Deformation Monitoring and Analysis Using Regional GPS Permanent Tracking Station Networks

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Key words: CORS, ITRF, precise ephemeris, deformation monitoring and analysis

SUMMARY

Natural disasters are of a problem of global concern and may cause significant human, economic, social and environmental losses and sometimes, threaten geopolitical stability. Natural hazards that have disastrous impacts on us include earthquakes, landslides, floods, storm surges, severe winds, bushfires, and tsunamis. Natural hazards are estimated at an average annual cost of $1.25 billion in Australia and about 15% of the most remarkable natural hazards in the world occurred in the last century in China. The availability of precise and reliable deformation information is critical for the monitoring and analysis of the earth's surface displacement, the movement of faults, landslide and some other deformations. In addition, proper site selection of important structures and their protection against hazards and the ability to analyse and predict natural and non-natural hazards are of great importance in geosciences.

GPS has been recognized as a vital technology for deformation monitoring due to its high-precision, 24 hours availability, operability under all weather conditions and automation. This paper will investigate the feasibility using continuously operating reference stations (CORS) in Victoria (termed GPSnet) for deformation monitoring and analysis. A number of critical issues associated with the suitability, geological stability, data quality of the GPS networks system, the precision and stability of the GPSnet solution are investigated using geological information. Methodologies for GPS data processing and deformation analysis are investigated. The precision and stability of the GPSnet solution are analysed and discussed using the raw observation data, GPS precise data processing software and statitic analysis method. The absolute and relative displacement of selected GPSnet stations are analysed using chronological GPS data and dedicated high precision scientific GPS data processing software packages. Detailed data-processing strategies and results of deformation analyses are presented. It is concluded that high-precision continuous tracking data from GPSnet is a very valuable asset and can provide a technically-advanced and cost-effective geoscientific infrastructure for deformation monitoring analysis.

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1. INTRODUCTION

Natural disasters are of a problem of global concern and may cause significant human, social, economic and environmental losses and sometimes, threaten geopolitical stability. Natural hazards that impact on Australian communities include earthquakes, landslides, floods, storm surges, severe winds, bushfires, and tsunamis. Natural hazards are estimated at an average annual cost of $1.25 billion in Australia (Geoscience Australia, 2004a). Victoria is one of the regions where earthquake epicentres are relatively concentrated (Figure 1) (Geoscience Australia, 2004a). There is potential risk of earthquake in this region. For example, Yallourn area within Victoria is a geologically active part and experiences earthquake from time to time (Brown, 2002). Landslide is another considerable geological hazard in Australia and south-eastern Victoria is a very active landslide area. The Earth's surface deformation due to human activities such as mineral mining may also cause hazards.

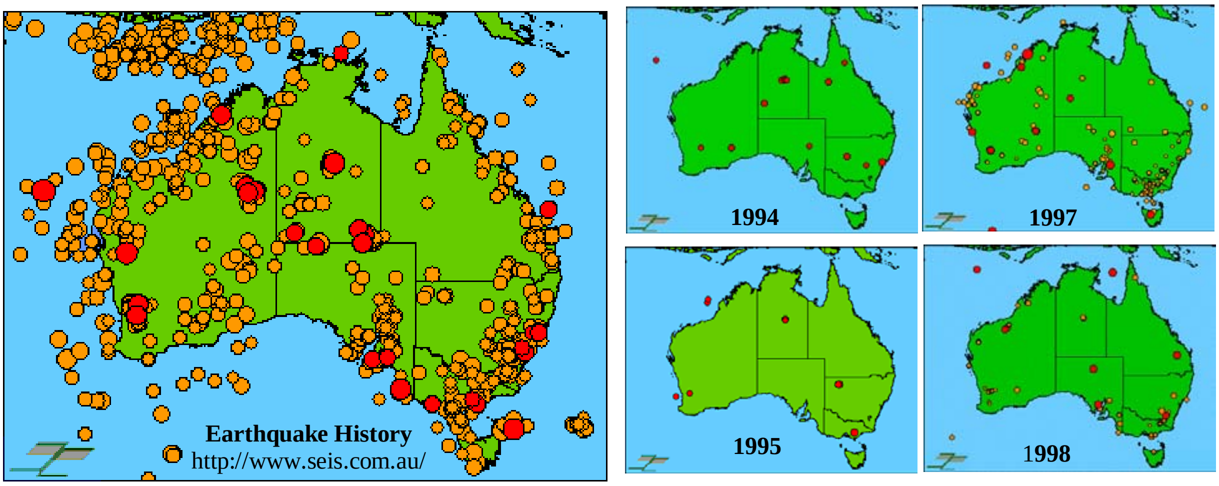


Figure 1 Historical distribution of earthquake epicentres in Australia (● indicates epicentres of earthquake)

For many applications, such as site selection of important engineering projects and constructions and their protection against hazards, the ability to analyse and predict natural and non-natural hazards is of great importance. Such ability depends heavily on precise and reliable deformation information which in turn can be acquired by using advanced technologies through the monitoring and analysis of the Earth's surface displacement, the movement of faults, landslide and some other deformations.

