of GPS receivers and antennas. Excluding two outlying stations (based on statistical analysis and problems encountered in the field), the internal precision estimates of the computed ITRF2000 (epoch 2002.37) horizontal coordinates show a mean precision of ~1 mm in north and east (and ~6 mm in the vertical). The vertical GPS coordinates will probably not be used because levelling is a more precise technique for detecting vertical motion.

Based on the accuracy with which the horizontal coordinates of the monitoring points can be estimated and the expected episodic reoccupation frequency of the monitoring epochs, indications of the time required to detect a particular magnitude of surface deformation can be estimated. Using the relationship provided by Coates *et al.* (1985), Dixon (1991) states that the uncertainty σ_v in any station velocity estimate is dependent on the single measurement point accuracy (not precision) σ_m, the (assumed constant) epoch separation Δt, and the time T between the first and last epoch:

$$\sigma_v = \frac{\sigma_m}{T}\left[\frac{12T/\Delta t}{(1+T/\Delta t)(2+T/\Delta t)}\right]^{1/2}$$

For a point measurement accuracy of 1.5 mm, an epoch separation (*i.e.* episodic re-measurement period) of two years and a total monitoring period of 10 years, this suggests a point velocity uncertainty of 0.2 mmy^{-1}. Extending the monitoring period to 20 years suggests a point velocity uncertainty of 0.1 mmy^{-1}. However, regarding the epoch-one results, it is stressed that, whilst the maximum horizontal internal precision estimate for the SWSZ monitoring points was ~1.5 mm (ignoring outliers), this is not an indicator of the accuracy of the point measurement and cannot necessarily be blindly used to obtain an estimate of the uncertainty in the computed velocity. Accordingly, the above velocity uncertainties are probably over-optimistic.

Furthermore, the equation for σ_v assumes negligible slowly varying systematic errors, yet coordinate time-series computed from the analysis of continuous GPS data by many analysts worldwide currently show pronounced seasonal variations (*e.g.* Dong *et al.* 2002). Blewitt *et al.* (2001) identified the response of the elastic solid-Earth to redistribution of surface load via seasonal changes in a GPS coordinate time-series. When surface deformation is monitored using coordinate time-series formed from episodic measurements, such seasonal effects could result in an under-sampled or aliased signal, resulting in biased velocity estimates. Hence in the presence of seasonal variations, simple linear regression techniques to estimate velocities (as above) may be inappropriate.

Another important consideration when computing station velocities is the correlation of the position error estimates between measurement epochs (*e.g.* Williams 2003). From an analysis of continuous GPS data resulting in a coordinate estimate each day, Mao *et al.* (1999) suggest that the velocity error may be underestimated by factors of 5-11 if such correlations are ignored. In the episodic approach to be used for the SWSZ network, this is perhaps less critical, but nevertheless will be considered. When computing station velocities, the stability of the geodetic monument should also be assessed, namely that it remains firmly anchored in the ground and represents movement of the Earth's crust, not simply a local effect. This was addressed in the new SWSZ network as best as possible by only establishing sites on firm bedrock.

Forming coordinate time-series (and subsequently station velocity estimates) using GPS has the added complication that dynamic reference frames such as the ITRF are regularly updated, typically every 3-4 years. This becomes an issue for long-term episodic GPS deformation monitoring since the precise satellite orbits attainable from the IGS are provided in the most recent realisation of the ITRF, which may be different from that used in the data processing of a previous GPS survey. In the data-processing approach adopted here, the estimated station coordinates are essentially in the same reference frame as the satellite orbit (as inferred via the control stations used). Since velocities can only be computed from coordinate estimates that are expressed in a common reference frame, it is usually necessary to re-process the data from a previous survey when the latest realisation of the ITRF becomes available, or transform the coordinates from the previous realisation of the ITRF to the most recent realisation (Boucher & Altamimi 1996). Therefore, these two different approaches will be experimented with after subsequent epochs are measured across the SWSZ.

The consortium intends to conduct a re-occupation of the 48-point network as soon as 2004. Depending on the number of different GPS receivers and antennas available, several reoccupations will be used to estimate inter-instrumental biases so as to better define the accuracy of the computed coordinates. However, where possible, the same GPS receivers and antennas will be used at the same stations as used for the epoch-one survey so that common systematic errors will cancel. Once reoccupations have been undertaken in 2004, and probably again in 2006, the GPS data will be reprocessed (using more sophisticated algorithms and techniques that may be available at that time, as well as implementing a consistent ITRF realisation) to give the first estimates of both absolute and relative station velocities in the SWSZ. These data can be analysed in a variety of ways, from simple vector plots through to stress and strain inversion (*e.g.* Wu *et al.*, 2001), in order to extract information relevant to GA's earthquake hazard research, as well as other programmes being undertaken by the consortium members.

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References

Anon (2002) Standards and Practices for Control Surveys (version 1.5). Inter-Governmental Committee on Surveying and Mapping, Canberra, Australia. http://www.icsm.gov.au/icsm/publications/sp1/sp1.htm

Bevis M, Bock Y, Fang P, Reilinger R, Herring T, Stowell J & Smalley R 1997 Blending old and new approaches to regional GPS geodesy. EOS Transactions, American Geophysical Union 78(6):61-66.

