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, reports on the 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, Wellman (1981) 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

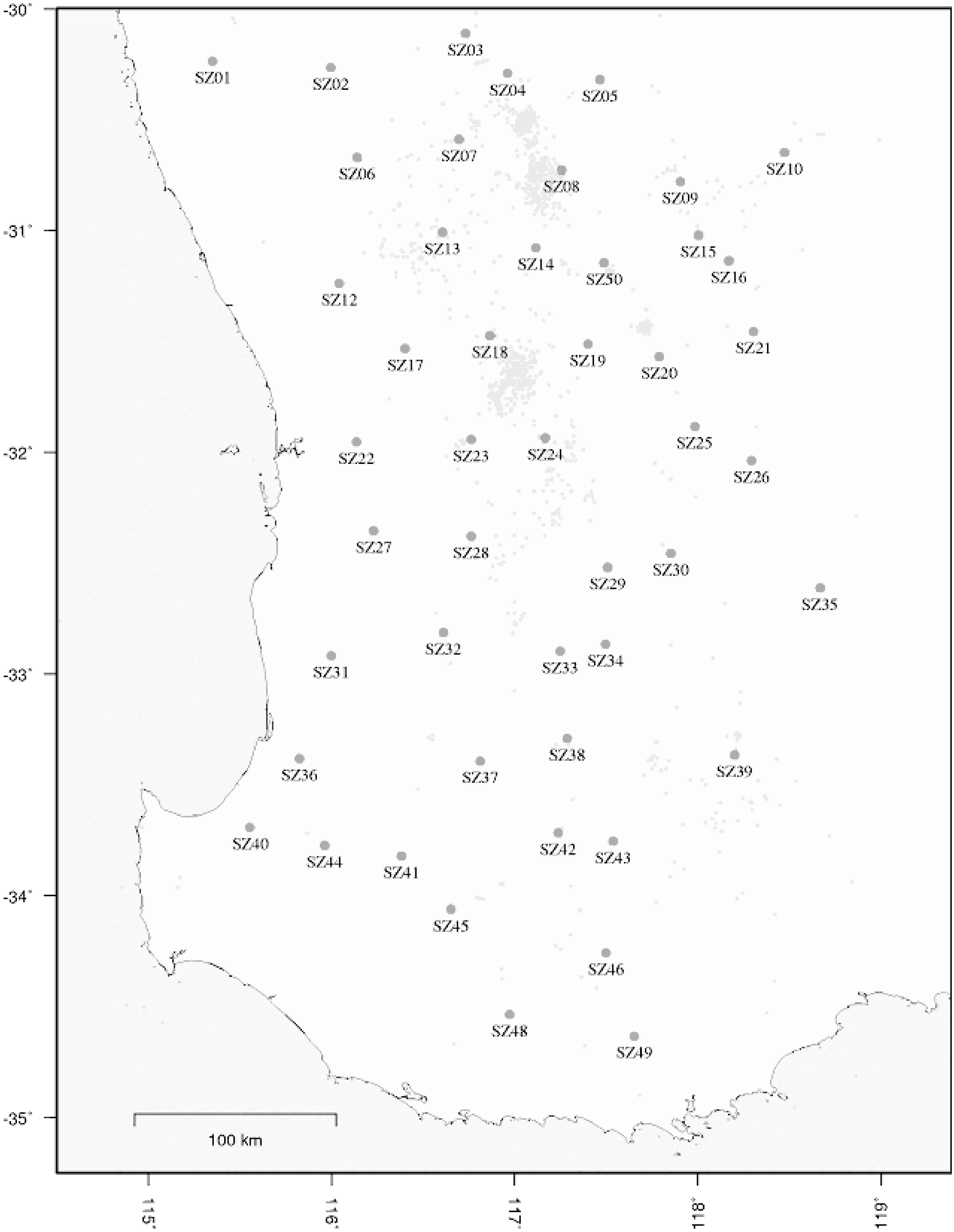

Figure 1. Distribution of the 48 GPS stations in the SWSZ, which were each surveyed for 5-7 days during May 2002 [SZ11 and SZ47 were not placed]. The dots show all the recorded earthquakes in this region (1970-2002).

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, Geoscience Australia 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.

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.

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

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, the resulting coordinate estimate each day, Mao et al (1999) suggests 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 Geoscience Australia's earthquake hazard research, as well as other programmes being undertaken by the consortium members.

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