Due to its high precision, 24 hours availability, operability under all weather conditions and automation, GPS technique has been widely used in deformation monitoring. In Victoria, GPSnet with its high-precision observation data provides a technically-advanced and cost-effective geoscientific infrastructure for deformation monitoring analysis. By mining the data from the GPSnet, not only reliable and high precision deformation information can be obtained, lots of expenditure required for establishing dedicated deformation monitoring networks in this area can also be saved.

Methodologies for GPS data processing and deformation analysis are investigated. The absolute and relative displacement of selected GPSnet stations subnet are calculated using chronological GPS data and AUSPOS scientific data-processing engine. The feasibility and effectiveness of the methodologies put forward are discussed and some useful conlusions are given.

2. VICTORIAN GPSNET

Land Victoria (a Division within the Department of Sustainability and Environment, formerly the Department of Natural Resources and Environment, State of Victoria/Australia) foresaw the rapid developments of global navigation satellite technology and initiated an ambitious project to establish a set of 20 permanent and continuously operating GPS Base Stations (GPSnet) across the State in early 1990s. The primary purpose of the GPSnet is to provide a range of users with a means of obtaining accurate and homogenous positioning within Victoria using the space-borne technology. As an integral part of the new geodetic strategy for Victoria, GPSnet is being established in partnership with industry and academia.

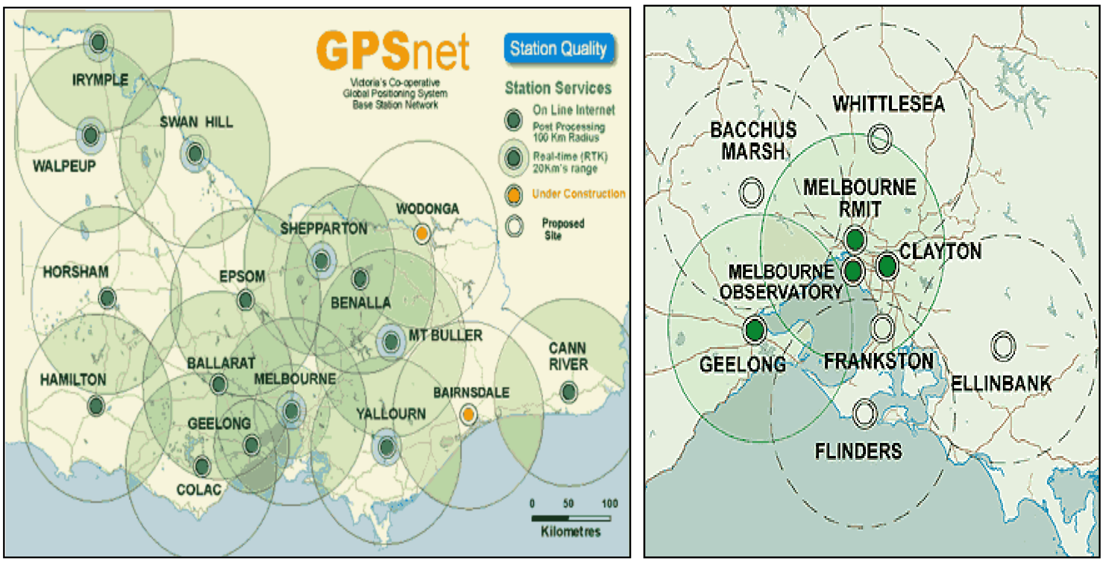


Figure 2. Victorian regional (left) and Melbournian (right) GPSnet base station network locations and their development status (Land Victoria, 2003)

The nominal design spacing of the GPSnet stations is approximately 50km in the Melbourne metropolitan region and 100km in rural Victoria, but the separations can range up to 200km in remote areas (see Figure 2). The Melbourne observatory base station has been connected to International GPS Service (IGS) network. GPSnet currently consists of 20 operational base stations that transmit, record and archive, hourly data files for accurate position determination with post-processing techniques. Eight sites also transmit local real-time kinematic (RTK) correction signals via radio. The GPSnet system provides a mechanism for centimetre level positioning relative to the Australian National Spatial Reference Systems. Recently, GPSnet infrastructure has been upgraded and enhanced to generate differential GPS (DGPS) correction service for real-time applications in support of location based service (LBS) in Victoria (Millner et al., 2004).

GPSnet uses a variety of receivers including Trimble 4000SSE, 4000SSI, 4700 and Leica SR9500 dual-frequency receivers. The receivers use dual-frequency (L_1/L_2) geodetic antennas with ground-planes and record C/A code, L_1/L_2 carrier phase and Doppler data in the RINEX format at all sites. All antennas are permanently mounted to provide an uninterrupted view of the surrounding sky. GPS antennas are usually sited on rooftops of buildings and at other stable locations free of multipath. Data processing is performed in the International Terrestrial Reference Frame (ITRF) 97 and then transformed to geocentric datum of Australian 1994 (GDA94). Results indicate that RMS of daily solutions is in the order of 2-4mm in easting and northing and 3-8mm in height using IGS final orbits products (Brown, 2002). Apart from high-precision geodetic applications, the GPSnet has been widely used since its inception, including but not limited to navigation, mapping, GIS, surface deformation monitoring (eg open pit coal mining), agriculture and surveying applications (Zhang & Roberts, 2003).