Blewitt G, Lavallee D, Clarke P & Nurutdinov K 2001 A new global mode of Earth deformation: seasonal cycle detected. Science 294:2342-2345.

Bock Y, Wdowinski S, Fang P, Zhang J, Williams S, Johnson H, Behr J, Genrich J, Dean J, van Domselaar M, Agnew D, Wyatt F, Stark K, Oral B, Hudnut K, King R, Herring T, Dinardo S, Young W, Jackson D & Gurtner W 1997 Southern California permanent GPS geodetic array: continuous measurements of regional crustal deformation between the 1992 Landers and 1994 Northridge Earthquakes. Journal of Geophysical Research 102(B8):18013-18033.

Boucher C & Altamimi Z 1996 International Terrestrial Reference Frame. GPS World, 7(9): 71-74.

Clarke P J, Davies R R, England P C, Parsons B, Billiris H, Paradissis D, Veis G, Cross P A, Denys P H, Ashkenazi V, Bingley R, Kahle H-G, Muller M V & Briole P 1998 Crustal strain in Central Greece from repeated GPS measurements in the interval 1989-1997. Geophysical Journal International 135:195-214.

Coates R J, Frey H, Mead G D & Bosworth J M 1985 Space-age Geodesy: The NASA crustal dynamics project. IEEE Transactions on Geoscience and Remote Sensing GE-23(4):360-368.

Coleman R & Lambeck K 1983 Crustal motion in south eastern Australia: is there evidence for it? Australian Journal of Geodesy, Photogrammetry and Surveying 39:1-26.

Dawson J 2002 South West Seismic Zone 2002: GPS analysis. Technical Report, National Mapping Division, Geoscience Australia, Canberra.

Dixon T H 1991 An introduction to the Global Positioning System and some geological applications. Reviews of Geophysics 29:249-276.

Dong D, Fang P, Bock Y, Cheng M K & Miyazaki S 2002 Anatomy of apparent seasonal variations from GPS-derived site position time series. Journal of Geophysical Research 107(B4).

Doyle H A 1971 Seismicity and structure in Australia. Royal Society of New Zealand Bulletin 9:149-152.

Everingham I B & Tilbury L 1972 Information on Western Australian earthquakes 1849-1960. Journal of the Royal Society of Western Australia 55(3):90-93.

Featherstone W E 1998 Geodetic monitoring of the South-west Seismic Zone. In: Tsakiri M (ed) Proceedings of the Advances in GPS Deformation Monitoring International Workshop, Curtin University of Technology, Perth, Australia, 24-25 September, ISBN 1-86308-073-2

Gaull B A & Michael-Leiba M O 1987 Probabilistic earthquake risk maps of south-west Western Australia. BMR Journal of Australian Geology and Geophysics 10(1):145-151.

Hugentobler U, Schaer S & Fridez P 2001 Bernese GPS Software Version 4.2. University of Berne, Switzerland.

Jackson JA & Mckenzie DP 1988 The relationship between plate motions and seismic moment tensors, and the rates of active deformation in the Mediterranean and Middle East. Geophysical Journal of the Royal Astronomical Society 93:45-73.

Mao A, Harrison C G A & Dixon T H 1999 Noise in GPS coordinate time series. Journal of Geophysical Research 104(B2):2797-2816.

Pan M, Sjöberg L E & Talbot C J 2001 Crustal movements in Skane, Sweden, between 1992 and 1998 as observed by GPS. Journal of Geodynamics 31:311-322.

Reynolds SD & Hillis RR 2000 The in situ stress field of the Perth Basin, Australia. Geophysical Research Letters 27:3421-3424.

Savage J C, Lisowsky M & Prescott W H 1996 Observed discrepancy between Geodolite and GPS distance measurements. Journal of Geophysical Research 101(B11):25547-25552.

Snay RA, Ni JF & Neugebauer HC 1994 Geodetically derived strain across the northern New Madrid Seismic Zone. Professional Paper 1538-F, United States Geological Survey, Washington, USA.

Wdowinski S 1998 A theory of intra-plate tectonics. Journal of Geophysical Research 103(B3): 5037-5059.

Weber J, Stein S & Engeln J 1998 Estimation of intra-plate strain accumulation in the New Madrid seismic zone from repeat GPS surveys. Tectonics, 17(2): 250-266.

Wellman P 1981 Crustal movement determined from repeat surveying - results from south-eastern and south-western Australia. Journal of the Geological Society of Australia 28(1):311-321.

Wellman P & Tracey R 1987 South-west Seismic Zone of Western Australia: measurement of vertical ground movements by repeat levelling and gravity surveys. BMR Journal of Geology and Geophysics 10:225-232.

Williams S P D 2003 The effect of coloured noise on the uncertainties of rates estimated from geodetic time series. Journal of Geodesy 76:483-494

Wu J C, Xu C J, Chao D B, Liu J N & Li Y X 2001 Research on an intraplate movement model by inversion of GPS data in north China. Journal of Geodynamics 31:507-518

Zobak M L 1992 First- and second-order patterns of stress in the lithosphere: the world stress map project. Journal of Geophysical Research 97(B6):11703-11728.