3. METHOD OF DEFORMATION ANALYSIS

Victorian GPSnet is of high precision (mm level in horizontal position), and most of its base station antennas are of good quality and high stability. The GPSnet is, therefore, capable of providing reliable and high-precision deformation data, such as the determination of both velocity and direction of Earth’s surface displacement, relative movement of large geological faults, the relation between the Earth’s surface displacement and tectonic motion, landslide deformation and the crustal deformation caused by mineral mining.

Figure 3 outlines a detailed process of this investigation using GPSnet measurements for deformation analysis. Major steps for data processing, deformation analysis and some important contributing factors are presented. The technical requirements and procedures of data-processing and deformation analysis are usually different for different types of deformation analyses, and the reference datum of deformation analysis and the GPS base stations in the GPSnet should be properly chosen to form an optimal deformation analysis subnet.

3.1 Datum selection of deformation analysis

A number of ITRFs (i.e. ITRF 93, 94, 96, 97 and 2000) are involved in Victorian GPSnet data due historical evolution. To obtain reliable results of deformation analyses, coordinate reference frames of GPSnet stations must be identical. The latest and most accurate reference frame of ITRF2000 should be used as the unique coordinate reference frame. The change of the GPSnet position due to tectonic motion of the Australian continent and the relative changes of GPSnet stations due to other factors (fault movement，landslide，mineral mining etc.) can be estimated reliably.

Coordinate transformation of an ITRF system to ITRF2000 can be performed using the transformation parameters provided by the International GPS Services (IGS, 2000). The deformation analysis can also be conducted in GDA94 or Map Grid of Australia (MGA) as long as the coordinates of GPSnet reference stations in ITRF2000 are transformed to GDA94 or MGA Grid using the transformation parameters between ITRF2000 and GDA94/MGA Grid (Dawson, 2002). The displacement of GPSnet reference stations derived from the coordinate differences in ITRF2000 from two different epochs reflects the resultant effects of all contributing factors on the stability of GPSnet stations. If the effects from Australian continent motion are subtracted from the "absolute" displacement, then the relative displacement of GPSnet reference stations can be obtained.

To obtain precise relative displacement, it is desirable that one relative stable station in GPSnet is used as the datum of deformation analysis and the GPS network for displacement analysis is adjusted using a non-constrained free network adjustment method. In GPSnet, the "Melbourne obs" station in IGS network should be ideally used as a relatively stable datum because it is built directly on bedrocks and of high stability. However, the station was established in 2002 and became operational since November 2002. Before then, no station in the GPSnet can be regarded of high stability since all of the GPSnet station antennas are mounted on rooftops of buildings. Therefore, currently, to compute and analyse relative displacement of the GPSnet, relatively stable and precise IGS/ARGN reference stations close to the GPSnet have to be selected and subsequently used as a stable datum for relative displacement analysis of the GPSnet stations. That is the GPS network for displacement analysis is adjusted using the free network adjustment method with no fixed datum.

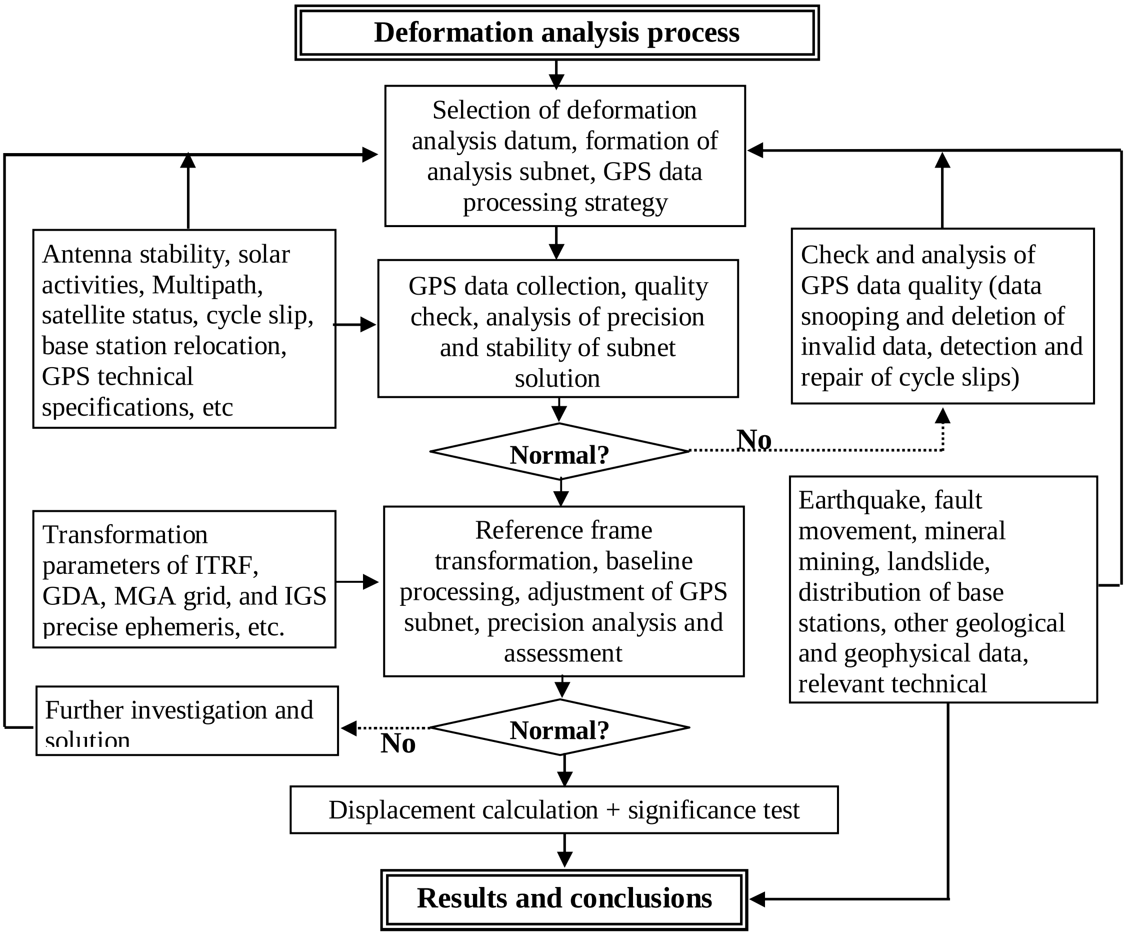


Figure 3. Flowchart of GPSnet data processing and stability analysis

3.2 Formation of deformation analysis subnet

A number of different deformation analyses are required. For example, displacement analysis of the entire GPSnet, local deformation analysis, comprehensive deformation analysis of the effects of multiple factors and individual analysis of the effects of a single factor. For a particular deformation analysis, GPSnet stations should be chosen to form a corresponding optimal deformation analysis network – “subnet”.

The subnet used for a specific deformation analysis should use the same network shape, same deformation analysis datum and compatible precision whenever the subnet data are processed and adjusted. By doing so, potential systematic errors caused by adopting different deformation analysis datums and minimised.

3.3 Data processing strategy of subnet

Given the fact that the velocity of the Earth’ s surface displacement is usually within a few centimetres per year and the current relative baseline precision of GPS measurement is in the order of 10^{-6}~10^{-8}, it is, in general, not necessary to process the GPSnet data continuously or in a short time interval. Instead, the GPSnet data processing should be carried out using an once a year or once a season scenario (so that the surface movement/displacement is large enough to be reliably detected). However, when the Earth's surface is active due to some reasons, the interval of the data processing sessions should be increased accordingly and the session interval can be as high as possible in order to extract real time and kinematic displacement information.

To achieve reliable deformation analysis results, the solution of the deformation analysis subnet needs to be stable and precise enough. The precision and stability of the network solutions are strongly related to the amount of GPS measurements used to generate the solution, which is usually measured in the length of observation time (for a given sampling rate). Research on the amount of data required has been conducted and solutions from a minimal of six hours data are usually considered stable and precise enough for a high precision deformation monitoring and analysis (Dawson et al., 2004). However, there are a number of important factors contributing to the stability of a GPS network solution, such as the length of observation time, the amount of valid data collected, baseline length, quality of GPS signal recorded, the station environment (eg multipath, solar activities, satellite status), and cycle slip, etc. Many of these factors vary with time. Therefore, it is necessary to investigate numerically the proper amount of data required to generate a reliable and precise solution from the deformation analysis subnet.

The precision and stability of GPS network solution can be conducted using precise GPS data processing software, such as GAMIT (Gamit, 2004), BERNESE (Bernese, 2004) or AUSPOS (Dawson et al., 2004). A number of trials are carried out to test the "best" software package for this research and it is found that all three packages give very similar baseline solution. AUSPOS is chosen due to its automation and access to the solutions in different reference frames. AUSPOS allows users to submit their data via the Internet. The RINEX data needs to be static and geodetic quality (ie dual frequency) and the turn–around time of the processing is very short. The quality of the coordinates with 6-hour data is: horizontal precision is better than 10mm and vertical precision is better 20mm (Dawson, 2002). AUSPOS processing report provides coordinates in ITRF, GDA94 and MGA, RMS of observations, precision of coordinates, percentage of observations removed etc. This information is very useful for analysing the precision and stability of the experimental network solution. AUSPOS processing engine uses IGS precise ephemeris products, Earth orientation and station coordinate and velocity parameters and differential technique to several IGS stations. The data processing is undertaken in accordance with the International Earth Rotation Service computation standards.

Note that for same deformation analysis network, the same data processing software should be used whenever the GPS network data is processed and adjusted so that any potential errors caused by different computational models and algorithms can be minimised.

4. PRECISION AND STABILITY OF GPSNET SOLUTION

The longest baseline (Cann River-Irymple, 723km) in Victorian GPSnet with a fixed datum derived from three IGS stations （Hob2，Str1，Tidb）is selected to form an experimental network for precision and stability analyses of the GPSnet (see Figure 4). GPS data preprocessing software “TEQC” (TEQC, 2004) is used for editing and quality check of the GPS data. The precise GPS data processing software AUSPOS is used to generate the solution of the experimental network.

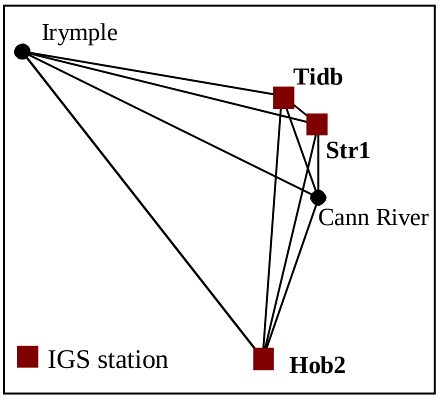


Figure 4. An experimental network for precision analysis of GPSnet solution

The data of the experimental network recorded on 14 April 2004 is used for precision and stability analysis of solutions. Figure 5 shows the relation between precision (m_X,m_Y,m_Z) of coordinates computed (in ITRF2000) and the amount of data used. Figure 6 shows the coordinate differences (dx,dy,dz) between the coordinate derived from different session lengths (amount of data) and the “ground truth” values that are derived from 24 hours amount of data.

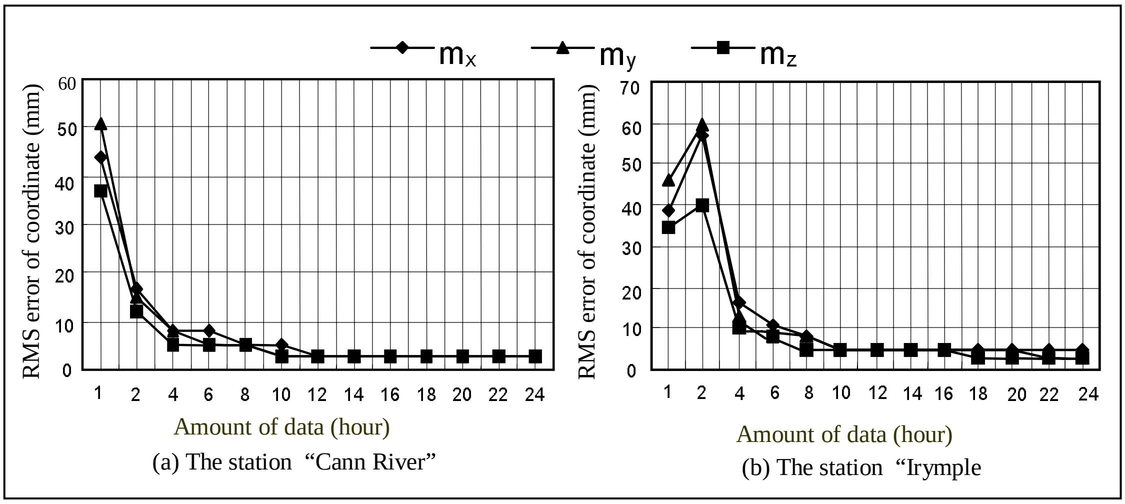
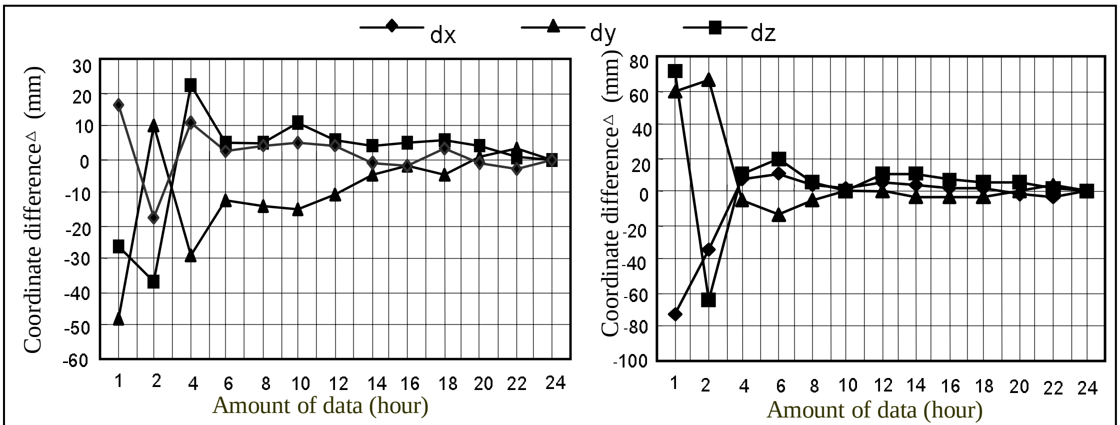


Figure 5. The relation between the Precision of GPS network solution in ITRF2000 and the amount

Figures 5 and 6 indicate that:

(1) Overall, the accuracy of the coordinates derived from different lengths of observations varies and their differences can be up to one decimetre level. The accuracy can be improved when more data is used and the solution is quite stable when more than 20 hours of data is used. The differences of coordinates decrease when the length of the session increases. This means that solutions converge (to the “ground truth”) when the length of data sessions increases.

(2) When the session length is less than six hours, the RMS error of coordinates can be more than 15mm, and the coordinate differences can be more than 20mm, which cannot meet the requirement of a high precision deformation monitoring. In addition, the solution is not stable enough, particularly when the session length is less than 2 hours. Figures 5(b) and 6(b) show that some coordinate differences and coordinate errors derived from 2 hours data are obviously more than those derived from 1-hour data, which are, theoretically, not normal. This is primarily due to bad data quality of "Irymple" station (see Figure 7). The data quality of three IGS stations is best (percentage of data deleted is basically within 10%). The data quality of three IGS stations is best (percentage of data deleted basically less than 10%). The data quality of "Irymple" station is worst (percentage of data deleted is 30~60%). The worst observation sessions fall between 1am-2am, which is most likely the reason that the precision of 2 hours solution is lower than 1 hour solution (Zhang, et al., 2004).



(a) The station "Cann River"   (b) The station "Irymple

Figure 6. The difference between the coordinates derived from different amount of GPS data and that derived from 24 hours data and the relation between the difference and mount of data

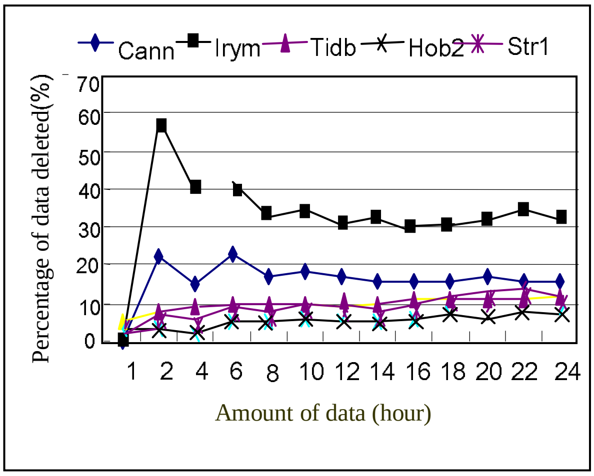


Figure 7. Percentage of GPS data deleted in different observation session

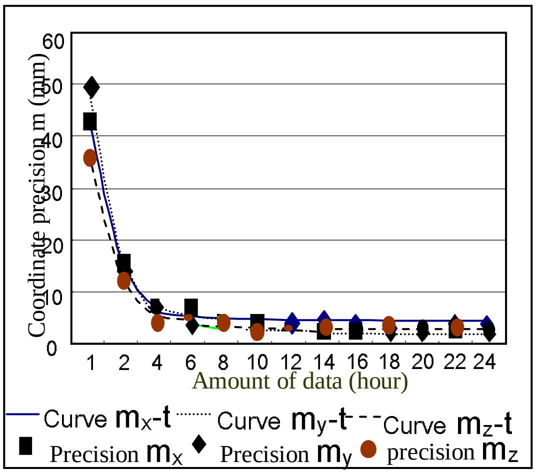


Figure 8. Comparison of the theoretical precision curve and the precision of direct solution

(3) When the length of a session is 12 hours, the coordinate error is about 5mm, and the coordinate differences can be less than 10mm indicating that the solution is relatively stable.

When the session length is close to 24 hours or more than 20 hours, the precision of coordinates is better than 5mm, and the coordinate differences can be less than 5mm, indicating that 24 hours solution has high precision and stability.

The feature and shape of the precision curves indicate that the RMS error of the solution consists of two parts: the fixed error component not relating to the amount of data used and the proportional error which decreases with the increase of the amount of data used. Using the law of error propagation, the coordinate precision of the solution can be expressed as follows:

$$m = \sqrt{a^2 + b^2 \cdot f(t)} \tag{1}$$

where, “m” is the precision of the coordinates, “f(t)” is a function of the amount of data used and “a” and ”b” are the fixed error and the proportional error coefficient respectively. Based on the result of a number of trial computations, it is found that $f(t)$ can be approximated by t^{-3}, ie.

$$m = \sqrt{a^2 + b^2 / t^3} \tag{2}$$

Let $Y = m^2$, $A = a^2$, $B = b^2$, $X = 1/t^3$, equation (1) can be expressed as the following linear equation：

$$Y = A + BX \tag{3}$$

For the station “Cann River”, we get the following equations:

$$m_x = \sqrt{19.853 + 1920.159 / t^3} \tag{4}$$

$$m_y = \sqrt{2.978 + 2585.786 / t^3} \tag{5}$$

$$m_z = \sqrt{7.646 + 1357.213 / t^3} \tag{6}$$

The corresponding correlation coefficients are: $\rho_x = 0.8146$, $\rho_y = 0.9054$, $\rho_z = 0.6468$. Taking a significance level of $\alpha = 0.05$, we get the critical value of correlation coefficient $\rho_0 = 0.553$. Since ρ_x, ρ_y and ρ_z are all bigger than ρ_0, the correlation between the precision of solution and amount of data is strong. The theoretical precision curve and actual precision curve agree well as shown in Figure 8.

From formula (2), it can be seen that “*m*” tends towards “*a*” when “*t*” tends towards “∞”. This suggests that, theoretically, the precision becomes stable if the amount of data is unlimited. The following results can be obtained from formulae (4)~(6):

$$\{(m^2 - a^2)/m^2\}_{\max} < 6\%, \quad \text{when } t = 24 \text{ hrs}$$

This indicates that, in practice, the precision of 24 hrs solution is stable enough.

Based on what is discussed above, it can be concluded that 24-hour solution (or single-day solution) can be used for high precision deformation analysis.

5. CALCULATION AND ANALYSIS OF DEFORMATION

Figure 9 shows the distribution of some geological features (earthquake epicentres, faults and landslides) in Victoria and the spatial position relations between Victorian GPSnet stations and these geological features. There are more than 10 relatively large faults in Victoria and some stations are close to faults and/landslide sites (eg Epson). Victoria, south-eastern Victoria in particular, is one of the regions where both earthquake epicentres and landslide sites are relatively concentrated. There are potential risks of earthquake and landslide in this area. In addition, human activities such as mineral mining can also cause deformation of the Earth's surface. Therefore GPSnet stations can be used to infer both regional deformation of the Earth's surface and the stability of faults and landslide sites.

5.1 Calculation of GPSnet station displacement

A number of factors are taken into consideration when choosing experimental network, length of sessions and epochs of comparisons. These factors include data file losing, improper data format and relocation of some stations. GPSnet data from 14 April 2002 to 14 April 2004 and seven base stations (see Figure 10) are used in this paper for local deformation analysis.

There are 21 simultaneous observation baselines in the subnet. The longest baseline length (Walpeup-Melbourne) is 399km and the shortest baseline length (Colac-Ballarat) is 90km. The subnet is adjusted using the free network adjustment method (with no fixed datum). The absolute displacements in horizontal directions (dE=Easting, dN=Northing) and vertical direction (dU=up direction) of the subnet stations (derived from the transformation of ITRF2000 to Australian Map Grid) are shown in Table 4. The total displacement magnitude "*V*" is calculated by the following formula: $V = \sqrt{(dE)^2 + (dN)^2 + (dU)^2}$. "*V/2*" is the mean annual velocity of the displacement. "dE_r" and "dN_r" are relative horizontal displacements and are free from the systematic horizontal displacement of the whole subnet.

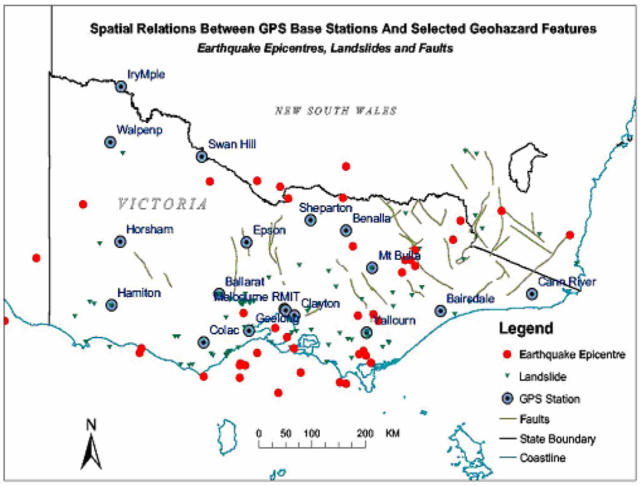


Figure 9. Schematic figure of the displacement vector a selected stations and spatial relations between GPSne stations and geological features

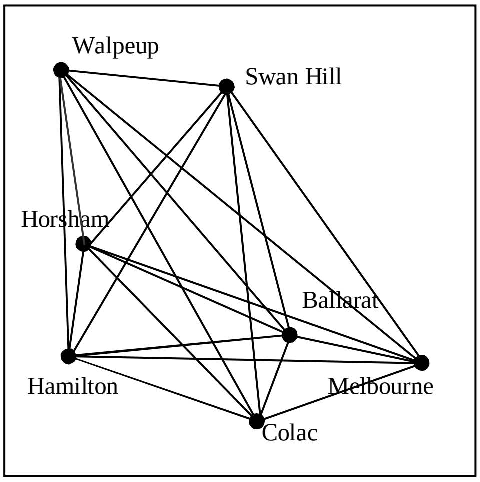


Figure 10. A seven-station GPSnet subnet selected for displacement analysis

Table 4. Absolute and relative displacements of the GPSnet subnet stations

station	Absolute displacement (mm) and velocity (mm/yr)						relative horizontal displacement (mm)		
	dE	dN	dU	V	V/2	significance test	dE_r	dN_r	significance test
Melbourne	21	124	32	130	65	√	-6	-5	×
Ballarat	24	121	25	125	62	√	-3	-8	×
Colac	32	125	18	128	64	√	5	-4	×
Hamilton	35	128	16	134	67	√	8	-1	×
Horsham	20	135	34	139	70	√	-7	6	×
Walpeup	33	138	47	148	74	√	7	9	×
Swan Hill	27	131	45	142	71	√	0	2	×

5.2 Deformation analysis

The significance of both absolute and relative displacements in Table 4 is tested. The displacement significance of both the entire subnet and a single station is tested using F-Test and T-test respectively and its results are listed in Table 4. Symbols "√" and "×" indicate significant and insignificant respectively. It is shown that the absolute displacements of all the subnet points are significant and absolute displacement directions of the subnet points are shown in Figure 11. The average displacement velocity of the subnet points is 6.8 cm/year. Both the magnitude and direction of the absolute displacement of all the base stations in the subnet agree well with the velocity of approximately 7cm/year and direction of current Australia tectonic motion (see Figure 12) derived from other IGS measurements (Geoscience Australia, 2004b).

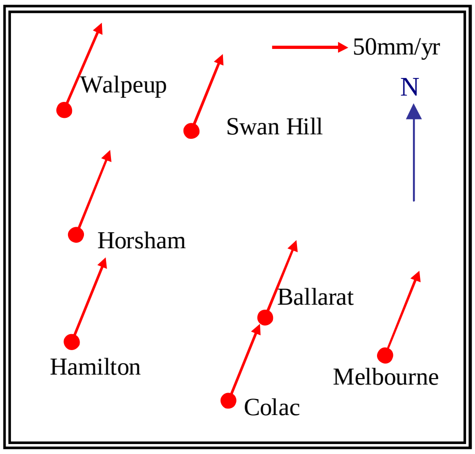


Figure 11. Amplitude and direction of the absolute displacement at the GPSnet subnet stations

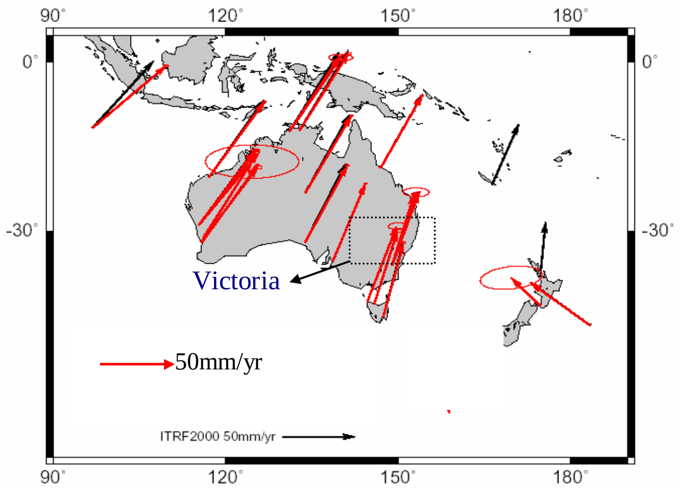


Figure 12. Australian tectonic motion vector from IGS stations (Geoscience Australia, 2004b)

Since the precision of vertical coordinate (height) is about 2-3 times lower than that of horizontal coordinates, the relative vertical displacements of the subnet points are not precise and reliable enough for high precise deformation analysis. Therefore, the relative vertical displacement of the subnet is not analysed in this paper. Significance tests show that the relative horizontal displacements of all the subnet points are not significant. Thus it can be seen that the relative horizontal positions of the subnet points are not notably affected from local geological features, implying that currently, the faults and/or landslide body near these base stations are relatively stable. However, the stability of the faults and landslide bodies needs to be analysed further in future.

6. CONCLUSIVE REMARKS

The precision of the GPS network solution are strongly related with the amount of data used and the corelation can be expressed as $m = \sqrt{a^2 + b^2 / t^3}$. The precision of the solution can be quickly improved with the increase of the amount of GPSnet data used for up to 6-hour and then the precision of the solution can only be slowly improved when the amount of data is more than 6 hours. The solution of CORS stations in Victoria (GPSnet) is not enough precise and stable for high precise deformation monitoring and analysis if the amount of data used to generate the solution is less than 6 hours. The precision of three-dimensional coordinates in ITRF2000 derived from daily GPSnet solution (24 hours amount of data) is better than 5mm and the solution is quite stable. This can meet the requirements of high precision deformation analysis. Therefore, continuous tracking data from GPSnet is a very valuable asset and can provide a technically-advanced and cost-effective geoscientific infrastructure for the regional deformation monitoring and analysis.

The average velocity of the displacement at subnet points is 6.8 cm/year. Both the magnitude and direction of the whole subnet displacement agree well with the velocity of approximately 7cm/year and direction of current Australian continent derived previously. The relative horizontal positions of the subnet points are not notably affected from local geological features. This implies that the faults and/or landslide bodies near these stations are relatively stable.

Preliminary results indicate that the methodology of data processing and deformation analysis is feasible and effective. However, further investigation is required when more GPSnet data is used to cover a larger chronological span and more GPSnet stations are used for deformation analysis. It is recommended that geological information needs to be taken into account when any new CORS stations are established. The improvement of data quality, stability of antenna, precision and reliability of the GPSnet solution will be of great help in the analysis of both absolute and relative displacements of the GPSnet stations. It is, therefore, anticipated that the GPSnet will play an important role in the regional deformation monitoring and analysis.

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